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Integrated Airport Surface Operations

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Abstract

The current air traffic environment in airport terminal areas experiences substantial delays when weather conditions deteriorate to Instrument Meteorological Conditions (IMC). Expected future increases in air traffic will put additional pressures on the National Airspace System (NAS) and will further compound the high costs associated with airport delays. To address this problem, NASA has embarked on a program to address Terminal Area Productivity (TAP). The goals of the TAP program are to provide increased efficiencies in air traffic during approach, landing, and surface operations in low-visibility conditions. The ultimate goal is to achieve efficiencies of terminal area flight operations commensurate with Visual Meteorological Conditions (VMC) at current or improved levels of safety.

During the last year, research activity culminated in the development, flight test and demonstration of a prototype Low-Visibility Landing and Surface Operations (LVLASO) system. A NASA led industry team and the FAA developed the LVLASO flight test system, integrating airport surface surveillance, aeronautical data link, DGPS navigation, automation systems, and controller and flight deck displays and interfaces. The LVLASO system supports both controllers and flight crews with guidance, control and situational awareness information to achieve improved efficiencies and safety of surface operations in IMC weather conditions. The LVLASO system was tested and demonstrated to a wide range of aviation industry members at the Atlanta Hartsfield International Airport during August, 1997.

This report describes the demonstration system and documents the activities pertaining to the development of the LVLASO demonstration system as part of the ATOPS Task 16 contract. In addition to the development and support of the LVLASO demonstration system this task also examined future TAP data link and to a lesser extent the avionics equipment and integrity requirements that must be considered for future LVLASO deployment.

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1.0 Introduction

With the advent of global, satellite-based navigation and data link communications technology, the aviation industry is now able to address air space solutions that provide for more efficient and safe air travel. Two such areas are the Future Air Navigation System / Air Traffic Management (FANS/ATM) system and airport terminal area capacity improvement initiatives. At present, much of the industry's focus is on the development of the Communications, Navigation and Surveillance (CNS) / ATM system with primary focus on enroute operations since immediate cost benefits are expected. One of the end goals of CNS/ATM is free flight, supported by seamless aeronautical data link communications, automatic dependent surveillance, and air traffic management by Air Traffic Control (ATC).

NASA Langley and NASA Ames Research Centers are also working to improve airport capacities via the Terminal Area Productivity Program (TAP). NASA's TAP Program is intended to support the industry with the development of appropriate technologies and system solutions, and also to involve industry in achieving improved efficiency and safety of terminal area operations, particularly during low-visibility weather conditions.

This report is in support of NASA's TAP program, addressing Low Visibility Landing and Surface Operations (LVLASO). Specifically, this report documents the activity related to NASA's Industry Demonstration and Flight Tests of LVLASO Technologies this past August at the Atlanta Hartsfield International Airport.

TAP Overview

The goal of NASA's TAP program is to achieve clear-weather capacities in terminal area operations in instrument weather conditions. Objectives are to develop and demonstrate integrated systems technologies and procedures that enable productivity of the airport terminal area to match that of visual conditions.

The four major components of TAP are 1) Low-Visibility Landing and Surface Operations (LVLASO), 2) Reduced Separation Operations (RSO), 3) Air Traffic Management, and 4) Aircraft and ATC Systems Integration.

LVLASO objectives are to develop and demonstrate an aircraft navigation, guidance and control system for surface operations to achieve or exceed safety and efficiency of visual operations under non-visual operations down to Cat III B conditions, while being compatible with evolving surface movement ground control automation. To accomplish these objectives, NASA has developed the Taxiway Navigation and Situational Awareness (T-NASA) system, which provides the flight crew with guidance and situational awareness information using integrated cockpit displays. In addition to T-NASA, LVLASO also includes the development of a dynamic runway occupancy measurement (DROM) system to determine the proper spacing of aircraft pairs during landing. LVLASO also addresses a high-speed Roll-Out Turn-Off (ROTO) system which assists the crew to achieve or improve upon visual condition runway occupancy under non-visual conditions.

RSO objectives are 1) to develop an Advanced (Wake)Vortex Spacing System (AVOSS) to be coupled with appropriate ATC automation aids, allowing dynamic separation standards for aircraft pairs; 2) to develop a capacity enhancing concept for integrating current flight management system (FMS) capabilities with emerging ATC automation aids, and 3) to develop and demonstrate a flight-deck based monitoring / surveillance system of aircraft on simultaneous, independent parallel approaches, allowing a reduction in parallel runway spacings to less than 3,400 ft during non-visual conditions.

Objectives of TAP Air Traffic Management are to develop and demonstrate enhanced Center TRACON Automation System (CTAS) automation aids to more fully utilize FMS and data link capabilities for increased airport capacities, utilize CTAS enhancements to incorporate dynamic separation standards and enable closely-spaced runway operations, and to allow for rapid reconfiguration of operational runways and airspace for terminal area operations.

Aircraft-ATC system integration objectives are to develop systems modeling / studies as tools to support TAP objectives and to provide guidelines for ongoing research and development, to improve understanding of root causes of inefficiencies in operations, project cost benefits for proposed concepts, develop procedures and technical solutions for safe and effective integration of flight deck and ATC operations, and to provide integrated flight test capability to demonstrate TAP products.

Flight tests and demonstration are planned in each area of TAP, with eventual integration of all TAP components into an overall demonstration of Terminal Area Productivity. The flight test and demonstration of the LVLASO system at Atlanta earlier this year was a major milestone for NASA in its TAP / LVLASO program goals.

Organization of Report

The primary activity of this task contract was to provide technical and equipment support for NASA's flight tests and subsequent industry demonstration of Low-Visibility Landing Approach and Surface Operations (LVLASO) technologies at Atlanta's Hartsfield International Airport. Subsequently the major portion of this report focuses on the development of the LVLASO demonstration system and available flight test results. Section 2 provides a top-level description of the LVLASO system that was demonstrated. Section 2 also examines each of the individual LVLASO sub-systems that were supported as part of the larger industry team in more detail, including description of interfaces, protocols and test results. In addition to avionics support to NASA's LVLASO demonstration, additional study activities were as follows:

1) Develop data link requirements for NASA's Terminal Area Productivity (TAP) program, i.e., data link requirements for terminal area operations in the future CNS/ATM airspace system.

2) Examine aircraft integration and avionics integrity issues related to providing Integrated Surface Operations capabilities to new and retrofit aircraft.

Section 3 discusses TAP data link and Section 4 addresses aircraft avionics equipment, integration and integrity issues related to LVLASO.

2.0 LVLASO Flight Test / Demonstration System Description

This section provides a description of the LVLASO system that was tested and demonstrated at the Atlanta Hartsfield International Airport during August, 1997. The Atlanta LVLASO test system represents a significant integration of several complex sub-systems by NASA, FAA and a number of industry partners. The majority of these sub-systems are expected to play an important role in the future CNS/ATM airspace system that will be used to provide benefits for both, free flight and also airport surface operations.

Before discussing the Atlanta LVLASO system that was implemented, it is useful to briefly review the expected components of an end-state Integrated Surface Operations system (such as the Airport Surface Movement Guidance and Control System {ASMGCS} concept being developed by RTCA SC-159). This allows a comparison of the generic end-state system with the one that was tested and demonstrated at Atlanta.

2.1 System Overview of Integrated Surface Operations

An Integrated Surface Operations / ASMGCS system has a diverse set of requirements that it must address and requires a wide range of technologies and system interactions to achieve high-traffic density operations during low-visibility conditions. This system must be capable of providing precise guidance and control for a range of aircraft and vehicle types throughout the airport movement and ramp areas in all types of weather conditions. The system must provide adequate separation and taxiway/runway incursion protection (especially in low-visibility conditions) and must provide planning and management of traffic in high-traffic densities and for complex airport layouts. The Surface Operations / ASMGCS system must also be compatible with the overall Air Traffic Management system that enables gate-to-gate operations.

Figure 2-1 provides a conceptual illustration of an Integrated Surface Operations system. Top-level system functions are surveillance, traffic routing, guidance, control, and detection and prevention of taxiway/runway incursions. In addition, data link plays a key role in enabling communications between end users and the various surface operations sub-systems.

Some of the technologies and systems that will likely play a role in an Integrated Surface Operations / ASMGCS system are:

1. Satellite-based navigation (Global Navigation Satellite System, GPS)
    a) Local Area Augmentation System (LAAS)
    b) Wide Area Augmentation System (WAAS)
2. Data link
3. Surveillance
4. Advanced information presentation displays
5. Ground automation systems
    a) Surface Movement Advisor (SMA) providing traffic routing and planning
    b) Airport Movement Area Safety System (AMASS) providing runway incursion alerts
    c) Smart airport lighting, e.g., SMGCS
6. Airport data bases
7. Airport lighting
8. High-speed Roll-out Turn-Off (ROTO)
9. Head-up displays
10. Enhanced Vision Systems

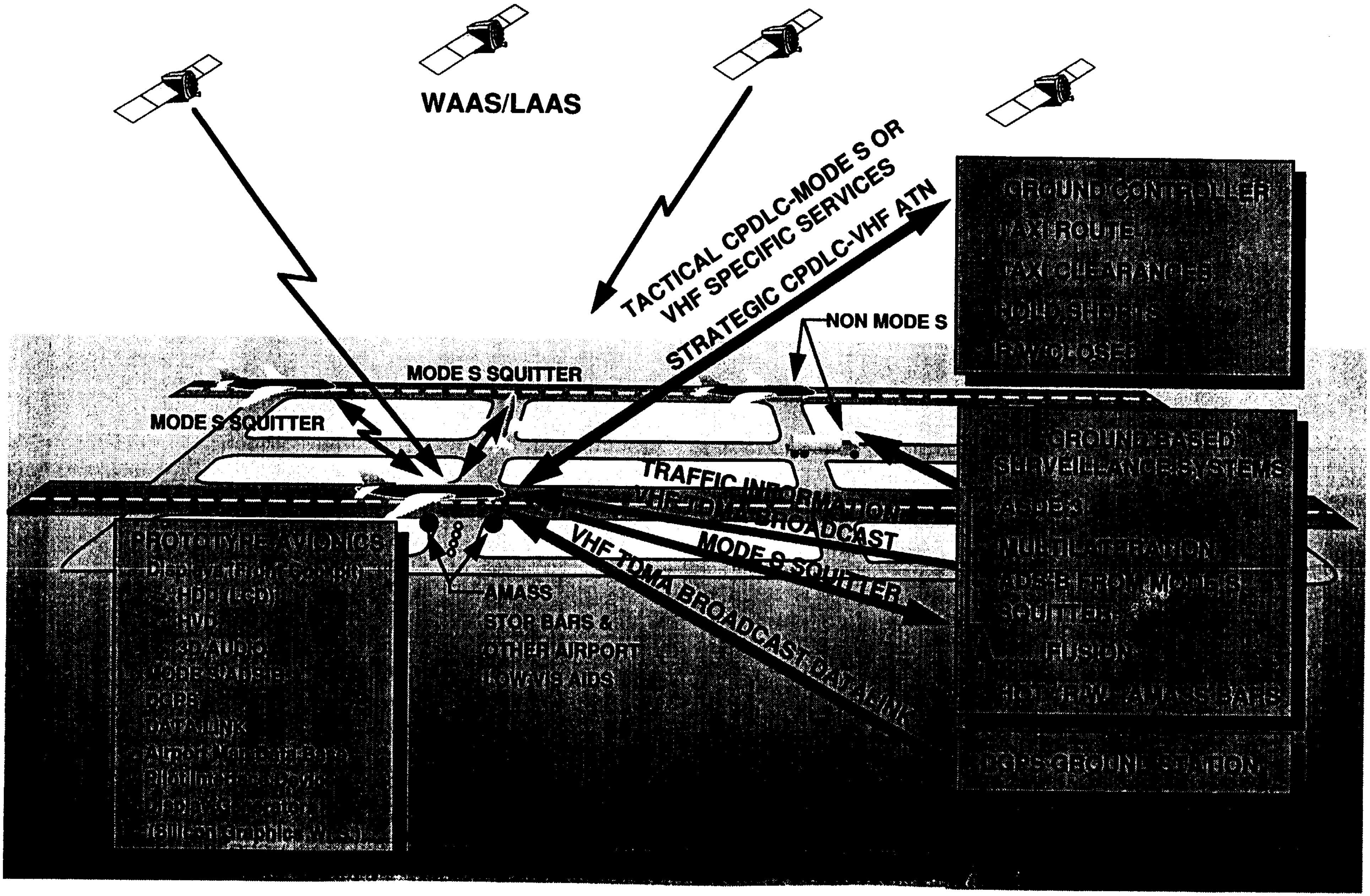


Figure 2-1 Integrated Surface Operations System Concept

2.2 *LVLASO Demonstration System*

The system demonstrated at Atlanta consists of several subsystems that were integrated to provide the intended capabilities of increased situational awareness and guidance information to air traffic controllers and pilots in conducting efficient and safe surface operations. Both ground sub-systems and airborne sub-systems provide services to meet the overall operational goals.

2.2.1 LVLASO Ground System Architecture

The LVLASO ground system is shown in Figure 2-2 and consists of the following sub-systems:

1. Surface surveillance sub-system
    a) Airborne Surface Detection Equipment (ASDE-3) surface radar (skin-paint radar, counterpart to primary radar used in enroute surveillance).
    b) Airport Traffic Identification System (ATIDS)
        - Multilateration surveillance on transponder transmissions (signal received by multiple sites, position calculated from time-of-arrival of signals at each site)
        - Automatic Dependent Surveillance broadcast (ADS-B) (GPS position reports using Mode-S extended squitters)
    c) Airport Movement Area Safety System (AMASS)
        - Automation system that provides runway incursion warnings
        - Data fusion of surveillance reports from ASDE-3, ATIDS and ARTS (Automated Terminal Radar System)
2. VHF Traffic data link (broadcast uplink of traffic information and runway holdbars)
3. Differential GPS (DGPS) base station and VHF DGPS data link (broadcast uplink of DGPS corrections information)
4. Controller Pilot Data Link Communications (CPDLC)
5. Data Acquisition
   (data recording of all ground system data transactions, e.g., DGPS uplink information, CPDLC messages, and Traffic Data)

The physical location of ground systems was as follows: 1) surveillance systems and VHF Traffic data link were located at the Atlanta control tower; 2) the DGPS base station, VHF DGPS data link, the Controller Interface, and one of the five ATIDS (or CAPTS) Receiver/Transmitters (ground portion of Mode-S link) were located at the Renaissance Hotel located immediately to the North of the airport.

A room in the Renaissance Hotel was set up as a pseudo ATC tower cab, with a test controller serving to intercept actual controller voice communications to the NASA 757 research aircraft (which served as the test vehicle) and converting them to data link messages. A remote AMASS display was provided via modem link to provide the surface traffic display that controllers typically see. Video telemetry of live video of NASA 757 aircraft displays (head-down taxi display (HDD) and the head-up display (HUD)) and outside visual scenes from nose and tail-mounted cameras on the 757 was provided for viewing in the hotel "demonstration" room.

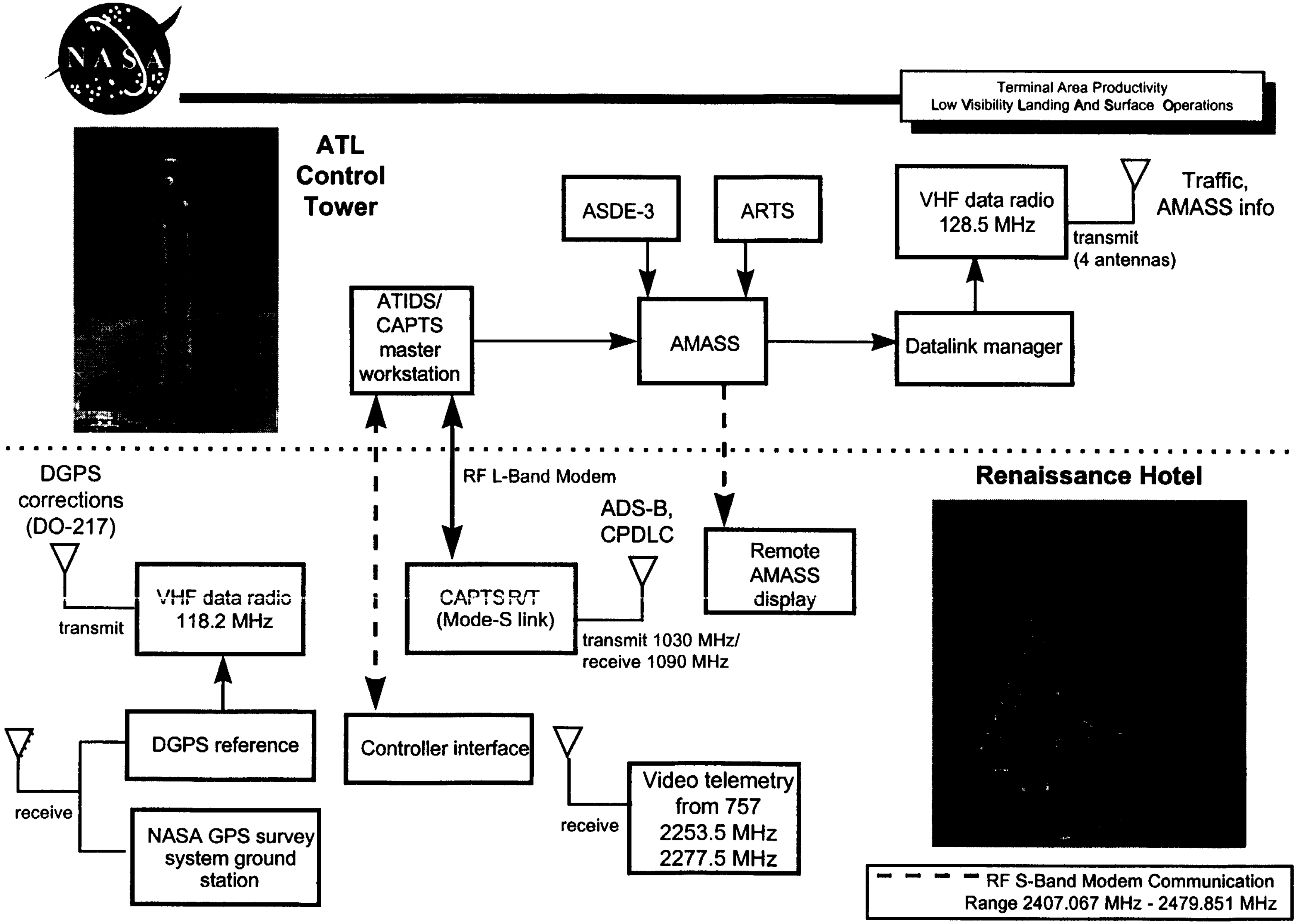


Figure 2-2 LVLASO Ground System

2.2.2 Airborne Systems

The NASA 757 experimental system architecture is shown in Figure 2-3. LVLASO aircraft sub-systems are as follows:

1. Data Links
    a) VHF Traffic broadcast data link receiver
    b) VHF DGPS broadcast data link receiver
    c) CPDLC via Mode-S link
    d) ADS-B downlink broadcast using Mode-S extended squitters
2. Airborne GPS receiver
   (provides DGPS position accuracies using DGPS corrections inputs from VHF DGPS data link)
3. Displays
    a) Airport moving map LCD display (HDD)
    b) Roll-out, turn-off and taxi guidance HUD
4. Pilot input device
   (allows pilot to select display modes and zoom levels; also serves as data link acknowledgment to CPDLC messages).
5. Data acquisition system
   (data recording of all aircraft system data transactions, e.g., received and transmitted data link messages, GPS sensor outputs, etc.)

The next section examines each of the LVLASO sub-systems that were supported by Collins in more detail and includes performance results where they are available. The LVLASO sub-systems supported by Collins are:

1) DGPS base station
2) VHF data links
    a) Traffic broadcast transmitter and receiver
    b) DGPS broadcast transmitter and receiver
3) Airborne GPS sensor
4) Mode-S transponder and associated Airborne Data Link Processor (ADLP)
   (The ADLP provides the Mode-S Specific Services (MSSS) for ADS-B and CPDLC)
5) LCD Head Down Display (HDD) taxi display and Remote Interface Unit (RIU)
   (RIU provides interface between NASA Silicon Graphics computer and the LCD HDD)

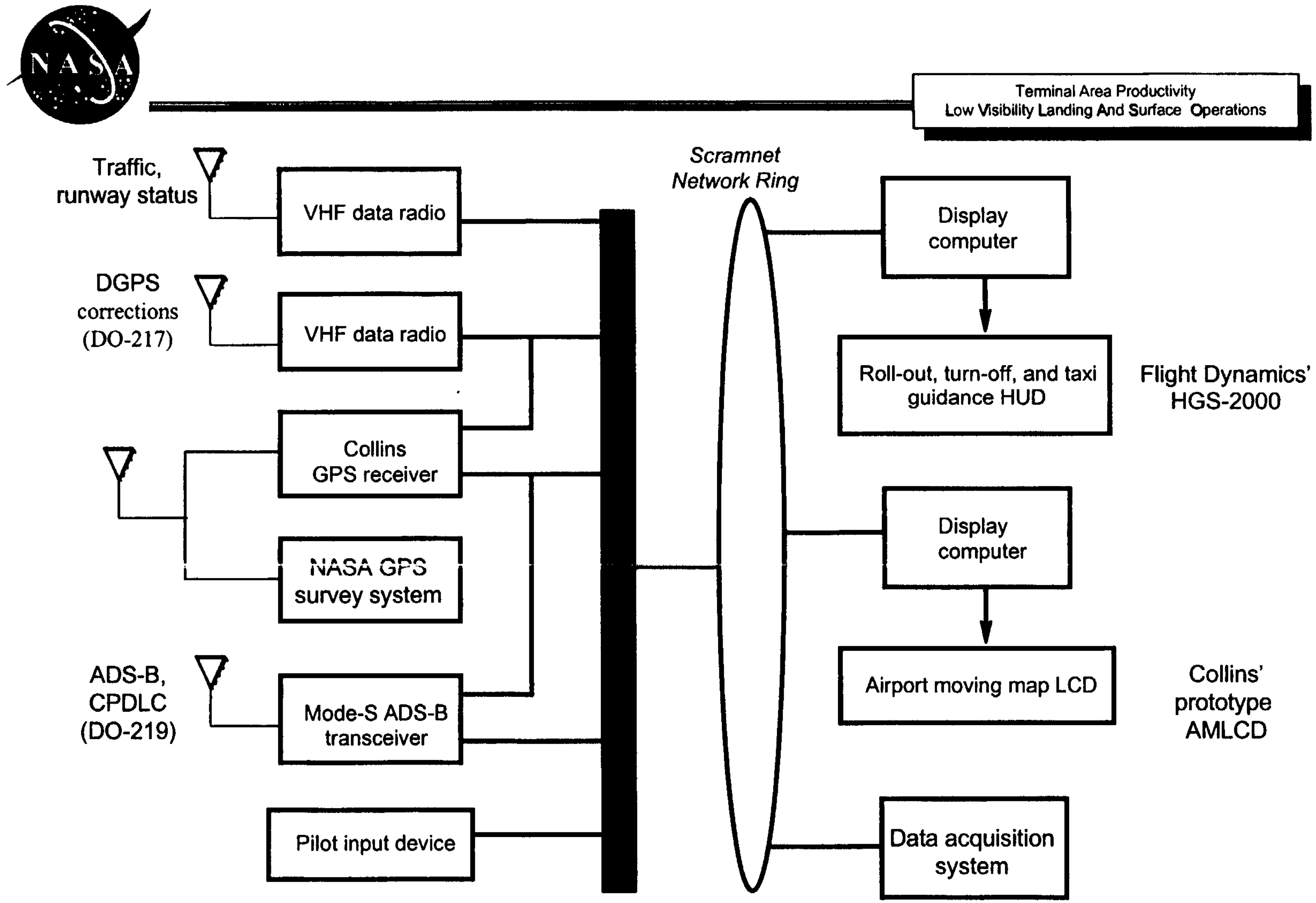


Figure 2-3 NASA 757 Experimental System Architecture

2.3 *LVLASO Sub-System Description and Performance Results*

This section describes each sub-system in more detail and, when available, provides performance results and observations based on data collected during preliminary sub-system tests and also during the actual LVLASO flight tests and industry demonstrations.

2.3.1 DGPS Sub-System

A Collins DGPS base station provided the DGPS corrections information, which was then broadcast via VHF DGPS data link. Figure 2-4 shows the DGPS base station and VHF data link configuration. A Collins GNR-4000 GPS receiver in the NASA 757 provided DGPS position reports for use by aircraft systems. NASA used a GPS survey system on the ground and onboard the aircraft (Ashtec GPS) to record "truth" position data for later post-processing. Initial DGPS performance results indicate the following performance for a 30 minute flight test run (other runs appear similar):

1) Horizontal RMS position error (mean = 0.728 m, standard deviation = 0.485 m)
2) Cross track error (mean = 0.056 m, standard deviation =0.494 m)
3) Along track error (mean = -0.142 m, standard deviation =0.706 m)

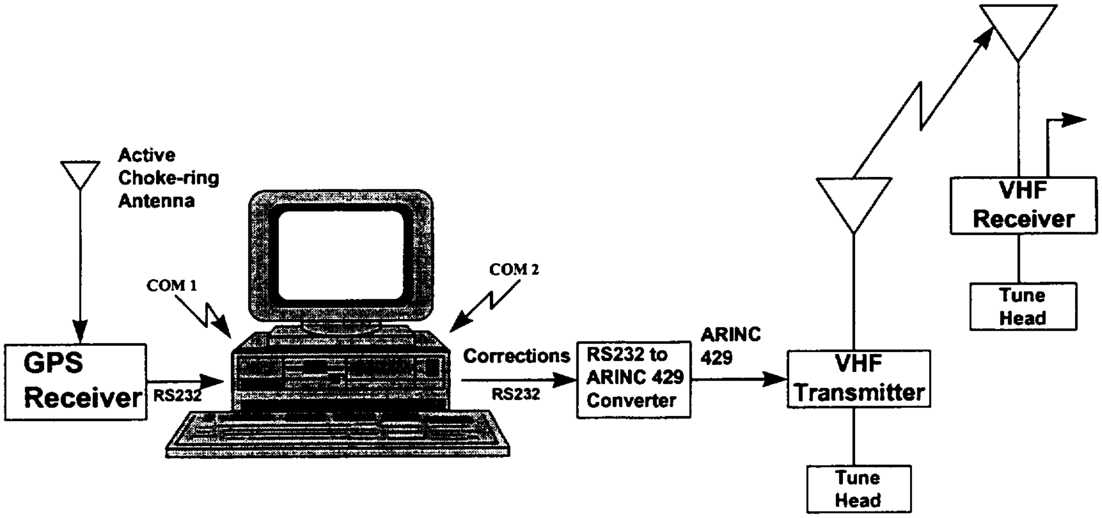


Figure 2-4 Differential GPS Base Station and VHF Data Link

2.3.2 VHF Data Links

Two identical pairs of broadcast VHF data links were utilized for 1) DGPS corrections uplink and 2) Traffic and AMASS runway holdbar information uplink. The VHF data links are prototype 31.5 kbps, D8PSK modulation radios similar to those planned for SCAT-I data link (RTCA DO-217, Appendix F).

2.3.2.1 VHF DGPS Data Link Coverage Tests (Van Taxi Tests)

In preparation for the formal LVLASO flight tests and demonstrations, VHF data link coverage tests were conducted on two separate occasions at Atlanta's Hartsfield. The purpose of the initial test was to determine siting locations and expected airport surface coverage of the two VHF data links and their respective applications. The VHF data link applications that are critical to the successful demonstration of the LVLASO system are 1) DGPS corrections broadcast uplink, and 2) Traffic / AMASS holdbar uplink (broadcast of surveillance information for use in the cockpit, i.e., LCD HDD).

The initial test was conducted October, 1996, and utilized two VHF transmitters located at two separate sites; 1) on the Hartsfield control tower, and 2) on top of the Renaissance Hotel located directly to the North of the airport (see Figure 2-5 below for the location of both sites relative to the airport layout). Using DGPS corrections inputs from separate DGPS base stations, both VHF transmitters transmitted this information at a one second rate. A van was equipped with two identical VHF pallets, each containing a VHF broadcast receiver and a Collins GNR-4000 GPS receiver which processed the DGPS correction outputs of the VHF data link to compute DGPS position. The GPS receiver, in addition to providing DGPS position outputs at a one second rate, was modified to also provide an indication of whether or not a DGPS data link message was received, and if so, whether the CRC error correction code was successfully decoded indicating an error free message. A 24-bit CRC was used based on an earlier version of the GPS ARINC Characteristic 743.

Taxi Routes

Airport surface coverage tests were performed by taxiing the airport surface while recording the GPS position and data link status information. It was thus possible to plot data link status as a function of location on the airport. Two distinct coverage routes were traversed in the coverage test: 1) ramp areas and the airport loop road surrounding the airport, and 2) all runways and taxiways. In ramp areas, maximum line-of-sight (LOS) blockage areas were traversed to the greatest extent possible to determine data link performance. These areas are primarily near the West walls of the passenger terminal buildings. Figures 2-5 and 2-6 illustrate the two coverage routes. Taxi tests were conducted during the night to gain access to the airport surface when traffic was low.

VHF Frequency Assignments

Two frequencies were assigned to the coverage test by the FAA; 118.2 MHz and 128.5 MHz. These assignments were maintained for all tests conducted at Atlanta, with the control tower VHF transmitter tuned to 128.5 MHz, which ultimately was used for VHF Traffic / AMASS holdbar data link, and the Renaissance Hotel VHF transmitter tuned to 118.2 MHz for VHF DGPS data link.

Antennas - Polarization and Placement

Both vertically and horizontally polarized antennas were tested to determine the effects of polarization on surface coverage. Several types of antennas were used: 1) folded dipole antennas that were oriented either vertically or horizontally (primarily at the control tower and the hotel, 2) a magnet-mount whip antenna for the van, and 3) a turnstile antenna, consisting of two crossed dipoles, for omnidirectional horizontal polarization.

Figures 2-7 and 2-8 show antenna placement at the control tower and the Renaissance Hotel, respectively. Since the control tower has four balconies (NW, NE, SE, SW corners), it was decided to place a dipole antenna at each balcony to avoid any potential blockage effects to LOS by the tower. Figure 2-7 shows one of the vertical dipole antennas pointing to the NW. The Renaissance Hotel is visible to the North of the airport (visible just to the left of the dipole antenna). Figure 2-8 shows a vertical dipole pointed to the South from the hotel. During the actual LVLASO test with the NASA 757, a horizontal turnstile antenna was used and was located closer to the SE corner of the hotel roof. While antenna placement at the hotel was optimum for surface operations, it was not ideal for terminal area operations. From Figure 2-8 it is apparent that the additional ~30 ft structure seen to the North of the antenna on the hotel roof does provide some signal blockage, primarily toward the NW direction. During flight tests with the NASA 757 in flight, some degradation in the data link was observed in the NW corner of the terminal area and this is directly attributable to the antenna siting. Flight test data link plots are shown later in this section.

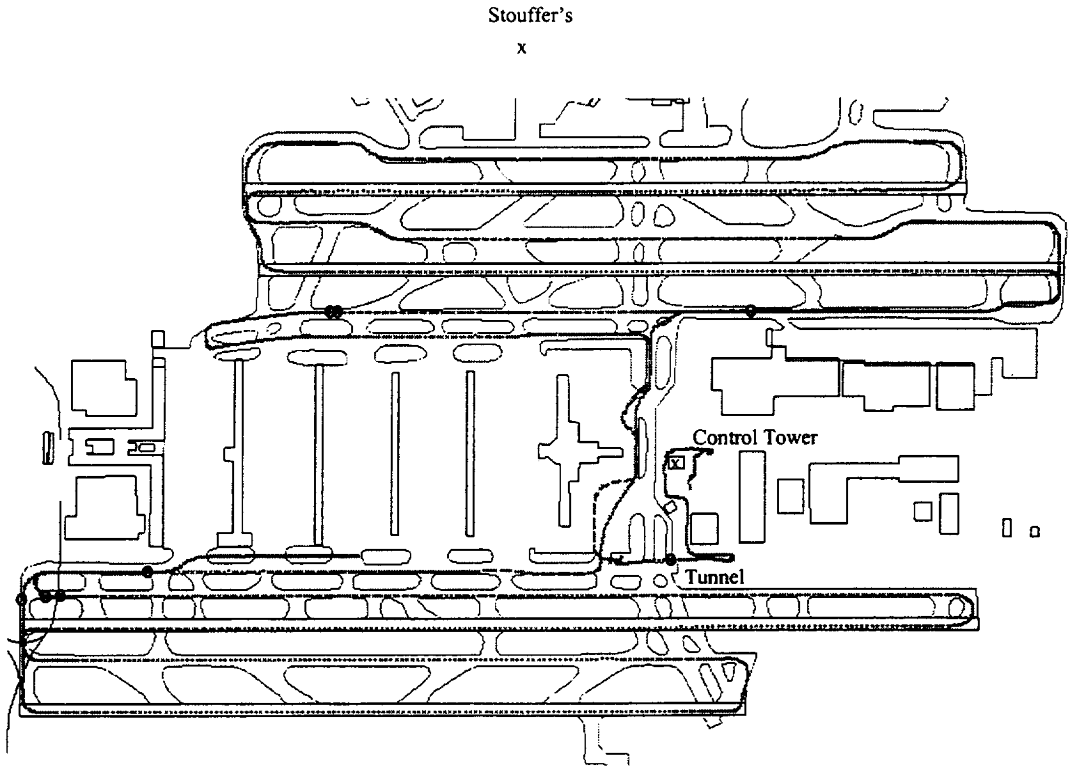
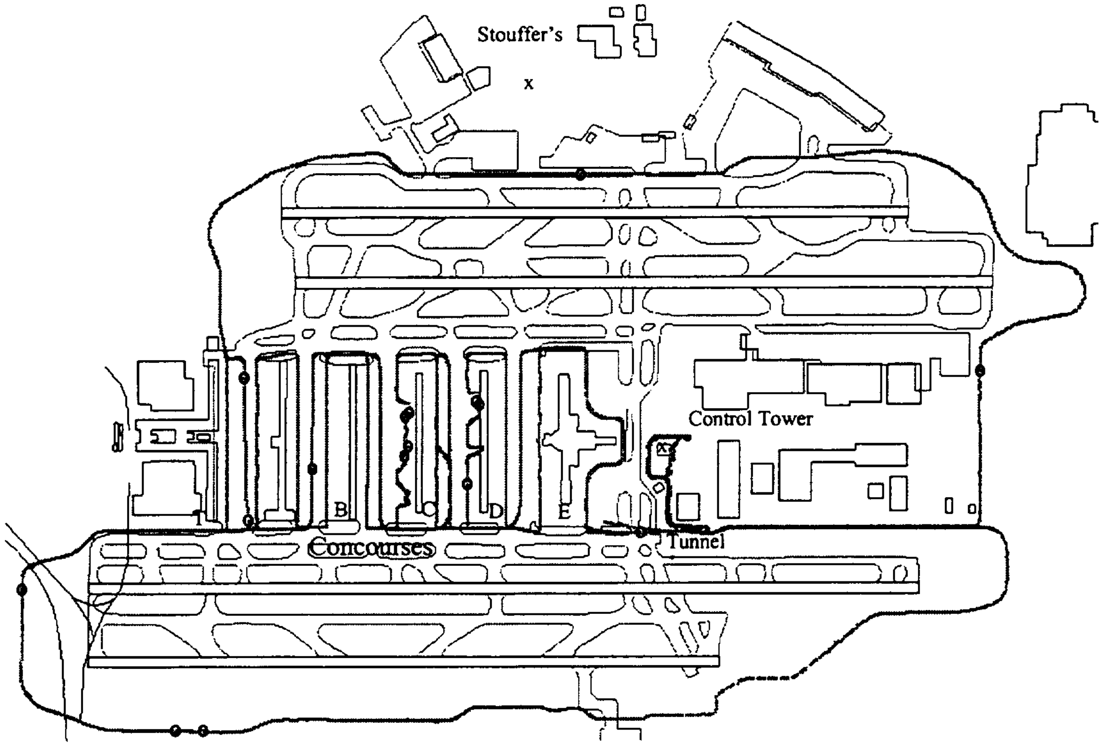


Figure 2-5 Coverage Test of Runways & Taxiways (Control Tower using Vertical Polarization)



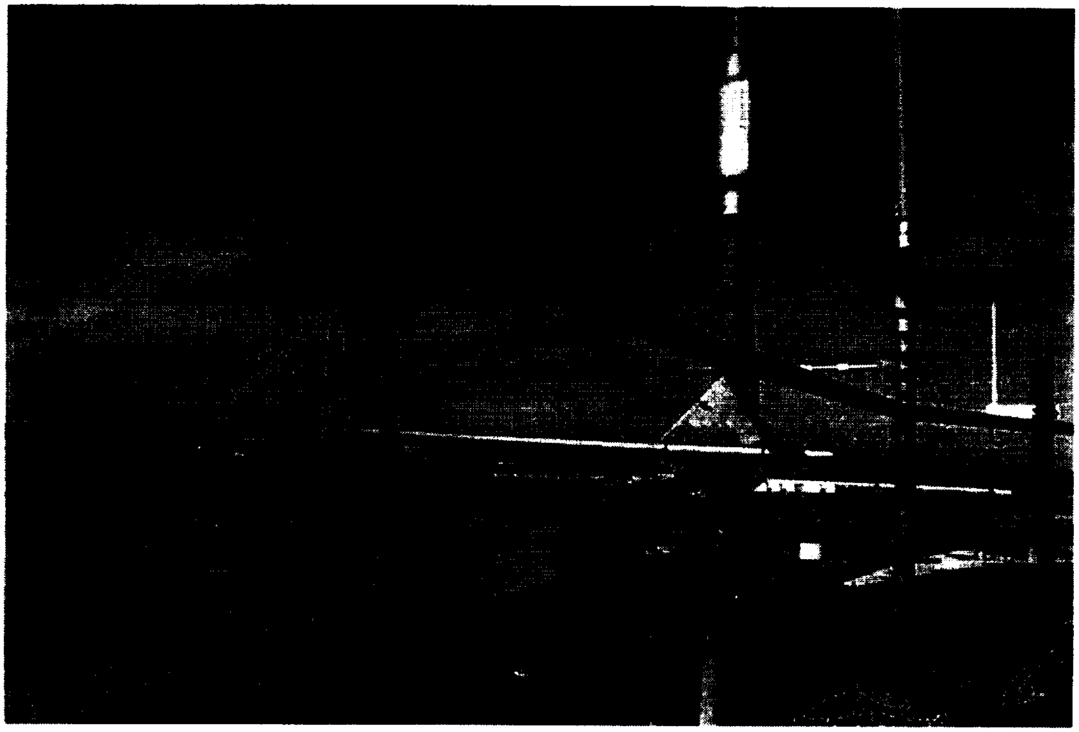


Figure 2-7 Control Tower Antenna Installation

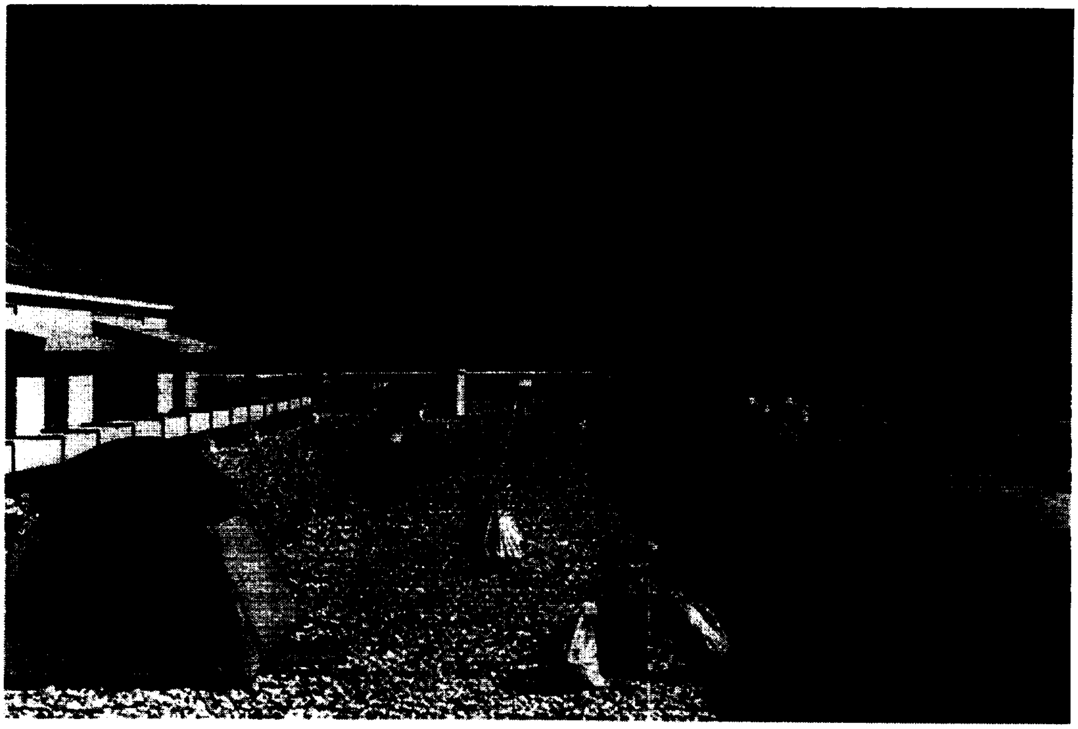


Figure 2-8 Renaissance Hotel Antenna Installation

DGPS Coverage Test Result Summary

The October 1996 VHF DGPS coverage test indicated that both the Control Tower and the Renaissance Hotel each provided excellent coverage of the airport surface. Message reception rate was excellent at ~ 99.75 % for all data link messages sent for all tests combined. There was no difference in performance for vertical and horizontal polarization. The primary areas where some messages were lost occurred along the West walls of the terminal buildings, which provide severe LOS blockage and in the NW corner of the South half of the airport, again where terminal buildings provide blockage. Some signals were also lost along the loop road, but these occurred in regions where the loop road was at least 50 ft below the level of the airport surface itself. Tables 2-1 and 2-2 summarize performance results for the October coverage test. A complete description of the coverage test results are provided in Appendix A, which contains a paper written for the ICAO GNSS Panel describing the Atlanta DGPS coverage test.

Probability of correctly receiving a single message per number of attempts	**Control Tower**	**Stouffer's Hotel**
Single attempt	99.77%	99.73%
Two attempts	99.97%	99.94%
Three attempts	99.995%	99.968%
Four attempts	100%	99.986%
Five attempts	100%	99.995%
Six or more attempts	100%	100%

Table 2-1 Message Reception Probability vs Number of Transmission Attempts (van tests)

	Control Tower	**Stouffer's Hotel**
Vertical Polarization, Ramp Area	99.75 % coverage, greatest difficulty on West side of Concourses C and D	99.85 % coverage, greatest difficulty between Concourses T, A, and B
Horizontal Polarization, Ramp Area	99.6 % coverage	99.5 % coverage
Vertical Polarization, Runways and Taxiways	99.77 % coverage, almost perfect coverage, a few minor exceptions on NW corner of South half	99.94 % coverage, nearly perfect coverage
Horizontal Polarization, Runways and Taxiways	99.95 % coverage, nearly perfect coverage	99.67 % coverage, almost perfect coverage except NW corner of South half

Table 2-2 Qualitative Comparison of Transmit Site Performance (van tests)

The April 1997 test confirmed the results of the earlier test but also provided additional information concerning the VHF Traffic / AMASS holdbar data link. When transmitting DGPS, only ~ 1/4 to 1/3 of the maximum message length of the data link is used. For traffic and AMASS holdbar information during high traffic times, full length messages are used, thus a test was conducted to determine coverage for long messages. As expected, message reception rate for long Traffic messages dropped somewhat to 97.75 % in regions of severe LOS blockage. This confirmed that the link would work reliably for the LVLASO test.

Based on the coverage test results, it was decided to 1) transmit DGPS from the Renaissance Hotel at 118.2 MHz using horizontal polarization, which concurs with ICAO and RTCA standardization activity for DGPS data link, i.e., DGPS data link in the aeronautical navigation band (108 to 118 MHz) uses horizontally polarized signals-in-space, and 2) transmit VHF Traffic / AMASS holdbars from the control tower at 128.5 MHz, since the LVLASO surveillance sub-system is also located there.

Interface definitions and protocols used in the LVLASO flight test system for VHF DGPS data link are shown in Appendix B.

2.3.2.2 VHF Traffic and AMASS Holdbar Data Link

The VHF data links used for broadcast uplink of traffic and AMASS holdbar from the surveillance system were the same type of radio used for VHF DGPS data link. As indicated earlier, the VHF Traffic data link transmitter was located at the Hartsfield control tower and used vertical polarization at a frequency of 128.5 MHz. For the LVLASO flight test a top-mounted, conventional VHF Comm blade antenna was used on the NASA 757 for reception of traffic data. Traffic reports were uplinked once per second. In addition, each second an AMASS runway status message was sent indicating whether or not runway / taxiway intersections are "hot", i.e., not to be crossed, due to an active runway. These runway holdbars are displayed on the HDD for runway incursion situational awareness.

Traffic information and AMASS runway status is output by AMASS each one second surveillance scan. Traffic data is collected and formatted by the Data Link Manager (developed by PMEI Inc., refer to Figure 2-1) for transfer to the VHF data link transmitter. The Data Link Manager takes as many targets as are available (up to 15) to build a single transmit message. For the worst case traffic loads of 40 to 50 aircraft observed during the Atlanta LVLASO tests, up to 3 to 4 maximum length messages are transmitted per second. This is well within the capabilities of the data link. As indicated above, due to the increased message lengths of Traffic messages, a slight reduction in message success rates was observed during van coverage tests; message reception rates decreased to ~97.5 % primarily in the presence of severe LOS blockages.

The VHF Traffic data link performed reliably throughout the LVLASO flight tests and industry demonstration. However, due to the deficiencies of the surveillance system (discussed previously), when the surveillance system fails traffic information becomes unavailable for transmission. As mentioned previously, latency between actual position and displayed position of traffic on the HDD was ~ 2 seconds and was most noticeable for aircraft on take-off or landing.

Traffic / AMASS Message Formats

The physical interface to the VHF Traffic / AMASS holdbar data link is an ARINC 429 bus. The message transfer protocol is described in Table 2-3. From Table 2-3 each ARINC 429 word contains two bytes of user data. The first ARINC 429 word using Label "045" provides the message length and indicates the number of Label "046" data messages that are to follow. The subsequent Label "046" ARINC 429 words contain the data to be transmitted. The maximum length message is 249 bytes or 125 ARINC 429 words.

Tx Seq	32	31 30	29…………………….22 21…………………….14	13..11	10 9	8…….. 1
N/A	Parity	SSM	Spare (3 bits) 1 Data Block Length (13 bits)	SSID	SDI	Label 045 (start)
1	Parity	SSM	2nd Transmitted Byte 1st Transmitted Byte	SSID	SDI	Label 046
2	Parity	SSM	4th Transmitted Byte 3rd Transmitted Byte	SSID	SDI	Label 046
3	Parity	SSM	6th Transmitted Byte 5th Transmitted Byte	SSID	SDI	Label 046
4	Parity	SSM	8th Transmitted Byte 7th Transmitted Byte	SSID	SDI	Label 046
• • •	• • •	• • •	• • •		• • •	
n	Parity	SSM	8 pad bits if odd # of bytes in block Last Transmitted Byte	SSID	SDI	Label 046
or n	Parity	SSM	Last Transmitted Byte (n-1) Transmitted Byte	SSID	SDI	Label 046

Table 2-3 ARINC 429 Message Input Interface to VHF Data Links

Two types of Traffic / AMASS holdbar messages are sent via VHF data link:

1. Airport Status Message
2. Target Information Message

The airport status message is shown in Table 2-4 and consists primarily of the AMASS holdbar information. Holdbar encoding is shown in Table 2-5 and shows that there are 44 runway / taxiway intersections at the Hartsfield airport. This message is sent during each one second surveillance scan and was used by the NASA 757 to initiate a traffic display scan for the HDD. When a runway is active and should not be entered, the holdbar is activated (and displayed in "red" on the NASA 757 HDD). The airport status message also has provisions for wind speed, wind direction, and runway visual range (RVR) information, although this information was not used in the LVLASO flight test.

order of transmission: first byte ⇒ last byte

Byte #	Data Field	Name	Description	Valid Range for Data	Type Interpretation
1	T	Message Type	4 bits ("nibble"), unsigned	[1]	Value is 1 for this message type
1	0	unused	4 bits ("nibble"), unsigned	[0]	unused, always 0
2-5	A4A3A2A1	Runway 8L/26R	32 bits, bit map	all (bit map)	1=ON, 0=OFF (see Table 2-5)
6-9	B4B3B2B1	Runway 8R/26L	32 bits, bit map	all (bit map)	1=ON, 0=OFF (see Table 2-5)
10-13	C4C3C2C1	Runway 9L/27R	32 bits, bit map	all (bit map)	1=ON, 0=OFF (see Table 2-5)
14-17	D4D3D2D1	Runway 9R/27L	32 bits, bit map	all (bit map)	1=ON, 0=OFF (see Table 2-5)
18	SS	Wind Speed	1 byte, unsigned BYTE or	[0-254] [255] or FF Hex	knots information unavailable
19-20	H2H1	Wind Direction	2 bytes, unsigned WORD or	[0-359] [65535] or FFFF Hex	degrees information unavailable
21-22	R2R1	RVR	2 bytes, unsigned WORD or	[0-65534] [65535] or FFFF Hex	feet information unavailable

Table 2-4 Airport Status Message Format

Runway 8L/26R (11 intersections)	**Runway 8R/26L (10 intersections)**	**Runway 9L/27R (15 intersections)**	**Runway 9R/27L (8 intersections)**
Bit 0: B15, A	Bit 0: E, B	Bit 0: M	Bit 0: N12
Bit 1: B13	Bit 1: E13	Bit 1: M20	Bit 1: J
Bit 2: B11, A6	Bit 2: E11, B10	Bit 2: M18	Bit 2: K, K
Bit 3: B7	Bit 3: D, D	Bit 3: M16	Bit 3: R, N10
Bit 4: D, D	Bit 4: C, C	Bit 4: J, J	Bit 4: N6
Bit 5: C, C	Bit 5: E7	Bit 5: K, D	Bit 5: N4
Bit 6: B5	Bit 6: E5, B6	Bit 6: D, D	Bit 6: N2
Bit 7: A4	Bit 7: E3, B4	Bit 7: S, S	Bit 7: P
Bit 8: B3	Bit 8: E1, B2	Bit 8: M12	Bit 8-31: 0-filled
Bit 9: B1	Bit 9: H, H	Bit 9: M10	
Bit 10: H, A	Bit 10-31: 0-filled	Bit 10: M6	
Bit 11-31: 0-filled		Bit 11: M4	
		Bit 12: T, T	
		Bit 13: M2	
		Bit 14: P, L	
		Bit 15-31: 0-filled	

Table 2-5 Holdbar Bit Map (Atlanta Hartsfield Runway Layout)

The second message type consists of target information. The target information message format is shown if Table 2-6. Message fields consist of the message type, flight number address (eight ASCII characters), and 32-bits latitude and longitude for aircraft position. Thus for a single aircraft, 16 bytes of data are required. The maximum number of targets stored in one message is therefore 15 aircraft. During peak traffic times, the data link was required to transmit as many as 3 full-length messages per second, which is well within the data link capacity. A 31.5 kbps D8PSK VHF broadcast data link should be able to support ~240 aircraft using the message encoding used in the LVLASO flight test.

T0 A0...A7 L0...L3 E0...E3 ... A0...A7 L0...L3 E0...E3

order of transmission: first byte => last byte

Byte #	Data Field	Name	Description	Valid Range for Data	Type Interpretation
1	T	Message Type	4 bits ("nibble"), unsigned	[2]	value is 2 for this message type
1	0	unused	4 bits ("nibble"), unsigned	[0]	unused, always 0
2-9	A7 – A0	1st address	8 ASCII characters		flight number (null or spaces if unknown)
10-13	L3 – L0	1st target latitude	32 bits, FLOAT	[+/- 89.99...]	degrees, WGS-84, North is positive
14-17	E3 – E0	1st target longitude	32 bits, FLOAT	[0.0 – 359.99...]	degrees, WGS-84, East is positive
	A7 – A0	nth address	8 ASCII characters		flight number
	L3 – L0	nth target latitude	32 bits, FLOAT	[+/- 89.99...]	degrees, WGS-84, North is positive
	E3 – E0	nth target longitude	32 bits, FLOAT	[0.0 – 359.99...]	degrees, WGS-84, East is positive

Table 2-6 Target Information Message Format

On the aircraft side, the output interface from the VHF data link receiver to the aircraft I/O network (Figure 2-3) is an ARINC 429 output bus. The file transfer protocol of received Traffic / AMASS holdbar data is the same shown in Table 2-3, using Label "045" and "046" ARINC 429 words, each carrying two bytes of data.

2.3.2.3 LVLASO Flight Test VHF Data Link Performance (DGPS)

Data link performance was characterized for the VHF DGPS data link aboard the NASA 757 aircraft by recording DGPS position and data link message status outputs from the GNR-4000 GPS sensor, and also recording received signal strength outputs based on internal receiver Automatic Gain Control (AGC) information from the VHF DGPS data link receiver. Three states of message status were recorded; 1) no message received, 2) message received but CRC failed, and 3) message received and CRC passed successfully indicating a correctly received message.

To facilitate interpretation of flight test results, a Jeppesen chart of the Hartsfield airport layout is provided in Figure 2-9. Figures 2-10 through 2-15 are six representative VHF DGPS data link performance plots, depicting the path traversed by the NASA 757 during a particular flight test, the signal strength (color coded) and providing an indication of message failures (indicated by larger, color-coded squares). Color coding is as follows:

1.	Red	signal strength ≤ - 87 dBm
2.	Yellow	signal strength -77 dBm to -87 dBm
3.	Green	signal strength -67 dBm to -77 dBm
4.	White	signal strength > -67 dBm.

Larger "blue squares" indicate that received messages were garbled (failed CRC) and larger "magenta squares" indicate messages were not received (recall that messages are sent at a one per second rate).

Two items of note in examining VHF DGPS data link results from the LVLASO flight tests are the received signal strength and message loss events. With respect to signal strength, our primary focus was to ensure proper signal coverage for the LVLASO flight tests. Earlier van tests provided an indication that signal coverage was excellent for surface operations and expectations were for continued excellent terminal area coverage for the NASA 757. In terms of signal coverage, our objectives were met exceedingly well throughout all the flight tests for both VHF data links. The only significant exception occurs in the NW corner of the terminal area, beyond 5 nmi range, where it is evident that signal blockage due to the additional building structure atop the Renaissance Hotel plays a significant role (see Figure 2-8).

Figures 2-10 and 2-11 illustrate two flight tests where the NASA 757 performed a flight, with takeoff on runway 26L and a loop to the NW and subsequent downwind leg, and then turning South to intercept the Localizer for approach and landing on runway 26 R. In Figure 2-10, the aircraft did an immediate turn toward the downwind leg, and thus the signal level remained strong as indicated by the 'white" trace throughout the West portion of the flight path. Even during the downwind leg that extended ~ 13 nmi beyond the location of the DGPS base station and VHF Transmitter site (Renaissance Hotel), the signal remained quite strong and no message failures occurred. In Figure 2-11, the NASA 757 did a more gradual climb and turn and went ~8 nmi to the WNW before turning downwind. The signal level dropped severely and some messages were garbled or lost. Signal level improved substantially on the downwind leg. Some signal degradation again occurred during the South leg and Localizer capture portion of the flight, but not as severe. The degradation in the NW corner of the flight path is the direct result of some signal blockage due to antenna siting of the DGPS data link indicated above.

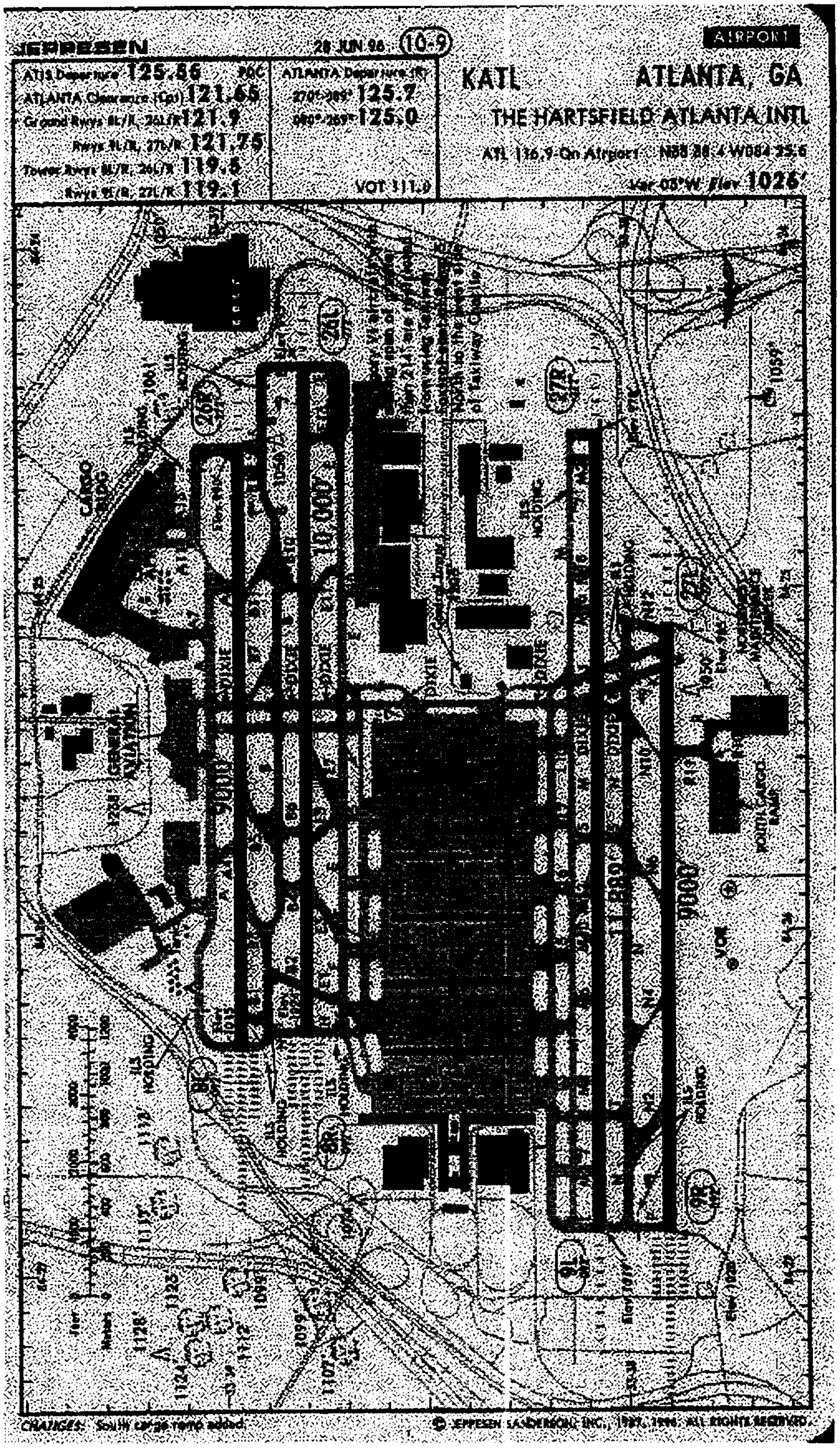


Figure 2-9 Jeppesen Chart of Atlanta Hartsfield Airport

Figures 2-12 and 2-13 illustrate data link flight test results when the NASA 757 conducted takeoff on 8R and flew a downwind leg to return on 8L. The effect of antenna blockage is very evident to the WNW in the pattern, where numerous messages were either garbled or lost entirely beyond 5 nmi range. Figure 2-12 shows the worst case results observed throughout the flight tests. Once the antenna blockage is no longer a factor, signal strength is very good throughout the flight with no additional messages failures. Figure 2-13 provides another perspective of a similar flight test, with a bit more signal degradation evident in the NE corner compared to Figure 2-12.

Figures 2-14 and 2-15 provide flight test data on scenarios that did not include flight. The aircraft was based at the Mercury Air Center to the North of the airport. In Figure 2-14 the NASA 757 taxied via taxiways Alpha, Dixie, and Echo for a simulated takeoff on 26L. The aircraft then performed a high-speed ROTO with exit on Echo 3 and return taxi to Mercury Air via Echo, Charlie and Alpha. As expected, the signal level was very strong throughout the scenario as indicated by the white trace. A few messages were actually lost and are attributed to multipath as a result of the large Delta hangars on the SE corner of the North runway area. Figure 2-14 illustrates a taxi scenario to the South half of the airport. Again signal levels were strong except in a few areas along the taxiway directly South of the terminal buildings, where some signal blockages are observed. Only a couple messages were not received correctly throughout the flight test scenario.

Table 2-7 summarizes the message reception performance of the VHF DGPS data link for flight tests with the NASA 757. Data collected for both taxi and airborne tests resulted in ~99.8 messages reception probability. (27 errors in 15792 messages for taxi, 76 errors in 37681 messages for airborne flight tests). Taxi message failures occurred only as single error events. For airborne flight tests one triple error event and 3 double error events occurred, with all other message failures being single events. Message failures in the NW corner were excluded since they are clearly due to line-of-sight blockage effects due to the hotel. Even when counting the message failures in the NW corner (with suboptimal antenna siting), the message reception probability is 99.2%.

The few message losses that did occur were in the vicinity of the following regions: 1) in the vicinity of the Mercury Air (A5) / Taxiway A intersection (multipath), 2) in front of the Delta Hangar to the Southeast of runway 8R/26L (multipath), 3) on the South half of the airport when the line-of-sight is blocked by terminal buildings (particularly Terminal E), 4) for a brief instant at the time the NASA 757 rotated when executing some of the takeoffs on runway 8R (multipath and/or aircraft antenna null), 5) a few occasions in the ENE corner during flight, and 6) the NW corner due to line-of-sight blockage effects by the hotel.

Probability of correctly receiving a single message per number of attempts	**Taxi only tests (15792 messages)**	**Airborne tests (37681 messages)**	**Total all flight tests (53473 messages)**
Single attempt	99.83%	99.80%	99.81%
Two attempts	100%	99.992	99.994%
Three attempts	100%	99.997%	99.998%

Table 2-7 Message Reception Probability vs Number of Transmission Attempts (757 tests)

The VHF Traffic / AMASS holdbar data link was not characterized in detail but also provided reliable coverage throughout all flight tests. As indicated previously, traffic messages are somewhat more vulnerable due to increased message length (Recall that van tests indicated ~ 99.75 % and ~97.5 % message reception rates for DGPS and Traffic / AMASS, respectively. Refer to Sections 2.3.2.1 and 2.3.2.2). The traffic / AMASS holdbar application did not utilize a CRC for error detection. However, reasonableness checks on message length and various message fields were made to reject erroneous traffic reports to minimize display of misleading information to the pilot via the HDD.

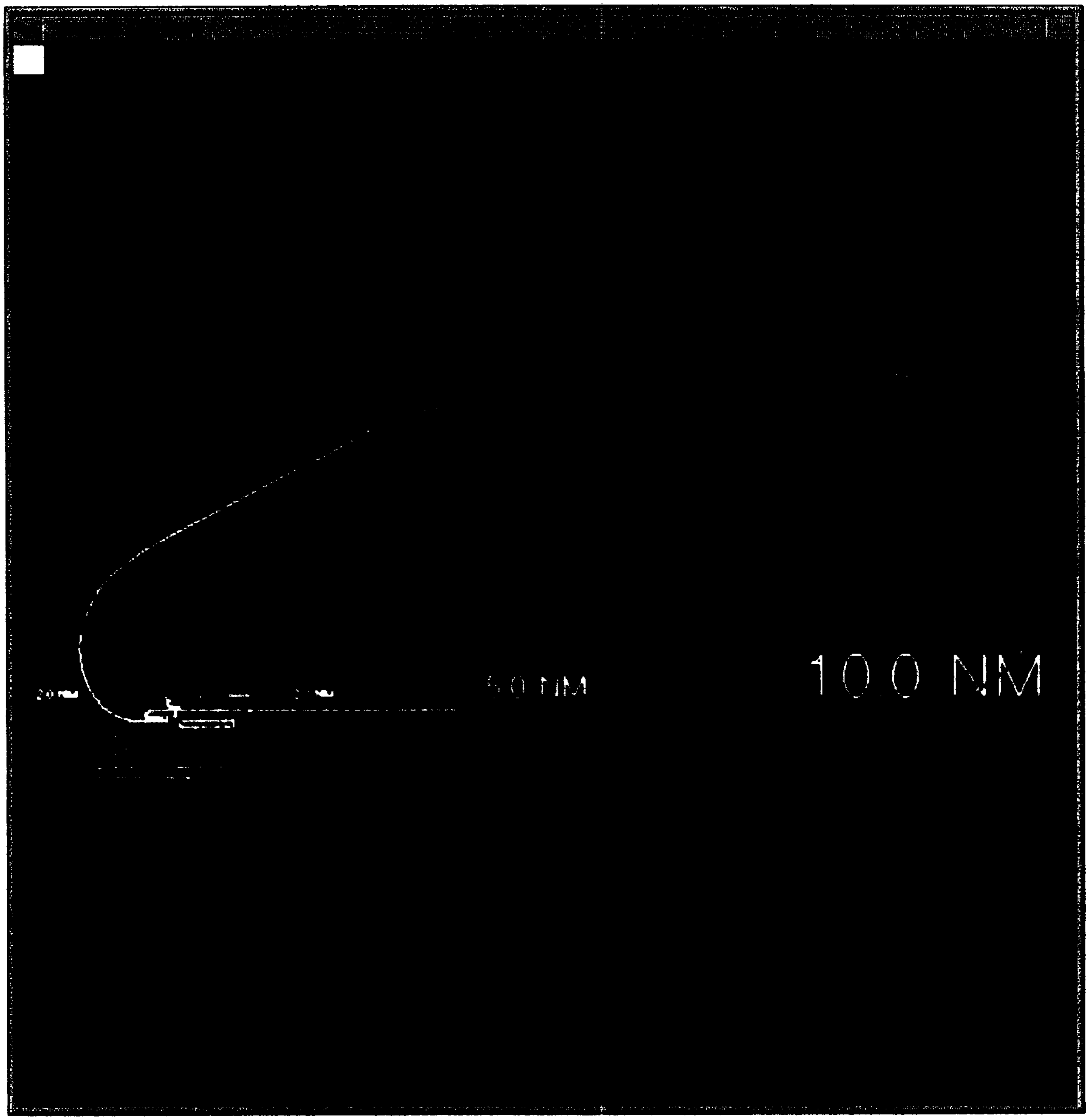


Figure 2-10 Flight Test Scenario # 1 - Takeoff on 26L, Downwind Leg, Landing on 26R

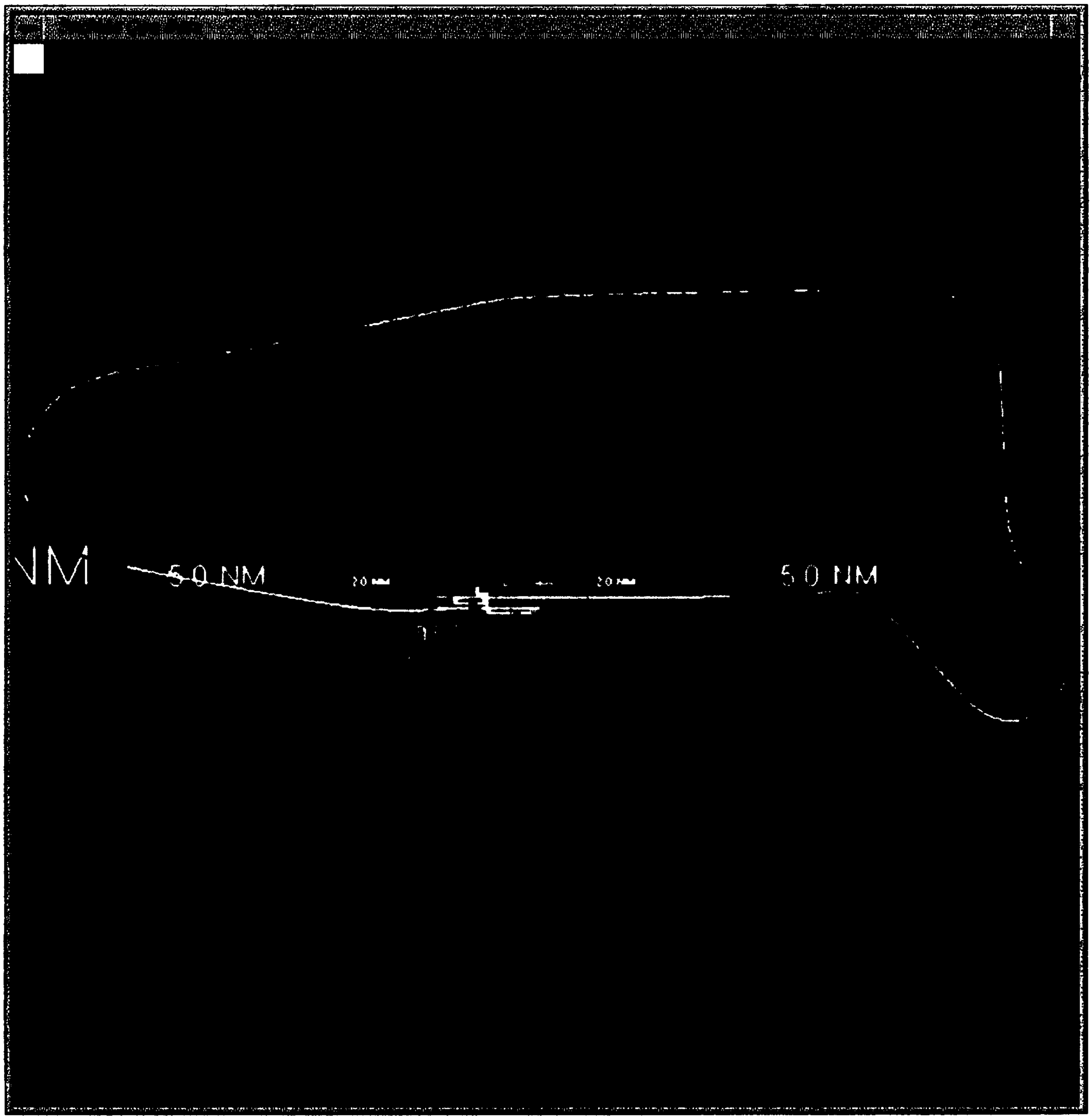


Figure 2-11 Flight Test Scenario # 2 - Takeoff on 26L, Downwind Leg, Landing on 26R

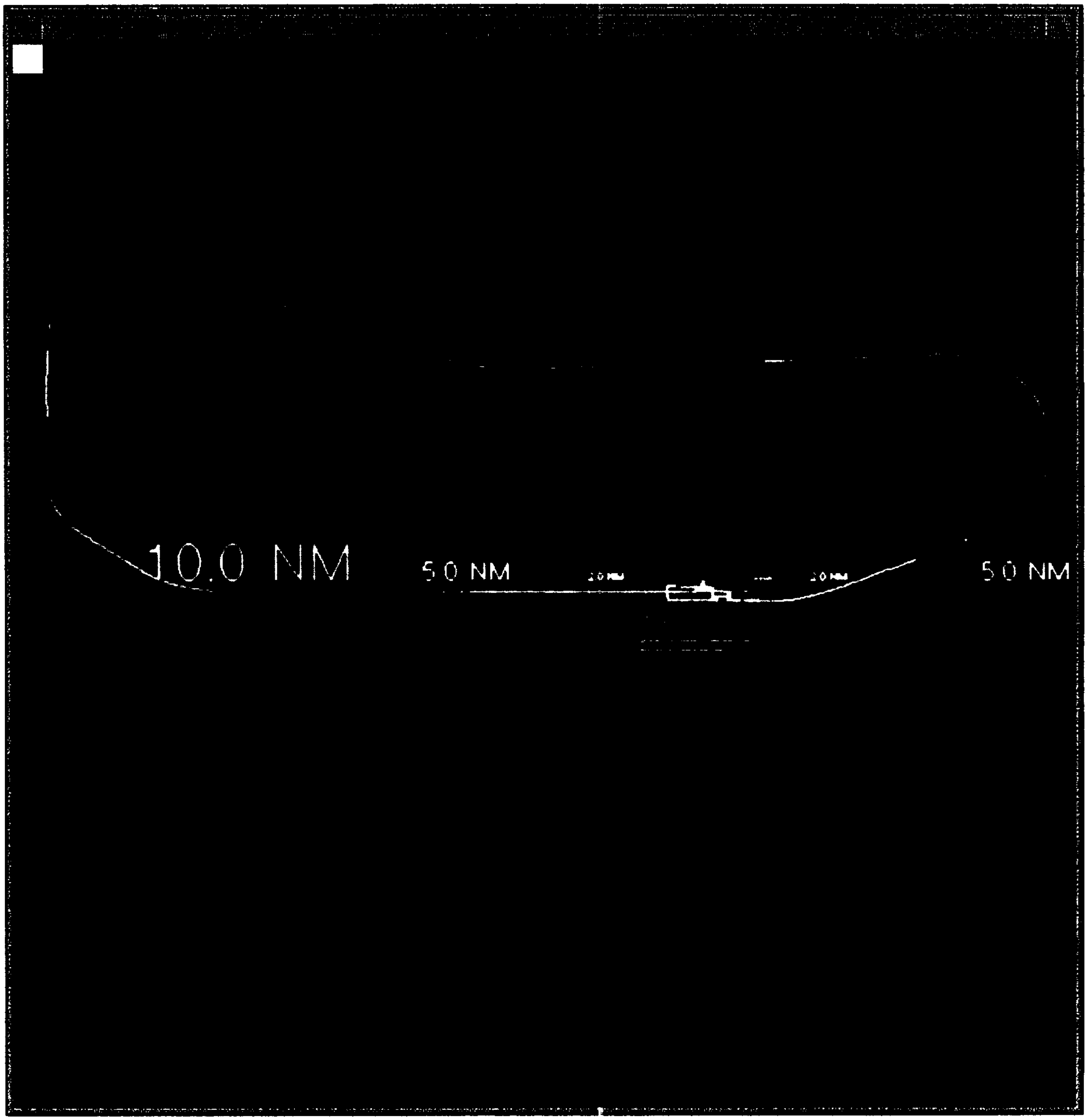


Figure 2-12 **Flight Test Scenario # 3 - Takeoff on 8R, Downwind Leg, Landing on 8L**

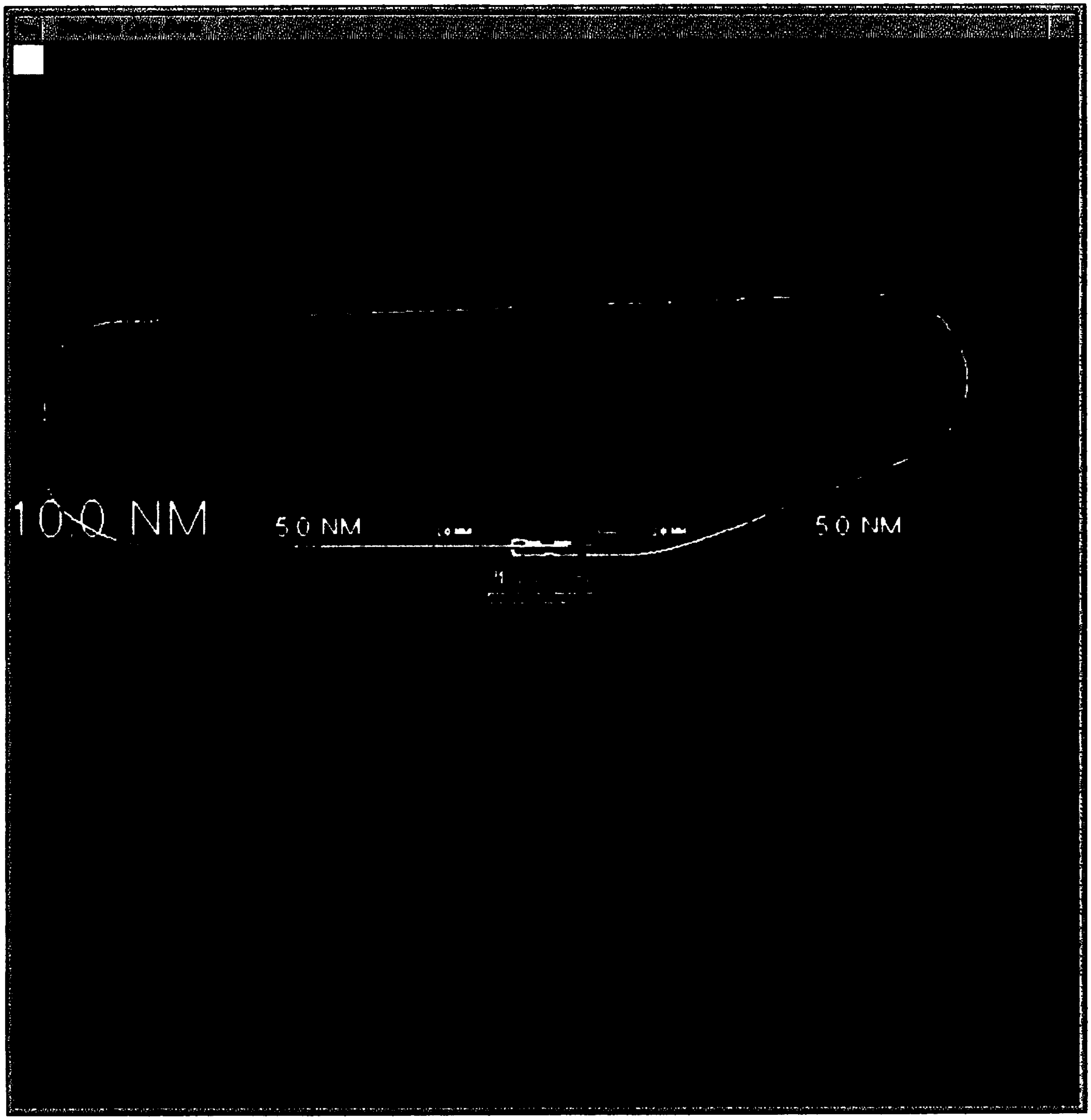


Figure 2-13 Flight Test Scenario # 4 - Takeoff on 8R, Downwind Leg, Landing on 8L

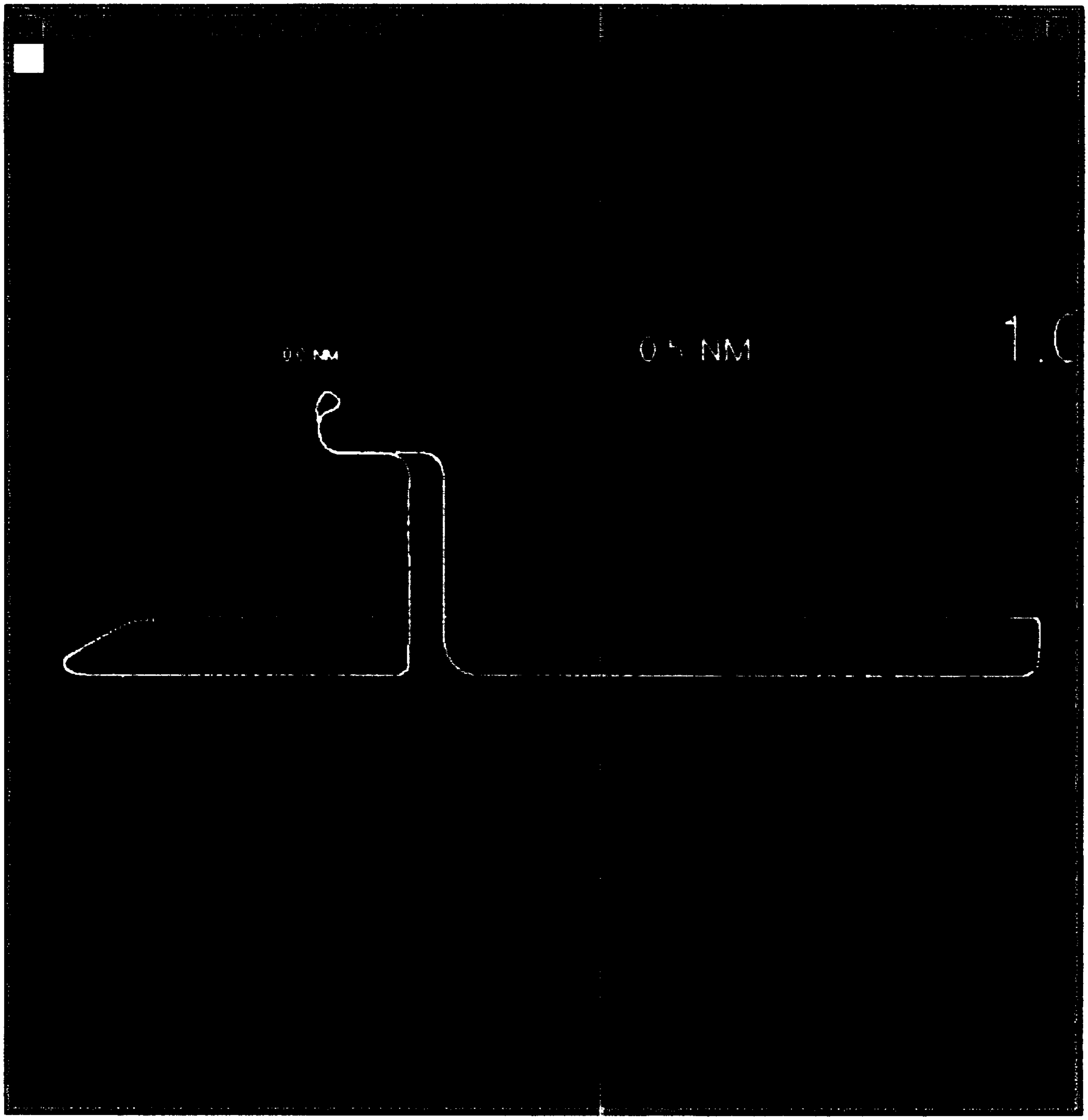


Figure 2-14 Flight Test Scenario # 5 - Taxi-Only Scenario with High-Speed ROTO

(Leave Mercury Air; taxi via Alpha, Dixie, Echo to 26L; simulate takeoff and perform high-speed ROTO with exit on Echo 3; taxi back to Mercury Air via Echo, Charlie and Alpha)

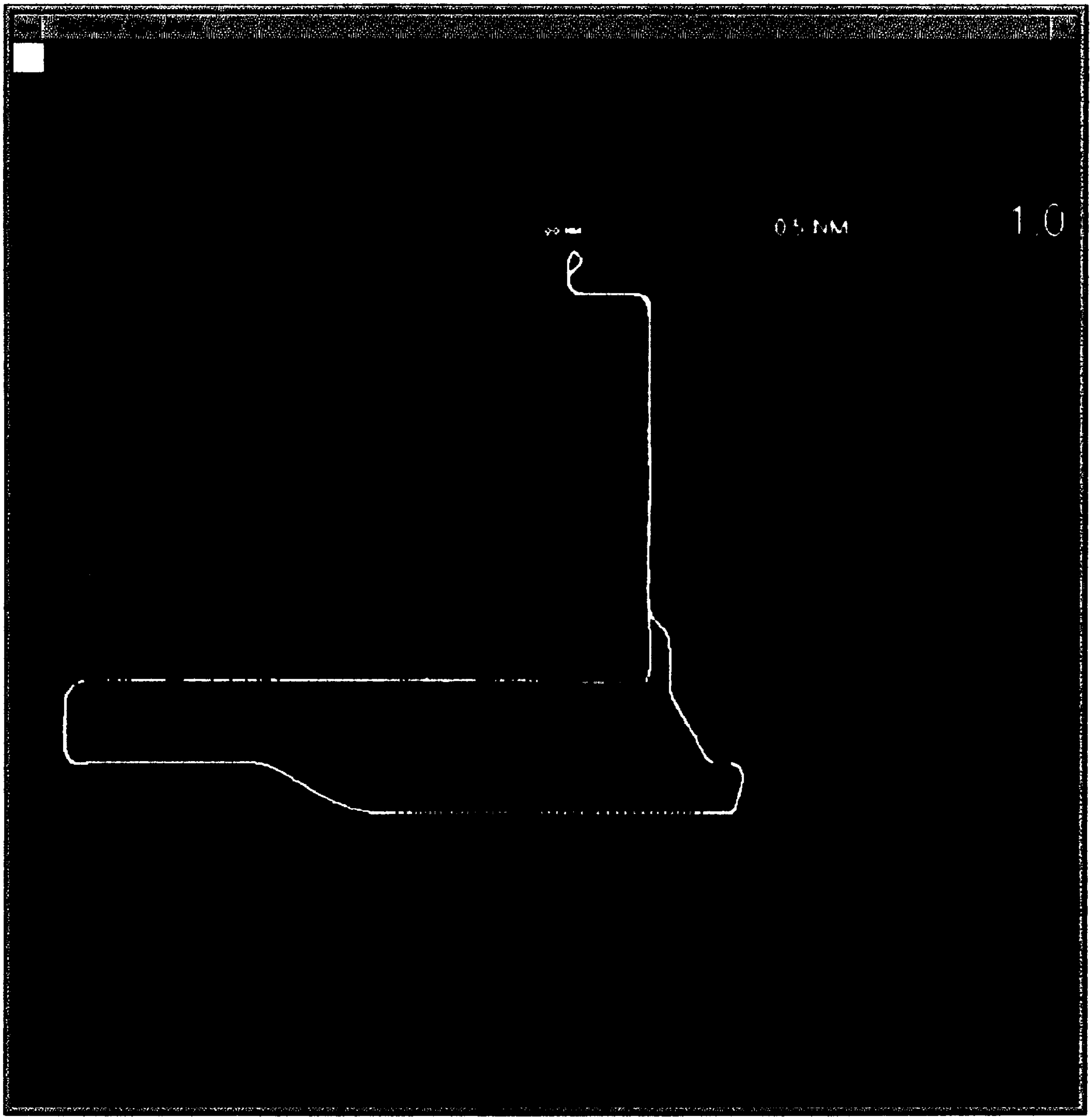


Figure 2-15 Flight Test Scenario # 6 - Taxi-Only Scenario with High-Speed ROTO (Leave Mercury Air; taxi via Alpha, Dixie, Juliet to 27L; simulate takeoff and perform high-speed ROTO with exit on November 4; taxi back to Mercury Air via November, Papa, Lima, Dixie and Alpha)

2.3.3 Mode-S Data Link

The Mode-S link was utilized for LVLASO Controller Pilot Data Link Communications (CPDLC) and also provided ADS-B extended squitters for surveillance. The Mode-S link consists of ATIDS R/Ts (uplink on 1030 MHz) on the ground and the Mode-S transponder and associated ADLP onboard the NASA 757 aircraft. The Mode-S transponder / ADLP provides the Mode-S Specific Services (MSSS) protocols needed for addressed CPDLC communications and broadcast ADS-B.

2.3.3.1 CPDLC Data Link

Controller - pilot data link communications for LVLASO were conducted as follows; 1) a test controller repeats actual ATC communications to the NASA 757 aircraft to convert the message into a data link message, 2) the data link message is encoded using RTCA DO-219 message encoding, using existing messages when possible, but also required development of new messages when not available, 3) encoded messages are sent to the ATIDS master workstation (see Figure 2-2) via modem for further encoding to MSSS protocol and subsequent transmission via 1030 MHz, 4) the NASA 757 Mode-S transponder receives the uplink message, decodes it (sending a transponder reply to acknowledge receipt of the interrogation) and provides it to the I/O network and flight computer for display on the HDD to the flight crew, 5) the flight crew acknowledges the message using the pilot interface device (PID), which encodes a downlink message via the Mode-S transponder/ADLP using DO-219 and MSSS protocols (1090 MHz downlink).

Note: Message retry protocols were implemented in the event a data link message collided with another transmission on the Mode-S link, which is entirely possible due to the random access protocol used by the Mode-S link. In addition, controller messages were highlighted to the controller when acknowledgments occurred. Failure to receive acknowledgments were thus immediately evident to the ATC controller.

Table 2-8 summarizes the CPDLC messages used in the LVLASO flight test.

LVLASO Uplink Messages	
Element ID	**Message**
117	Contact [icaoname][frequency]
120	Monitor [icaoname][frequency]
200	Hold Short [position]
212	Taxi [runway] Via [route]
219	Taxi [ramp] Via [route]
220	Cross [position] [without delay]
221	Continue Taxi
223	Taxi Into Position and Hold
224	Cleared For Takeoff
LVLASO Downlink Messages	
1	Roger
3	Unable
202	Taxiway Deviation
203	Turned-off on Taxiway [#]
204	Taxiway Deviation Resolved

Table 2-8 LVLASO CPDLC Messages

Two methods of repeating and converting ATC voice messages to data link messages were demonstrated by the test controller: 1) Aural repetition of actual ATC messages using a Verbex voice recognition unit to digitized the message; 2) touch screen input to enter the data link message. In both cases, the digital message is encoded using DO-219 encoding.

The Controller Interface voice recognition system requires training to the controllers voice. After initial adjustments to voice recognition, and reducing the vocabulary to a subset specific to the Atlanta airport, voice recognition provided ~98 % recognition of all messages. It was evident that voice recognition is preferable over touch screen input due to controller workload. CPDLC raises significant issues in both the ATC cab and the flight deck in terms of human factors, workload and maintaining the man-machine interface information flow, which will require further research by industry. The Controller Interface described above was developed by St. Cloud St. University.

The physical Mode-S data link itself worked as expected, but was at times adversely effect by ATIDS master work station failures.

2.3.3.2 ADS-B

The NASA 757 aircraft reliably transmitted ADS-B extended squitters at a 0.5 second update rate. ADS-B squitters provided aircraft position with DGPS accuracies. ATIDS surveillance of ADS-B reports is superior to multilateration surveillance, since reception of the signal by just one ATIDS R/T allows tracking of the aircraft (versus reception by multiple R/Ts for multilateration).

Figures 2-16 and 2-17 illustrate sample plots for ADS-B surveillance of the NASA 757 aircraft that were recorded. Figure 2-16 represents ADS=B surveillance for a taxi test to the South half of the airport (similar to the Figure 2-15 scenario). From Figure 2-16, obvious LOS outages are observed whenever the NASA 757 taxied near a terminal building (refer to Figure 2-9 for layout of airport). The outages are simply explained by the fact that the 5 ATIDS R/Ts are deployed only on the North half of the airport and thus did not provide LOS to the regions blocked in the South half. The problem would be easily corrected by proper deployment of ATIDS R/Ts to include the South half of the airport. With the exception of the blockage regions, ADS-B surveillance on the NASA 757 was reliable.

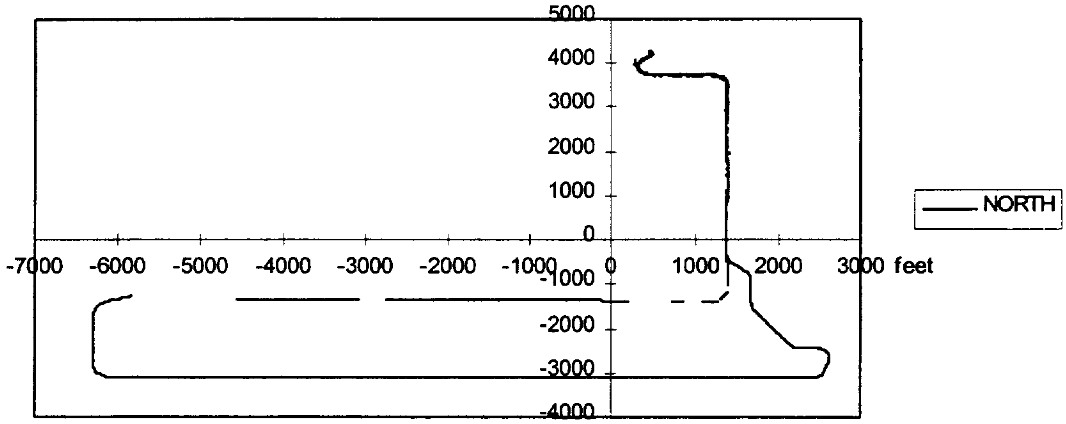


Figure 2-16 NASA 757 ADS-B Surveillance Coverage - Taxi Scenario

Figure 2-17 shows a flight scenario and again demonstrates good ADS-B surveillance with the exception of some outages in the NE corner of the flight pattern.

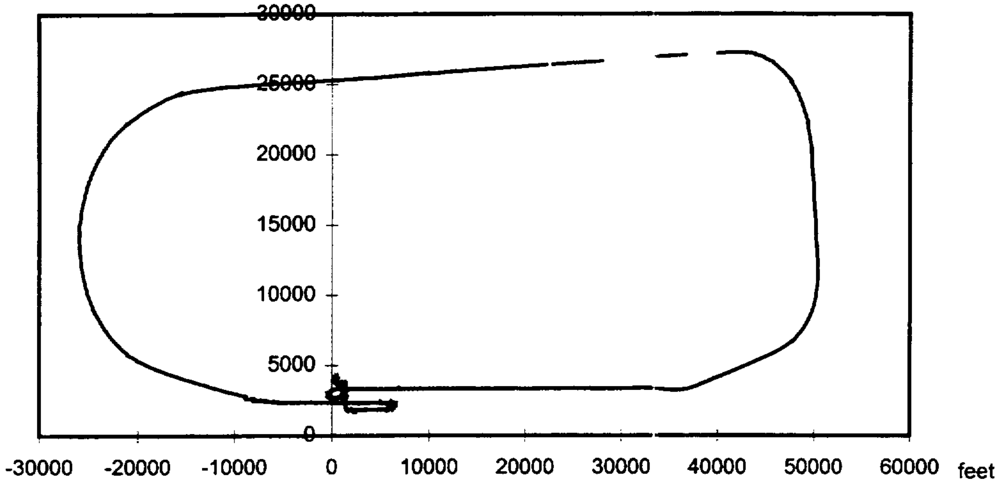


Figure 2-17 NASA 757 ADS-B Surveillance Coverage - Flight Scenario

Schematics of all data links and the GPS sensor and the layout of the LVLASO data link and GPS equipment racks of the NASA 757 used in the LVLASO flight test system are provided in Appendix B. A detailed description of Mode-S interfaces and communications protocols for all interfaces associated with the CPDLC link is provided in Appendix C. Figure 2-18 shows a photograph of the LVLASO data link and GPS sensor equipment rack in the NASA 757 aircraft.

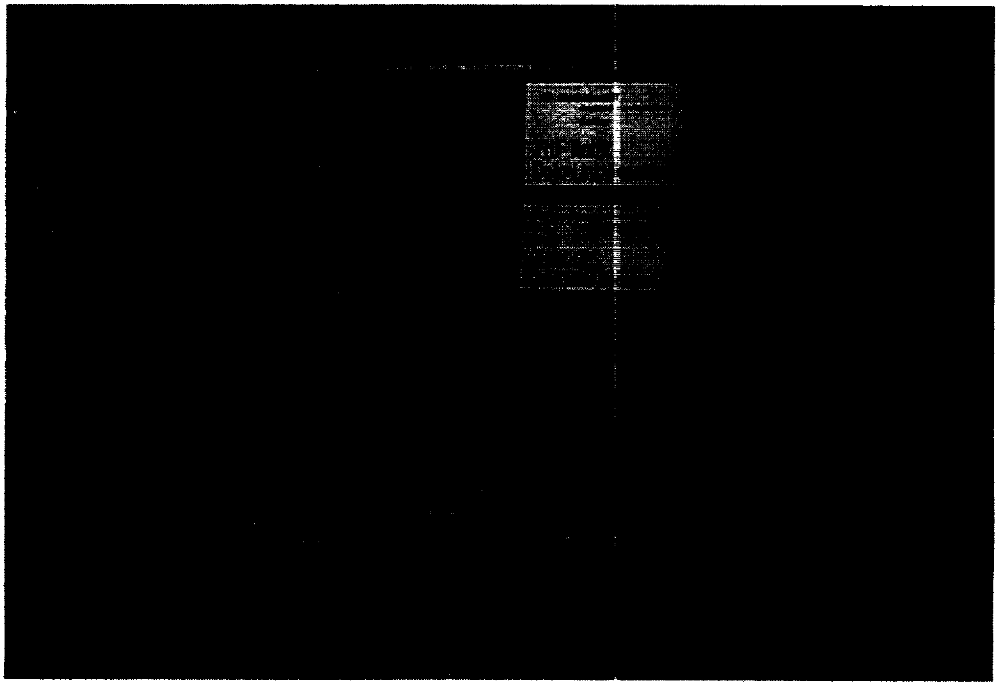


Figure 2-18 LVLASO Data Link and GPS Equipment Rack on NASA 757.

3. Terminal Area Productivity (TAP) Data Link

3.1 Introduction

This section of the report examines the issues concerning the future direction of aeronautical data link communications as they pertain to TAP data link and the future Communication Navigation Surveillance (CNS) / Air Traffic Management (ATM) system that is currently being addressed within the industry. Since the majority of TAP data link applications are also utilized outside terminal area airspace, the approach taken here is to examine the overall CNS/ATM data link environment in developing candidate avionics data link architectures, and then mapping these results back to TAP data link.

Several data link technologies will play an important role in providing the needed capabilities for the future CNS/ATM and TAP data link system, each providing specific services that are best suited to that particular technology. Data link technologies are VHF, Mode-S, HF, and SATCOM data link. While SATCOM and HF data link have clearly defined roles in the future CNS/ATM data link system (i.e., providing data link coverage in oceanic and remote-area enroute regions, the role of VHF and Mode-S data link is considerably less clear. It is the VHF and Mode-S data links that have the greatest impact on future TAP data link.

At present, two distinct VHF data link approaches are currently being developed within the industry that are central to the future direction of the CNS/ATM and TAP data link system. This report provides considerable focus on these approaches and develops candidate data link architectures (from an avionics perspective) in meeting future CNS/ATM and TAP data link requirements.

The two VHF data link approaches that affect the direction of CNS/ATM data link are as follows:

1) Transition from today's VHF ACARS data link (also referred to as VHF Data Link {VDL} Mode 1) to a higher data rate VDL Mode 2 and subsequently to VDL Mode 3, which provides the capability for multiple, simultaneous digital voice and data services on a single 25 KHz VHF frequency channel.
2) Self-Organizing TDMA (STDMA) also referred to as VDL Mode 4.

Both of these VHF data link approaches are vying to provide a range of data link applications and services, some of which are in direct competition with one another, while others may be more synergistic. The VDL Mode 1, 2, and 3 transition approach is primarily intended to address the conventional communications services of Air Traffic Services, consisting of Air Traffic Control (ATC) data link and Air Traffic Services (ATS) such as flight information services, and Airline Operational Communications (AOC) and Airline Administrative Communications (AAC). These data link applications are primarily strategic in nature, many of which would be sent via the Aeronautical Telecommunications Network (ATN).

VDL Mode 4 (i.e., STDMA) is envisioned by its proponents to provide a wide range of data link applications from tactical, broadcast communications such as Automatic Dependent Surveillance (ADS-B) and Differential GPS (DGPS or DGNSS) corrections uplink, to tactical non-ATN ground-to-air and air-to-air services, and the more strategic ATC/ATS and AOC/AAC services indicated above.

Section 3.2 provides an overview of future CNS/ATM data link applications that are currently being planned the role of the Aeronautical Telecommunications Network (ATN) in providing these applications, and provides summaries of the various data links candidates that will likely implement these applications. Emphasis will be on the evolution of the two VHF data link approaches indicated above (VDL Modes 1, 2, and 3 and VHF STDMA / VDL Mode 4) and Mode-S data link.

Section 3.3 provides a brief description of each of the CNS/ATM data link applications and their role in TAP data link. A more detailed description of VHF data link candidates is provided as an appendix (Appendix D in Volume II of report) in support of developing data link architectures. Section 3.4 discusses candidate mappings of data link applications to data link architectures / implementation approaches, while Section 3.5 examines viable CNS/ATM data link architectures from an avionics equipment perspective. Section 3.6 summarizes conclusions from the viewpoint of TAP data link.

3.2 Aeronautical Data Link Overview

3.2.1 Future CNS/ATM Data Link System

While the current National Airspace System (NAS) relies almost entirely on analog voice communications for Air Traffic Services (ATS) via VHF radio and uses ACARS data link for AOC, AAC and some limited ATS data link services, it is expected that the use of data link will greatly expand and play a vital role in the future CNS/ATM system.

The future CNS/ATM system will rely on global satellite navigation, ground-based and satellite-based communications via the Aeronautical Telecommunications Network (ATN), and on Automatic Dependent Surveillance (ADS and ADS-B) to bring about needed improvements in efficiency and safety of operations to address the problems associated with increasing levels of air traffic. Data link will be an integral part of the future CNS/ATM system and the systems that support TAP for ATS/ATC communications, ADS-B surveillance, augmentation to GPS for precision approaches and enhanced navigation, support of automation functions both ground-based and in the aircraft to allow 4-D navigation, route negotiation and reduced separation (i.e., free flight), and numerous other flight services and traffic services applications. While there will always be a need for voice communication, its use is expected to decline over time for delivery of more infrequent, non-routine messages and as backup for data link. Data link is expected to provide the majority of routine, standard ATC communications.

Figure 3-1 provides a breakdown of data link applications (services) planned for the future CNS/ATM system and identifies the RTCA subcommittees that are developing standards. Individual data link applications are listed in Table 3-1. These applications pose different communications requirements in terms of latency (strategic versus tactical), addressed versus broadcast, coverage (enroute, terminal area, surface, oceanic enroute or remote areas), capacity, integrity, availability, and quality of service, i.e., Required Communication Performance (RCP). A commonly accepted view of the end-state CNS/ATM data link system which addresses many of these requirement is illustrated in Figure 3-2. Each of the data link applications shown in Table 3-1 is described in more detail in Section 3.3.

As shown in Figure 3-2 the Aeronautical Telecommunications Network plays a fundamental role in the future CNS/ATM data link system, providing point-to-point (i.e., addressed) connectivity between ground and airborne end-user systems. A number of physical data links and sub-networks are interconnected by ATN. The future CNS/ATM data link system utilizes VHF, SATCOM, HF and Mode-S data links to satisfy the diverse communications requirements (RCP) of end-user applications. SATCOM and HF data link provide services primarily in remote and oceanic enroute areas where terrestrial VHF and/or Mode-S cannot be employed.

Data link communications via the ATN are strategic in nature and have moderate to high latencies. Some CNS/ATM communications require tactical communications and will rely on specific (non-ATN) communications, e.g., Mode-S Specific Services (MSSS) or VHF Specific Services (VSS). In addition to addressed communications, broadcast services play a vital role in the future CNS/ATM data link system (e.g., ADS-B, DGPS/DGNSS, FIS-B). Since the ATN does not support broadcast communications, broadcast data link are typically provided by specific, non-networked services.

SATCOM and HF data links shown in Figure 3-2 are indicated for reference only. The focus of this paper is on VHF data link (VDL) and the CNS/ATM data link applications that are most appropriately allocated to VDL. Mode-S enters into the discussion for ADS-B and perhaps tactical ground-to-air and air-to-air communications, where both Mode-S and VDL specific services are viable candidates.

3.2.2 Aeronautical Telecommunications Network (ATN)

As indicated in the previous section, the ATN provides the interconnectivity of the various CNS/ATM sub-networks to allow point-to-point communications among end-users. The ATN accomplishes this interconnectivity and routing of information by using the Open Systems Interconnect (OSI) layered communications protocols shown in Figure 3-3. The ATN routing architecture indicating connectivity among the various end-user domains is illustrated in Figure 3-4.

Figure 3-3 shows the 7 OSI layers that provide various services for the end user, which is represented by the application layer. The top four layers of the OSI stack (i.e., application, presentation session, and transport layers) are referred to as the "upper layers" and are defined in ARINC 637 and ARINC 638 for aeronautical data link communications. The actual ATN router function is provided by the upper portion of the network layer.

The physical, data link and network layers are referred to as the "lower layers". While the physical and data link layers may be different for various aeronautical sub-networks, a common sub-network interface is defined for all aeronautical data link communications, which allows ATN interconnectivity via the router. The common subnetwork layer interface to the aeronautical sub-networks and lower layers is specified by the ISO 8208 protocol.

It is in the lower layers where the various VDL modes utilize different techniques and protocols (i.e., upper layers are the same, regardless of VDL mode). The differences in the "lower layers" for the various VDL modes are described in Appendix D.

Due to the multiple protocol layers, ATN communications typically require moderate to high transfer delays and thus are more appropriate for strategic communications. Low-latency, tactical communications should be conducted outside of the ATN. For non-ATN communications, the upper layers are bypassed, with typically only physical layer, data link layer and perhaps network layer services being used to provide specific services for local coverage and tactical communications. The VDL Mode 1, 2 and 3 transition plan is intended to address strategic communications and no VHF specific services (VSS) are currently being defined. VDL Mode 4 and Mode-S are currently the only available candidate data links that have VSS and Mode-S specific service (MSSS) capability.

3.2.3 Overview of VHF Data Link (VDL)

3.2.3.1 ACARS VDL Mode 1

Historically, the initial aeronautical data link capability was provided via ACARS data link (i.e., VDL Mode 1) over a conventional ARINC 716 AM voice radio for Out-Of-On-In (OOOI) data link reporting of aircraft operations using a character-oriented protocol (ARINC 618). ACARS data link use has expanded to include a range of AOC and AAC communications (e.g., maintenance reports, engine performance monitoring, flight data, etc.) and also includes some limited ATS communications (e.g., predeparture clearance, oceanic clearance, and Automatic Terminal Information Services {ATIS}).

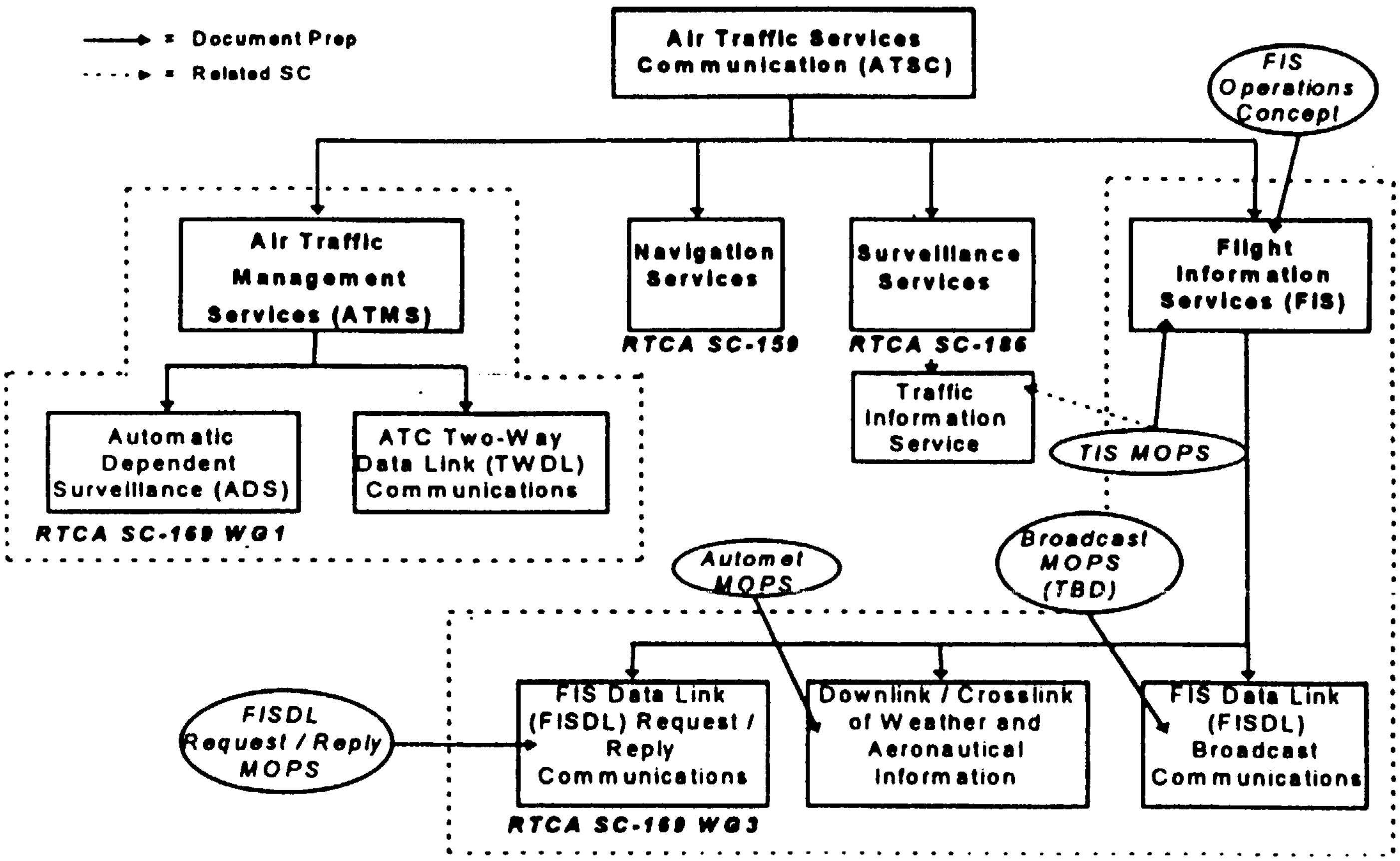


Figure 3-1 Planned CNS/ATM Data Link Services

CNS/ATM Data Link Application	Type of Service	Candidate Data Links
CPDLC (Controller Pilot Data Link Communications) RTCA DO-219	Air Traffic Services (ATS) for Air Traffic Control (ATC), addressed data link via ATN, currently only strategic comms (i.e., moderate latencies)	VHF, SATCOM, and HF data links
ADS-A (ADS-C) Automatic Dependent Surveillance - Addressed or Contract RTCA DO-212, ARINC 745	ATS/ATC addressed communications via ATN, strategic (i.e., moderate latencies)	VHF, SATCOM, and HF data links
ADS-B (RTCA SC-186 MASPS), Data link for numerous surveillance and separation assurance end-user applications (e.g., CDTI, parallel runway approaches, entrail climb, etc.)	broadcast data link, tactical (i.e., low latency communications)	Mode-S or VHF data link
DGPS/DGNSS (DGPS corrections uplink) RTCA SC-159 MASPS and ICAO GNSSP SARPS	broadcast data link, tactical (i.e., low latency communications)	VHF data link, (D8PSK or GFSK modulation)
FIS and FIS-B (Flight Information Services) - Predeparture clearance - Digital ATIS, - TWIP (terminal weather) - ETRR (taxi ramp route) - etc.,	addressed and broadcast communications	VHF data link
TIS and TIS-B (Traffic Information Services)	broadcast data link	Mode-S or VHF data link
AOC/AAC (airline operational and administrative communications)	addressed communications via ATN strategic (moderate latencies)	VHF, SATCOM, and HF data links
Air-Air Communications - e.g., trajectory negotiation, - collision avoidance crosslink	addressed communications, primarily tactical and some strategic communications	Mode-S crosslink (e.g., collision avoidance crosslink) or VHF data link

Table 3-1 Planned CNS/ATM Data Link Applications

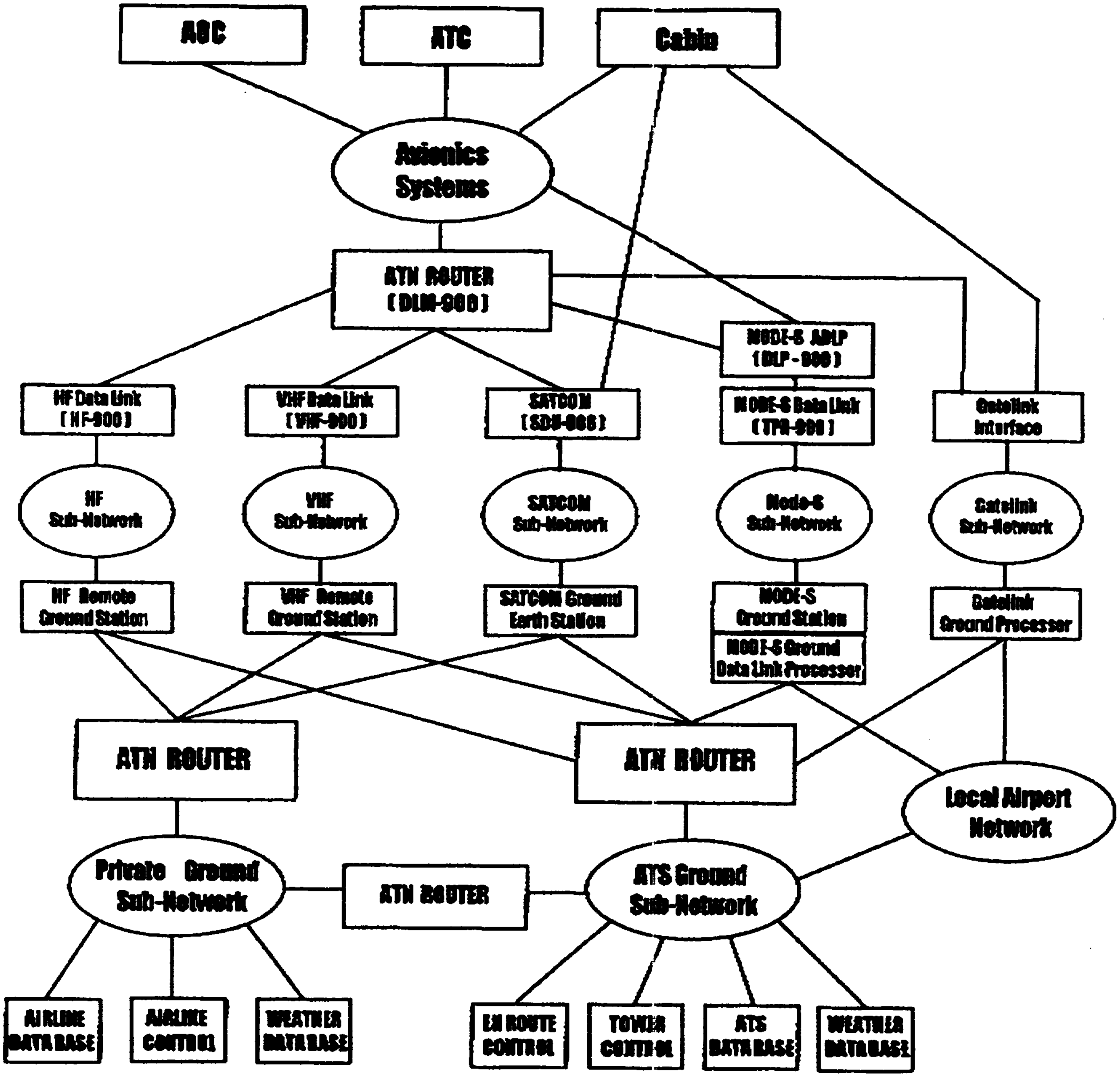


Figure 3-2 CNS/ATM Data Link System

To support future compatibility with ATN, the character-oriented protocol is being upgraded and replaced with code/byte independent binary-oriented protocols (BOP). The ACARS ARINC 618 protocol is thus being upgraded to the Aviation Packet Communication (AVPAC) bit-oriented protocols (ARINC 631), which defines the lower 3 layers of the OSI stack (Figure 3-3) for VDL.

For VDL Mode 1, the physical layer uses 2400 bps Minimum Shift Keying (MSK) modulation which then modulates the AM carrier. The media access channel (MAC) layer, which is the lower layer of the data link layer, uses Carrier Sense Multiple Access (CSMA) p-persistent protocol to determine channel access for data link message exchange.

Application
Presentation
Session
Transport
Network
Data Link
Physical Layer

Figure 3-3 OSI Layers

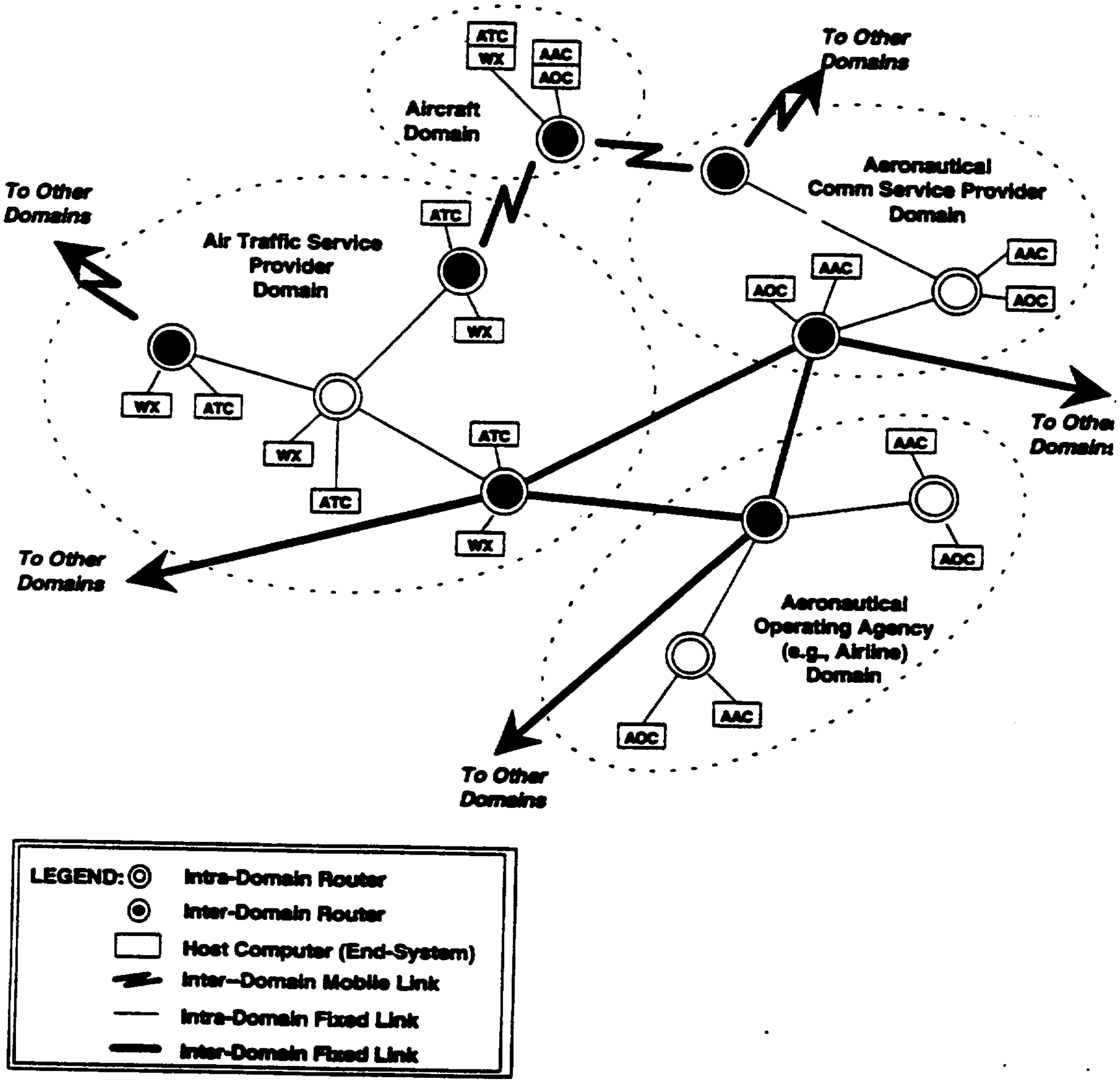


Figure 3-4 Aeronautical Telecommunications Network

VHF Frequency Congestion Problem

The use of VHF data link is expected to increase substantially in the future CNS/ATM system. At the same time, as air traffic levels continue to increase, some regions in the world are already experiencing shortages in the available number of VHF communications frequencies. This problem is expected to continue to become more severe and Europe has already mandated implementation of 8.33 KHz channels for VHF analog voice communications to alleviate frequency congestion.

In order to provide higher data rates and to provide more efficient use of available frequencies, i.e., more bits per Hz of bandwidth, industry has arrived at two, distinct VDL approaches. As indicated earlier, the FAA and Mitre have developed a transition plan from VDL Mode 1 to Modes 2 and 3, while Sweden has developed an entirely new VDL approach based on self-organizing TDMA (STDMA) also called VDL Mode 4.

The next sections provides summary descriptions of VDL Modes 2, 3 and 4, which provide substantially more system capacity than the current VHF ACARS (VDL Mode 1 system). This information is later used in developing data link allocations between CNS/ATM and TAP data link applications and individual data links.

3.2.3.2 Summary of VDL Mode 2

VDL Mode 2 is a data-only data link (i.e., no digital voice capability) that provides an order of magnitude increase in channel capacity versus VDL Mode 1 (ACARS). The increase in capacity is the direct result of the 31.5 kbps D8PSK waveform (versus the 2400 bps MSK waveform used by VDL Mode 1). D8PSK requires a D/U of 16 to 20 dB (compared to 14 dB for analog voice), which influences frequency reuse. Like VDL Mode 1, VDL Mode 2 uses Carrier Sense Multiple Access (CSMA) channel access protocol. In addition, VDL Mode 2 uses the bit-oriented protocol (versus character-oriented protocol of ACARS) that provides compatibility to the Aeronautical Telecommunications Network (ATN).

VDL Mode 2 is the simplest of the high-rate VDL modes being developed and is well suited when channel efficiency and access demands are not at a premium. The CSMA protocol limits VDL Mode 2 to providing strategic data link communications and cannot be used for time-critical, tactical communications. VDL Mode 2 is intended for addressed, air-ground communications, and can also provide a broadcast data link capability for high-rate broadcast applications, e.g., weather information, including precipitation maps, etc..

In order to achieve a simplex broadcast data link using VDL Mode 2 will require additional standardization activity to allow the AVLC data link sublayer to be bypassed, eliminating the need for message ACKs (acknowledgments) that are currently required to maintain a link connection. VDL Mode 2 is defined in detail in the ICAO Annex 10 [10] and the associated ISO standards.

3.2.3.3 Summary of VDL Mode 3

Compared to VDL Mode 2, VDL Mode 3 is considerably more complex, providing a wide range of system configurations for digital voice, data and simultaneous, integrated voice and data communications via the TDMA time slots. Time slot duration is 30 to 40 ms to accommodate vocoder frames and range guard time. VDL Mode 3 was designed to make very efficient use of the 25 KHz channel in order to increase VHF Comm data link capacity and to help alleviate VHF Comm frequency congestion. VDL Mode 3 data link communications are ATN-compatible.

Within a single frequency channel VDL Mode 3 is capable of supporting four dedicated voice sub-channels or circuits (4V mode) or can trade off one of the voice circuit as a shared data circuit (3V1D mode). A 2V2D mode allows a dedicated pair of voice circuits to have their own associated data circuit. The 3T mode allows for demand assigned voice and data. Since VDL Mode 3 uses discrete addressing in most of its system configurations, this allows for "caller ID" and "selective calling" and also allows a ground station to pre-empt an airborne voice transmission due to a stuck microphone condition or voice priority.

Digital voice is accomplished by use of a 4800 bps vocoder. To accommodate four voice circuits on a 25 KHz channel requires a signalling rate of ~31.5 kbps. Thus the VDL Mode 3 requires 31.5 kbps D8PSK modulation to support the intended voice and data capacity. One of the considerations in using 31.5 kbps D8PSK in a 25 KHz is its sensitivity to co-channel interference (D/U). VDL Mode 3 has the ability to mitigate some of this interference by using a coded squelch, which provides time windows around the time of expected signalling bursts. Any signal detected outside of these times is considered to be interference and is ignored.

VDL Mode 3 communications are directly under ground station control, which provides centralized timing and reservation-based access among all users, allowing priority-based access. Airborne users gain access to the channel using polling and random access for reservation requests to downlink data.

Sufficient guard times are allocated to the TDMA slots to allow collision free communications for all line-of-sight scenarios (e.g., 200 nmi range or greater).

With its range of system configurations, VDL Mode 3 is ideally suited for providing ATC/ATS communications of CPDLC, FIS and FIS-B and at the same time provides voice capability. The end-to-end transfer delay for VDL Mode 3 messaging is expected to be 3 seconds (95% of the time). This relatively low latency (compared to VDL Mode 2) is sufficient for ATC/ATS communications currently being planned. Any new requirements for tactical data link messaging (latencies on the order of 1 second) may not be accommodated by VDL Mode 3.

Unlike VDL Mode 2, VDL Mode 3 will require more significant changes to protocols to allow for a broadcast data link mode, e.g., uplink of weather information. For broadcast services VDL Mode 2 is the better candidate.

Much more detail is available in the VDL Circuit Mode MASPS developed by RTCA SC-172 [12], and Appendix A of the ICAO SP COM/OPS Divisional Meeting [11], although the later is somewhat dated.

3.2.3.4 Summary of VDL Mode 4

VDL Mode 4 is a data only (i.e., no digital voice) data link that utilizes TDMA channel access protocols for efficient channel utilization. The signalling rate is 19.2 kbps GFSK. TDMA time slots are ~ 13.33 ms long with ~ 10 ms of the slot available for data transfer, resulting in 192 bits per slot.

VDL Mode 4 makes integral use of GPS/GNSS time and position information for TDMA timing and slot selection protocols. All airspace users exchange synchronization bursts (which include position information) to develop system timing, allowing autonomous, self-organizing network access. Channel access can also be controlled directly by ground stations. In addition, VDL Mode 4 includes address and slot reservation information within messages to allow all users to build and maintain a network slot reservation table. This slot reservation table serves as the mechanism for all users to reserve future time slots for desired signal transmissions, thus minimizing slot transmit contention / collisions. As the network becomes more fully loaded, it may become difficult to find available slots. VDL Mode 4 utilizes position information on all users to override slot selections of distant users or those that will not be affected by co-channel interference due to geometry.

A VDL Mode 4 user listens to network transmissions for one superframe (1 minute) before selecting available time slots. Time slot selections are maintained for 4 to 8 minutes before a new reservation using different slots is made.

While VDL Mode 4 was originally intended for broadcast services, e.g., ADS-B, it also has provisions for a range of addressed communications and slot reservation protocols and is thus capable of providing a number of data link services. Some envision VDL Mode 4 to be a common CNS/ATM data link for CPDLC, DGPS/DGNSS, AOC/AAC, FIS, FIS-B, TIS-B and ADS-B data link applications. VDL Mode 4 is capable of both ATN-compatible and VHF Specific Services (VSS) data link. VSS supports low-latency tactical communications.

While VDL Mode 4 has many attractive features and capabilities, there are also a number of potential shortcomings. VDL Mode 4, like VDL Mode 3 is considerably more complex than VDL Mode 2. This is primarily due to the TDMA protocol. In addition VDL Mode 4 is dependent on precise timing from GPS/GNSS for all users and uses minimal guard times to attain maximum channel data rate. The VDL Mode 4 network, while extremely flexible, does not appear as robust as VDL Mode 3, which uses centralized timing control from ground stations. "Separation of function" of communications, navigation and surveillance is an important consideration for VDL Mode 4 ,which has a tendency to promote integration of these functions. CNS separation of function, i.e., independence among these functions to avoid common failures, is an important concept in certification of airspace operations.

VDL Mode 4 is highly reliant on low D/U performance of the 19.2 kbps GFSK waveform in order to avoid co-channel interference effects. The robustness of the waveform reduces the available signalling rate to 19.2 kbps. The lower signalling rate along with the associated time slot structure may be inadequate for some high data rate applications such as ADS-B, requiring additional channel resources. It is likely that a bank of VHF channel resources requiring multiple VHF receiver and transmitter modules may be required to satisfy the future CNS/ATM data link requirements using VDL Mode 4. Since the VHF spectrum is already at a premium, allocation of additional services to the VHF band (e.g., ADS-B surveillance) may not be possible.

ADS-B Considerations

Since VDL Mode 4 is envisioned by some to become the future data link for ADS-B data link, two significant issues arise: 1) the ability of VDL Mode 4 to provide the required data link capacity and coverage for ADS-B, and 2) the interoperability of VDL Mode 4 ADS-B with the current TCAS / Mode S surveillance system. Since ADS-B is expected to support separation assurance and collision avoidance applications, additional interfaces to TCAS are required. Dual equipage is likely needed during any transition phase before a VHF-based ADS-B and ACAS system can evolve. Since Mode-S is envisioned by some to be the ADS-B data link, with little additional modifications to the current system, a VDL Mode 4 solution may not be cost effective. Table 3-2 summarizes ADS-B data link issues for Mode-S and VDL Mode 4.

Note: It is expected that four receivers and two transmitters will be required to support VDL Mode 4 ADS-B in a worst case traffic environment such as the LA Basin (refer to Appendix D, Section 4.3.6 for details). Since two Global Signalling Channels are required for enroute ADS-B and two channels are required for terminal area ADS-B, four receivers are expected to be required in the transition between enroute and terminal area operations. While the LA Basin represents an extreme traffic scenario [4], possibly inflating the channel resource requirements, capacity studies also use ideal channel access, correct message reception and imply that ADS-B reports can be sent in a single transmission. Any deficiencies in channel access, need for retransmission of messages to assure availability, or additional message transmissions due to additional ADS-B data can result in further increase in required VDL receiver modules needed to support ADS-B. Further validation is required to confirm the estimate of four receiver and two transmitter modules for VDL Mode 4 ADS-B.

ATC/ATS Comm Considerations

For VHF Comm applications, VDL Mode 4 does not provide digital voice capability and thus additional, dedicated radio resources are required to provide both voice and data link services. The competing VDL Mode 3 offers integrated voice and data services simultaneously over the same frequency channel and does not require additional radio resources. In addition, the 31.5 kbps signalling rate supports four voice channels on a single 25 KHz channel and thus provides efficient frequency use in the crowded VHF spectrum. Use of 8.33 KHz analog voice channels in concert with VDL Mode 4 data link may also provides more efficient channel utilization, but requires separate radios.

VDL Mode 2 is ideally suited for simplex broadcast services. VDL Mode 4 is also capable of broadcast services but is less effective than VDL Mode 2.

Concluding Comments on VDL Mode 4

While VDL Mode 4 has the potential for becoming a unified data link solution for all CNS/ATM data link applications, there are also several potentially serious issues of its use as the end-state CNS/ATM data link for all or even some of these applications. In order to totally resolve these issues will require significant validation activity. At the same time, the industry has been forging ahead with definition and development of Mode-S ADS-B and VDL Mode 2 and 3 for ATC/ATS data link, with several years of development efforts having already been committed. VDL Mode 4 is a relative newcomer to the various ICAO and RTCA industry committees that are developing data link applications and may have a difficult time gaining acceptance since other solutions are already well along in the development and validation phase.

3.2.3.5 Summary of VDL Mode Capabilities

All VDL candidates (Modes 2, 3 and 4) provide ATN-compatible, addressed communications protocols and essentially use the same data link service (DLS) sublayer based on the Aviation VHF Link Control (AVLC), which is a modified version of the High Level Data Link Control (HDLC) protocol (ISO 3309). However, significant difference occur among VDL modes due to the physical layer modulation waveform (D8PSK versus GFSK) and the Media Access Control (MAC) sublayer (CSMA versus TDMA structure). Based on these differences, the following observations are made:

1) VDL Mode 2 is a simple data link protocol ideally suited for low capacity ATN-compatible data link applications, where CSMA protocols provide simple and efficient channel access. In addition, VDL Mode 2 is the best suited of the three data link modes for simplex broadcast services (a few minor protocol changes will be required to the current VDL Mode 2 definition).
2) VDL Mode 3 well suited for ATC/ATS digital voice and data communications and has the needed flexibility to accommodate a wide range of data link services that can accommodate ~ 3 seconds (95%) end-to-end transfer delays. VDL Mode 3 likely cannot support latencies on the order of 1 second. VDL Mode 3 is the most frequency efficient of all VDL approaches, capable of providing up to four voice or combination voice / data sub-channels per a single 25 KHz frequency channel.

ADS-B Requirement / Issue	Mode-S	VDL Mode 4
Interference immunity	Demonstrated in relatively high density traffic environment for ASGMCS	TBD based on D/U and interference from other VHF Comm applications
Availability, integrity	achievable	achievable
Autonomous	yes	yes in low density traffic, TBD in high density traffic
Range	100 nmi plus (to be verified)	yes (200 nmi)
Traffic density	single wideband, high-speed channel provides capacity [2][3]	requires several narrowband, lower-rate channels [4], potentially requires numerous channels (to be verified)
Independence of function (Comm, Nav, Surveillance)	yes	potential problem
Independent validation of position	yes	no
Spectrum and spectrum availability	Mode-S band already assigned for surveillance	surveillance via VHF may not be possible due to frequency assignment policy; availability of additional VHF frequency resources in crowded band is TBD
Update rate	high, allowing retransmission of ADS-B reports for increased availability, also needed for TCAS/ACAS	low, but may not be as important in terms of message retry requirement due to TDMA protocol (TBD) likely cannot provide sufficient capacity to support ACAS update rates of ~ 1 second (if required). Requires numerous channel resources in high traffic densities.
Compatibility with TCAS and SSR surveillance, legacy issue	fully compatible with current system	not compatible, likely a difficult transition period
Full message content of ADS-B report	yes	not sure (baro altitude, a/c call sign)?
Hidden user problem	no (not for long time periods)	TBD
Omnidirectional transmit coverage volume	TBD	VHF signal more amenable, TBD
Error correction coding	yes, sufficiency to be verified	none at physical layer, potential issue

Table 3-2 ADS-B Data Link Issues for Mode-S and VDL Mode 4

3) VDL Mode 4 is a highly flexible, ATN-compatible, addressed data link. In addition VDL Mode 4 is capable of VHF Specific Services to provide broadcast and low-latency addressed communications. Similar to Mode 2, VDL Mode 4 is a data only (i.e., no digital voice) data link, requiring an additional radio resource for providing simultaneous voice and data communications that will be required in the future CNS/ATM system.

   In providing ADS-B, VDL Mode 4 requires a bank of four receiver modules and two transmitter modules to provide the needed capacity. Additional receiver and transmitter resources are required for other data link services, e.g., CPDLC, FIS, AOC, etc.. It is possible to combine these applications (in low traffic density areas) on one or a few dedicated frequency channels (thus saving receiver and transmitter resources). However, this study assumes that in order to achieve capacities dictated by high traffic areas, separation of function, and the likely institutional separation of services on dedicated frequencies, separate radio resource will be required. A fully VDL Mode 4 solution to CNS/ATM data link will likely result in a VHF data link cabinet with multiple receiver and transmitter modules.

   For ADS-B, a VDL Mode 4 solution must consider interoperability with the existing TCAS / Mode-S surveillance system. If Mode-S is capable of providing the ADS-B function, it will likely be more cost effective to implement ADS-B via Mode-S due to the legacy of the TCAS / Mode-S surveillance system. Separation of function, i.e., independence, between surveillance and communications functions is also a concern for VDL Mode 4 due to the dependence on GPS/GNSS time and position information for both communications and surveillance.

3.2.4 Overview of Mode-S Data Link

At present, the Mode-S link is used for surveillance applications, supporting ground surveillance using Secondary Surveillance Radar (SSR) and air-air surveillance and resolution advisory coordination for collision avoidance using TCAS. Surveillance is provided using interrogation-reply protocols. Using interrogations and subsequent, precisely timed replies, aircraft position (slant range and approximate bearing) and identification information are derived. Unlike the old ATC Radar Beacon System (ATCRBS) transponder, Mode-S provides data link capability and is capable of broadcast and point-to-point addressed communications using Mode-S Specific Services (MSSS).

Short Mode-S interrogations and replies are 56 bits in length and are used for conventional surveillance interrogation-reply protocol, with a 24-bit address/parity field provided for aircraft addressing and identification. In addition, 112 bit interrogations and replies allow for an additional 56 bits of information to be exchanged, while still providing the conventional surveillance capability.

Mode-S data link capability is provided by the MSSS using the Mode-S Specific Protocol (MSP). MSP supports both addressed and broadcast communications. Uplink and downlink message types have been defined for ground-air and air-air communications. Uplink format (UF) and downlink format (DF) message types 0 and 16 represent short and long Mode-S interrogation / reply messages, respectively, for air-air data link with TCAS. UF / DF message types 4, 5 and 20, 21 are the short and long message types used for ground-air surveillance and data link. The DF 17 message type is used for downlink broadcast of extended squitters for ADS-B (ADS-B is discussed in Section 3.3.3). Mode-S also has extended length messages (UF/DF message type 24) that do not utilize the typical surveillance messages and allow transfers of as many as sixteen 80-bit message segments per transaction.

In addition to providing downlink broadcast squitter capability for ADS-B, the Mode-S MSP also provides the capability for Ground Initiated Comm-B (GICB) data link. Mode-S maintains 255 registers, each 56 bits long, that store a variety of important aircraft information that can be requested for downlink transmission by ground station interrogations. This information is collected by the Mode-S and updated at specified rates to maintain the integrity of the information. Thus, using initiated requests allows aircraft to reply with the requested information using Comm-B replies (i.e., long replies). Current Mode-S registers information definitions and update rates are listed in Table 3-3.

REGISTER NUMBER	ASSIGNMENT	MIN UPDATE RATE
00_{16}	Not valid	N/A
01_{16}	Unassigned	N/A
02_{16}	Linked Comm-B segment 2	N/A
03_{16}	Linked Comm-B segment 3	N/A
04_{16}	Linked Comm-B segment 4	N/A
05_{16}	Extended squitter airborne position	1.0 s
06_{16}	Extended squitter surface position	1.0 s
07_{16}	Extended squitter status	1.0 s
08_{16}- $0A_{16}$	(Reserved) extended squitter data	TBD
$0B_{16}$	Air/air State information 1	1.0 s
$0C_{16}$	Air/air State information 2	1.0 s
$0D_{16}$- $0E_{16}$	(Reserved) air/air State information	TBD
$0F_{16}$	Reserved for ACAS	TBD
10_{16}	Data link capability report	≤ 4.0 s
11_{16}-17_{16}	(Reserved) Extension to data link capability	5.0 s
18_{16}-$1F_{16}$	Mode S specific services capability report	5.0 s
20_{16}	Aircraft identification	5.0 s
21_{16}	Aircraft registration number	15.0s
22_{16}	Aerial Positions	15.0s
23_{16}	Reserved for Aerial Positions	15.0s
24_{16}	Reserved for Static Aircraft Parameters	15.0s
25_{16}-$2F_{16}$	Unassigned	N/A
30_{16}	ACAS active resolution advisory	see ACAS SARPs
31_{16}-$3F_{16}$	Unassigned	N/A
40_{16}	Aircraft intention	1.0 s
41_{16}	Next waypoint identifier	1.0 s
42_{16}	Next waypoint position	1.0 s
43_{16}	Next waypoint information	0.5 s

Table 3-3 Current Mode-S GICB Register Definition (Mode-S SARPS)

44_{16}	Meteorological routine air report	1.0 s
45_{16}	Meteorological hazard report	1.0 s
46_{16}	(Reserved) Flight management system Mode	TBD
47_{16}	(Reserved) Flight management system Mode	TBD
48_{16}	VHF frequency report	5.0 s
49_{16}-$4F_{16}$	Unassigned	N/A
50_{16}	Ground/air referenced state vector	0.5 s
51_{16}	Position report coarse	0.5 s
52_{16}	Position report fine	0.5 s
53_{16}	Air referenced state vector	0.5 s
54_{16}	Tactical waypoint 1	5.0 s
55_{16}	Tactical waypoint 2	5.0 s
56_{16}	Tactical waypoint 3	5.0 s
57_{16}-$5E_{16}$	Unassigned	N/A
$5F_{16}$	Quasi-static parameter monitoring	0.5 s
60_{16}-FF_{16}	Unassigned	N/A

Table 3-3 Current Mode-S GICB Register Definition (Mode-S SARPS) (continued)

The information contained in the Mode-S register allows for improved surveillance of aircraft by ground stations. In addition, this information allows ground automation functions, such as CTAS/FMS, to extract aircraft state, flight progress, aircraft intent (i.e., current and next waypoints in flight plan) and meteorological information to allow improved metering, aircraft vectoring and time-of-arrival calculations in increasing efficiency of operations in terminal areas while maintaining or improving safety.

ADS-B and/or air-air crosslink can also contribute to increased efficiency and safety of operations during parallel approaches to closely spaced runways, by providing a high-rate, low latency surveillance and coordination data link between aircraft, allowing for low-visibility operations using runway spacings that are closer than those allowed today. Currently, operations are limited to 3400 ft runway spacings if the airport is equipped with Precision Runway Monitor (PRM) equipment. It is anticipated that runway spacings of 2,500 ft or lower can be supported using ADS-B / crosslink surveillance between aircraft on parallel approaches.

In summary, Mode-S MSP is capable of both broadcast and addressed data link applications, supporting low-latency, tactical communications. The FAA and RTCA have indicated that Mode-S data link shall be used for surveillance applications, i.e., ADS-B, GICB, TCAS and possibly air-air crosslink. Thus, Mode-S is not intended for CPDLC (which will be provided by VHF data link). However, in the terminal area, particularly for surface operation, where time critical data link may be required, either Mode-S or VHF Specific Services (VSS) may be needed to provide reliable, low-latency communications.

The next section examines each of the planned CNS/ATM data link applications in more detail and identifies the impact of each application on Terminal Area Productivity (TAP) data link. Table 3-4 provides a cross reference of data link capability in providing respective data link application services and is later used in making allocation decisions (Section 3.4).

Data Link Application	VDL Mode 2	VDL Mode 3	VDL Mode 4	Mode-S
CPDLC (strategic)	yes	yes	yes	N/A (Mode-S intended for surveillance)
CPDLC (tactical)	no	yes (limited to 3 second transfer delays)	yes (capable of low-latencies using VHF specific services)	yes (Mode-S currently intended for surveillance only)
ADS-A/C	yes	yes	yes	N/A
ADS-B	no	no	yes? (to be validated) may require receiver bank, (see Table 3-2 for list of issues)	yes (see Table 3-2 for list of issues)
DGPS/DGNSS	yes	no	yes	N/A (VHF band is likely candidate for DGPS data link)
FIS	yes	yes	yes	N/A
FIS-B, TIS-B	yes	?	yes	N/A
TIS (tactical requirement)	no	yes (probably offered as part of CPDLC)	yes	yes (primary candidate; TIS is a product offered to provide benefits to general aviation aircraft and to encourage equipage with Mode S)
AOC/AAC	yes	yes	yes	N/A
Air-Air Communications	no	no	yes	yes
Ground Initiated Comm-B	no	no	no	yes

Table 3-4 Data Link Application / Data Link Cross Reference

3.3 Overview of Planned CNS/ATM Data Link Applications

This section examines each of the planned CNS/ATM data link applications (shown in Table 3-1) in terms of their communications requirements as they pertain to their possible allocation to VDL. Among the top-level communications requirements for each application are coverage, throughput, latency or transfer delay, addressed versus broadcast, availability, and integrity. Required Communications Performance (RCP) for the various data link applications are currently being developed in SARPS developments by the ICAO ATNP. RTCA SC-169 has published draft MASPS for RCP for Safety Services [1].

3.3.1 CPDLC

Controller Pilot Data Link Communications (CPDLC) provides for routine air traffic management communications via data link that are currently conducted via voice communications. These communications include air traffic control and traffic flow management. RTCA DO-219 defines a message set and provides Minimum Operational Performance Standards for a number of routine ATC messages.

The DO-219 message set was originally defined primarily to handle ATC communications that occur during enroute operations. These messages are strategic in nature and can be received within relatively modest transfer delays (~ 1 to 10 sec are appropriate) via the ATN. CPDLC communications are of high priority for flight safety and thus require high availability and integrity services from the ATN.

At present inconsistencies exist in the various definitions of the CPDLC message set (i.e., FANS-1 versus CNS/ATM-1) and the character-oriented and bit-oriented protocols (ARINC 622 and 623 data link layers). Hopefully, these inconsistencies will merge into a cohesive definition of end-state CPDLC communications, otherwise ground and/or airborne data links will need to be able to converse in multiple dialects of CPDLC, which is highly undesirable due to cost.

Candidate data links for CPDLC are VDL for enroute operations where a VHF ground network is available, and SATCOM and HF data link in oceanic and remote enroute operations.

As aircraft approach terminal areas and particularly for surface operations, CPDLC communications become tactical in nature (i.e., taxi instructions, hold short of runway, etc.,). In addition, the currently defined message set must be upgraded to include surface and terminal area communications.

The current VDL Mode 1, 2 and 3 transition approach is focused primarily on providing strategic CPDLC communications and is not addressing tactical CPDLC communications at this time. Worst case VDL Mode 3 latency is expected to be ~ 3 sec (95%). Potential candidates for providing these tactical CPDLC messages are the VHF specific services (VSS) of VDL Mode 4 and the Mode-S specific service (MSSS).

CPDLC for TAP Data Link

As indicated above, the focus of CPDLC definition activity has been primarily on enroute operations, with limited focus on terminal area operations. For the LVLASO flight tests, a number of data link messages were created for surface operations CPDLC data link to supplement those already defined in DO-219. VHF data link is expected to provide CPDLC data link in controlled air space. However, for terminal area CPDLC, particularly surface operations CPDLC, low-latency communications will be required. Whether current VDL Mode 3 can provide the needed latency requirements are TBD. As indicated above, VSS of VDL Mode 4 or MSSS of Mode-S can provide the low-latency, tactical communications needed for terminal area CPDLC.

In terms of message loading, individual aircraft require only minimal capacity (i.e., on the order of ~ 10 bps), thus 31.5 kbps and 19.2 kbps should provide sufficient data link capacity per frequency channel.

While not categorized specifically as CPDLC, data link support for automation functions, such as CTAS/FMS, could also be considered to fall into the category of CPDLC. GICB using Mode-S is a likely candidate to provide the needed, low-latency aircraft information that supports the ground automation functions.

3.3.2 ADS-A (ADS-C)

Two forms of Automatic Dependent Surveillance (ADS) data link are being developed; 1) addressed (also referred to as contract), ADS-A / ADS-C, and 2) broadcast ADS-B. These are significantly different applications. ADS-A is described in this section. RTCA DO-212 MOPS and ARINC Characteristic 745 have been developed to define ADS-A data link. ADS-B is discussed in the next Section (3.3.3).

As indicated ADS-A are addressed, air-ground communications that provide information from the aircraft to ground stations for air traffic control and management (ATC/ATM) and air traffic services (ATS) purposes. ADS-A data link is primarily intended for oceanic and remote enroute operations, allowing ATC to more closely monitor flight progress, aircraft state, meteorological conditions, etc.. One of the key benefits of ADS-A is the ability for closer spacings between aircraft in oceanic and remote areas compared to the large range buffers currently used for spacing. This allows selection of preferred routes and supports higher traffic densities.

ADS-A communications are ground initiated (except for emergencies). Ground stations arrange communications with individual aircraft on a contract basis using three distinct contract modes: 1) periodic, 2) event, and 3) demand driven. Typical communications are established using periodic ADS reports as prearranged between the ground and the aircraft. ADS reports can also be transmitted by the aircraft as a result of the occurrence of a particular event (e.g., vertical rate event, waypoint change event, etc.), allowing ATC to track and monitor any significant changes that may impact ATC/ATM. In addition, the ground station can request specific ADS reports from the aircraft via the demand contract mode. ADS reports are strategic in nature and are expected to be sent via the ATN using ~5 minute reporting rates (~1 minute rates in case of emergencies). ADS-A requires high availability and integrity to enable closer separation for oceanic and remote area enroute operations.

The Basic ADS Group report contains aircraft position (latitude, longitude, altitude), time stamp information indicating when the information is in effect, and a Figure of Merit (FOM) which indicates the quality of the aircraft navigation source. Among the numerous other ADS report groups that have been defined are the Flight Identification Group, Predicted Route Group, Earth Reference and Air Reference Groups, Meteorological Group, Intermediate Projected Intent and Fixed Projected Intent groups, etc., and event groups indicating Lateral Deviation Change, Vertical Rate Change, Altitude Range, and Waypoint Change events.

ADS-A is primarily intended for oceanic and remote enroute regions and utilizes the ATN for inter-network communications via SATCOM and HF data link. Note: ADS-A could also be used in controlled enroute regions using VDL, although the intent is primarily for use in oceanic and remote areas. VDL Modes 2 through 4 will ultimately all be ATN compatible and can thus provide the ADS-A service (Mode 1 is expected to be replaced with the higher data rates of Modes 2, 3 and 4 and is not considered a long-term candidate for ADS-A.

ADS-A / C for TAP Data Link

ADS-A / C is not intended for terminal area operations.

3.3.3 ADS-B

Unlike ADS-A(ddressed), Automatic Dependent Surveillance - broadcast (ADS-B) consists of data link reports from aircraft that are broadcast to all interested ground and airborne users. In addition, ADS-B provides tactical, low-latency communication within Radio Line of Sight (RLOS) by using mode specific communications, i.e., non-ATN, which enables a wide range of time-critical surveillance end user applications using the ADS-B messages set.

RTCA SC-186 recently completed the development of the ADS-B MASPS (version 6.0), which defines the ADS-B message set in terms of information content and accuracy, specifies ADS-B report update rates and reception success rates, service availability, and report integrity. Some of the major surveillance-based applications envisioned to be supported by ADS-B are Cockpit Display of Traffic Information (CDTI), Airborne Collision Avoidance System (ACAS), conflict management, ATS surveillance, ATS conformance monitoring, and a runway occupancy and incursion alert function. These applications impose a range of ADS-B data link requirements to insure integrity and availability of function.

In addition to the wide range of ADS-B end user applications, a wide range of ADS-B capability and equipage is envisioned for the various aircraft /vehicle types depending on the level of capability desired. Low-end general aviation aircraft will likely require a minimal set of ADS-B capability / equipage, sufficient to achieve desired benefits, while at the same time being compatible with the overall ADS-B surveillance in the air space system. High-end air transport aircraft will have increased ADS-B capabilities in support of more complex applications that provide added benefits, e.g., air-air separation assurance in support of free flight.

The following tables from the ADS-B MASPS serve as a summary of the ADS-B message set and state data link and operational requirements for several intended ADS-B end-user applications. Table 3-5 provides a top level summary of the ADS-B message set as a function of ADS-B applications. Most of the information elements are self-explanatory (NUC represents the navigation uncertainty category, which indicates the quality of the aircraft's navigation system; TCP refers to trajectory change point, providing aircraft intent information on planned changes in the flight trajectory).

Table 3-6 identifies ADS-B performance requirements for a number of air-to-air ADS-B applications, e.g., conflict avoidance, separation assurance, simultaneous approaches and airport surface operations. The majority of these applications require high update rates on the order of 1 per second (update success rates). This is particularly the case for simultaneous approaches and surface operations. Table 3-6 indicates expected acquisition ranges, aircraft / vehicle densities, alert times, NUC and availability and integrity of ADS-B reports.

Table 3-7 provides a summary for ADS-B performance requirements in support of ground-based ATS surveillance and conflict management as a function of flight phase. ADS-B report update rates for enroute, terminal area, and surface operations are 12 seconds, 5 seconds, and 1 second, respectively, with parallel runway approaches also requiring 1 second updates. Operational ranges for ATS surveillance can be as large as 200 nmi.

While Tables 3-6 and 3-7 represent air-to-air and ground-to-air surveillance applications, respectively, it is expected that air-to-air ADS-B applications will be the first to become operational since they do not require deployment of ground infrastructure. Regardless of air or ground-based surveillance applications, it is evident that ADS-B requires a tactical data link.

Information Element	Aid to Visual Acquisition	Conflict Avoidance	Separation Assurance & Sequencing	Flight Path Deconfliction Planning	Simultaneous Approaches	Airport Surface (A/V to A/V & A/V to ATS)	ATS Surveillance
Identification							
Call Sign[1]	n/r	n/r	R	R	R	R	R
Address	R	R	R	R	R	R	R
Category	n/r	n/r	R	R	R	R	R
State Vector							
Horizontal Position	R	R	R	R	R	R	R
Vertical Position	R	R	R	R	R	n/r	R
Horizontal Velocity	R	R	R	R	R	R	R
Vertical Velocity	R	R	R	R	R	n/r	R
Turn Rate	n/r	n/r	R	R	R	n/r	n/r
Speed Change Rate	n/r	n/r	n/r	n/r	n/r	R	n/r
NUC$_P$,NUC$_R$	R	R	R	R	R	R	R
Status and Intent							
Emergency/Priority Status	n/r	n/r	n/r	n/r	n/r	n/r	R
TCP[2]	n/r	n/r	R	R	n/r	n/r	n/r
TCP+1[2]	n/r	n/r	n/r	R	n/r	n/r	n/r

R = Required
n/r = not required to support the indicated ADS-B application. The item, if provided, may be used to improve the performance of the application.

Table 3-5 Summary of Information Needs for Applications Supported by ADS-B (from ADS-B MASPS)

3.3.3.1 ADS-B Data Link Considerations

The ADS-B MASPS defines performance requirements independent of any specific data link media. Thus any data link system that satisfies the most stringent ADS-B requirements in terms of message size and corresponding update rate, availability, integrity and coverage is a potential candidate for ADS-B data link. Several data link approaches are being considered in industry to provide the ADS-B data link application, the two most prominent being Mode-S and VDL Mode 4 data link. Studies have been conducted that have assessed the capacity (and in the case of Mode-S the interference effects of ADS-B on existing 1030/1090 MHz transmissions) of providing ADS-B data link in high density traffic using the Los Angeles Basin as the worst case traffic load (in excess of 1250 aircraft for a distribution of airborne and surface traffic) [2][3][4].

These studies suggest that either of these data links can provide the necessary ADS-B data link capacity. Mode-S uses random access protocols on the 1090 MHz frequency for broadcast of ADS-B reports. VDL Mode 4 uses TDMA channel access protocols using several dedicated VHF frequencies for ADS-B for the enroute global signaling channels, terminal area, precision approach monitor and surface operations. While multiple VHF frequencies would be required for ADS-B in the LA Basin area, only a subset of these will be required at any given time for reception in the aircraft. Discussion of the numerous, and somewhat complex issues pertaining to Mode-S versus VDL Mode 4 for ADS-B data link is deferred to Section 4.3.6 and 4.3.7 in Appendix D. Implications of the selection of either data link on the future CNS/ATM data link architecture are addressed in Section 3.5.

3.3.3.2 ADS-B and ACAS (Airborne Collision Avoidance System)

This section examines the relationship between ADS-B and ACAS and its potential impact on the selection of the ADS-B data link. As indicated above ADS-B is envisioned to support numerous applications that require surveillance information. These can be categorized as 1) separation assurance, 2) collision avoidance, and 3) situational awareness. Separation assurance applications receive ADS-B surveillance information and perform conflict detection processing to determine when loss of separation may occur. Before this occurs, aircraft can negotiate route changes that continue to assure separation.

Collision avoidance is intended as a last resort safety function, when the separation assurance function has failed. Thus, collision avoidance and separation assurance must be independent functions. Situational awareness provides supplemental information to the flight crew and does not impose any independence requirements.

Both collision avoidance and separation assurance functions can benefit from data provided by ADS-B. The current TCAS (also referred to as ACAS II) can greatly benefit from the additional state vector and intent ADS-B reports in reducing nuisance alarms, particularly when aircraft are closely spaced as in simultaneous parallel runway approaches. At the same time, ADS-B can be used to support the separation assurance function associated with closely-spaced parallel approaches. However, the independence required between separation assurance and collision avoidance function necessitates that the information used by these systems is also derived independently (i.e., measured independently not just transmitted independently). TCAS can accomplish this independence by using active interrogations to confirm the accuracy of the ADS-B report. It is likely that any new ADS-B and ACAS system must provide this mechanism for independence.

Another requirement for collision avoidance is that two or more aircraft which have lost separation coordinate their intended evasive maneuvers. This requires a cross-link between the aircraft. TCAS accomplishes this using the Mode-S link.

Any new ACAS using ADS-B via a new data link faces the following obstacles:
1) independence of ADS-B data must be assured with the separation assurance function (use of active interrogations is the likely means), 2) requirement for a cross-link for coordination of resolution advisories, and 3) compatibility with the current TCAS II which is Mode-S based. The latter point requires that fielded TCAS equipment be made compatible with any new ADS-B and ACAS function, or more likely, that a new ACAS be fully compatible with the existing TCAS.

	Operational Capability								
		Conflict Avoidance		Separation Assurance and Sequencing	Flight Path Deconfliction Planning	Simultaneous Approach		Airport Surface	
Information	Aid To Visual Acquisition	Future Collision Avoidance	Terminal Station Keeping	Free Flight/ Cooperative Separation in Overflight	Cooperative Separation in Oceanic/ Low Density Enroute	Simultaneous Approaches (*1000* ft. sep.) (305 m. sep)	Simultaneous Approaches (*2500* ft. sep.) (760 m. sep)	Airport Surface Operations (Blind Taxi)	Airport Surface Operations (Runway Incursion)
Initial Acquisition of Required Information Elements (nmi)	10	20	20	40^f	90 (120 desired)^f	10	10	5	5
Operational Traffic Densities (# A/V < range [nmi])^c	21 < 10	21 < 5; 80< 10; 250 < 20	6	120	30	32 landing; 3 outside extended r/w; 5 beyond r/w	32 landing; 3 outside extended r/w; 5 beyond r/w	25 w/ih 500 ft (152 m.)	25 w/in 500 ft (152 m.)
Alert Time^b	n/a	1 min	2 min	2 min	4.5 min (6 min)	15sec	15 sec	n/a	5 s
Expected NUC$_p$ Expected NUC$_R$	3/1 1/1	4/2 3/2	4/2 3/2	4/2 3/2	4/2 3/2	5/4 4/2	5/4 4/2	5/n/a 4/na/	5/n/a 4/n/a
Service Availability^d%	95	99.9	99.9	99.9	99.9	99.9	99.9	99.9	99.9
Report Integrity ^{g}	10^{-5}	10^{-7}	10^{-6}[14]	10^{-6}	10^{-6}	10^{-6}[14]	10^{-6}[14]	10^{-6}[14]	10^{-6}[14]

Table 3-6 Summary of ADS-B Air-to-Air Performance Requirements for Support of Indicated Applications (from ADS-B MASPS)

	Operational Capability			
Information	**En Route**	**Terminal**	**Airport Surface**	**Parallel Runway Conform Mon.**
Initial Acquisition of A/V Call Sign and A/V Category	**w/in 24 sec.**	**w/in 10 sec.**	**w/in 10 sec.**	**n/a**
Horizontal Position Error	**350 m. [7]**	**150 m. [7]**	**3 m. rms, 9 m. bias [24],[7], [15]**	**9 m.**
Received Update Period^{b}	**12 sec. [14]**	**5 sec. [7]**	**1 sec.**	**1 sec.**
Update Success Rate	**98%**	**98%**	**98% [7]**	**98%**
Operational Domain Radius (nmi)	**200**	**60**	**5**	**10**
Operational Traffic Densities^{c} (# A/V)	**1250 [7]**	**750 [7]**	**100 in motion; 150 fixed**	**50 dual; 75 triple; w/o filter: 150**
Service Availability^{d} (%)	**99.999 [14] 99.9 (low alt)**	**99.999 [14] 99.9 (low alt)**	**99.999 [14]**	**99.9**
Report Integrity^{f}	**10^{-7} [14]**	**10^{-7} [14]**	**10^{-7} [14]**	**10^{-7} [14]**

a) References are provided where applicable. Else, best judgment was used to obtain performance data.

b) Received update period is the period between received state vector updates. A/V Call Sign and A/V Category can be received at a lower rate.

c) One or multiple ground receivers may be used in the operational domain to ensure acceptable performance for the intended traffic load.

d) Service availability includes any other systems providing additional sources of surveillance information.

e) Altitude accuracy: additional benefits can be gained by using 25 ft., or better.

f) Integrity values are defined as the probability of two successive reports having undetected correlated errors.

Table 3-7 Summary of ADS-B Requirements for ATS Provider Surveillance and Conflict Management Applications (as a function of Flight Phase) (from ADS-B MASPS)

Use of a data link that supports future ADS-B and ACAS that is incompatible with Mode-S must deal with the legacy of TCAS using the Mode-S link. For example, assuming that ADS-B is provided via a VHF data link such as VDL Mode 4, separation assurance applications can be developed based on this capability. ACAS on the other hand will consist of TCAS equipment, at least in the short term, and continues to require transponder equipage for all aircraft. Thus, during initial deployment of VHF ADS-B, aircraft will require dual equipage with VHF ADS-B and Mode-S transponders. Not until a VHF based ACAS is developed, which is capable of active interrogations (for independence with separation assurance functions) and provides a cross-link between aircraft for coordination, can the air space system transition to a fully VHF ADS-B and ACAS system, eliminating the need for Mode-S transponders. During the interim, a difficult and carefully orchestrated transition away from TCAS to ACAS would be required.

Thus while the previous section indicates that from a technical perspective, ADS-B can be provided by either Mode-S or VDL Mode 4 data links, the selection of the appropriate data link is greatly influenced by the relationship of ADS-B to TCAS / ACAS.

3.3.3.3 Ground Interrogation of Aircraft Mode-S Registers

In the evolution of the development of Mode-S, 255 registers have been allocated within the Mode-S transponder (also referred to as the Mode-S registers) for storage of a wide range of useful aircraft information. A number of these registers have been set aside to contain the extended squitters that represent the ADS-B message set. While the intent of ADS-B is to broadcast these extended squitters periodically (per the requirements defined by the ADS-B MASPS) for use by all other users to provide the ADS-B surveillance applications, an alternate or supplementary approach being considered is to use ground station interrogators for control of this information. Using this ground-based approach, ground-initiated interrogations using the Mode-S Specific Protocol (MSP) defined by the ICAO Mode-S Specific Services can request read-outs of specific registers via transponder replies (also referred to as Ground Initiated Comm-B {GICB}).

Thus, there are two distinct philosophies to surveillance, 1) air traffic control using strictly ground-based control / surveillance, with the ground being fully responsible for all control, and 2) a shared responsibility for air traffic management using ADS-B between ground and airborne users, with reliance on air-to-air separation assurance, while ground stations provide conformance monitoring of flight progress, and intervene in case of loss of separation. The second approach, where ADS-B is at parity with the ground surveillance system in sharing responsibility for separation assurance is the preferred approach by air space users, since it is compatible with the goals of free flight.

A mix of ADS-B and some GICB data link messaging can also be used to provide pertinent information, such as weather reports by aircraft, and to provide 4-D surveillance for better time-of-arrival estimation and sequencing by the CTAS (Center TRACON Automation System) to improve terminal area operations.

ADS-B for TAP Data Link

ADS-B plays a vital role in Terminal Area Productivity (TAP) data link. ADS-B supports surveillance of aircraft operations in the terminal area airspace, during landing and approach (including parallel runway approaches) and for surface operations. This is particularly important during low-visibility weather conditions, when controllers and pilots can no longer rely on visual contact in conducting operations. For efficient, safe terminal area operations in low-visibility conditions, high integrity surveillance using ADS-B is a requirement.

Mode-S and VDL Mode 4 data link are the primary candidates for ADS-B. The FAA and RTCA have selected Mode-S as the near-term data link for ADS-B. Both Mode-S and VDL Mode 4 are expected to provide the necessary data link capacity for terminal area ADS-B for worst case traffic densities (i.e., LA Basin) [2][3][4]. The 1030 / 1090 MHz Mode-S link is expected to provide the required communications performance for terminal area ADS-B (5 sec update rates in terminal area and 1 sec update rates for parallel runway approaches and surface operations). Four VHF channels are anticipated to be needed for VDL Mode 4 to provide the necessary capacity and performance for terminal area ADS-B (refer to Section 4.X.X in Volume II of report).

3.3.4 DGPS/DGNSS (LAAS)

The ICAO Global Navigation Satellite System Panel (GNSSP) and RTCA SC-159 are currently developing SARPS and MASPS requirements for the Local Area Augmentation System (LAAS) in support of precision approaches (Cat I, II and III). This activity includes the definition of the message set and data link for uplink of GPS/GNSS corrections and integrity information to airborne GPS receivers. The DGPS/DGNSS data link application is a broadcast ground-to-air service and is flight critical, requiring very high integrity, availability, and continuity of service. The data link requires low transfer delays, i.e., is non-ATN, only using the physical layer and TDMA MAC layer services. Expected data link coverage range is a 20 to 30 nmi radius from the airport.

The data link defined in RTCA DO-217, Appendix F is the leading candidate for LAAS, using 31.5 kbps D8PSK modulation and TDMA channel access using 0.5 second frames, each consisting of eight 62.5 ms time slots. This data link approach is being upgraded to meet LAAS requirements. The DO-217 VHF data link physical layer modulation waveform is very similar to the VDL Mode 2. Another candidate approach being considered is 19.2 kbps GFSK modulation, using either the same TDMA slot structure as indicated above or a derivative of VDL Mode 4 TDMA time slots. Data link selection considerations are frequency reuse (based on D/U co-channel interference of the modulation waveform), data link capacity, and compatibility with other VDL modes (compatibility with VDL Modes 2 and 3 or with VDL Mode 4).

DGPS / DGNSS for TAP Data Link

DGPS / DGNSS data link will be required for TAP data link for precision approach services and for low-visibility surface operations when used for navigation guidance. VHF data link is the expected broadcast data link for DGPS / DGNSS using 31.5 kbps D8PSK or possibly 19.2 kbps GFSK signals-in-space.

3.3.5 FIS, FIS-B

The future CNS/ATM system is expected to provide a number of flight information services (FIS) that provide for increased flight safety. Some FIS data link services are already in use (e.g., Predeparture Clearance, D-ATIS). FIS data link uses both addressed and broadcast communications depending on the application. The following list of FIS applications are either currently in use or are in the planning stages:

- Predeparture clearance
- Digital Automatic Terminal Information Services (D-ATIS) consisting of latest weather observations and specific airport data
- Windshear advisory service
- Pilot reports (PIREP) service
- Notice to Airman (NOTAM) service
- Runway Visual Range service
- Precipitation map
- Terminal Weather Service
    1) Terminal Weather Information to Pilots (TWIP) consisting of information from Terminal Doppler Weather Radar (TDWR) or Integrated Terminal Weather Service (ITWS)
    2) Graphical Weather Service (GWS) consisting of precipitation maps and a graphic version of TWIP
    3) Textual weather products.

Some of the above services have been implemented via request-reply ACARS data link (VDL Mode 1), while GWS of precipitation maps and TWIP using image compression and subsequent transmission via Mode-S extended length messages (ELMs) are also being developed. The motivation for these FIS products are to utilize the existing ACARS link to provide services and also to use Mode-S to provide benefits for general aviation aircraft that encourage them to equip with Mode-S transponders. In the long term, the ACARS FIS data link applications are expected to transition to the higher data rate VDL modes (VDL Modes 2 and 3 or VDL Mode 4) using ATN-compatible sub-networks.

In addition to these addressed FIS services, the use of broadcast services (FIS-B) of graphical weather information can be achieved by utilizing VDL in a broadcast mode, e.g., using VDL Mode 2 (CSMA) in a simplex broadcast mode. VDL Modes 3 and 4 could also provide FIS-B services.

FIS, FIS-B for TAP Data Link

The above FIS and FIS-B services are expected to be provided for both enroute and terminal area operations using VDL Modes 2, 3 or 4.

3.3.6 TIS, TIS-B

Traffic Information Service (TIS) is intended to increase pilot situational awareness by providing information of proximate traffic to the attention of the pilot and is particularly beneficial to general aviation pilots. By providing the TIS service, it is hoped that general aviation pilots see sufficient benefits to equip with Mode-S transponders, which at the same time facilitates the transition to ADS-B surveillance. The TIS service is provided by ground stations using Mode-S sensors that are equipped with the TIS software package, which processes surveillance replies to detect close proximity traffic to TIS equipped aircraft and uplinks this information to that aircraft as part of a long Mode-S interrogation. In this manner, TIS equipped aircraft are informed of transponder equipped aircraft even if the other aircraft is not TIS equipped. The TIS equipped aircraft initiates the TIS service by including a TIS request to the ground sensor.

TIS is intended to display traffic within 5 nmi and +/-1200 ft altitude of the requesting aircraft. Clearly TIS is a tactical data link application and is implemented using mode specific data link services (i.e., non-ATN).

TIS-B (TIS-broadcast) is a potential data link application for future broadcast services of traffic. This is particularly important on the airport surface in low-visibility weather conditions, where the ground surveillance system informs all surface aircraft and vehicles of the other traffic. Due to the potential for a large amount of surface traffic, a broadcast data link is more efficient than using addressed TIS data link. On the airport service, a broadcast VHF data link (Modes 2, 3, or 4) similar to the FIS-B data link for weather services could be used to provide this service.

TIS, TIS-B for TAP Data Link

TIS is intended to be a service primarily for low-end general aviation aircraft to aid "see and avoid" traffic operations and to alert pilots of proximate aircraft. TIS-B is expected to play a significant role in terminal area operations for situational awareness for both controllers and pilots (Cockpit Display of Traffic Information). TIS-B was demonstrated in the LVLASO flight tests and demonstration and is expected to be a requirement for low-visibility surface operations, providing both controllers and pilots with a consistent view of the traffic environment. A single VHF channel is expected to provide sufficient throughput to support broadcast uplink of traffic information for greater than 200 aircraft per second (Section 2.4.3.2). At this time, the TIS-B data link concept / application has not been developed by industry committees. The LVLASO flight test employed an experimental TIS-B data link to provide traffic information for display in the NASA 757 flight deck.

3.3.7 AOC/AAC

Airline Operational Communications (AOC) and Airline Administrative Communications (AAC) are currently sent via ACARS VDL Mode 1 addressed data link. In the future CNS/ATM system, these communications can be sent via VDL Modes 2, 3 or 4 or SATCOM and HF data link in remote areas. These communications are strategic in nature and will be sent via the ATN between aircraft, the service provider, and the airline.

AOC/AAC for TAP Data Link

No additional role for AOC/AAC is envisioned. These communications will continue to evolve in time and are expected to transition to the higher-rate VDL modes (Modes 2, 3, or 4) for higher update rates and capacity.

3.3.8 Air-Air Communications

Currently the only air-air data link application in use are TCAS air-to-air coordination interrogations and replies via the Mode-S link between aircraft selecting appropriate resolution advisories to resolve threatening encounters. In the future the use of Airborne Collision Avoidance System (ACAS) cross-link is expected to provide improved surveillance for separation assurance and collision avoidance, by providing an independent cross check on ADS-B surveillance reports and also providing high update rate, low latency information exchanges between aircraft. In the near term the Mode-S link is expected to serve as the ACAS cross-link data link. Another future air-to-air data link application is for route or trajectory negotiations between aircraft conducting free flight operations.

Air-to-air addressed data link applications are tactical in nature and require use of non-ATN mode specific service. Mode-S and VDL Mode 4 are candidate data links using MSSS and VSS, respectively

Air-to-Air Communications for TAP Data Link

Air-to-air communications are expected to provide significant benefits for surveillance during parallel runway approaches to closely-spaced runways in low-visibility conditions. The exact role of active air-air crosslink between aircraft on parallel approach and passive ADS-B surveillance is yet to be determined. However, air-air crosslink will likely be required to assure independence between separation assurance and collision avoidance functions and to provide coordination between aircraft as a threatening situation develops.

It is apparent that most of the CNS/ATM data link applications indicated above also play a significant role for Terminal Area Productivity (TAP) data link. Thus the data link allocations discussed next (Section 3.4) and the candidate data link architectures (section 3.5) directly apply to TAP data link.

3.4. *Allocation of CNS/ATM Data Link Applications to Data Links*

This section examines possible allocations of CNS/ATM data link applications to respective data link candidates. From these allocations it then becomes possible to postulate data link architectures. Tables 3-8 to 3-10 list the anticipated CNS/ATM data link applications and indicate which of the data links (VDL Modes 1 to 4, Mode-S, SATCOM and HF) are likely candidates in providing the service. Table 3-8 identifies data link allocations for terminal area and airport surface operations, Table 3-9 addresses enroute (non-remote area, i.e., with ATC ground networks in place) operations, and Table 3-109 is for oceanic and remote enroute operations. From Tables 3-8 to 3-10, it is evident that a wide range of data link mappings are possible.

In order to compress the available options, data link applications are reduced into four distinct groups, since it is expected that services within any one of these groups would be assigned to the same data link. The four data link groups identified are as follows:

1) Air traffic control (ATC) group consisting of CPDLC and ADS-A
2) ADS-B group (ADS-B but may also include TIS and air-air data link)
3) Air traffic services (ATS) group consisting of FIS, FIS-B, and TIS-B
4) AOC/AAC group for airline communications

Note that DGPS/DGNSS data link has been removed from the list of data link applications since it is expected that it will be implemented as a separate module within a Multi-Mode Receiver (MMR) for precision approaches, or within the GPS sensor itself. It is desirable for cost purposes that the physical layer modulation of the VHF DGPS/DGNSS data link is the same as that used by VDL, however this is not a requirement. DGPS/DGNSS data link will likely use either 31.5 kbps D8PSK or 19.2 kbps GFSK modulation and will use its own specific TDMA frames and time slot structure (i.e., similar but not the same as VDL).

TIS and air-to-air data link (for trajectory negotiation and /or ACAS cross-link) are grouped with the ADS-B group. These applications primarily use specific services (i.e., non-ATN) that could be accomplished via MSSS using Mode-S or VSS on VDL Mode 4. TIS is primarily a service intended for low-end general aviation users.

In addition, SATCOM and HF data links will not be considered in further allocation mappings since they are used primarily during distinct operational phases (i.e., oceanic and remote enroute) and can easily be separated from the other more complex data link allocations. Table 3-11 shows a compressed mapping of data link services based on the allocations of Tables 3-8 to 3-10.

Since VDL Mode 4 is relatively new compared to the more established VDL Modes 2 and 3 and Mode-S, Table 3-11 is organized as follows. Option #1 describes a data link allocation that does not utilize any VDL Mode 4 capability (i.e., ATC, ATS and AOC/AAC group data links are all allocated to VDL Mode 2 and / or VDL Mode 3 and ADS-B is via Mode-S). Subsequent allocation options that may be feasible allocate an increasing number and various combinations of data link applications to VDL Mode 4. A total of eight allocation options were identified, with Option #8 consisting of an all VDL Mode 4 data link system.

CNS/ATM Data Link Application	VHF Data Link				Mode-S	SATCOM	HF Data Link
	Mode 1	Mode 2	Mode 3	Mode 4			
CPDLC (strategic)	X	X	X	X			
CPDLC (tactical)			X[0]	X[1]	X[2]		
ADS-A (ADS-C)	▨	▨	▨	▨	▨	▨	▨
ADS-B				X[3]	X		
DGPS/DGNSS		X[4]		X[4]			
FIS	X	X	X	X			
FIS-B		X[5]	X[6]	X[7]			
TIS				X	X		
TIS-B		X[5]	X[6]	X[7]			
AOC/AAC	X	X	X	X			
Air-Air Communications				X	X		

Table 3-8 Candidate Data Links for future CNS/ATM Data Link Applications - Terminal Area and Airport Surface Operations

Note: "X" indicates that the data link can likely provide the data link service (although additional validation is likely required).
The gray area indicates that the service is not applicable for the operation flight phase.

[0] VDL Mode 3 latency ~3 sec (95%)

[1] Availability and latency are not well known but are assumed to be sufficient to provide service (requires validation).

[2] While Mode-S has capability for tactical CPDLC using MSSS, the proposed NAS architecture states that Mode-S should only be used for surveillance applications.

[3] Concern whether VHF Comm band has sufficient frequencies and can be used for ADS-B, which is a surveillance function.

[4] DGPS/DGNSS data link will likely have its own unique TDMA frame and time slot structure but will generally be similar to VDL.

[5] VDL Mode 2 is most ideally suited for VHF broadcast data link.

[6] Significant changes to current protocol are required to support pure broadcast applications.

[7] Suitability of VDL Mode 4 for broadcast of large messages is to be verified based on time slot architecture.

CNS/ATM Data Link Application	VHF Data Link				Mode-S	SATCOM	HF Data Link
	Mode 1	Mode 2	Mode 3	Mode 4			
CPDLC (strategic)	X	X	X	X			
CPDLC (tactical)	▨	▨	▨	▨	▨	▨	▨
ADS-A (ADS-C)	X[1]	X[1]	X[1]	X[1]			
ADS-B				X[2]	X		
DGPS/DGNSS[3]		X[4]		X[4]			
FIS	X	X	X	X			
FIS-B		X[5]	X[6]	X[7]			
TIS				X	X		
TIS-B		X[5]	X[6]	X[7]			
AOC/AAC	X	X	X	X			
Air-Air Communications				X	X		

Table 3-9 Candidate Data Links for future CNS/ATM Data Link Applications - Enroute (Non-remote areas) Operations

Note: "X" indicates that the data link can likely provide the data link service (although additional validation is likely required).
The gray area indicates that the service is not applicable for the operation flight phase.

[1] In enroute non-remote areas, where ground ATC infrastructure is in place, it is unclear whether ADS-A will be used or if ADS-B and CPDLC provide the necessary ATC data link applications, or a combination of both.

[2] Concern whether VHF Comm band has sufficient frequencies and can be used for ADS-B, which is a surveillance function.

[3] In case the Wide Area Augmentation System (WAAS) is used, that data link function is internal to the GPS and is not considered here.

[4] DGPS/DGNSS data link will likely have its own unique TDMA frame and time slot structure but will generally be similar to VDL.

[5] VDL Mode 2 is most ideally suited for VHF broadcast data link.

[6] Significant changes to current protocol are required to support pure broadcast applications.

[7] Suitability of VDL Mode 4 for broadcast of large messages is to be verified based on time slot architecture.

CNS/ATM Data Link Application	VHF Data Link				Mode-S	SATCOM	HF Data Link
	Mode 1	Mode 2	Mode 3	Mode 4			
CPDLC (strategic)						X	X
CPDLC (tactical)	▨	▨	▨	▨	▨	▨	▨
ADS-A (ADS-C)						X	X
ADS-B				X[1]	X		
DGPS/DGNSS[2]	▨	▨	▨	▨	▨	▨	▨
FIS						X[3]	X[3]
FIS-B						X[3]	
TIS	▨	▨	▨	▨	▨	▨	▨
TIS-B	▨	▨	▨	▨	▨	▨	▨
AOC/AAC						X	X
Air-Air Communications				X	X		

Table 3-10 Candidate Data Links for future CNS/ATM Data Link Applications - Oceanic/Remote Area Enroute Operations

Note: "X" indicates that the data link can likely provide the data link service (although additional validation is likely required). The gray area indicates that the service is not applicable for the operation flight phase.

[1] Concern whether VHF Comm band has sufficient frequencies and can be used for ADS-B, which is a surveillance function.

[2] GPS augmentation will likely be via the Wide Area Augmentation System (WAAS). This data link will be internal to the GPS and is not considered here.

[3] Role of FIS in oceanic, remote area operations is TBD but would need to be supported by SATCOM and/or HF data link. SATCOM is also capable of broadcast using a dedicated circuit mode channel.

Data Link Application	Allocated Data Link	Comments (From perspective of VDL Mode 4 allocation)
Option #1	VDL Mode 2 and / or VDL Mode 3	No applications using VDL Mode 4 in this scenario
ATC group (CPDLC, ADS-A)		
ATS group (FIS, FIS-B, TIS-B)		
AOC/AAC group (airline group)		
ADS-B group	Mode-S	
Option #2	VDL Mode 2 and / or VDL Mode 3	AOC/AAC group via VDL Mode 4
ATC group (CPDLC, ADS-A)		
ATS group (FIS, FIS-B, TIS-B)		
AOC/AAC group (airline group)	VDL Mode 4	
ADS-B group	Mode-S	
Option #3	VDL Mode 2 and / or VDL Mode 3	AOC/AAC and ATS groups via VDL Mode 4
ATC group (CPDLC, ADS-A)		
ATS group (FIS, FIS-B, TIS-B) AOC/AAC group (airline group)	VDL Mode 4	
ADS-B group	Mode-S	
Option #4	VDL Mode 4	All groups use VDL Mode 4 except ADS-B group
ATC group (CPDLC, ADS-A)		
ATS group (FIS, FIS-B, TIS-B)		
AOC/AAC group (airline group)		
ADS-B group	Mode-S	

Table 3-11 Data Link Allocations Per Application Groups

Data Link Application	Allocated Data Link	Comments (From perspective of VDL Mode 4 allocation)
Option #5	VDL Mode 2 and / or VDL Mode 3	ADS-B group via VDL Mode 4
ATC group (CPDLC, ADS-A)		
ATS group (FIS, FIS-B, TIS-B)		
AOC/AAC group (airline group)		
ADS-B group	VDL Mode 4	
Option #6	VDL Mode 2 and / or VDL Mode 3	AOC/AAC and ADS-B groups via VDL Mode 4
ATC group (CPDLC, ADS-A)		
ATS group (FIS, FIS-B, TIS-B)		
AOC/AAC group (airline group)	VDL Mode 4	
ADS-B group		
Option #7	VDL Mode 2 and / or VDL Mode 3	All service except ATC group via VDL Mode-4
ATC group (CPDLC, ADS-A)		
ATS group (FIS, FIS-B, TIS-B)	VDL Mode 4	
AOC/AAC group (airline group)		
ADS-B group		
Option #8	VDL Mode 4	All groups use VDL Mode 4 in this scenario
ATC group (CPDLC, ADS-A)		
ATS group (FIS, FIS-B, TIS-B)		
AOC/AAC group (airline group)		
ADS-B group		

Table 3-11 Data Link Allocations Per Application Groups (continued)

The rationale for these allocation options using incrementally more VDL Mode 4 use are as follows:

Option #1: No VDL Mode 4; Mode-S ADS-B with all other data link via VDL Modes 2/3. These data links meet the application requirements and VDL Mode 4 adds no additional benefits.

Option #2: AOC/AAC to VDL Mode 4, i.e., a new service provider network for airline communications via VDL Mode 4.

Option #3: AOC/AAC and ATS (FIS, FIS-B, TIS-B) to VDL Mode 4, i.e., all service provider and flight services data link via VDL Mode 4.

Option #4: All data link via VDL Mode 4, except for Mode-S ADS-B.

Option #5: Only ADS-B via VDL Mode 4, all other data link via VDL Modes 2/3.

Option #6: All ATC/ATS services via VDL Modes 2/3 using integrated digital voice and data capability; ADS-B and airline communications via VDL Mode 4.

Option #7: Controller data link (i.e., ATC group) via VDL Modes 2/3 using efficient, integrated digital voice and data capability; all other data link and ADS-B via VDL Mode 4.

Option #8: All data link via VDL Mode 4.

The next section develops CNS/ATM data link architecture candidates based on these eight data link allocation options.

3.5. Candidate Avionics Data Link Architectures for CNS/ATM and TAP

The candidate data link architectures below are developed for CNS/ATM capable air transport aircraft and will thus consider worst case data link requirements in terms of 1) number of services, 2) required communications performance (RCP), and 3) high-density traffic loadings (e.g., LA Basin being worst case loading). These candidate data link avionics architectures therefore reflect a typical avionics data link suite required for air transport aircraft.

The following data links are assumed to be included in all of the future CNS/ATM data link architectures discussed below:

1) WAAS data link (data link accomplished via GPS signal and thus included in GPS sensor). Dual WAAS GPS receivers are expected to be required.
2) LAAS (DGPS /GNSS) data link is expected to be a VHF data link using either 31.5 kbps D8PSK or 19.2 kbps GFSK. The LAAS data link is expected to be integrated in a Multi-mode Receiver (MMR) or the GPS sensor and is not considered within the VDL modes discussed below. Dual or triple redundant MMR or GPS sensors are expected to be required.
3) Dual SATCOM and dual HF data link are required for oceanic and remote-area enroute data link.

3.5.1 VHF Radio Resource Requirements versus Data Link Allocation Options

The data link allocations from Table 3-11 are examined more closely to determine the radio resource requirements. A number of observations are in order:

1) Conventional analog AM voice capability must be included since not all parts of the world will have digital voice capability for a very long time.
2) ADS-B end user applications that provide Airborne Separation Assurance System (ASAS), Airborne Collision Avoidance System (ASAS), and Situational Awareness (SA) are expected to be functionally integrated in TCAS, FMS etc., avionics equipment.
3) ADS-B data link candidates are Mode-S data link or VDL Mode 4. For Mode-S ADS-B, dual Mode-S transponder are required (on/standby).
4) For low-latency, tactical CPDLC, only VDL Mode 3 and VDL Mode 4 are viable candidates. VDL Mode 2 (CSMA protocol) is not adequate for low-latency CPDLC. To achieve 1 sec latencies may require VHF Specific Services (VSS) in place of ATN-compatible services. Mode-S Specific Service (MSSS) are also capable of low-latency CPDLC. However, FAA and RTCA have stated that Mode-S shall only be used for surveillance.
5) VHF/VDL radio tuning/retuning can be accomplished manually by the pilot via aural or data link instructions from ATC. Tuning/retuning can also be done automatically by FMS or data link equipment. Radio tuning is accomplished via the physical and data link layers and should be invisible to the virtual circuit connection of the network layer. There is a potential for a "make-before-break" requirement, where the next station is contacted ("make") before the current station is dropped ("break"). If "make-before-break" is a requirement, an additional radio resource will be required, at least until the new connection is made. For this analysis, "make-before-break" is assumed not to be a requirement.
6) Based on VDL Mode 4 capacity studies (refer to Appendix D, Section 4.3.6), for high-traffic densities, two receive channels are required for enroute ADS-B using the two Global Signalling Channels (GSCs), and two receive channels are required for terminal area ADS-B. During the

transition between these operational regions, it is assumed that four ADS-B receivers are required at a minimum (also two transmitters are assumed, one for GSCs and one for terminal area ADS-B). These four ADS-B receive channels can be reallocated from enroute GSCs to terminal area, parallel approach monitoring (PRM) and surface operations (ASMGCS).

7) Reference to VDL Mode 2 implies the following capability: AM voice (25 KHz / 8.333KHz), VDL Mode 1 (ACARS) and VDL Mode 2.
8) Reference to VDL Mode 3 implies the following capability: AM voice (25 KHz / 8.333KHz), VDL Mode 1 (ACARS), VDL Mode 2 and VDL Mode 3.
9) Reference to VDL Mode 4 implies only VDL Mode 4 capability, unless specifically stated otherwise.

Table 3-12 identifies radio resource requirements versus the data link allocation options identified in Table 3-11. The initial entry in Table 3-12 is for the conventional system configuration used in today's air transport aircraft, i.e., three VHF Comm radios (AM voice and VDL Mode 1) and dual Mode-S transponders for ATC surveillance. The remainder of Table 3-12 addresses future, end-state CNS/ATM data link requirements, which represent considerably more data link services and data link capacity requirements then addressed in current avionics. Table 3-12 lists the data link application allocations and then uses the middle columns to illustrate radio requirements for "left", "center", and "right" radios. Options #1 to #4 all use Mode-S for ADS-B. Options #5 to #8 all use VDL Mode 4 for ADS-B. ADS-B via VDL Mode 4 requires multiple transmit and receive resources, thus the conventional "left/center/right" radio view is replaced with a view point of transmitter and receiver banks that are integrated into one or more fault-tolerant VHF data link radio cabinet.

Table 3-13 provides a condensed version of Table 3-12 in terms of radio resource requirements as a function of the data link allocation options considered. From Table 3-13 three options are highlighted that appear to be the most feasible data link allocations:

1) VDL Modes 2 and/or 3 for voice and ATC/ATS data link; Mode-S for ADS-B (Option #1)
2) VDL Modes 2 and/or 3 for voice and ATC/ATS data link; VDL Mode 4 for ADS-B (Option #5)
3) VDL Mode 4 for all applications (Options #8).

Most of the other options were eliminated, because the mix of allocations to the various VDL modes results in either a) excessive radio resources being required, or b) multi-mode VDL radios with both, Mode 3 and Mode 4 capability being required. Since both VDL Mode 3 and Mode 4 are both quite complex, high cost radios would result if both Mode 3 and 4 must be supported in a multi-mode radio.

Option #1b provides the least equipage options; VDL Mode 3 provides integrated voice and data via one frequency channel and reduces the number of resources required. The need for providing legacy analog AM voice in areas that will not yet have fully upgraded to VDL Mode 3 will require an additional radio for simultaneous AM voice and CPDLC support. Thus four VDL Mode 3 radios are required.

Figures 3-6 through 3-9 illustrate several VDL Mode 4 radio implementations using banks of transmitter and receiver modules. The requirement for multiple transmitters and receivers is primarily due to the ADS-B application. While it is conceivable that some data link applications can be combined over one or a few frequency channels, it is likely that dedicated radio resources (i.e., frequencies) must be provided due to data link capacity and separation of function considerations. Whether it is more appropriate that all radio modules are integrated in a single, fault-tolerant VHF radio cabinet, or in several smaller radios is TBD based on failure mode analysis.

Data Link Allocation Option	Physical Data Links Required (including spares)			Comments
	Left Radio(s)	Center Radio(s)	Right Radio(s)	
Conventional System Configuration: ATC analog voice, ACARS data link (AOC/AAC, etc.), Direct company (airline) voice comms, ATIS, AWOS services Mode-S transponder for ATC surveillance	VDL Mode 1 radio Pilot ATC Voice DSB AM using 25 KHz channels Mode-S transponder (active)	VDL Mode 1 radio ACARS data link (AOC/AAC)	VDL Mode 1 radio mostly an idle spare, co-pilot use for direct company voice, and AWOS, ATIS Mode-S transponder (standby/spare)	**3 VHF Comm radios** (AM voice, VDL Mode 1 capable) **2 Mode-S transponders**
Option #1a: **Data Link Group** — **Data Link** ATC (CPDLC, ADS-A) — VDL Mode 2 ATS (FIS, FIS-B, TIS-B) — VDL Mode 2 AOC/AAC — VDL Mode 2 ADS-B (also TIS, air-air) — Mode-S	VDL Mode 2 radio AM voice mode (pilot ATC Voice) DSB AM using 25 KHz / 8.33 KHz channels VDL Mode 2 radio data link mode (pilot CPDLC) Mode-S transponder ADS-B data link (active)	VDL Mode 2 radio data link mode (AOC/AAC)	VDL Mode 2 radio mostly an idle spare, co-pilot use: voice for direct company comms, AWOS, ATIS or FIS, FIS-B, TIS-B data link Mode-S transponder (standby/spare)	**4 VDL Mode 2 radios required** (possibly 5 radios if large # of FIS services are needed) Radio modes supported: AM voice (25 KHz / 8.33KHz), VDL Mode 1, VDL Mode 2 **2 Mode-S transponders** Note: WAAS, LAAS, SATCOM, and HF data links also required. ADS-B airborne separation assurance (ASAS), airborne collision avoidance (ACAS), and situational awareness (SA) applications will likely be implemented within TCAS, FMS or other end-user systems

Table 3-12 Radio Resource Requirements as a function of Data Link Allocation Option

Data Link Allocation Option	Physical Data Links Required (including spares)			Comments
	Left Radio(s)	Center Radio(s)	Right Radio(s)	
Option #1b: **Data Link Group** — **Data Link** ATC (CPDLC, ADS-A) — VDL Mode 3 ATS (FIS, FIS-B, TIS-B) — VDL Mode 3 AOC/AAC — VDL Mode 3 ADS-B (also TIS, air-air) — Mode-S	VDL Mode 3 radio Pilot ATC (digital) voice and CPDLC data link, simultaneously (3V1D, 2V2D modes, etc.) Mode-S transponder (active)	VDL Mode 3 radio data link (3T) mode (AOC/AAC)	VDL Mode 3 radio mostly an idle spare, co-pilot use: voice for direct company comms, AWOS, ATIS or FIS, FIS-B, TIS-B data link Mode-S transponder (standby/spare)	**3 VDL Mode 3 radios required** (possibly 4 radios if large # of FIS services are needed) Radio modes supported: AM voice (25 KHz / 8.33KHz), VDL Modes 1, 2 and 3 **2 Mode-S transponders**
Option #2a: **Data Link Group** — **Data Link** ATC (CPDLC, ADS-A) — VDL Mode 2 ATS (FIS, FIS-B, TIS-B) — VDL Mode 2 AOC/AAC — VDL Mode 4 ADS-B (also TIS, air-air) — Mode-S	VDL Mode 2 radio AM voice mode (pilot ATC Voice) DSB AM using 25 KHz / 8.33 KHz channels VDL Mode 2 radio data link mode (pilot CPDLC) Mode-S transponder (active)	VDL Mode 4 radio data link (AOC/AAC) VDL Mode 4 spare for AOC/AAC?	VDL Mode 2 radio mostly an idle spare, co-pilot use: voice for direct company comms, AWOS, ATIS or FIS, FIS-B, TIS-B data link Mode-S transponder (standby/spare)	**3 VDL Mode 2 radios required** (possibly 4 radios if large # of FIS services are needed) Radio modes supported: AM voice (25 KHz / 8.33KHz), VDL Mode 1, VDL Mode 2 **1 VDL Mode 4 radios required** (possibly 2, AOC/AAC backup) single R/T for VDL Mode 4 Note: Above assumes separate VDL Mode 4 for AOC/AAC. If radios are capable of all modes, a total of 4 radios are required. **2 Mode-S transponders**

Table 3-12 Radio Resource Requirements as a function of Data Link Allocation Option (continued)

Data Link Allocation Option		**Physical Data Links Required (including spares)**			**Comments**
		Left Radio(s)	**Center Radio(s)**	**Right Radio(s)**	
Option #2b: **Data Link Group** ATC (CPDLC, ADS-A) ATS (FIS, FIS-B, TIS-B) AOC/AAC ADS-B (also TIS, air-air)	 **Data Link** VDL Mode 3 VDL Mode 3 VDL Mode 4 Mode-S	VDL Mode 3 radio Pilot ATC (digital) voice and CPDLC data link, simultaneously (3V1D, 2V2D modes, etc.) Mode-S transponder (active)	VDL Mode 4 radio data link (AOC/AAC) VDL Mode 4 spare for AOC/AAC?	VDL Mode 3 radio mostly an idle spare, co-pilot use: voice for direct company comms, AWOS, ATIS or FIS, FIS-B, TIS-B data link Mode-S transponder (standby/spare)	**2 VDL Mode 3 radios required** (possibly 3 radios if large # of FIS services are needed) Radio modes supported: AM voice (25 KHz / 8.33KHz), VDL Modes 1, 2 and 3 **1 VDL Mode 4 radio required** (possibly 2, AOC/AAC backup) single R/T for VDL Mode 4 Note: Above assumes separate. VDL Mode 4 for AOC/AAC. If radios are capable of all modes, a total of 3 radios are required **2 Mode-S transponders**
Option #3a: **Data Link Group** ATC (CPDLC, ADS-A) ATS (FIS, FIS-B, TIS-B) AOC/AAC ADS-B (also TIS, air-air)	 **Data Link** VDL Mode 2 VDL Mode 4 VDL Mode 4 Mode-S	VDL Mode 2 radio AM voice mode (pilot ATC Voice) DSB AM using 25 KHz / 8.33 KHz channels VDL Mode 2 radio data link mode (pilot CPDLC) Mode-S transponder (active)	VDL Mode 4 radio data link (AOC/AAC) VDL Mode 4 radio data link mode (FIS, FIS-B, TIS-B)	VDL Mode 2 radio mostly an idle spare for voice comms and CPDLC Mode-S transponder (standby/spare)	**3 VDL Mode 2 radios required** Radio modes supported: AM voice (25 KHz / 8.33KHz), VDL Mode 1, VDL Mode 2 **2 VDL Mode 4 radios required** single R/T for VDL Mode 4 Note: Above assumes separate VDL Mode 4 radios. If radios are capable of all modes, a total of 4 radios are required. **2 Mode-S transponders**

Table 3-12 Radio Resource Requirements as a function of Data Link Allocation Option (continued)

Data Link Allocation Option	Physical Data Links Required (including spares)			Comments
	Left Radio(s)	Center Radio(s)	Right Radio(s)	
Option #3b: **Data Link Group** — **Data Link** ATC (CPDLC, ADS-A) — VDL Mode 3 ATS (FIS, FIS-B, TIS-B) — VDL Mode 4 AOC/AAC — VDL Mode 4 ADS-B (also TIS, air-air) — Mode-S	VDL Mode 3 radio Pilot ATC (digital) voice and CPDLC data link, simultaneously (3V1D, 2V2D modes, etc.)	VDL Mode 4 radio data link (AOC/AAC)	VDL Mode 3 radio mostly an idle spare for voice comms and CPDLC	**2 VDL Mode 3 radios required** Radio modes supported: AM voice (25 KHz / 8.33KHz), VDL Modes 1, 2 and 3 **2 VDL Mode 4 radios required** single R/T for VDL Mode 4 Note: Above assumes separate. VDL Mode 4 radios. If radios are capable of all modes, a total of 3 radios may be sufficient.
		VDL Mode 4 radio data link (FIS, FIS-B, TIS-B)		
	Mode-S transponder (active)		Mode-S transponder (standby/spare)	**2 Mode-S transponders**
Option #4: **Data Link Group** — **Data Link** ATC (CPDLC, ADS-A) — VDL Mode 4 ATS (FIS, FIS-B, TIS-B) — VDL Mode 4 AOC/AAC — VDL Mode 4 ADS-B (also TIS, air-air) — Mode-S	VHF Comm radio AM voice mode (pilot ATC Voice) DSB AM using 25 KHz / 8.33 KHz channels	VDL Mode 4 radio data link (AOC/AAC)	VHF Comm radio mostly an idle spare for voice comms	**2 VHF radios for voice comms** AM voice (25 KHz / 8.33KHz) **3 VDL Mode 4 radios required** single R/T for VDL Mode 4 Note 1: Above assumes separate VDL Mode 4 radios. If radios are capable of all modes, a total of 4 radios are required. Note 2: If CPDLC, AOC/AAC and FIS are provided as an integrated service, 3 full mode radios are sufficient.
	VDL Mode 4 radio data link (pilot CPDLC)	VDL Mode 4 radio data link (FIS, FIS-B, TIS-B)		
	Mode-S transponder (active)		Mode-S transponder (standby/spare)	**2 Mode-S transponders**

Table 3-12 Radio Resource Requirements as a function of Data Link Allocation Option (continued)

Data Link Allocation Option		Physical Data Links Required (including spares)			Comments
		Left Radio(s)	Center Radio(s)	Right Radio(s)	
Option #5:					
Data Link Group	**Data Link**	VHF Comm/VDL same as Option #1	VHF Comm/VDL same as Option #1	VHF Comm/VDL same as Option #1	VHF Comm/VDL same as Option #1
ATC (CPDLC, ADS-A)	VDL Mode 2/3				
ATS (FIS, FIS-B, TIS-B)	VDL Mode 2/3				
AOC/AAC	VDL Mode 2/3				
ADS-B (also TIS, air-air)	VDL Mode 4	An integrated VDL Mode 4 R/T radio is envisioned - **2 to 3 XMT modules, 5 to 6 RCV modules** Refer to Figure 3-5 for possible VDL Mode 4 configurations			Fault tolerant VDL Mode 4 radio(s) with sufficient redundancy to overcome XMT and RCV failures
Option #6a:		VDL Mode 2 radio		VDL Mode 2 radio	**3 VDL Mode 2 radios required** (possibly 4 radios if large # of FIS services are needed)
Data Link Group	**Data Link**	AM voice mode (pilot ATC Voice)		mostly an idle spare, co-pilot use: voice for direct company comms, AWOS, ATIS or FIS, FIS-B,TIS-B data link	Radio modes supported: AM voice (25 KHz / 8.33KHz), VDL Mode 1, VDL Mode 2
ATC (CPDLC, ADS-A)	VDL Mode 2	DSB AM using 25 KHz / 8.33 KHz channels			
ATS (FIS, FIS-B, TIS-B)	VDL Mode 2	VDL Mode 2 radio data link mode (pilot CPDLC)			Which VDL takes care of legacy AOC/AAC communications (VDL Mode 2 or VDL Mode 4)?
AOC/AAC	VDL Mode 4	An integrated VDL Mode 4 R/T radio is envisioned - **3 to 4 XMT modules, 5 to 6 RCV modules** Refer to Figure 3-6 for possible VDL Mode 4 configurations			Fault tolerant VDL Mode 4 radio(s) with sufficient redundancy to overcome XMT and RCV failures
ADS-B (also TIS, air-air)	VDL Mode 4				

Table 3-12 Radio Resource Requirements as a function of Data Link Allocation Option (continued)

Data Link Allocation Option		Physical Data Links Required (including spares)			Comments
		Left Radio(s)	Center Radio(s)	Right Radio(s)	
Option #6b:		VDL Mode 3 radio		VDL Mode 3 radio	**2 VDL Mode 3 radios required** (possibly 3 radios if large # of FIS services are needed)
Data Link Group	**Data Link**	Pilot ATC (digital) voice and CPDLC data link, simultaneously (3V1D, 2V2D modes, etc.)		mostly an idle spare, co-pilot use: voice for direct company comms, AWOS, ATIS or FIS, FIS-B, TIS-B data link	Radio modes supported: AM voice (25 KHz / 8.33KHz), VDL Modes 1, 2 and 3 Which VDL takes care of legacy AOC/AAC communications (VDL Mode 3 or VDL Mode 4)?
ATC (CPDLC, ADS-A)	VDL Mode 3				
ATS (FIS, FIS-B, TIS-B)	VDL Mode 3				
AOC/AAC	VDL Mode 4				
ADS-B (also TIS, air-air)	Mode-S				
AOC/AAC ADS-B (also TIS, air-air)	VDL Mode 4 VDL Mode 4	An integrated VDL Mode 4 R/T radio is envisioned - **3 to 4 XMT modules, 5 to 6 RCV modules** Refer to Figure 3-6 for possible VDL Mode 4 configurations			Fault tolerant VDL Mode 4 radio(s) with sufficient redundancy to overcome XMT and RCV failures
Option #7a:		VDL Mode 2 radio		VDL Mode 2 radio	**3 VDL Mode 2 radios required**
Data Link Group	**Data Link**	AM voice mode (pilot ATC Voice) DSB AM using 25 KHz / 8.33 KHz channels VDL Mode 2 radio data link mode (pilot CPDLC)		mostly an idle spare for voice comms and CPDLC	Radio modes supported: AM voice (25 KHz / 8.33KHz), VDL Mode 1, VDL Mode 2 Which VDL takes care of legacy AOC/AAC communications (VDL Mode 2 or VDL Mode 4)?
ATC (CPDLC, ADS-A)	VDL Mode 2				
ATS (FIS, FIS-B, TIS-B) AOC/AAC ADS-B (also TIS, air-air)	VDL Mode 4 VDL Mode 4 VDL Mode 4	An integrated VDL Mode 4 R/T radio is envisioned **- 4 XMT modules, 6 to 8 RCV modules** Refer to Figure 3-7 for possible VDL Mode 4 configurations			Fault tolerant VDL Mode 4 radio(s) with sufficient redundancy to overcome XMT and RCV failures

Table 3-12 Radio Resource Requirements as a function of Data Link Allocation Option (continued)

Data Link Allocation Option		Physical Data Links Required (including spares)			Comments
		Left Radio(s)	**Center Radio(s)**	**Right Radio(s)**	
Option #7b: **Data Link Group** ATC (CPDLC, ADS-A)	 **Data Link** VDL Mode 3	VDL Mode 3 radio Pilot ATC (digital) voice and CPDLC data link, simultaneously (3V1D, 2V2D modes, etc.)		VDL Mode 3 radio mostly an idle spare for voice comms and CPDLC	**2 VDL Mode 3 radios required** Radio modes supported: AM voice (25 KHz / 8.33KHz), VDL Modes 1, 2 and 3 Which VDL takes care of legacy AOC/AAC communications (VDL Mode 3 or VDL Mode 4)?
ATS (FIS, FIS-B, TIS-B) AOC/AAC ADS-B (also TIS, air-air)	VDL Mode 4 VDL Mode 4 VDL Mode 4	An integrated VDL Mode 4 R/T radio is envisioned **- 4 XMT modules, 6 to 8 RCV modules** Refer to Figure 3-7 for possible VDL Mode 4 configurations			Fault tolerant VDL Mode 4 radio(s) with sufficient redundancy to overcome XMT and RCV failures
Option #8: **Data Link Group** ATC (CPDLC, ADS-A) ATS (FIS, FIS-B, TIS-B) AOC/AAC ADS-B (also TIS, air-air)	 **Data Link** VDL Mode 4 VDL Mode 4 VDL Mode 4 Mode-S	VHF Comm radio AM voice mode (pilot ATC Voice) DSB AM using 25 KHz / 8.33 KHz channels		VHF Comm radio mostly an idle spare for voice comms	**2 VHF radios for voice comms** AM voice (25 KHz / 8.33KHz) How are legacy AOC/AAC communications using VDL Modes 1 and 2 dealt with? If combinations of ADS-B, CPDLC, AOC/AAC and FIS are provided as an integrated service over one or more channels, significantly fewer radio resources are required. This is problematic in high-density areas.
		An integrated VDL Mode 4 R/T radio is envisioned **- 5-6 XMT modules, 8 to 10 RCV modules** Refer to Figure 3-8 for possible VDL Mode 4 configurations			Fault tolerant VDL Mode 4 radio(s) with sufficient redundancy to overcome XMT and RCV failures

Table 3-12 Radio Resource Requirements as a function of Data Link Allocation Option (continued)

Allocation Option	**Radio Resources Count (single-mode VDL Mode 4 radios)**	**Radio Resource Count (multi-mode VDL Mode 4 radios)**
Option #1a: (no VDL Mode 4)	4 (5) VDL Mode 2 radios, 2 Mode-S transponder	NA
Option #1b: (no VDL Mode 4)	4 (3 + 1 AM voice) VDL Mode 3 radios, 2 Mode S transponder	NA
Option #2a: (AOC on Mode 4)	3 (4) VDL Mode 2 radios, 1 (2) VDL Mode 4 radios, 2 Mode-S transponders	4 VDL Mode 4 multi-mode radios (i.e., also capable of AM voice, VDL Modes 1, 2, and 4), 2 Mode-S transponders
Option #2b: (AOC on Mode 4)	3 (2 + 1 AM voice) VDL Mode 3 radios (possibly 4 due to increased FIS services), 1 (2) VDL Mode 4 radios, 2 Mode-S transponders	4 (3 + 1 AM voice) VDL Mode 4 multi-mode radios (AM, Mode 1, 2, 3, and 4), 2 Mode-S transponders
Option #3a: (AOC/FIS on Mode 4)	3 VDL Mode 2 radios, 2 VDL Mode 4 radios, 2 Mode-S transponders	4 VDL Mode 4 multi-mode radios (AM, Mode 1, 2, and 4), 2 Mode-S transponders
Option #3b: (AOC/FIS on Mode 4)	3 (2 + 1 AM voice) VDL Mode 3 radios, 2 VDL Mode 4 radios, 2 Mode-S transponders	4 VDL Mode 4 multi-mode radios (AM, Mode 1, 2, 3 and 4), 2 Mode-S transponders
Option #4: (AOC/FIS/CPDLC on Mode 4)	2 VHF Comms (AM voice), 3 VDL Mode 4 radios, 2 Mode-S transponders	4 VDL Mode 4 multi-mode radios (AM, Mode 4; Mode 1,2(?) for legacy data link), 2 Mode-S transponders
Option #5a: (ADS-B on Mode 4)	4 (5) VDL Mode 2 radios, VDL Mode 4 (2 to 3 XMT, 5 to 6 RCV)	⇐(see Figure 3-5)
Option #5b: (ADS-B on Mode 4)	4 (3 + 1 AM voice) VDL Mode 3 radios, VDL Mode 4 (2 to 3 XMT, 5 to 6 RCV)	⇐(see Figure 3-5)
Option #6a: (ADS-B, AOC on Mode 4)	3 (4) VDL Mode 2 radios, VDL Mode 4 (3 to 4 XMT, 5 to 6 RCV)	⇐(see Figure 3-6)
Option #6b: (ADS-B, AOC on Mode 4)	3 (2 + 1 AM voice) VDL Mode 3 radios (possibly 4 due to increased FIS services), VDL Mode 4 (3 to 4 XMT, 5 to 6 RCV)	⇐(see Figure 3-6)
Option #7a: (ADS-B, AOC, FIS on Mode 4)	3 VDL Mode 2 radios, VDL Mode 4 (4 XMT, 6 to 8 RCV)	⇐(see Figure 3-7)
Option #7b: (ADS-B, AOC, FIS on Mode 4)	3 (2 + 1 AM voice) VDL Mode 3 radios, VDL Mode 4 (4 XMT, 6 to 8 RCV)	⇐(see Figure 3-7)
Option #8: All on Mode 4	VDL Mode 4 (5 to 6 XMT, 8 to 10 RCV)	⇐(see Figure 3-8)

Table 3-13 Radio Resource Requirements as a Function of Data Link Allocation Option

XMT	XMT	RCV	RCV	RCV
1	2	1	2	3
ADS-B	spare	ADS-B	ADS-B	spare

Global Signalling Channel ADS-B radio

XMT	XMT	RCV	RCV	RCV
1	2	1	2	3
ADS-B	spare	ADS-B	ADS-B	spare

ADS-B channels for terminal area, etc.

a) Dual Radios

XMT	XMT	XMT	RCV	RCV	RCV	RCV	RCV	RCV
1	2	3	1	2	3	4	5	6
ADS-B	ADS-B	spare	ADS-B	ADS-B	ADS-B	ADS-B	spare	spare ?

b) Integrated Fault Tolerant Radio

Figure 3-5 VDL Mode 4 Configurations for ADS-B

XMT	XMT	RCV	RCV	RCV
1	2	1	2	3
ADS-B	AOC, AAC	ADS-B	ADS-B	AOC, AAC

Global Signalling Channels ADS-B radio

XMT	XMT	RCV	RCV	RCV
1	2	1	2	3
ADS-B	spare	ADS-B	ADS-B	spare

ADS-B channels for terminal area, etc. and AOC/AAC

a) Dual Radios

XMT	XMT	XMT	XMT	RCV	RCV	RCV	RCV	RCV	RCV
1	2	3	4	1	2	3	4	5	6
ADS-B	ADS-B	AOC, AAC	spare	ADS-B	ADS-B	ADS-B	ADS-B	AOC, AAC	spare

b) Integrated Fault Tolerant Radio

Figure 3-6 VDL Mode 4 Configurations for ADS-B and AOC/AAC

XMT	XMT	RCV	RCV	RCV	RCV
1	2	1	2	3	4
ADS-B	FIS or spare	ADS-B	ADS-B	FIS	FIS-B or spare

Global Signalling Channels ADS-B radio

XMT	XMT	RCV	RCV	RCV	RCV
1	2	1	2	3	4
ADS-B	AOC, AAC	ADS-B	ADS-B	AOC, AAC	TIS-B or spare

ADS-B channels for terminal area, etc. and AOC/AAC

a) Dual Radios

XMT	XMT	XMT	XMT	RCV	RCV	RCV	RCV	RCV	RCV	RCV	RCV
1	2	3	4	1	2	3	4	5	6	7	8
ADS-B	ADS-B	AOC, AAC	FIS or spare	ADS-B	ADS-B	ADS-B	ADS-B	AOC, AAC	FIS	FIS-B or spare	TIS-B or spare

b) Integrated Fault Tolerant Radio

Figure 3-7 VDL Mode 4 Configurations for ADS-B, AOC/AAC, FIS/FIS-B/TIS-B

XMT	XMT	RCV	RCV	RCV
1	2	1	2	3
ADS-B	AOC, AAC	ADS-B	ADS-B	AOC, AAC

XMT	XMT	RCV	RCV	RCV
1	2	1	2	3
ADS-B	FIS or spare	ADS-B	ADS-B	FIS-B or spare

XMT	XMT	RCV	RCV	RCV
1	2	1	2	3
CPDLC	spare	CPDLC	FIS-B, TIS-B	spare

a) Triple Radio Configuration

XMT	XMT	XMT	RCV	RCV	RCV	RCV	RCV
1	2	3	1	2	3	4	5
ADS-B	ADS-B	ADS-B spare	ADS-B	ADS-B	ADS-B	ADS-B	spare

XMT	XMT	XMT	RCV	RCV	RCV	RCV	RCV
1	2	3	1	2	3	4	5
CPDLC	AOC, AAC	FIS or spare	CPDLC	AOC, AAC	FIS	FIS-B or spare	TIS-B or spare

b) Dual RadioConfiguration

XMT	XMT	XMT	XMT	XMT	XMT	RCV	RCV	RCV	RCV	RCV	RCV	RCV	RCV	RCV	RCV
1	2	3	4	5	6	1	2	3	4	5	6	7	8	9	10
ADS-B	ADS-B	CPDLC	AOC, AAC	FIS	spare	ADS-B	ADS-B	ADS-B	ADS-B	CPDLC	AOC, AAC	FIS	FIS-B or spare	TIS-B or spare	spare ?

Figure 3-8 VDL Mode 4 Configurations for ADS-B, CPDLC, AOC/AAC, FIS/FIS-B/TIS-B

3.6 TAP and CNS/ATM Data Link Summary / Conclusions

Since the TAP data link applications are a substantial subset of CNS/ATM data link, the data link allocations and candidate architectures discussed in the previous sections are directly applicable to TAP.

In order to determine the specific data link architecture to be utilized for TAP and CNS/ATM data link, the following primary issues must be resolved by industry:

The primary issues driving the data link architectures are:

1) Should VDL Mode 4 be used to provide the ADS-B data link application?

   While VDL Mode 4 may technically be able to provide the ADS-B capability, requiring approximately four receiver and two transmitter modules, Mode-S is the likely candidate due to the compatibility with the current airspace surveillance system. Mode-S ADS-B must still be validated to provide the desired range, uniform coverage volume and capacity. The FAA plans to push ahead with Mode-S ADS-B at this time with VDL Mode 4 not receiving further consideration. VDL Mode 4 could be used as a secondary surveillance system of airport surface vehicles for surface operations using lower-cost equipment.

2) Should VDL Mode 4 be used as an alternative to VDL Mode 3?

   VDL Mode 3 provides integrated, simultaneous voice and data link communications capability. VDL mode 4 is a data only system. While VDL Mode 3 is relatively complex, so is VDL Mode 4. Unless VDL Mode 3 falters due to difficulties in providing digital voice vocoders, VDL Mode 3 is the likely choice.

Thus while VDL Mode 4 is an intriguing data link concept, it may be difficult for it to find a niche (at least in the interim) against more incumbent Mode-S ADS-B and VDL Mode 3 ATC/ATS data link. That leaves VDL Mode 4 for the remaining applications for AOC/AAC and possibly DGPS/DGNSS. It is desirable for the DGPS data link to be compatible in terms of signal-in-space with the VDL radios to take advantage of commonality of function.

If VDL Mode 4 is not used for any of the CNS/ATM data link applications, it is expected that 4 (perhaps as low as 3) VDL Mode 3 radios (single transceiver per LRU) will be required for cockpit use (and 2 Mode-S transponders).

If VDL Mode 4 provides all CNS/ATM data link applications, 5 to 6 transmitters and 8 to 10 receivers are expected to be required (Figure 3-8). Mode-S transponders would still be required for TCAS, until a new VHF-based surveillance system evolves. If all data link applications except ADS-B use VDL Mode 4, 4 multi-mode VDL Mode 4 radios are needed along with 2 Mode-S transponders.

Conversely, if VDL Mode 4 is used only for ADS-B, 4 VDL Mode 3 radios are required for ATC/ATS, and 2 to 3 transmitter and 5 to 6 receiver modules using VDL Mode 4 are needed for ADS-B. Mode-S transponders are still needed in the interim until a full VHF-based surveillance system evolves. Other combinations of data link allocations require additional equipment (as summarized in Table 3-13).

4.0 Avionics Integration, Retrofit and Integrity Issues for LVLASO

This section briefly examines some of the key issues concerning aircraft avionics integration, retrofit and integrity related to LVLASO. This topic is very complex and industry developments of operational requirements in this area are immature at this time.

LVLASO (or ASMGCS) pose complex operational problems when conducting surface operations in low-visibility conditions and are dependent on the integration of numerous sub-systems to provide the necessary capabilities. While providing situational awareness to pilots and controllers in marginal visual conditions is relatively straightforward, providing low-visibility guidance at low Runway Visual Range (RVR) is considerably more difficult. Development of low-visibility guidance requirements is only in the early stages in industry committees.

Some of the key issues concerning the development of LVLASO / ASMGCS are as follows:

1) What are the various operational capabilities and modes of operation envisioned that provide cost benefits to end users (airlines, ATC, airport operators, etc.)?
2) What are the system requirements (ground-system infrastructure and avionics capabilities) needed to meet operational goals?
3) What are the availability, continuity and integrity requirements and how will they be achieved?
4) What are the obstacles to avionics integration and retrofit to provide the needed capabilities?
5) What is the cost of providing the needed system capabilities?

While the ultimate goal of a LVLASO / ASMGCS system is simply stated, "to provide system capabilities that provide the operational capacity and level of safety achieved in VFR operations during low-visibility weather conditions", the above questions are difficult to answer.

Using operational requirements developed by RTCA SC-159 [15] as guidance inputs, [16] made a somewhat qualitative assessment of operational modes and the ground infrastructure and avionics requirements needed to provide the desired operational mode. The following surface operations modes were considered:

1) Movement area taxiing (taxi speeds of 5 , 10 and 20 knots at longitudinal aircraft spacings of 100 ft, 500 ft and 1500 ft were considered)
2) Ramp area taxiing (5 knot taxi speed, 100 ft spacings)
3) High-speed Roll-out and Turn-off (ROTO)
4) Take-off
5) Approach and Landing.

Surface operations system functions considered were 1) surveillance, conflict detection and conflict resolution, 2) traffic planning and routing, 3) guidance and control, 4) navigation, and 5) communications. Based on these operational modes and system requirements, minimum avionics capabilities were identified for a range of airport configurations (from non-tower airports to full capability airports with advanced surveillance, DGNSS / LAAS, data link and enhanced lighting systems in place) and various RVR conditions. Minimum avionics were identified based on the controller's ability to control (i.e., "see" all aircraft / vehicles and maintain adequate spacings between aircraft) and the pilot's ability to taxi and also to avoid collisions as a shared responsibility with controllers.

Summary of Minimum Avionics Capabilities as a function of Operational Mode

A summary of the minimum avionics capabilities required as identified by [16] are as follows:

Takeoff operations require a HUD for operations at an RVR of 300 ft.

High-speed ROTO requires:

1) Head-Down Display (HDD) with GNSS augmentation using the Wide Area Augmentation System (WAAS) for RVRs down to 1200 ft.
2) HUD/WAAS for RVRs down to 600 ft
3) HUD/LAAS for RVRs down to 300 ft.

For approach/landing operations, use of a head-up guidance system permits landings to lower minima and reduces the cost of Cat II and III avionics and training. However, HUD is not a requirement, but is an option.

Taxi operations consist of traffic avoidance and guidance. Traffic avoidance for higher density surface traffic (500 ft spacings) requires Cockpit Display of Traffic Information (CDTI), since the controllers cannot provide proper spacings for collision avoidance and thus pilots share the responsibility for collision avoidance. CDTI is not required for lower density surface traffic, where controllers can utilize hold points to achieve enforceable 1500 ft spacings.

Taxi operations guidance requirements require HUD/WAAS, which allows for VFR taxi speeds (20 knots) for RVR down to 300 ft. Reduced taxi speeds (10 knots) at RVRs down to 300 ft are supported by taxiway lighting.

Queuing operations (prior to takeoff) require HDD/WAAS below 600 ft RVR and a HUD/LAAS below 300 ft RVR.

For ramp taxi operations use of HUD/WAAS and HDD/WAAS allows taxiing down to 300 ft RVR with lane lighting. The HDD is also required due to the HUD's limited field of view. Without lane lighting, use of both HUD/LAAS and HDD/LAAS allow taxiing down to 300 ft RVR. CDTI is also required at these RVRs due to the unstructured nature of ramp traffic.

LVLASO / ASMGCS Avionics

The LVLASO flight test and demonstration system described in Section 2 provides an indication of the type of systems capabilities (both ground systems and avionics) that are needed to support surface operations in low-visibility conditions. Section 3 focused specifically on the future data link architecture needed and to support Terminal Area Productivity (including LVLASO), which closely follows the planned CNS/ATM data link system The previous paragraphs also provided a qualitative assessment of needed minimum avionics capabilities to support the various operational modes of Surface Operations as a function of RVR. Clearly, considerable validation activities must be conducted to demonstrate the validity of these assessments. In addition, to ensure availability, continuity and integrity of needed system functions in support of LVLASO and ASMGCS, fault hazard analyses are required to determine the level of redundancy and cross checks needed among the various sub-systems to ensure safety of operations. Much work is required in these areas before LVLASO / ASGMCS systems can be deployed. However, avionics requirements can be postulated for a future LVLASO / ASGMCS system as discussed below.

The following avionics capabilities are required for a full capability LVLASO / ASMGCS system:

1) Displays
   - Head-Down Displays (HDD)
   - HUD
2) Navigation
   - WAAS / LAAS
   - Precision approach system, e.g. Multi-Mode Receiver (integrated DGNSS, ILS, MLS)
   - Flight management system
3) Communications / Data Link
   - VHF data link (voice, CPDLC, AOC, FIS, FIS-B, TIS-B, ADS-B (possibly))
   - Mode-S data link (ATC surveillance, ADS-B (probable), air-air crosslink)
4) Pilot interface
5) Mass storage device for airport data base

In terms of navigation and communications avionics, no additional unique systems are anticipated to be needed that will not already be required by the future CNS/ATM system. WAAS and LAAS system definitions are currently being developed by various industry committees and are expected to evolve over the next several years. WAAS capability will be included in future GPS sensors providing precision navigation to support Cat I approaches and also support surface operations. LAAS is expected to be provided within Multi-Mode Receiver (MMR) precision approach systems (i.e., DGNSS, ILS or MLS capability). Aircraft are expected to be equipped with at least dual WAAS systems for Cat I approaches and dual or triple redundant MMRs for Cat II and Cat III precision approaches. Thus this high integrity capability will be available for LVLASO / ASGMCS.

For data link communications, the future CNS/ATM system will rely on high integrity CPDLC, ADS-A/C, ADS-B, AOC, FIS, FIS-B and TIS-B. Again LVLASO / ASGMCS can rely on utilizing these capabilities to obtain surface operations benefits. While there is some uncertainty on how data link applications will be allocated to specific data links, future data link avionics will likely consist of one of two scenarios 1) three to four multi-mode VHF data links, capable of voice, CPDLC, AOC, FIS, FIS-B, TIS-B and possibly ADS-A; dual Mode-S providing ADS-B and air-air crosslink or 2) one large or several smaller fault tolerant VHF data link radios containing a bank of transmitters (total of 5 or 6) and receivers (total of 8-10) to provide the above data link applications, including ADS-B. Mode-S would still be required for ATC ground surveillance and TCAS for the foreseeable future.

While no impact is anticipated for data link avionics for LVLASO / ASGMCS, the ground infrastructure will require that full coverage of the airport surface and terminal area be provided for all the data link services. Based on the LVLASO flight test results, several observations can be made concerning data link and surveillance:

1) VHF data link provides excellent coverage of the airport surface and should be able to support various data link applications, i.e., TIS-B, DGPS, CPDLC and FIS, FIS-B.
2) ADS-B surveillance is required to support high integrity surveillance. While ASDE-3 provides generally good surveillance performance, it has serious multipath / false target problems that cannot be overcome for high integrity surveillance. For Mode-S ADS-B surveillance, several ground stations will be required to provide line-of-sight coverage and to eliminate areas where fading nulls and multipath occur.

The most significant problems for incorporating avionics capabilities to support LVLASO / ASGMCS are in the area of the display system for older generation aircraft. Today's aircraft fleet has a high variance in avionics equipage and capability, ranging from "classic" aircraft, that are non-FMS equipped and use round dial flight instruments for VOR / DME / ILS navigation, to FMS / EFIS equipped aircraft using CRT stroke displays, and new aircraft with LCD displays.

For new aircraft, it is anticipated that in the longer term, the navigation displays (ND) and primary flight displays (PFD) will be capable to provide guidance information to the pilot through all phases of flight, from enroute through approach and landing and then for surface operations. Thus LVLASO / ASGMCS HDD taxi display capabilities as demonstrated in the T-NASA system are most easily provided for new aircraft, where sufficient graphics processing capabilities will be provided.

For EFIS stroke display systems, surface operations displays will be limited to simple stroke display formats to provide some situational awareness and guidance information to obtain benefits of operations in low-visibility conditions. The capabilities of graphics processing among many of these aircraft may be very limited to provide additional display capability.

To provide LVLASO / ASGMCS taxi display capabilities to "classic" aircraft will require major rework of the entire flight deck to incorporate glass cockpit displays. Unless clear cost benefits can be demonstrated, such a retrofit seems unlikely.

At the time of writing this report, an equipage study is being conducted for the NASA Advanced Air Transport Technologies (AATT) program. Commercial air transport carriers, regional airlines, business aircraft and military aircraft are being surveyed to determine the levels of avionics equipage and capabilities of the current fleet. Once available, results from this study will provide important inputs for a range of cost benefit analyses for providing future CNS/ATM capabilities including for LVLASO / ASMGCS.

In addition to the display system, additional processing capability will be required for providing LVLASO / ASGMCS application processing for situational awareness, guidance, conformance monitoring, separation assurance, and collision avoidance. Whether these capabilities reside in the FMS or another avionics processor is to be determined. Future avionics equipment is being developed with increasing use of software data loading to facilitate avionics upgrades, thus it is expected that future LVLASO / ASGMCS capability will also be provided in this manner. Since the future CNS/ATM system will also require and rely on high integrity situational awareness, guidance, separation assurance and collision avoidance processing, LVLASO / ASGMCS can be viewed as an additional operational mode of CNS/ATM operation.

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Appendix A

VHF DGPS Data Link Coverage Test Results

GLOBAL NAVIGATION SATELLITE SYSTEM PANEL

WORKING GROUP A, B, C, D MEETING

Brisbane, Australia

February 17 - 28, 1997

Airport Surface Communications Performance of a VHF DGPS Data Link Using D8PSK Modulation

(presented by J. M. Wichgers)

(prepared by S. Koczo)

Summary

A VHF broadcast data link using Differential 8-ary Phase Shift Keying (D8PSK) modulation at a 31.5 kbps signaling rate was evaluated at Atlanta's Hartsfield International Airport to determine surface communication coverage and message reception reliability. This paper describes the results of our data link test at Atlanta that occurred during October, 1996.

Airport Surface Communications Performance of a VHF DGPS Data Link using D8PSK Modulation

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Abstract

The future CNS/ATM National Airspace System is expected to rely on GNSS as its primary source for navigation. Various GNSS augmentation system concepts are being developed by industry to further increase the integrity, availability, and accuracy of service of GNSS. In working with NASA Langley Research Center in developing airport surface operations technologies, including DGPS navigation and surveillance, we had the opportunity to evaluate airport surface data link performance of a VHF DGPS data link that augments GPS with differential corrections. A VHF broadcast data link using Differential 8-ary Phase Shift Keying (D8PSK) modulation at a 31.5 kbps signaling rate was evaluated at Atlanta's Hartsfield International Airport to determine surface communication coverage and message reception reliability. This paper describes the results of our data link test at Atlanta that occurred during October, 1996.

Introduction

Our association with the NASA Langley research team, which is developing integrated surface operations technologies for Low-Visibility Landing and Surface Operations (LVLASO) as part of their Terminal Area Productivity (TAP) program, has allowed us the opportunity to test and evaluate the performance of CNS/ATM data links in an airport surface operations environment such as Atlanta's Hartsfield. In preparation for NASA's planned system demonstration of LVLASO technologies at Atlanta later in 1997, and with the support of the FAA, we have evaluated the performance of a VHF D8PSK broadcast data link that will be used for uplink broadcast of DGPS corrections data in the LVLASO system demonstration. The data links used consisted of a pair of experimental VHF transmitters and a pair of VHF receivers that were designed to meet the performance specifications of the VHF data link defined in RTCA DO-217, Appendix F (change 1). Communications coverage tests were repeated for both vertically polarized and horizontally polarized signals-in-space in order to determine their relative data link performance for the VHF D8PSK data link.

Test Configuration

In preparing for the coverage test we anticipated that as many as two transmit sites may be required to provide full airport coverage. Thus, our strategy was to deploy two independent VHF transmit stations, one located at the Atlanta ATC Control Tower and the other atop the Stouffer's Hotel located just to the North of the airport. Two independent VHF receive stations were deployed in a van provided to us by FAA and MIT Lincoln Laboratories, which was used to taxi across the airport surface.

We were assigned two frequencies in the VHF Comm band to conduct the test. The Stouffer's site was tuned to 118.2 MHz, while the Control Tower site was tuned to 128.5 MHz. Transmit power was set to 20 Watts as specified by RTCA DO-217, Appendix F.

Antenna installations at both the transmit and receive sites were as follows: At the Control Tower, four balconies facing NW, NE, SE, and SW were available for installation of antennas. In order to avoid line-of-sight blockage due to the tower structure itself we chose to install four low-cost antennas, one at each balcony. Each balcony was provided with a single folded dipole antenna that was tuned to the center of the aeronautical VHF Comm/Nav band. All four antennas were driven by a single VHF transmitter using a 1:4 power splitter. The dipole antennas were either oriented vertically or horizontally depending on the desired polarization.

A single antenna was used atop the Stouffer's Hotel site facing southward toward the airport. A vertically-oriented folded dipole antenna was used for vertically-polarized signals, while a conventional FM broadcast band turnstile antenna was used for omni-directional, horizontal polarization.

For the van, a turnstile antenna was installed for horizontal polarization and was shared by both VHF receivers. For vertical polarization we used a magnet-mount whip antenna.

Figure 1 shows the installation of one of the vertical dipole antennas atop the Control Tower (NW corner balcony). The lower left of the picture shows the edge of the ramp area and shows taxiways that lead to two parallel runways that are oriented from left to right. The Stouffer's Hotel can be seen across the airport just to the left of the antenna element.

Figure 2 shows the antenna installation atop Stouffer's for the vertical dipole. Also shown are the GPS antenna (on tripod) and a tent used to shelter the GPS base station and VHF DGPS transmitter. A small portion of the airfield can be seen on the right side of the photo.

A full layout of the airport is provided in the performance results section along with the respective locations of the two transmit sites (Figure 3).

Data Collection

The following parameters were recorded for each of the receive stations (one tuned to the Control Tower, the other tuned to the Stouffer's frequency) as we traversed the airport surface: UTC time, latitude, longitude, altitude (MSL), number of GPS satellites visible, number of GPS satellites tracked, GPS navigation mode, and data link status. Data link status consisted of two status bits, one indicating whether or not the VHF receiver was providing DGPS corrections data to GPS; the other bit indicating the status of DGPS message CRC decoding (pass/fail). While received signal levels were not automatically recorded, we used a spectrum analyzer to monitor the received signal strength. Signal levels were recorded manually and time tagged with UTC time when unusual events occurred.

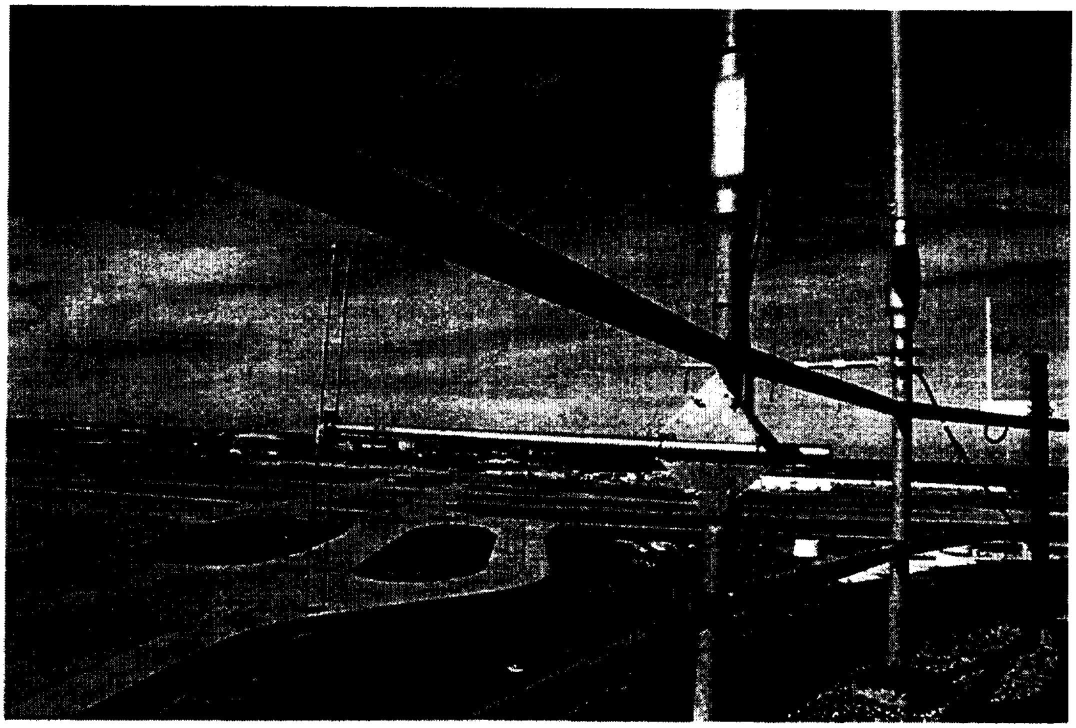


Figure 1 Control Tower Antenna Installation

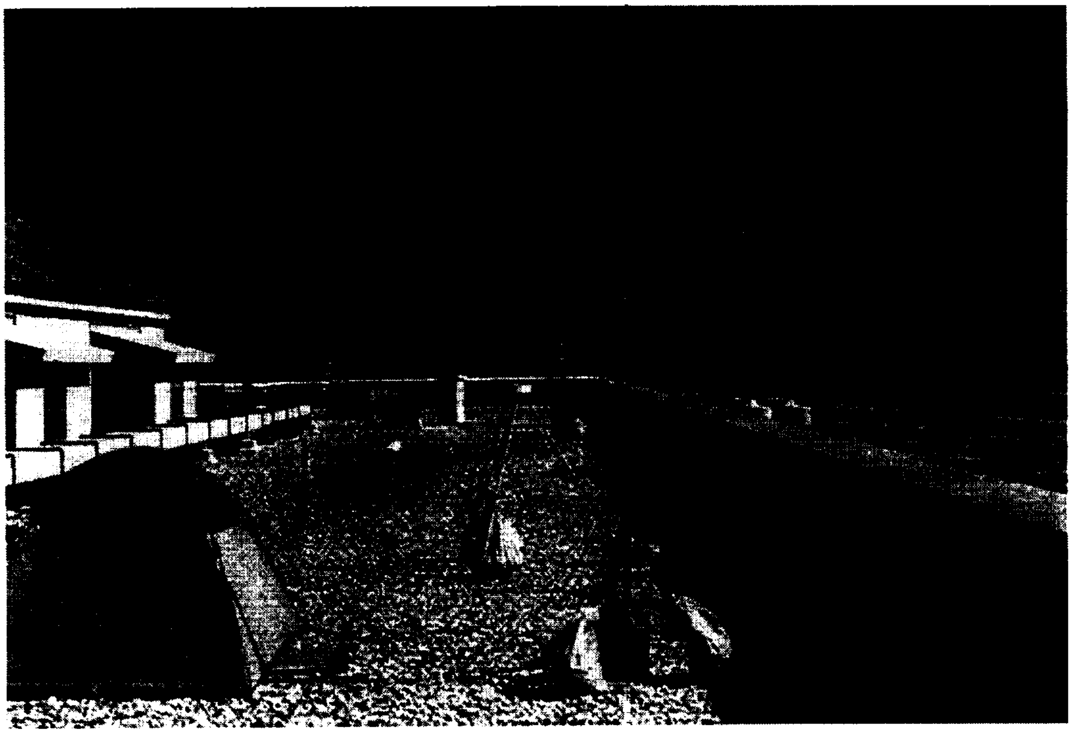


Figure 2 Stouffer's Hotel Antenna Installation

Line-of-Sight Review of Atlanta Hartsfield Airport Layout

Based on the layout of the Atlanta airport and the location of the transmit sites (Figure 3), the following observations can be made. While somewhat centrally located, the Control Tower was expected to experience considerable Line-of-Sight (LOS) blockages in the ramp areas between the various concourses, particularly along the West side of each concourse. The Control Tower was expected to have direct line of sight to most runways and taxiways on both the North and South half of the airport. On the other hand, the Stouffer's site was expected to have improved LOS to some of the ramp areas, but was expected to have somewhat reduced LOS to runways and taxiways on the South half of the airport.

Coverage Tests

Four separate test runs were made each lasting approximately one to two hours. Tests were conducted in the following order:

1) Ramp area coverage test (areas between concourses and also the airport utility road that traverses the periphery of the airport) using vertically polarized signals as used for VHF Comm.
2) Ramp area coverage test using horizontally polarized signals as used for VHF Nav.
3) Coverage test of runways and taxiways using horizontal polarization.
4) Coverage test of runways and taxiways using vertical polarization.

Due to the high density of traffic, our coverage tests in the ramp area were conducted during the hours of 7 PM to 11PM, while coverage tests of runways and taxiways were conducted between midnight and 4 AM when traffic is considerably less. There was still a surprising amount of traffic at around midnight, but traffic died down by 2 AM.

The van in which we were setup to collect data was guided around the airport by a pace car manned by two Atlanta FAA Airways Transportation Systems employees that were in constant contact with the Control Tower.

VHF DGPS Data Link Performance Results

Ramp Area Coverage

Figures 3 through 6 capture the data link coverage performance for the ramp area and the loop road that surrounds the airport. Each of these figures illustrates the taxi route of the van (shown by gray path) using one per second GPS position updates. Each position report is encoded to indicate whether or not a successfully DGPS corrections message was received during the last update. Anomalous messages, i.e., those that failed the CRC check due to excessive symbol errors or those that the VHF receiver was unable to receive are denoted by circles. As is immediately evident from the data, the majority of DGPS messages are decoded correctly.

Figures 3 and 4 illustrate ramp area coverage results using vertically polarized signals for the Control Tower and Stouffer's Hotel transmit sites, respectively. From Figure 3 it is evident that the greatest concentration of message failures occurred along the West wall of Concourses D and E, and occasional message losses also occurred along the loop road. Some items of note: We made special efforts to have the pace car take us as close as possible along the West wall of the concourses for maximum LOS blockage to the Control Tower. On a number of occasions we drove right up to the concourse wall (30 to 50 ft in height), while on other occasions we literally drove beneath large aircraft (747s, 757s, L1011s, etc.) to make it most difficult for the data link in terms of LOS. In addition, on a number of stretches along the loop road we experienced below grade conditions of as much as 50 ft (particularly in the NE, SE, and SW corners). A final note concerns the tunnel that we passed through (located just South of the Control Tower) in order to cross below a taxiway. Messages from the Control Tower were received almost unhindered even through the tunnel, while GPS satellite reception was totally disrupted.

As expected, the Stouffer's transmitter (Figure 4) provided improved LOS in the ramp areas of Concourses D and E, while experiencing more difficulty in the ramp areas of Concourses A and B due to diminished LOS. The Stouffer's site also experienced a few message failures along the loop road. Messages reception in the tunnel was totally disrupted for the Stouffer's site.

Figures 5 and 6 provide coverage results for the ramp area using horizontally polarized signals for the Control Tower and Stouffer's transmit sites, respectively. Performance is comparable to those for vertical polarization (Figures 3 and 4), with somewhat more message losses on taxiways in the NW corner on the South half of the airport, where relatively severe LOS blockage occurs for both transmit sites.

Taxiways and Runways Coverage

Figures 7 through 10 capture the data link coverage performance for taxiways and runways. Figures 7 and 8 represent coverage for horizontal polarization for the Control Tower and Stouffer's sites, respectively. Performance was improved over those of the ramp area, although the NW corner of the South half of the airport again experienced the greatest number of lost or corrupted messages. Due to some procedural problems in our initial taxiing attempts and subsequent coordination with ground controllers while taxiing on the North half taxiways, and unexpectedly high traffic, we failed to gain access to the two parallel runways on the North half of the airport. Later tests using vertical polarization allowed us to capture data for these runways and due to the excellent message reception experienced on all runways, we elected not to repeat this coverage test. Figures 9 and 10 provide taxiway and runway coverage results for vertical polarization for the Control Tower and Stouffer's transmit sites, respectively. Again message reception was quite good for both sites.

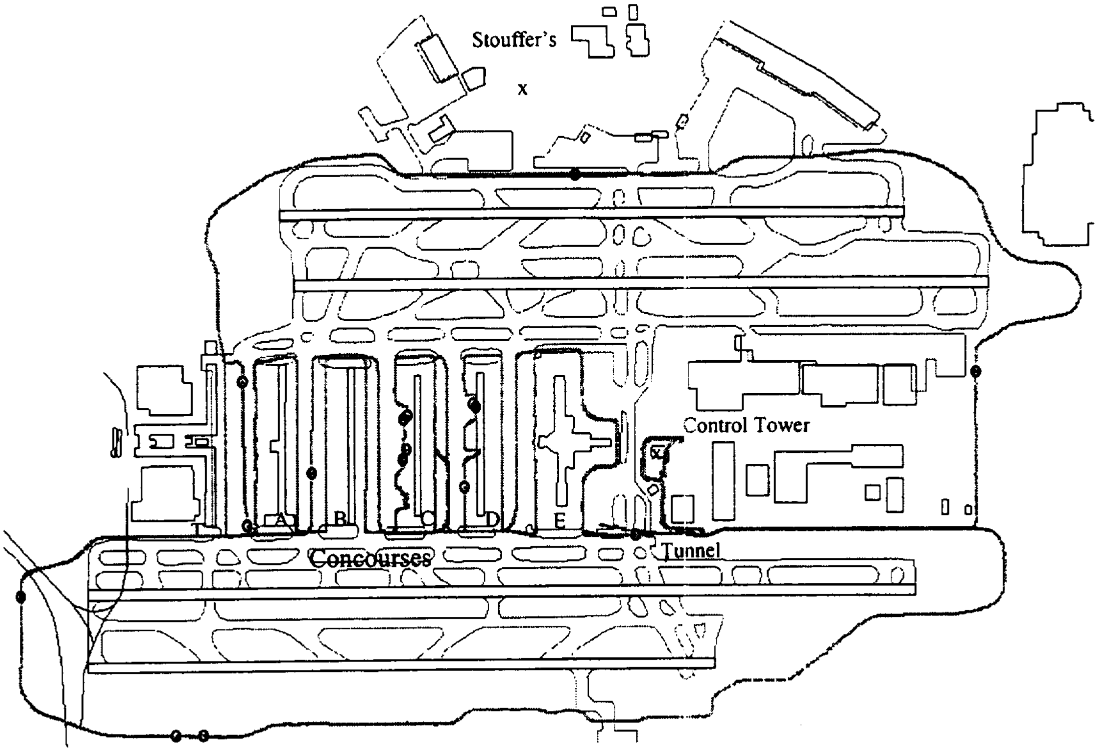


Figure 3 Coverage for Vertical Polarization, Control Tower, Ramp Area

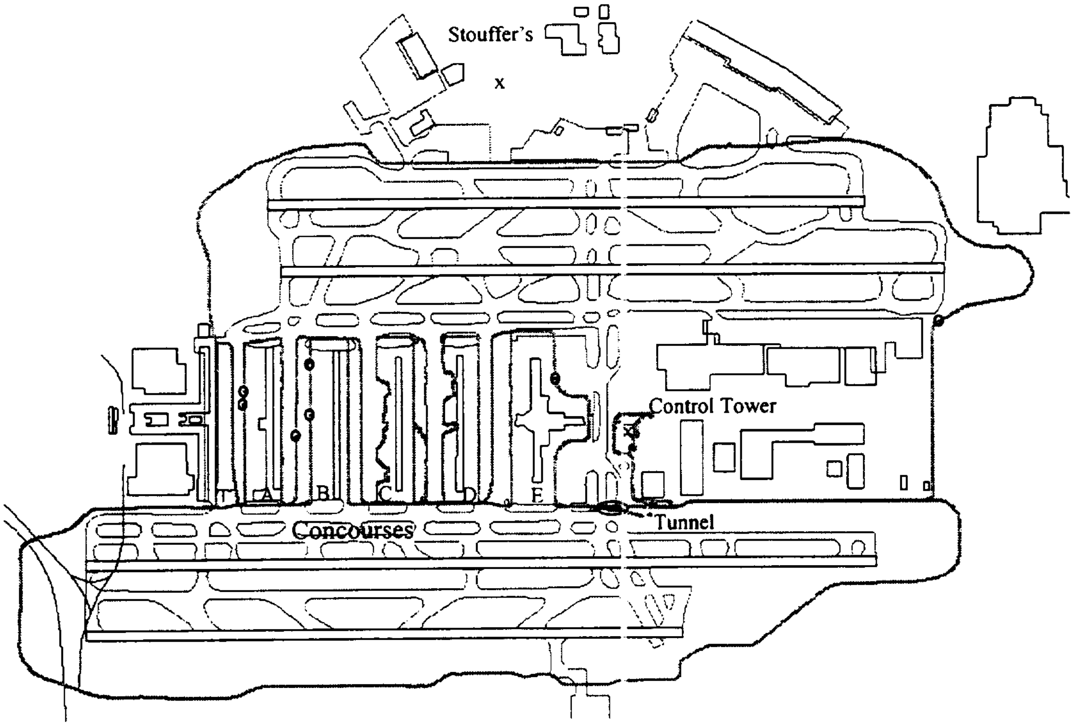


Figure 4 Coverage for Vertical Polarization, Stouffer's, Ramp Area

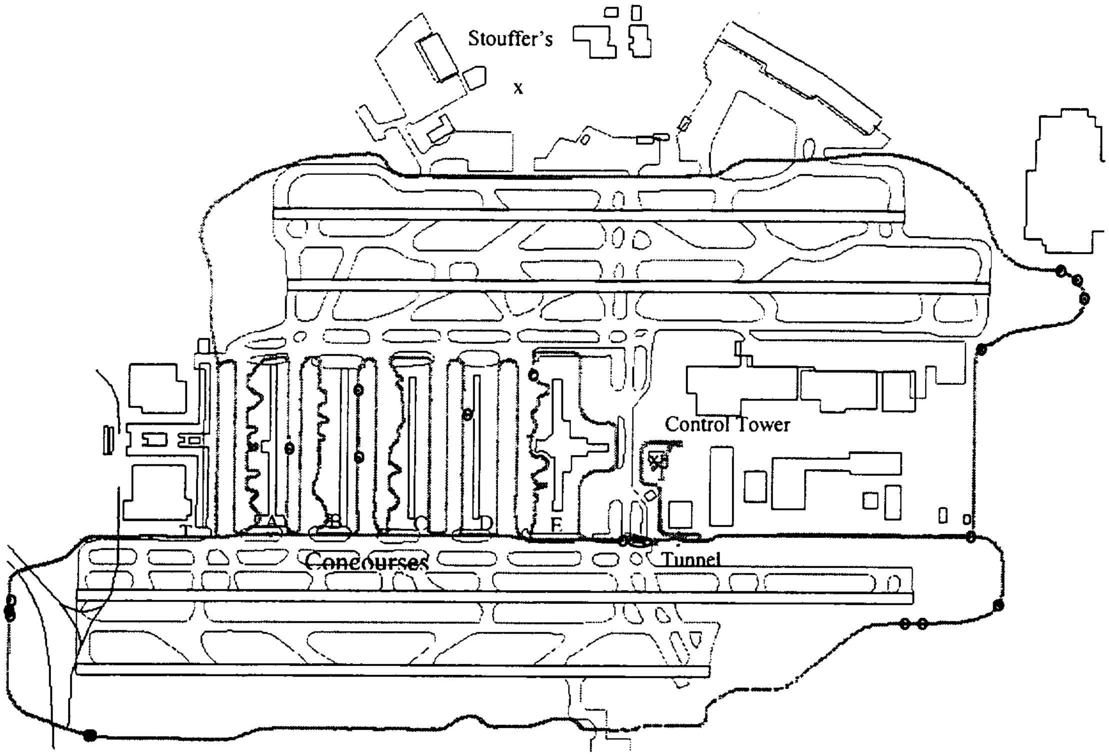


Figure 5 Coverage for Horizontal Polarization, Control Tower, Ramp Area

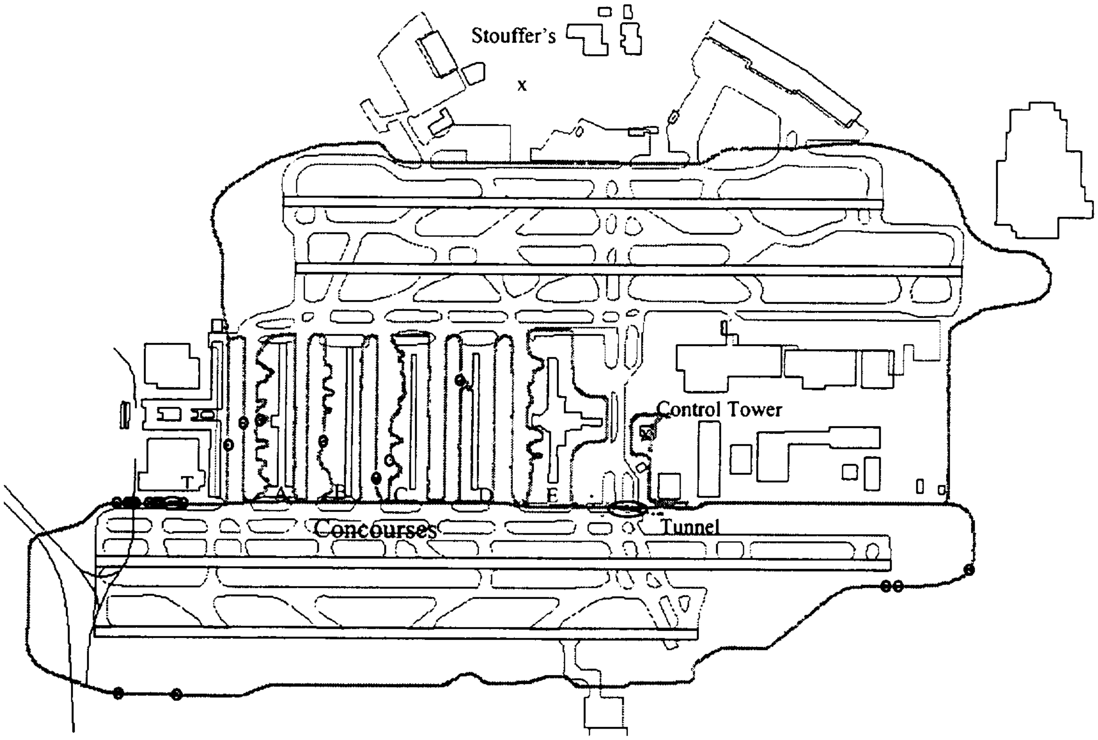


Figure 6 Coverage for Horizontal Polarization, Stouffer's, Ramp Area

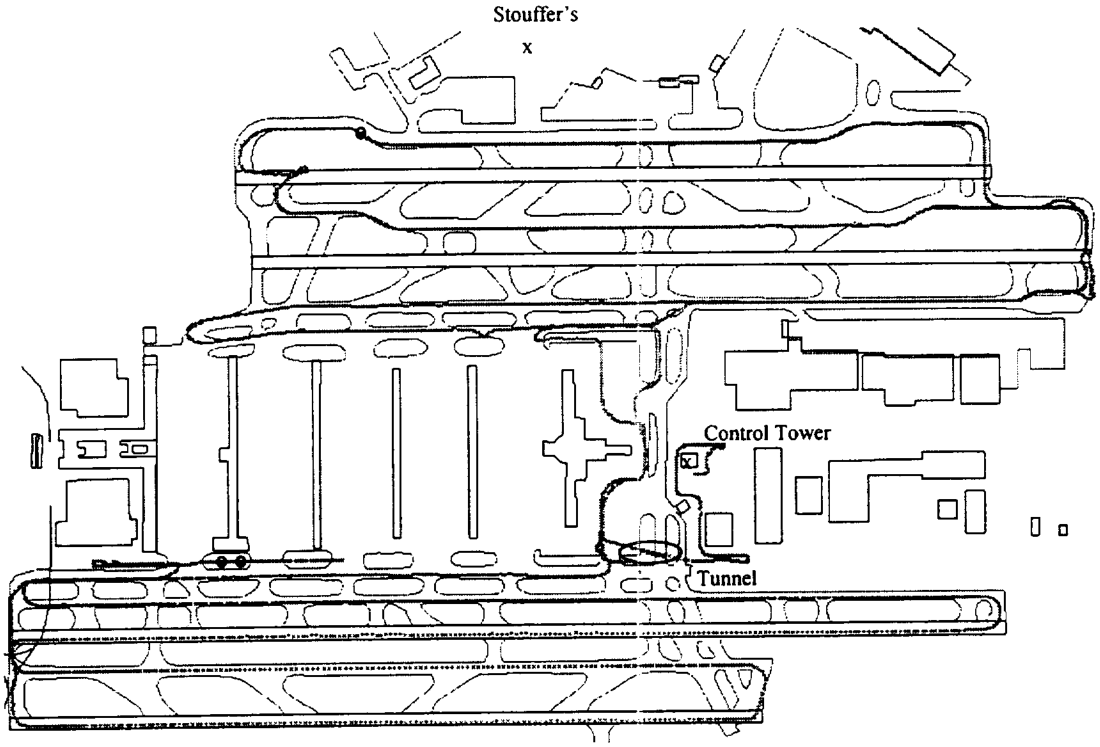


Figure 7 Coverage for Horizontal Polarization, Control Tower, Runways and Taxiways

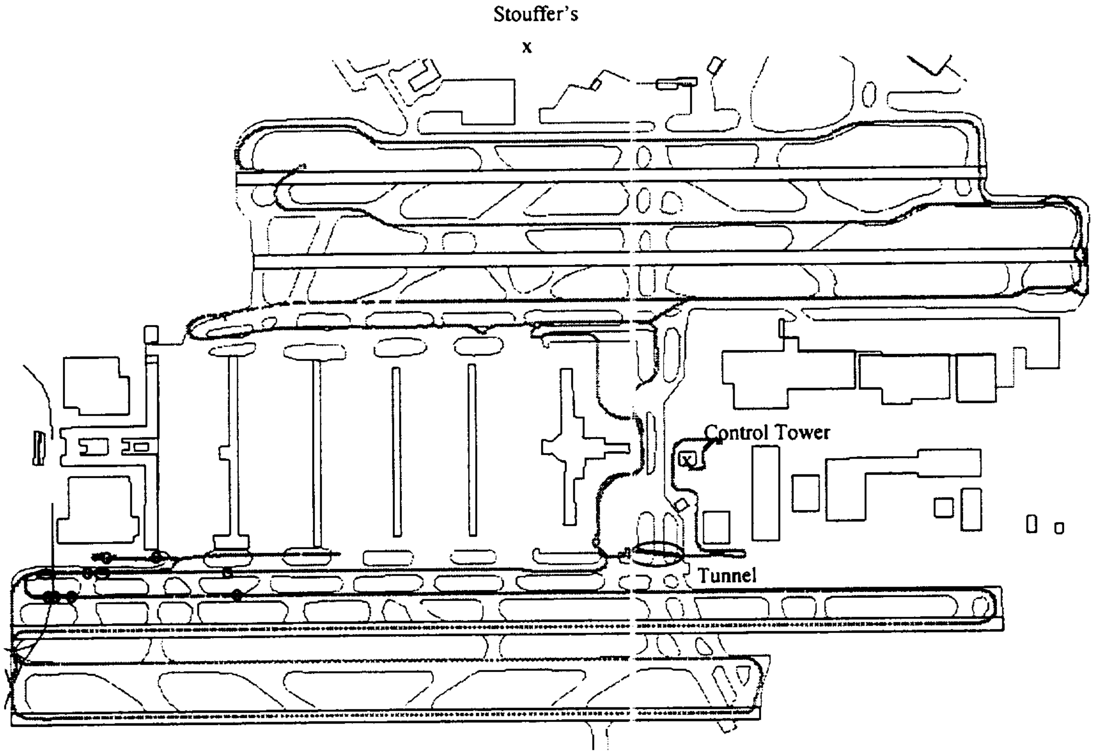


Figure 8 Coverage for Horizontal Polarization, Stouffer's, Runways and Taxiways

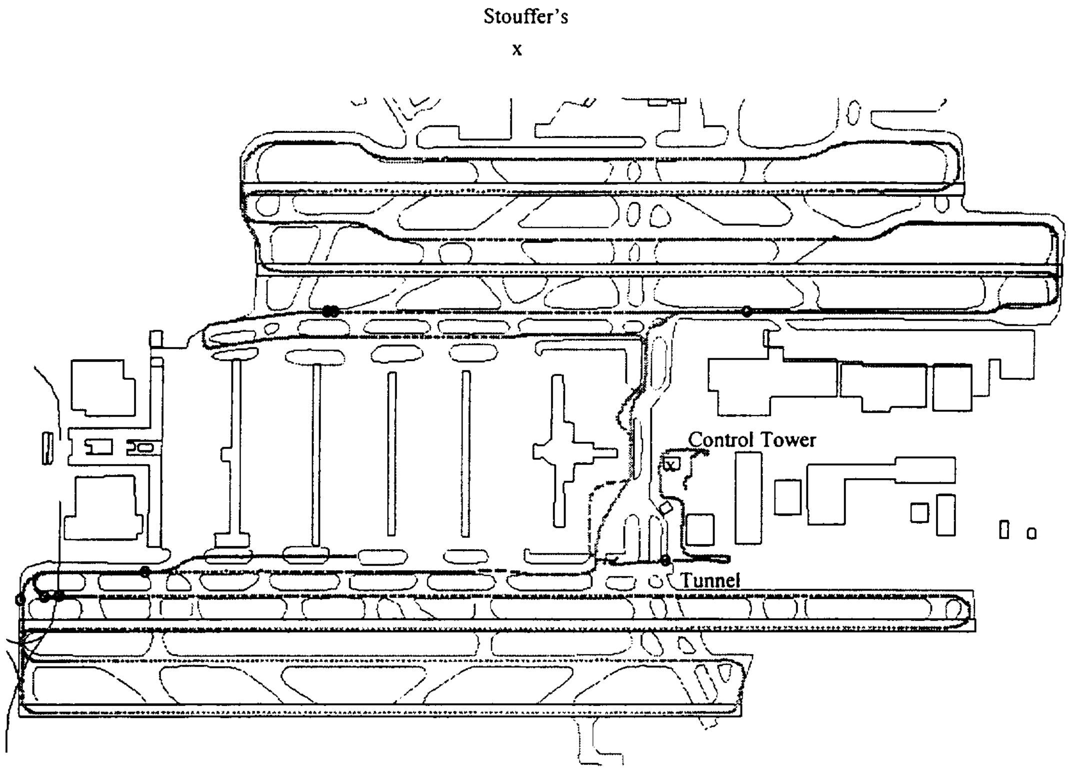


Figure 9 Coverage for Vertical Polarization, Control Tower, Runways and Taxiways

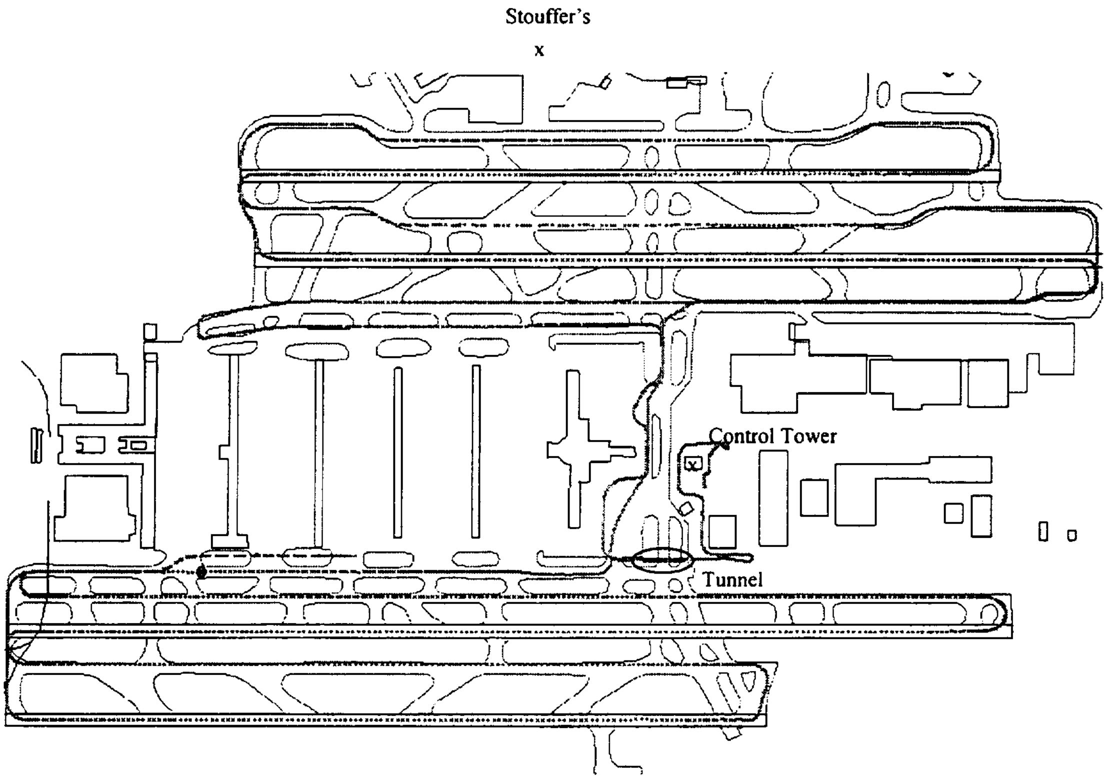


Figure 10 Coverage for Vertical Polarization, Stouffer's, Runways and Taxiways

Evaluation of Results

The message reception rate averaged for all data collection runs was 99.75% for the VHF DGPS data link. As indicated in Figures 3 to 10, the entire airport was traversed several times with relatively uniform spatial coverage. The results include a number of areas of severe line-of-sight (LOS) signal blockage provided by concourses and below grade regions that occurred along the airport loop road. The blocking effects of the tunnel were not included in the calculation of message reliability.

Most of the relatively few data link message failures were single duration events, where signal reception resumed after losing a message. Most of the garbled or lost messages are the result of relatively weak received signals (~ -78 dBm) due to severe LOS blockages. However, these signal levels are well above the VHF DGPS receiver sensitivity and the cause of the link failure mechanism has not yet been adequately explained. It should be noted that while we did observe some multipath fading signal conditions, these effects seemed relatively insignificant. Throughout the entire test we did not observe any deep fades, suggesting that there were a sufficient number of reflected signal paths available that would fill in for any deep fades that would have been suggested by theory. VHF signal propagation also allows for some bending of LOS that is beneficial for providing surface coverage when LOS is lost.

We found very little difference in the coverage provided by the Control Tower and the Stouffer's transmit sites. Depending on the final communications requirements for any data link application such as DGPS, it appears that a single transmit site is sufficient in providing full airport coverage. Both, vertically polarized and horizontally polarized signals performed equally well in providing high message reception reliability and airport surface coverage.

Table 1 provides a more detailed breakdown of message reception reliability as a function of message transmission attempts. From Table 1, the overall 99.75 % message reception improved to 99.94 % if two transmission attempts are permitted for receiving a single message. The most severe communications failure that was observed was a single event of 5 consecutive dropped messages that occurred on the NW corner taxiway on the South half of the airport for the Stouffer's transmit site. The data in Table 1 is based on 21,831 message transmissions (one per second), with a total of 50 message failures being experienced for the Control Tower and 60 message failures for Stouffer's, respectively. Table 2 provides a qualitative comparison of transmit site performance for the Control Tower and the Stouffer's sites.

Probability of correctly receiving a single message per number of attempts	Control Tower	Stouffer's Hotel
Single attempt	99.77%	99.73%
Two attempts	99.97%	99.94%
Three attempts	99.995%	99.968%
Four attempts	100%	99.986%
Five attempts	100%	99.995%
Six or more attempts	100%	100%

Table 1 Message Reception Probability versus Number of Transmission Attempts

	Control Tower	Stouffer's Hotel
Vertical Polarization, Ramp Area	99.75 % coverage, greatest difficulty on West side of Concourses C and D	99.85 % coverage, greatest difficulty between Concourses T, A, and B
Horizontal Polarization, Ramp Area	99.6 % coverage	99.5 % coverage
Vertical Polarization, Runways and Taxiways	99.77 % coverage, almost perfect coverage, a few minor exceptions on NW corner of South half	99.94 % coverage, nearly perfect coverage
Horizontal Polarization, Runways and Taxiways	99.95 % coverage, nearly perfect coverage	99.67 % coverage, almost perfect coverage except NW corner of South half

Table 2 Qualitative Comparison of Transmit Site Performance

Summary

A VHF DGPS broadcast data link using the D8PSK, 31.5 kbps waveform as per RTCA DO-217 Appendix F (change 1) was tested and evaluated to determine its performance in providing airport surface coverage and message reception reliability. Atlanta's Hartsfield International Airport served as the site for the test. Two transmit sites were used to compare airport coverage performance; one transmitter was located at the Control Tower, the other atop the Stouffer's Hotel located just to the North of the airport. Each transmit site was allocated a dedicated frequency channel (118.2 MHz and 128.5 MHz). Data link performance of both transmit sites was comparable achieving an overall message reception reliability of 99.75 %. Tests were conducted for both horizontal and vertical polarization in order to compare their relative data link performance. Message reception for both polarizations was very good with no perceptible difference in performance. While pure line-of-sight theory suggests that some multipath fading could occur, we did not observe any deep fading effects throughout the duration of the test. These results confirm that the beneficial signal propagation properties of VHF provide a sufficient number of signal paths and bending in line-of-sight to provide good coverage of the airport surface. Depending on eventual system requirements for surface communications, it is likely that a single transmit site can provide adequate coverage of an airport such as Atlanta's Hartsfield.

Acknowledgements

The author wishes to acknowledge Vinnie Capezutto from JIL Information Systems; and Jim Triantos, Mike Curry, and Steve Nuzzi from Trios Associates, all of whom represented the FAA in making the necessary arrangements and coordinating with the airport authorities to allow us to conduct the data link test. The author also wishes to thank John Hughes from the FAA Airways Transportation Systems branch at Atlanta for his support. Also special thanks to Greg Evans and Terry Dickey from the Airways Transportation Systems group for the long hours they worked in guiding us around the airport surface and interfacing with Air Traffic Control. A final thanks is to Bob Kenney from MIT Lincoln Laboratory who supported us with the van and was our driver throughout the test.

Appendix B

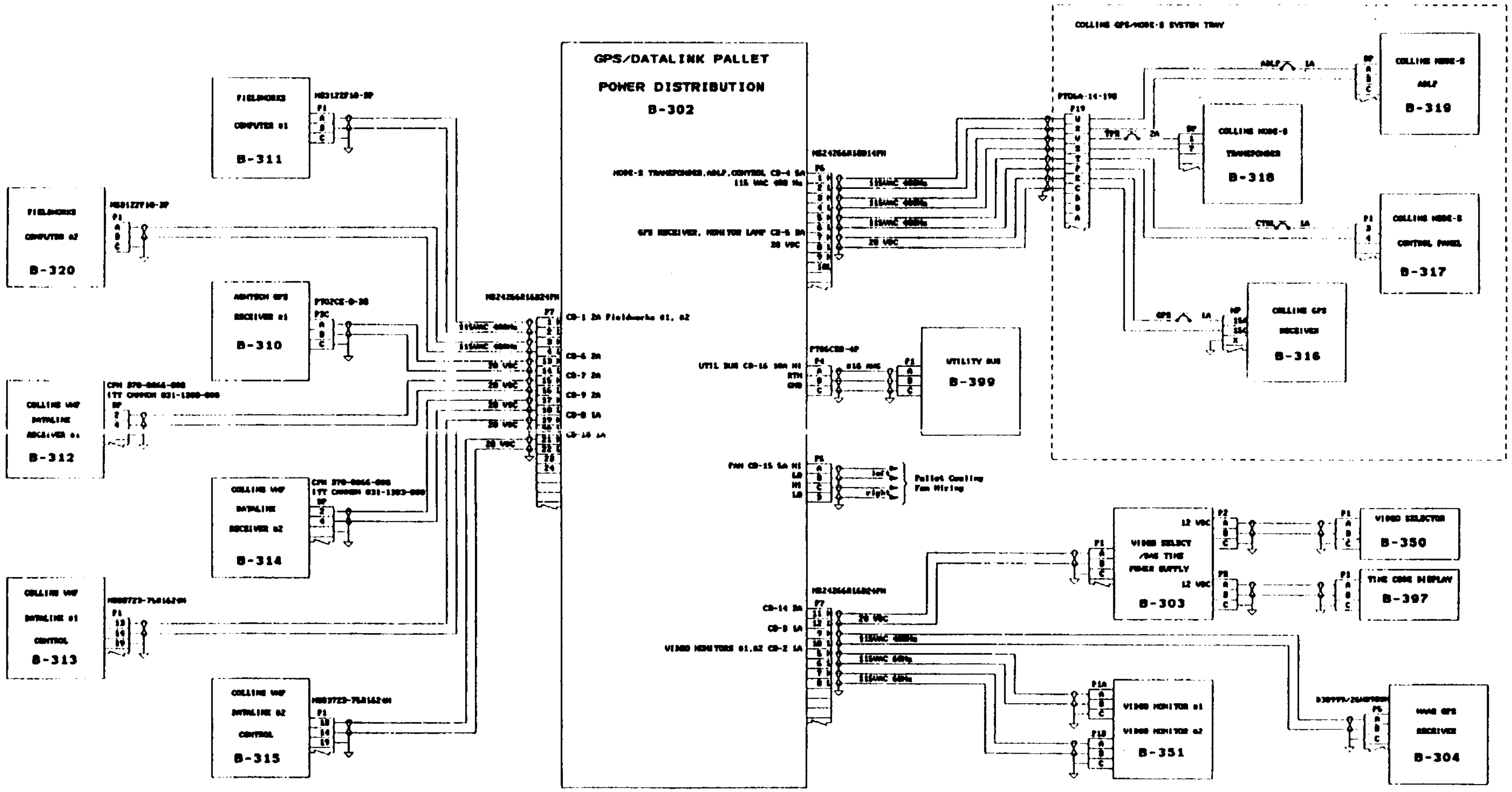
LVLASO GPS / Data Link Pallet

Interfaces and Schematics

TX Seq	32	31 30	29......14 Data Field	13..11	10 9	8......1 ARINC label
	Parity	SSM	Spare (3 bits) Data Block Length (13 bits)	SSID	SDI	Label 045
1	Parity	SSM	Ref Station ID (8 LSB) (1001 1001) Message Block ID (8 bits)	SSID	SDI	Label 046
2	Parity	SSM	Ref Station ID (16 MSB)	SSID	SDI	Label 046
3	Parity	SSM	Msg Length (8 bits) (000001) Msg Type (6 bits) Res (2 bits)	SSID	SDI	Label 046
4	Parity	SSM	Accel Err Bound (3 bits) Modified Z-Count (13 bits)	SSID	SDI	Label 046
5	Parity	SSM	Pseudo Range Correction (10 LSB) Satellite ID (6 bits)	SSID	SDI	Label 046
6	Parity	SSM	Range Rate Cor (2 LSB) IOD (8 bits) Pseudo Range Correction (6 MSB)	SSID	SDI	Label 046
7	Parity	SSM	UDRE (6 bits) Range Rate Cor (10 MSB)	SSID	SDI	Label 046
	●		●			●
	●		●			●
	●		●			●
n-4	Parity	SSM	Pseudo Range Correction (10 LSB) Satellite ID (6 bits)	SSID	SDI	Label 046
n-3	Parity	SSM	Range Rate Cor (2 LSB) IOD (8 bits) Pseudo Range Correction (6 MSB)	SSID	SDI	Label 046
n-2	Parity	SSM	UDRE (6 bits) Range Rate Cor (10 MSB)	SSID	SDI	Label 046
n-1	Parity	SSM	16 Least Significant Bits of 24 bit CRC	SSID	SDI	Label 046
n	Parity	SSM	8 pad bits 8 Most Significant Bits of 24 bit CRC	SSID	SDI	Label 046

ARINC 429 Communications Protocol for DGPS Data Link Interface

GPS/DATALINK PALLET POWER DISTRIBUTION



All wires are M22759/43 #20 AWG except as noted

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APPROVALS	DATE	TITLE GPS/DATALINK PALLET POWER DISTRIBUTION
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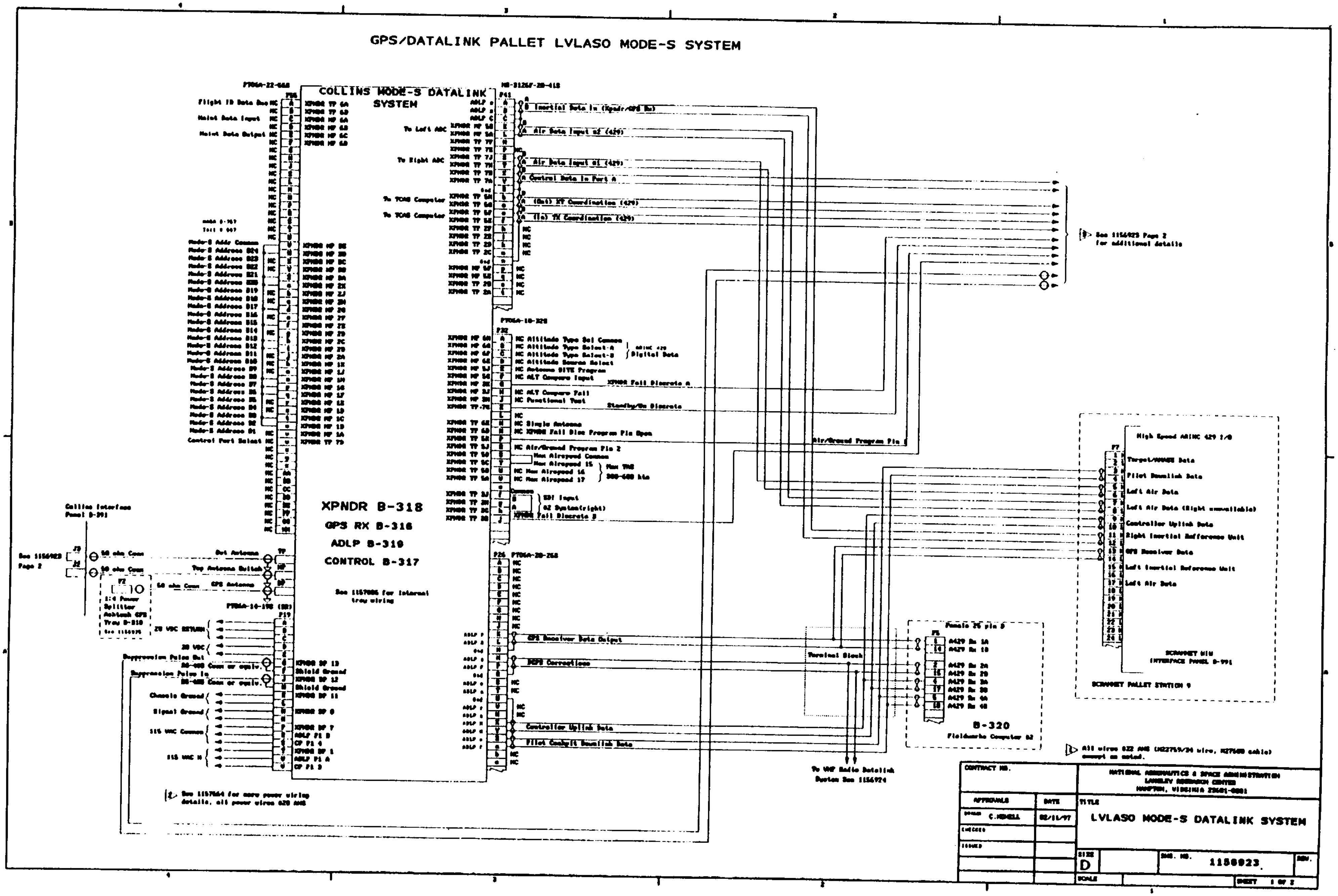
ISSUED		SIZE DWG. NO. 1158922 REV.


GPS/DATALINK PALLET LVLASO MODE-S SYSTEM
COLLINS MODE-S DATALINK SYSTEM
XPNDR B-318
GPS RX B-316
ADLP B-319
CONTROL B-317
P41
P32
P26
P19
P7
P5
Inertial Data In (Xpndr/GPS Rx)
To Left ADC
Air Data Input #2 (429)
To Right ADC
Air Data Input #1 (429)
Control Data In Port A
To TCAS Computer
(Out) XT Coordination (429)
(In) TX Coordination (429)
NC Altitude Type Sel Common
NC Altitude Type Select-A
NC Altitude Type Select-B
ARINC 429 Digital Data
NC Altitude Source Select
NC Antenna SITE Program
NC ALT Compare Input
XPNDR Fail Discrete A
NC ALT Compare Fail
NC Functional Test
Standby/On Discrete
NC Single Antenna
NC XPNDR Fail Disc Program Pin Open
NC Air/Ground Program Pin 2
Air/Ground Program Pin 1
Max Airspeed Common
Max Airspeed 15
NC Max Airspeed 16
NC Max Airspeed 17
Max TAS 300-600 kts
Common
SDI Input
#2 System(right)
XPNDR Fail Discrete B
GPS Receiver Data Output
DGPS Corrections
Controller Uplink Data
Pilot Cockpit Downlink Data
Collins Interface Panel B-391
Bot Antenna
Top Antenna
GPS Antenna
50 ohm Coax
1:4 Power Splitter
28 VDC RETURN
28 VDC
Suppression Pulse Out
Suppression Pulse In
Chassis Ground
Signal Ground
115 VAC Common
115 VAC H
Terminal Block
To VHF Radio Datalink System See 1156924
High Speed ARINC 429 I/O
Target/ADS-B Data
Pilot Downlink Data
Left Air Data
Left Air Data (Right unavailable)
Controller Uplink Data
Right Inertial Reference Unit
GPS Receiver Data
Left Inertial Reference Unit
Left Air Data
SCRAMNET VIM INTERFACE PANEL B-991
SCRAMNET PALLET STATION 9
Female 25 pin D
B-320
Fieldworks Computer #2
See 1156923 Page 2 for additional details
All wires #22 AWG (M22759/34 wire, M27500 cable) except as noted.
See 1157664 for more power wiring details, all power wires #20 AWG
See 1157665 for internal tray wiring
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SCALE
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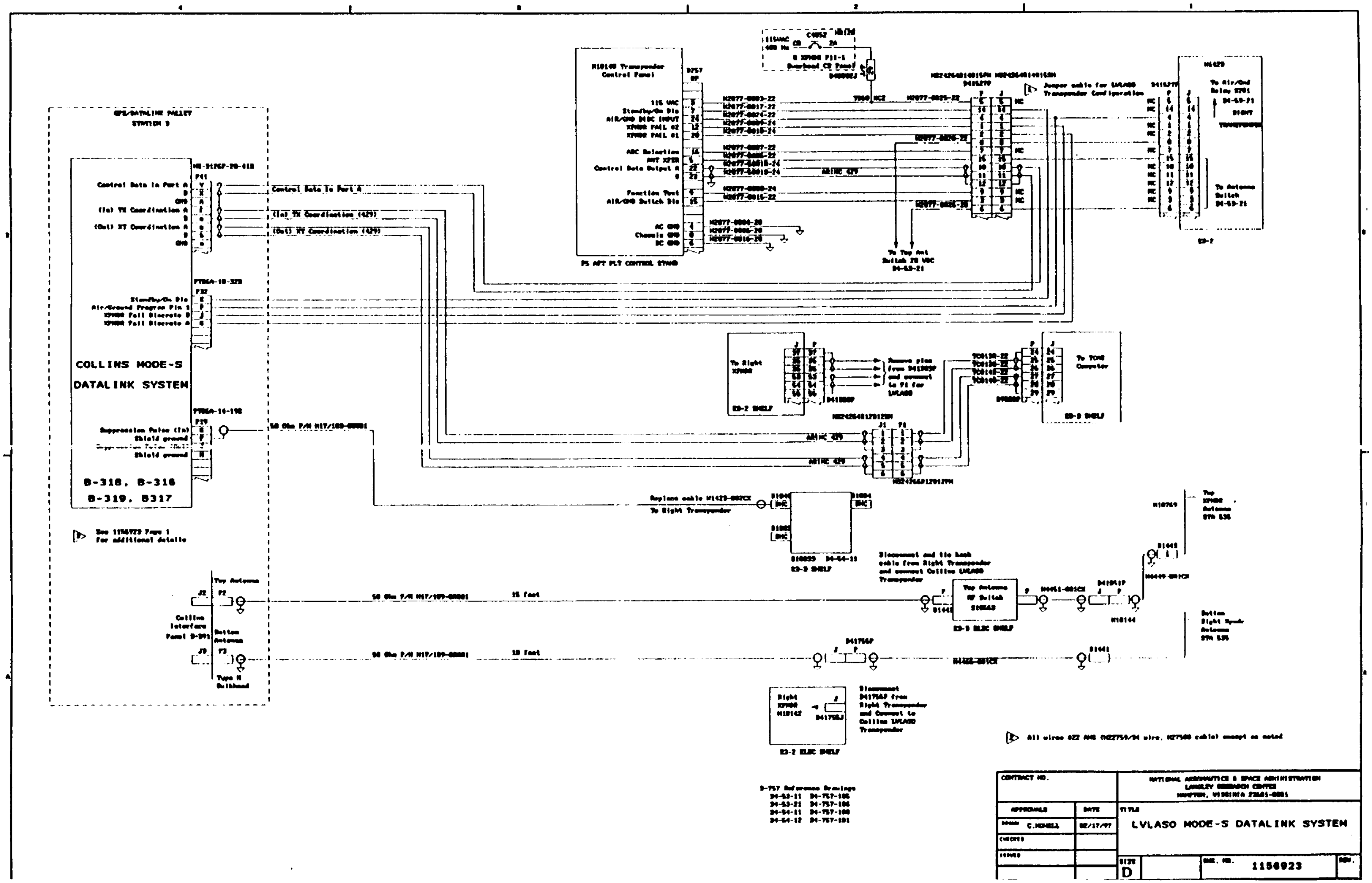
GPS/DATALINK PALLET
STATION 3
COLLINS MODE-S
DATALINK SYSTEM
B-318, B-316
B-319, B317
P41
Control Data In Port A
B
GND
(In) TX Coordination A
B
(Out) XT Coordination A
B
GND
P32
Standby/On Dis
Air/Ground Program Pin 1
XPNDR Fail Discrete B
XPNDR Fail Discrete A
P19
Suppression Pulse (In)
Shield ground
Suppression Pulse (Out)
Shield ground
See 1156923 Page 1
for additional details
Control Data In Port A
(In) TX Coordination (429)
(Out) XT Coordination (429)
Top Antenna
J2
P2
Collins
Interface
Panel
J3
P3
Bottom
Antenna
Type N
Bulkhead
M10140 Transponder
Control Panel
115 VAC
Standby/On Dis
AIR/GND DISC INPUT
XPNDR FAIL #2
XPNDR FAIL #1
ADC Selection
ANT XFER
Control Data Output A
B
Function Test
AIR/GND Switch Dis
AC GND
Chassis GND
DC GND
P5 AFT PLT CONTROL STAND
115VAC
400 Hz
CB
2A
R XPNDR P11-1
Overhead CB Panel
ARINC 429
To Top Ant
Switch 28 VDC
34-63-21
Jumper cable for LVLASO
Transponder Configuration
P
J
NC
M1429
To Air/Gnd
Relay R201
34-63-21
RIGHT
TRANSPONDER
To Antenna
Switch
34-63-21
E3-2
To Right
XPNDR
E3-2 SHELF
Remove pins
from D41303P
and connect
to P1 for
LVLASO
J1
P1
ARINC 429
ARINC 429
To TCAS
Computer
E3-3 SHELF
Replace cable M1423-002CX
To Right Transponder
BNC
BNC
BNC
34-54-11
E3-3 SHELF
Disconnect and tie back
cable from Right Transponder
and connect Collins LVLASO
Transponder
Top Antenna
RF Switch
E3-3 ELEC SHELF
Top
XPNDR
Antenna
STA 535
Bottom
Right Xpndr
Antenna
STA 535
Right
XPNDR
M10142
E3-2 ELEC SHELF
Disconnect
D41756P from
Right Transponder
and Connect to
Collins LVLASO
Transponder
50 Ohm P/N M17/189-00001
15 feet
10 feet
B-757 Reference Drawings
34-53-11 34-757-185
34-53-21 34-757-186
34-54-11 34-757-180
34-54-12 34-757-181
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C.HOWELL
02/17/97
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SIZE
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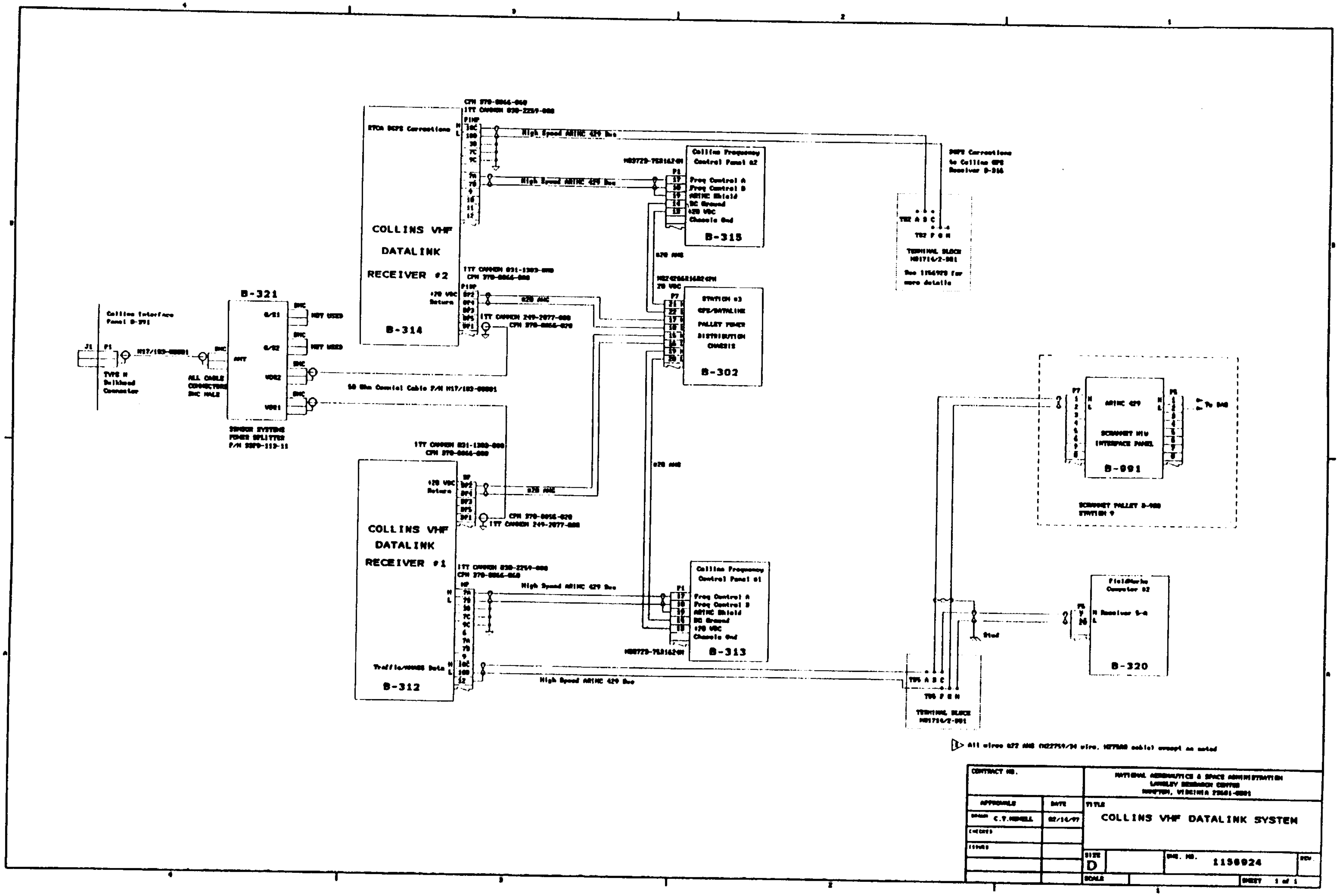
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B-314
RTCA DGPS Corrections
P1HP
High Speed ARINC 429 Bus
ITT CANNON 831-1303-000
+28 VDC Return
#20 AWG
ITT CANNON 249-2077-000
Collins Frequency Control Panel #2
Freq Control A
Freq Control B
ARINC Shield
DC Ground
+28 VDC
Chassis Gnd
B-315
STATION #3 GPS/DATALINK PALLET POWER DISTRIBUTION CHASSIS
P7
B-302
28 VDC
DGPS Corrections to Collins GPS Receiver B-316
TB2 A B C
TB2 F G H
TERMINAL BLOCK
See 1156920 for more details
B-321
Collins Interface Panel B-391
J1
P1
TYPE N Bulkhead Connector
ALL CABLE CONNECTORS BNC MALE
BNC
NOT USED
ANT
VOR2
VOR1
50 Ohm Coaxial Cable P/N M17/183-00001
COLLINS VHF DATALINK RECEIVER #1
B-312
Traffic/WAAS Data
Collins Frequency Control Panel #1
B-313
ARINC 429
INTERFACE PANEL
B-991
STATION 9
To DAS
Computer #2
B-320
Stud
TB5 A B C
TB6 F E H
TERMINAL BLOCK
1 All wires #22 AWG except as noted
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TITLE
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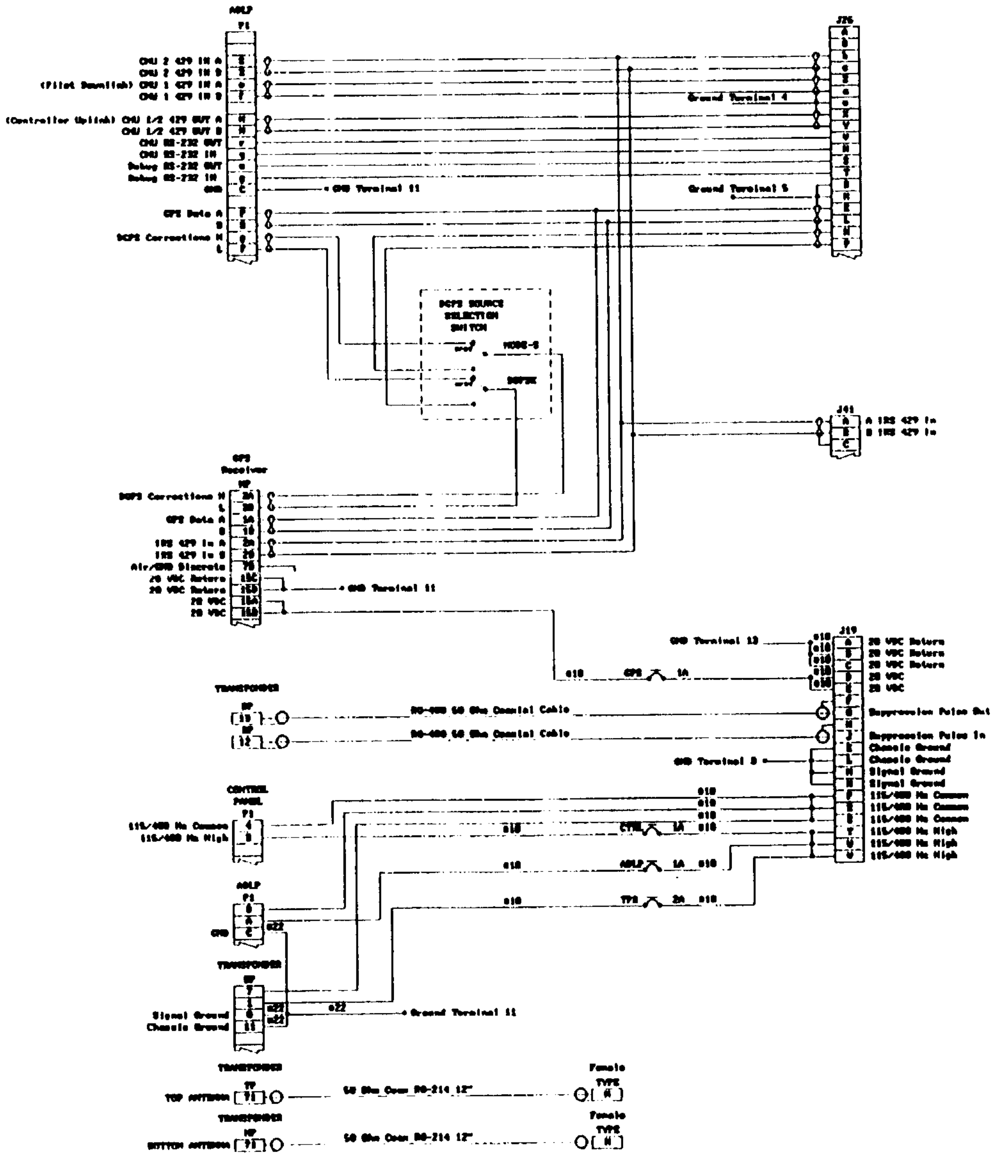
COLLINS MODE-S TRAY INTERNAL WIRING



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Appendix C

Mode-S Pallet Interfaces and Protocols

Controller Pilot Data Link Communications (CPDLC) Data Link

for

NASA LVLASO Demonstration

Interface Control Document

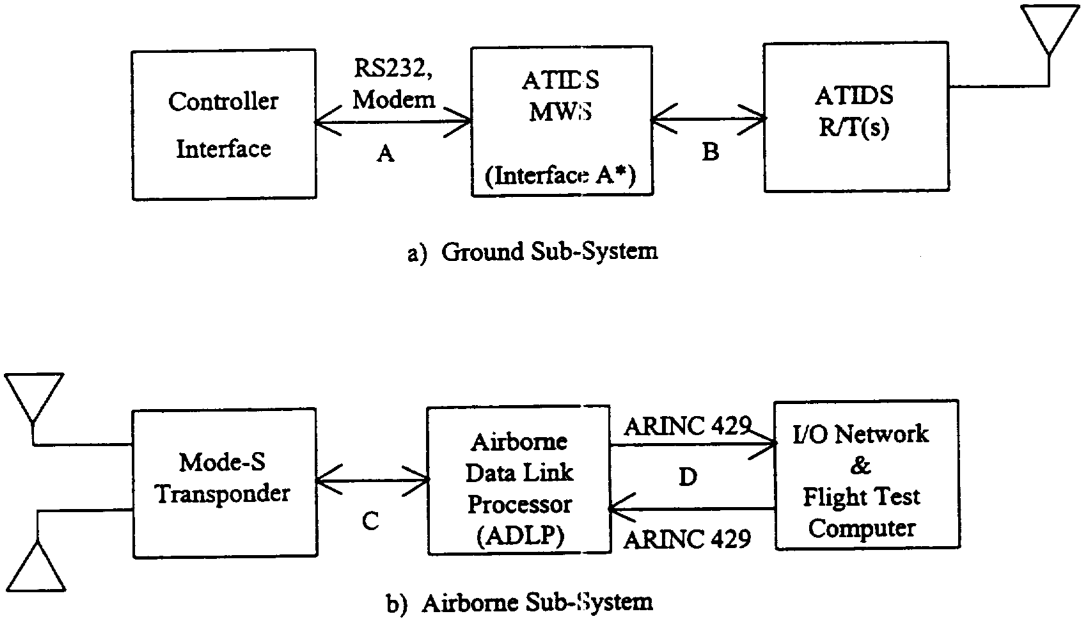
1.0 Introduction

This document provides an overview of the CPDLC interfaces and describes the Mode-S data link message formats and protocols that support CPDLC data link for the NASA LVLASO demonstration at Atlanta.

Figure 1 identifies the interfaces of the various sub-system components of the CPDLC data link system. Sub-system components consist of the Controller Interface (CI), being developed by St. Cloud State University; the ATIDS Master Work Station (MWS) and ATIDS Receivers/Transmitters (R/Ts) that are provided by Cardion; the Mode-S transponder and Airborne Data Link Processor (ADLP) provided by Rockwell-Collins, and the NASA I/O Network and Flight Test Computer.

From Figure 1, Interface 'A' between the Control Interface and the ATIDS MWS is documented by [1]. [1] describes the application data interface, physical layer RS-232/modem interface and associated communication protocols. CPDLC messages used in the LVLASO demonstration are listed in [1,2].

Interfaces 'B' and 'C' are internal to ATIDS (Cardion) and Mode-S/ADLP (Rockwell-Collins), respectively, and will thus not be specified. Section 2 of this document describes Interface A* contained within the ATIDS MWS (see Figure 1), and Section 3 describes Interface 'D' located between the ADLP and NASA I/O Network.



a) Ground Sub-System

b) Airborne Sub-System

Figure 1 CPDLC Data Link System

2.0 ATIDS MWS - Mode-S Interface

While not explicitly shown in Figure 1, the ATIDS MWS is responsible for an additional interface (Interface A*) that maintains the Mode-S communication protocols with the airborne Mode-S transponder/ADLP. This section describes the Mode-S communications protocols that must be supported by the ATIDS MWS and the airborne Mode-S/ADLP for CPDLC data link. CPDLC data link for the LVLASO demonstration uses the Mode-S Specific Protocol (MSP) which is a subset of the Mode-S Specific Services Protocols (MSSP) [3]. Protocols for uplink and downlink CPDLC messages are described.

2.1 Uplink CPDLC Messages - MSP Protocol

Uplink CPDLC messages are transmitted using the Mode-S Specific Protocol (MSP). Depending on the overall length of the CPDLC application message, messages are either encoded as Short Form MSP Packets (for messages of 26 bytes or less) or as Long Form MSP Packets (for message lengths from 27 bytes to 159 bytes). For the LVLASO demonstration system, all CPDLC messages are less than 27 bytes long and thus only Short Form MSP Packets are required.

The data associated with Short Form MSP Packets is partitioned and inserted into the 56-bit MA subfield (format shown below) of long (112-bit) Mode-S surveillance interrogations, which serve as the basic building block for uplink of MSP messages. The format of the 112-bit Mode-S surveillance interrogation using Uplink Formats (UF=20 or 21) is described first, followed by the encoding of Short Form MSP Packets.

2.1.1 Format of 112-bit Uplink CPDLC Mode-S Messages

Uplink CPDLC messages consist of long, 112-bit Mode-S interrogations using Uplink Formats UF=20 or UF=21. The message format of these interrogations is as follows:

UF:5	PC:3	RR:5	DI:3	SD:16	MA:56	AP:24

UF = Uplink Format (5-bit subfield);	All CPDLC uplink messages use either UF=20 (i.e., '10100') for altitude requests or UF=21 (i.e., '10101') for identity requests.
PC* = ProtoCol (3-bit subfield);	Always set to '000' for uplink messages in the LVLASO demonstration (no change in transponder state).
RR* = Reply Request (5-bit subfield);	Always set to '00000' for uplink messages in the LVLASO demonstration.
DI* = Designator, Identification (3-bit subfield)	This subfield is used to identify the coding contained in the SD subfield. Always set to '001' for uplink messages in the LVLASO demonstration (indicates SD field contains multisite information).
SD = Special Designator (16-bit subfield)	Coding of the SD subfield is as follows:

SD Subfield Encoding					
IIS:4	MBS:2	MES:3	LOS:1	RSS:2	TMS:4

IIS = Interrogator Identifier (4-bit subfield)	This field is arbitrarily chosen to be '1000' for the ATIDS ground interrogator in the LVLASO demonstration. (Note: The Atlanta ground interrogator IIS code is '0110').
MBS* = Multisite Comm-B Subfield (2 bits)	Always set to '00' for uplink messages in LVLASO demonstration.

*Note: Encoding of PC, RR, DI and MBS subfields may be different for interrogations that are in response to requests of air-initiated or multisite-directed downlink CPDLC messages by the aircraft; refer to section 2.2 for details).

MES = Multisite ELM Subfield (3 bits)	Always set to '000' for LVLASO demonstration (no ELM action).
LOS = Lockout Subfield (1 bit)	Always set to '0' for LVLASO demonstration (no change in transponder all-call reply lockout state).
RSS = Reservation Status Subfield (2 bits)	Always set to '00' for uplink messages in LVLASO demonstration (no reservation status requests).
TMS = Tactical Message Subfield (4 bits)	TMS encoding is as follows:

TMS Subfield Encoding	
Spare:1	LAS:3

The most significant bit of TMS is a spare bit.

LAS = Linked Comm-A Subfield (3 bits)

LAS Value	Meaning
0	single segment
1	linked, 1st segment
2	linked, 2nd but not final segment
3	linked, 3rd but not final segment
4	linked, 4th and final segment
5	linked, 2nd and final segment
6	linked, 3rd and final segment
7	unassigned.

Note: For the LVLASO demonstration, the maximum length uplink CPDLC message is expected to require two segments. Encoding of this message will require two consecutive uplink UF=20 or UF=21 messages with LAS = 1 for the initial segment and LAS = 5 for the second and final segment. Should a longer CPDLC message be required in the future, LAS encoding will be as defined above.

Most uplink CPDLC messages require only a single segment, i.e., LAS = 0.

MA = Message, Comm-A (56-bit subfield)	The MA subfield is used to transport uplink Short Form MSP Packet data, which contains uplink CPDLC application data. Encoding of Short Form MSP Packet data is described in Section 2.1.2.
AP = Address/Parity (24-bit subfield)	Contains parity overlaid on the 24-bit ICAO address for the aircraft. Occurs at end of all Mode-S uplink and downlink messages (except DF=11).

2.1.2 Format of Short Form MSP Packets (Uplink)

CPDLC application data is inserted into Short or Long Form MSP Packets. Since CPDLC messages used in the LVLASO demonstration are relatively short they will always be in the form of Short Form MSP Packets. The Short Form MSP Packet is partitioned and inserted into successive 56-bit MA subfields of UF=20 or UF=21 interrogations. The format of an uplink Short Form MSP Packet for the LVLASO demonstration is as follows:

Short Form MSP Packet Encoding (Uplink)				
DP:1	MP:1	M/CH:6	Fill:0	UD:v

DP = Data Packet type (1-bit subfield)	Always set to '0' for uplink messages in the LVLASO demonstration.
MP = MSP Packet type (1-bit subfield)	Always set to '0' for the LVLASO demonstration (indicates a Short Form MSP Packet).
M/CH = MSP CHannel # (6-bit subfield)	Always set to '000110' for the CPDLC data link application in the LVLASO demonstration (i.e., CPDLC uses MSP channel 6).
Fill = Fill bits (0-bits)	No fill bits are required for uplink CPDLC messages.
UD = User Data (v-bit subfield)	Application data for CPDLC uplink messages is inserted into this field. The length of data is variable depending on the specific uplink message. Since 6-bytes of application data are inserted at a time into the MA subfield for each uplink interrogation (recall that the first byte of the MA subfield is a control byte containing DP:1, MP:1 and M/CH:6), application data must be zero padded to provide an integer multiple of 6-byte data blocks. The control byte is always the first byte in the MA field for uplink messages in the LVLASO demonstration. Note: As currently defined, the Controller Interface transfers 6-byte data segments (of a CPDLC message) at a time to the ATIDS MWS [1]. The ATIDS MWS is then responsible for formatting the collection of these segments into the proper sequence of Mode-S uplink interrogations (UF=20 or UF=21).

Note 1: In response to UF=20 or UF=21 uplink CPDLC interrogations, the airborne Mode-S transponder will automatically acknowledge receipt of an interrogation with a downlink reply. This will be referred to as a "transponder acknowledgment" or XPDR ACK. The ATIDS MWS must monitor successful receipt of XPDR ACKs to any of its CPDLC uplink messages. For a two segment UF=20 or UF=21 uplink message, the ATIDS MWS must verify that two XPDR ACKs were received that confirm transponder reception of both segments (i.e., the entire message). Alternately, the ATIDS MWS could report back to the Controller Interface the XPDR ACKs on a per segment basis, with the Controller Interface assuming responsibility for monitoring whether messages were acknowledged by the transponder.

Note 2: Some CPDLC uplink messages require the pilot to respond with a downlink CPDLC message. This acknowledgment or response will be referred to as a PILOT ACK and should not be confused with a XPDR ACK. PILOT ACKs occur at the application layer while XPDR ACKs occur at the physical / data link layer.

When the ADLP receives a downlink message from the pilot (in response to a previous received uplink message), the ADLP generates either an air-initiated or a multi-site directed downlink CPDLC message and transfers it to the Mode-S transponder for transmission. Downlink message protocols associated with the ADLP/Mode-S transponder and the ATIDS MWS are described in section 2.2.

2.1.3 Encoding Examples of Uplink CPDLC Messages

This section provides two examples of uplink CPDLC messages; one requiring only a single uplink interrogation and a second example where two uplink interrogations are needed.

2.1.3.1 Single-Segment Uplink CPDLC Message Example

"Maintain Altitude" uplink message

Encoding of this message is as follows (per RTCA DO-219):

Preamble	Message ID	Element ID	Altitude Choice	Altitude Value	Pad
00	001001	00010011	000	001010111100	0000000000000000

This application data encodes into: 09 13 05 78 00 00 in hexadecimal format. Note that the data is zero-padded to 6 bytes. The Controller Interface provides this data to the ATIDS MWS [1].

The 56-bit MA subfield thus encodes to: 06 09 13 05 78 00 00
where the leading byte is (DP = '0', MP = '0', and M/CH = '000110' or 06 H).

The full encoding of the 112-bit uplink interrogation is as follows:

UF:5	PC:3	RR:5	DI:3	SD:16							MA:56
				IIS:4	MBS:2	MES:3	LOS:1	RSS:2	Spare:1	LAS:3	(already in hex)
10100	000	00000	001	1000	00	000	0	00	0	000	(06 09 13 05 78 00 00)

This encodes to: A0 01 80 00 06 09 13 05 78 00 00 (AP:24 must also be appended).

Note 1: LAS = '000' indicates that this uplink CPDLC message is only a single segment message.

Note 2: This example assumed a UF=20, which also provides altitude data in the transponder reply. UF=21 could also be used if an identity reply is requested.

2.1.3.2 Two-Segment Uplink CPDLC Message Example

"Contact ATL Tower 119.5" uplink message

Encoding of application message is as follows (per RTCA DO-219):

Field Name	Value	Comment
Preamble	'00'	
Message ID	'00 0011'	Arbitrarily selected value of message ID counter
Element ID	'0111 0101'	Uplink message #117
ICAOunitname	'10'	ICAOfacilitydesignation (2-bit flag)
	'1000001'	ICAOfacilitydesignation (1st character = A)
	'1010110'	" (2nd character = T)
	'1001100'	" (3rd character = L)
	'0000000'	" (4th character = 'null')
	'010'	ICAOfacilityfunction ('Tower')

Frequency	'01'	Frequency Choice = 'frequencyvhf'
	'000100111000100'	Frequency Value = '119.500 MHz'
Pad	'00 0000 0000 0000 0000 0000 0000 0000'	Application data is padded with zeros to fill an integer multiple of 6-bytes blocks, where each 6-byte block represents a segment in a Short Form MSP Packet).

Concatenating these fields and converting them into hexadecimal format results in the following encoding:

03 75 A0 D4 98 01 22 71 00 00 00 00 H

Note: The application message consists of 12 bytes of data which is provided by the Controller Interface to the ATIDS MWS in two separate 6-byte data transfers [1].

The 56-bit MA subfields encodes to:

06 03 75 A0 D4 98 01 (MA subfield for segment #1)
06 22 71 00 00 00 00 (MA subfield for segment #2)

where the leading byte in each segment is 06 H (DP = '0', MP = '0', and M/CH = '000110').

The full encoding of the two 112-bit uplink interrogation required for uplink of "Contact ATL Tower 119.5" is as follows:

Interrogation #1:

UF:5	PC:3	RR:5	DI:3	SD:16							MA:56
				IIS:4	MBS:2	MES:3	LOS:1	RSS:2	Spare:1	LAS:3	(already in hex)
10100	000	00000	001	1000	00	000	0	00	0	001	(06 03 75 A0 D4 98 01)

This encodes to: A0 01 80 01 06 03 75 A0 D4 98 01 (AP:24 must also be appended).

Interrogation #2:

UF:5	PC:3	RR:5	DI:3	SD:16							MA:56
				IIS:4	MBS:2	MES:3	LOS:1	RSS:2	Spare:1	LAS:3	(already in hex)
10100	000	00000	001	1000	00	000	0	00	0	101	(06 22 71 00 00 00 00)

This encodes to: A0 01 80 05 06 22 71 00 00 00 00 (AP:24 must also be appended).

Note 1: LAS = '001' for interrogation #1 indicates that this uplink CPDLC message is the first segment of a series of linked segments. LAS = '101' for interrogation # 2 indicates that this is the second and final segment of the series of linked messages.

Note 2: This example assumed a UF=20, which also provides altitude data in the transponder reply. UF=21 could also be used if an identity reply is requested.

2.2 Downlink CPDLC Messages - MSP Protocol

This section describes the MSP protocol used between the ADLP and the ATIDS MWS for downlink CPDLC messages.

For the LVLASO demonstration, downlink CPDLC messages are actuated at the pilot interface and Flight Test Computer and are transferred to the ADLP via the NASA I/O network using an ARINC 429 bus and using a modified Williamsburg ARINC 429 file transfer protocol. This protocol and the format of the data file of the downlink message are described in section 3.2. Using the downlink data provided by the I/O network, the ADLP uses the Mode-S Specific Protocol (MSP) to downlink CPDLC messages.

2.2.1 Overview of Mode-S Downlink (Comm-B) Messaging

Before describing the specific message formats for downlink messages, it is useful to review the Mode-S downlink (Comm-B) messaging protocol as it pertains to the LVLASO demonstration. Two types of downlink transmissions are of particular interest for the LVLASO demonstration: 1) Downlink transponder reply that is in response to an uplink CPDLC message interrogation, thus providing a XPDR ACK; 2) Downlink CPDLC message initiated by the pilot (either a request or status message, or a reply/acknowledgment message that is in response to a previous uplink CPDLC message).

If the Mode-S transponder does not require downlink transmission of a pilot-initiated CPDLC message at the time an interrogation is received, the Mode-S transponder simply transmits a conventional surveillance reply. However, if a downlink CPDLC message needs to be transmitted, the Mode-S transponder includes in the reply a notification to the ground interrogator (i.e., ATIDS MWS) that it has a downlink message that needs to be transmitted.

Note: When the ADLP has a multi-segment downlink message to be transmitted, it transfers each segment to the transponder, where the transponder then stores the first 56-bit segment in the air-initiated register (register 0) and stores the remaining segments in ground-initiated registers number 2, 3, and 4, respectively. Once the complete message has been stored in these registers, the Mode-S transponder provides a notification to the ground interrogator that a message is available for downlink. It does this in one of two ways:

1) "Air-initiated Comm-B" protocol
When transmitting a DF=11 (All-Call reply or squitter) or a DF=17 (extended squitter), the transponder sets the CA (Capability) subfield to '111', which indicates to the ground interrogator that the transponder has a message waiting to be downlinked. Upon detecting the CA = 7 condition, the ground station schedules a UF = 4, 5, 20 or 21 interrogation to the Mode-S transponder in order to read the DR (Downlink Request) subfield in the DF = 4, 5, 20 or 21 transponder reply. DR indicates the type of downlink message (if any) that is stored in the transponder for eventual downlink.

2) "Multi-site Directed Comm-B" protocol
Independent of whether or not the transponder has set the CA subfield in previously sent DF=11 or DF=17 squitters, the Mode-S transponder also informs the ground interrogator of a Comm-B request by setting the DR subfield in DF = 4, 5, 20, or 21 replies to '00001' or '00011', which indicate a 'request to send Comm-B message'.

   Note: DR = '00011' also indicates that TCAS information is available. However, since the Mode-S aircraft installation will be independent of TCAS for the LVLASO demonstration, this DR code will not occur.

Upon detecting a DR = '00001' or '00011' in the transponder reply, the ground interrogator sends a UF = 4, 5, 20 or 21 interrogation with RR = '1 0000' and DI = '001' to extract the first segment of the Comm-B downlink message (which is stored in the air-initiated register in the transponder). DI = '001' provides the transponder with multi-site information (i.e., the Interrogator Identifier Subfield, IIS, which is located in the SD subfield). The transponder includes the first segment of the downlink message stored in the air-initiated register in the MB:56 subfield of the corresponding DF=20 (if UF=4 or 20) or DF=21 (if UF=5 or 21) reply. The transponder continues to set the DR subfield to '00001' or '00011' until the interrogator closes out the downlink message.

Contained in the MB subfield in the initial downlink segment is the two-bit LBS (Linked Comm-B) subfield which indicates the length of the stored downlink message to be retrieved, i.e., message length ranges from 1 to 4 segments. The ground interrogator uses this information to schedule the appropriate number of additional interrogations. Encoding of the MB and LBS subfields is discussed in section 2.2.3 below.

Interrogations that solicit additional message segments for downlink consist of UF=4, 5, 20 or 21 interrogations with RR set to '1 0000', DI set to '111' and RRS set to '0010', '0011', or '0100'. DI='111' indicates that the SD subfield in the interrogation contains an extended data readout request of one of the 255 Mode-S data registers. The address of the extended data readout request consists of the 8-bit Comm-B Definition Subfield, i.e., the BDS address. The RRS subfield, contained within the SD subfield, represents the lower four bits of the BDS address, i.e. BDS2. The BDS1 address (upper four bits of BDS) is contained within the lower four bits of the RR subfield when the leading bit in RR = '1'. Thus RR='1 0000' (also DI='111') and RRS='0010', '0011', and '0100' represent BDS registers 2, 3 and 4, respectively.

Once all downlink message segments have been received, the ground interrogator closes out the downlink message by sending a UF=4, 5, 20 or 21 with the PC (Protocol) subfield set to '100' (cancel Comm-B), RR='00000' and DI='001'. Alternately, the interrogator could set PC = '000' (no changes in transponder state), RR = '00000', DI = '001' (indicating that SD subfield contains multi-site information), with SD encoded as follows:

> IIS = '1000' (ATIDS interrogator ID), MBS = '10' (Comm-B Closeout), MES = '000', LOS = '0' (no lockout of All Calls), RSS = '00', and TMS/LAS = '0000'.

Note1: At this time, all of the CPDLC downlink messages that will be used in the LVLASO demonstration are sufficiently short to fit into a single downlink message segment.

Note 2: Several references have been made regarding the encoding of the SD subfield in uplink interrogations. SD is encoded in one of two ways, depending on whether DI='001' or '111'. SD encoding is summarized as follows:

<u>SD:16 for DI='001'</u>

SD Subfield Encoding					
IIS:4	MBS:2	MES:3	LOS:1	RSS:2	TMS:4

<u>SD:16 for DI='111'</u>

SD Subfield Encoding					
IIS:4	RRS:4	Spare:1	LOS:1	Spare:2	TMS:4

Section 2.1.1 discussed the encoding of SD (with DI='001') for typical interrogations. For the LVLASO demonstration, IIS is always set to '1000' for ATIDS; MBS='00' in all cases except '10' for a Comm-B Closeout; MES, LOS and RRS are always set to '00', '0' and '00', respectively. TMS encoding is as described in Section 2.1.1.

For DI='111', SD encoding always uses IIS='1000' and LOS='0'. RRS represents the lower 4 bits of the BDS address of the Mode-S registers. TMS encoding is defined in Section 2.1.1.

Specific formats for the downlink messages (replies) issued by the Mode-S transponder are described in the next section.

2.2.2 Format of Downlink CPDLC Mode-S Messages (Replies)

The Mode-S transponder uses a DF=4 or 5 (short 56-bit reply) or DF=20 or 21 (long 112-bit reply) in response to uplink CPDLC interrogations. The message format of the DF=4 or 5 and DF=20 or 21 Mode-S replies are as follows:

DF:5	FS:3	DR:5	UM:6	AC:13 (for DF=4,20) ID:13 (for DF=5,21)	MB:0 (for DF=4,5) or MB:56 (for DF=20,21)	AP:24

DF = Downlink Format (5-bit subfield);

DF=4 replies are used for XPDR ACKs to UF=20 (and UF=4) interrogations (i.e., when RR subfield = '0xxxx'). Alternately, DF=5 replies are used for XPDR ACKs to UF=21 (and UF=5) interrogations (also when RR subfield = '0xxxx').

DF=20 or 21 are used in response to UF = 4, 20 or 5, 21, respectively, when the ground interrogator sets the RR subfield to '10000', requesting downlink of a CPDLC message segment in the MB:56 subfield. Note that the DF = 20 or 21 reply implicitly also provides a XPDR ACK. DF coding is '00100', '00101', '10100' and '10101' for DF = 4, 5, 20, and 21, respectively.

FS = Flight Status (3-bit subfield);

FS coding is as follows:

Code	Alert	SPI	Airborne	On the ground
0	no	no	yes	no
1	no	no	no	yes
2	yes	no	yes	no
3	yes	no	no	yes
4	yes	yes	either	
5	no	yes	either	
6,7	not assigned			

DR = Downlink Request (5-bit subfield);

Set to '00000' when Mode-S transponder has no downlink CPDLC messages that require transmission. Thus the reply is simply a XPDR ACK to an interrogation.

When the Mode-S transponder requires a downlink transmission of a CPDLC message, it sets DR = '00001' or '00011', which is a 'request to send a Comm-B message'.

UM = Utility Message (6-bit subfield)

UM encoding is as follows:

UM Subfield Encoding	
IDS:2	IIS:4

IDS (Identifier Designator Subfield)

0 = No information available
1 = Comm-B reservation active

2 = Comm-C reservation active
3 = Comm-D reservation active.

Due to the multi-site nature of Mode-S communications at Atlanta (i.e., separate ATIDS and Atlanta SSR interrogators), IDS will be set to '01' in any reply where ATIDS is requesting downlink of a CPDLC message..

IIS (Interrogator Identifier Subfield)

For LVLASO demonstration the ATIDS IIS = '1000'.
Note: IIS for Atlanta's Secondary Surveillance Radar interrogator is '0110'.

AC = Altitude Code (13-bit subfield);	Stores aircraft altitude information for DF=4 or DF=20 replies.
ID = Identification (13-bit subfield);	Stores aircraft ID (4096 code) in DF = 5 or DF = 21 replies.
MB = Message, Comm-B (56-bit subfield)	MB is not used for DF = 4 or DF = 5 replies. In the LVLASO demonstration, DF = 20 or DF = 21 replies use the MB subfield to transport Short Form MSP Packet data, which contain downlink CPDLC application data. Encoding of the MB subfield and the downlink Short Form MSP Packet is described in Section 2.2.3.
AP = Address/Parity (24-bit subfield)	Contains parity overlaid on the 24-bit ICAO address for the aircraft. Occurs at end of all Mode-S uplink and downlink messages (except DF=11).

2.2.3 Format of MB Subfield and Short Form MSP Packets (downlink)

Encoding of the MB subfield of DF = 20 or DF = 21 replies is as follows:

The first two bits in the initial MB subfield segment of a linked Comm-B downlink CPDLC message consist of the LBS subfield (Linked Comm-B Subfield). LBS coding is as follows:

LBS	Meaning
0	Single segment downlink message
1	initial segment of a two-segment message
2	initial segment of a three-segment message
3	initial segment of a four-segement message.

The LBS subfield indicates to the ground interrogator the length of the pending CPDLC downlink message in terms of its number of segments that must be solicited via ground interrogations. The remaining 54 bits available in the initial MB subfield are used to store application data that is stored in the format of a Short Form MSP Packet (described below). Subsequent MB subfields of linked Comm-B messages allow all 56 bits to be used for Short Form MSP Packet application data.

The format of the Short Form MSP Packet for downlink CPDLC messages is identical to that used for uplink CPDLC messages with the exception of the Fill bit subfield; Fill:0 is used for uplink messages while Fill:6 is used for downlink messages, i.e., downlink messages have 6 fill bits which are set to zero.

Short Form MSP Packet Encoding (Downlink)				
DP:1	MP:1	M/CH:6	Fill:6	UD:v

DP = Data Packet Type (1-bit subfield);	Always set to '0' for downlink messages in LVLASO demonstration.

MP = MSP Packet Type (1-bit subfield);	Always set to '0' for LVLASO demonstration (indicates a Short Form MSP Packet).
M/CH = MSP CHannel number (6-bit subfield)	Always set to '000110' for CPDLC message application in LVLASO demonstration (i.e., CPDLC uses MSP channel 6).
Fill = Fill bits (6-bit subfield)	6 fill bits are required for downlink CPDLC messages in LVLASO demonstration. Fill bits are set to zero.
UD = User Data (v-bit subfield)	Application data for CPDLC downlink messages is inserted into this field. The length of data is variable depending on the specific downlink message.

2.2.4 Encoding Example of a Downlink CPDLC Message

This section provides an example encoding of a downlink CPDLC message and the associated Mode-S protocols. The sample message is the "Descending to 4500 ft" downlink message.

Encoding of this message is as follows (per RTCA DO-219):

Preamble	Message ID	Element ID	Altitude Choice	Altitude Value	Pad
00	000101	00011110	000	000111000010	0

This application data encodes into: 05 1E 03 84 in hexadecimal format. This is the CPDLC application data sent from the NASA I/O network to the ADLP. Note that the data is zero padded by the Flight Test Computer to fill any spare bits in the ARINC 429 data file (to the nearest ARINC 429 data word). For this example, a single '0' pad bit is required. Section 3.2 further discusses the interface protocols between the NASA I/O network and the ADLP.

Upon receiving the downlink CPDLC message from the NASA I/O network, the ADLP formats the downlink message into the appropriate set of message segments using the Short Form MSP Packet format. The resulting message encoding is as follows:

LBS:2	DP:1	MP:1	M/CH:6	FILL:6	UD:v
00	0	0	000110	000000	05 1E 03 84 00

which encodes into the following hexadecimal format that is inserted into the 56-bit MB subfield:

01 08 05 1E 03 84 00

(Note that the ADLP adds additional zero padding to the message to fill the 56-bit MB subfield).

The full encoding of the 112-bit downlink CPDLC message is as follows:

DF:5	FS:3	DR:5	UM:6	AC:13 or ID:13	MB:56 (already in hex)	(AP:24)
1010x	xxx	0001x	01 1000	xxxxxxxxxxxxx	01 08 05 1E 03 84 00	AP:24

2.2.5 Mode-S Interrogation / Reply Scenarios for the LVLASO Demonstration

The following exchanges between the ground interrogator (ATIDS) and the airborne Mode-S transponder / ADLP should be expected in the LVLASO demonstration. Compatibility with the Atlanta SSR interrogator in terms of the Interrogator ID Subfield (IIS) must be ensured.

1) ATIDS may send an All-Call Interrogation, i.e., UF = 11.

   The Mode-S transponder replies with a DF = 11. If a downlink CPDLC message has been received by the ADLP / Mode-S transponder, the transponder sets the CA subfield = 7 (i.e., '111'), indicating that a message is available for downlink.

2) ATIDS sends a UF = 4, 5, 20 or 21 surveillance interrogation. UF = 4 or 5 are used for surveillance interrogations only. UF = 20 or 21 are used if an uplink CPDLC message is included in the surveillance interrogation. For UF = 20 or 21, RR = '00000', DI = '001' (indicating that the SD subfield contains multi-site information, MA contains the uplink CPDLC message using the Short Form MSP Packet, with SD encoded as follows:

   > IIS = '1000' (ATIDS interrogator ID), MBS = '00' (no Comm-B action), MES = '000', LOS = '0' (no lockout of All Calls), RSS = '00', and TMS/LAS = '0000' (single segment message) or '0001' (first segment of two message segments), '0101' (second of two message segments).

   The Mode-S transponder replies with a typical DF = 4 or 5 surveillance reply. If an uplink CPDLC message was included, the ADLP processes the message and transfers the complete message to the NASA I/O network once all segments are received. In the event a downlink CPDLC message has been received by the ADLP / Mode-S transponder from the I/O network, the transponder sets the DR subfield = '00001' or '00011', indicating a request for a downlink (Comm-B) message to the ground interrogator. If no downlink request is needed, DR is set to '00000'.

3) DF = 11 or DF =17 squitters.

   The Mode-S transponder will transmit occasional squitter messages. If a downlink CPDLC message needs to be transmitted, the transponder sets CA = 7 ('111'). The DF = 17 squitter also provides ADS-B position reports for ADS-B surveillance by ATIDS.

When ATIDS receives an indication of an air-initiated Comm-B (CA = 7 in a DF=11 or 17) or a multi-site directed Comm-B request (DR = '00001' or '00011' in a DF = 4, 5, 20 or 21 reply) ATIDS schedules a UF = 4, 5, 20 or 21 with the RR subfield set to '1 0000', and the DI subfield = '001', which requests the transponder to downlink the initial segment of the CPDLC message in the reply.

The Mode-S transponder, upon receiving the UF = 4, 5, 20 or 21 interrogation replies with a DF = 20 or 21 with DR = '00001', IDS (in UM subfield) = '01' and IIS (in UM subfield) = '1000' (which is the ATIDS Interrogator ID). The MB subfield contains the LBS subfield and the Short Form MSP Packet data stored in air-initiated Comm-B register (register 0). LBS = '00' indicates a single downlink message segment.

ATIDS upon receiving the downlink CPDLC message, closes out the downlink message by sending a UF = 4, 5, 20 or 21 with the PC subfield = '100' (cancel Comm-B), RR = '00000' and DI = '000'. Alternately, the interrogator could set PC = '000' (no changes in transponder state), RR = '00000', DI = '001' (indicating that SD subfield contains multi-site information), with SD encoded as follows:

> IIS = '1000' (ATIDS interrogator ID), MBS = '10' (Comm-B Closeout), MES = '000', LOS = '0' (no lockout of All Calls), RSS = '00', and TMS/LAS = '0000'.

Note: Recall that LVLASO downlink messages are only one segment long.

3.0 Mode-S ADLP - I/O Network Interface

This section describes the interface between the Airborne Data Link Processor (ADLP) and the end user CPDLC application located in the Flight Test Computer (via the I/O Network). This interface is denoted as Interface 'D' in Figure 1. The physical interface consists of dedicated uplink and downlink ARINC 429 buses configured in the high-speed mode (100 KHz). The data link layer uses a modified Williamsburg ARINC 429 file transfer protocol to uplink and downlink CPDLC messages. The following sections discuss the uplink and downlink ARINC 429 file transfer protocols, respectively.

3.1 Uplink CPDLC Message Transfer (ADLP to I/O Network)

Upon successfully decoding an uplink CPDLC message, the ADLP builds a message file that is transferred to the I/O Network using ARINC 429 file transfer protocols. Section 3.1.1 describes the ARINC file transfer protocol. Section 3.1.2 describes the encoding of file data. Section 3.1.3 provides an uplink file transfer example.

3.1.1 ARINC 429 File Transfer Protocol

The ARINC file transfer protocol is as follows: The ADLP transmits a Request-To-Send (RTS) ARINC 429 protocol word to prepare the I/O Network for a file transfer. This is followed by a Start of Transmission (STX) word and subsequently by a number of ARINC 429 Data Words. The file transfer concludes with an End-of-Transmission (EOT) word. Specific formats are described below:

<u>RTS Protocol Word</u>

32 31 30 29 28 27 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1

P 1 0 0 0 0 0 1 (Destination Code)(Word Count)(SAL)

<u>SOT Protocol Word</u>

32 31 30 29 28 27 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1

P 1 1 0 (GFI) (File Sequence Number) (LDU Sequence No.) (SAL)

<u>Full Data Word #1</u>

32 31 30 29 28 27 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1

P 0 0 0 (Lo Byte 3) (Byte 2)(Byte 1)(SAL)

<u>Full Data Word #2</u>

32 31 30 29 28 27 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1

P 0 0 0 (Byte 5)(Byte 4) (Hi Byte 3) (SAL)

<u>Partial Data Word #3</u>

32 31 30 29 28 27 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1

P 0 0 1 1 0 1 1 (Byte 7)(Byte 6)(SAL)

<u>EOT Protocol Word</u>

32 31 30 29 28 27 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1

P 1 1 1 0 0 0 x (Checksum)(SAL)

The contents of the fields are defined as follows:

1)	Destination Code	Destination code for the I/O Network = '01001011'.
2)	Word Count	Represents the number of ARINC 429 Words to be transferred following the RTS protocol word. Word Count = STX + # of Data Words + EOT. For the example above the word count = 5.
3)	GFI	General Format Identifier. GFI = '0011' indicating use of general purpose bit-oriented protocol.
4)	File Sequence Number	This number is 0 for the first file sent and is incremented (modulo FF) each time a new file is sent.
5)	LDU Sequence Number	Set to '00000000'. Not used in protocol.
6)	SAL	System Address Label. The SAL for the I/O Network = '104' octal = '00100010' binary (bit 8 - bit 1)
7)	Checksum	Cyclic Redundancy Check of Data Words only in file, not including the label or parity bit.

8) Partial Data Word Encoding (as a function of remaining data nibbles).
Note: Unused data nibbles are zero padded.

```
32 31 30 29 28 27 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1
P  0  0  1  1  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  ( Nibble 1) (   SAL   )
P  0  0  1  1  0  0  1  0  0  0  0  0  0  0  0  ( Nibble 2) ( Nibble 1) (   SAL   )
P  0  0  1  1  0  1  0  0  0  0  0  ( Nibble 3 ) ( Nibble 2) ( Nibble 1) (   SAL   )
P  0  0  1  1  0  1  1  (Nibble 4 ) ( Nibble 3 ) ( Nibble 2) ( Nibble 1) (   SAL   ).
```

3.1.2 Encoding of ARINC 429 File Data (uplink)

No special control information is included in an uplink data file. The data consists solely of D0-219 application messages as defined in [2]. Recall that CPDLC application data is zero padded to integer multiples of 6 bytes since each Mode-S uplink message is limited to 48 bits of CPDLC uplink data at a time. This zero padding is performed by the Controller Interface. (For example: A 4 byte message requires 2 bytes of zero padding; a 9 byte message requires 3 bytes of zero padding and is transmitted using two UF=20 interrogations).

3.1.3 Uplink CPDLC Message Examples

Section 2.1.3 provided two examples of uplink CPDLC messages as they were obtained from the Controller Interface in the form of application data and were then converted to the proper Mode-S uplink interrogations. This sections uses the same two examples to describe the file transfer from the ADLP to the NASA I/O Network.

3.1.3.1 Example of a "Maintain Altitude" Uplink CPDLC Message

From section 2.1.3.1 the uplink interrogation received by the Mode-S/ADLP for a "Maintain Altitude" message is:

A0 01 80 00 06 09 13 05 78 00 00 (and the AP:24 parity/address field).

Upon receiving this message the Mode-S transponder transmits the appropriate XPDR ACK reply to the ATIDS MWS and forwards the uplink message to the ADLP. The ADLP recognizes this as a MSP protocol message using MSP channel = 6 indicating that this is a CPDLC message. The ADLP then formats the received CPDLC application data into an ARINC 429 data file using the modified Williamsburg ARINC 429 file transfer protocol.

The data transferred by the ADLP is as follows:
13 06 09 13 05 78 00 00

Note: The MSP_Type code '13' is only included once at the beginning and the Channel_ID '06' is inserted for each uplink interrogation, i.e., it will occur every 7th byte prior to the actual data). In this example only one interrogation is received and thus only channel_ID (06) occurs only once.

The subsequent ARINC 429 file transfer from the ADLP to the I/O Network is as follows (using hexadecimal representation):

32 … 1	ARINC word bit locations
41 4B 05 22	RTS Protocol Word (with word count = 6, SAL = 22 H (label 104))
63 EA 00 22	STX Protocol Word (GFI = 3, file sequence number arbitrarily selected as EA, LDU sequence number = 00)
0 9 06 13 22	Full Data Word #1 (byte 1 = 13, byte 2 = 06, low byte 3 = 9)
0 05 13 0 22	Full Data Word #2 (hi byte 3 = 0, byte 4 = 13, byte 5 = 05)
0 0 00 78 22	Full Data Word #3 (byte 6 = 78, byte 7 = 00, low byte 8 = 0)
18 00 0 0 22	Partial Data Word #4 (hi byte 8 = 0)
71 57BB 22	EOT Protocol Word (checksum = 57BB)

3.1.3.2 Example of a "Contact ATL Tower 119.5" Uplink CPDLC Message

From section 2.1.3.2 two uplink interrogations are required to transmit the "Contact ATL Tower 119.5" message. The uplink interrogations received by the Mode-S/ADLP are:

Interrogation #1: A0 01 80 01 06 03 75 A0 D4 98 01 (AP:24 must also be appended).

Interrogation #2: A0 01 80 05 06 22 71 00 00 00 00 (AP:24 must also be appended).

Upon receiving each of these messages, the Mode-S transponder transmits the appropriate XPDR ACKs replies to the ATIDS MWS and forwards the uplink message segments to the ADLP. The ADLP recognizes these uplinks as MSP protocol CPDLC message segments (MSP channel = 6). The ADLP then rebuilds the application message and formats it into an ARINC 429 data file.

The data transferred by the ADLP is as follows:

13 06 03 75 A0 D4 98 01 **06** 22 71 00 00 00 00

Note: The MSP_Type code '13' is only included once at the beginning and the Channel_ID '06' is inserted for each uplink interrogation, i.e., it will occur every 7th byte prior to the actual data):

The subsequent ARINC 429 file transfer from the ADLP to the I/O Network is as follows (using hexadecimal representation):

32 1	ARINC word bit locations
41 4B 08 22	RTS Protocol Word (with word count = 8, SAL = 22 H (label 104))
63 EA 00 22	STX Protocol Word (GFI = 3, file sequence number arbitrarily selected as EA, LDU sequence number = 00)
0 3 06 13 22	Full Data Word #1 (byte 1 = 13, byte 2 = 06, low byte 3 = 3)
0 A0 75 0 22	Full Data Word #2 (hi byte 3 = 0, byte 4 = 75, byte 5 = A0)
0 1 98 D4 22	Full Data Word #3 (byte 6 = D4, byte 7 = 98, lo byte 8 = 1)
0 22 06 0 22	Full Data Word #4 (hi byte 8 = 0, byte 9 = 06, byte 10 = 22)
0 0 00 71 22	Full Data Word #5 (byte 11 = 71, byte 12 = 00, lo byte 13 = 0)
0 00 00 0 22	Full Data Word #6 (hi byte 13 = 0, byte 14 = 00, byte 15 = 00)
71 B508 22	EOT Protocol Word (checksum = B508)

3.2 Downlink CPDLC Message Transfer (I/O Network to ADLP)

Upon receiving a downlink CPDLC message from the pilot interface, the Flight Test Computer builds a message file that is transferred via the I/O Network to the ADLP using ARINC 429 file transfer protocols. Section 3.2.1 describes the ARINC file transfer protocol. Section 3.2.2 describes the encoding of file data for downlink CPDLC message transfers. Section 3.2.3 provides an example of a downlink file transfer.

3.2.1 ARINC 429 File Transfer Protocol

The ARINC file transfer protocol for downlink CPDLC messages is the same as for uplink message transfers. The Flight Test Computer transmits a Request-To-Send (RTS) ARINC 429 protocol word via the I/O Network to prepare the ADLP for a file transfer. This is followed by a Start of Transmission (STX) word and subsequently by a number of ARINC 429 Data Words. The file transfer concludes with an End-of-Transmission (EOT) word. Specific formats are described in section 3.1.1.

3.2.2 Encoding of ARINC 429 File Data (downlink)

Unlike the uplink file transfer of a CPDLC message, the downlink CPDLC data file does include some additional control data that precedes the CPDLC application data. The Flight Test Computer (via the I/O Network) includes the following control fields prior to the application data:

MSP_Type	represents a 1-byte value encoded as a hexadecimal 13H or '0001 0011'
Channel_ID	a 1-byte MSP channel ID encoded as a hexadecimal 06H or '0000 0110'
Data_Length	a 1-byte field that indicates the length of the application data in bytes.

This control data is followed by the application data that consists of the D0-219 encoding of downlink CPDLC messages that are listed in [1,2]. CPDLC application data is zero padded to fill the spare bits of any partially filled ARINC 429 data words. This zero padding is performed by the Flight Test Computer.

3.2.3 Downlink CPDLC Message Example

Section 2.2.4 provided an example of a downlink CPDLC message as it was received by the ADLP (from the I/O Network) and subsequently converted to the proper Mode-S downlink reply. This sections uses the same example to describe the file transfer from the NASA I/O Network to the ADLP. The example is a "Descending to 4500 ft" downlink CPDLC message.

The ARINC 429 file transfer from the I/O Network to the ADLP is as follows (using hexadecimal representation):

32 ··· 1	ARINC word bit locations
41 00 05 A2	RTS Protocol Word (with word count = 5, SAL = A2 H (label 105))
63 02 00 A2	STX Protocol Word (GFI = 3, file sequence number arbitrarily selected as 02, LDU sequence number = 00)
0 4 06 13 A2	Full Data Word #1 (byte 1 = 13, byte 2 = 06, low byte 3 = 4)
0 1E 05 0 A2	Full Data Word #2 (hi byte 3 = 0, byte 4 = 05, byte 5 = 1E)
1B 84 03 A2	Partial Data Word #3 (byte 6 = 03, byte 7 = 84)
71 6A66 A2	EOT Protocol Word (checksum = 6A66)

Thus the data transferred is: 13 06 04 05 1E 03 84, where 13, 06, and 04 represent control data (message type, MSP channel, and message length, respectively). 05 1E 03 84 represents the application data of the CPDLC message.

[1] 'Controller Interface to ATIDS - Interface Control Document (Rev. 1.2)", Jim Rankin, St. Cloud St. University, Dec. 4, 1996.

[2] "Controller-Pilot Data Link Communications (CPDLC) Messages (Rev. 4)", Jim Rankin, St. Cloud St. University, Nov. 22, 1996.

[3] "Minimum Operational Performance Standards for the Mode-S Airborne Data Link Processor", RTCA DO-203, June 21, 1993.

Appendix D

Terminal Area Productivity (TAP) Data Link

Description of candidate VHF data link modes

Appendix D

1. VHF Data Link Approaches

This section examines each of the VDL approaches being considered by industry: 1) transition of VDL Mode 1 to VDL Modes 2 and 3, and 2) VDL Mode 4. Since each of these approaches provides a compatible sub-network interface to the overall ATN, it is only necessary to discuss the lower sub-network layers for each of these approaches. Capabilities and potential shortcomings of the sub-network "lower layers" for these approaches are identified in terms of meeting the data link application requirements discussed in the Section 3.3 of Volume I. Where applicable, VHF Specific Service (VSS) are identified that bypass the ATN to provide local, low-latency communication services.

Discussion of this section allows data link applications to be allocated to respective data links (Section 3.4 of Volume I).

2. VHF Data Link Sub-Network Layers

The aeronautical data link architecture utilizes a number of sub-networks (e.g., HF, VHF, SATCOM, and Mode-S) that are combined into the ATN using the 7-layer OSI stack. For all of these sub-networks, a common interface is developed at the sub-network layer using the ISO-8208 protocol. Figure D-1 illustrates the VHF data link sub-network architecture. The upper layers, which are common to all aeronautical data link communications are not shown and are not discussed here.

From Figure D-1, three distinct layers of the OSI model are indicated; the physical layer, data link layer, and network layer. The network layer is shown in more detail consisting of three sublayers, 1) the lower portion of the network layer is the ISO-8208 protocol that is common to all ATN data link, 2) the portion of the network layer that is dependent on the type of sub-network layer (in this case the ISO-8208), also called the sub-network dependent convergence facility (SNDCF), and 3) the sub-network interface to the internetwork router, which is independent of the type of sub-network.

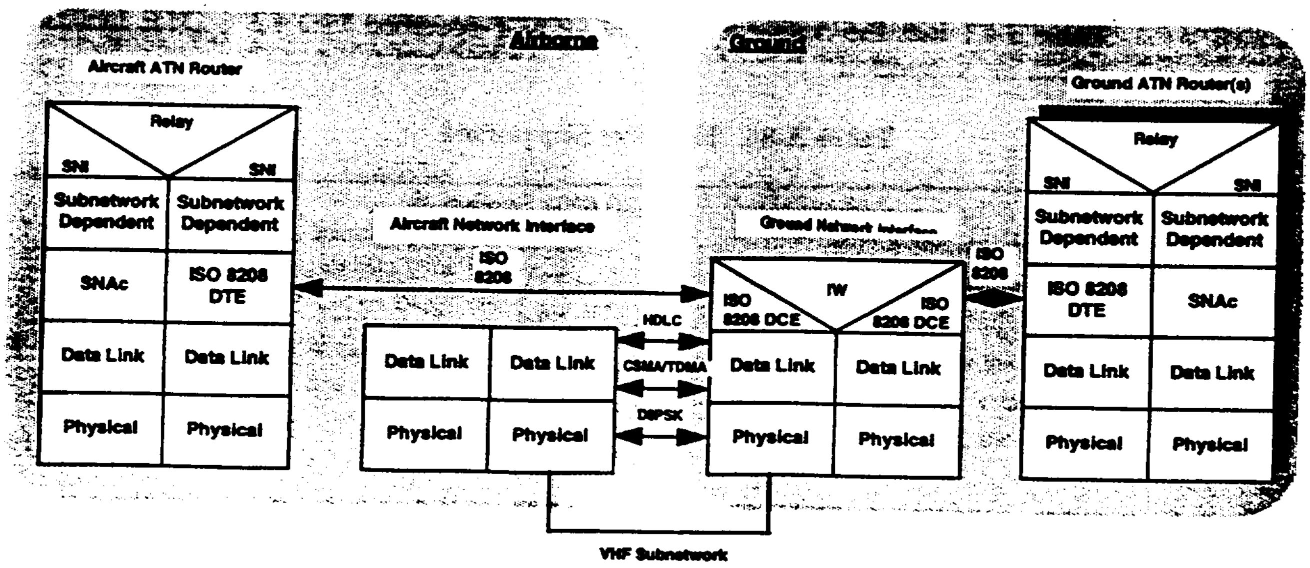


Figure D-1 VHF Data Link Sub-Network Architecture

In Figure D-1 the ground and aircraft ATN routers connect to the various aeronautical data link end-user applications via the upper layers (not shown). Data link messages from ground applications from the ATN are sent through the OSI layer to the ground network interface (GNI), which then uses the VHF sub-network to uplink the application message to the aircraft network interface (ANI) via the VHF radio frequency link, i.e., the physical layer. Once received by the aircraft, the message is sent to the aircraft ATN router, which then sends the message upward through the OSI stack to the end-user application. The purpose of each of the layers of the VDL sub-network, as illustrated in Figure D-2, is briefly described in the next paragraphs.

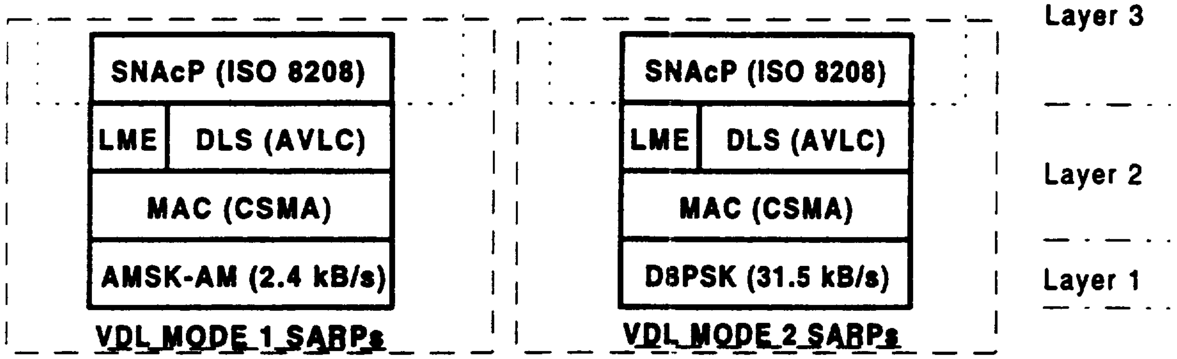


Figure D-2 VDL Sub-Network Layers (VDL Mode 1 and 2)

2.1 Physical Layer

The role of the physical layer in the ATN is to provides the radio frequency (RF) signal-in-space to transmit and receive data link messages physically between ground and airborne radios. For Figure D-2, the physical layer for VDL Mode 1 is 2,400 bps AMSK sent via the AM VHF Comm transceiver. VDL Mode 2 is also shown which uses 31.5 kbps D8PSK. VDL modulation waveform candidates and performance considerations are discussed later in Section 3.

In addition to providing the RF signal-in-space connection, the physical layer also provides transceiver frequency control and provides a notification service to the lower layer of the data link layer (i.e., the MAC layer) regarding channel access and status on received messages.

2.2 Data Link Layer

The data link layer as shown in Figure D-2 is split into two sublayers, the media access control (MAC) and data link service (DLS) sublayers, and also contains the a management function referred to as the Link Management Entity (LME).

The MAC sublayer provides access to the physical layer using channel access protocols. For VDL Modes 1 and 2, the channel access protocol is Carrier Sense Multiple Access (CSMA). VDL Modes 3 and 4 both use forms of Time Division Multiple Access (TDMA), although the actual time slot structure is different for each mode.

CSMA is a simple channel access protocol but has a relatively low channel access efficiency on the order of ~18 %. TDMA provides as high as 80 % to 100 % channel access, but is more complex due to the need for precise slot timing among all users.

The DLS sublayer is composed of the Aviation VHF Link Control (AVLC) derived from the High Level Data Link Control (HDLC) protocol (ISO 3309). The DLS functions are frame exchanges, frame processing and error detection. The LME is responsible for link establishment between peer DLS entities.

2.3 Network Layer

The lowest layer of the network layer (Figure D-2) is the sub-network access protocol (SNAcP) layer, which uses the ISO 8208 protocol. It provides packet exchanges over a virtual circuit, error recovery, connection flow control, packet fragmentation, and subnetwork connection management functions. The internetwork sublayer provides the conversion from the IS0 8208 sublayer using the sub-network dependent convergence facility (SNDCF) and provides the interface to the transport layer.

3. VDL Physical Layer - Modulation Waveform Candidates

Signal Waveform Selection Issues for Aeronautical VHF Data Link

Selection of the appropriate data link modulation waveform is dependent upon the fundamental constraints of transmit power, available spectrum bandwidth and the desired data link capacity (signalling rate) in providing an accepted level of quality of service (bit error rate). Other factors that influence the design of the modulation waveform are performance of the data link in the presence of channel impairments such as noise, fading and interference. Cost of providing the needed data link capability/technology is of course also a factor.

Given the constraints of current VHF Comm channel spacing and transmit power (25 KHz and ~ 20 Watts, respectively) and the desire to provide as much channel capacity as possible, the following observations are made:

1) 20 Watts of transmit power is more than enough to provide for reliable line-of-sight communications, i.e., sufficient E_b/N_0 and S/N can be provided in the presence of expected path losses and attainable receiver noise figures.
2) Available data link capacity is constrained by the available (25 KHz) bandwidth of VHF channels.

Since data link capacity is expected to be at a premium for future CNS/ATM data link, the aeronautical VHF data link channel is "bandwidth-limited" rather than "power-limited".

Since we have a "bandwidth-limited" communication channel it is expected that the most effective signaling waveform will be from the family of spectrally-efficient, m-ary Phase-Shift-Keying (PSK) modulations. These waveforms provide a high bits-per-second (bps) per unit bandwidth (Hz) data rate capability. This high bps/Hz comes at the expense of requiring additional signal power, which is readily available in the VHF band. Conversely, it would be expected that m-ary Frequency-Shift-Keying (FSK) modulation for large values of m are unsuitable since they are intended primarily for power-limited channels and are spectrally inefficient, i.e., provide low bps/Hz ratios. Thus it is not surprising that D8PSK and GMSK were selected by the industry as suitable candidate waveforms

3.1 D8PSK Modulation

31.5 kbps D8PSK was selected to provide high data rate for future CNS/ATM data link and to provide the capability of four digital voice subchannels for VDL Mode 3.

In order to achieve the high data rate of 31.5 kbps within the available 25 KHz channel, PSK modulation using an 8-ary signal constellation was required. Raised-cosine filtering of the signal waveform provides low sidelobes of the channel spectrum to mitigate effects of adjacent channel interference. Figure D-3 shows spectra of the D8PSK waveform as a function of the length of the raised cosine filter [5]. For a duration of t = +/- 2.5 symbol periods or longer, sidelobe levels approach -70 dB at 25 KHz from the center of the channel (this occurs at FT= ~2.4, where F is the frequency offset and T is symbol period of 1/10,500 symbols/sec).

Differential signalling was selected in order to a) increase the robustness of the signal to the ill effects of multipath fading, b) maintain the efficiency of the signal waveform by minimizing the length of preambles and training sequences that would otherwise be needed when using coherent detection, and c) to simplify the design of the demodulator.

While having a relatively constant envelope, the D8PSK waveform requires that a linear power amplifier be employed to maintain low sidelobe levels provided by the raised cosine filter.

In order to achieve a bit error rate (BER) of 10^{-3}, the spectrally efficient data communications provided by D8PSK (i.e., 31.5 kbps/25 KHz = 1.26 bps/Hz) requires an Eb/No of 12.9 dB.

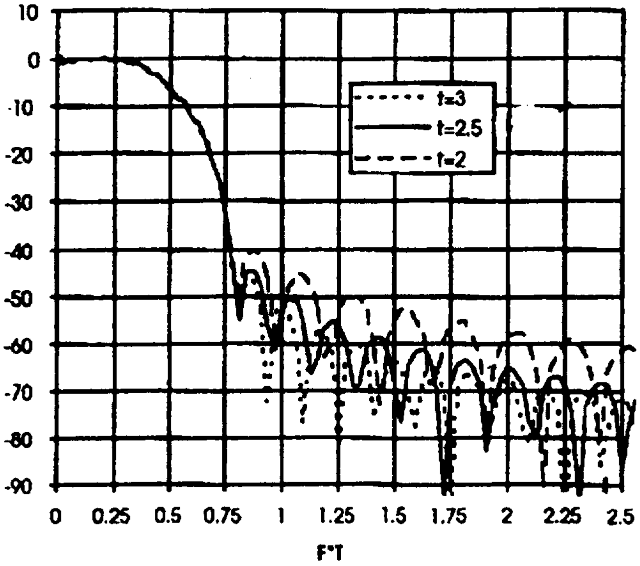


Figure D-3 D8PSK Power Spectra (with Nyquist Truncation)

3.2 GMSK / GFSK Modulation

In addressing future CNS/ATM data link applications such as ADS-B, ATC two-way data link, and GNSS corrections data link, Sweden has developed a data link modulation based on the Gaussian Minimum Shift Keying (GMSK)/ Frequency Shift Keying (GFSK) waveform. As indicated previously, initial work focused on GMSK modulation using a 9600 bps data rate over a 25 KHz channel bandwidth. This was upgraded to 19.2 kbps for increased data link capacity. The waveform is intended to support the VDL Mode 4 data link. VDL Mode 4 is discussed in Section 4.3.3).

The GMSK waveform has a number of desirable features:

1) GMSK is a spectrally-efficient, robust modulation, providing low sidelobe levels needed for mitigating adjacent channel interference. Low sidelobe levels are attained versus pure MSK modulation by using a Gaussian pre-filter in the modulation process. Figure D-4 shows power spectra of GMSK as a function of B_bT, where B_b is the pre-filter bandwidth, and T is the signaling period [6]. For 9600 bps in a 25 KHz channel the normalized frequency $((f - f_c)/T) = 2.6$ and sidelobe levels drop off rapidly for B_bT of 0.7 or less. For 19200 bps in a 25 KHz channel the normalized frequency $((f - f_c)/T) = 2.6$ and a B_bT of 0.16 to 0.2 is required for low sidelobe levels.

2) Like MSK, GMSK is a constant envelope signal and does not require a linear power amplifier, thus providing somewhat lower implementation cost.

3) GMSK is used by the European GSM digital telephone system, providing access to readily available technology for its implementation and an established experience base with the waveform. GSM utilizes a B_bT of 0.3 for sidelobe management.

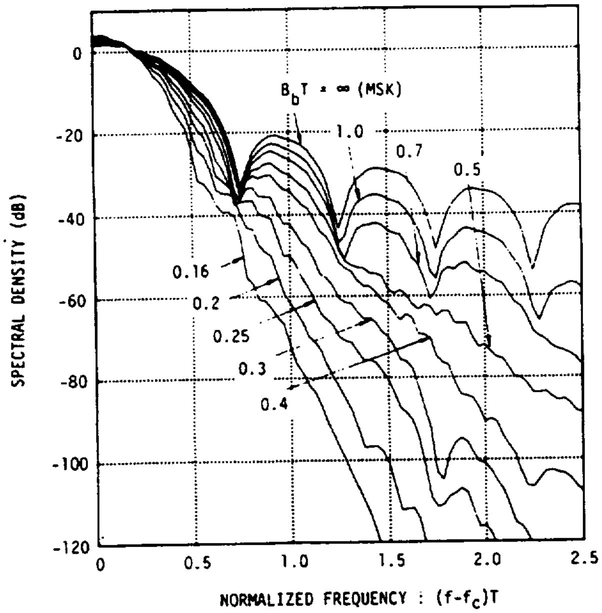


Figure D-4 Power Spectra of GMSK

GMSK is a robust, spectrally efficient modulation that was selected for GSM. GMSK is also a very interesting waveform since it can be viewed from a number of perspectives:

1) GMSK can be viewed as a member of the m-ary PSK modulation waveforms with m=4. Demodulation is either coherent or differentially coherent (if data is encoded differentially).

2) GMSK can also be viewed as m-ary FSK modulation with m=2 (thus the reference as GMSK/GFSK). FSK can be detected either coherently or non-coherently.

The actual implementation approach followed by GMSK/GFSK is significant since it effects the E_b/N_0 needed to achieve a specific bit error rate (BER). For a BER of 10^{-3}, the following E_b/N_0 ratios are required:

1) $E_b/N_0 = 6.8$ dB if GMSK is demodulated coherently using ideal matched filter detection.
2) $E_b/N_0 = 9.8$ dB is needed if the waveform is demodulated as coherent GFSK.
3) $E_b/N_0 = \sim 9.3$ dB is needed if the waveform is demodulated as differential-coherent GMSK, where the data is differentially encoded prior to transmission.

The above E_b/N_0 ratios are computed for ideal signal detection and represent the best attainable performance. Clearly, the selected demodulation approach greatly effects the achievable E_b/N_0.

An additional consideration in determining E_b/N_0 for GMSK is the effect of the Gaussian pre-filter. While ideal MSK ($B_bT = \infty$, i.e., no pre-filter) achieves the E_b/N_0 computed above, the effect of any prefiltering begins to degrade the E_b/N_0. Figure D-5 shows the adjacent channel interference of GMSK as a function of B_bT [6]. In order to achieve -60 dB of rejection for 25KHz channel spacings (f_s/T = 25KHz/19.2 kbps = 1.3), B_bT must be between 0.16 and 0.2. This represents significant bandlimiting of the signal in order to fit the 19.2 kbps data rate into the 25 KHz channel. As shown in Figure D-6, the degradation to E_b/N_0 for GMSK as a function of B_bT requires an additional 1 to 2 dB of E_b/N_0 [6].

To avoid excessive intersymbol interference for low B_bT (0.12 to 0.2), the 19.2 kbps GMSK waveform was modified to use a $B_bT = 0.3$ and used a lower modulation index to provide the necessary bandlimiting (i.e., the GMSK modulation index, $h = 0.5$ was reduced to $h = 0.25$). The waveform can no longer be considered GMSK and is instead GFSK.

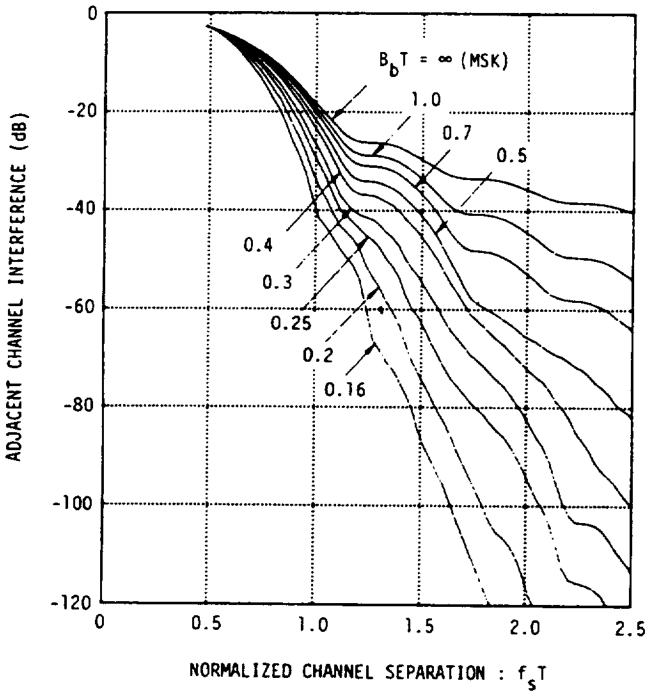


Figure D-5 Adjacent Channel Interference of GMSK

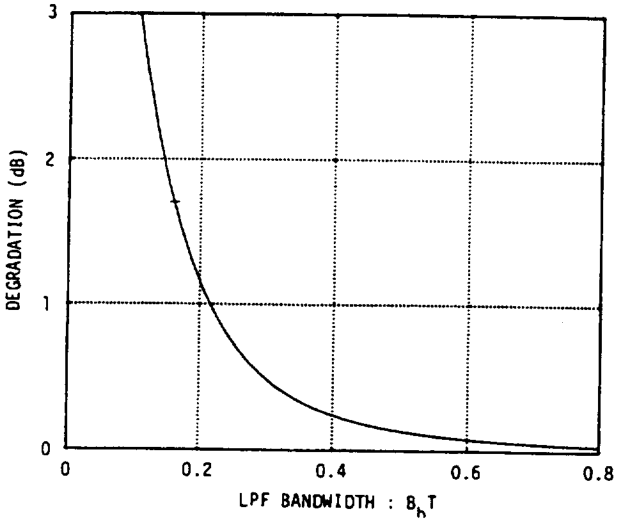


Figure D-6 Theoretical Eb/No Degradation of GMSK

3.3 Comparison of D8PSK (31.5 kbps) and GMSK/GFSK (19.2 kbps) (in Terms of E_b/N_o, S/N and D/U)

With the above background information on the two modulation candidates, this section provides a relative performance comparison of D8PSK and GMSK/GFSK. Table D-1 summarizes the E_b/N_o, S/N and D/U performance of these waveforms. A BER of 10^{-3} is assumed.

	Bit Error Rate = 1 E-3		
Waveform	E_b/N_o [1]	S/N = (E_b/N_o) * R/W [2]	D/U [3]
D8PSK at 31.5 kbps	12.9 dB	17.7 dB (12.9 + 4.8)	23 dB (16 dB + 7 dB fade margin)
GMSK/GFSK at 19.2 kbps			
- as coherent PSK	7.8 to 8.8 dB (6.8 dB + 1 to 2 dB due to B_bT)	10.8 to 11.8 dB (7.8/8.8 + 3)	14 dB (7 dB + 7 dB fade margin)
- as coherent FSK	10.8 to 11.8 dB (9.8 dB + 1 to 2 dB due to B_bT)	13.8 to 14.8 dB (10.8/11.8 + 3)	14 dB (7 dB + 7 dB fade margin)
- as differentially coherent PSK	10.3 to 11.3 dB (9.3 dB + 1 to 2 dB due to B_bT)	13.3 to 14.3 dB (10.3/11.3 + 3)	14 dB (7 dB + 7 dB fade margin)

Table D-1 Comparison of D8PSK and GMSK/GFSK in Terms of E_b/N_o, S/N and D/U

[1] Data link system performance is typically compared in terms of E_b/N_o. While GMSK/GFSK demodulated as coherent PSK has an advantage in terms of E_b/N_o, this demodulation approach is not as robust as GMSK/GFSK using coherent FSK or differential PSK. Coherent PSK demodulation requires accurate phase tracking and likely will require lengthy training and synchronization sequences to achieve phase coherence. Coherent PSK is also more vulnerable to channel impairments and self-interference (D/U) during initial signal acquisition. The more likely method for GMSK/GFSK demodulation is either as coherent FSK or differentially coherent PSK. When compared to D8PSK, the performance difference between GMSK/GFSK for coherent FSK or differentially coherent PSK demodulation is 1 to 2.5 dB. This 1 to 2.5 dB is the price paid for the higher channel data rate for D8PSK.

[2] Signal to Noise ratios (S/N) are computed using the appropriate R/W ratios for each waveform. For D8PSK, R = 31.5 kbps and W = 10.5 KHz as the matched filter detection bandwidth. For GMSK/GFSK, R = 19.2 kbps and W = 9.6 KHz as the matched filter detection bandwidth.

Typically, the S/N ratio is not used for one-on-one comparison of modulation waveforms since it includes the data rate, R, and thus no longer provides an apples-to-apples comparison. The S/N ratio is important in terms of determining that a sufficient amount of signal power is available to achieve the desired signal rate.

[3] D/U represents the 'Desired versus Undesired' signal ratio that can be tolerated in meeting the specified BER. It is an important parameter of the robustness of a waveform to self-interference and affects frequency reuse. From Table D-1, D8PSK is clearly not as robust as GMSK/GFSK when it comes to D/U. The impact of D/U on frequency reuse is discussed in Section 3.5.

Based on the assumption that GMSK/GFSK will use demodulation other than coherent PSK demodulation, Table D-1indicates that there is only a 1 to 2.5 dB difference between the D8PSK and GMSK/GFSK waveforms in terms of E_b/N_0. There is a considerable difference between D/U for D8PSK versus GMSK/GFSK with GMSK being more robust. This is the unavoidable price of trying to achieve a higher data rate using D8PSK.

3.4 GMSK Demodulation Performance

To gain a better understanding of GMSK/GFSK performance beyond the theoretical results just stated, several demodulation approaches were evaluated based on published papers. Figures D-7, D-8 and D-9 show typical demodulators for coherent orthogonal detection, differentially coherent detection, and non-coherent limiter discriminator detection of GMSK.

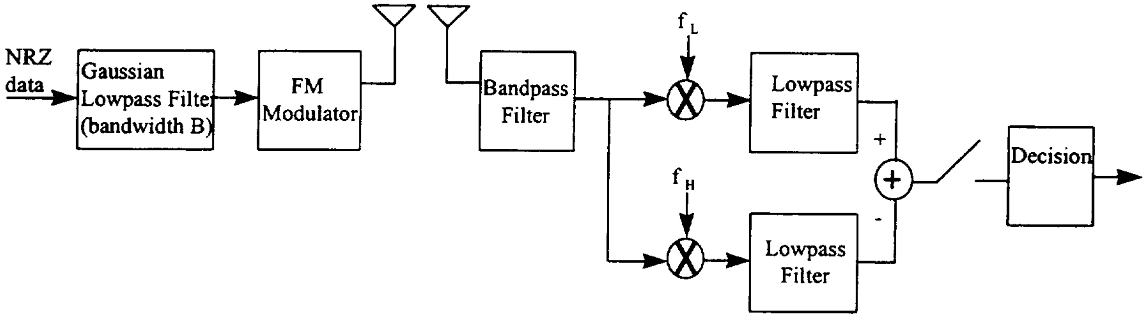


Figure D-7 **Coherent orthogonal GMSK detection**

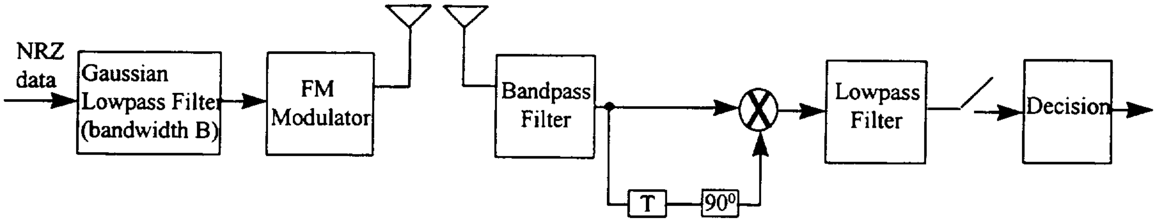


Figure D-8 **Differentially coherent GMSK detection**

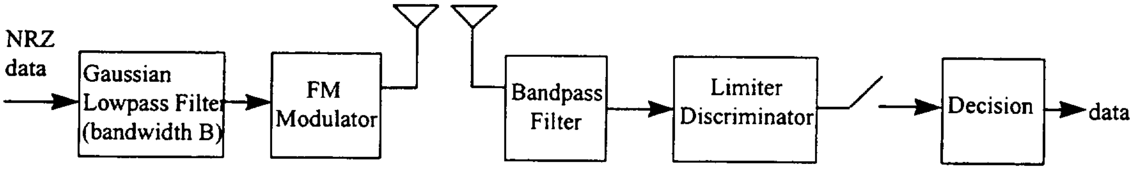


Figure D-9 **Noncoherent limiter discriminator GMSK detection**

The most promising detectors for GMSK are the differentially coherent detector and the noncoherent limiter discriminator detector. Coherent orthogonal detection requires phase coherence of both the high and low frequency tones, which is difficult for burst type communications such as VDL Mode 4. Since the proposed 19.2 kbps GFSK waveform is no longer MSK in nature, orthogonal detection is no longer possible. In addition, it is not evident whether differential coherent detection can be applied to GFSK since it is no longer MSK in nature and no longer exhibits +/- 90 degree phase shifts between bit intervals (perhaps frequency doubling to recreate the +/- 90 degree phase shifts may still allow use of differential detection).

Performance Results for Differentially-Coherent Detection of GMSK

The performance of various differentially coherent detectors for GMSK is described in [7]. Using the conventional differential detector shown in Figure D-8, the required E_b/N_0 increases to ~ 18 dB for GMSK with BT = 0.3 (~9 to10 dB worse than for a coherent detector). By using decision feedback, much of the degradation is recovered. Figure D-10 provides performance curves for 1-bit differential detectors with and without decision feedback for BT = 0.3 and 0.25.

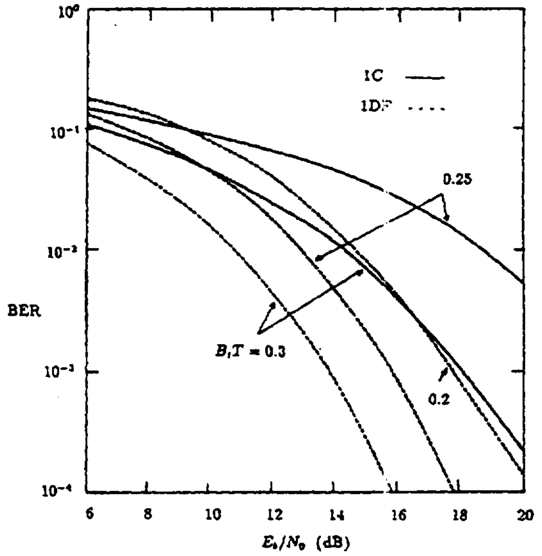


Figure D-10 BER performance of one-bit differential detectors [7]
(1C for conventional detector, 1DF using decision feedback)

Additional improvements can be gained by using two-bit differential detectors. Figure D-11 provides performance curves for conventional 2-bit differential detectors with Gaussian predetection filters (2CG), Butterworth predetection filters (2CBW) and a combination of one and two-bit differential detectors using decision feedback (1+2DF) for BT = 0.3 and 0.25. Figure D-12 summarizes performance curves for a range of 1 and 2-bit differential detectors, with and without decision feedback for BT = 0.25. Also shown is the performance curve for coherent detection.

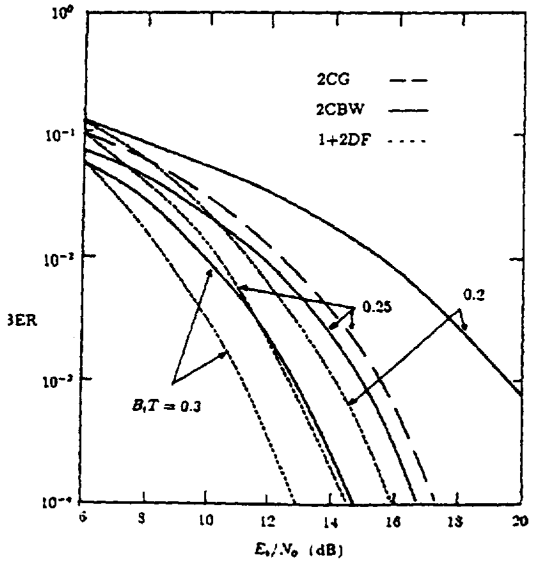


Figure D-11 BER performance of two-bit differential detectors [7]
(2C for a conventional, 1+2DF using combined one and two-bit decision feedback)

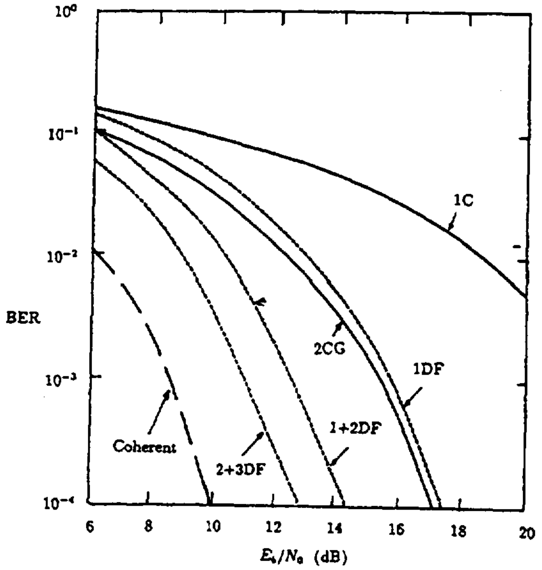


Figure D-12 BER performance of various differential GMSK receivers (BT = 0.25) [7]

From Figure D-12 it is evident that differential detection results in considerable E_b/N_0 degradation of 6 - 8 dB relative to coherent detection at a BER of 10^{-3}, unless decision feedback and more complex, combined feedback circuits are used to reduce intersymbol interference effects. By using a two stage, 2 and 3-bit differential detector (2+3DF), ~4 dB of performance are recovered, bringing it within ~3 dB of coherent demodulation.

It is not clear how a differentially coherent type of demodulator can be used for GFSK unless some type of frequency doubling is used to regenerate the +/- 90 degree phase shifts between successive bit intervals as is the case for GMSK.

Performance Results of Noncoherent Limiter Discriminator Detection of GMSK/GFSK

The noncoherent limiter discriminator, shown in Figure D-9, is a simple and low-cost detector that has been used in earlier prototype 9.6 kbps GMSK aeronautical data links. Figure D-13 [8] illustrates performance of such a detector for BT = 0.25, where $K = \infty$ represents the curve of interest ($K = \infty$ represents a non-fading environment; $F_D = 0$ indicates no Doppler present). Without decision feedback, ~16 dB of E_b/N_0 is needed for the limiter discriminator detector for a BER of 10^{-3}. With decision feedback, E_b/N_0 reduces to ~12 dB.

It is also suggested in [9] that intersymbol effects due to Gaussian premodulation filtering are reduced by using Viterbi decoding with the limiter discriminator detector. Figure D-14 illustrates the additional 2 - 4 dB improvement that can be gained using Viterbi decoding with the limiter discriminator, bringing it within the performance of the coherent detector. Viterbi decoding can also provide performance benefits for the differential decoder discussed earlier.

Summary on GMSK/GFSK Demodulation

The most likely demodulation algorithms used for GMSK/GFSK VDL Mode 4 are the differentially coherent detector and the non-coherent limiter discriminator detector. By themselves, these detectors experience considerable degradation in the required E_b/N_0 ratio, in the vicinity of 16 - 18 dB for a BER of 10^{-3} and BT = 0.3. However, by using decision feedback equalizers or Viterbi decoding in conjunction with these detectors, much of the degradation can be eliminated. Thus, these demodulators are no longer as simple as the basic limiter discriminator; their implementation complexity is TBD. Use of the differential detector for 19.2 kbps GFSK may not be possible unless frequency doubling is used to regenerate the +/- 90 degree phase shifts between bit intervals.

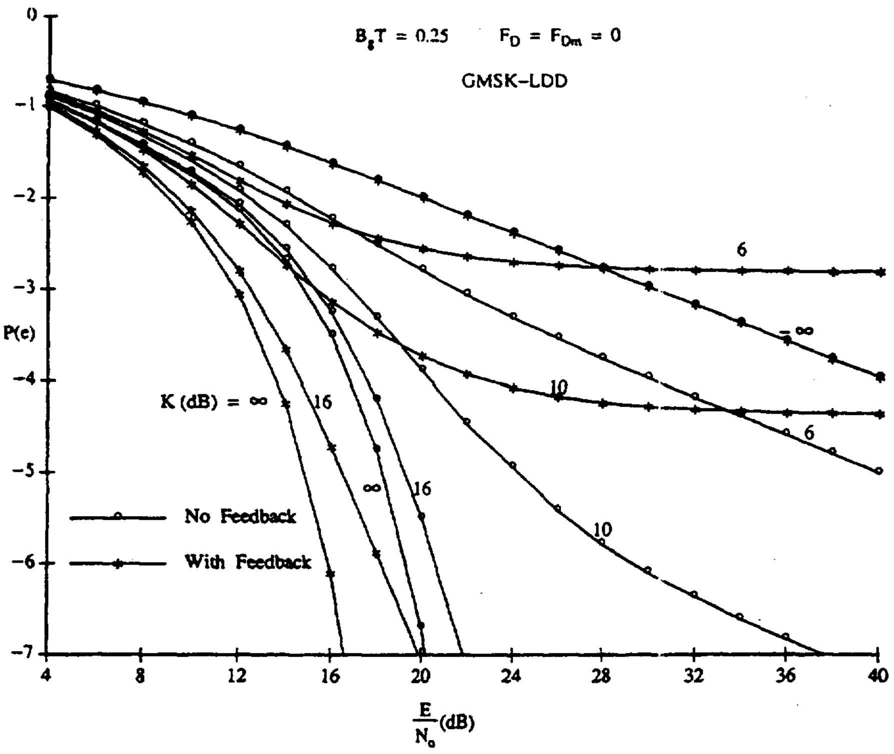
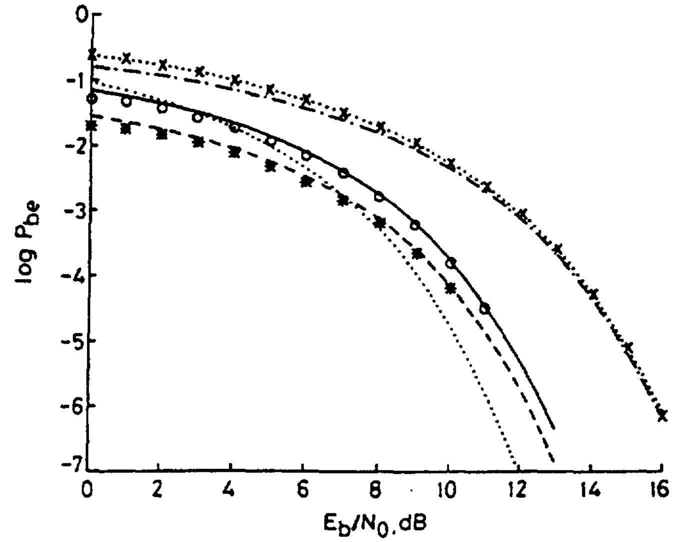


Figure D-13 BER performance of non-coherent limiter detection of GMSK (BT = 0.25) [8]



______ Limiter discriminator detection (LDD) with VD, L' = 1 Gaussian approx.

--------- LDD with VD, L' = 2 Gaussian approx.

._._._._._. LDD with decision feedback (FB), Gaussian approx.

······x····· LDD with FB, actual

··············· Coherent optimal receiver

o LDD with VD, L' = 1, simulated

* LDD with VD, L' = 2, simulated

Figure D-14 BER performance of non-coherent limiter detection of GMSK (BT = 0.25) with decision feedback (FB) and/or Viterbi decoding (VD) [9]

Throughout all of this discussion, it is not clear what the effect of BT = 0.3 and using a modulation index of h = 0.25 has on the D/U performance of 19.2 kbps GFSK. Additional simulation analysis is required to determine expected D/U performance for these detectors.

3.5 VHF Frequency Engineering for VHF Aeronautical Data Link

This section examines the frequency reuse distance as it relates to VHF aeronautical data link.

Co-channel D/U

Figure D-15 illustrates the cylindrical coverage models that are typically used in determining the frequency reuse distance for co-channel D/U ratios. Figure D-15a illustrates the model for two-way data link, while Figure D-15b illustrates the model for ground broadcast stations. In both cases, an aircraft is shown at the edge of the coverage volume at a range of d_D and is subjected to unintended co-channel interference by another aircraft in the case of Figure D-15a, or another ground station in the case of Figure D-15b. In either case, this unintended distance is d_U. The D/U (dB) ratio is related to range as 20 log (d_U / d_D). Assuming that radio line of sight (RLOS) is not encountered first, the facility separation distance for frequency reuse is thus the sum of the distances as follows: 1) for two-way data link facilities this distance is equal to ~ $d_{D(A)}$ + d_U (own aircraft to interfering aircraft) + $d_{D(B)}$., and 2) for ground broadcast facilities the reuse distance ~ d_D + d_U. If this distance exceeds RLOS, then the interference distance, d_U becomes equal to RLOS.

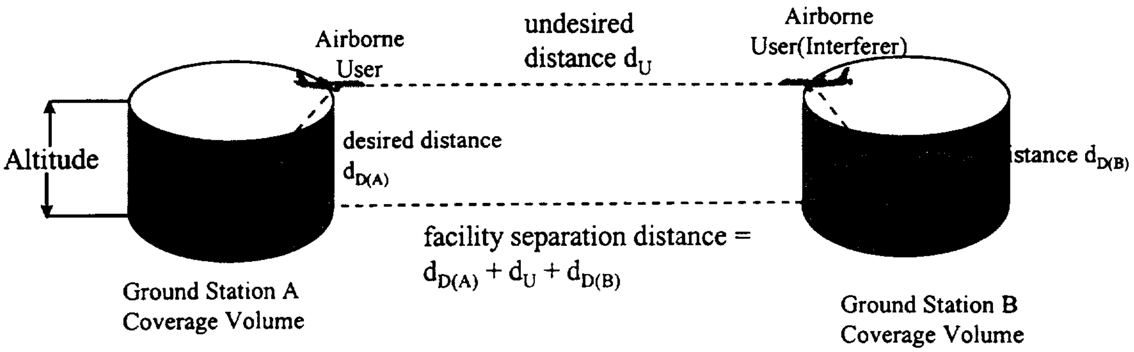


Figure D-15a Facility Separation for Two-Way Data Link Communications

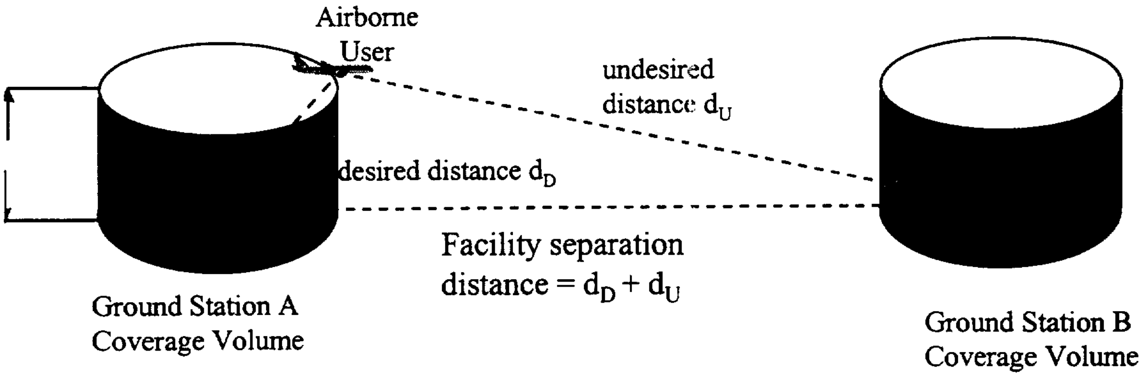


Figure D-15b Facility Separation for Ground Broadcast Data Link Communications

Table D-2 summarizes the frequency reuse distance calculation for a number of aeronautical data link services as a function of D/U. The service radii of both ground facilities are assumed to be equal. D/U ratios of 14 dB and 20 dB are currently used in making frequency reuse assignments for conventional aeronautical VHF voice communications in the USA and by ICAO, respectively. Previously, D/Us used for D8PSK were 23 dB (16 dB + 7 dB margin) and for GFSK 14 dB (7 dB + 7 dB margin). The 7 dB margin represents additional allocation to D/U, beyond what is provided by the actual modulation waveform. This margin includes fading effects, any imbalances in transmitter gains, transmit and receive antenna gains, etc.. As will be seen, the actual margin used can greatly effect the frequency reuse distance.

Table D-2 uses 14, 18 , 20 and 23 dB to calculate the expected frequency separation needed in making frequency reuse calculations.

Note 1: Radio line of sight (RLOS) calculations are based on 4/3 earth radius radio coverage. For two elevated sites the RLOS (nmi) = 1.23 (sqrt (h1) + sqrt (h2)). A 100 ft antenna height is assumed for ground broadcast stations. For two-way data link, h1 and h2 are the heights associated with the two aircraft, e.g., h1 = h2 = 45,000 ft for high altitude enroute areas, and RLOS is ~522 nmi.

Note 2: Frequency reuse distance is computed as follows (refer to Figure D-15):

a) Two-way data link reuse distance = $d_{D(A)} + \min(10^{(D/U)/20} * d_{D(A)}, \text{RLOS}) + d_{D(B)}$, for ground stations A and B.

b) Ground broadcast stations reuse distance = $d_D + \min(10^{(D/U)/20} * d_D, \text{RLOS})$

In Table D-2, the columns of interest are D/U = 14 dB and D/U = 23 dB, which represent GFSK and D8PSK, respectively. The frequency reuse distance can be used to compute data link capacity as bits-per-second per unit area (bps/nmi^2. Table D-3 lists the data link capacities for the various VHF aeronautical data link applications.

From Table D-2, it is observed that low D/U ratios provide frequency reuse advantages for data link applications with relatively high altitude but relatively short range coverage regions due to the relatively large RLOS, e.g., terminal area Local Controller communications (refer to Tables D-2 and D-3). Conversely, there is no benefit of having low D/U ratios (at least D/Us of 14 dB) for 1) long range communications regions, since RLOS becomes the limiting interference range, and for 2) relatively low altitude coverage regions with moderate communications ranges, which provide low RLOS. High altitude (45,000 ft) enroute two-way data link (Table D-2) is an example where RLOS limits the interference region for all D/Us greater than 14 dB.

Clearly, the D/U margin that is required to ensure high-integrity data link performance (in addition to the D/U associated with the modulation waveform) has a significant effect on whether any frequency reuse benefits can be gained. With the exception of terminal area Local Controller two-way data link, most other aeronautical VHF data link applications show little or no frequency reuse advantage for D/Us ≥ 18 dB.

Adjacent Channel Performance

The first adjacent channel is the most difficult off-channel interference requirement for both D8PSK and GFSK modulations. Typical VHF Comm receivers are capable of attenuating adjacent channel signals by ~60 dB. This level of performance is also expected for D8PSK and GFSK data link receivers. The 60 dB adjacent channel attenuation is allocated to D/U, with the remainder being available for "near-far" protection. Typical VHF Comm receivers use a D/U of 14 dB, thus leaving 46 dB of "near-far" protection. For a 150 nmi service volume (i.e., "far" transmitter) the interfering transmitter (i.e., "near" transmitter) can be as close as 0.75 nmi from the receiver. Thus for VHF Comm the adjacent channel interferer (usually another airborne aircraft) can be very close to the receiver without causing any degradation. Thus VHF Comm service volumes on adjacent channels can be assigned to reach within 0.75 nmi (see Figure D-16). This greatly facilitates frequency reassignment.

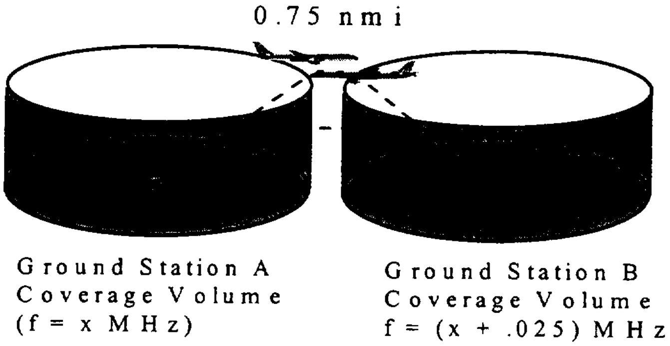


Figure D-16 **Adjacent channel coverage region assignment (two-way data link)**

Facility Type	Service Radius (nmi)	Radio Line of Sight (nmi)	Undesired Distance (nmi) (refer to Figure D-15) - ac to ac for two-way data link - ground to ac broadcast (e.g., DGPS)				Frequency Reuse Distance (nmi)			
			D/U				D/U			
			14 dB	18 dB	20 dB	23 dB	14 dB	18 dB	20 dB	23 dB
Enroute two-way data link (45,000 ft altitude)	150	522	522*	522*	522*	522*	822	822	822	822
Enroute two-way data link (25,000 ft altitude)	60	389	300	389*	389*	389*	420	509	509	509
Terminal area Local Controller (25,000 ft altitude)	30	389	150	240	300	389*	210	300	360	449
NABS-V (20,000 ft altitude)	20	186	100	160	186*	186*	120	180	206	206
NABS-V (20,000 ft altitude)	30	186	150	186*	186*	186*	180	216	216	216
Weather (AWOS/ASOS) (10,000 ft altitude)	25	135	125	135*	135*	135*	150	160	160	160
Departure ATIS (100')	5	25	25*	25*	25*	25*	35	35	35	35

*RLOS is limit on undesired range

Table D-2 Frequency reuse distance as a function of D/U for various aeronautical data link communications services (two-way and broadcast)

Facility Type	GFSK Frequency Reuse Distance (D/U = 14 dB)	D8PSK Frequency Reuse Distance (D/U ≥ 23 dB)	Relative Data Link Capacity (bps/nmi^2) D8PSK/GFSK
Enroute two-way data link (45,000 ft altitude)	822	822	1.64 (e.g., 31500/19200)
Enroute two-way data link (25,000 ft altitude)	420	509	1.12
Terminal area Local Controller (25,000 ft altitude)	210	449	0.36
NABS-V (20,000 ft altitude) 20 nmi service radius	120	206	0.56
NABS-V (20,000 ft altitude) 30 nmi service radius	180	216	1.14
Weather (AWOS/ASOS) (10,000 ft altitude)	150	160	1.44
Departure ATIS (100')	35	35	1.64

Table D-3 Relative Data Link Capacities of D8PSK versus GFSK for Various Data Link Applications

4. Description of VHF Data Link Modes

This section provides an overview of each of the VHF data link modes currently being developed for future CNS/ATM data link applications. The expected benefits and potential shortcomings of each approach are identified.

VDL Modes 2 and 3 have been under development in RTCA SC-172 and the ICAO AMCP for ATC/ATS data link applications for about 4 years. VDL Mode 4 is receiving more recent consideration for ADS-B and is also capable of providing ATC/ATS services.

4.1 VDL Mode 2

VDL Mode 2 is intended to serve as an air-ground data link and is capable of both two-way, addressed communications and can also provide broadcast services. VDL Mode 2 sub-network layers are described below.

4.1.1 Physical Layer

The VDL Mode 2 physical layer uses 31.5 kbps D8PSK modulation using raised cosine filtering ($\alpha = 0.6$) for spectral shaping to maintain the signal within the 25 KHz channel, with low sidelobes on the adjacent channel. The VDL Mode 2 RF pulse consists of the following:

1) Transmitter power stabilization sequence - this interval allows the transmitter to ramp up its RF power and to provide a stable signal to allow the receiver to establish an Automatic Gain Control Setting (AGC) in preparation for acquiring message synchronization. The transmission sequence consists of four '000' symbols
2) Synchronization and ambiguity sequence - a 16 symbol (48 bits) unique word synchronization sequence is used to acquire precise message synchronization to allow data demodulation.
3) Message header - the header consists of a 17-bit message length word and 3 reserved bits, yielding 20-bits of header. The 17-bit message length word indicates the number of data bits that follow the header. A (25,20) block code for error correction yields an additional 5 bits of coding. The 25-bit header is appended with 2-bits to yield a nine symbol header.
4) Data sequence - the maximum length data message that can be transmitted in a single RF pulse is 255-bytes. The data sequence uses a Reed Solomon RS(255,249) 2^8-ary forward error correction code to ensure a 10^{-4} bit-error-rate. Thus a maximum of 1992 bits of data can be sent in a single VDL Mode 2 transmission. For shorter messages, the RS code can be reduced, i.e., fewer parity symbols are used. Interleaving of data bytes is used to improve the performance of the RS code. Prior to transmission, the bit stream is bit-scrambled using a pseudo noise (PN) code to aid clock recovery at the receiver and to provide a random data sequence to create a more uniform signal spectrum.

The physical layer performs channel sensing to determine if the channel is available for signal transmission. In addition, receive-to-transmit and transmit-to-receive turnaround time is critical and is maintained to a minimum to support the Carrier Sense Multiple Access (CSMA) protocol used in the data link layer.

4.1.2 Data Link Layer (MAC sublayer)

The media access channel (MAC) sublayer provides transparent channel access to the DLS sublayer. The VDL Mode 2 MAC layer uses non-adaptive p-persistent CSMA to allow equitable access opportunity to all stations. The MAC sublayer also provides an indication of channel congestion to the management entity, which determines the quality-of-service of the link. The MAC layer uses a number of timers, the persistence parameter (p) and retry counter to perform CSMA and to compute channel congestion.

4.1.3 Data Link Layer (DLS sublayer)

The data link services (DLS) sublayer implements the Aviation VHF Link Control (AVLC), which is a modified version of the High Level Data Link Control (HDLC) protocol (ISO 3309). The DLS processes data link frames and transfers received and transmit data to / from the ISO-8208 sub-network layer. The AVLC frame format is shown in Figure D-17.

From Figure D-17 an AVLC frame begins and ends with a '01111110' flag that provides the demarcation between frames. Contained within the frame are the destination and source addresses that indicate the participant DLS entities. Following the addresses is a link control field that implements the AVLC frame message exchange and protocols. The control field is followed by the information field, which represents the user data. The frame ends with a 16-bit frame check sequence that is used to detect frame errors.

AVLC DLS services consist of frame sequencing, error detection, station identification, broadcast addressing and data transfer. The DLS determines if a frame is addressed to it, detects whether or not the frame was received correctly, and ensures that no redundant frames are transferred to the sub-network layer.

		BIT NUMBER							first bit transmitted
DESCRIPTION	OCTET NO	8	7	6	5	4	3	2	1
FLAG	-	0	1	1	1	1	1	1	0
Destination Address Field	1	22	23	24	25	26	27	A/G*	0
	2	15		Destination				21	0
	3	8		DLS Address				14	0
	4	1						7	0
Source Address Field	5	22		24	25	26	27	C/R	0
	6	15		Source				21	0
	7	8		DLS Address				14	0
	8	1						7	1
Link Control Field	9				P/F				
INFORMATION	N-2			USER DATA					
FRAME CHECK SEQUENCE	N-1	9		MOST SIGNIFICANT OCTET					16
	N	1		LEAST SIGNIFICANT OCTET					8
FLAG	-	0	1	1	1	1	1	1	0

Figure D-17 AVLC Frame Format [10]

AVLC control commands and responses are shown in Table D-4. These commands implement the frame processing protocols. ISO 4335 and ISO7809 describe the detailed HDLC protocols, with the ICAO Annex 10 on VDL [10] describing any modifications to these protocols to implement the AVLC.

Commands	Responses
INFO (Information)	INFO
RR (Receive Ready)	RR
XID (Exchange Identity)	XID
TEST	TEST
SREJ (Selective Reject)	SREJ (Selective Reject)
FRMR (Frame Reject)	
UI (Unnumbered INFO)	UA (Unnumbered Acknowledge)
DISC (Disconnect)	DM (Disconnect mode)

Table D-4 AVLC Commands and Responses [10]

Data is transferred in the information fields of INFO, UI and XID frames. INFO frames provide connection-oriented user data exchanges between two data link entities. UI (unnumbered information frames) are used for connectionless data transfer for broadcast services. XID (exchange identity information) frames are used to provide supervisory information for management of the AVLC.

Similar to the MAC layer, the DLS / AVLC uses a number of timers and counters (e.g., for retransmit, acknowledgment, link initialization timing, maximum frame length, and number of transmissions) that control the frame message exchange protocol. These timers /counters are defined in [10].

4.1.4 Data Link Layer (management entity)

The VDL management entity (VME) utilizes a separate Link Management Entity (LME) to manages the DLS with a peer LME (an aircraft or ground station). Communications with more than one ground stations or aircraft require additional LMEs. The LME uses XID (exchange identity) parameters to manage the data link. Again, a number of timers and counters implement the link management protocol.

4.1.5 Sub-Network Layer

All VDL modes utilize the ISO 8208 protocol as the lower network sublayer of the OSI stack. This layer interfaces to the data link layer to receive error-free data link communications from the AVLC sublayer and interfaces to the upper sublayers of the network layer to enable internetwork communications.

4.1.6 Summary of VDL Mode 2

VDL Mode 2 is a data-only data link (i.e., no digital voice capability) that provides an order of magnitude increase in channel capacity versus VDL Mode 1. The increase in capacity is the direct result of the 31.5 kbps D8PSK waveform (versus the 2400 bps MSK waveform used by VDL Mode 1). As indicated in Section 3, D8PSK requires a D/U of 16 to 20 dB which influences frequency reuse. Like VDL Mode 1, VDL Mode 2 uses CSMA channel access protocol. In addition, VDL Mode 2 uses the bit-oriented protocol (versus character-oriented protocol of ACARS) that provides compatibility to the ATN.

VDL Mode 2 is the simplest of the high-rate VDL modes being developed and is well suited when channel efficiency and access demands are not at a premium. The CSMA protocol limits VDL Mode 2 to providing strategic data link communications and cannot be used for time-critical, tactical communications. VDL Mode 2 is intended for addressed, air-ground communications, and can also provide a broadcast data link capability for high-rate broadcast applications, e.g., weather information, including precipitation maps, etc..

In order to achieve a simplex broadcast data link using VDL Mode 2 will require additional standardization activity to allow the AVLC data link sublayer to be bypassed, eliminating the need for message ACKs (Acknowledgements) that are currently required to maintain a link connection. Table D-5 summarizes the performance of VDL Mode 2. VDL Mode 2 is defined in detail in the ICAO Annex 10 [10] and the associated ISO standards.

Communications Performance	
Throughput delay	moderate (~ 10 sec), depends on channel loading
Message integrity, priority	yes
ATN Compatibility	yes
VHF Specific Services (VSS), i.e., non-ATN	not currently planned but possible
Broadcast Capability	well suited for efficient high-rate broadcast link (additional standardization work required)
Voice/Data	Data only
D8PSK	D/U of 16/20 dB for frequency reuse

Table D-5 VDL Mode 2 Communications Performance Summary

4.2 VDL Mode 3

Mitre, under the sponsorship of the FAA, has developed the VDL Mode 3 concept as the next generation VHF communications system, also called NEXCOM. VDL Mode 3 provides a flexible architecture that allows a range of system configurations for voice, data and integrated VHF digital voice and data link simultaneously for multiple users on one channel resource. VDL Mode 3 was designed, in part, to address the VHF frequency congestion problem by providing digital voice and data link services with efficient use of available VHF Comm frequency resources. VDL Mode 3 MASPS and SARPS are currently being developed by RTCA SC-172 and the ICAO AMCP. This section provides an overview of VDL Mode 3 and examines its communications performance.

Unlike VDL Mode 2, which provides data link services using CSMA, VDL Mode 3, using TDMA channel access, is capable of providing a range of communications capabilities. The VDL Mode 3 communications modes are 4V, 3V1D, 2V2D and 3T for standard range communications and 3V, 3S, 2V1D and 3U modes when extended communications range is desired. The 4V mode indicates that the VDL channel is configured to provide 4 independent, dedicated digital voice sub-channels within the 25 KHz VHF Comm channel. This is accomplished using different time slots for each voice sub-channels. For the 3V1D mode, one of the four voice channels is used to provide a shared data channel (1D). The 2V2D mode provides two voice and data sub-channels. Each voice channel is paired with a dedicated data channel to allow, for example, two separate ATC controllers providing dedicated voice and data services for voice and CPDLC data link simultaneously on one channel. The 3T mode is intended to provide demand assigned voice and data services.

Extended range modes have fewer time slots available to them due to additional range guard time requirements and are thus constraint to providing 3V sub-channels. The 3S mode allows a dedicated voice channel to be sent via 3 ground stations, intended for providing site diversity. 2V1D is similar to 3V1D but is intended for extended range communications. The 3U mode allows voice sub-channels that are not managed by the ground station, i.e., they are unprotected (U).

4.2.1 Physical Layer

Similar to VDL Mode 2, VDL Mode 3 RF pulses use 31.5 kbps D8PSK modulation using raised cosine filtering ($\alpha = 0.6$) to maintain the signal within the 25 KHz channel and provide low sidelobes on the adjacent channel. The typical RF pulse is also similar to VDL Mode 2. However, since VDL Mode 3 is a TDMA system and has a number of different modes, RF pulses are assigned within time slots in several ways. Figure D-18 shows a typical time slot and the associated RF pulse transmissions for both airborne and ground transmissions.

Unlike VDL Mode 2, where one basic RF pulse is transmitted using CSMA, VDL Mode 3 uses two RF pulses within a single time slot, a management (M) burst, and a voice/data (V/D) burst. Each of these bursts has the typical ramp-up (5 symbol times) and ramp-down (2 symbol times) intervals, 16-symbol synchronization sequences, system data for the M burst, and a header and user information in the V/D burst.

Special synchronization sequences are used to allow successful synchronization, yet distinguish between the different types of requests and responses that are indicated by the transmission. Synchronization sequences are as follows:

Standard synch	S_1 (for M burst downlink)
Net entry requests	S_1* (for M burst downlink)
Poll responses	S_2* (for M burst up/downlink)
V/D burst synch	S_2 (for V/D burst)

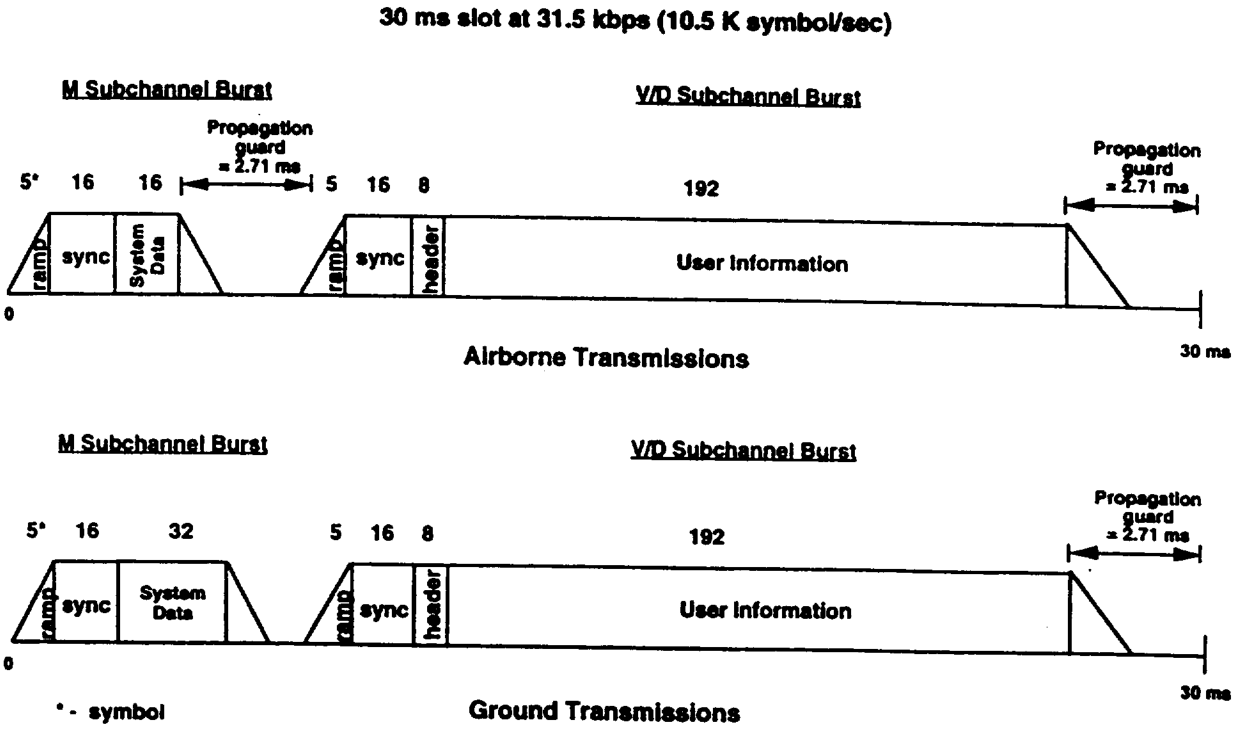


Figure D-18 VDL Mode 3 Burst Transmissions - TDMA Timing Budget [11]

The M burst contains system data, consisting of message ID, slot ID, ground station code, channel configuration (4V, 3V1D, etc.), voice signal and squelch window information and a range of message dependent data that is used to maintain channel and communications management of the VDL sub-network. The M-channel burst format is as follows:

1) Uplink M-burst

   For the non-3T configuration, 32 symbols are transmitted, i.e., 96 bits. The 96 bits consists of 4 Golay (24,12) codewords. For 3T, system data consists of 128 symbols, i.e., 384 bits, consisting of 16 Golay (24,12) codewords. The Golay count corrects up to 3 bit errors or detects as many as four bit errors.

2) Downlink M-Burst

   16 symbols, i.e., 48 bits, are transmitted, consisting of 2 Golay (24,12) code words.

The V/D burst consists of header and user information data. The header consists of 8 symbols (or 24 bits) and is a single Golay (24,12) codeword. User information consists of 192 symbols (or 576 bits). When transmitting data, the user information is encoded as a single Reed Solomon RS(72,62) 2^8-ary code word capable of correcting up to five codeword symbol errors. For voice, error correction is included in the vocoder itself. The vocoder is expected to provide satisfactory performance at bit-error-rates of 10^{-3}. The vocoder rate (including internal error correction) is 4800 bps (a 4000 bps vocoder is used in truncate mode, which occurs when system timing has degraded below a specified level).

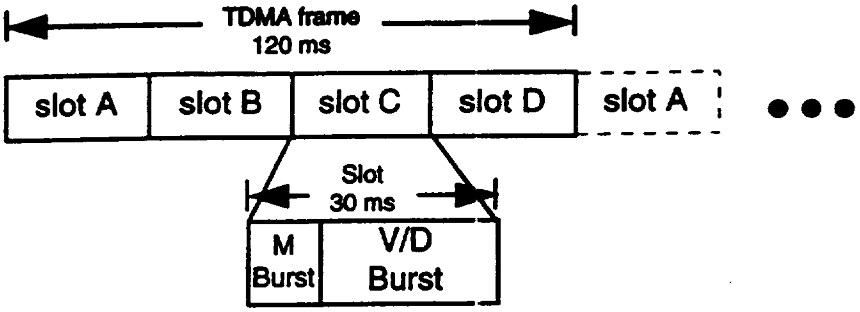
Interleaving is not used in VDL Mode 3, but bit scrambling is used.

As for VDL Mode 2, the physical layer shall minimize transmit/receive turnaround times to enhance performance.

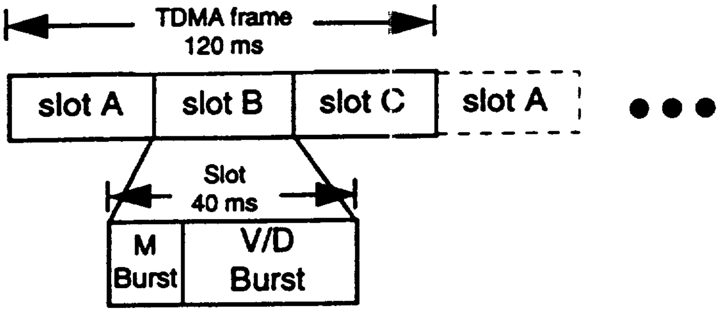
4.2.2 Data Link Layer (MAC sublayer)

The MAC sublayer supports both voice and data operations. For data, the MAC sublayer implements a ground station centralized, reservation-based access to the channel, which permits priority-based access. In addition, the MAC sublayer implements polling and random access methods for reservation requests. For voice, access is primarily on a "listen before talk" discipline. In order to avoid a "stuck" microphone, the ground can preempt the airborne user who is occupying the channel.

The MAC protocol timing is as follows: A TDMA frame consists of a 120 ms time interval that contains either three or four time slots. The duration of the time slot was selected based on conventional 4800 bps vocoder frames which are on the order of 20 to 30 ms. For standard range communications, a TDMA frame consists of four 30 ms time slots with a round trip guard time of 2.71 ms (Figure D-19). Extended range uses three 40 ms time slots, which were increased in duration to accommodate the increased guard time. Each time slot contains an M burst for signalling and link management and a V/D burst for user information.



a) Standard Range



b) Extended Range

Figure D-19 VDL Mode 3 Frame Structure [12]

User Groups and System Configuration

Using the TDMA frame and time slot structure just described, and the communications modes indicated previously (4V, 3V1D, etc.), a number of user groups and system configurations are defined for VDL mode 3. These are listed in Table D-6. Up to 4 user groups are possible per VHF Comm channel. Time slots are identified as slots A, B, C, and D. The system configuration is determined by the controlling ground station.

	System Config.	User Groups Supported/ Identifying Time Slots	Services to Each Group	Slots Assigned to Each Group
Standard Range	4V	4/(A, B, C, D)	Dedicated voice ckt	1
	3V1D	3/(A, B, C)	Dedicated voice ckt w/shared data ckt	2
	2V2D	2/(A, B)	Dedicated voice ckt w/dedicated data ckt	2
	3T	1 to 3/(B, C, D)	Demand assigned voice and data	1 to 3
Extended Range	3V	3/(A, B, C)	Dedicated voice ckt	1
	3S	1/(A)	Dedicated voice circuit with 3 station diversity	3
	2V1D	2/(A, B)	Dedicated voice ckt w/shared data ckt	2
	3U	3/(A, B, C)	Unprotected voice ckt	1

Table D-6 VDL Mode 3 System Configurations [12]

Logical Burst Access Channels

Media access is controlled as follows; two TDMA frames (120 ms each) are used to define a media access (MAC) cycle, with individual frames denoted as odd and even. During each MAC cycle, the VDL grants access using Logical Burst Access Channels (LBACs). LBACs are defined for the standard configurations (4V, 3V1D, 2V2D, 3V, 2V1D, 3U), the 3T configuration, and the 3S configuration. The LBACs provide dedicated bursts within the MAC cycle for various types of communications; e.g., Table D-7 describes the type of channel access defined for the standard LBAC configurations. From Table D-7, eight LBACs are available for uplink and downlink transfers; 1) three M burst downlink LBACs for polling responses, acknowledgements and random access, 2) two voice and two data LBACs for odd and even frame voice and data transmissions, and 3) an M burst uplink LBAC that also serves as the M burst that provides the timing reference point. The timing reference M burst is generated by the ground station to provide the overall synchronization of the MAC TDMA protocol. In addition to the eight standard LBACs, the 3T configuration uses 18 LBACs, while the 3S configuration uses 12 LBACs (not shown). LBACs are precisely timed within the time frames based on the timing reference point.

MAC Timing States

The VDL derives its primary timing from the "timing reference point", which is the time of the first received symbol of the synchronization sequence of an M burst uplink from the ground station. If the airborne VDL has not received an updated timing reference, he will eventually fall out of the primary timing state and will attempt to obtain timing from Voice/Data (V/D) bursts. The timing state when V/D timing is used is referred to as the Alternate Timing State (ATS). If timing is further lost, the "free running" timing state is entered. Channel access using Logical Burst Access Channels (LBACs) is dependent upon the timing state and the management signalling information obtained from the M uplink burst during the previous MAC cycle.

LBAC#*	Applicability	Description
1	air only	M downlink burst used for polling response or Random Access (RA)
2	air, ground	V/D (voice) burst even frame
3	air only	M downlink burst used for ACK or RA
4	air, ground	V/D (data) burst even frame
5	ground only	M uplink burst and timing reference point
6	air, ground	V/D (voice) burst odd frame
7	air only	M downlink burst used for ACK or RA
8	air, ground	V/D (data) burst odd frame

Table D-7 Logical Burst Access Channels (LBACs) for Standard Configurations [12]

Voice Access

For voice transmissions, channel access is granted based on the timing state, the voice signalling information received in the M uplink burst during the previous MAC cycle, and the system configuration (4V versus 3T). The 4V, 3V1D, 2V2D, 3V and 2V1D modes provide for dedicated voice access LBACs. The 3T configuration supports voice using reservation signalling. In the event primary timing degrades sufficiently, voice communications will be "truncated", where a reduced rate vocoder algorithm is used to shorten the require V/D burst transmission (instead of using a 4800 bps vocoder, a reduced rate 4000 bps vocoder is used). Unprotected voice access (3U) is allowed even in the "free running" timing state.

Link Management & Data Operation Support

The MAC layer at the command of the Link Management Entity (LME) in the Data Link Services (DLS) sub-layer (Section 4.2.3) uses specific Logical Burst Access Channels (LBACs) to send messages to support the polling, net entry, and leaving net message protocols.

In the event the user data is longer than the V/D burst, the MAC layer segments the data into individual bursts. The end-of message (EOM) flag is sent in the final burst transmission. Airborne users attain channel access either using "polling" or "random access". When data is available for downlink, a Reservation Request LBAC is sent to the ground station to indicate that data is available for downlink. The ground station then sends a Reservation Response LBAC that signals an "access scheduled" indication along with information of which slots should be used in the following MAC cycle. There are no acknowledgment messages required since those are handled by the DLS sub-layer AVLC protocol. The protocol also allows for automated handoff of ground stations for the 3T mode, assuming the radio can be retuned within 2 ms.

4.2.3 Data Link Layer (DLS sublayer)

The DLS sub-layer is functionally identical to the DLS sublayer of VDL Mode 2 using the Aviation VHF Link Control (AVLC) protocol which is a modified version of the ISO 3309 HDLC protocol. The only differences are in the interface to the MAC layer (TDMA for VDL Mode 3 versus CSMA for VDL Mode 2).

The primary difference is that the DLS uses the M bursts as part of its link management. Before any link can be established by a DLS Link Management Entity (LME) the VDL must acquire two consecutive M uplink bursts containing the same information in the initial 3 control bytes (i.e., system configuration, squelch window, slot ID and ground station code). The M bursts also provide the timing reference. Once the net is initialized, net entry involves the following sequence of message exchanges: 1) sending a downlink net entry message, 2) receiving a net entry response from the ground station, 3) sending an 'initial poll response" downlink, and 4) receiving a polling message from the ground station that provides channel access information when data can be downlinked.

M bursts are also used for "link release" and "handoff" between ground stations and / or a Ground Network Interface (GNI). All handoff activity is confined to the lower layers (MAC and DLS). The sub-network virtual connection is undisturbed. Depending on the time duration associated with a handoff, an issue of making and breaking connections may arise. While typical radio communications today use a break-before-make handoff, it may be necessary to perform a make-before-break handoff (TBD). Make-before-break requires that a new connection is made before abandoning the previous connection. This may be necessary to avoid loss of important messages, i.e., a controller instruction via CPDLC. The impact of make-before break may require an additional channel / sub-channel resource.

As always, a number of timers and counters are used by the DLS to control protocol processing.

4.2.5 Sub-Network Layer

The sub-network layer is the same for all VDL modes and is not discussed here.

4.2.6 Summary of VDL Mode 3

Compared to VDL Mode 2, VDL Mode 3 is considerably more complex, providing a wide range of system configurations for digital voice, data and simultaneous, integrated voice and data communications via the TDMA time slots (refer to Table D-6 for a list of the system configurations). VDL Mode 3 was designed to make very efficient use of the 25 KHz channel in order to increase VHF Comm data link capacity and to help alleviate VHF Comm frequency congestion. VDL Mode 3 data link communications are ATN-compatible.

Within a single frequency channel VDL Mode 3 is capable of supporting 4 dedicated voice sub-channels or circuits (4V mode) or can trade off one of the voice circuit as a shared data circuit (3V1D mode). A 2V2D mode allows a dedicated pair of voice circuits to have their own associated data circuit. The 3T mode allows for demand assigned voice and data. Since VDL Mode 3 uses discrete addressing in most of its system configurations, this allows for "caller ID" and "selective calling" and allows a ground station to pre-empt an airborne voice transmission due to a stuck microphone condition or voice priority.

Digital voice is accomplished by use of a 4800 bps vocoder. To accommodate four voice circuits on a 25 KHz channel requires a signalling rate of ~31.5 kbps. Thus the VDL Mode 3 requires 31.5 kbps D8PSK modulation to support the intended voice and data capacity. One of the considerations in using 31.5 kbps D8PSK in a 25 KHz is its sensitivity to co-channel interference (D/U). VDL Mode 3 has the ability to mitigate some of this interference by using a coded squelch, which provides time windows around the time of expected signalling bursts. Any signal detected outside of these times is considered to be interference and is ignored.

VDL Mode 3 communications are directly under ground station control, which provides centralized timing and reservation-based access among all users, allowing priority-based access. Airborne users gain access to the channel using polling and random access for reservation requests to downlink data.

Sufficient guard times are allocated to the TDMA slots to allow collision free communications for all line-of-sight scenarios (e.g., 200 nmi range or greater). Guard times must account for round-trip timing since ground station "timing reference" transmissions experiences a range delay to distant users, whose own sense of timing is thus delayed. The return trip is to account for the range delay back to the ground station. The round-trip time is also needed to support party-line voice for users that are at maximum range, but on opposite sides of the ground station.

With its range of system configurations, VDL Mode 3 is thus ideally suited for providing ATC/ATS communications of CPDLC, FIS and FIS-B and at the same time provides voice capability. The end-to-end transfer delay for VDL Mode 3 messaging is expected to be 3 seconds (95% of the time). This relatively low latency (compared to VDL Mode 2) is sufficient for ATC/ATS communications currently being planned. Any new requirements for tactical data link messaging (latencies on the order of 1 second) may not be accommodated by VDL Mode 3.

Unlike VDL Mode 2, VDL Mode 3 will require more significant changes to protocols to allow for a broadcast data link mode, e.g., uplink of weather information. For broadcast services VDL Mode 2 is the better candidate.

The discussion of this section was intended to provide an overview of VDL Mode 3 Much more detail is available in the VDL Circuit Mode MASPS developed by RTCA SC-172 [11], and Appendix A of the ICAO SP COM/OPS Divisional Meeting [12], although the later is somewhat dated. Table D-8 summarizes the performance of VDL Mode 3.

Communications Performance	
Throughput delay	low (3 seconds, 95 %) (may not accommodate tactical communication)
Message integrity, priority	yes
ATN Compatibility	yes
VHF Specific Services (VSS), i.e., non-ATN	not currently planned but possible
Broadcast Capability	substantial standardization activity required to provide simplex broadcast mode
Voice/Data	Capable of both voice and data
31.5 kbps D8PSK	D/U of 16 to 20 dB for frequency reuse

Table D-8 VDL Mode 3 Communications Performance Summary

4.3 VDL Mode 4

The VDL Mode 4 concept was developed by Sweden to support future CNS/ATM technology using a Cellular CNS Concept (CCC). CCC is intended to provide a single CNS system solution for all air space users for all phases of flight. Like VDL Mode 3, VDL Mode 4 uses TDMA access techniques for efficient use of the channel resource, although the two approaches differ. Unlike VDL Mode 3, VDL Mode 4 is a data-only data link, i.e., it does not support digital voice.

When combined with GPS/GNSS for position and time information, VDL Mode 4 can provide a wide range of capabilities that are suitable for CNS/ATM data link. VDL Mode 4 supports an autonomous, self-organizing TDMA (STDMA) protocol that allows a network of aircraft and vehicles to participate in a communications network without the use of a ground station. VDL Mode 4 also supports data link networks using passive ground stations used for ADS-B surveillance, or one or more active ground stations, which direct network communications (i.e., more centralized control by the ground).

While originally developed more for broadcast applications such as ADS-B and DGPS/DGNSS data link, VDL Mode 4 also includes capability for addressed point-to-point communications for a range of applications. VDL Mode 4 is ATN-compatible but also provides VHF Specific Services (VSS) data link that are non-ATN, which are used for local area, time critical (tactical) communications.

This section provides an overview of VDL Mode 4 from the sub-network perspective (i.e., lower layers) and summarizes the key issues associated with using VDL Mode 4 for CNS/ATM data link. Additional attention is given to the ADS-B application since VDL Mode 4 is being considered as an alternative to Mode-S for the ADS-B data link (Section 4.3.3.5 discusses VDL Mode 4 use for ADS-B).

4.3.1 Physical Layer

Physical layer modulation candidates for VDL Mode 4 are 31.5 kbps D8PSK and 19.2 kbps GFSK. Both of these waveforms were discussed in detail in Section 3. The D8PSK waveform is primarily indicated as a candidate due to the legacy of the original VDL Mode 2 and VDL Mode 3 waveform design. However, 19.2 kbps GFSK is the desired waveform for VDL Mode 4 by its developers. The GFSK waveform requires Gaussian prefiltering using a BT of 0.3 and a modulation index of 0.25 to maintain the signal within a 25 KHz channel and provide low sidelobes on the adjacent channel. As indicated in Section 3, GFSK is less sensitive to co-channel interference (D/U ratio) facilitating frequency reuse for some data link applications and coverage areas. D/U performance is especially critical for ADS-B , where it is important that distant aircraft do not interfere excessively with ADS-B reports of close aircraft. As indicated, GFSK provides a lower channel data rate versus D8PSK in a fixed 25 KHz channel (i.e., 19.2 kbps versus 31.5 kbps). This is the direct result of the higher signalling constellation of D8PSK compared to GFSK, but is also the reason why D8PSK is less robust to D/U. The effective link capacity is affected by the channel signalling rate, D/U ratio and the intended coverage region (i.e., radio-line-of-sight).

As with VDL Modes 2 and 3, VDL Mode 4 uses a similar RF pulse that consists of transmitter stabilization and synchronization segments followed by header (optional) and data segments and a transmitter power ramp-down segment. Since VDL Mode 4 intends on all users to have the same system time (using GPS/GNSS time), the range guard times must only account for one-way range delays (recall VDL Mode 3 requires round-trip guard times since timing emanates from the ground station and also experiences a range delay).

With a 13.33 ms time slot (see next section), RF pulse timing is as follows:

1) Transmitter stabilization sequence (832 μs or 16 bits duration)
2) Synchronization sequence (1250 μs or 24 bits)
3) Header sequence (0 μs since no header is used for VDL Mode 4)
4) User data (10 ms or 192 bits of data)
5) Transmitter ramp-down (300 μs)
6) Guard time (1250 μs or 24 bits, providing a one-way guard time for 203 nmi).

VDL Mode 4 is capable of 75 time slots per second (based on 13.33 ms slots) or 4500 time slots per minute, with each time slot capable of transmitting 192 bits of data.

As with VDL Modes 2 and 3, the physical layer is responsible for data transmit and receive processing, frequency control and provides notification services. The physical layer determines signal quality based on outputs from the demodulator, determines time of arrival of received messages, and performs channel sensing to determine if the channel is idle or busy. This information is provided to the upper layers.

4.3.2 Data Link Layer (MAC sublayer)

The MAC layer for VDL Mode 4 implements a TDMA frame structure as per Figure D-20. The top-level timing construct is the superframe, which spans a 1 minute time interval and consists of 4500 time slots that are available for all users in the sub-network for information exchange.

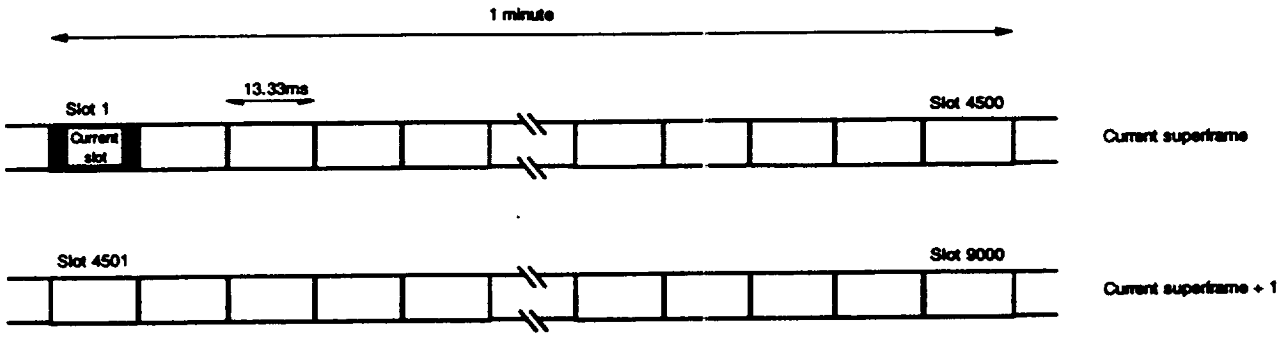


Figure D-20 VDL Mode 4 Superframe [13]

As with all TDMA systems, time synchronization is critical in managing channel access among all users in order to prevent self-interference. VDL Mode 4 plans to use an integrated timing concept (ITC) to achieve system time based on UTC time. Five methods of achieving this timing are being considered (order of preference from 1 to 5):

1) Primary timing for all users is to use GPS/GNSS time, which provides time to within 400 ns (2σ).
2) Ground station network provides timing via broadcast synchronization messages.
3) Use of atomic clocks by all users.
4) Synchronization from other users, providing timing to 1 μs.
5) Floating network, where all users have lost GPS/GNSS time and continue to synchronize off each others transmission based on an "average drift rate" of received message timing.

While GPS/GNSS time is the most convenient and accurate timing approach, there is concern that the independence between the CNS communications and the navigation functions is compromised by failure of GPS.

The MAC layer determines slot occupancy based on two factors: 1) the reservation table indicates that the slot is reserved, and 2) the physical layer indicates that the channel is busy.

The MAC layer shall transmit in the current slot if 1) a reservation has been made previously for the slot, and 2) there is no reservation, but the slot is unoccupied. In 2) the MAC layer uses random or CSMA access to gain channel access.

The MAC layer is also responsible for error detection processing of the frame cyclic redundancy code (CRC). In the event of an error, the received burst is discarded. If a correctly received burst contains reservation information, the MAC layer forwards the reservation information and the received time to the VHF Specific Services (VSS) sub-layer. Received data and signal quality and transmission start times of frames are also passed to the VSS and Data Link Services (DLS) layers.

4.3.3 VHF Specific Service (VSS) Sublayer

Figure D-21 illustrates the sub-network "lower layers" used by VDL Mode 4. The physical and MAC sublayers have already been described. This section discusses the VSS sublayer.

The VSS sublayer provides many functions:

1) Burst formatting, encoding, decoding and data error detection
2) Maintains the reservation table
3) Provides various access protocols (reserved, random and fixed access)
4) Manages the transmission queues
5) Determines slot selection in scheduling future transmissions
6) Provides notification of channel congestion.

VSS Burst Format and Access Protocols

Figure D-22 shows the structure of the VDL Mode 4 burst, which provides a flexible message structure that allows a user to transmit messages while at the same time making future slot reservations for upcoming data exchanges with other users. This is accomplished by allowing each message to contain a number of key information elements: 1) reservation data, 2) synchronization data including position, and 3) fixed and variable information fields.

The reservation field includes reservation ID and associated reservation data that support several autonomous and controlled access protocols. The protocols supported are as follows:

a) null reservation
b) periodic broadcast
c) incremental broadcast
d) combined periodic and incremental broadcast
e) unicasted request
f) information transfer request
g) directed request
h) response.

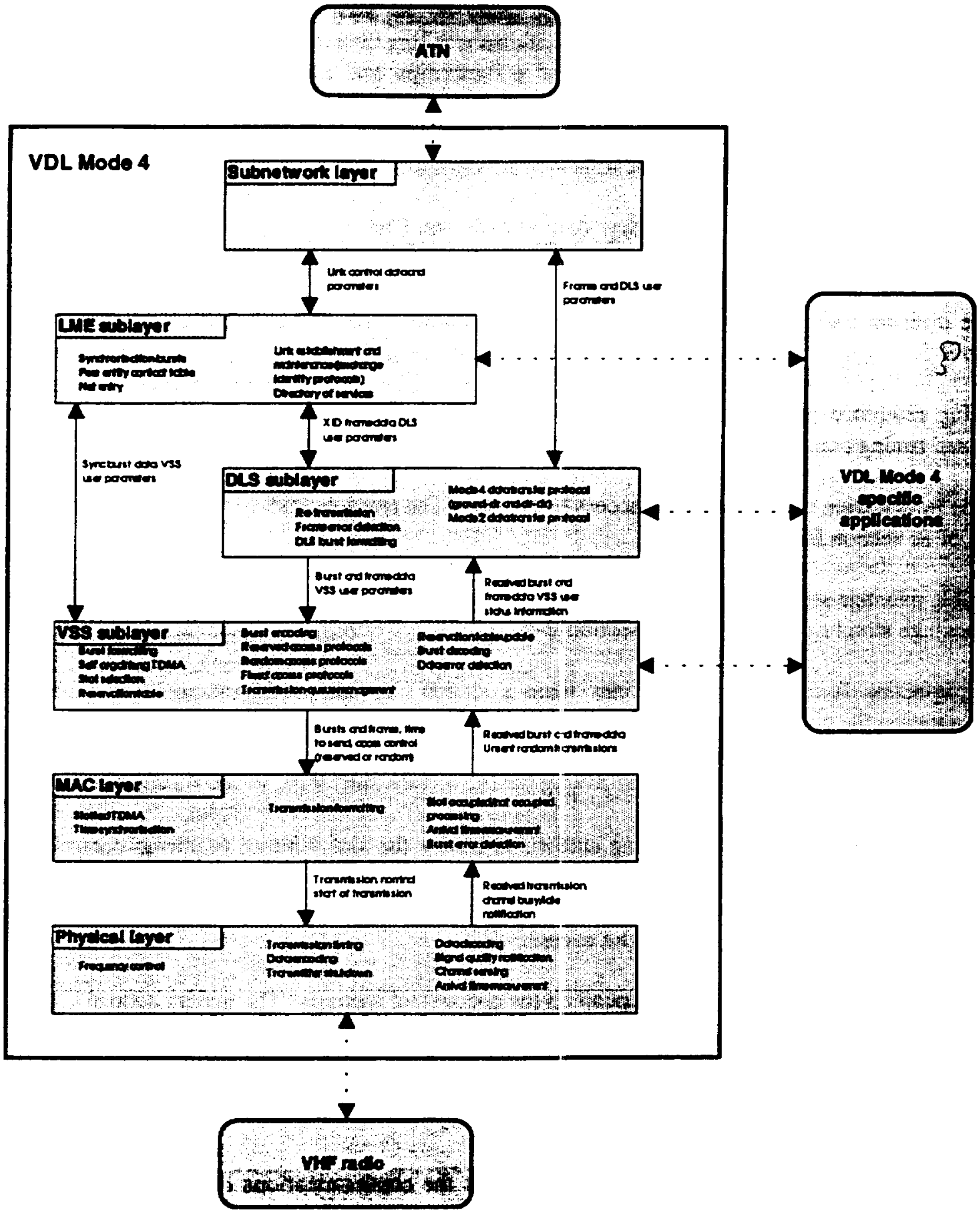


Figure D-21 VDL Mode 4 Sub-Network Layers [13]

As indicated, the access protocols b) to d) above are broadcast protocols. The periodic broadcast protocol is the most important autonomous scheme, which supports broadcast of position and identity information by all users in the vicinity and allows the system to operate effectively regardless of the presence of ground stations. The protocol is illustrated in Figure D-23. Each periodic broadcast contains the station ID of the user, position information, and reservation information consisting of a periodic time out value, and a periodic offset. The time out value indicates for how many superframes (1 minute frame) the broadcast slot reservation remains in effect (from the current frame) and the offset value from the current slot position in the frame to which the reservation will move to once the time out count expires.

In order to make future slot selections, the user must listen to the network for one superframe (~ 1 minute) in order to assess slot availability. Once a slot selection is made, the user maintains the reservation for 3 to 8 minutes. The slot selection process for making these future reservations is discussed below.

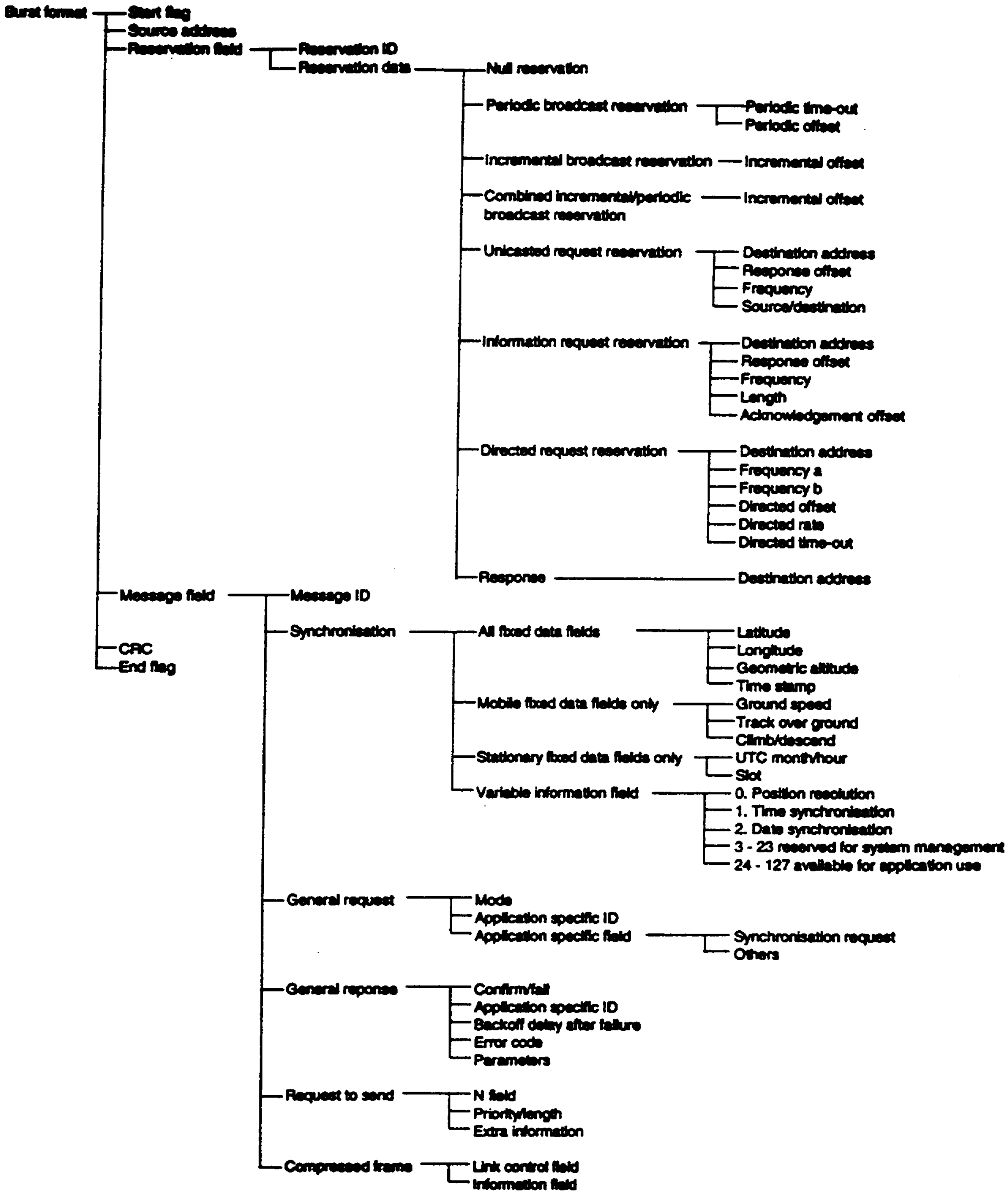


Figure D-22 VDL Mode 4 Burst Structure [13]

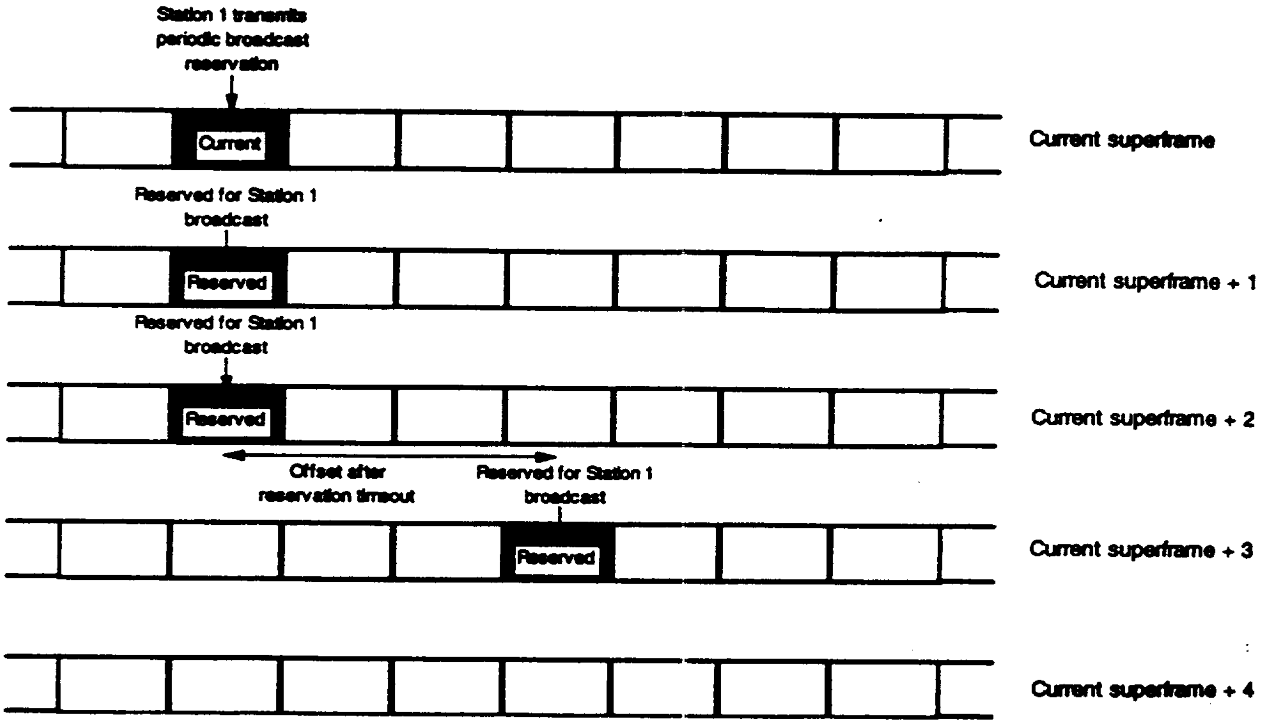


Figure D-23 Periodic Broadcast Protocol [13]

Incremental broadcast is used when an application must broadcast data over a short period of time, typically within the same superframe. The user includes an incremental offset value in its transmission to reserve a slot as indicated by the offset value from the current slot. Periodic and incremental broadcast channel access can be combined.

The unicasted request protocol (see list above) is used by a station that requires a response from another station. In sending the request, the user includes a slot reservation for the other station for sending the reply transmission. This requires that the destination address is included along with frequency of the channel and the response offset from the current slot.

The information transfer request protocol is used to obtain a data series from another user. Slots are reserved for the transmission of the requested information from the other user, and also reserved for an acknowledgment of the requesting user.

Directed requests are similar to the periodic broadcast protocol in obtaining regular broadcasts, but the allocation of slots is enforced by a single user that is most likely a ground station. The ground station sends slot offset and rate information to each user to allocate slots for transmission of broadcast information.

In addition to the above access protocols, VDL Mode 4 also supports random access and fixed access protocols. Random access can be used when sufficient slots are available to transmit the full message. A p-persistent CSMA protocol is used for random access. Fixed access can be provided by permanently allocating certain slots for fixed purposes (primarily for use by ground stations).

Reservation Table Maintenance and Slot Selection Protocol

As each user receives bursts, slot reservation information is extracted and used to update the Reservation Table. It is important that each user maintains a reservation table in order to maintain the integrity of the slot selection process.

When preparing to make a reservation for an upcoming transmission, the user must determine the amount of data to be transmitted (number of consecutive bursts) and then determines the available number of slots in the reservation table. If a sufficient number of slots are available, the user makes a selection and schedules the transmission accordingly. If there is not a sufficient number of slots, the user can select from previously reserved slots by other users.

Two methods of borrowing slots are used: 1) slots that do not result in co-channel interference (CCI), and 2) Robin Hood selection. CCI selection is illustrated in Figure D-24. Station 1 wants to communicate with Station 2, but an insufficient number of slots are available for transmission. In order to free up additional slots, Station 1 examines the reservation table to determine if it can borrow slots from other reservations. It looks to find reservations between other user pairs (Stations 3 and 4) that are more distant and would not be interfered with since the D/U of the geometry is such that no CCI results.

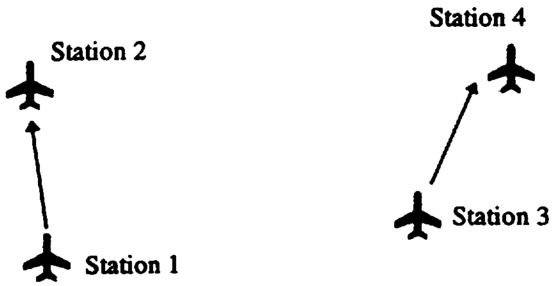


Figure D-24 Slot Selection based on Co-Channel Interference Protection [13]

The second method using previously reserved slots is to borrow them from aircraft that are at long distances. This is referred to as Robin Hood and is illustrated in Figure D-25. The effect of Robin Hood is to gracefully degrade the communications range as the channel loading increases. It is evident that a modulation waveform that is robust to co-channel interference, i.e., low D/U, is critical for extending network capacity using CCI and Robin Hood.

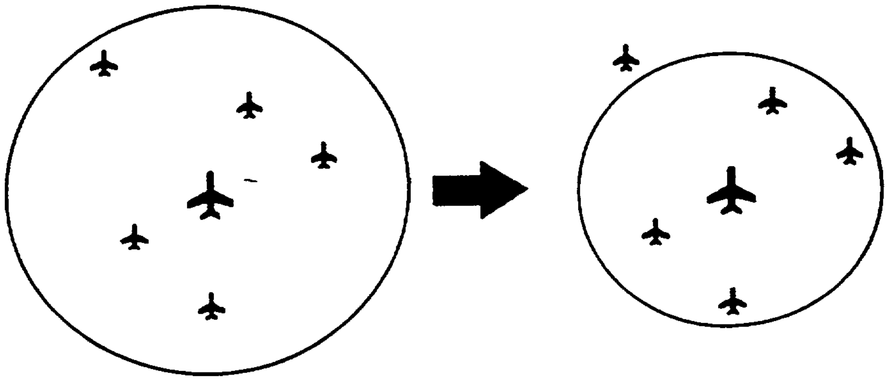


Figure D-25 Slot Selection based on Robin Hood

Use of CCI and Robin Hood is acceptable for data link applications such as ADS-B. However, for CPDLC applications it is important that the ground controller maintain communication with all aircraft within the intended coverage volume and that use of CCI and Robin Hood would not be acceptable. Quality of service parameters are used to control the extent (if any) to which CCI and Robin Hood are used in the slot selection process.

Observation: As the network becomes more loaded, a substantial number of reservation table calculations must be made in real time to determine future slot reservations, especially for CCI and Robin Hood calculations. This is likely not a problem with the fast processors available today.

4.3.4 Data Link Layer (DLS sublayer) and Link Management

The data link services (DLS) sublayer used by VDL Mode 4 is similar to the one used by VDL Modes 2 and 3. The same command and response AVLC protocol (Table D-4) is implemented. The various access protocols described above and the slot reservation approach of the VSS supports the DLS protocol.

The link management function of the data link layer of VDL Mode 4 uses the synchronization bursts and the XID (exchange ID) frames to establish and maintain links between stations. Synchronization bursts provide identity and position information of aircraft. XID frames provide link control information.

Global Signalling Channels

VDL Mode 4 plans to utilize a world-wide pair of Global Signalling Channels (GSCs) that provide for communication control in all airspaces. These global signalling channels are used to transmit VDL Mode 4 Directory of Service (DOS), which provides frequency channel information on the various services that are available in the airspace of interest, e.g., AOC, GPS/GNSS data link, etc.. The two GSCs are also used for enroute ADS-B, where each aircraft transmits synchronization bursts on an alternating 20 sec period on each channel for an effective 10 sec update for ADS-B enroute surveillance.

4.3.5 Sub-Network Layer

The sub-network layer is the same for all VDL modes and is not discussed here.

4.3.6 VDL Mode 4 and ADS-B

The primary driver for VDL Mode 4 from a data link application perspective is ADS-B. Thus this section examines VDL Mode 4 use for ADS-B. As described in the previous sections, ADS-B is inherently integrated into the VDL Mode 4 protocols. GNSS time and position are key elements in providing TDMA timing and channel / slot access. VDL Mode 4 supports periodic broadcasts of aircraft state information (i.e., position, rate of change, aircraft identification, trajectory change points, etc.) as part of its synchronization bursts.

Section 3.3 (Volume I report) presented ADS-B requirements as developed in the ADS-B MASPS. The ADS-B MASPS identifies the data link requirements in terms of 1) information content, 2) update rate, 3) coverage range, 4) and a number of required communication performance factors such as latency, availability, integrity, etc. needed to support ADS-B applications. The typical ADS-B data report is ~200 bits long. ADS-B report update rates for enroute, terminal area, and surface operations are 12 seconds, 5 seconds, and 1 second, respectively. Not all information fields must be updated at the maximum rate. Coverage range requirements can be several miles up to 200 nmi depending on the end-user application.

An assessment of VDL Mode 4 data link loading and resource requirements to support ADS-B in the high-traffic Los Angeles (LA) Basin environment is found in [4]. The LA Basin has been identified as a worst case traffic density. Traffic densities for the LA Basin used in [4] are as follows:

1) 1000 aircraft in enroute airspace
2) 750 aircraft in terminal area airspace
3) 150 aircraft on airport movement areas (per airport)
4) 100 aircraft on closely-spaced parallel approaches (single airport)
5) 50 airports, with 10 large airports are located within the LA Basin.

Enroute Data Link Requirement

As indicated previously, VDL Mode 4 utilizes 4500 time slots per minute (i.e., 75 slots per sec), each slot transmitting 192 bits of information in a typical ADS-B synchronization burst. Assuming that each synchronization burst / slot accommodates a single ADS-B report (to be validated), a single narrowband VHF channel is capable of supporting up to 750 enroute aircraft at a 10 second update rate. Thus two channels are required to meet the 1000 aircraft LA Basin requirement for enroute ADS-B applications (with each aircraft transmitting on both channels at a 20 sec rate per channel). The two VDL Mode 4 channels utilize ~ 66 % capacity for fixed ADS-B synchronization bursts. An additional 25 % capacity is estimated for lower rate ADS-B data (e.g., next trajectory change point, etc.). Also 10 % of capacity is anticipated for directory of services (DoS) messages and autotuning messages. Thus both channels are fully loaded for the worst case LA Basin enroute region.

VDL Mode 4 plans to use the two Global Signalling Channels (GSCs) to provide enroute ADS-B, also providing DoS indicating other available services. GSCs typically utilize self-organizing protocol, where all airspace users develop their own network timing via received synchronization bursts, without need for ground control (i.e., directed services).

Terminal Area Data Link Requirements

With a 5 second update rate for ADS-B, ~ 375 (75*5) aircraft can be supported on a single channel. Terminal area ADS-B is expected to be under ground control, i.e., a ground station assigns time slots for user ADS-B transmissions. Autotuning commands require ~3% loading. Thus two ADS-B channels are needed for LA Basin terminal area ADS-B applications. The same two frequencies are expected to be reused among all airports in the LA Basin due to the relatively low D/U performance of 19.2 kbps GFSK (a low D/U waveform is absolutely essential for VDL Mode 4 ADS-B data link). Aircraft are expected to be able to discriminate between the desired (near) airport and undesired (more distant airports).

Surface Operations (ASMGCS) and Parallel Approaches (PRM) Data Link Requirements

[4] indicates one channel required for each application; Airport Surface Movement Guidance and Control System (ASMGCS) and Precision Runway Monitoring (PRM). With ~ 1 second update rates for moving aircraft / vehicles, some adaptive update rates for stationary or slow moving aircraft / vehicles may be needed to achieve all ADS-B data link within a single channel for each, ASMGCS and PRM.

Summarizing VDL Mode 4 channel requirements from [4]:

1) 2 Global Signalling Channels (GSCs) for enroute ADS-B
2) 2 frequency channels for terminal area ADS-B
3) 1 frequency channel for the ASMGCS ADS-B application
4) 1 frequency channel for the PRM ADS-B application

Note: For VDL Mode 4 data link applications other than ADS-B, [4] estimates that four frequencies are required for DGPS/DGNSS data link, and one frequency is required for each, FIS-B and TIS-B. Thus a total of 10 frequencies are estimated to provide the above services in the LA Basin (not including the two GSCs).

Due to the GSCs, the basic VDL Mode 4 radio configuration consists of two dedicated receivers and one transmitter that tunes between the two GSC frequencies. Additional receivers and perhaps additional transmitters are needed if additional services are included. The number of dedicated transmitter and receiver modules required for VDL Mode 4 are highly dependent on how many of the CNS/ATM data link applications are integrated within a particular radio frequency.

The assumption in this paper is that data link applications (e.g., CPDLC, AOC/AAC, FIS, ADS-B, etc.) will primarily be maintained as separate services (by frequency) due to capacity constraints, "separation of function" considerations, and institutional separation of services. Sections 3.4 and 3.5 (in Volume I report) examine CNS/ATM data link application allocation to various data links, including VDL Mode 4, and develop data link architecture resource requirements.

In Sections 3.4 and 3.5 (Volume I), a dedicated ADS-B resource requirement of 2 transmitters and 4 receivers is assumed, representing the worst case requirement when an aircraft transitions between enroute and terminal area regions under ADS-B surveillance, in an LA Basin type of environment. Both enroute and terminal area ADS-B must be maintained simultaneously in the transition region. Two transmitters are assumed in order to allow independence between enroute and terminal area ADS-B networks. It may be possible to use a single transmitter that can be retuned to transmit on one of four frequencies as long as the occurrence of simultaneous transmit requests to accommodate both ADS-B networks is low.

The above ADS-B loading estimates represent a worst case traffic environment. Conversely, the above estimates also assume 1) near perfect TDMA slot selection in a heavily loaded network (self-organized and ground directed), 2) perfect message reception, i.e., no need for retransmissions or higher update rates due to possible corrupted messages, and 3) that a single VDL Mode 4 slot is sufficient for sending an entire ADS-B report. For high-density areas it is possible that additional channels may be required to offset any additional overhead due to imperfect channel access (e.g., less than ~90 %), message errors, and extra transmissions due to longer message requirements. Further validation of these effects is required.

Additional Considerations of VDL Mode 4 ADS-B

The following are additional factors that impact VDL Mode 4 ADS-B:

1) D/U ratio
2) Range guard time
3) Hidden user, net entry and reservation updates
4) Interoperability with TCAS
5) Frequency band.

D/U Ratio

A low D/U ratio is essential for VDL Mode 4 ADS-B otherwise the concept will not work. A high D/U results in distant aircraft being able to interfere with the reception of ADS-B reports of aircraft that are relatively close. In tracking an aircraft within 25 nmi, a D/U of 18 dB allows an aircraft as far away as 200 nmi to interfere with signal reception. Similarly, tracking a 50 nmi aircraft can be interfered with by an aircraft 400 nmi away.

Two aircraft located either side of the receiving aircraft may not be within radio line-of-sight (RLOS) and are thus hidden (hidden user) and may inadvertently select the same periodic time slots assignments for signal transmission. Time slot assignments are selected based on a one minute (one superframe) listening interval and are maintained for 4 to 8 minutes before they are changed. Thus an aircraft within 25 to 50 nmi may be hidden for 4 to 8 minutes, which due to high closure rates is unacceptable for safe operations. A low D/U allows the aircraft to discriminate between these two aircraft, and a hidden user in this case is not a problem. In addition by using two GSCs, it is unlikely that both hidden users will make the same time slot selections on both channels.

For a low D/U of 6 dB, an aircraft being tracked at 50 nmi can be interfered with by other aircraft within 100 nmi of the receiving aircraft. The two transmitting aircraft will be within RLOS and will make appropriate slot reservations to avoid selecting the same time slots. In high traffic densities, where Robin Hood is used to override time slot assignments of distant users, a low D/U is also beneficial.

An additional margin in the required D/U may be required to account for channel effects and gain imbalances in transmitters and antenna gains. The extent of this margin is critical in determining ADS-B performance and must be investigated.

Range Guard Time

In order to maximize data link throughput, a range guard time of ~1.25 ms is available in the VDL Mode 4 time slot, supporting ~200 nmi range. For ground stations performing long-range ADS-B surveillance, the guard time may become an issue, although a low D/U will discriminate to the closer aircraft. Whether this guard time selection is adequate is TBD.

Hidden User, Net Entry, Reservation Updates

The hidden user was described above and becomes a problem when two aircraft are beyond RLOS of each other and inadvertently select the same time slots for transmitting ADS-B reports. In addition, hidden users can occur when signals are blocked by terrain (e.g., mountains) or buildings, etc., on the airport surface. In selecting slots, aircraft / ground vehicles maintain reservation tables of the entire network (reservation information is included in transmitted messages). These selections are typically made while monitoring the channel for 1 superframe (1 minute). Reservations are maintained for 4 to 8 minutes, before a new series of periodic time slots are selected. Thus it is possible that hidden users could stay hidden up to 8 minutes. Using two independent channels reduces the possibility of message conflicts once users are visible, even if the 8 minutes have not expired. Use of more frequent reservation updates (less than 4 minutes) in order to minimize the duration of possible message collisions due to hidden users may be difficult in high traffic densities due to the excessive reservation changes by all users.

Interoperability with TCAS

Section 3.3.2 (Volume I) discusses issues related to ADS-B surveillance and ACAS/TCAS. Since ADS-B is also expected to support the ACAS application, interoperability with the current TCAS is a requirement. Since TCAS currently uses the Mode-S link for surveillance and an air-to-air resolution advisory link between aircraft, new interfaces to TCAS would likely be required with VDL Mode 4 as the provider of ADS-B reports. Additional issues of independence of ASAS and ACAS, and transition to a new ACAS based on VDL Mode 4 are also discussed in Section 3.3.2 (Volume I).

Independence of Surveillance and Navigation Functions

The independence of surveillance and navigation for VDL Mode 4 is a potential concern. VDL Mode 4 is dependent upon GPS/GNSS time and position information to maintain the data link, while surveillance makes use of the same position information.

Frequency Band Issues

Currently, the VHF Comm band is designated for Aeronautical Mobile Route Services (AMRS) and may not allow transmission of ADS-B surveillance information. In addition, the VHF frequency band is already heavily congested and may not support additional requirements for ADS-B.

4.3.7 Mode-S and ADS-B

Mode-S is also a candidate for ADS-B data link and builds upon the existing Mode-S based surveillance system (Secondary Surveillance Radar and TCAS). Mode-S utilizes a single, wide-band high data rate channel, providing all airspace users with a seamless, global frequency resource for transmitting ADS-B reports. Important issues with Mode-S for ADS-B are capacity, range, and near omnidirectional coverage of transmitting signals, i.e., absence of significant nulls.

Mode-S data link capacity and interference studies indicate that Mode-S is capable of meeting ADS-B requirements for high-density traffic environments (~700 aircraft in LA Basin). In addition, while previously the need for longer range surveillance was not a requirement for airborne TCAS / Mode-S, additional range capabilities needed for ADS-B are possible with these systems and must be validated. Enhanced signal processing of received ADS-B reports will be needed to improve reception probability in high-density traffic areas. Omnidirectional antenna patterns must be investigated. Upper and lower diversity receivers may be required for most aircraft (current air transport aircraft already utilize diversity Mode-S systems). Table D-9 summarizes many of the key issues of ADS-B with respect to Mode-S and VDL Mode 4.

4.3.8 Summary of VDL Mode 4

VDL Mode 4 is a data only (i.e., no digital voice) data link that utilizes TDMA channel access protocols for efficient channel utilization. The signalling rate is 19.2 kbps GFSK. TDMA time slots are ~ 13.33 ms long with ~ 10 ms of the slot available for data transfer, which results in 192 bits per slot.

VDL Mode 4 makes integral use of GPS/GNSS time and position information for TDMA timing and slot selection protocols. All airspace users exchange synchronization bursts (which include position information) to develop system timing, allowing autonomous, self-organizing network access. Channel access can also be controlled directly by ground stations. In addition, VDL Mode 4 includes address and slot reservation information within messages to allow all users to build and maintain a network slot reservation table. This slot reservation table serves as the mechanism for all users to reserve dedicated time slots for desired signal transmissions, thus minimizing slot contention. As the network becomes more fully loaded, it may become difficult to find available slots. VDL Mode 4 utilizes position information on all users to override slot selection of distant users or those that will not be affected by co-channel interference due to geometry.

A VDL Mode 4 user listens to network transmissions for one superframe (1 minute) before selecting available time slots. Time slot selections are maintained for 4 to 8 minutes before a new reservation using different slots is made.

While VDL Mode 4 was originally intended for broadcast services, e.g., ADS-B, it also has provisions for a range of addressed communications and slot reservation protocols and is thus capable of providing a number of data link services. Some envision VDL Mode 4 to be a common

ADS-B Requirement / Issue	Mode-S	VDL Mode 4
Interference immunity	Demonstrated in relatively high density traffic environment for ASGMCS	TBD based on D/U and interference from other VHF Comm applications
Availability, integrity	achievable	achievable
Autonomous	yes	yes in low density traffic, TBD in high density traffic
Range	100 nmi plus (to be verified)	yes (200 nmi)
Traffic density	single wideband channel [2,3]	several narrowband channels, potentially requires numerous channels (to be verified); [4]
Independence of function (Comm, Nav, Surveillance)	yes	potential problem
Independent validation of position	yes	no
Spectrum and spectrum availability	Mode-S band already assigned for surveillance	surveillance via VHF may not be possible due to frequency assignment policy; availability of additional VHF frequency resources in crowded band is TBD
Update rate	high, allowing retransmission of ADS-B reports for increased availability, also needed for TCAS/ACAS	low, but may not be as important in terms of message retry requirement (TBD) due to TDMA protocol likely cannot provide sufficient capacity to support ACAS update rates of ~ 1 second (if required). Requires numerous channel resources in high traffic densities.
Compatibility with TCAS and SSR surveillance, legacy issue	fully compatible with current system	not compatible, likely a difficult transition period
Full message content of ADS-B report	yes	not sure (baro altitude, a/c call sign)?
Hidden user problem	no (not for long time periods)	TBD
Omnidirectional transmit cover volume	TBD	VHF signal more amenable, TBD
Error correction coding	yes, sufficiency to be verified	none at physical layer, potential issue

Table D-9 Data Link Issues for ADS-B (Mode-S and VDL Mode 4)

CNS/ATM data link for CPDLC, AOC/AAC, FIS, FIS-B, TIS-B and ADS-B data link applications. VDL Mode 4 is capable of both ATN-compatible and VHF Specific Services (VSS) data link. VSS supports low-latency tactical communications.

While VDL Mode 4 has many attractive features and capabilities, there are also a number of potential shortcomings. VDL Mode 4, like VDL Mode 3 is considerably more complex than VDL Mode 2. This is primarily due to the TDMA protocol. In addition VDL Mode 4 is highly dependent on precise timing from GPS/GNSS and uses minimal guard times to attain maximum channel data rate. The VDL Mode 4 network, while extremely flexible, does not appear as robust even as VDL Mode 3, which uses centralized timing control from ground stations. "Separation of function" of communications, navigation and surveillance is an important consideration for VDL Mode 4 ,which has a tendency to promote integration of these functions. CNS separation of function, i.e., independence among these functions to avoid common failures, is an important concept in conducting airspace operations.

VDL Mode 4 is highly reliant on low D/U performance of the 19.2 kbps GFSK waveform in order to avoid co-channel interference effects. The robustness of the waveform reduces the available signalling rate to 19.2 kbps. The lower signalling rate along with the associated time slot structure may be inadequate for some high data rate applications such as ADS-B, requiring additional channel resources. It is possible that a bank of VHF channel resources requiring multiple VHF receiver and transmitter modules may be required to satisfy the future CNS/ATM data link requirements. Since the VHF spectrum is already at a premium, allocation of additional services to the VHF band (e.g., ADS-B surveillance) may not be possible.

Since VDL Mode 4 is envisioned by some for providing the ADS-B data link, significant issues arise in terms of the current legacy TCAS / Mode S surveillance system. Since ADS-B is expected to support separation assurance and collision avoidance applications, additional interfaces to TCAS are required. Dual equipage is likely needed during any transition phase before a VHF-based ADS-B and ACAS system can evolve. Since Mode-S is envisioned by some to be the ADS-B data link, with little additional modifications to the current system, a VDL Mode 4 solution may not be cost effective.

For VHF Comm applications, VDL Mode 4 does not provide digital voice capability and thus additional, dedicated radio resources are required to provide both voice and data link services. The competing VDL Mode 3 offers integrated voice and data services simultaneously over the same frequency channel and does not require additional radio resources. In addition, the 31.5 kbps signalling rate supports four voice channels on a single VHF 25 KHz channel and thus provides efficient frequency use in the crowded VHF spectrum. Use of 8.33 KHz analog voice channels in concert with VDL Mode 4 data link may also provides more efficient channel utilization, but requires separate radios.

While VDL Mode 4 provides the potential for a unified data link solution for all CNS/ATM data link applications, there are also numerous potentially serious issues of its use as the end-state CNS/ATM data link for all or even some of these applications. In order to totally resolve these issues will require significant validation activity. At the same time, the industry has been forging ahead with definition and development of Mode-S ADS-B and VDL Mode 2 and 3 for ATC/ATS data link, with substantial investments in time (i.e., many man years of effort have been spent). VDL Mode 4 is a relative newcomer to the various ICAO and RTCA industry committees that are developing data link applications and may have a difficult time gaining acceptance since other solutions are already well along in the development and validation phase. Table D-10 summarizes the performance of VDL Mode 4.

Communications Performance	
Throughput delay	capable of very low latencies due to VHF Specific Services
Message integrity, priority	yes
ATN Compatibility	yes
VHF Specific Services (VSS), i.e., non-ATN	yes
Broadcast Capability	yes
Voice/Data	data only
19.2 kbps GFSK	D/U of ~ 6dB for frequency reuse

Table D-10 VDL Mode 4 Communications Performance Summary

4.4 Comparison of VDL Modes 2, 3 and 4

Table D-11 provides a summary comparison of characteristics and capabilities of the various VDL modes.

VDL Mode 2	VDL Mode 3	VDL Mode 4
air-ground comms	air-ground comms	air-ground, air-air comms
ATN-compatible (addressed comms)	ATN-compatible (addressed comms)	ATN-compatible (addressed comms)
currently no VHF specific services (VSS), i.e., non-ATN, capability	currently no VHF specific services (VSS), i.e., non-ATN, capability	**VSS capability** for local, tactical communications
ideally suited for simplex **broadcast** (some minor modifications to current protocols required)	not well suited for broadcast	broadcast capable
CSMA (efficient channel access for low channel traffic)	TDMA (high efficiency channel access possible)	TDMA (high efficiency channel access possible)
simple protocols, timing	complex, protocols, timing	complex protocols, timing
high latency	low to moderate latency	low latency
data only	**simultaneous voice and data**	data only
31.5 kbps D8PSK	**31.5 kbps** D8PSK	19.2 kbps D8PSK
high D/U (16 to 20 dB)	high D/U (16 to 20 dB)	**low D/U** (~6 dB) to be verified
linear power amplifier required	linear power amplifier required	**nonlinear amplifier**
not a candidate for ADS-B	not a candidate for ADS-B	**ADS-B candidate, capability requires validation (see Table D-9).**
N/A	adequate range guard times	**range guard times marginal**
frequency reuse is TBD (function of coverage volume and D/U margin)	frequency reuse is TBD (function of coverage volume and D/U margin)	frequency reuse is TBD (function of coverage volume and D/U margin)
can meet integrity, availability	can meet integrity, availability	can meet integrity, availability

Table D-11 Summary of VDL Characteristics

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13. ABSTRACT (Maximum 200 words)

The current air traffic environment in airport terminal areas experiences substantial delays when weather conditions deteriorate to Instrument Meteorological Conditions (IMC). Research activity at NASA has culminated in the development, flight test and demonstration of a prototype Low Visiblity Landing and Surface Operations (LVLASO) system. A NASA led industry team and the FAA developed the system which integrated airport surface surveillance systems, aeronautical data links, DGPS navigation, automation systems, and controller and flight deck displays. The LVLASO system was demonstrated at the Hartsfield-Atlanta International Airport using a Boeing 757-200 aircraft during August, 1997. This report documents the contractors role in this testing particularly in the area of data link and DGPS navigation.

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