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AIRPORT SURFACE OPERATIONS REQUIREMENTS ANALYSIS

John L. Groce
Greg J. VonBokern
Rick L. Wray

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Boeing Commercial Airplane Group
P.O. Box 3707
Seattle, WA 98124

NASA
National Aeronautics and Space Administration

Langley Research Center
Hampton, Virginia 23681-0001

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FINAL REPORT

J. Groce
G. Von Bokern
R. Wray

Avionics/Flight Systems
Boeing Commercial Airplane Group
Seattle, Washington

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1.0 SUMMARY

This report documents the results of the Airport Surface Operations Requirements Analysis (ASORA) study. This study was conducted in response to task 24 of NASA Contract NAS1-18027.

This study is part of NASA LaRC's Low Visibility Surface Operations program, which is designed to eliminate the constraints on all-weather arrival/departure operations due to the airport/aircraft ground system. The goal of this program is to provide the capability for safe and efficient aircraft operations on the airport surface during low visibility conditions down to zero. The ASORA study objectives were to (1) develop requirements for operation on the airport surface in visibilities down to zero; (2) survey and evaluate likely technologies; (3) develop candidate concepts to meet the requirements; and (4) select the most suitable concept based on cost/benefit factors.

1.1 REQUIREMENTS

Overall operational requirements were determined to be: situational awareness (including route planning and clearance coordination), steering guidance, ATC surveillance, and obstacle avoidance. Relevant parameters were identified and required accuracies determined for position, speed, track, range, range rate, and relative bearing. Update rate and integrity requirements were also determined.

1.2 COMPARISON OF CANDIDATE CONCEPTS

Four candidate concepts for low visibility surface operations were developed, based on matching technology capabilities to operational and performance requirements. As shown in the table below, concept A used differential GNSS satellite navigation and automatic dependent surveillance (ADS), ASDE-3 airport surface detection radar, and enhanced vision systems (EVS). Concept B used ASDE-3 and EVS; concept C used Mode S Trilateration, ASDE-3, and EVS; and concept D used DGNSS/ADS and ASDE-3.

Concept	Technology Used
A	DGNSS/ADS, ASDE-3, EVS
B	ASDE-3, EVS
C	Mode S Trilateration, ASDE-3, EVS
D	DGNSS/ADS, ASDE-3

1.3 CONCLUSIONS

It was concluded, based on cost/benefit factors which included low visibility probabilities for five airports, that concept A was the most suitable for low visibility surface operations. Analysis determined that it offered the most operational and safety enhancement at a relative cost that appeared only moderately higher than the other candidate concepts.

1.4 RECOMMENDATIONS FOR FURTHER STUDY

Aircraft separation criteria and procedures for surface operations, runway and ground movement optimization, ATC data link requirements and integration, airport data base structure, and appropriate levels of automation were among the most significant areas identified for further study.

2.0 INTRODUCTION

This report presents the results of a study to investigate requirements and concepts for airport surface operations. This study is part of the NASA LaRC Low Visibility Surface Operations program.

2.1 PURPOSE AND GOALS

The purpose of the overall Low Visibility Surface Operations program is to eliminate the constraints on all-weather arrival/departure operations due to the airport/aircraft ground system. The goal of this program is to provide the capability for safe and efficient aircraft operations on the airport surface during low visibility conditions down to zero.

2.2 OBJECTIVES

The objectives of the Airport Surface Operations Requirements Analysis (ASORA) study documented by this report were as follows.

2.2.1 Operations Analysis

Determine the constituent tasks and their related information requirements for operation on the airport surface.

2.2.2 Requirements Analysis

Develop operational and performance requirements to provide the necessary information for low visibility operations on the airport surface; to include navigation, guidance, and obstacle detection.

2.2.3 Technology Survey

Identify and evaluate a broad range of candidate technologies to meet the operational and performance requirements.

2.2.4 Concept Recommendation

First, develop candidate concepts, utilizing selected promising technologies, to meet the requirements for low visibility surface operations. Second, recommend the most suitable concept, based on criteria to include cost/benefit factors and estimated frequencies of low visibility.

3.0 ACRONYMS

ACARS	Aircraft Communications Addressing and Reporting System
ADS	Automatic Dependent Surveillance
AIMS	Airplane Information Management System
AMASS	Airport Movement Area Safety System
APU	Auxiliary Power Unit
ARINC	Aeronautical Radio, Inc.
ARTS	Automated Radar Terminal System
ASDE	Airport Surface Detection Equipment
ASORA	Airport Surface Operations Requirements Analysis
ASRS	Aviation Safety Reporting System
ASTA	Airport Surface Traffic Automation
ATA	Airline Transport Association
ATC	Air Traffic Control
ATIS	Automatic Terminal Information Service
ATN	Aeronautical Telecommunication Network
ATOPS	Advanced Transport Operating System
AVPAC	Aviation VHF Packet Communications
AWDS	Automated Weather Display System
BRITE	Bright Radar Indicator Tower Equipment
CAT	Category, e.g., Cat 3 ILS
CDROM	Compact Disc, Read Only Memory
CGM	Computer Graphics Metafile
CRT	Cathode Ray Tube
DGNSS	Differential GNSS
DGPS	Differential GPS
DOC	Direct Operating Cost
EFIS	Electronic Flight Instrument System
EHSI	Electronic Horizontal Situation Indicator
ELS	Electronic Library System
ESAS	Enhanced Situational Awareness System
EVS	Enhanced Vision System
FAA	Federal Aviation Administration
FCR	Field Condition Report
FDEP	Flight Data Entry and Printout
FLIR	Forward Looking Infrared
FMC	Flight Management Computer
FMS	Flight Management System
FOV	Field of View
GA	General Aviation
GEO	Geosynchronous Earth Orbit
GIC	GNSS Integrity Channel
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HDD	Head Down Display
HUD	Head Up Display
ID	Identification
ILS	Instrument Landing System
INS	Inertial Navigation System
IRS	Inertial Reference System
LaRC	Langley Research Center
LAWRS	Limited Aviation Weather Reporting Station
LEO	Low Earth Orbit

LIDAR	Light Detecting and Ranging System
LLWAS	Low-Level Wind-Shear Alert System
LORAN	Long Range Navigation
MG	Main Gear
MLS	Microwave Landing System
MMW	Millimeter Wave Radar
Mode S	Mode Select, Secondary Surveillance Radar
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NFP	Non-flying Pilot
NG	Nose Gear
NOAA	National Oceanic and Atmospheric Administration
NOTAM	Notice To Airmen
NWS	National Weather Service
OSI	Open System Interconnect
PIREP	Pilot Report
RAIM	Receiver Autonomous Integrity Monitoring
RCS	Radar Cross Section
RVR	Runway Visual Range
RVV	Runway Visual Value
RW	Runway
SAE	Society of Automotive Engineers
SGML	Standard General Markup Language
SIA	Status Information Area
SID	Standard Instrument Departure
SIGMET	Significant Meteorological Information
SMGCS	Surface Movement Guidance and Control System
STAR	Standard Terminal Arrival Route
TCAS	Traffic Alert and Collision Avoidance System
TSRV	Transportation Systems Research Vehicle
TW	Taxiway
U.S.	United States
UTC	Universal Time, Coordinated
V_1	Takeoff Decision Speed
V_2	Initial Segment Climb Speed
VFR	Visual Flight Rules
VHF	Very High Frequency
V_R	Takeoff Rotation Speed

4.0 SCOPE AND ASSUMPTIONS

Ground rules were developed to define the scope of the study so that a reasonable amount of detail could be reached in the concept development stage.

4.1 TIME FRAME FOR SYSTEM IMPLEMENTATION

The time frame from 1997-2001 is assumed. Factors to consider here are whether or not ATC automation programs will be in place to support the identified ASORA concepts. A key component may be a data link system, as well as AMASS (Airport Movement Area Safety System) and ASTA (Airport Surface Traffic Automation) programs. AMASS will provide data tags on ASDE-3 surface radar displays, as well as provide alerts of potential or actual runway incursions. ASTA will go further, providing Mode S data link communications for taxi route guidance and monitoring, as well as direct cockpit alerts, and automatic runway status lights. The FAA's Runway Incursion Plan indicates the following system implementation dates:

AMASS First Operational Readiness - 11/30/94
ASTA Taxi Routing in Cockpit - 1/31/00
Direct Cockpit Alerts - 3/31/01

The assumed time frame will also support implementation of several airport ground installations which are key to low visibility operations. As described in a recently released advisory circular on low visibility surface operations (ref. 1), ASDE-3 is targeted for implementation at 29 major airports in the U.S. Reference 1 also sets forth requirements for airport lighting, signage, routing, and various procedural requirements in areas such as crash/fire/rescue, airline, and airport authority, etc. Visibility minima are also stated for various elements of low visibility surface operations discussed in reference 1.

4.2 BASELINE AVIONICS TECHNOLOGY

The development of concepts for low visibility taxi navigation, guidance, and obstacle avoidance will be directly affected by the nature of the avionics available on-board the aircraft. Current air transport flight deck technology is sharply divided between a) electro-mechanical instruments without FMC's (e.g., B-727, B-737-200, B-747-200, DC-9, etc.) and b) glass cockpit flight decks employing EFIS and FMC (e.g., B-757/67, B-737-3,4,500, B-747-400, MD-80, etc.) Many of the electro-mechanical instrument, non-FMC aircraft are 20 to 25 years old, and could well be out of service due to aging aircraft and stage 2/3 noise regulations. Implementation of low visibility guidance on the EFIS/FMC equipped class of aircraft would seem to provide the most long term benefit to the ATC system and airlines. Therefore, baseline equipage is assumed to include Electronic Flight Instruments (EFIS) and Flight Management Computers (FMC).

The target flight deck will also be assumed to be equipped with an Inertial Reference or Navigation System (IRS/INS) as a basic part of its navigation capability, as well as computer processing and data storage capabilities available for uses outside the standard FMS applications.

4.3 AIRPORT EQUIPAGE CLASS

Baseline airport equipage is assumed to be that of an airport having a Category 3 (Cat 3) ILS approach. This is significant for low visibility surface operations due to the enhanced ground installations required at airports having a Cat 3 ILS approach. Even though operation in actual zero visibility will probably not benefit, Cat 3 airport features such as airport runway and taxiway lighting, pavement marking, and signs are expected to have a major impact on taxi requirements in low visibility levels where some visual reference is still possible. Since this limited visibility condition will be more common than zero visibility, a comprehensive airport ground installation will be assumed.

4.4 SCOPE OF SURFACE OPERATIONS

Aircraft surface operations will be considered from runway exit during landing to runway entrance on takeoff, including all intervening surface operations in the movement and non-movement areas. Factors to consider here are that airplane operations in the non-movement area are usually considered outside the jurisdiction of ATC control, while aircraft operations in the movement area require an ATC clearance. The non-movement area usually is indicated by a red and white line painted on the ramp which divides the gate and ramp area from the taxiways and runways.

Currently, airport traffic is quite reduced during low visibility periods, resulting in fewer ramp and taxiway operations. Marshallers, tugs, or follow-me trucks are sometimes used to guide aircraft into or out of the gate/ramp area, and on occasion on the taxiway as well.

If a future environment having near-VFR capacity is to be achieved in low visibility conditions, however, much heavier traffic densities will have to be accommodated, negating the use of such simplistic and time consuming methods as tugs and follow-me trucks. Pushback of other aircraft, identification of appropriate gates, and avoidance of buildings and other obstructions will probably necessitate new solutions.

4.5 SCOPE OF SURFACE VEHICLE OPERATIONS

Vehicular operations will be considered only in the movement area.

Vehicular traffic in the movement area must be controlled by ATC, just as aircraft must be, requiring 2-way radio contact with each vehicle. A study of low visibility surface operations must consider vehicles along with aircraft, due to the potential for vehicle-caused runway incursions and traffic conflicts.

Vehicular traffic in the non-movement area, however, is not controlled by ATC, and usually remains within vehicle lanes painted on the ramp surface or within the confines of each airline's gate complex. Some very busy airports (e.g., Chicago O'Hare) have airline ramp controllers to coordinate airplane and vehicular operations in the non-movement area. In either case, however, the responsibility of vehicle drivers to see and avoid all aircraft will become much more difficult to perform as visibility levels decrease. Airline unique requirements, and the wide variation in potential solutions to such difficult problems indicates that this phase of operation should be outside the scope of this study.

4.6 SCOPE OF HAZARDS

Potential collision with vehicles, aircraft, animals, people, buildings, fences, and construction equipment will be addressed.

Hazards due to operations off paved weight-bearing areas, operations on paved areas designated as unsuitable for a specific aircraft weight, operations in areas designated closed for construction, and operations in areas temporarily closed due to operational considerations (e.g., ILS critical area during Cat 2/3 approaches or low visibility route limitations) will be addressed.

4.7 VISIBILITY LEVEL

Visibility levels from 600 feet RVR to zero will be considered. Current surface operations are fairly well defined at major airports with visibilities down to 600 feet. Reference 1 also proposes additional airport requirements below 600 feet.

5.0 BACKGROUND

Aircraft maneuvering on the airport surface is becoming more of a problem as new airport and flight deck installations permit takeoffs and landings at lower visibility levels than before, while system capabilities for taxi operations lag far behind.

Category 3 ILS ground installations transmit very accurate runway approach information to double or triple-redundant autopilot/flight director systems that compute guidance commands for the pilot. The airline industry trend is toward more fleet equipage with sophisticated controls and displays to allow arrivals and departures in visibilities down to 300 feet RVR, often allowing automatic touchdown and rollout. Accurate surveillance of airborne traffic in the terminal area is provided by ARTS 2 or ARTS 3 radar, allowing ATC to detect and resolve conflicts and maintain safe separation. Alphanumeric data tags are displayed for each flight, showing identity, altitude, and groundspeed, as well as a graphic depiction of position and track. Prospects for lower takeoff and landing minima are promising. Current European Cat 3 operations sometimes go as low as 150 feet RVR, while research into enhanced vision and synthetic vision systems consider operations down to zero visibility.

In sharp contrast, the only information available to the pilot for maneuvering to/from the runway/gate is based on visual cues through the flight deck windows. The perimeters of taxiways and runways are defined by painted lines on the pavement, with blue or white lights placed periodically along the edges. Color-coded signs are used to indicate intersections and taxiway/runway numbers or names. Runway hold lines and ILS critical areas are indicated by painted lines on the pavement with additional lighting sometimes used to mark the lines. Taxiway centerlines are indicated by painted lines on the pavement, with flush-mounted centerline lights installed at Cat 3 certified airports. ATC surveillance of surface traffic at most airports is provided simply by visual scanning by the controllers, supplemented by pilot-reported positions transmitted over the tower/ground control VHF frequency. Cat 3 certified airports also have ASDE equipment installed, which provides a primary radar display of objects on the airport surface. ASDE has serious limitations, including lack of target identification, and poor resolution.

The discrepancies of navigation/surveillance capabilities between taxi and arrival/departure operations result in increasing use of gate hold and other procedural techniques to limit the number of aircraft taxiing into or out of the gate area. These discrepancies will be exacerbated by the industry trend for even lower takeoff/landing minima.

5.1 CURRENT RESEARCH

Various aspects of the low visibility surface operations problem are currently being investigated by NASA, FAA, and industry groups.

5.1.1 Requirements Development

Boeing is pursuing this under NASA ATOPS Task Assignment 24, Airport Surface Operations Requirements Analysis, documented by this report. RTCA Task Force 1, Global Navigation Satellite System Transition and Implementation Strategy Task Force (ref. 8), has developed requirements for utilizing satellite navigation systems for airport surface, terminal and enroute airspace.

The FAA's Runway Incursion Program is developing guidelines and procedures for ATC and pilots to prevent runway incursions. It specifically addresses low visibility problems in a recently released advisory circular (ref. 1) defining the Surface Movement Guidance and Control System (SMGCS). A new generation of ASDE and improved airport signs and lighting are being developed, although the pilot must still rely on visual scanning techniques to follow the desired route and avoid obstacles.

5.1.2 Sensor Technology Research

Vendor teams have recently been formed to develop millimeter wave radar (MMW), forward looking infrared radar (FLIR), and light detecting and ranging (LIDAR) sensors. The TRW Company is participating with NASA LaRC in a low visibility sensor display effort, and FAA-sponsored tower tests will collect sensor data under various visibility conditions with a variety of sensors.

5.1.3 GPS Navigation Development

The Global Positioning System (GPS) industry is developing new GPS receivers. Carrier phase tracking experiments indicate extremely accurate positioning will soon be possible. NASA LaRC has an on-going program of GPS testing in their Transportation Systems Research Vehicle (TSRV) test aircraft.

Aeronautical Radio, Inc. (ARINC), the City of Chicago, and United Airlines are cooperating in an evaluation and demonstration of GPS for vehicle and aircraft surface applications at O'Hare airport. ARINC will be collecting position accuracy data for vehicles and aircraft operating on a designated course.

5.1.4 Data Link Development

A wide range of data link activity is occurring. The Society of Automotive Engineers (SAE) G-10 committee is studying data link issues, with industry, ATC, NASA, and Mitre Co. participation. The Airline Transport Association (ATA) human factors task force is also investigating data link issues.

NASA Ames and LaRC have both been actively conducting piloted simulations of data link, references 19 and 20. Boeing is developing data link for FMC updates to the B-747, as well as for the B-777. A pilot error study was performed by Boeing under FAA contract DTFA01-90-C-0056 which also included the effects of data link on pilot error. Current Boeing research is focussed on comparisons of alternative pilot interfaces for data link.

FAA's AMASS and ASTA programs also use data link.

5.1.5 Flight Deck Displays

NASA Ames is currently conducting preliminary investigations into how pilots may use a taxi display. The focus is on the ways that a pilot may misuse such a display, and how those errors may be minimized.

NASA LARC is planning to develop taxi displays for implementation on their TSRV aircraft. Incorporation of sensor images as well as GPS positioning data is being considered.

GP&C, a Swedish research firm, has developed a PC-based taxi display which it will operate in a general aviation aircraft during the O'Hare GPS trials.

The Boeing Enhanced Situation Awareness System (ESAS) project is initially oriented toward autonomous aircraft operations into CAT 1 equipped airports under CAT 3A visibility conditions. Three component parts make up this effort, namely the EVS (Enhanced Vision System), Terrain Awareness, and Low-Visibility Taxi Operations. The study concentrates primarily on EVS operations, although aspects of it, such as the display development effort, are intended to support the other components, and progress in the other areas will hopefully provide useful insights and perhaps valuable research tools in the study of low-visibility taxi operations and overall airport surface management and control.

6.0 INFORMATION ANALYSIS

This section discusses results of an information analysis conducted in preparation for subsequent requirements development. A broad approach was taken which studied surface operations from both the pilot's and the controller's perspective, to allow a systems approach to be used for subsequent requirements and concepts development.

Observations of ATC controllers were conducted at Seattle-Tacoma Airport control tower during both high and low visibility conditions, noting tasks such as clearance issuance, ASDE-2 radar monitoring, and general strategic planning and tactical intervention. Jump-seat observations were also made aboard various commercial jet transports, studying areas such as taxi clearance coordination, obstacle detection, speed and directional control, and general situational awareness. Further discussions with controllers and pilots provided additional insights into surface operations.

6.1 PILOT PERSPECTIVE

Table 6-1 describes a functional breakdown of pilot tasks associated with surface operations. The methodology illustrated in the table was adopted from a previous NASA ATOPS study (ref. 2) which analyzed pilot tasks for all phases of flight. For an entire mission analysis, surface operations are typically considered as one phase of operation referred to as "taxi". The following analysis breaks surface operations into multiple phases for a more thorough investigation. The takeoff and touchdown phases are also included to capture any transition or coordination type situations as surface operations are begun or terminated.

TABLE 6-1
PILOT TASKS FOR SURFACE OPERATIONS

I. PREPARE FOR PUSHBACK
  - A. Start APU if required
    - 1. Determine ground services available (air/electrical))
    - 2. Determine area around APU is clear
  - B. Configure airplane systems
    - 1. Set systems for operation as required
    - 2. Adjust for appropriate airport conditions
      - a) Departure Runways (RW's) in use
      - b) Wind/alt. Setting
  - C. Coordinate with airline ground crew
    - 1. Determine if area is clear for pushback
  - D. Coordinate pushback time with ATC
    - 1. Comply with Ground Hold Procedures
      - a) Determine which/if procedures in effect
      - b) Comply with gate hold procedures
        - (1) Determine gate delay required
      - c) Comply with flow control procedures
    - 2. Advise Ground Control when ready for pushback
      - a) Determine cleared for pushback
      - b) Determine ramp constraints for pushback

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TABLE 6-1 (Continued)

II. PUSHBACK FROM GATE INTO NON-MOVEMENT AREA (RAMP/APRON)
- A. Confirm ready for push
  1. Doors closed
  2. Jetway retracted
  3. Ground equipment clear
- B. Monitor pushback
  1. Brakes released
  2. Nosegear free
  3. Clear area behind airplane
  4. Stop when in desired position

III. START ENGINES
- A. Clear around engines
- B. Initiate start
- C. Monitor for abnormalities, abort if necessary

IV. TAXI THROUGH NON-MOVEMENT AREA
- A. Plan taxi path to runway entrance
  1. Ground control issued constraints
  2. Published constraints (Airplane size/weight limitations)
  3. Airport signs and surface markings
- B. Follow desired route to movement area
  1. Present position/heading
  2. Desired position/heading
  3. Determine steering error
     - a) Nosewheel steering commands
     - b) Differential thrust/braking commands
  4. Determine if deviation from cleared route has occurred
     - a) Determine new ground control-issued route
- C. Avoid obstacles
  1. Position of nearby obstacles
  2. Identify obstacle/airplane conflicts
  3. Maneuver as required to avoid
     - a) Nosewheel steering commands
     - b) Differential thrust/braking commands
- D. Avoid new obstacles
- E. Remain in non-movement area
- F. Avoid foreign object ingestion
  1. Identify dangerous foreign objects
     - a) Position of nearby people/foreign objects too close to engine intakes
     - b) Determine if hazardous to ingest
  2. Maneuver as required to avoid
- G. Avoid upsetting other obstacles with jet exhaust
  1. Detect obstacles behind engine nozzles
  2. Determine if upsettable
  3. Eliminate upset
     - a) Nosewheel steering commands
     - b) Thrust limit commands
     - c) Remove obstacle

TABLE 6-1 (Continued)

H. Control Speed
   1. Set breakaway thrust as required, then reduce
   2. Maintain safe ground speed
      a) Min/max safe ground speed
      b) Actual ground speed
      c) Speed error
         (1) Thrust command
         (2) Braking command
   3. Stop as required
      a) Location of beginning of movement area
      b) Predicted braking distance
      c) Thrust command
      d) Braking command

I. Obtain taxi clearance
   1. Pilot-preferences and constraints for taxi routing
      a) Published airport data
         (1) Airplane size/weight limitations
         (2) Relevant amendments (e.g., construction)
   2. Cleared taxi route
   3. Verify clearance is acceptable

V. PROCEED OUTBOUND ALONG TAXIWAY TO RUNWAY ENTRANCE

A. Re-plan taxi route to runway entrance
   1. Ground control issued constraints
   2. Published constraints (airplane size/weight limitations)
   3. Airport signs and surface markings

B. Merge into movement area
   1. Identify aircraft traffic to follow (if any)
      a) Position of traffic to follow
   2. Taxi path to cleared taxiway (if not specified by ATC)
   3. Control taxi path to taxiway
      a) Steering/braking/thrust commands

C. Follow desired route to runway entrance
   1. Present position
   2. Desired position
   3. Corrective action
      a) Determine if left/right steering will correct route
         (1) Nosewheel steering commands
         (2) Differential thrust/braking commands
      b) Determine if deviation from cleared route has occurred
         (1) New route to intercept path

D. Avoid runway incursions
   1. Position of nearby crossing runways
   2. Runway identities
   3. Status of clearance to cross
   4. Verify that runway is clear
      a) Presence of aircraft, vehicles, obstacles on runway

TABLE 6-1 (Continued)

E. Avoid obstacles
   1. Detect obstacles
   2. Identify obstacle/airplane conflicts
   3. Maneuver as required to avoid
   4. Steer left/right and slow down as required
   5. Avoid new obstacles
   6. Remain on weight-bearing surface

F. Avoid foreign object damage
   1. Detect foreign objects close to engine intakes
   2. Determine if hazardous to ingest
   3. Avoid hazardous objects

G. Avoid upsetting other obstacles with jet exhaust
   1. Detect obstacles behind engine nozzles
   2. Determine if upsettable
   3. Eliminate upset
      a) Change direction, limit thrust, remove obstacle

H. Control speed
   1. Set breakaway thrust as required, then reduce
   2. Maintain safe ground speed
      a) Determine min/max safe ground speed
      b) Adjust speed to maintain safe separation from taxiing traffic
      c) Monitor actual ground speed
         (1) If fast, reduce thrust/increase braking
         (2) If slow, increase thrust/reduce braking
   3. Stop as required
      a) Predict braking distance
      b) Idle thrust
      c) Apply brakes
      d) Set parking brake as needed

VI. PREPARE FOR TAKEOFF

A. Set airplane systems to takeoff configuration

B. Advise local controller ready for takeoff

VII. PROCEED INTO TAKEOFF POSITION ON RUNWAY

A. Receive and acknowledge clearance onto runway

B. Re-plan taxi route onto runway, if necessary
   1. Note any ground control issued constraints
   2. Note published constraints (airplane size/weight limitations)
   3. Note airport signs and surface markings

C. Confirm runway/approach path clear of traffic

D. Control speed
   1. Set breakaway thrust as required, then reduce
   2. Maintain safe ground speed
      a) Determine min/max safe ground speed
      b) Monitor actual ground speed
         (1) If fast, reduce thrust/increase braking
         (2) If slow, increase thrust/reduce braking

TABLE 6-1 (Continued)

3. Stop as required
    a) Identify beginning of movement area
    b) Predict braking distance
    c) Idle thrust
    d) Apply brakes
    e) Set parking brake as needed

E. Follow desired route onto runway
1. Determine present position
2. Determine desired position
3. Determine corrective action
    a) Determine if left/right steering will correct route
        (1) Use nosewheel steering
        (2) Use differential thrust, braking
    b) Determine if deviation from cleared route has occurred
        (1) Coordinate with ground control to intercept route

F. Align airplane with runway
1. Track runway centerline until nosegear neutral
2. Confirm actual heading checks with runway heading
3. Confirm sufficient runway remaining for takeoff

G. Avoid obstacles
1. Detect obstacles
2. Identify obstacle/airplane conflicts
3. Maneuver as required to avoid
4. Steer left/right and slow down as required
5. Avoid new obstacles
6. Remain on runway

H. Avoid foreign object ingestion
1. Detect foreign objects close to engine intakes
2. Determine if hazardous to ingest
3. Avoid hazardous objects

I. Avoid upsetting other obstacles with jet exhaust
1. Detect obstacles behind engine nozzles
2. Determine if upsettable
3. Eliminate upset
    a) Change direction, limit thrust, remove obstacle

VIII. TAKEOFF

A. Receive and acknowledge takeoff clearance
B. Confirm runway clear of traffic
C. Confirm airplane systems set for takeoff
D. Set takeoff thrust
E. Track runway centerline
1. Use nosewheel steering at low speeds
2. Use rudder pedal steering at high speeds
3. Monitor steering authority
4. Manipulate aileron and rudder to counter cross winds

TABLE 6-1 (Continued)

F. Monitor takeoff parameters
    1. Airspeed
    2. Acceleration
    3. Runway length remaining
    4. Thrust
    5. Non-normal system alerts
    6. Vibration levels

G. Avoid obstacles
    1. Detect obstacles
    2. Identify obstacle/airplane conflicts
    3. Maneuver to avoid as required
    4. Steer left/right and slow down as required
    5. Avoid new obstacles
    6. Remain on runway

H. Make takeoff decision
    1. Identify approaching V_1
    2. Determine acceptable acceleration
    3. Determine acceptable runway length remaining
    4. Determine acceptable airplane systems

I. Rotate and initial climb
    1. Identify V_R
    2. Rotate to correct pitch attitude
    3. Avoid tailstrike
    4. Confirm positive rate of climb
    5. Maintain V_2 airspeed

IX. LANDING FLARE AND TOUCHDOWN

A. Track runway centerline
    1. Follow flight director commands
        a) Zero localizer deviation with aileron and rudder
    2. Manipulate aileron and rudder to counter crosswinds

B. Control vertical path
    1. Maintain correct glide slope
    2. Determine and maintain proper aim point
    3. Maintain approach speed
    4. Avoid excessive rate of descent
    5. Avoid very low thrust settings

C. Make landing decision
    1. Identify decision height (if applicable)
    2. Visually identify runway environment (if applicable)
    3. Determine acceptable runway length remaining
    4. Confirm runway clear of obstacles

D. Landing flare and touchdown
    1. Identify flare height
    2. Increase pitch to flare attitude
    3. Reduce thrust
    4. Reduce pitch to lower nose

TABLE 6-1 (Continued)

X. ROLLOUT
- A. Track runway centerline
  1. Follow flight director commands
     - a) Zero localizer deviation with aileron and rudder
  2. Manipulate aileron and rudder to counter cross-winds
  3. Visually acquire and track centerline
     - a) Use rudder pedals until slow enough for nose wheel steering
- B. Avoid obstacles
  1. Detect obstacles
  2. Identify obstacle/airplane conflicts
  3. Maneuver as required to avoid
  4. Steer left/right and slow down as required
  5. Avoid new obstacles
  6. Remain on runway
- C. Determine desired runway exit point
  1. Determine location of high speed taxiway exits
  2. Determine location of parking area
  3. Receive advisories and instructions from local controller
- D. Decelerate to runway exit speed
  1. Determine runway exit speed based on:
     - a) High speed or standard runway exit
     - b) Runway condition
  2. Apply braking
     - a) Speed brakes
     - b) Thrust reversers
     - c) Wheel brakes
  3. Monitor actual deceleration/runway remaining

XI. PROCEED ONTO RUNWAY EXIT
- A. Identify desired runway exit
  1. Determine current position on runway
  2. Determine distance and direction (left/right) to exit
  3. Visually acquire lead-in lines to exit
  4. Visually acquire runway exit sign
- B. Track lead-in lines to runway exit
  1. Use rudder pedal steering if high speed
  2. Use nose wheel steering at slow speed
  3. Follow lead-in lines
- C. Avoid obstacles
  1. Detect obstacles
  2. Identify obstacle/airplane conflicts
  3. Maneuver as required to avoid
  4. Steer left/right and slow down as required
  5. Avoid new obstacles
- D. Proceed until clear of active runway
  1. Proceed onto runway exit until tail clears runway
  2. Ensure that runway hold line is crossed
- E. Contact ground control
  1. Advise ground control of current location and desired parking

TABLE 6-1 (Continued)

XII. MERGE ONTO TAXIWAY
- A. Obtain taxi clearance
  - 1. Request and receive clearance from ground control
  - 2. Plan taxi path to non-movement area
    - a) Identify pilot-preferences and constraints for taxi routing
      - (1) Reference published airport data
        - (a) Consider airplane size, weight limitations
        - (b) Determine relevant amendments (e.g.,Construction)
      - (2) Recall ATIS info
    - b) Verify clearance is acceptable and acknowledge ATC
- B. Merge onto taxiway
  - 1. Identify aircraft traffic to follow and maintain separation
  - 2. Determine path to cleared taxiway (if not specified by ATC)
  - 3. Control taxi path to taxi way

XIII. PROCEED INBOUND ALONG TAXIWAY TO NON-MOVEMENT AREA
- A. Plan taxi route to gate
  - 1. Note any ground control issued constraints
  - 2. Note published constraints (airplane size/weight limitations)
  - 3. Note airport signs and surface markings
- B. Follow desired route
  - 1. Determine present position
  - 2. Determine desired position
  - 3. Determine corrective action
    - a) Determine if left/right steering will correct route
      - (1) Utilize nosewheel steering
      - (2) Utilize differential thrust/braking
    - b) Determine if deviation from cleared route has occurred
      - (1) Coordinate with ground control to intercept route
- C. Avoid runway incursions
  - 1. Detect proximity of crossing runways
  - 2. Identify runway and active/inactive status
  - 3. Determine if taxi clearance allows crossing
  - 4. Visually check for traffic on runway
- D. Avoid obstacles
  - 1. Detect obstacles
  - 2. Identify obstacle/airplane conflicts
  - 3. Maneuver to avoid as required
  - 4. Steer left/right and slow down as required
  - 5. Avoid new obstacles
  - 6. Remain on weight-bearing surface
- E. Avoid foreign object damage
  - 1. Detect foreign objects close to engine intakes
  - 2. Determine if hazardous to ingest
  - 3. Avoid hazardous objects
- F. Avoid upsetting other obstacles with jet exhaust
  - 1. Detect obstacles behind engine nozzles
  - 2. Determine if upsettable
  - 3. Eliminate upset
    - a) Change direction, limit thrust, remove obstacle

TABLE 6-1 (Continued)

G. Control speed
   1. Set breakaway thrust as required, then reduce
   2. Maintain safe ground speed
      a) Determine min/max safe ground speed
      b) Adjust speed to maintain safe separation from taxiing traffic
      c) Monitor actual ground speed
         (1) If fast, reduce thrust/increase braking
         (2) If slow, increase thrust/reduce braking
   3. Stop as required
      a) Predict braking distance
      b) Idle thrust
      c) Apply brakes
      d) Set parking brake as needed

XIV. PROCEED TO GATE
A. Re-plan taxi path to gate, if necessary
   1. Note any ground control issued constraints
   2. Note published constraints (airplane size/weight limitations)
   3. Note airport signs and surface markings
B. Follow desired route to gate
   1. Determine present position
   2. Determine desired position
   3. Note airport surface markings
   4. Determine corrective action
      a) Determine if left/right steering will correct route
         (1) Utilize nosewheel steering
         (2) Utilize differential thrust/braking
      b) Determine if deviation from cleared route has occurred
         (1) Coordinate with ground control to intercept route
   5. Visually acquire and follow ground crew hand signals
C. Avoid obstacles
   1. Detect obstacles
   2. Identify obstacle/airplane conflicts
   3. Maneuver to avoid as required
   4. Steer left/right and slow down as required
   5. Avoid new obstacles
   6. Remain on non-movement area
D. Avoid foreign object ingestion
   1. Detect foreign objects close to engine intakes
   2. Determine if hazardous to ingest
   3. Avoid hazardous objects
E. Avoid upsetting other obstacles with jet exhaust
   1. Detect obstacles behind engine nozzles
   2. Determine if upsettable
   3. Eliminate upset
      a) Change direction, limit thrust, remove obstacle

TABLE 6-1 (Continued)

F. Control speed
  1. Set breakaway thrust as required, then reduce
  2. Maintain safe ground speed
    a) Determine min/max safe ground speed
    b) Monitor actual ground speed
      (1) If fast, reduce thrust/increase braking
      (2) If slow, increase thrust/reduce braking
  3. Stop as required
    a) Identify beginning of gate area
    b) Predict braking distance
    c) Idle thrust
    d) Apply brakes
    e) Set parking brake as needed

6.2 ATC CONTROLLER PERSPECTIVE

Table 6-2 describes a functional breakdown of controller tasks associated with surface operations. FAA operational procedures, techniques, and regulations related to surface operations (ref. 3 & 4) were used in developing this information.

TABLE 6-2
CONTROLLER TASKS FOR SURFACE OPERATIONS

I. FLIGHT DATA - TOWER CAB
  A. Process weather information
    1. Receive/observe weather information from:
      a) Appropriate tower equipment
      b) Adjacent facilities
      c) National Weather Service (NWS)
      d) Flight data entry and printout (FDEP) printer
      e) Pilot reports (PIREPS)
      f) Limited aviation weather reporting station (LAWRS)
      g) Tower visibility criteria (tower controller estimate)
    2. Disseminate weather information to:
      a) Adjacent facilities
      b) Other tower cab positions
      c) Aircraft (via the Automatic Terminal Information Service (ATIS))
  B. Prepare, record, and monitor ATIS
    1. Prepare ATIS information to include:
      a) Phonetic alphabet code
      b) Time of report (in UTC)
      c) Ceiling
      d) Visibility
      e) Obstructions to vision
      f) Temperature
      g) Dew point
      h) Density altitude advisory
      i) Wind direction (magnetic) and velocity
      j) Altimeter setting
      k) Instrument/visual approach(es) in use
      l) Landing/departing runways

TABLE 6-2 (Continued)

m) Notifications; NOTAMS, PIREPS, SIGMETS (pertinent to terminal area operations)
n) Braking action reports or advisories
o) Low level wind shear advisories
p) Other remarks or advisories

2. Record ATIS information
3. Check ATIS recording for accuracy
4. Report ATIS out of service/return to service

C. Process miscellaneous flight data
1. Request or receive miscellaneous flight data, including:
a) Notices to Airmen (NOTAMS)
b) National Airspace System (NAS) status
c) Facility equipment status
d) Flow restrictions
e) Special use airspace
f) Special activities
2. Maintain Status Information Area (SIA)
3. Distribute miscellaneous flight data

D. Process Field Condition Report (FCR)
1. Receive and review FCR via landline or other tower cab position
2. Disseminate FCR to adjacent facilities and/or tower cab positions

E. Process flight plan information (arrival, departure)
1. Receive flight plan via FDEP, interphone, or commercial lines
2. Review flight plan information for completeness and accuracy
3. Process flight plan information (including flight progress strip)
4. Disseminate flight plan information to appropriate positions

F. Process traffic management message
1. Receive traffic management message via FDEP or interphone
2. Review traffic management message for operational use
3. Disseminate traffic management message to appropriate positions

G. Communicate and coordinate air traffic information
1. Analyze air traffic information to determine its priority
2. Determine the correct means and routing for dissemination

H. Operate or monitor tower cab equipment
1. Electrowriter
2. Flight Data Entry and Printout (FDEP)
3. Automatic Terminal Information Service (ATIS)
4. Interphones
5. Automated Weather Display System (AWDS)
6. Automated Radar Terminal System (ARTS)
7. Rotating beam ceilometer
8. Transmitters/receivers
9. Twenty-four-hour clock
10. NAVAID monitor panel
11. Recorder equipment and monitor panel
12. Altimeter

II. GATE HOLD

A. Initiate, implement, and terminate gate hold procedures
1. Initiate gate hold procedures when warranted (declared by controller-in-charge, under specific departure delay conditions)

TABLE 6-2 (Continued)

2. Implement gate hold procedures
    a) Ensure "push-back" (engine start) sequence is consistent with the initial call-up sequence
    b) Issue to pilot and record estimated engine start time
    c) Update engine start time estimate
3. Notify appropriate personnel when gate hold is terminated

III. CLEARANCE DELIVERY

A. Process flight plan information
   1. Receive flight plan information via radio or flight data position
   2. Review, amend and disseminate information if necessary
   3. Process flight progress strips
B. Receive, formulate, and issue clearances, instructions
   1. Receive clearance request from flight crew, then correlate request with flight plan
   2. Formulate clearance to include:
      a) Aircraft identification
      b) Clearance limit
      c) Departure procedure
      d) Route of flight
      e) Altitude
      f) Departure frequency
      g) Transponder code when required
   3. Issue clearances/amendments/instructions to flight crew via radio or data link
   4. Forward flight strip to the appropriate position (gate hold or ground control)
C. Operate or monitor equipment
   1. Interphones
   2. Automated Radar Terminal System (ARTS)
   3. Transmitters/receivers
   4. Twenty-four-hour clock

IV. GROUND CONTROL

A. Definition of ground controller decision process
   1. Scan the outside movement area(s)
      a) Taxiways/runways
      b) Run-up areas/holdline
      c) Park areas for taxiway entry
      d) Turning points/intersections
      e) Congestion areas
      f) ILS critical areas
      g) Restricted areas
      h) Local airport problem areas
   2. Scan the inside work environment
      a) Wind instruments
      b) Low level wind shear alert system (LLWAS)
      c) Altimeter setting indicator
      d) Runway visual range/runway visibility value (RVR/RVV)
      e) Strips/pad/facility-developed forms
      f) Airport surface detection equipment (ASDE)
      g) Bright radar indicator tower equipment (BRITE)

TABLE 6-2 (Continued)

3. Develop/coordinate a ground movement plan which accommodates the airport objectives:
    a) Provide safe surface movement, on requested route (if feasible), with minimal delay
    b) Provide airport/flight information
    c) Protect critical/special areas
    d) Observe noise abatement criteria
4. Continually scan for factors that may affect the operation:
    a) Development of the situation as planned
    b) Detection of flaws in the plan
    c) Unauthorized aircraft/vehicle movements
    d) Traffic conflicts
    e) Emergency/unusual situations
    f) Weather phenomena
    g) Location of aircraft/vehicles
    h) Violation of restricted/ILS critical area
    i) Equipment malfunctions
    j) Surface conditions

B. Receive request for ground traffic movement
1. Receive ground traffic (aircraft/vehicle) movement request via:
    a) Radio
    b) Visual observation
    c) Other controller position
2. Fulfill ground movement requirements
    a) Obtain aircraft/vehicle identification, location and intentions
    b) Ensure that aircraft taxiing for departure have received the required departure information (i.e. ATIS information)

C. Coordinate with a control position
1. Request intended operation which requires coordination with another control position (i.e. runway crossing)
2. Relay/respond to aircraft or vehicle (approved, unable or stand by)
3. Report to coordinating controller when operation is complete

D. Issue ground movement instructions
1. Ground movement instructions
    a) Unrestricted taxi instructions to an assigned take-off runway
    b) Unrestricted aircraft/vehicle movement instructions to a specific point other than an assigned take-off runway
    c) Restricted instructions where taxi route to an assigned take-off runway is specified
    d) Restricted aircraft/vehicle movement instructions to a specific point via a specific route
    e) Restricted ground movement instructions at any point (enroute) due to traffic or other operational considerations.
    f) Instructions for expeditious compliance when traffic or other operational considerations are a factor
    g) Denial of a request when ground movement can not be approved
2. Issue traffic information between conflicting traffic by specifying position and intentions of each
3. Use of non-prescribed phraseology
    a) Issue clear and concise instructions when the usual phraseology does not cover the situation
    b) Issue instructions that state what to do rather than what not to do

TABLE 6-2 (Continued)

4. Issue progressive ground movement instructions when:
   a) Pilot/operator requests
   b) Pilot/operator is unfamiliar with route issued
   c) The controller deems it necessary due to traffic or field conditions
5. When aircraft/vehicle is not visible from the tower, confirm location by:
   a) Reports of progress by pilot/operator via radio
   b) ASDE to confirm pilot/operator-reported position
   c) Reports by other pilots/operators
6. Issue airport condition information, useful to pilot/operators

E. Process flight progress strips
   1. Prepare/obtain flight progress strips for aircraft preparing for ground movement
   2. Review/revise progress strip information
   3. Issue revised/amended flight progress information to pilot
   4. Mark the flight progress strip with a symbol indicating that the pilot has received the following departure information:
      a) Current ATIS information
      b) Current weather information
      c) Assigned departure runway
      d) Mid-runway departure point, if point is non-standard
   5. Forward flight progress strip to appropriate control position

F. Receive, analyze, and disseminate information that may modify or affect the airport/tower operations

G. Record required ground movement information on flight progress strip, pad, or facility-developed form

H. Operate or monitor tower cab equipment
   1. Runway visual range/runway visibility value (RVR/RVV)
   2. Airport surface detection equipment (ASDE)
   3. Light gun
   4. Field lighting
   5. Coordination lights
   6. Instrument landing system (ILS) panel
   7. Radar display
   8. Low level wind shear alert system (LLWAS)
   9. Interphones
   10. Automated weather display system (AWDS)
   11. Automated radar terminal system (ARTS)
   12. Transmitters/receivers
   13. Twenty-four-hour clock

V. LOCAL CONTROL (Partial List Relevant to Surface Operations)

A. Definition of local controller decision process
   1. Scan the outside movement area(s)
      a) Active runways
      b) Taxiway/turning points
      c) Local airport problem areas
      d) Airport traffic area
      e) Traffic pattern
   2. Scan the inside work environment
      a) Wind instruments
      b) Low level wind shear alert system (LLWAS)

TABLE 6-2 (Continued)

   c) Altimeter setting indicator
   d) Runway visual range/runway visibility value (RVR/RVV)
   e) Strips/pad/facility-developed forms
   f) Airport surface detection equipment (ASDE)
   g) Bright radar indicator tower equipment (BRITE)
   h) Field light settings
3. Develop/coordinate an air traffic movement plan which accommodates the airport and adjacent airspace objectives
   a) Provide safe local area movement, with minimal delay, maintaining aircraft separation standards
   b) Provide airport/flight information
   c) Protect critical/special areas
   d) Observe noise abatement criteria
4. Continually scan for factors that may affect the operation:
   a) Development of the situation as planned
   b) Detection of flaws with the plan
   c) Unauthorized aircraft/vehicle movements
   d) Traffic conflicts
   e) Emergency/unusual situations
   f) Weather phenomena
   g) Location of aircraft/vehicles
   h) Violation of restricted/ILS critical area
   i) Equipment malfunctions
   j) Surface conditions

6.3 NASA ASRS ANALYSIS-DETROIT GROUND INCIDENTS

As a further aid in understanding aircraft surface operations, an analysis of NASA Aviation Safety Reporting System (ASRS) surface incidents was conducted (ASRS Search Request No. 2127, April 14, 1991). Detroit stood out as a particularly problematic airport, and further study revealed the following data, which is based on a case-by-case analysis of incident narratives entered into the ASRS from 1983 to 1990. A total of 48 incidents involving surface operations at Detroit were reported, and can be categorized as follows.

Takeoff/Taxi Conflict - 8
Landing/Takeoff Conflict - 7
Landing/Taxi Conflict - 5
Taxi/Taxi Conflict - 5
Ramp airplane to Ramp airplane conflict - 1
Taxi - No conflict - 11
Takeoff - No conflict - 2
Landing - No conflict - 0

Number not relevant - 9

6.3.1 Potential Solutions

A detailed review of each incident suggested the following types of solutions that, if implemented, would appear to prevent a similar incident from occurring. These solutions will be used at the conclusion of this report as a cross-check on the validity of the low visibility concept recommended by this study. Note that the ASRS incident reference numbers are listed if future reference is desired.

a. Taxi Sequence Display

An unambiguous, clear method of indicating to the pilot the taxi sequence is needed, especially when several aircraft are taxiing close together. Ground control will sometimes tell one aircraft to yield to another, allowing it to pass by at an intersecting taxiway. Confusion can occur when one airplane mistakes another clearance for his own, or when ATC mistakes one aircraft for another. It becomes more critical when the aircraft to yield to is on the runway instead of taxiway. A related situation is when a large jet needs to reduce thrust for a light plane taxiing behind it. Confusion can be compounded by similar call signs.

Reference:
Taxi/Taxi Conflict - #32694, #51291
Takeoff/Taxi Conflict - #31456
Takeoff-No conflict - #44783
Taxi -No conflict - #136608

b. Proximate Ground Traffic Display

When an aircraft is about to turn onto a taxiway or runway, the pilots view of oncoming traffic could be blocked by the other pilot or by cockpit structure. The captain typically taxis, so his view to the right could be blocked by the first officer, who could be heads down and not able to clear his side of the aircraft. The left rear view is typically blocked as well. Especially bad is when the high speed exit is used to enter a runway for takeoff, and the oblique angle obscures any view along the approach path. An onboard display or warning system of proximate traffic could alleviate this.

Reference:
Taxi/Taxi Conflict - #31367, #33853
Landing/Takeoff Conflict - #145615

c. Departure Runway Orientation/Improved Airport/Taxiway Signs And Markings

The pilot needs a system to point toward the takeoff runway as an orientation aid. This will be more important at airports with poor markings and signs.

Reference:
Taxi/Taxi conflict - #61803
Landing/Taxi conflict - #78254
Taxi - no conflict - #52334

d. Display Of Assigned Runway For Close-In Arrivals

The local controller sometimes forgets which parallel runway has been assigned to an arrival, and sometimes taxies another airplane onto the same runway. Either a ground ATC device to remind controller of RW assignments, or a flight deck device to indicate proximate arrival traffic and its assigned runway would eliminate this problem.

Reference:
Landing/Takeoff conflict - #32238

e. Separation Prediction Algorithm

The local controller sometimes uses bad judgement in anticipating separation between arrivals and departures. The separation prediction algorithm could be used to delay giving runway clearance to a departure if adequate separation was not predicted.

Reference:
Landing/Takeoff conflict - #34483, #42739, #145615

f. Runway Clearance Verification

Poor phraseology or other voice communication problems sometimes result in "Hold short" clearances being mistaken for "Position and hold" clearances, with subsequent conflicts. A clear and reliable way to ensure timely receipt of "Hold Short" is needed, along with verification back to ATC that the message is received. Another way to verify clearance onto the runway would also help.

Reference:
Landing/Takeoff conflict - #40708
Taxi - no conflict - #45479
Takeoff-taxi conflict - #32327

g. Aircraft Positional Display For ATC

The controller needs to know if a runway is/will be clear prior to clearing another arrival or departure. Some runways are crowned, making visibility limited, even in good visibility conditions. The controller also needs a way to verify compliance with clearances.

Reference:
Landing/Takeoff Conflict - #74017

h. Enhanced Visibility Taxiway/Runway Markings In Snow

Snow, ice, sand, etc. could obscure taxiway and runway markings. These markings could be critical to prevent crossing an active runway, especially where an intersection with several taxiways/runways occur.

Reference:
Landing/Taxi conflicts - #50541, #50727
Taxi - no conflicts - #49638, #131876

i. Runway Hold Short Reminder/Warning

The pilot sometimes forgets a clearance to hold short of a runway during landing or taxi. Distractions in the flight deck often create problems with remembering such clearances. The first officer sometimes has copied the clearance, told the captain, then gone on to another task and the captain forgets to hold short.

Reference:
Landing/Taxi conflicts - #56508, #63068
Takeoff-Taxi conflicts - #40710, #41762, #50071
Taxi-no conflict - #43743, #48477, #49638
Dept-No conflict - #31828

j. ATC Coordination/Shift Change System

When a controller shift change occurs, the new controller needs a way to know the entire taxi situation, and the clearances that have already been issued to taxiing aircraft, especially who is cleared to cross a runway.

Reference:
Takeoff-Taxi conflict - #50399, #124567

k. Aircraft Tail Positional Awareness

Due to the length of the aircraft, a pilot clearing a runway does not always stop with the tail clear of the runway.

Reference:
Takeoff-Taxi conflict - #130799

l. Wing Tip Positional Awareness

In low visibility or at night, even with wing walkers in the gate area, it is difficult to judge wing tip clearance.

Reference:
Ramp conflict - #32530

m. Flying Pilot/Non-Flying Pilot Coordination

When the non-flying pilot is distracted by heads down tasks (e.g., company communications), the flying pilot needs to know his entire taxi clearance, including any runways he has to hold short of.

Reference:
Taxi - no conflict - #50415

n. Permanent Record Of Taxi Clearance

A pilot could read back one thing but remember something different, due to distractions, misconceptions, etc. The written record should include the takeoff/landing runway.

Reference:
Taxi - no conflict - #66286

o. Runway Status Indication

The Automatic Terminal Information Service (ATIS) recording sometimes indicates a runway is closed, even though ATC may actually be using it for arrivals or departures. The runway status should be obvious, including criteria such as open, closed, available upon request, etc.

Reference:
Taxi-no conflict - #67456, #91231

7.0 PRELIMINARY REQUIREMENTS

This section presents the preliminary requirements for aircraft surface operations in visibility conditions from 600 feet RVR down to zero visibility. These are overall ATC/aircraft system requirements, and include operational requirements (what the system must do) and performance requirements (how well the system must do it). The information analysis results are first used in defining task categories by phase of operation, which then allow performance criteria to be developed, based on airplane/airport geometry considerations, ATC surveillance and control tasks, and aircraft surface operations tasks. Overall operational and performance requirements are then derived.

7.1 SURFACE MOVEMENT TASK CATEGORIES BY PHASE OF OPERATION

A review of the data from the previous section indicates that when aircraft and ATC perspectives are viewed in combination, the various objectives for surface operations fall within six major task categories; plan route, coordinate clearance, follow cleared route, ATC surveillance, situational awareness, and obstacle avoidance. The nature of these objectives is also sensitive to whether it occurs on the ramp, taxiway, or runway. Table 7-1 summarizes this organization, and is further described in the following sections.

7.1.1 Plan Route

a. Ramp

(1) Aircraft

Little is needed for aircraft route planning on the ramp. A possible consideration may be an estimate of the taxi time out to the runway, to aid in determining when to pushback from the gate when trying to meet a specific takeoff time. Otherwise, the only other planning information of use would be the position of aircraft using nearby gates, so that a direction of pushback could be anticipated.

(2) ATC

Prior to entry and/or movement in the ramp area (that part which is part of the movement area), ground control requires certain knowledge for route planning: vehicle ID, vehicle type, current location, point and time at which movement is desired to begin, and the desired point of departure (i.e. departure runway, gate, parking area, hangar). The individual vehicle intentions are integrated into the total movement plan by the controller.

b. Taxiway

(1) Aircraft

The aircraft must know its destination on the airport surface, the desired entrance to the active departure RW if departing, or the assigned gate if arriving.

The location of ATC-preferred taxi routes connecting origin and destination, location of closed or unsuitable taxi-ways, location of crossing runways, location of fixed obstructions (buildings, towers, fences, etc.), location of temporary obstructions (construction equipment, etc.) are important for route planning on the taxiway.

Table 7-1. Surface Movement Task Categories

	Ramp	Taxiway	Runway
Plan Route	ATC & A/C - Suitable taxi route (preferred, 1-way, low vis, closed, weight-limited) Taxi time estimate to gate/runway. Consider time constraint	ATC - Potential conflicts, alternative routings A/C - Anticipate and avoid delays, anticipate speed, braking changes, route mod requests	ATC - Optimum RW exit for arrivals, considering traffic flow, taxiway and ramp situations A/C - Length of remaining RW to/from exit/entrance, acceptable exits
Coordinate Clearance	ATC - Proximate aircraft, nearby gates to be used, potential bottlenecks A/C - Advisory to ATC unless impacting movement area or unless gate hold in effect	ATC - Include: clearance limit, traffic sequence, clearance valid time, route, turn direction, clearance limit, areas to avoid or use caution A/C - Verify, check for consistency, acknowledge	ATC - Sequencing for takeoff, proper runway, urgency A/C - Verify correct runway and action to be taken
Follow Cleared Route	A/C - Taxi up to movement area but do not enter without clearence, follow taxilanes	A/C - Verify on assigned taxiway, avoiding active runways, following designated traffic, remain on weight-bearing surface.	A/C - Proper alignment for takeoff, correct RW, desired/required exit/entrance
ATC Surveillance	ATC - Issue advisories for potential gate blockage	ATC - Compliance with clearance, verify sequence or position, potential conflicts, potential RW incursions or restricted area incursions	ATC - Verify A/C on correct RW, potential RW incursions-RW clear, A/C holding short
Situational Awareness	A/C - Proximity to movement area, obstacles, buildings, aircraft, docking support - correct gate	A/C - Comply with clearance, proximity to hold lines, restricted areas, obstacles, proximate traffic. Surface visibility and conditions. Stopping ability.	A/C - Verify on correct RW, acceptable (within performance limits) RW entrances/exits, stopping ability, takeoff ability, visibility and surface conditions
Obstacle Avoidance	A/C - Imminent collision with buildings, structures, aircraft, vehicles, animals	A/C - Imminent collision with structures, aircraft, vehicles, animals	A/C - Aircraft, vehicles, animals on runway

(2) ATC

Aircraft and vehicles on the taxiway are primarily enroute. Route planning for the controller is therefore generally rerouting, due to observed problems or requested changes to the original routing plan. Airport ground vehicles may have segmented movement requests (with intermediate stops) while conducting airport facilities operations. The controller must therefore maintain knowledge of vehicle ID, vehicle type, current location and destination of each vehicle. They must also maintain an overall "picture" of airport conditions and vehicle interactions.

c. Runway

(1) Aircraft

The aircraft must know the desired or cleared runway exit if arriving, or the desired or required runway entrance if departing. The length of runway available or remaining will be another factor in planning the desired route to/from the runway.

(2) ATC

Route planning on the runway is the most dynamic environment. Accurate and frequent knowledge of position, speed, acceleration and heading is required for all vehicles occupying the runway (takeoff, landing or crossing). From this information runway occupancy time can be estimated as well as selection of the best runway exit for arriving aircraft.

7.1.2 Coordinate Clearance

a. Ramp

(1) Aircraft

The aircraft is not usually constrained by ATC clearances on the ramp, although coordination with ATC usually is accomplished to facilitate rapid taxi clearance when needed. A few airports require pushback clearance on the ramp due to confining areas where the gate is very close to the taxiway.

(2) ATC

The ground controller requires sequencing information such that a fair, efficient order is established for delivering clearances (who follows who). Due to space limitations in the ramp/gate area, the interference between aircraft which are inbound, outbound or "pushed back", must be considered in this sequencing. The controller requires knowledge of aircraft/vehicle position and heading, as well as crew understanding, acceptance and readiness to execute the cleared movement.

b. Taxiway

(1) Aircraft

The specific clearance could consist of: clearance limit, traffic to follow, clearance valid time, cleared taxi route, direction of movement, direction of turn via taxiway, via runway, runways cleared to cross, runways to hold short of, taxi-way to hold short of, urgency of compliance, airport areas to avoid due to weight limits, airport areas to avoid due to construction, thrust setting limits due to proximate light aircraft, new route constraints.

Advisories and/or warnings could also be issued as a specific situation develops. Traffic, vehicle and visibility/weather advisories, frequency handoffs, conflict warnings should be considered.

(2) ATC

Clearance coordination during taxi is primarily a result of a modification or addition to a previous clearance. The controller requires knowledge of aircraft/vehicle position and speed, as well as crew understanding, acceptance and readiness to execute the revised and/or additional cleared movement.

c. Runway

(1) Aircraft

Clearances for surface operations issued on the runway are usually for specific runway exits or entrances.

(2) ATC

Clearance coordination with an aircraft on the runway must be performed in a timely manner. Accurate and frequent knowledge of position, speed, acceleration and heading is required such that the coordination can be performed at the appropriate time and location on the runway.

7.1.3 Follow Cleared Route

The following are applicable to ramp, taxiway, and runway operations. The criticality or preciseness with which they are achieved will be affected by the location, however.

a. Control Direction

The following information is needed to keep the aircraft wheels on the weight-bearing surface, and to follow the intended taxi route.

(1) Current position

(2) Current heading

(3) Desired position

(4) Desired heading

(5) Lateral deviation from route clearance

(6) Distance from centerline

(7) Commanded heading

(8) Nosewheel/Rudder steering cues

(9) Distance to go to planned heading change

(10) Next planned heading

(11) Differential thrust/braking cues

b. Control Speed

The following information is needed to maintain a speed appropriate for the current and intended future path of the airplane.

(1) Current groundspeed

(2) Desired groundspeed

(3) Braking (Deceleration) cues

(4) Predicted braking distance

(5) Min/Max groundspeed

7.1.4 ATC Surveillance

a. Ramp

The controller generally provides advisory information for aircraft in the ramp area. Information is therefore required by the controller of which specific areas are blocked due to pushbacks in adjacent gates or along an intended taxi route. The controller should also be aware of other specific hazards or obstacles on the ramp area. The controller requires position, speed and heading information so that the progress toward the movement area can be monitored.

b. Taxiway

The controller requires information to support conflict detection and resolution. Misidentified (by the crew) taxiways and intersections can lead to conflicts, disrupted flow and runway incursions. The likelihood of such problems increase during low visibility operations. The controller requires position, speed and heading information to monitor and detect vehicle movement errors as well as other unforeseen developments.

c. Runway

Aircraft on the runway during takeoff and landing are traveling at high speeds; are under the greatest potential danger; and have the least ability to change their trajectory. The controller requires frequent and reliable position, speed, acceleration, and heading information to assess the required "buffer zone" for these aircraft, and to know when it is safe to clear other vehicles/aircraft to the runway.

Runway occupancy status is a prime concern, as is the hold short status of other aircraft. Verification of correct runway for takeoff is also important.

7.1.5 Situational Awareness

The following information is needed for the aircraft to ensure that the taxi clearance is followed, and that all operational and procedural constraints are observed.

a. Distance to go to clearance limit

b. Relative bearing to clearance limit.

c. Current position of lead aircraft

d. Current heading of lead aircraft

e. Current distance/bearing to lead aircraft

f. Distance to RW hold line

g. Distance to RW

h. Distance to ILS critical areas

i. Distance to crossing taxiway

7.1.6 Obstacle Avoidance

The following information is needed to identify and resolve potential conflicts with fixed or moving obstacles.

a. Position of non-conflicting obstacle

b. Presence of conflicting obstacle

c. Range to conflicting obstacle

d. Range rate to conflicting obstacle

e. Bearing to conflicting obstacle

f. Identity of obstacle

g. Predicted/intended path of obstacle

h. Predicted/required heading to resolve conflict

i. Predicted/required speed to resolve conflict

j. Predicted/required braking (deceleration) to resolve conflict

k. New route constraints if required by ATC

7.2 PERFORMANCE CRITERIA

The task requirements and information analysis from previous sections are now used to specify how well a low visibility surface operations system must function.

7.2.1 Identification of Relevant Parameters

As an intermediate step in defining specific parameters needed, a more detailed version of the previously discussed data from table 7-1 was developed, as shown in tables 7-2a, 7-2b, and 7-2c. Many of the parameters are sensitive to phase of operation, so this was made one of the primary dimensions in this table.

A comprehensive list of parameters is identified which accommodates ramp, taxiway, and runway operations for the overall task categories of route planning, clearance coordination, following route, surveillance, situational awareness, and obstacle detection, using the detailed organization from section 7.1. Criteria for the following parameters are defined in the table. These criteria are used, along with other factors, in section 7.4 to determine specific levels of performance required for these parameters.

Aircraft state vector data for position, speed, acceleration, and heading (track) have varying degrees of importance, depending on phase of operation and task.

Range, range rate, and relative bearing to obstacles will be needed only for the obstacle detection task.

The update rate parameter indicates the frequency with which raw data is incorporated into the system. Note that this is not the same as display update rate. Display update rate will be set by pilot response characteristics, which dictates a minimum update rate of 10 Hz.

Data base parameters will be important to differing degrees for all the task categories, depending on the criticality of each function.

Integrity will be a key element of system performance. It is defined as the ability of the system to provide timely warnings to the user when the system should not be used due to a fault or out-of-limit condition. The FAA methodology for system design analysis (ref. 5) was adopted in placing tasks in either a minor, major, or catastrophic failure category. A minor failure is one which may include a slight reduction in safety margins or functional capability, a slight increase in workload, or some inconvenience to occupants. A major failure would reduce the capability to cope with adverse conditions, significantly reduce safety margins, significantly increase workload, or significantly reduce functional capability. A catastrophic failure would prevent continued safe operation.

7.2.2 Aircraft/Airport Geometry Considerations

Airport taxiway and runway design criteria are contained in reference 6, which does not have the force of a regulatory requirement, but does have specific and detailed recommendations for sizing the operational surfaces to be used by aircraft while operating on the airport surface. This advisory circular defines Aircraft Design Group as an aircraft sizing category, based on wingspan, which is used to ensure that larger aircraft are provided with correspondingly larger safety margins and clearances for surface operations. Two relevant parameters specified as a function of Aircraft Design Group are taxiway width and runway width.

a. Edge Clearance Along Straight Paths

As shown in table 7-3, current Boeing airplanes fall in either of two categories of taxiway/runway width. The B-737 and B-727-100 aircraft are able to operate on 50 foot wide taxiways and 100 foot wide runways, while the B-757, B-767, B-747, and B-777 are required to operate on 75 foot taxiways and 150 foot runways. A straight forward requirement for positioning accuracy is easily derived from this information by computing

Table 7-2a. Parameters Needed For Operations On Ramp

Parameter	Plan Route ATC Aircraft	Coordinate Clearance ATC Aircraft	Follow Cleared Route Aircraft	Surveillance/Sit. Awareness ATC Aircraft	Avoid Obstacles Aircraft
Position	ATC - should support selection of most suitable taxi route considering preferred/low vis/one-way/closed/weight limited taxiways. Aircraft - should support taxi time estimate to RW.	ATC - to determine: Location prior to entry into movement area, selection of sequencing of traffic, or advise pushback if could interfere with taxiing aircraft. Aircraft - should enable pilot to edge up to the movement area to get taxi clearance.	Not Applicable (N/A)	ATC - should know if specific gates are blocked due to pushback at adjacent gates. Should enable ATC to advise of specific hazards or obstacles on the ramp (as required). Aircraft - should enable pilot to know when close to: movement area, other aircraft at gates or on ramp, buildings, obstructions, etc., vehicles.	When absolute position of obstacle is known, accuracy will support warning to avoid collision.
Speed	N/A - Aircraft usually not moving when on ramp while planning future path.	N/A	N/A	ATC - should support time estimate to the movement area or gate Aircraft - to allow precise docking without jarring passengers.	Combined with positional accuracy to give adequate warning without high false alarm rate.
Accel.	N/A	N/A	N/A	N/A	Combined with positional accuracy to give adequate warning without high false alarm rate.
Heading or Track	N/A	ATC - should support progressive taxi clearance (eg. turn Left/Right) or advisory of nearby traffic during pushback.	N/A	ATC - Should enable ATC to advise of specific hazards or obstacles on the ramp (as required). Aircraft - to allow precise docking.	Combined with positional accuracy to give adequate warning without high false alarm rate.

Table 7-2b. Parameters Needed For Operations On The Taxiway

Parameter	Plan Route ATC Aircraft	Coordinate Clearance ATC Aircraft	Follow Cleared Route Aircraft	Surveillance/Sit. Awareness ATC Aircraft	Avoid Obstacles Aircraft
Position	ATC - should support selection of most suitable taxi route considering preferred/low vis/one-way/ closed/weight limited taxiways. Aircraft - should support taxi time estimate to RW/Gate	ATC - should support selection of sequencing of traffic, clearing to cross active runway to not block arrivals/departures, avoiding conflicts. Aircraft - if an on-board display of taxi clearance is utilized, should allow determination of actual taxiway on vs. cleared taxiway.	Should enable pilot to compare estimated present position with desired route to determine: Are wheels on pavement? Is aircraft on the desired taxiway? Is aircraft approaching a turn? Is aircraft near a clearance limit?	ATC - should support conflict detection/resolution for traffic situations, support RW incursion prediction, enable ATC to detect if deviation from clearance. Aircraft - should enable pilot to know when approaching RW hold lines, ILS critical areas, other closed areas, proximate traffic, proximate changes in taxi route.	When absolute position of obstacle is known, accuracy will support warning to avoid collision.
Speed	Aircraft - should support taxi time estimate to RW/Gate	N/A	To allow low speed for precise maneuvering so aircraft can stop rapidly/turn sharply. (Edging up to hold line/turning onto different taxiway.)	ATC - should support conflict detection/resolution for traffic situations, support RW incursion prediction, enable ATC to detect if deviation from clearance. Aircraft - to allow pilot to estimate time to certain features on the airport.	Combined with positional accuracy to give adequate warning without high false alarm rate.
Accel.	N/A	N/A	N/A	N/A	Combined with positional accuracy to give adequate warning without high false alarm rate.
Heading or Track	N/A	ATC - should support progressive taxi clearance (eg. turn left/right).	Should enable pilot to know if going wrong direction on a taxiway or runway (based on ATC clearance or overall goal - eg. to ramp/RW) may factor into guidance control laws for steering information.	ATC - should support conflict detection/resolution for traffic situations, support RW incursion prediction, enable ATC to detect if deviation from clearance. Aircraft - should let pilot detect discrepancies with clearance.	Combined with positional accurary to give adequate warning without high false alarm rate.

Table 7-2b. Parameters Needed For Operations On The Taxiway (continued)

Parameter	Plan Route ATC Aircraft	Coordinate Clearance ATC Aircraft	Follow Cleared Route Aircraft	Surveillance/Sit. Awareness ATC Aircraft	Avoid Obstacles Aircraft
Range To Obstacle	N/A	N/A	N/A	N/A	To meet warning limits without false alarms.
Range Rate to Obstacle	N/A	N/A	N/A	N/A	To meet warning limits without false alarms.
Update Period (Raw Data)	Long update period OK due to strategic nature of task.	Should be based on maximum taxi speed and position error.	Should be based on maximum taxi speed and position error.	Should be based on maximum taxi speed and position error.	To meet warning limits without false alarms.
Update Period (Guidance Displays)	N/A	N/A	Compatible with other flight deck displays and human factors guidelines.	N/A	N/A

Table 7-2c. Parameters Needed For Operations On The Runway

Parameter	Plan Route ATC Aircraft	Coordinate Clearance ATC Aircraft	Follow Cleared Route Aircraft	Surveillance/Sit. Awareness ATC Aircraft	Avoid Obstacles Aircraft
Position	ATC - support selection of suitable RW exit for arrivals. Should enable ATC to know when an aircraft is holding in position on RW. Aircraft - should support taxi time estimate to gate, and to alert pilot to upcoming RW exit.	ATC - should support sequencing of takeoffs, support knowing when aircraft holding between parallel RW's. Aircraft - If an on-board display of takeoff clearance is utilized, should allow determination of actual RW on, vs. cleared RW.	Should enable pilot to compare estimated present position with desired route, should allow pilot to line up with centerline of cleared RW, including crossing any parallel RW's along the way.	ATC - should support conflict detection/resolution for traffic situations, support RW incursion prediction, enable ATC to detect if deviation from clearance. Aircraft - should enable pilot to know when approaching RW hold lines, ILS critical areas, other closed areas, proximate traffic, should support pilot knowing RW length remaining for takeoff.	When absolute position of obstacle is known, accuracy will support warning to avoid collision.
Speed	ATC - support ATC knowing when takeoff roll has begun, or when taxi speed reached for an arrival could use it to predict RW occupancy time. Aircraft - tell pilot when its possible to turn off onto RW exit.	ATC - tell ATC when arrival can follow taxi instructions. Aircraft - tells pilot when can safely follow taxi clearance.	To support taxiing into position on RW if departing. To support taking specific RW exit if arrival.	ATC - should support conflict detection/resolution for traffic situations, support RW incursion prediction, enable ATC to detect if deviation from clearance. Aircraft - to allow pilot to predict which RW exit aircraft can make, or if takeoff should abort.	Combined with positional accuracy to give adequate warning without high false alarm rate.
Accel.	ATC - could provide more accurate RW occupancy prediction. Aircraft - probably N/A except for possible Takeoff Performance mon.	N/A	Possibly support taking specific RW exit if an arrival.	N/A	Combined with positional accuracy to give adequate warning without high false alarm rate.
Heading or Track	ATC - to know when an arrival is turning off the RW, or when a departure is aligned with the RW. For Aircraft - N/A	ATC - should support progressive taxi clearance (eg. turn left/right). Aircraft - N/A	Should enable pilot to know if aligned with wrong RW (doesn't help if parallel RW's).	ATC - should support conflict detection/resolution for traffic situations, support RW incursion prediction, enable ATC to detect if deviation from clearance. Aircraft - should let pilot detect discrepancies with clearance.	Combined with positional accuracy to give adequate warning without high false alarm rate.

Table 7-2c. Parameters Needed For Operations On The Runway (continued)

Parameter	Plan Route ATC Aircraft	Coordinate Clearance ATC Aircraft	Follow Cleared Route Aircraft	Surveillance/Sit. Awareness ATC Aircraft	Avoid Obstacles Aircraft
Range Rate to Obstacle	N/A	N/A	N/A	N/A	To meet warning limits without false alarms.
Range Rate to Obstacle	N/A	N/A	N/A	N/A	To meet warning limits without false alarms.
Update Period (Raw Data)	RW occupancy/Takeoff Performance Monitor could require fast updates.	N/A	Fast updates especially for taking a high speed exit if arrival.	Should be used with taxi speed so that compatible with the position error.	To meet warning limits without false alarms.
Update period (Guidance Displays)	N/A	N/A	Compatible with other flight deck displays and human factors guidlines.	N/A	N/A

Table 7-3. Boeing Airplane Geometry Characteristics

	737-100	727-100	757	767-300	747-400	777-200
Wing span-feet	93	108	125	156	213	200
Minimum taxiway/ runway width - feet	50/100	50/100	75/150	75/150	75/150	75/150
Wheel span - feet	20.7	22.6	27.8	35.3	41.4	41.6
Minimum width for U-turn - feet	56	82.5	120	146	158	152
Forward vision - feet cut-off distance	43.5	47.0	36.3	47.3	84.9	–
Taxiway edge margin - feet	14.6	13.7	23.6	19.85	16.8	16.7
Runway edge margin - feet	39.6	38.7	61.1	57.35	54.3	54.2

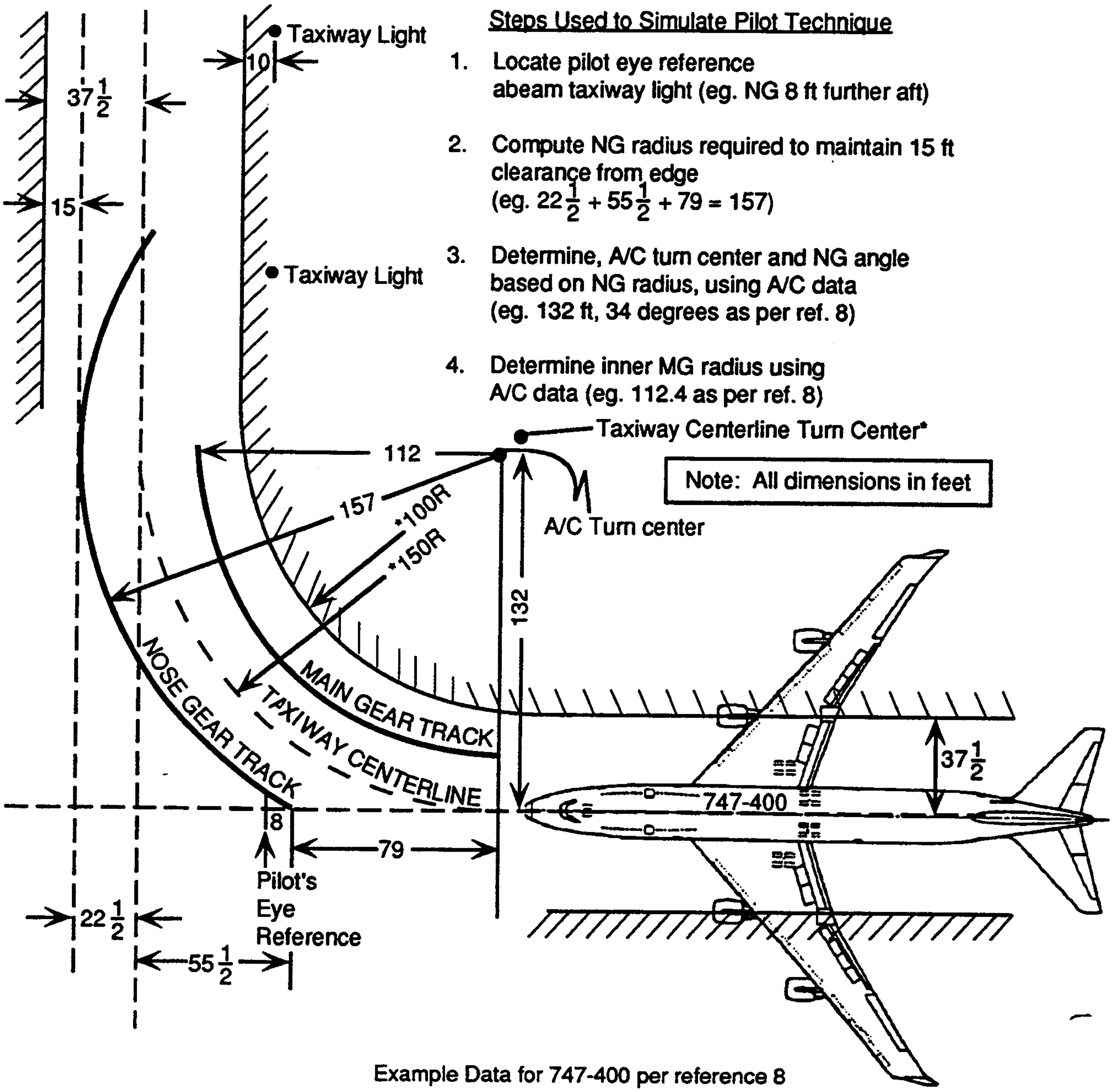
the taxiway and runway edge margin, based on the wheel span subtracted from the pavement width. The wheel span is the lateral distance from the outer edge of the outboard left main tire(s) to the outer edge of the outboard right main tire(s). As shown in the table, the B-727-100 has the narrowest edge margin (the B-727-200 actually requires a 60 foot taxiway, based on its wheel base (ref. 6), for both the taxiway and runway. It should be noted that a shoulder is usually provided beyond the edge of the taxiway or runway, however it is not a weight bearing surface and cannot be considered for use. The U-Turn dimension is listed in the table as a comparative indication of each aircraft's turning ability, which is primarily a function of the wheel base (longitudinal distance from nose wheel to main gear) and maximum nose wheel steering angle (which is in the 65 to 75 degree range for all Boeing aircraft). The various derivatives of a specific Boeing airplane type differ primarily in the wheel base dimension, as the forward fuselage is stretched or shortened.

b. Edge Clearance Along Curved Paths

Maneuvering of a large aircraft along a curved segment of a taxiway can be a difficult task. Large aircraft have long wheel bases, resulting in large turn radii. Nose wheel steering using the flight deck tiller usually provides for between 65 and 75 degrees nose wheel angle, however even this large angle is insufficient for U-turns to reverse course on the runway for the B-747, as shown in the table. Turns around a narrow, curved path are also difficult. The pilot must use a nose wheel angle which is tight enough to provide nose wheel clearance from the far edge of the pavement, but yet shallow enough to keep the tires on the inside of the turn also on the pavement. Reference 6 also specifies taxiway turn radii for the centerline of the turn (which is painted on the surface), radii for the outside corners, and also triangular fillet dimensions to provide increased wheel clearance for this type of situation. Taxiway fillets, however, are typically lacking at older airports that were upgraded to handle newer, larger aircraft.

(1) Judgmental Over-Steering

Figure 7-1 illustrates a pilot technique commonly used in such constraining turning situations. Referred to as judgmental oversteering (due to the lack of precise steering cues), the pilot will position the aircraft for a tight right angle turn from one taxiway to another by taxiing straight ahead until sighting down the row of taxi lights along the perpendicular taxiway. The lights at large jet airports are usually 10 feet from the taxiway edge, and provide a ready indication of when to start the turn. This point is substantially past the beginning of the curved taxiway centerline, hence the term oversteer. The steering tiller is then rotated to provide an intermediate nose wheel angle, determined by pilot experience, of about 30-35 degrees, and as the aircraft proceeds along the turn, the pilot judges the clearance from the nose wheel to the far edge of the new taxiway, adjusting the nose wheel angle as required to remain on the pavement. In the illustration shown for a B-747, a 15 foot edge margin (ref. 6) is preserved, resulting in the outer edge of the inside mainwheels actually increasing their edge distance as the turn progresses. Very low visibilities restricting a view of the taxiway lights and/or far edge of the taxiway may necessitate some means of augmenting the pilots visual cues. This figure was developed based on data in reference 7.



Example Data for 747-400 per reference 8

* As specified in reference 6

Figure 7-1. Judgmental Over-Steering Algorithm for Taxiway Turn

(2) Simplified Over-Steering

Figure 7-2 illustrates a concept which approximates judgmental oversteering by maintaining the main gear over the taxiway centerline, probably being more easily adaptable to some form of electronic augmentation. As shown, the turn is begun approximately 15 feet earlier than the previous example, based on an aircraft turn center which coincides with the taxiway turn center, thus allowing the main gear to straddle the centerline. A nose wheel angle is computed, based on providing the desired inner main gear radius. The 15 foot safety margin for the nose wheel is maintained, resulting in 11 1/2 foot clearance for the inside main tire about half way through the turn. An alternative iterative process could determine the optimum nose gear angle to maximize the clearance for both the nose wheel and the inside main wheel.

7.3 OVERALL OPERATIONAL REQUIREMENTS

The task categories described in section 7.1 are now organized into top level operational requirements, as illustrated below. The Route Planning and Clearance Coordination (for the aircraft) functions defined and discussed in the previous section 7.1 have now been included in the Situational Awareness function. This grouping is based on the similarities of needed information in the Plan Route and Coordinate Clearance categories, and the anticipated integration of this information for graphic depiction. The Follow Cleared Route function has been re-labeled as Steering Guidance to indicate its nature as a requirement rather than a task category. ATC surveillance and Obstacle Avoidance requirements remain similar to the previous table.

Task Categories	Top Level Operational Requirements
1. Plan Route 2. Coordinate Clearance 3. Situational Awareness	1. Situational Awareness
4. Follow Cleared Route	2. Steering Guidance
5. ATC Surveillance	3. ATC Surveillance
6. Obstacle Avoidance	4. Obstacle Avoidance

These overall operational requirements, summarized in table 7-4, are used in section 9 to evaluate the various technologies identified in section 8.

7.4 OVERALL PERFORMANCE REQUIREMENTS

This section summarizes the performance requirements for situational awareness, steering guidance, ATC surveillance, and obstacle detection. In certain cases, key assumptions were made about operational or procedural techniques used. These assumptions are described as the various requirements are developed in the following sections. The performance requirements are also listed in table 7-5.

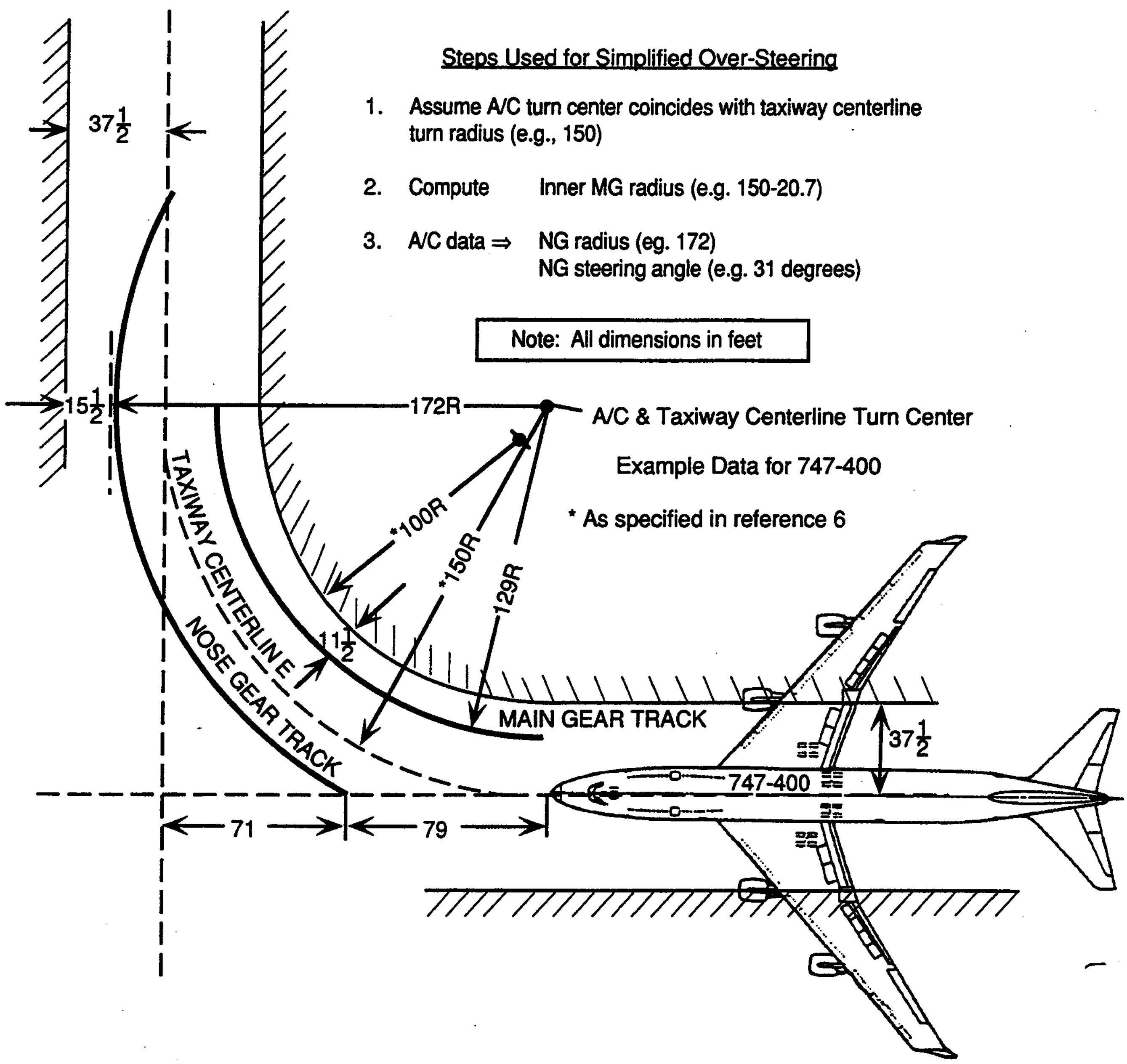


Figure 7-2. Simplified Judgmental Over-Steering Algorithm

Table 7-4. Operational Requirements For Aircraft And ATC Surface Operations

SITUATIONAL AWARENESS
-AIRCRAFT-

Objectives - Comply with taxi clearance, avoid RW incursions, observe operational constraints

- Current/predicted position of self, shown with respect to:
  - cleared taxi route
  - clearance limit
  - active RW's
  - restricted areas
  - relevant airport features
- Current position/ID/intent (taxi clearance) of proximate aircraft and vehicles shown with respect to self
- Taxiway RVR, surface conditions, braking conditions

OBSTACLE AVOIDANCE
-AIRCRAFT-

Objectives - Detect imminent collision, execute avoidance maneuver to avoid aircraft, vehicles, other obstacles

- ID or other description of threat
- Criticality - "imminent collision" vs. only "incursion"
- Relative range and bearing to threat
- Time to closest approach
- Predicted miss distance
- Intent (original taxi clearance, subsequent avoidance maneuver)
- Internally generated avoidance maneuver
- ATC - issued avoidance maneuver

STEERING GUIDANCE
-AIRCRAFT-

Objective - Keep wheels on weight bearing surface

- Current/predicted lateral deviation from cleared path
- Guidance cues to return to path
- Current/predicted distance of wheels from edge of pavement
  - on a straight segment, both main gear are critical
  - along a curve, nose gear and inside main gear are critical

SURVEILLANCE
-ATC-

Objectives - Verify compliance with clearance, to avoid RW incursion, ensure separation, provide assistance as required

- For each aircraft and vehicle on movement area:
  - current ID/position
  - taxi clearance or intent
  - predicted loss of separation w/proximate traffic
  - predicted violation of taxi clearance (route, clearance limit, ...)
- Displayed with respect to relevant airport features:
  - active/inactive RW's
  - taxiways
  - restricted areas

Table 7-5. Low Visibility System Performance Requirements

	Situational Awareness	Steering Guidance	Surveillance	Obstacle Avoidance
Position Accuracy	80 ft, 2 sigma	7 ft, 2 sigma	50 ft, 2 sigma	Incorporated in range accuracy
Speed Accuracy	2 kts	2 kts	TBD	Incorporated in range accuracy
Acceleration Accuracy	Not Applicable (N/A)	TBD	N/A	TBD
Heading (Track) Accuracy	2 degrees	2 degrees	10 degrees	Incorporated in relative bearing accuracy
Range Error to Obstacle	N/A	N/A	N/A	40 ft
Relative Bearing to Obstacle Accuracy	N/A	N/A	N/A	3 degrees
Update Rate	1 second	1 second	1 second	1 second
Integrity (Probability of Undetected Failure)	$1x10^{-3}$	$5x10^{-6}$	$1x10^{-6}$	$1x10^{-3}$
Range Rate to Obstacle Accuracy	N/A	N/A	N/A	2 kts

a. Situational Awareness

Many of the parameters for situational awareness will have similar performance values as for surveillance because the overall concept of situational awareness is quite similar to that of surveillance. While surveillance is conducted by ATC and must include all aircraft and vehicles on the movement area, situational awareness is done by an individual aircraft, but may still be concerned with all other aircraft and vehicles, or possibly certain aircraft and vehicles within a given geographic or operational window.

(1) Position

The highest level of positional accuracy for situational awareness is needed to satisfy the requirement to hold short of a runway. The lack of this capability, which represents the ability to prevent runway incursions, is deemed a "major failure" based on the reference 5 criteria for "... a significant to large reduction in safety margins...", and its occurrence should be "improbable". The probability to be assigned this level, according to reference 5, is between 10^{-5} and 10^{-9}. The value of 10^{-6} will be adopted, based on other applications used in conditions of low visibility which have also used this value.

Note that a runway incursion can be prevented by the aircraft (by recognizing the situation and stopping the aircraft) or ATC (by recognizing the situation and telling the pilot to stop the aircraft). Either the pilot or ATC could act independently of the other, in such a situation. Although the reference 5 criteria is defined for use by transport aircraft, an assumption is made that this criteria would be valid for ground-based ATC systems as well. The 10^{-6} probability of runway incursion can thus be borne by either the aircraft or ATC. Assuming equal weighting is given to both sides, the individual probability assigned for either aircraft situational awareness or ATC surveillance can be derived as 10^{-3}.

The magnitude of the positional accuracy is determined by considering the case of an aircraft correctly positioned to hold short (remaining clear) of a runway while a B-747-400 is landing or taking off with its outboard wheel positioned on the edge of the runway. In this case, based on reference 5 criteria, the radome or tail of the holding aircraft will have 120 feet clearance to the wing tip of the B-747-400 as it passes abeam its position. This distance is taken as the positional accuracy allowable to prevent the "...significant to large reduction in safety margins.."; in other words, the positional accuracy shall be 120 feet with a probability of .999. This could be restated in terms of standard deviation (although the correctness of assuming a normal error distribution remains to be determined) by noting that this probability corresponds to approximately 3 sigma. Similar FAA criteria for enroute navigation and autoland use 2 sigma levels. The positional accuracy in that context would be stated as 80 feet, 2 sigma. Note that this same methodology and result is repeated for the position requirement for surveillance in the subsequent section.

Positional accuracy is an overall aircraft or ATC system requirement, so that data base accuracy would also be a component of it. It is assumed that data base accuracy will be at least an order of magnitude better than the overall system accuracy.

(2) Speed

Speed is required for situational awareness primarily to maintain a reasonable taxi speed when outside visual cues are lacking. Anticipation of deceleration requirements due to impending turning or stopping situations dictate a groundspeed accuracy of 2 to 3 knots, which can be provided within the accuracy limits of an INS.

(3) Heading (Track)

Heading (on the ground it is usually identical to track except for low speed turning situations when the aircraft heading will lag behind the track) is required to a low level of accuracy to enhance the pilot's situational awareness. The most critical use of heading would be to verify that a clearance was being correctly followed, by comparing actual heading to that depicted on a situational display for the cleared route. For this application, a heading accuracy of 2 to 3 degrees is deemed sufficient.

(4) Update Rate

Update rate of raw data such as position, speed, heading, etc. will be dictated by processing requirements to produce a usable display for the pilot. Alternatively, assuming a taxi speed of 25 kts, 42 feet will be covered during every second in between updates, producing an uncertainty in position equivalent to half the positional accuracy value derived previously of 80 feet, 2 sigma. A one second update rate would thus allow acceptable situational awareness without additional processing and correction by an INS.

(5) Integrity

Integrity, the probability of an undetected failure, is determined for situational awareness to be set by the avoidance of runway incursions, which is assumed to fit the category of a "major failure", and should then meet the probability of undetected failure level of "improbable". This probability is assumed to be 10^{-6} for the overall ATC/aircraft system, and 10^{-3} for the portion contributed by the aircraft situational awareness.

b. Steering Guidance

The most critical situations for steering guidance involve runway operations, where the consequences of taxiing off the weight-bearing surface are not only the cost of possible damage to the aircraft and retrieval operations, but also the potentially more adverse closing of a runway due to blockage from the disabled aircraft.

(1) Position

The runway operation requiring the highest positional accuracy is that of an arrival turning off the runway. Assumptions about the guidance for negotiating this turn are needed to estimate the positional accuracy required. Assuming that sophisticated algorithms that maximize edge distance are available to compute the optimum path through the turn, the minimum edge distance of the computed path would not decrease over that available on a straight segment of taxiway. The B-727-100 theoretically has the least edge distance of 13.7 feet, however this is based on a 50 foot taxiway which is almost never the case at airports that accommodate B-727's. The B-727-200 requires a 60 foot taxiway, but in practice most air-carrier airports provide 75 foot taxiways to enable B-757/B-767/B-747 operations as well. The B-737 has the next most constraining edge distance of 14.6 feet along a straight taxiway segment, assuming a minimum size taxiway of 50 feet, which is probably overly pessimistic for large Cat 3 ILS equipped airports such as this study is considering. The B-777 and B-747 are the next most constraining based only on edge margin, however with the more limited turning ability of the B-747, it becomes the most constraining airplane. The edge distance of 16.8 feet available along a straight taxi path could be preserved along a turning taxi path computed by sophisticated guidance algorithms. The previously discussed (sec. 7.3.2.2) procedure of keeping the main gear centered while executing a taxiway to taxiway turn resulted in about a 20 percent reduction in minimum edge distance over that available along a straight taxiway. When this simplified method is applied to a runway-to-taxiway turn, no reduction should occur due to the increased edge distances during the beginning of the turn off the runway. Assuming a slightly more conservative number, based on the reference 7 taxiway edge safety margin of 15 feet, a positional accuracy can be stated by considering the consequences of blocking a runway if this accuracy is not met.

Discussions with Chicago O'Hare ATC personnel indicate the difficulties associated with shifting traffic flows to different runways. The effect of re-sequencing close-in aircraft for a different runway due to a closure usually ripples through the system, causing airborne holding for closer-in aircraft, and possible flow control procedures and ground holding if the traffic flow becomes disrupted enough. Based on these factors, an assumption was made that a major airport, such as is being considered for this study, could tolerate a runway closure due to a blocked runway only once per year. To accept additional closures would probably negate any benefits otherwise achievable with a low visibility taxi system. There are approximately 1000 operations per day at O'Hare. Assuming half the operations are arrivals, a probability of one arrival per year not meeting the requirement translates to 1 in 180,000, or 5×10^{-6}. Assuming a normal error distribution (which would need to be verified), this is approximately a 4.5 sigma value. Restating in terms used in the previous section, the positional accuracy requirement for steering guidance is derived as 7 feet, 2 sigma.

(2) Speed

Requirements are the same as for situational awareness.

(3) Heading (Track)

Steering guidance will require track information to generate correct steering cues to the pilot. Its required accuracy is expected to be on the order of 2 to 3 degrees.

(4) Acceleration

Incorporation of braking or thrust commands would probably require acceleration, however further analysis and testing will be required before recommendations for a value can be made.

(5) Update Rate

Update rate of raw data such as position, speed, and track will be dictated by processing requirements to produce a usable display for the pilot. A display frame rate of 10 Hz is commonly accepted as the minimum allowable for acceptable pilot tracking performance, however the use of an INS to smooth data and provide intermediate solutions should significantly reduce update rate needed for raw data. Assuming a worst case INS drift scenario where the INS position drifts directly toward a taxiway edge in between updates, a 2 kt drift would cause a reduction in clearance of 3.5 feet every second. A one second update rate would thus result in an error equal to about half that of the position error previously derived, which should be acceptable.

(6) Integrity

A probability of 5×10^{-6} is selected as the requirement, based on the same criteria used to derive positional accuracy.

c. Surveillance

As discussed in the previous section on situational awareness, surveillance is quite similar in overall concept to situational awareness.

(1) Position

Assuming that an aircraft is equipped to provide positional accuracy as defined for situational awareness, the required surveillance positional accuracy is the same; 80 feet, 2 sigma. Consideration should be given, however, to the case where an aircraft is not equipped for such situational awareness, and the surveillance requirement is still to prevent runway incursions. In this case, the full 10^{-6} probability should be borne by the surveillance positional accuracy requiring the target position to be shown within 120 feet of its true position. Assuming a normal error distribution, this probability is equivalent to approximately 4.8 sigma. Based on this, the positional accuracy can be restated as 50 feet, 2 sigma.

(2) Speed

Speed is a requirement for surveillance only if conflict detection is automated as a surveillance function. ASTA concepts have identified such a function, however additional system development is required before a speed accuracy can be derived.

(3) Heading (Track)

Heading or track should be accurate enough to determine the intentions of a target. An accuracy of 10 degrees is considered sufficient to identify which taxiway of several possible an aircraft is headed for from an intersection.

(4) Update Rate

The same update rate as for situational awareness, 1 second, is specified.

(5) Integrity

Loss of surveillance is assumed to fit the category of a "major failure" when visibilities are below 600 feet RVR due to its assumed role in preventing runway incursions. An undetected surveillance failure would "significantly reduce safety margins" and is assigned a probability of 10^{-6}. When ATC uses such a surveillance system in conjunction with aircraft having electronic situational awareness capabilities as previously discussed, the 10^{-6} probability can be shared by both ATC and the aircraft. The surveillance capability could then be assigned a 10^{-3} level of integrity.

d. Obstacle Detection

The determination of specific performance requirements for obstacle detection necessitates several key assumptions about the nature of such a concept. A nominal taxi speed of 25 kts is assumed, yielding a nominal stopping distance (for large aircraft) of 400 feet. (This is an estimate made by experienced pilots who have quantified braking in terms of 2 airplane lengths at that speed. An emergency stop would take less space.) A 10 second delay time is assumed, to include processing time, coordination with ATC (if any), and crew response time. Most of this delay would be due to crew response, in keeping with previous collision avoidance concepts. A buffer or safety margin around the airplane is assumed of 200 feet, about the length of a large transport. As shown in figure 7-3, these assumptions produce an overall minimum detection distance of 1000 feet, and a minimum detection time of 30 seconds.

(1) Range Rate To Obstacle

The accuracy of the range rate measurement (i.e., the closing velocity between ownship and the obstacle) can be derived by allocating half the 200 foot buffer to this error. An obstacle that was detected as motionless could thus have up to a 2 kt forward speed and still remain within 100 feet during the 30 second time period. This would include errors in ownship speed accuracy.

(2) Update Rate And Range To Obstacle

The range error to the obstacle can be derived by assuming it should not be greater than the range uncertainty produced by projecting the assumed taxi speed over the update period. A one second update rate would thus produce a range uncertainty of about 40 feet.

(3) Position And Relative Bearing To Obstacle

At a minimum detection distance of 1000 feet (600 foot protected area plus 400 foot crew reaction time based on 10 seconds at 25 kts), the relative bearing accuracy to a stationary obstacle will be based on desired missed distance. Assuming an aircraft holding short of a runway while another aircraft is landing or taking off, a nominal wingtip to radome clearance of about 170 feet can be assumed for a B-747 on the runway. If the desired minimum separation for obstacle avoidance is assumed to be 120 feet, which is what it would be if the B-747 had deviated with an outer wheel on the edge of the runway, the corresponding required bearing accuracy would be approximately 3 degrees (50 out of 1000 feet).

(4) Integrity

As for surveillance, the integrity for obstacle detection is assumed to fit the category of a "major failure" when it is used for visibilities below 600 feet RVR. An undetected obstacle detection failure would "significantly reduce safety margins" and is assigned a probability of 10^{-6}. If another requirement of surveillance is to provide a redundant means of obstacle detection, then the overall system integrity would be 10^{-6}, and by giving equal weight to obstacle detection by ATC surveillance as well as by the aircraft, an individual integrity level of 10^{-3} can be assumed.

8.0 TECHNOLOGY CAPABILITIES

This section discusses the capabilities of a wide range of technologies which may be potentially applicable to low visibility surface operations. An attempt has been made to identify and quantify the relevant parameters, although it should be noted that due to the wide variation in technologies, there is sometimes little correlation or continuity between them.

8.1 POSITIONING

This general grouping of technologies provides aircraft positional information.

8.1.1 Absolute

A number of technologies provide position determination with respect to a fixed (absolute) reference system. An advantage of this form of positioning is its compatibility with pre-defined data bases of relevant features and objects on the airport surface.

Several of these technologies use precise timing signals to determine time of receipt of ranging signals transmitted by ground or space-based navigational transmitters. Time, and thus distance, to geographically separated transmitters at known locations allows triangulation of position. The more precise the time measurement, more transmitters, favorable geography, and integration time for position calculation contribute toward enhanced accuracy.

a. GNSS-GPS

The Global Navigation Satellite System (GNSS) is currently emerging with significant roles in airport surface operations, along with enroute and terminal phases of operation, through government and industry-sponsored GNSS Task Force requirements definition and implementation activities (ref. 8). GNSS is a world-wide position, velocity, and time determination system, that includes one or more satellite constellations, receivers, and system integrity monitoring. GNSS may be augmented as necessary to support the required navigation performance for the actual phase of operation, such as surface operations. The Global Positioning System (GPS), a U.S. Department of Defense (DOD) operated precision navigation system, is currently the central satellite constellation for GNSS, although Glonass in the near-term, and perhaps other constellations in the long term will also be incorporated into GNSS as they come on line. The remainder of this section on GNSS-GPS will focus on GPS performance characteristics, although some overall GNSS requirements are also relevant and will be mentioned as well.

(1) Positional Accuracy

GPS computes positional data by accurately timing receipt of satellite transmissions, and then triangulating position with respect to a reference volume (referred to as the geoid). The WGS-84 ellipsoid is currently used as the datum. The use of WGS-84 will have later implications for data base design and updating, since several different reference data bases are in use today, with the FAA currently using NAD-83, which in some cases causes substantial positional differences from WGS-84. Selective availability accuracy degradations imposed irregularly by DOD limit GPS horizontal positional accuracy to a DOD/FAA negotiated minimum of 333 feet (100m), 2 drms (distance root mean square, equivalent to 2 sigma). An upper cap has also been negotiated to provide 1000 feet (300m) accuracy 99.99% of the time. During the times when selective availability degradation is not imposed, or if/when DOD decides to totally eliminate selective availability, DOD specified accuracies of 50 feet (16m), 2 sigma will be available.

(a) Local Area Differential GPS

It should be noted that even without selective availability degradation, the 50 foot accuracy is insufficient for navigational steering guidance as defined in the previous section on requirements. This means that some form of augmentation will be needed to enhance the accuracy of the system without regard to selective availability. Various demonstration and test programs of an augmentation concept known as differential GPS (DGPS) have indicated accuracies from 3 feet (1 m) to 33 feet (10 m), based on a local differential concept where a ground-based station computes and broadcasts correction factors for aircraft within a 50 to 100 nmi radius. The differential station, at an accurately surveyed site (presumably at the primary airport for the region served), computes pseudo-range and range-rate corrections for all satellites in view and broadcasts them via a digital data link. The specific accuracy achieved will depend on factors such as the actual distance from the differential station (due to ephemeris (orbital) and ionospheric error sensitivity to range), and the correction update rate. The differential update interval for each satellite in use required to support 3-33 foot accuracies is expected to be less than 10 seconds, with 3 foot accuracies requiring updates closer to 1 second. There seems to be limited statistical data on positional accuracies achievable with DGPS, although a notable exception is the autoland testing performed by NASA LaRC which substantiated a positional accuracy level of 7 feet, 1 sigma.

A wide area differential concept has also been proposed which would cover a much larger area (perhaps a 1000 nm radius) and use a geostationary satellite system such as Inmarsat. The accuracies would suffer due to tropospheric and ionospheric delays which vary with local atmospheric disturbances. Wide area may suffice for certain lower accuracy surface applications, however.

(b) Carrier Phase Differential

This is a more complex differential correction using broadcasts of carrier phase differences as well as pseudorange corrections. Although well proven for survey applications not requiring realtime position determination, "kinematic" carrier-phase as it is referred to, is still considered experimental for moving applications, although accuracies in the decimeter range appear theoretically achievable. In addition to a higher correction update rate of once per second, a major disadvantage to current experimental implementations is that a continuous lock on the satellite carrier frequency is required. The airport surface would be a difficult environment in which to operate with such a constraint.

(c) Pseudolites

Pseudolites, an acronym for pseudo-satellites, have been considered conceptually for enhancing GPS accuracies within a limited range. A pseudolite is analagous to an earth-based GPS satellite which transmits a similar ranging signal. There is the potential for improved accuracy due to the lack of ephemeris errors and lack of ionospheric effects. The near-far effect and multi-path problems may prove difficult, however. GNSS receivers would also require modification.

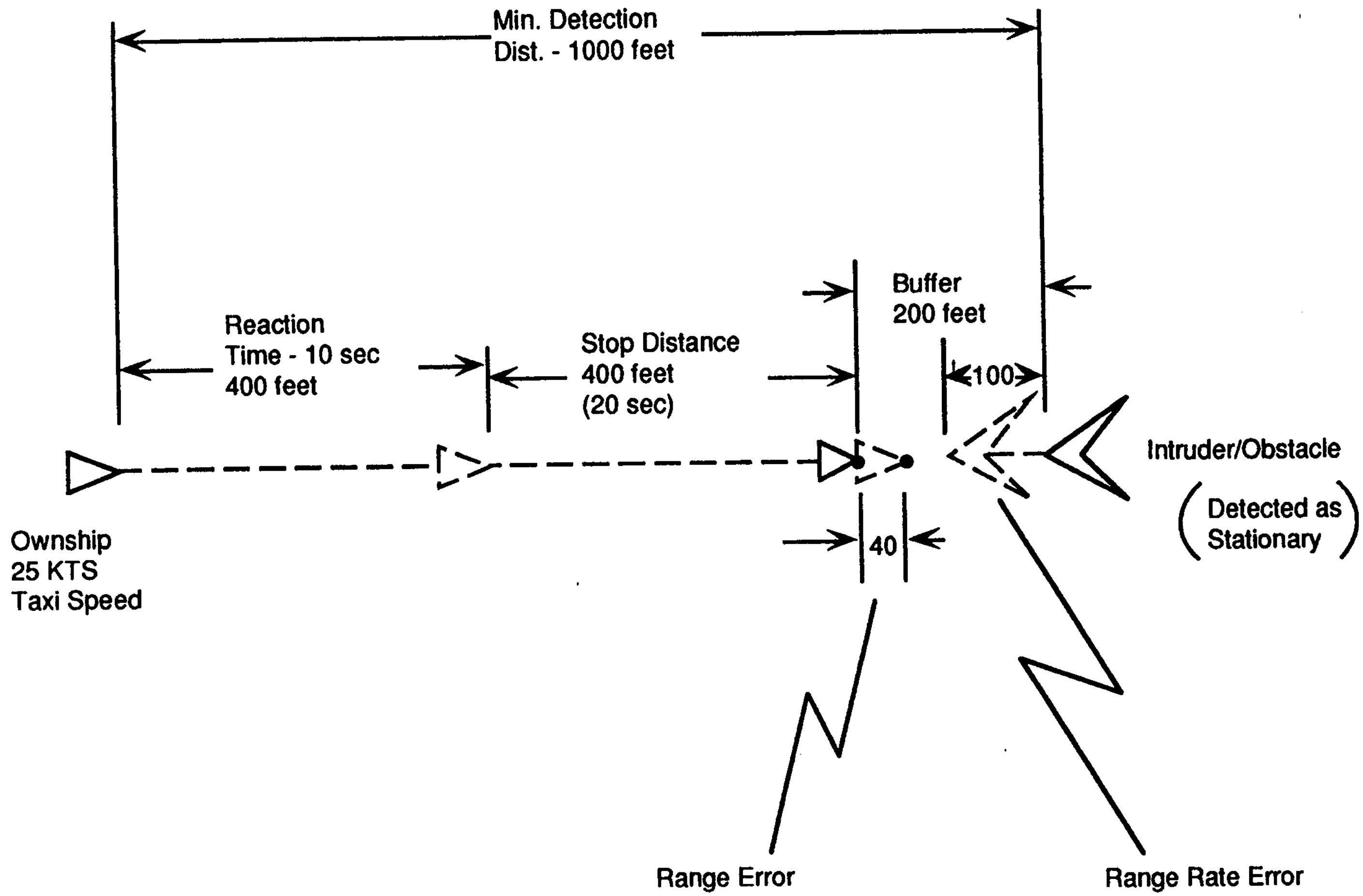


Figure 7-3. Obstacle Detection/Avoidance Concept

(2) Reliability

The reliability of GPS has been established by estimating a 98% probability that 21 out of the full 24 satellites in the constellation will be operable at a given time. The probability of all 24 satellites being operable has been estimated at 70%.

(3) Integrity Monitoring

Integrity monitoring is an augmentation of GNSS to provide a very low probability of undetected failure (meaning an out-of-limit condition) of the system. Alarm limit and time-to-alarm parameters have also been defined for GNSS, depending on the specific phase of operation and situation. A goal of undetected failure probability of 10^{-9} has been identified for the most critical situations, and would probably require an onboard method of integrity monitoring referred to as Receiver Autonomous Integrity Monitoring (RAIM) providing a 1 second time to alarm. RAIM requires six satellites to be in view, however, and the alternative would be some form of ground-based integrity monitoring which would necessitate a data link of integrity information to the aircraft, requiring a longer time-to-alarm of up to 10 seconds based on geo-synchronous satellite relay schemes. The GNSS Integrity Channel (GIC) is one such integrity monitoring scheme.

(4) Fix Update Rate

GPS can support a fix update rate of once per second. This has been deemed adequate for all precision navigation tasks considered for GNSS, including steering guidance, when integrated into an INS solution. The required bandwidth of the differential correction data link will be directly effected by the update rate. A local area differential with once per second updates may need a data rate on the order of hundreds of bits per second, while a carrier phase differential correction data link may require thousands of bits per second.

(5) Automatic Dependent Surveillance

Automatic Dependent Surveillance (ADS) has been identified as one of the most promising applications of GNSS. While not explicitly part of GPS or GNSS, it is closely related. Data link of aircraft determined GPS positions could provide faster and more accurate surveillance data to ATC than any other systems currently in use. Data link capacities will be stretched much more than for only differential corrections, however. Estimates place the needed data rate at busy airports in the tens of thousands of bits per second range. Data link integrity will be an important element of the overall GNSS system integrity. Aviation Packet Radio (AVPAC) and the Inmarsat T-channel have been identified as candidates for this service.

b. Microwave Landing System

The Microwave Landing System (MLS) has been targeted for implementation as the replacement for ILS as a precision landing aid. MLS is a system in which ground-based equipment transmits signals to an appropriate receiver in the aircraft. The position information is computed as angle coordinates and a range coordinate. The angle information is derived by measuring the time difference between successive passes of highly directive narrow fan-shaped beams. Range information is provided by Precision Distance Measuring Equipment (P-DME).

The signal format is time-multiplexed, that is, it provides information in sequence on a single carrier frequency for all functions (azimuth, elevation, basic and auxiliary data). The format includes a time slot for 360 degrees azimuth guidance with provision for growth of additional functions. The angle guidance and data channel plans provide 200 C-band channels between 5031 and 5091 MHz.

Narrow fan-shaped beams are generated by ground equipment and scanned electronically to fill the coverage volume. In azimuth, the fan beam scans horizontally, providing at least an 80 degree coverage volume, centered on the approach and departure corridors for the primary runway. The vertical pattern is shaped to control illumination of the airport surface. In elevation, the arrays are designed to minimize unwanted radiation towards the airport surface, thereby providing accurate guidance to very low angles.

The airborne equipment receives the sector and scanning beam signals associated with each angle function and, in sequence, determines the identity of the angle function and then decodes the scanning beam angle information. It subjects the received signals to acquisition criteria before they are accepted and continues validation following acceptance to provide reliable interference-free angle information.

Accuracies achievable by MLS could support ground operations if full coverage of the airport surface could be achieved. The current concept provides for a beam of about 80 degrees width centered on the approach and departure paths of the primary runway, leaving the center of the airport without MLS coverage. A scheme to expand coverage of the surface would be needed to be useful for surface operations.

c. LORAN

LORAN-C was developed to provide the Department of Defense with a radio navigation capability having longer range and much greater accuracy than its predecessor, LORAN-A. It was subsequently selected as the U.S. Government provided radio navigation system for civil marine use in the U.S. coastal areas.

LORAN-C is a pulsed, hyperbolic system, operating in the 90-110 kHz frequency band. The system is based upon measurement of the difference in time of arrival of pulses of radio frequency energy radiated by a group, or chain of transmitters which are separated by hundreds of miles. Within a chain, one station is designated as the master station, and the other stations are designated as secondary stations. Pulse signals transmitted from the secondary stations are slaved to the master station and transmit in a known sequence. Since each chain of ground stations is in a known geometry, relative to each other and the earth, most transmission delays can be eliminated from the position calculations. A receiver computes it's location based on the principle that the difference in distance from any point on a hyperbola to the two foci of the hyperbola is a constant. If multiple hyperbolas can be defined, then the intersection of the hyperbolas is the location of the receiver. When the time-difference is measured by the receiver, from multiple pairs of transmitters in the same chain, a hyperbola is computed assuming the transmitter pair are at the foci.

LORAN-C will provide the user with predictable accuracy of 0.25 nm or better. Accuracy is dependent on user location within the signal coverage area of the chain, the local terrain and current weather conditions. Accuracy of less than 300 ft is possible when navigating to a known (measured and stored) set of coordinates.

The use of LORAN-C for navigation in the National Airspace System (NAS) has increased considerably in recent years. In 1990, LORAN-C installations in aircraft were estimated to be in excess of 100,000; most of which are not approved for IFR use. Approximately 10 percent of these installations are approved for IFR use during enroute and terminal operations; however, not during instrument approach operations.

There are currently 13 LORAN chains worldwide, which provide coverage in most of the coastal areas and North American mid-continent areas.

The LORAN transmission frequency and system structure is designed for long range position determination. In the airport surface environment however, a similar system would probably be impractical and expensive.

d. Other Transponder Systems

Other transponder systems also use the time of arrival concept. Differences are in the mode and frequency of transmission of the reference signals, and the means by which time synchronization is obtained. Portable transceivers communicate with an array of stationary receivers at surveyed sites. A high capacity data link (up to 680 K bits per second) relays time of arrival data to a central processing site which then computes position. Typical accuracies of about 20 to 25 feet are claimed for these systems.

e. Buried Guidewires and Other In-Ground Installations

From time to time over the years various proposals have surfaced for buried substances under the airport surface, which would allow sensitive onboard sensors to detect, providing error signals to guidance algorithms. One such concept is a buried guidewire which carries a current to produce an electromagnetic field which is detected and measured by onboard sensors. On-board sensors can track the cable, with some researchers claiming a 1 foot accuracy for this method. However there are some obvious disadvantages with this approach. There would be no general navigational capability with this concept, since the limited range of such a guide wire would require it to be closely tracked at all times. Perhaps covering the entire airport surface with a continuous grid of guide wires would provide this wide area navigation, however the economic and practical limitations of this would seem prohibitive. There is also the potential for damage to shallow guide wires by snow plows or construction equipment.

Other systems such as radioisotopes (Krypton-85 gas tube buried in taxiway) with an onboard scintillation crystal detector/photomultiplier have been proposed (ref. 9). The heavy lead shielding for directional sensitivity (195 lbs) is one disadvantage of this concept. Optical sensors, mechanical guidepaths, laser beacons, and odometry are other concepts which have been proposed for vehicular guidance, however these are much more suited to the predictable and controlled environment of factory automation rather than to the airport surface.

8.1.2 Imaging Sensors

Imaging systems, in a broad sense, provide a form of relative positioning based on the pilot's ability to translate a visual scene perceived through some sort of display device into a cognitive model of aircraft position. A "perfect" imaging system would provide the pilot with a real world view, within the physical dimensions of the display device, of the outside environment without regard to atmospheric or other conditions which limit the pilots unaided out-the-window vision. This is labeled a relative positioning system due to its reliance on the pilots visual comparison of some onboard aircraft reference point to an image (graphic or symbolic representation) of a relevant airport feature such as a taxiway, runway, or obstacle. More advanced processing could potentially provide absolute positioning by incorporating onboard data bases for correlation with sensed imagery, however this is an area for far-term research. An onboard data base could also be used to enhance a sensed image by superimposing or "fusing" a stored image with the sensed one. A head up display is commonly considered for imaging use, due to the close similarities to normal visual reference, although certain situations have been considered for heads down display of imagery as well (e.g., weather radar). Head up and head down display device technology is discussed in a subsequent section on flight deck displays. The imaging sensors themselves, however, represent the most variation in performance and are discussed in the following sections.

a. Sensor Trade-Offs

Imaging sensors are useful to the pilot because they sense radiated energy at a frequency range which is less effected by atmospheric attenuation and scattering than the visual spectrum. The obvious example is fog which blocks the transmission of energy in the visible light spectrum, causing difficulties for unaided visual operation, but which allows lower frequency radar waves to pass freely. The penalty of this lower frequency, however, is reduced resolution.

Sensor operating frequency is a primary parameter in distinguishing among the various types of sensor technology, due to this basic trade-off. In other words, as the sensor operating frequency increases, the resolution increases; however the ability to penetrate adverse atmospheric properties (such as fog) decreases. For sensors which rely on reflection of actively emitted radiation, power requirements and their attendant ground safety problems also are increased as operating frequency is increased, although the size of the equipment is reduced.

b. Atmospheric Phenomena

A primary adverse condition encountered in visual operation is fog, which can be classified as either radiation (inland) or advection (coastal) fog. Radiation fog consists of fine water droplets of average 10 micron diameter, and can maintain a liquid water content of up to 1 gm/m^3 and can limit visibility to as low as 100 feet RVR. Advection fog consists of coarser water droplets average 20 micron diameter, but can maintain liquid water content of only up to .4 gm/m^3 and can reduce visibility to as low as about 350 feet RVR (ref. 10). The higher water content of advection fog attenuates sensor performance (especially infra-red due to its high frequency just under visible light) more so than radiation fog which is producing the same level of visual obscuration.

Heavy rain and snowfall can also attenuate sensor energy. Heavy rain of an intensity which would seriously degrade sensors is not expected to be a problem, however, since even at very high rates of over an inch per hour where sensors may be questionable, visual reference can still be maintained at about Cat 2 levels (1200 feet RVR) (ref. 10). Heavier rainfalls than that would most likely be avoided for other reasons anyway. A similar situation has been described for heavy snow falls. A somewhat different effect would occur due to rain or snow accumulating on the ground, however, since the various ground features (texture and temperature difference) that contribute to contrast in the radiated energy may be substantially altered.

c. Radar Sensors

This category of sensors is characterized by its relatively low frequency band, and by its measurement of reflected energy from a transmitted beam, referred to as active radar. The higher energy reflected from the environment produces greater range performance, and less attenuation through the atmosphere; however, increased scattering and reflections tend to degrade the image resolution. Active radar sensors are azimuth/range devices which produce displays directly in this format, referred to as B-scan (range, azimuth). To produce an image equivalent to a visual representation from the flight deck, known as a conformal presentation, the sensor output must be transformed first from B-scan to a plan view based on x, y coordinates, referred to as a PPI-map mode. Another transformation is needed to convert to an elevation, azimuth display, referred to as a C-scan. There are non-linearities (referred to as image registration errors) produced as a result of these transformations which distort the image, when compared to an actual visual representation as may be seen through a head up display in good visibility. General expectations are that azimuth errors will be less than 0.6 degree, and elevation errors less than 0.3 degree. At 950 feet range, this would produce a 10 foot lateral shift of the image, as compared to its true position. Bore-sight errors, due to mis-alignment of sensors with respect to the aircraft frame of reference, are expected to be in the 0.2 to 0.3 degree range. It should be noted that the limitation of scanning only in azimuth produces no information on the vertical dimension of targets. Flat airport surfaces such as runways and taxiways would be imaged normally, however obstacles such as vehicles or aircraft would appear unrealistically flat.

Another concern is the trade between field of view and image update rate. The nature of active radar sensors is that a narrow beam antenna must usually be mechanically scanned in azimuth to produce a useable field of view for the displayed image to the pilot. The head up display device also constrains the field of view, in the range of about 30 degrees in azimuth. A slewable field of view, where the sensor bore-sight or zero azimuth reference is steered left or right from the aircraft centerline, has been considered as one way to enhance field of view within these constraints, however its effectiveness when combined with a head up display still centered on the original boresight is uncertain. The sensor field of view is also limited by the maximum angular rate of movement of the scan mechanism. Image processing time and display latency also contribute to the overall image update rate, which (based on human factors guidelines) should not exceed 100 milliseconds for satisfactory tracking performance by the pilot.

Another factor for onboard radar sensors operated on the ground is the shallow grazing angle which results. This serves to accentuate any variability in radar cross section of the various scanned surfaces, and can produce a rapidly changing or unpredictable image. For airport features having little contrast in reflectivity, radar reflectors may need to be installed to enhance the contrast. For example, the grass/pavement boundary is a primary means of producing a useable runway or taxiway image as the grass reflects more energy than the pavement. Large airports often use painted lines and lights to delineate taxiways, within a wide expanse of pavement. Taxiway lights and/or conventional light reflectors are not expected to provide adequate reflectivity for radar sensors. In these circumstances, radar reflectors may be needed to produce a useful image.

(1) Active Millimeter Wave

Active millimeter wave (MMW) radar imaging concepts take advantage of an atmospheric attenuation "notch" that occurs at both 94 GHz and 35 GHz, allowing better fog penetration than at other MMW frequencies. Although systems have been developed at both frequencies, 35 GHZ is preferred due to less attenuation (about .7 $dB/km/g/m^3$), while 94 GHz provides better resolution (by as much as three times) but more attenuation in fog (about 2.5 $dB/km/g/m^3$) (ref. 11).

Antenna polarization is circular which allows man-made and natural objects to be more easily discriminated. Two modes of operation are possible; FM/CW and pulse. The FM/CW mode allows shorter minimum ranges due to shorter transmit time of CW, which also provides more average power on target, producing better range resolution. Pulse operation requires a very narrow pulse width for good range resolution. A 36 nanosecond pulse produces about 33 feet (11m) range resolution, while FM/CW improves range resolution to about 10 feet (3m). Maximum range at 35 GHz is about 6500 feet (2 km), while at 94 GHz is about 4900 feet (1.5 km).

Most azimuth scanning designs provide a ± 15 degree wide scan, with 300 degrees per second being a typical scan rate. This rate provides a 5 Hz scan frequency, with 2 passes through a given target per cycle. This provides an average 100 millisecond update time between passes. Image integration processing is employed to generate pixel data for display. Fast fourier transform algorithms are usually used, and typically produce data for pixel arrays of about 240 vertical pixels by 320 horizontal. As scan rate is slowed down, more time is available for additional image integration, sometimes improving image quality. The slow scan rate can be mitigated by motion compensating. As an example, one vendor claims a 10 Hz image rate can be boosted to a 30 Hz display frame rate.

Azimuth resolution is a function of aperture (antenna) size. One vendor claims a 0.35 degree horizontal beam width at 94 GHz. Another processing scheme divides a 30 degree FOV into 224 azimuth sectors, producing 0.134 degrees per sector.

Reliability for active MMW will probably be driven by the mechanical scanning assembly. Resonant scanning concepts use a natural frequency tailored to the scanning frequency, allowing smaller, lighter, and more reliable motors to be used. Scanning a smaller reflector, at only half the angular deflection, is another concept for improving reliability.

(2) Weather Radar with Beam Sharpening

Weather radar enhancements to allow imaging appear feasible, driven by the desire to maximize use of existing hardware. Doppler beam sharpening is used to improve the otherwise poor resolution of low X-band frequencies. This allows a common aperture antenna to be used for both X-band and W-band (MMW) frequencies, for weather radar or imaging applications. When used for imaging, an up-converter boosts the operating frequency to W-band. A disadvantage of this approach is the slower scan rate required due to the larger aperture size, about 45 degrees per second. It does allow a wide angle FOV of ± 90 degrees, although the update rate would be low at 0.25 Hz. Another concept would use a split aperture antenna where the X-band antenna is truncated. This would allow a faster scan for the smaller aperture MMW antenna. Reliability would probably be driven by the mechanical drive, and has been estimated at 15,000 hours mean time between failures.

(3) Microwave

Microwave sensors have been considered for imaging applications, primarily due to the lower operating frequency providing better adverse weather penetration than MMW. A disadvantage would be that the resolution would be inferior to MMW, although doppler beam sharpening has been discussed as a means of improving it.

d. Passive Millimeter Wave

Passive millimeter wave (also referred to as radiometry) is analogous to forward looking infrared (FLIR), in that no sensor energy is required to illuminate the target. It operates at the lower MMW frequencies, typically 94 GHz. Since no energy is transmitted from the sensor, there is less of a problem with false reflections which can cause ground clutter on active radar systems. This also means, however, that there is no direct range information available for an image; it is more a direct picture of ambient, emitted, and reflected MMW energy coming from all ranges within the FOV. Signal contrast is a function of distance due to scatter, which is made worse by adverse weather. Texture pattern masking can occur due to variable fog densities, and overcast sky conditions also serve to reduce MMW contrast levels.

Although research is continuing, a state-of-the-art passive MMW sensor would consist of a focal plane array of detectors each having a spatial resolution of about 0.34 degrees (6 mrad) at a signal-to-noise ratio of 6 dB with a sensitivity of 1 degree Kelvin. An array of about 5200 detectors would be required to produce a 30 by 20 degree field of view. An update rate of 10 Hz is considered possible.

e. FLIR

Forward looking infrared (FLIR) sensors operate in two primary ranges of wavelength; 3-5 micron (considered adequate for high contrast objects such as found on the airport, and preferred due to having radiation peaks near room temperature and reduced atmospheric absorption), and 8-12 micron (preferred by the military for detecting low contrast objects). The 3-5 micron region is considered mid-IR, and platinum silicide detectors on a staring focal plane (or electronically scanned) array are commonly used.

Based on sensing radiated thermal energy, sensitivity is stated in terms of a minimum resolvable temperature difference, and is in the range of 0.13 to 0.16 degrees K. The update rate is referred to as frame rate, analagous to a TV picture and at almost the same frequency of 30 to 50 Hz. As the frame rate is slowed, more time for signal integration can improve the signal to noise ratio. Image resolution is a function of the number of pixels, usually from 250K to 300K, one such array being 640 by 486 pixels.

Atmospheric attenuation in fog is most severe for this class of sensors, due to IR wavelengths being much closer to that of the droplet sizes found in certain fogs. The determination of actual performance of FLIR in fog is somewhat problematic due to the vagaries of weather in general, and to the unknown properties of any given fog condition. In lieu of much experimentally determined data, a theoretical methodology utilizing an atmospheric visibility parameter known as extinction coefficient has been employed by the Maryland Advanced Development Laboratory to predict FLIR performance in fog. The net result is that an effective visibility of FLIR can be derived in terms of the actual RVR encountered. Assuming a 1 degree K temperature difference between grass and runway boundary, the effective FLIR visibility is predicted to be about twice the actual RVR. This means that if a runway is discernible by unaided visual reference at 1200 feet, use of FLIR would allow it to be visible at 2400 feet. However, this visibility increase in fog due to FLIR has not been seen for visibilities below about 700 feet. Anecdotal reports have indicated FLIR visibility sometimes less than unaided visibility.

Reliability of FLIR sensors will probably be driven by the need to cool IR detectors to 77 degrees K for optimum sensitivity. A mean time to failure for a sterling cycle cooling system for FLIR has been measured at about 4000 hours.

Video fusion is sometimes mentioned as a means of enhancing a FLIR image. By combining signals from both visual and thermal detectors, an image could be produced that had the highest overall contrast, typically better than either FLIR or video by itself.

Another means of enhancement is the use of thermal beacons which emit infrared energy and can substantially increase range. The runway and taxiway lights used on airports have a fairly thick glass lens that apparently limits the amount of thermal energy radiated. Some means of modifying the lens or light itself may possibly provide an IR beacon-like system.

f. LIDAR

LIDAR sensors are a form of active infrared, utilizing lasers to transmit infrared light which is detected after reflection from the environment. A more common application for LIDAR has been for clear air turbulence, wind shear, and ash cloud detection, although it is thought that it may provide better weather penetration than passive IR for ground applications. This is a future concept at this point, and there are also disadvantages of possible hazards due to laser light and the large size required for equipment.

g. Sensor Fusion

Sensor fusion refers to two primary concepts. First, as already mentioned for FLIR, multiple sensor data could be processed and integrated into an enhanced image. Second, an onboard data base containing a hierarchical list of objects, their locations, and their relevant physical properties (e.g., reflectance, emittance) could be accessed based on detected sensor data. Images may be enhanced on a pixel basis, or potentially a stored graphic or symbolic representation of the detected image could be displayed, based on proper correlation of a sensed image with a stored object. Reflectance and emittance properties of objects may need to be provided for a range of ambient temperatures and other surface conditions or situations, such as seasonal variations.

8.2 SURVEILLANCE

8.2.1 ASDE-3

Airport Surface Detection Equipment, version 3, (ASDE-3) is planned for installation by late 1993 at the following 30 sites, listed in order of installation: Pittsburgh, FAA Academy, FAA Technical Center, Denver, Dallas, Philadelphia, Los Angeles, Chicago, Atlanta, San Francisco, Boston, Newark, New York (JFK), Cleveland, Seattle, Portland, Washington (Dulles), Miami, New York (La Guardia), St. Louis, Houston, Washington National, Memphis, Minneapolis, Detroit, Tampa, Baltimore, New Orleans, Kansas City, and Anchorage. Note that there are a total of 38 Type 3 (Cat 3 certified) airports in the U. S. To date, Pittsburgh is the only major airport where ASDE-3 has been installed.

ASDE-3 is a primary surveillance radar optimized for detecting surface movements (ref. 12), and is an enhancement over previous versions of ASDE which have been in use for about the past 35 years. It operates on 16 GHz, using a frequency agile, variable focus, circular polarization antenna for good near-field signal-to-noise, and to reduce back-scatter due to rain. Its resolution was sized to enable target heading to be determined. A 16 foot aperture provides a beam width of 0.25 degrees, yielding an azimuth resolution of 2.2 feet at 500 feet range, and 44 feet at 10,000 feet range. Maximum range is about 15,000 feet, with a range resolution of 40 feet at 10,000 feet range. A digital scan converter maps radar data onto a 1024 x 1024 pixel grid, providing a pixel display resolution of about 10 feet at a selected overall range dimension of 10,000 feet.

An update rate of once per second is achieved by rotation of the antenna within an enclosure called a "rotodome", at 60 RPM. The rotodome design minimizes adverse effects due to heavy rain, allowing rapid rain shedding, and operation in rain rates of up to 0.6 inches per hour. The frequency agile transmitter uses 13 frequencies at 30 MHz spacing to decorrelate clutter returns, providing a 6 dB improvement; and reduces fluctuations due to target aspect ratio variations (from small targets) to 15 dB. The pulse width of 36 nanoseconds allows 42 hits on a target at 10,000 feet (for improved range accuracy), based on the pulse repetition frequency of 20 kHz. The display processing time for each target is about 250 millisecond. Reliability is specified by a mean time between failure (MTBF) of 2000 hours, with an availability specified as 99.8%.

Experience at Pittsburgh has indicated substantially less reliability, however, this should improve as experience is gained.

There has also been a problem reported from initial installations of returns from certain large aircraft breaking up into multiple returns due to the shallow look angle and limited dynamic range of ASDE. Long, tubular fuselages such as the MD-80 and DC-9 do not provide sufficient radar cross section, causing the return to break up into a wing/nose group and a tail group.

8.2.2 DGNSS/ADS

The application of DGNSS as a positioning system for automatic dependent surveillance has figured prominently in recent ATC system concepts. The reader is referred to the previous section on GNSS positioning systems for more detail on the ADS concept (section 8.1.1.a).

8.2.3 Mode-S Trilateration

Mode S trilateration is a positioning concept developed and tested by Lincoln Labs (ref. 13) which capitalizes on a feature of Mode S aircraft transponders to autonomously transmit a Mode S reply referred to as a squitter. The squitter is designed to allow ATC to detect and track previously unknown targets, however on the airport surface the squitter transmissions from aircraft can be used to derive accurate positioning information correlated with specific aircraft ID. Five to six omnidirectional antennas around the airport perimeter are used to determine the time of arrival of the squitter transmission, using a very accurate calibration signal for time synchronization. A triangulation technique, roughly similar to that used by GPS, is used to compute the aircraft position. Accuracies of about 25 feet are expected, although this is a theoretical estimate. A disadvantage to this technique is the wide bandwidth required for the time synchronization signal, which could be up to 50 MHz.

8.3 ATC DATA LINK

This section discusses several technologies which may satisfy the communications requirements for clearance coordination, surveillance, and proximate traffic information for situational awareness; as discussed in the preliminary requirements section.

8.3.1 Aeronautical Telecommunications Network

The Aeronautical Telecommunications Network (ATN) is a new system under development, which will provide interoperability for air/ground digital (bit oriented) telecommunications. This system can use any combination of Mode S, satellite, gatelink, VHF, HF or other data link system to be developed. The ATN provides standardized interfaces and communication protocols to allow interoperation of FAA, airline and other data networks.

The ATN architecture is represented in figure 8-1. Multiple airborne applications are connected to an airborne ATN router which will select an efficient air/ground path to a ground router which, in turn, will direct messages to the appropriate end user. A mirror functionality on the ground will provide uplink message routing.

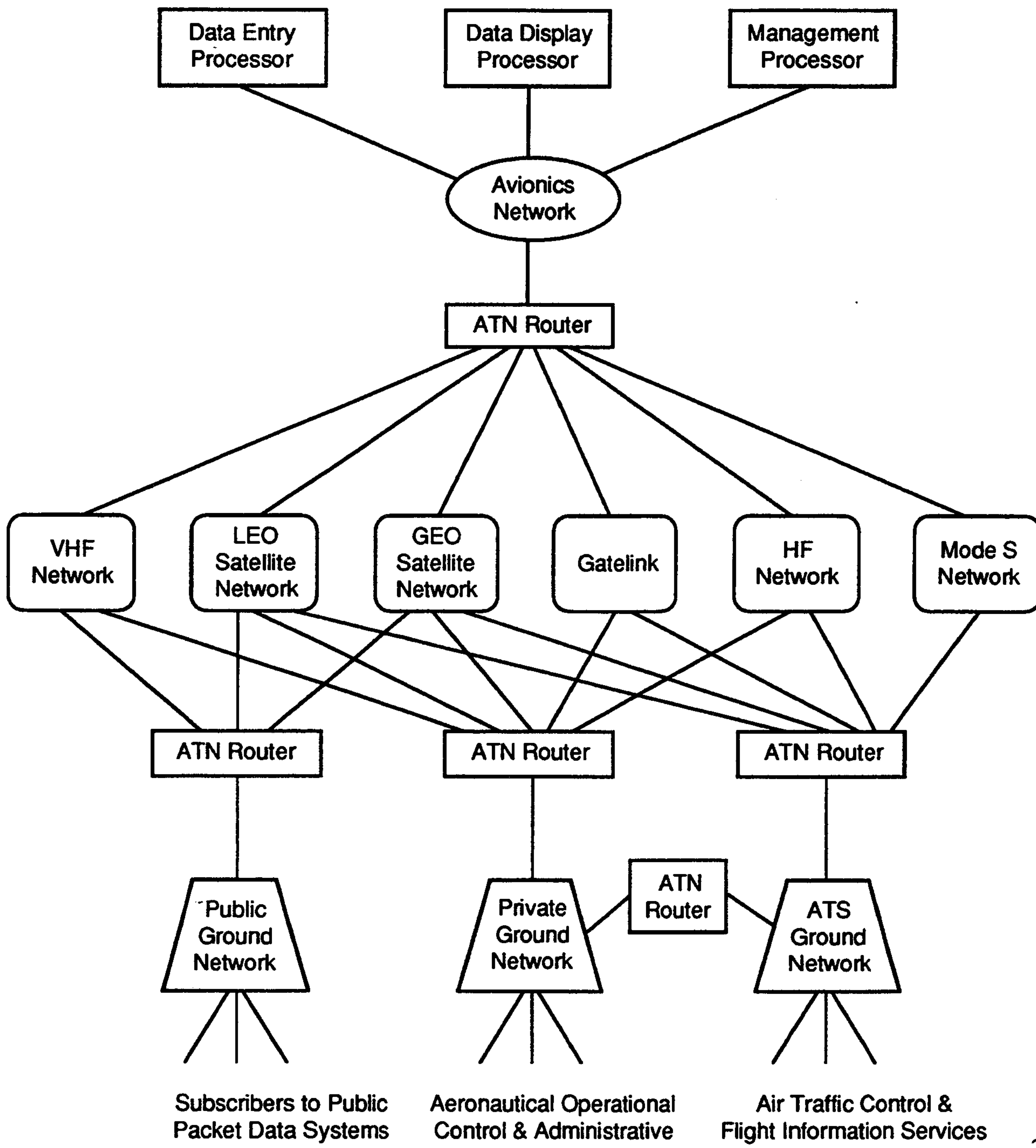


Figure 8-1. Aeronautical Telecommunications Network Architecture

115M-000

The standardization of ATN depends on the Open System Interconnection (OSI) model developed by the International Organization for standards. The OSI model provides a seven-level structure that defines necessary communication tasks. The seven layers and their functions are summarized as follows:

The "physical layer" provides transmission of bit streams over physical links.

The "link layer" provides reliable transfer of data across the physical link

The "network layer" establishes, maintains and terminates message connections

The "transport layer" provides end-to-end integrity and flow control

The "session layer" establishes, manages and terminates connections between cooperating applications.

The "presentation layer" provides services such as encryption, compression, and reformatting.

The "application layer" provides services such as file transfer protocols and network management.

There are two basic kinds of message protocols for the exchange of data packets between end users. The first is connection-oriented, where a logical channel is established (point-to-point) and packet data is referenced to the existing channel. The other is connectionless, where a data packet must contain sufficient address information to be relayed to the final destination.

The scope of potential ATN applications identified by various government and industry groups is quite broad and includes:

Air Traffic Control (ATC)
- Emergency and cautionary information
- Tactical traffic control
- Strategic planning and control
- Position (progress) reports

Flight Information Services (FIS)
- Weather reports and forecasts
- Notices to Airmen (NOTAMs)
- Automatic Terminal Information Services (ATIS)
- Pilot Reports (PIREPs)

Aeronautical Operational Control (AOC)
- Routine operational control
- In-flight medical emergency requests
- Aircraft Maintenance

Aeronautical Administrative Communication (AAC)

Aeronautical Passenger Communication (APC)

Aviation Packet Radio (AVPAC) and Mode S appear to be the most likely candidates for implementation of the ATN "link layer" for airport surface communications applications.

a. ACARS/AVPAC

Aircraft Communications Addressing and Reporting System (ACARS) is a character-oriented digital data link operating over dedicated VHF frequencies in the U.S. It is currently used by major airlines for flight planning, weather updates, and dispatch coordination. It could potentially be applied to address surface operations communications requirements such as differential correction data for DGPS, or to send proximate traffic data for situational awareness use by other aircraft operating on the surface. Its nature as a character-oriented system precludes its incorporation into ATN, however its functionality is maintained through implementation of Aviation Packet Radio (AVPAC) which is planned to replace ACARS as a bit-oriented system. The nature of the airport surface, with line-of-sight and multi-path difficulties, would benefit from a VHF transmission mode such as ACARS uses. Satellite communication, included in the AVPAC concept, may require repeater stations on the airport.

b. Mode S

Mode S data link may provide a viable data link system for rapid and reliable ATC clearance coordination on the airport surface. The UHF frequencies will require some form of repeater, however, to provide coverage throughout the airport surface. The Mode S trilateration concept previously discussed in the surveillance section could potentially be expanded to enhance Mode S uplinks, as well as monitor downlinks. Mode S has also been identified as a means to provide ASDE-3 target displays with alphanumeric target labels of ID and speed.

8.4 OBSTACLE DETECTION

Obstacle detection technologies suitable for onboard implementation have already been discussed in the imaging technology section. FLIR and active MMW appear to be promising candidates for obstacle detection.

8.4.1 AMASS

The Airport Movement Area Safety System (AMASS), a prominent part of the FAA's Runway Incursion Plan, is a concept for an ASDE-3 radar system enhancement which uses the radar data to detect and monitor runway traffic and to issue alerts in potential or actual runway incursion situations (visual alert on the ASDE-3 display and audibly by alarm in the tower).

A pre-production unit should be available for validation testing to determine the operational suitability of the system late in FY 1992. This pre-production unit will accommodate a full set of targets (up to 128), quality centroiding and tracking of radar returns, and an interface with the ARTS (Automated Radar Terminal System). Production units of AMASS software and hardware are scheduled to be installed with the airport ASDE-3 units beginning in late 1993.

8.4.2 ASTA

Airport Surface Traffic Automation (ASTA) is a long term FAA development program to develop airport surface surveillance, communication and automation techniques to provide enhanced airport capacity, effective runway incursion prevention and alert capability. The implementation schedule for ASTA is in the 1996 to 2001 time frame.

ASTA will provide a departure traffic management system to assist controllers in the sequencing of aircraft to the departure end of the runway in accordance with schedules designed to expedite traffic flow out of the airport traffic area, and to increase the capacity of the airport surface in all weather conditions. ASTA will ultimately provide automation which integrates terminal, enroute, and central flow control automation functions.

ASTA objectives include extending Mode S surveillance identity and data link communications to aircraft on the airport surface; building upon ASDE-3 radar processing augmentations developed under AMASS. ASDE, Mode S, and ASR-9 air surveillance sensors will be integrated to provide continuous coverage throughout terminal airspace and surface movement areas. This integration will enable identity tags to be provided on controller ASDE displays, as well as rapid data link communications to surface and airborne aircraft within several miles of the airport. A comprehensive surface safety system will be provided, including automatic alerting to aircraft and controllers, information on ASDE-3 displays, automatic runway status lights integrated into taxiway stopbars, active taxi route guidance and compliance monitoring, delivery of surface traffic data to the cockpit, and direct cockpit alerts. The ASTA program also includes plans to develop a low cost ASDE for secondary airports.

8.5 FLIGHT DECK DISPLAYS

Recent advances in flight deck display technology will enable designers and human factors experts to develop intuitive, reliable, and error-tolerant pilot interfaces for low visibility surface operations.

8.5.1 Head Up Displays

A head up display (HUD) allows a pilot positioned at the normal eye reference point to see symbology or images superimposed on the normal out-the-window view. A collimator and combiner are used to project symbology and imagery at an apparent range of infinity so that the pilot will not have to re-focus and will be able to view outside scenes simultaneously (ignoring the cognitive switching aspects of this concept).

The capability to display raster images is a new one for commercial jet transports. The resolution of the HUD image is a significant parameter, but in many cases may be dictated by the nature of the sensor rather than the HUD. Horizontal and vertical parallax performance of the HUD will be important, though. Convergence over 95% of the field of view (FOV) is expected to be less than 0.14 degrees (2.5 mrad), and divergence less than 0.06 degrees (1 mrad). Dipvergence (vertically) will be less than 0.09 degrees (1.5 mrad).

The FOV can be improved using holographic optical elements. Three FOV terms are relevant. A "total" FOV (the total angular display viewing area visible by either eye while moving the head in any direction) of 30 degrees horizontally, by 24 degrees vertically, has been demonstrated. This total FOV was accompanied by an "instantaneous" FOV (the angular display viewing area visible by either eye while maintaining a fixed head position) which in this case was also 30 degrees by 24 degrees. Early HUD's, however, often had an instantaneous FOV which was smaller than the total FOV. The corresponding third FOV parameter, "overlapping" FOV, (that portion of the instantaneous FOV which is visible to both eyes simultaneously) was shown to be 25 degrees horizontally, by 24 degrees vertically.

Another parameter, indicative of allowable head motion, is referred to as the "eye box", and has been defined as the three dimensional region surrounding the cockpit design eye reference point within which a FOV of 10 degrees by 10 degrees is obtained for either eye. Minimum desired dimensions of the eye box are 3 inches vertical, 5 inches horizontal, and 6 inches longitudinal.

A future goal for an advanced HUD is a FOV of 35 degrees by 28 degrees. FOV can be extended to about 40 degrees using helmet mounted systems, which would also provide the ability to align an imaging sensor with the direction the pilots head is pointed, using a head tracker. Referred to as field of regard, this pointing capability allows the boresight or zero azimuth of a sensor to be rotated around to point to the side of the airplane to anticipate turns or achieve more situational awareness. Scanning mechanisms on the sensor, sometimes referred to as a snap-look function, would need to be installed as well.

The holographic combiner will allow a minimum light transmission of 75-85% for daylight levels, and to 87% scotopic (night adapted).

The range of brightness control will be important in determining the levels of outside illumination that are acceptable for good image contrast. Variable fog conditions on an airport surface could lead to rapidly changing illumination levels necessary to maintain contrast. Phosphor efficiency of 35-45% provides a peak display brightness of 4000 foot-lamberts. The contrast ratio has been measured as 1.3 to 1 against 10,00 foot-lamberts illumination.

HUD reliability varies for the various components. The optical head unit mean time between failure is quoted as 5,000 hours, from one vendor, with higher values for display computer, combiner, HUD computer, etc. Schemes for improving integrity to the point of using the HUD as a primary flight instrument have been developed, based on a dual-channel processing technique which generates symbology parameters from sensor data and compares results to that on the display.

A HUD guidance display has been considered as a logical application for low visibility ground steering cues. If clutter does not prevent HUD symbology from showing the runway or taxiway outline, then no other cues may be necessary except current position. On the other hand, resolution and clutter effects may combine to create a difficult task without a steering command. Many styles and formats of steering cues have been used in various applications, perhaps with ground steering producing another type of cue.

8.5.2 Head Down Displays

Cathode ray tube (CRT) technology for head down displays (HDD) is well established on commercial jet transports. Color flat panel displays are being introduced on the B-777 flight deck, and will improve on the CRT's reliability. Raster images have been in use for some time on the electronic horizontal situation indicator (EHSI) and the navigation display, and will continue to be useful for surface operations. Resolution will probably be an important parameter, along with display formats. Depending on what the HDD is used for, resolution could become a limiting factor. Current printed airport diagrams use high quality printing to show substantial detail on one page with print resolution of 600 dots per inch often used. Current resolution of CRT or flat panel displays is much less, with representative resolutions from 80 to 120 dots per inch. Declutter techniques will have to be developed to provide access to the various levels of information that the pilot may need.

a. Map Displays

Various orientations of map displays have been used in the past, including track up, heading up, and North up, along with either moving airplane symbol or moving map concepts. Development of new methods for control over map orientation, display range, and clutter may be needed for low visibility surface applications.

b. Perspective Displays

A heads down perspective view is a relatively new idea, based on giving the pilot greater situational awareness, usually in the context of an airborne phase of flight. The two-dimensional nature of airport surface operations would suggest that the third dimension of a perspective view would be unnecessary. However, the possibility of having to rapidly correlate head down information with HUD or actual out-the-window information may require the HDD and HUD formats to be in a similar or compatible format. Current research on HDD perspective views, such as for curved approach "tunnels", should transfer to the airport surface operations problem.

8.6 DATA BASES

Flight deck data base technology is transitioning toward much higher capacity systems. Current concepts are based on magnetic-optical devices which combine the dynamic data input capabilities of magnetic storage with the high capacity storage capabilities of Compact Disc/Read Only Memory (CDROM) devices, allowing a read-write capability of one-half gigabyte per device. Current Electronic Library System (ELS) concepts are projecting a need for seven such data storage devices to encompass the full range of projected uses for maintenance, flight deck, and cabin applications. Future developments are projected to allow a full gigabyte per device.

Recommendations for standardizing the formatting of data for ELS applications have recently been made by Airline Transport Association (ATA) committees. Committee 89-9A has recommended that the Standard General Markup Language (SGML) format be adopted for electronic representation of document-related text. The SGML format may have potential for airport taxi related data. This format allows linking with hyper-text (a more general and high performance version of HyperCard, which is a user-friendly shell for managing both textual and graphic information). This may allow a very intuitive means for the crew to access text associated with taxi functions, including textual data associated with airport taxi diagrams, and NOTAMS.

ATA Committee 89-9B has recommended that Computer Graphics Metafile (CGM) format be adopted for graphics representation. CGM format has been recommended for storage of electronic representations of aeronautical charts, such as enroute and approach charts, and airport taxi diagrams. It defines images in terms of vectors, which allows rapid drawing rates for display generation, and also enables zoom functions to be used without reducing the image resolution. A typical approach chart or airport diagram is expected to require approximately 300 kilobytes storage using the CGM format. This can be contrasted to another common format, the CCITT group 4, which is a bit map format. At a resolution equivalent to that for a CGM image, a CCITT image would require about 1.3 megabytes. This could be reduced somewhat using data compression techniques, however. Each airline would probably have unique requirements for the total number of airports and charts needed in ELS. If 200 charts were stored in CGM format (perhaps 10 charts for 20 airports each), this would require only 60 megabytes, a small fraction of the 500 megabytes available on one drive. Data layering techniques, such as dividing runways, taxiways, obstacles, etc., into different groups or layers would be within the capabilities of CGM, however, specific recommendations for data structures are still being developed by industry committees.

There is a major constraint, however, associated with the use of ELS for storage of aeronautical chart data, due to the categorization of ELS as a "non-essential" system (i.e., not required for dispatch, no redundancy). For ELS aeronautical chart data to be displayed in a moving map or moving airplane symbol format, high frequency data on airplane position and heading or track would be needed. Aircraft navigation systems which contain such data are categorized as "critical", however, and are prevented from receiving data from "non-essential" systems such as ELS. ELS could generate its own display, however on the B-777 the needed navigation parameters are architecturally within the Airplane Information Management System (AIMS), which is currently limited to sending data only at low update rates. Origin or destination airport could be sent to ELS to automatically select appropriate charts for display, however transmission of high frequency data such as position or heading is not currently possible. The initial offering for such an ELS-based display would thus be a static display.

Longer-term plans for an ELS upgrade may consider placing ELS into "essential" or possibly "critical" categories. This would require redundant ELS's however, each with its own data base. Situational awareness type displays, with dynamic airport taxi diagrams on the navigation display would probably be feasible in the "essential" category, while steering guidance displays would probably require the "critical" category.

It should be noted that expanding the current Flight Management Computer (FMC) data base to include taxi diagrams would provide this data directly to AIMS type displays such as the navigation display. Unfortunately, in many cases FMC data storage is at capacity now, with several other potential applications competing for FMC storage space.

9.0 CONCEPT TRADE STUDIES

This section develops alternative concepts for comparison. The various technologies discussed in section 8 are evaluated against the preliminary requirements of section 7, and four concepts are identified which use the various technologies to meet the preliminary requirements.

9.1 METHODOLOGY FOR CONCEPT SYNTHESIS

The overall requirements of a low visibility taxi system (as developed in section 7.3) are: situational awareness, steering guidance, ATC surveillance, and obstacle avoidance. The various technology capabilities for each of the major requirements are assessed and appropriate technology parameters identified and quantified for comparison to the requirements.

9.1.1 Situational Awareness

In a general sense, situational awareness provides the pilot with an integrated understanding of the factors that contribute to a safe flight under normal or non-normal conditions. It allows the pilot to anticipate situations and think ahead of the aircraft. The components of situational awareness which are important for operations on the airport surface include spatial awareness, and awareness of environment. A brief discussion of awareness of environment is repeated in the obstacle avoidance section, but is also described here for completeness.

Spatial awareness can be defined further as the knowledge of where the aircraft is on the airport surface, including which taxiway or runway is being followed, which taxiway or runway intersection is being crossed or about to be crossed, the proximity of cautionary or restricted or closed areas, proximity to fixed obstacles such as buildings or semi-permanent construction equipment, and other positional elements which the pilot does not actually use to steer the aircraft. Spatial awareness provides the pilot with route planning information, as discussed in the next section. Spatial awareness enables the pilot to determine if he is complying with his taxi clearance, and is usually thought of in display terms with actual position indicated on a map display along with a graphic display showing his cleared taxi route. This is discussed in more detail in section 9.1.1.2.

Positioning and data base requirements drive the technology needed to provide spatial situational awareness. Required positional accuracy must be more precise than GNSS without differential correction. Uplinks of Mode S trilateration or ASDE-3 data, DGNSS, and sensor imaging techniques would meet this requirement.

Awareness of environment can be defined further as the knowledge of (a) airport surface weather (including visibility at present position as well as at various points around the airport, and pavement conditions such as ice or snow as well as braking action) and (b) other aircraft, vehicles, or moving objects. Requirements for visibility and braking action measurement and dissemination are discussed in this report, although specific concepts are not addressed. Awareness of other aircraft, vehicles, or other moveable objects does provide significant opportunity for concept development in this study. This aspect of situational awareness is included in the obstacle avoidance function.

Route planning and clearance coordination are specific surface movement elements of situational awareness, as developed in section 7.3.

9.1.1.1 Route Planning

The route planning function is fairly straight forward, and does not appear to present any real trade-offs in terms of technologies.

Displays and data bases are the primary technologies needed to satisfy this requirement. A CRT/flat panel color display will be needed for a heads down display of route planning information. The most efficient and cost effective use of flight deck resources would be to use the navigation display already in place in advanced technology flight decks. A selection for a taxi display format would need to be added to the navigation display control panel, and additional range selections would be needed for the airport surface. Minimal impact on flight operations would result, however, since a new ground display mode would not effect existing inflight display modes.

The most cost effective means of providing semi-permanent onboard taxi data for display appears to be either (a) expanding the existing FMC data base (which already includes enroute and terminal area navigation data) to also include airport surface navigation data, or (b) storing it in a mass storage device such as CDROM and accessing it through an electronic library system. Although there may be obstacles associated with these two alternatives, as discussed in section 8.6, the other alternative of data linking all needed surface navigation data to the aircraft would not be technically or procedurally effective in the near future.

More frequently up-dated data such as NOTAMS could be efficiently accessed at the beginning of each flight by use of data link technology, however. While still at the gate before pushback, a gatelink type of data link would probably be the most suitable solution; while inflight updates could be provided by ACARS/AVPAC, or perhaps by Mode S, based on priority and capacity considerations.

9.1.1.2 Coordinate Clearance

The general requirement to coordinate the taxi clearance is not a technology problem; VHF voice communication technology is well established. The situation becomes more difficult, however, when high reliability and integrity of overall end-to-end transactions are considered. Disadvantages of current ATC voice communications such as the readback and hearback problems, frequency congestion, mistaken identities, etc. are well documented. These problems could potentially be at their worst during low visibility conditions at major Cat 3 airports if higher levels of surface traffic are achieved with low visibility taxi systems. Data link for ATC coordination may well be the key to ensuring high reliability and integrity communications. Data link technology will also enable route planning and navigation to benefit from efficient access to taxi clearances which are stored as digital data.

The specific version of data link used, although expected to be Mode S based on the FAA's published goals, may need to be adapted to fit the unique requirements of the airport surface environment. Complete coverage on the airport may require multiple Mode S sensors, or possibly repeaters using a different spectrum, such as ACARS or AVPAC. As for the route planning function, clearance coordination could also be accomplished at the gate before pushback using gatelink. Changes to ATC ground control procedures may be needed to support gatelink, however, since currently the taxi clearance at busy airports such as O'Hare is based on very dynamic tactical traffic situations that would only be known after pushback. As the ATC system transitions to a time-based operation, however, strategic taxi clearances issued before pushback would become more advantageous.

9.1.2 Steering Guidance

This function provides the pilot with flight deck steering guidance to track a pre-determined taxi path, and will ensure adequate edge distance between the outer wheels and the edge of the weight bearing surface. Guidance can be either in the form of a bore-sighted image displayed to the pilot (which can be tracked visually similar to current visual taxi techniques), or in the form of computed commands or cues which the pilot follows using nosewheel or rudder pedal steering and braking techniques.

Technology requirements for this function are quite severe, due to the sometimes limited clearance distances available for maneuvering large aircraft on the surface. DGNSS and sensor imagery appear to be the only suitable choices for steering guidance positioning technology at present, given installation, integrity, and other problems associated with the other technologies studied.

9.1.3 ATC Surveillance

The surveillance function is a primary requirement of the ATC ground control system for low visibility airport surface operations. An ASORA study ground rule was established that ASDE-3 airport surface radar would be available at all the airports assumed for this study, and is therefore incorporated in all the following alternative concepts described in this section of the report. Mode S trilateration is another promising technique for accurate surveillance data, as is an ADS mode of DGNSS.

9.1.4 Obstacle Avoidance

This function acts as a backup to the basic monitoring role of ATC, in much the same way that the Traffic Alert and Collision Avoidance System (TCAS) operates inflight. There are two different technology approaches for this function; first to use an onboard sensor to detect obstacles, and second to rely on uplinked information from the ATC surveillance system. The first approach will potentially allow more accurate information, using sensor imagery. The second approach will be subject to the resolution inadequacies of the surveillance system, and may also cause data link capacity problems, resulting in less frequent updates.

9.1.5 Technology Summary

Table 9-1 summarizes the various advantages and disadvantages among the most competitive technologies, grouping requirements into situation awareness, steering guidance, surveillance, and obstacle avoidance.

9.2 ALTERNATIVE CONCEPTS

This section identifies four alternative concepts for implementing low visibility taxi operations. Each concept represents a specific mix of available technologies which appears to satisfy the technical requirements developed in section 7 of this report.

It should be noted that the following concepts all share some technology elements, based on the groundrules developed in section 1. Assuming an EFIS/FMC equipped aircraft, all four alternative concepts use head down electronic displays (CRT or flat panel technology) for pilot interface for route planning, situational awareness, and clearance coordination. An INS or IRS is also assumed to be onboard. All the concepts use ASDE-3 and ASTA/AMASS capabilities for the surveillance function, as well. An ATC digital data link is also assumed for each concept. The ASTA capability of data linking strategic taxi clearances as well as warnings and alerts, is assumed. VHF voice would be used for tactical messages and as a backup for data link. There are also specific passive airport elements assumed to be available for use by all concepts. The additional technologies used by each alternative concept are described in the following sections.

Table 9-1. Technology Advantages/Disadvantages

	Situation Awareness	Steering Guidance	Surveillance	Obstacle Avoidance
DGNSS	**Satisfies Requirement** — Concept would require a high capacity data link to broadcast proximate traffic, needs on-board data base of airport features.	**Satisfies Requirement** — May need INS smoothing for satisfactory guidance cues.	**Satisfies Requirement** — Requires an automatic data link of traffic position to ATC.	**Partially Satisfies Requirement** — Will detect moving obstacles (aircraft, vehicles) only when equipped with GNSS transponders. Fixed obstacles must be in positional data base.
ASDE-3	**Does Not Address Requirement** — Without means of interface to a data link system for broadcast of proximate traffic data.	**Does Not Address Requirement.**	**Satisfies Requirement** — Except in heavy rain, and with limitation of multiple-target phenomena due to long tubular fuselage (eg. DC-9, MD-80).	**Partially Satisfies Requirement** — Can't detect animals, people, multiple target phenomena may hinder obstacle detection, requires data link to warn aircraft.
MODE S Trilateration	**Satisfies Requirement** — Needs high capacity data link to broadcast proximate traffic, needs on-board data base of airport features.	**Does Not Address Requirement.**	**Partially Satisfies Requirement** — When enough receiving sensors (5 to 6) are installed around airport perimeter. Requires mode-S equipped targets.	**Partially Satisfies Requirement** — Detects only Mode-S equipped targets, requires data link to warn aircraft.
MMW	**Partially Satisfies Requirement** — For ranges <2km. Limited resolution may take more time to interpret. Hazy overcast may degrade. Limited FOV.	**Satisfies Requirement** — Radar Reflectors may be needed for reduced RCS areas, may need to enhance center line.	**Does Not Address Requirement.**	**Might Satisfy Requirement** — Limited by 2 km range (clearing runway for takeoff?) Variability of RCS could be difficult.
FLIR	**Partially Satisfies Requirement** - For RVR >300 feet, range perceived by pilot, limited FOV may hinder planning.	**Satisfies Requirement** — May be limited to RVR >300, may need IR beacons in adverse surface conditions of rain, snow, etc.	**Does Not Address Requirement.**	**Partially Satisfies Requirement** — For adequate temperature difference, surface conditions, visibility > 300 RVR. Range rate and range based on pilot perception.

9.2.1 Concept A: DGNSS/ASDE-3/EVS

Concept A uses DGNSS/ADS and EVS (MMW and FLIR sensors with HUD) flight deck technology, along with ASDE-3 for ATC, to meet the requirements of a low visibility taxi system. Figure 9-1 illustrates this concept.

The aircraft determines its absolute position using DGNSS. An onboard GNSS receiver determines current position based on the GNSS constellation (as discussed in section 8.1, GPS is expected to serve as the initial GNSS constellation), and combines that with differential correction data broadcast from a reference differential station located at a surveyed point on the airport. The differential broadcast utilizes a high speed digital data link, such as ACARS or AVPAC, or another special purpose data link.

The corrected GNSS position is input to the INS/IRS system, and then interfaced with an event/time-based ADS system which downlinks airplane state data (position, groundspeed, track angle) using ACARS or AVPAC to a centralized airport surveillance system, which also uses ASDE-3 surface surveillance radar to track ground targets, including non-ADS targets. In the ASTA/AMASS concept, ADS data is used to provide target ID as well as to improve accuracy of the target.

AMASS/ASTA automation generates a display of surface traffic for the ATC controller, and also generates alerts of potential traffic conflicts. This surveillance data is uplinked to aircraft using the ATN. A broadcast available to all aircraft may be adequate for general surveillance data, however the possibility of AMASS/ASTA generated alerts being uplinked to the appropriate aircraft may suggest the ATN use of Mode S data link to allow selective addressing with high integrity and reliability. Coverage of the airport surface may be incomplete unless multiple Mode S sensors are installed to cover blind spots.

Current position and other traffic are displayed on the navigation display, using a specially developed taxi display format for surface operations. A plan view format is expected to be the most suitable for general situational awareness, with current position and other traffic overlaid with significant airport features such as taxiways, runways, critical or restricted areas, etc. Various display ranges will be available, although the maximum magnification to be provided should in large part be dictated by whether the display provides steering guidance information. In this concept, steering guidance is assumed to be provided on the HUD, although future research into areas such as crew procedures could well indicate the utility of steering guidance on a head down display, as well. The taxi display will also indicate traffic and temporary obstacles sensed by AMASS/ASTA and ASDE-3, and those fixed obstacles stored in the onboard data base.

A stroke/raster head up display mounted in front of the captain (and possibly the first officer) will display sensor images from detected obstacles, which may also be displayed on the head down taxi display from AMASS/ASTA. A combination of FLIR and active MMW is expected to be required to provide sufficient range and resolution in adverse weather conditions such as dense fog or rain. Depending on atmospheric conditions, taxiway or runway lights and/or markings, and IR/radar reflective markings will enhance the image and provide more detail. HUD steering symbology similar to that used for runway rollout guidance will be driven by an error signal based on current position and a reference taxi path. The pilot manually controls nosewheel steering to follow the HUD steering commands, although advanced concepts may consider an automatic steering mode when sufficient integrity and reliability are available. Other information could be displayed on the HUD, such as groundspeed and acceleration. Alerts from AMASS/ASTA could also be displayed on the HUD, possibly generating braking commands or cautionary advisories. Onboard conflict detection algorithms based on range and range rate of

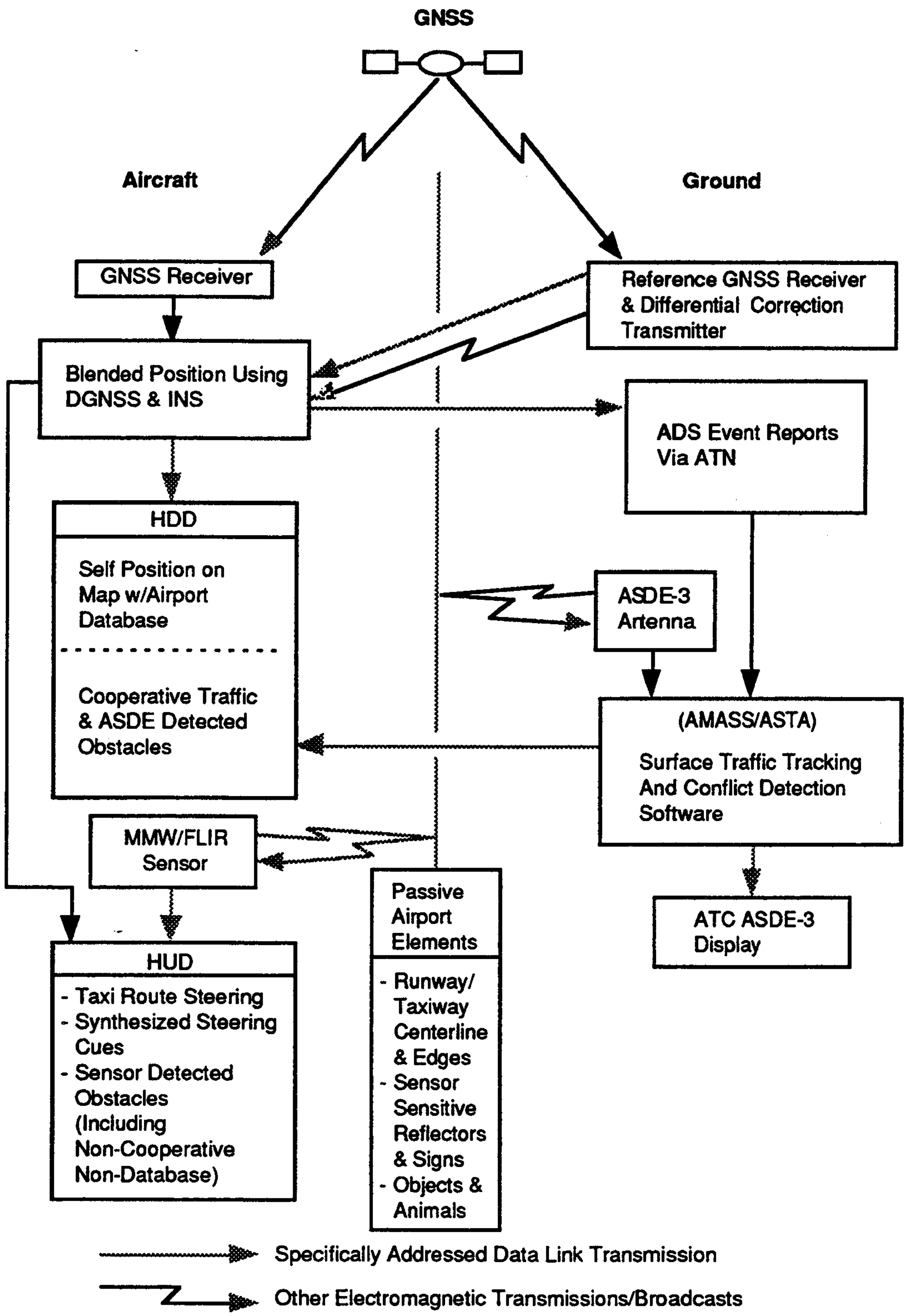


Figure 9-1. Concept A: DGNSS/ADS, ASDE-3, EVS

sensor-detected obstacles could also generate alerts, with the conflicting sensor images highlighted or otherwise enhanced.

9.2.2 Concept B: ASDE-3/EVS

This concept, illustrated in figure 9-2, does not use a differential correction for GNSS positioning. Without this correction, the aircraft position uncertainty (assuming selective availability in use) will be small enough to partially satisfy the situational awareness requirement, but too large for steering guidance. In this concept, steering guidance is performed solely with the sensor-driven HUD imagery of the airport environment.

A GNSS receiver is onboard, presumably for other flight applications, and the current position output is blended with the INS/IRS output. This onboard determined position is displayed with a database generated airport surface map on a CRT/flat color display. The aircraft determined position could be transmitted for display on the ATC surveillance display (via ADS), but this would offer no accuracy benefit over ASDE-3 and would not be required.

As in all four concepts, the ground based ASDE-3 radar and AMASS/ASTA traffic automation systems would monitor cooperative and non-cooperative surface targets. Surface radar target information could be broadcast to all aircraft, with conflict alert information being addressed to specific aircraft. Surface target information would be depicted on the surface map display (HDD) and the alert information displayed on either the HDD or HUD.

The stroke/raster head up display, described in concept A, would also be used in this concept. The only difference would be that the computed steering cues generated by DGNSS, would not be available. A greater reliance on sensor sensitive reflectors/markings would be required. Corner reflectors, colocated with edge lights, could enhance runway/taxiway edges in certain low visibility conditions. A taxiway center line could possibly be synthesized on the HUD when the taxiway surface edges were detected with sufficient confidence.

9.2.3 Concept C: Mode-S Trilateration/ASDE-3/EVS

This concept, illustrated in figure 9-3, uses Mode S trilateration to improve surveillance performance. Availability of surveillance should be improved over what could be achieved by ASDE-3 alone, for instance during periods of heavy rain when ASDE-3 may not operate satisfactorily, or when temporary blockages or overloads of the Mode S system occur.

EVS sensors would provide the navigational capability, as in concept B.

9.2.4 Concept D: DGNSS /ASDE-3

This concept, illustrated in figure 9-4, uses DGNSS for steering guidance as well as situational awareness, without providing any backup in the form of an EVS system. DGNSS in an ADS mode is also used to improve the surveillance performance beyond what ASDE-3 achieves. For operation in visibilities down to zero, steering guidance cues would be displayed on the HDD taxi display, or on a HUD (although this concept does not include sensors). The choice of steering cues on a HDD or a HUD could be affected by whether the HUD would have other applications (eg., Cat 3 ILS guidance) on the flight deck, and crew procedures for low visibility taxi.

9.3 BENEFIT ANALYSIS OF ALTERNATIVE CONCEPTS

This benefits analysis compares four alternative concepts and attempts to quantify benefits in terms of an individual airline operator. A key assumption made, due to the focus of this study on

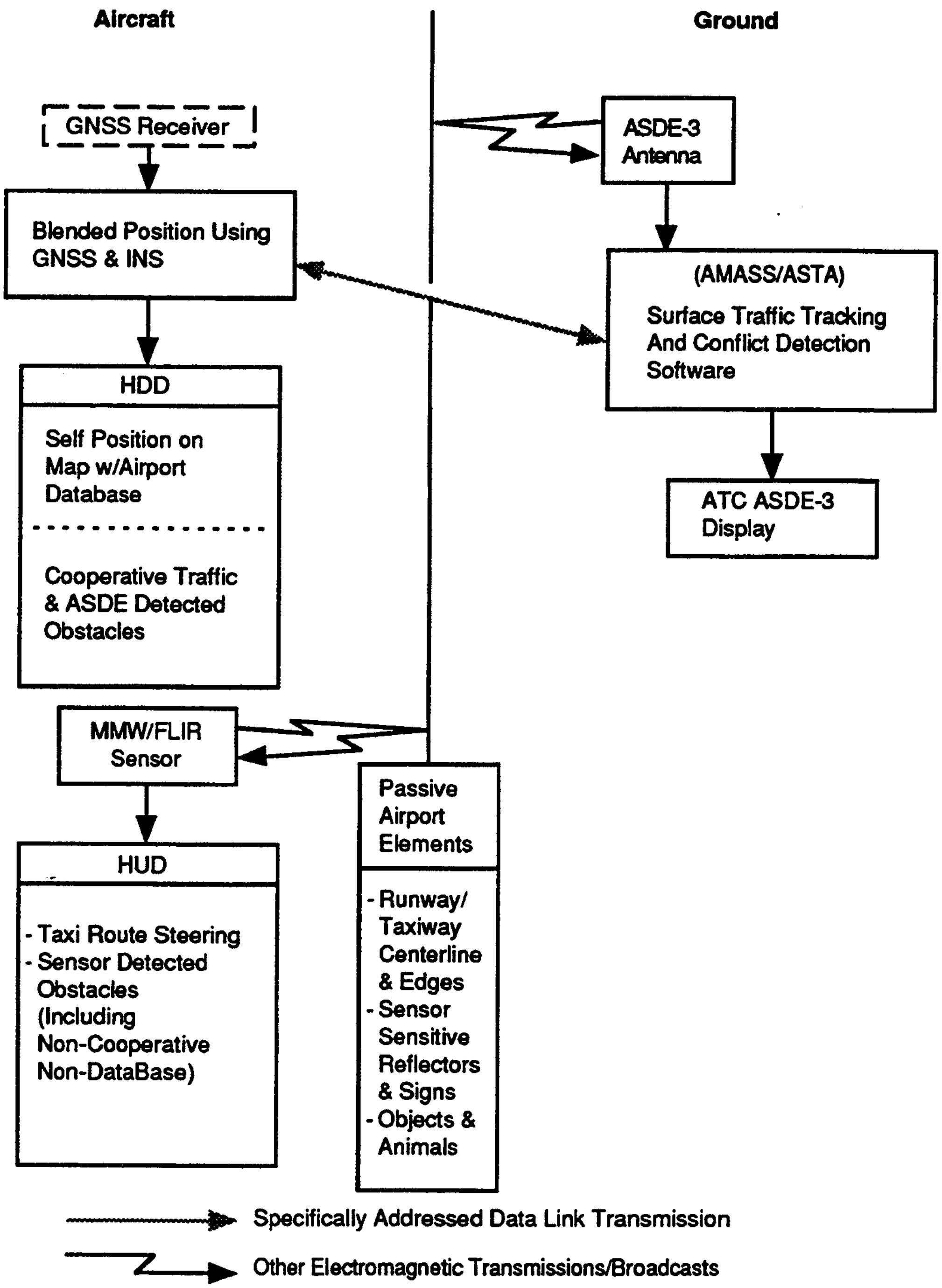


Figure 9-2. Concept B: ASDE-3, EVS

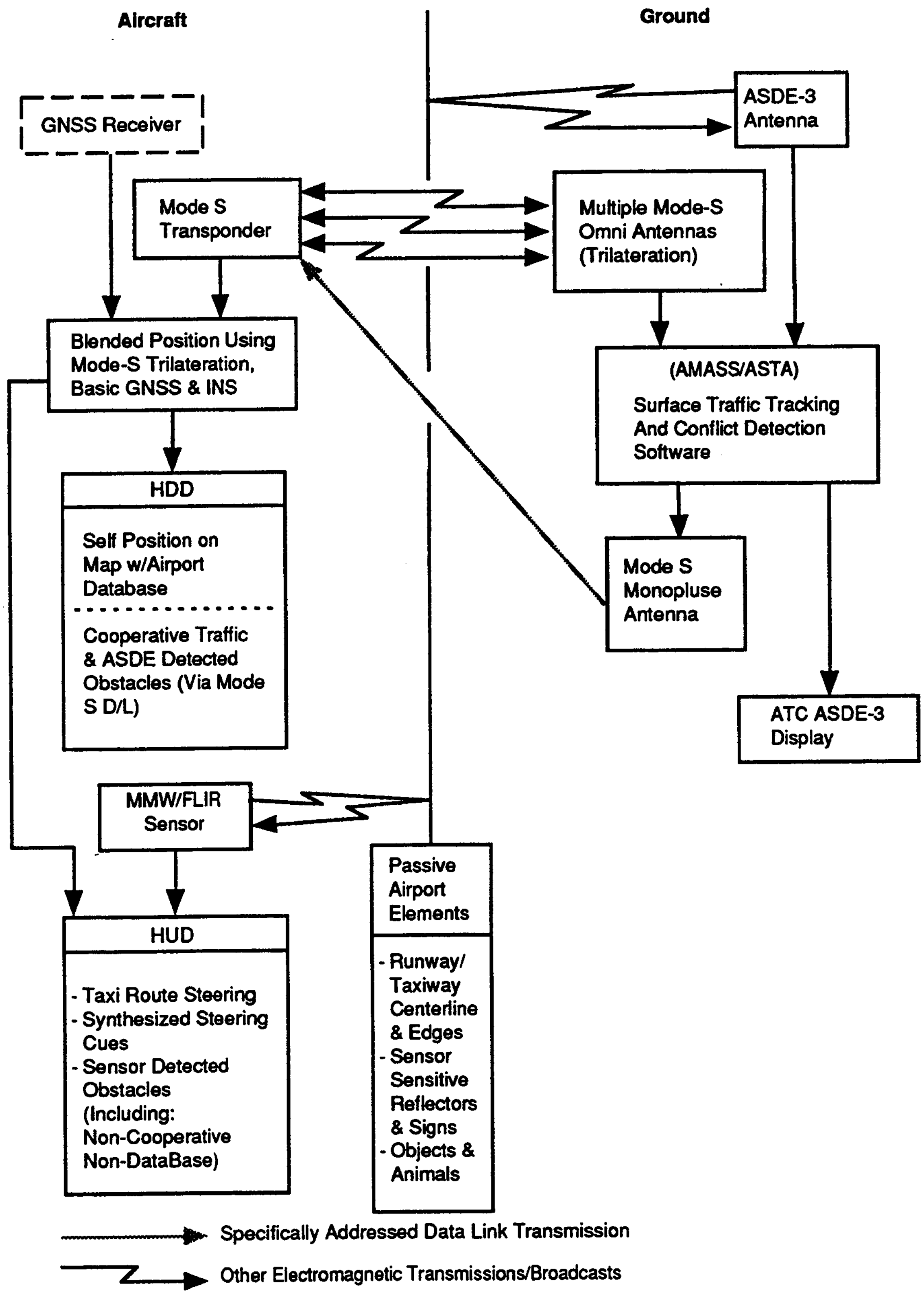


Figure 9-3. Concept C: ASDE-3, Mode S Trilateration, EVS

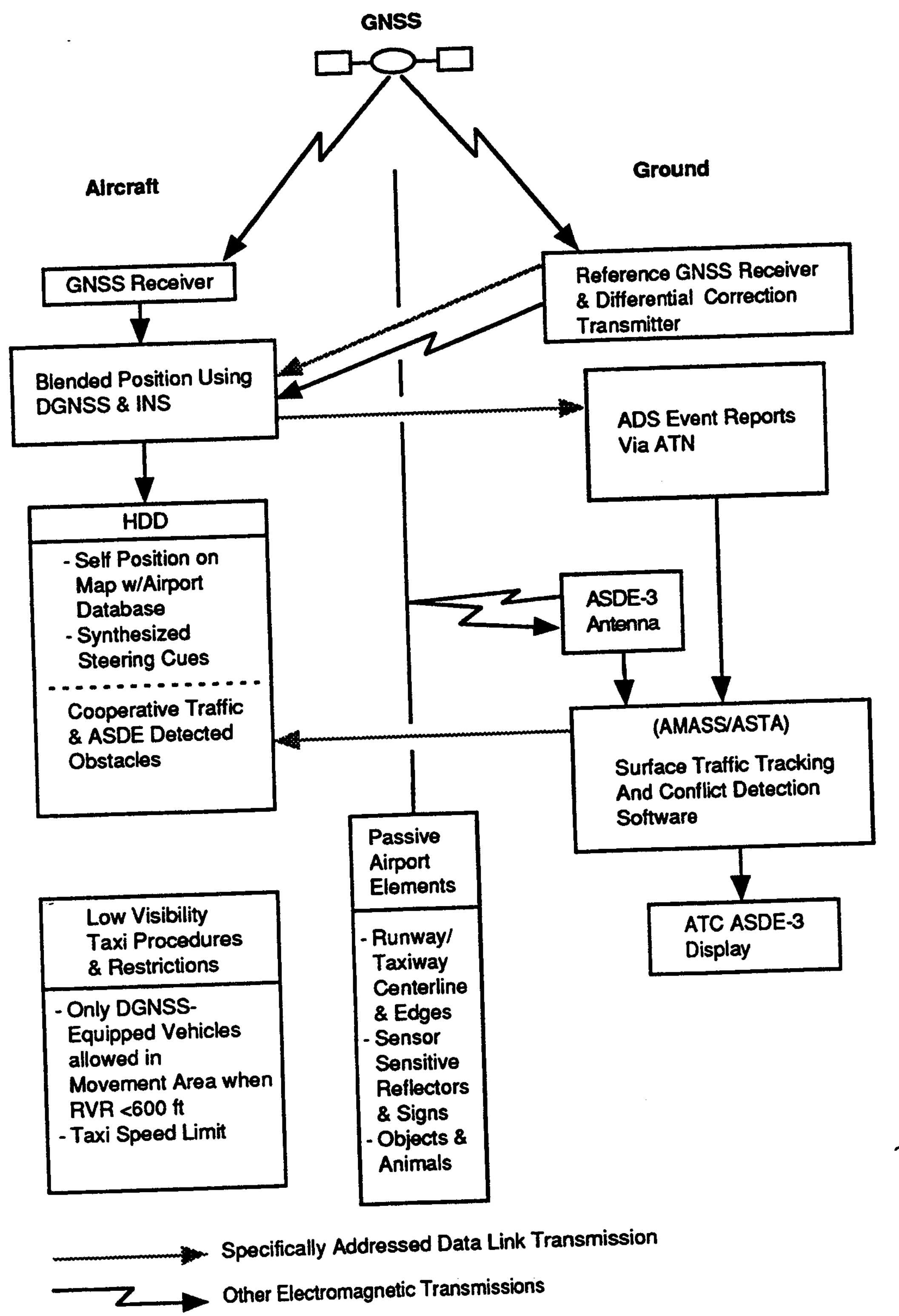


Figure 9-4. Concept D: DGNSS/ADS, ASDE-3

surface operations, is that only benefits attributable to improved surface operations will be addressed. Similarly, in the next section which develops cost factors for the alternative concepts, only those costs attributable to low visibility surface operations are addressed. It is hoped that the following results will be useful to analysts in assessing the benefits and costs of improving low visibility operations for departure and arrival flight phases, in addition to surface operations. A more global analysis would also take into account such benefits as ATC flow control optimization which would accrue on a system-wide basis.

The basic approach used was to determine what a hypothetical airline fleet's disruption costs would be due to low visibility related events. This technique was originally developed by Flight Dynamics, Inc. to quantify the benefits of their Head Up Guidance System to customer airlines. The authors of this report appreciate the significant contribution made by Flight Dynamics, Inc. in this regard.

Another key assumption is that during periods of low visibility, ATC procedures would be adopted to require specific ground-based and onboard capabilities for the ATC system and aircraft. Lack of required capabilities would deny access to the airport movement area, and would result in a planned departure remaining at the gate. The inability of a planned arrival to maneuver as required in the movement area is assumed to result in denied access to the landing runways, as well, since subsequent arrivals could otherwise be impacted. Diversion to an alternate or airborne holding is assumed for such an unequipped arrival.

Based on material in the previous section identifying the four candidate concepts, two equipage categories are assumed. An overall surveillance equipage category is defined which provides positional data to ATC on all aircraft and vehicles in the movement area, and allows ATC to monitor obstacle avoidance. An overall navigation equipage category is also defined, which provides situational awareness, obstacle avoidance, and steering guidance functions for the aircraft. Assumptions are that when visibilities drop below 600 feet RVR, surveillance equipage is required for ATC; and that when visibility drops below 300 feet RVR, an additional navigation equipage is also required for aircraft. The roles of the individual technologies for each of the alternative concepts in each equipage category are as follows:

	Visibility < 300 feet RVR	
	Visibility < 600 feet RVR	
CONCEPT	SURVEILLANCE	NAVIGATION
A.	DGNSS/ADS ASDE-3	DGNSS EVS
B.	ASDE-3	EVS
C.	Mode S trilateration ASDE-3	EVS
D.	DGNSS/ADS ASDE-3	DGNSS

9.3.1 Visibility Minima Requiring Surveillance

It is assumed that surface operations below 600 feet RVR would not be permitted without one of the above forms of low visibility ATC surveillance in operation. This is supported by criteria in reference 1, and by considering that another study guideline was to provide near-VFR type capacities in very low visibilities. It is assumed that when visibility is below 600 feet RVR, lack of this surveillance capability would prevent departures from entering the movement area and would prevent arrivals from landing.

9.3.2 Visibility Minima Requiring Navigation

It is further assumed that surface operations below 300 feet RVR would not be permitted without one of the above forms of low visibility aircraft navigation in operation, in addition to the ATC surveillance equipage. This visibility is the lowest level identified in reference 1; which mentions, however, no specific equipage as yet. It should be noted that aircraft have been towed or taxiied very slowly in the movement area in visibilities below 300 feet RVR using only visual reference; however, again the guideline for near-VFR type capacities would seem to provide justification for this surface navigation equipage minima.

9.3.3 Events vs. Impacts

A low visibility event, for the purposes of this analysis, is a scheduled airplane operation (arrival or departure) which is affected by the visibility being below the allowable minima. The analysis uses the predicted frequency of airline flights, combined with a statistically determined visibility model to estimate the number of events which will be affected by the relevant visibility levels, in this case 600 and 300 feet RVR. An impact factor is then used, which acts as a multiplier on the number of events, to predict the total number of impacts which will result from a specific visibility situation. An impact is defined as any flight/ground disruption, on a airline fleet wide basis, that occurs due to an event. The impact factor concept can be thought of as a ripple-effect which is intensified by the hub and spoke concept commonly used by the major carriers. In other words, a single event such as a delayed departure can "ripple" through an airline's entire route structure, ultimately causing several other operational "impacts" which could occur at other airports, at hours or sometimes even days later than the initial event. Empirical data from four airlines has been used to quantify this ripple effect. Recent detailed investigations and analysis done during specific below minima fog periods have validated this data, indicating that a typical impact factor for a fleet of narrow-body aircraft such as a B-727 or B-737 is about 5. The impacts were determined to be distributed among five primary categories; cancellations, diversions, airborne delay, departure delay, and ferry flights.

In the above context, then, the benefit of a low visibility system is derived by estimating the otherwise incurred fleet disruption costs associated with each impact.

9.3.4 Availability of Low Visibility System Components

The availabilities of the various surveillance and navigation elements of the four concepts are important parameters needed to quantify benefits. Whenever a low visibility system component is not available for use during a low visibility condition, (i.e., below 600 RVR for surveillance, below 300 RVR for navigation) fleet disruption costs are incurred.

Availability, as used in this context, is defined in reference 8 as the percentage of time that the services of a system are within required performance limits, and is an indication of the ability of the system to provide usable service within the specified coverage area. Availability is a function of both the physical characteristics of the environment and the technical capabilities of the system.

A conservative approach was adopted in assuming availability values for the various technologies. DGNSS availability was set at 95%, both for navigation and surveillance. This is the same level of availability as the basic GPS 100 meter horizontal accuracy guaranteed by DOD. Although GNSS availability is expected to be enhanced considerably (to above 99%) by augmentations such as GIC and RAIM, the additional need for a data link (of GNSS correction signals for navigation and position reports for surveillance) in the airport surface environment was felt to represent a difficult challenge. DGNSS availability of 95% was assumed as a conservative estimate for near term implementation.

The EVS navigation system availability was also assumed to be 95%, felt to be representative of both a MMW and FLIR sensor collocated together to complement and supplement during adverse weather conditions. ASDE-3 availability, although originally specified years ago as 99.8%, may fall somewhat short of that goal, as did the original ASDE and ASDE-2 installations. Based on the frequent (about 50%) unavailability at Pittsburgh, a compromise number of 75% availability was assumed. This same level was assumed for Mode S trilateration, although insufficient development has occurred to really have a good idea what it should be. Conceptually, it should be better than ASDE-3, which must overcome the inherently less reliable mechanical mechanisms for rotating the antenna. These various technology availabilities are then combined (either in series or parallel depending on if multiple technologies provide redundancy or if they are all required) to produce an overall availability for each candidate navigation and surveillance component.

The variation in availabilities, combined with the estimated number of impacts due to below 600 feet RVR and due to below 300 feet RVR weather, produces a total annual number of impacts avoided by each of the four candidate concepts.

The number of impacts for cancellations, diversions, air delays, departure delays, and ferry flights is determined from the total number of impacts. Cancellation costs are estimated based on the number of passengers accommodated (meals, lodging, etc.) and lost to other airlines, and mitigated by the direct operating cost (DOC) saved. Diversion costs are estimated based on the number of passengers accommodated (meals, lodging, transportation, etc.) and lost to other airlines, DOC added, alternate landing fees, and added crew costs. Air delays are estimated based on the number of passengers lost (to other airlines) and DOC added. Departure delay costs are estimated based on the number of passengers lost to other airlines. Ferry flight costs are estimated based on DOC added.

9.3.5 Other Assumptions

Another increment of benefit is derived from assuming a taxi speed enhancement due to the various steering guidance technologies. This benefit is assumed to accrue during the time period when visibilities are between 600 and 300 feet RVR, since by assumption only surveillance is required, and is further assumed to provide a taxi speed of 10 kts. A 2 nm taxi distance is also assumed. A benefit for having EVS, DGNSS, or EVS/DGNSS steering guidance is derived by computing the reduced taxi time (and thus reduced DOC) due to taxi speeds of 20 kts, 20 kts, and 25 kts, respectively. No benefit is derived for visibilities less than 300 feet RVR, since one of the EVS, DGNSS, or EVS/DGNSS steering guidance modes is assumed to be required anyway, and the differences in taxi speed among them is considered insignificant.

Other assumptions needed to estimate fleet disruption costs include average values of load factor, segment length, direct operating cost, and net passenger revenue. A composite frequency of occurrence of low visibility must also be determined, based on data from relevant airports within an airline's route structure. Data from the National Oceanic and Atmospheric Administration's (NOAA) 10 year airport climatological studies was used in determining frequency of occurrence averaged over five airports: Anchorage, Seattle, Portland, Los Angeles, and San Francisco. This process indicates that the probability of the visibility being less than 600 feet RVR is about 0.5%, while the probability of the RVR being less than 300 feet is about 0.25%. The confidence level of the 300 feet RVR probability is somewhat lower than that for 600 feet RVR, since transmissiometers reading RVR below 600 feet have only recently been installed at a few airports. Isolated spot data, however, tends to substantiate this number.

9.3.6 Derived Benefits

The above assumptions and methodologies produced gross benefits on an annual, per airplane basis (fig. 9-5) of $72K for concept A, $54K for concept B, $67K for concept C, and $71K for concept D. The trends are about as might be expected, based on the increased availabilities which result from redundancy; as in concept A, where there are two redundant navigation systems, and two redundant surveillance systems. In considering the annual benefits for the four candidate concepts, remember that this process did not account for any costs associated with these technologies. The next section will attempt to address costs, although a somewhat less specific approach must be taken.

9.4 COST FACTORS FOR ALTERNATIVE CONCEPTS

Cost increments incurred due only to providing navigation and surveillance capabilities for airport surface operations were identified. This is consistent with the approach taken by the previous benefits analysis which determined benefits accrued due only to those same surface navigation and surveillance capabilities.

Specific acquisition and installation costs for the various technologies are not addressed. Cost factors are identified, rather than attempting to identify specific costs, in part due to the difficulties in allocating specific segments of a system such as DGNSS or EVS to surface operations. Concepts such as these are expected to play major roles in enroute, terminal area, and precision approach phases of flight, as well as surface operations. A complete picture of the cost to benefit ratio would reflect multiple applications of such a technology. This type of detailed cost/benefit analysis is recommended for a future study, when concepts for integrated flight deck technologies can be refined to the point where system-wide benefits of lower weather minima operations can be determined.

9.4.1 DGNSS Cost Factors

It is assumed that DGNSS will be integrated into terminal area operations at major airports (including the ground stations needed to broadcast local area differential corrections), and incorporated into the flight decks of most commercial transports for enroute and terminal area operations, as well as surface operations. It is not clear what the long-term economic structure to support GNSS will be; however, any FAA or airport authority, and/or user fees are not considered in identifying cost factors for surface operations.

However, a potentially significant increment in cost due to surface operations using GNSS is identified, however, in developing airport data bases compatible with GNSS. Enroute and precision approach applications will only require a few data points for each airport, however surface operations at large complex airports such as Chicago-O'Hare could require potentially hundreds of points, surveyed to within fractions of a foot if used for steering guidance. Large airports are usually well specified in terms of engineering and architectural drawings, however several different reference systems are often used for various types of data. GNSS has adopted the WGS-84 coordinate system, which is an earth-centered, earth-fixed system requiring complex transformations to other types of reference systems. Attempts to analytically convert existing airport data is not expected to support steering guidance levels of accuracy. Carrier-phase and differential GPS surveying techniques are well established, and have already been employed in developing airport data in WGS-84 coordinates. Typical costs for GPS surveys of many points run in the neighborhood of $150 to $300 per point. Often, fewer GPS control points can be established and conventional survey techniques used to then determine other needed points at sometimes better accuracy than GPS. A rough estimate for surveying a large airport might be in the $50K to $75K range. This data must then be incorporated into a data base useable by EFIS/FMC equipped aircraft. Cost factors here could include payback to a vendor

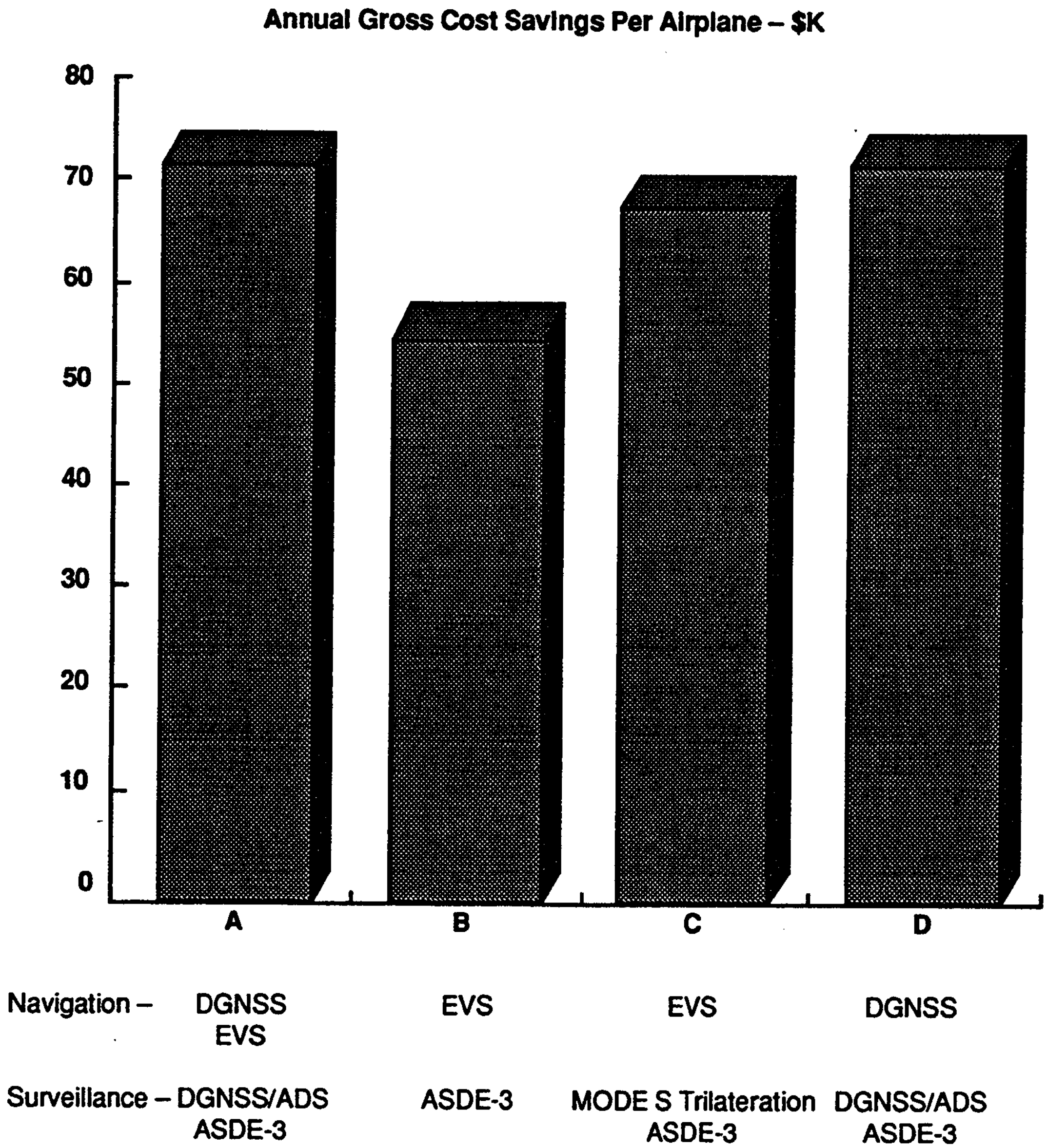


Figure 9-5. Economic Benefits Of Candidate Concepts For Surface Operations

based on the frequency of updates and the user charges levied. Since most airport features requiring a survey are relatively stable and would not require a regular update cycle, addition of other more frequently updated data such as NOTAMS, closed/preferred areas, etc. may be needed to provide a payback for the initial survey cost.

Another cost factor for surface operations may be the need for a higher capacity data link to handle a greater volume of traffic than needed for enroute or terminal area operations. The many vehicles that operate on the airport surface, as well as aircraft, plus the addition of situational awareness broadcasts of proximate traffic could well result in higher bandwidth requirements than for other inflight applications of GNSS. Non-movement area surveillance and situational awareness information may be segregated onto separate data link systems from higher priority movement area data.

Use of DGNSS for steering guidance will necessitate control law development and certification of the algorithms, processors, and symbology used to generate guidance cues for the pilot. This is an expensive process, and would have multiple cost factors which would not benefit other phases of flight.

9.4.2 EVS Cost Factors

It is assumed that FLIR and MMW sensors and HUD displays will be implemented for other phases of operation, including enroute and terminal area operations. A cost factor that may be incurred due only to surface operations, however, is installation of radar reflectors or IR beacons. These may be required on portions of an airport surface where a natural grass/pavement boundary does not exist, as on a large open expanse with multiple taxiways/lanes delineated by painted lines. Installation costs of about $35 to $50 per reflector are estimated, plus possible operational delays for rerouting while an area is closed. This cost could possibly be subsidized by federal funds from the Airport Improvement Program.

Another possible cost factor could be due to a "snap-look" function, needed to quickly and accurately shift the field of regard of the sensor suite. This capability may be required only for surface operations, although windshear or terrain applications in the terminal area may possibly benefit from it as well.

9.5 COSTS AND BENEFITS SUMMARY FOR CANDIDATE CONCEPTS

Table 9-2 compares cost factors, annual savings, and safety and efficiency enhancement criteria for the candidate concepts. The relative cost has been categorized as low, moderate, or high, based on the discussion in the previous section on cost factors.

9.5.1 Concept A: DGNSS, ASDE-3, EVS

The relative cost of this concept is categorized as moderate to high, due to its reliance on (1) a newly developed airport data base and data link system, as well as for steering guidance development for DGNSS implementation; (2) EVS cost factors for ground reflectors, and a "snap-look" function.

Safety enhancements should accrue due to redundancy of navigation and surveillance functions. The use of DGNSS/ADS as well as ASDE-3 for surveillance should lower the probability of runway incursions, as well as undetected obstacles. Accurate DGNSS positioning could permit onboard automatic conflict checking for stored obstacles in an airport data base, while the MMW and FLIR sensors could ensure that non-transponder equipped vehicles and aircraft were detected even without DGNSS infrastructure. Situational awareness will be enhanced with access to an on-board airport data base.

Table 9-2. Cost/Benefit Comparisons for Low Visibility Surface Operations Concepts

Concept	Cost Factors	Gross Savings Per Airplane Per Year	Safety/Efficiency Factors
A. DGNSS ASDE-3 EVS	<u>Moderate-High</u> Airport data base development High capacity data link Steering guidance development Radar/IR reflector installations Snap-Look sensor pointing	$72K	* Greater situational awareness due to on-board data base * Fewer runway incursions due to more accurate positioning * Accurate DGNSS positioning unaffected by visibility * ATC surveillance availability improved with DGNSS/ADS * Improved obstacle detection with minimal infrastructure changes * Detection of uncooperative targets and uncharted obstacles
B. ASDE-3 EVS	<u>Low</u> Radar/IR reflector installations Snap-Look sensor pointing	$54K	* Less situational awareness without airport data base * Higher probability of runway incursions in adverse weather * Improved obstacle detection with minimal infrastructure changes * ASDE-3 surveillance outages may cause procedural difficulties * Detection of uncooperative targets and uncharted obstacles
C. ASDE-3 Mode S Trilateration EVS	<u>Low</u> Radar/IR reflector installations Snap-Look sensor pointing Multiple Mode S sensors	$67K	* Less situational awareness without airport data base * Improved obstacle detection with minimal infrastructure changes * ATC surveillance availability improved with Mode S Trilateration
D. ASDE-3 DGNSS	<u>Moderate</u> Airport data base development High capacity data link Steering guidance development	$71K	* Greater situational awareness due to on-board data base * Fewer runway incursions due to more accurate positioning * Accurate DGNSS positioning unaffected by visibility * ATC surveillance availability improved with DGNSS/ADS * Procedural changes to infrastructure may be needed

9.5.2 Concept B: ASDE-3, EVS

This concept has a low relative cost, since DGNSS costs are omitted. Reliance on ASDE-3 could mean increased delays due to surveillance outages. Procedural difficulties, rerouting aircraft, using tugs or follow-me vehicles, etc. may result from such an outage if aircraft are stranded throughout the airport surface. Obstacle detection may be less robust, also, due to less redundancy in detecting GNSS-transponder equipped aircraft. Potential difficulties in adverse weather may occur by relying on EVS sensors. For example, a limited range may prevent the pilot from checking the far end of a runway for obstacles prior to takeoff, forcing reliance on ATC surveillance for this function. Situational awareness will be degraded without access to an on-board data base.

9.5.3 Concept C: ASDE-3, Mode S Trilateration, EVS

This concept also has a low relative cost since DGNSS costs are omitted. The incorporation of Mode S trilateration is assumed to occur without additional cost to the user. As ATC data link communications expand toward airport surface operations, the additional Mode S omnidirectional sensors needed for trilateration could be expanded to handle transmissions as well, so that two-way Mode S to all parts of the airport is possible. The FAA may take on trilateration as part of its upgrade program. Increased surveillance redundancy for Mode S equipped targets will result, using this concept. Less redundancy in detecting GNSS-equipped targets would result, although this may be compensated for by interfacing the Mode S trilateration system with a data link broadcast to other aircraft of proximate traffic. Potential difficulties in adverse weather may occur by relying on EVS sensors. For example, a limited range may prevent the pilot from checking the far end of a runway for obstacles prior to takeoff, forcing reliance on ATC surveillance for this function.

9.5.4 Concept D: ASDE-3, DGNSS

The relative cost of this concept is categorized as moderate, since it requires the various DGNSS costs but does not incur EVS costs. Lack of EVS could result in greater difficulty in detecting non-DGNSS equipped threats, relying instead on potential obstacles detected by ASDE-3 uplinked to the aircraft. Imposition of a procedural rule requiring aircraft and vehicles to be DGNSS transponder equipped before being allowed to enter the airport movement area may overcome the lack of EVS, however enforcement and guarding against unintentional blunders could be a problem.

10. CONCLUSIONS AND RECOMMENDATIONS

This study identified four top-level requirements for aircraft operation on the airport surface in visibilities from 600 feet RVR to zero.

1. Situational Awareness
2. Steering Guidance
3. ATC Surveillance
4. Obstacle Avoidance

10.1 RECOMMENDED CONCEPT

Concept A, using DGNSS/ADS and ASDE-3 for surveillance, and using DGNSS and EVS for navigation, is the recommended concept for low visibility surface operations. The estimated higher cost is judged to be offset by the safety enhancements which should result. The annual gross benefits of $72K per airplane per year do not adequately reflect these safety enhancements, which could actually represent significant additional savings. In addition, concept A would represent a multiple-use concept, where both DGNSS and EVS could provide benefits for enroute and terminal area operations as well as surface operations.

The capabilities represented by this concept were projected into the scenarios discussed in section 6.3, which analyzed ASRS surface incidents. The ASRS analysis developed 15 "solutions" suggested by the incident reports. Considering that the scope of Concept A would include airport surface marking enhancements, as well as AMASS/ASTA automation, it was determined that this concept would encompass all 15 ASRS-based solutions.

10.2 RECOMMENDATIONS FOR FURTHER STUDY

During the process of developing requirements and identifying concepts for airport surface operations, the following areas were determined to warrant further study.

10.2.1 Aircraft Separation Criteria and Procedures

As discussed in the section on obstacle detection requirements, separation between aircraft on the surface could become an important new criteria in developing low visibility operational procedures. Currently, using visual references, pilots are primarily operating on the "see and avoid" principle with ATC mainly providing sequencing instructions, and ensuring that there are no runway incursions. Checking for conflicts between aircraft is largely left up to each pilot. This would not be a workable concept in visibilities lower than the stopping distance of a taxiing airplane. Specific, new separation criteria and procedures may prove necessary for near-VFR capacities. Joint responsibility between ATC and aircraft may be a desirable goal, and the coordination issues should be addressed.

Use of DGNSS technology appears to provide a solution to this problem, using GNSS transponders and broadcasting situational awareness position reports on proximate traffic. The GNSS accuracies achievable due to a given set of conditions could be viewed as an "error bubble" surrounding the aircraft, representing a protected safety buffer which would not be penetrated.

Use of EVS could provide a slightly different methodology, however. A high quality image could provide the capability for VFR-like obstacle detection and avoidance. Pilot range perception, however, may prove to be problematic in the absence of absolute range data. Careful study of how the pilot perceives range and range rate from an image may be needed.

10.2.2 Failure Procedures for Low Visibility Taxi

Whatever system is used for low visibility navigation and surveillance, it will not be fully available all the time. When a system fails while an aircraft is out on the movement area in very low visibility, some means for ensuring that the aircraft can avoid runway incursions and obstacles, and remain on the pavement should be developed. The easy answer is that since surface operations are being considered, a failure could be handled simply by having the aircraft stop. While this may in fact be the best solution for some situations, other circumstances such as when one aircraft can no longer navigate but the one in back can, simply stopping and blocking another aircraft may not be the best answer.

10.2.3 Braking Action Reports and Runway Optimization

The measurement of runway braking could prove quite beneficial (ref. 8). Most often, pilots are asked for their subjective opinion as to braking action, providing significant variations and inaccuracies. As conditions worsen, the runway of interest must be closed to aircraft while a vehicle fitted with a runway friction tester is driven along the surface. Variations in runway condition must be manually noted and correlated with position along the runway, relayed to the control tower, and then relayed to individual aircraft.

A more suitable alternative would be to use the anti-skid systems of advanced jet transports to determine braking action experienced during landing and roll-out. Typically, anti-skid systems compare individual wheel speed with airplane speed (inertially sensed) and the speed of the other wheels. When a skid is detected (such as when maximum brake pressure is applied), the antiskid controller commands the respective antiskid valve to reduce brake pressure which then stops the wheel from skidding. The antiskid controller can also be commanded to release brake pressure based on exceeding a maximum torque level, sensed by a brake torque sensor on each wheel. Future research could provide a correlation between applied brake pressure or torque at the point of a skid and the corresponding coefficient of friction of the runway surface. Airplane weight, thrust, drag, and groundspeed would also be available for correlation. Automatic transmission of position referenced braking action reports via data link to ATC and/or to nearby aircraft would then enable more efficient use of the runways.

Under very low visibility conditions, existing centerline lights and markings may be inadequate to alert the pilot of an upcoming runway exit if the groundspeed is too high when those visual cues first appear. The resulting immediate moderate deceleration and subsequent slow taxi to the next available exit can involve extra time on the active runway. ATC often provides an allowance for this possible delay due to lower visibility, by increasing spacing between arriving aircraft. Airport capacity is then reduced, and gate holds follow. The accurate surveillance positioning available with GNSS could be used to optimize deceleration after landing to slow the aircraft such that the desired runway exit was reached at close to maximum exit speed, based on reported runway braking action or friction coefficient. Prior to approach and landing, the pilot could select the most operationally efficient runway exit for the assigned gate.

10.2.4 Ground Movement Optimization

When most aircraft and ATC are equipped to navigate and provide surveillance as recommended in this study, there would be the potential for significant surface movement optimization. A form of strategic control, such as envisioned by the ASTA concept, could greatly enhance efficiencies and eliminate most ground delay. Specific algorithms and techniques for computing optimum taxi paths should be developed, with some provision made for the unequipped or lesser-equipped aircraft to fit into the system also.

10.2.5 ATC Data Link Optimization

Significant problems exist for surface operations due to the congested frequencies, wide physical separation between aircraft and tower, and confusing or nonstandard phraseology resulting from VHF voice communications. Use of a graphical interface for both display and control of clearances could minimize many of these problems. Ground movement optimization would benefit from ATC data link integration. Specific taxi paths analagous to SIDs and STARs could be created and stored in onboard and ATC data bases for easy and reliable taxi route coordination. Flight deck studies should ensure that whatever out the window visibility is available can still be used by not forcing extensive heads down requirements on the crew. Consideration of HUD symbology integration with data link may prove beneficial.

10.2.6 Low Visibility Operations at Lesser-Equipped Airports

Consideration should be given to providing low visibility operations at airports without ASDE. Only 29 airports in the U.S., all of which have Cat 3 ILS approach capability, are scheduled for ASDE-3. Runway and taxiway centerline lights are another low visibility feature usually found only at Cat 3 equipped airports. Extending low visibility operations to airports without these existing low visibility aids should be considered, including methods of quantifying and replacing the benefits of ASDE and centerline lights.

10.3 UNRESOLVED ISSUES

The following were determined to be unresolved issues.

10.3.1 Measuring RVR Along the Taxi Path

Due to the lack of a visibility requirement for taxi operations, (other than the need for take-off or landing minimums), there is currently no means to measure visibility along a taxi route. Three transmissiometers are used to provide the required touchdown, mid, and rollout RVR readings along runways having a Cat 3 ILS approach. Criteria for taxiway locations for visibility measurement, and the method of measurement, should be studied. Onboard visibility measurement may also be a possibility.

10.3.2 Airport Data Bases

Requirements for determining the nature of an airport data base should be addressed. Surveys of hundreds of points per airport could be quite expensive, methods of computing precision taxi paths from a minimum number of points should be considered. Reflectivity and emissivity of airport features should also be investigated for possible enhancement of MMW or FLIR imagery.

10.3.3 Impact of Autonomous Crew Actions

Early concerns over autonomous crew actions based on TCAS advisories may be exaggerated. Ground operations should be considered from this point of view, as well. The nature of the situational awareness information broadcast on proximate aircraft would have an effect, as would the roles of ATC and aircraft in preventing conflicts.

10.3.4 Operational Capability vs. Equipage

The various aircraft currently operating in low visibility surface conditions have a wide range of avionics capability. As DGNSS, EVS, and other precision positioning and imaging technologies evolve on the flight deck, consideration should be given to accommodating lesser-equipped aircraft in a manner which will utilize their capabilities to the fullest, without imposing arbitrary limits on their surface movement. A means of providing a continuously increasing operational capability based on higher performance avionics could provide incentive for improved equipage without unduly limiting access for less equipped aircraft.

10.3.5 Appropriate Levels of Automation

The realm of surface operations has always been one of manual control after landing rollout. Precision guidance based on DGNSS would appear to make possible further automation on the ground. Careful thought should be given to the roles of automation, however, to ensure that current surface problems such as situational awareness are not actually made worse.

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John L. Groce, Greg J. VonBokern, and Rick L. Wray

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13. ABSTRACT *(Maximum 200 words)*

Operational requirements for aircraft operation on the airport surface in visibilities down to zero were determined to be situational awareness (including route planning and clearance coordination), steering guidance, ATC surveillance, and obstacle avoidance. Relevant parameters were identified and required accuracies determined. Positional accurancies (2 sigma) were derived as; situational awareness - 80 feet, steering guidance - 7 feet, ATC surveillance - 50 feet, obstacle detection - 40 feet. A technology survey produced four candidate implementation concepts. It was concluded, based on cost/benefit factors which included low visibility probabilities for five airports, that differential GNSS/ADS (Global Navigation Satellite System/Automatic Dependent Surveillance), ASDE-3 (Airport Surface Detection Equipment), and enhanced vision systems were the most suitable for low visibility surface operations, considering the operational and safety enhancements available at a moderately higher relative cost.

14. SUBJECT TERMS
ATC, low visibility, taxi/surface operations, GPS, GNSS, data link, information analysis, surveillance, situational awareness, imaging sensors, FLIR, MMW, HUD, ASDE-3.

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