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Command and Control Through Space-Based Systems

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Abstract - A new space-based command and control concept is presented that combines a ground station in conjunction with satellites utilizing modern RF communications technology. By using current satellites such as TDRSS, GPS or the proposed LEO/MEO commercial constellations, the command system of the future will provide a reliable and highly redundant replacement for the current command system that requires as many as seven UHF transmitter sites along the various launch vehicles' flight paths. This space-based command system requires a look at new technologies to provide innovative ways to transmit secure and jam resistant messages from the launch operations center. These messages would then be relayed through a satellite to the launch vehicle and back to the operations center for confirmation. This new command system must conform to Range Safety guidelines in terms of minimal propagation time, communication security, maximum reliability and design efficiency to ensure that no single point of failure will deny the capability to terminate or result in the inadvertent termination of a launch vehicle or payload.

I. Introduction

The purpose of this research is to investigate the feasibility of implementing a space-based command system as a replacement to the current ground-based UHF Command Destruct System (CDS). A space-based system must be useable under nominal and non-nominal launch/flight conditions and must be compatible with day-to-day launch vehicle operations. The system must be able to transmit and confirm the Flight Control Officer's (FCO) command messages within time parameters specified in EASTERN AND WESTERN RANGE 127-1 RANGE SAFETY REQUIREMENTS and EASTERN RANGE 127-9 RANGE SAFETY COMMAND DESTRUCT SYSTEM REQUIREMENTS.

II Background

The Current Eastern Range CDS consists of a network of six UHF radio transmitter sites located at Cape Canaveral Air Station ((CCAS) - two sites) FI, Jonathan Dickinson Missile Tracking Annex (JDMTA) FI, Antigua West Indies, Argentia, Newfoundland and Wallops Island, Va. These sites are linked to the Central Command Remoting System (CCRS) located in the CCAS Range Operations Control Center (ROCC). FCOs evaluate real-time data displayed on the Range Safety Display system to determine if a vehicle's flight path is outside of mission parameters and terminate its flight if necessary. Range customer's utilization of the CDS includes the transmission of commands such as Safe and Engine Cut-off, as well as vehicle control messages.

Providing the necessary level of reliability and security for potentially hazardous launch operations has resulted in the development of a highly complex, ground-based CDS. The system provides the capability to issue commands from any of four consoles at the ROCC, and to transmit those commands, via the CCRS, through any of the command sites. Three of these sites — Cape High Power, JDMTA and Antigua — can selectively transmit commands to as many as four in-flight

vehicles. Modulated commands are monitored at the transmitting antenna, decoded, checked for accuracy, and relayed back to the CCRS's Command Message Encoder Verifier (CMEV) unit and the FCO console to confirm the transmission. The signal strengths at each vehicle's command receivers are reported in real-time to the FCO via telemetry. Command transmissions are also recorded for post flight evaluation. Coupled with the above capabilities is a system for secure command generation that makes it virtually impossible to accidentally transmit a destruct command, or for an unfriendly source to intentionally do so.

The advantages of a UHF system are:

- Its low susceptibility to flame attenuation, atmospheric/solar conditions or multipath effects as compared to the higher frequency bands.
- The availability to commercially purchase continuous high output power transmitter (10 kW) vs other frequency bands transmitters back in the 60s and 70s.

The disadvantages are:

- The Command sites are at fixed locations, with corresponding horizon coverage limitations.
- Several sites must deal with problems of operating in foreign countries, such as the cost and logistics of importing food and supplies, providing an independent AC power supply, and being subject to local regulations.

There is also the uncontrollable possibility that a foreign government could decide to cancel the facility's lease. The range would then be forced to build a new facility elsewhere (i.e. JDMTA replaced the Grand Bahamas site) or accept the coverage loss as in the case of the imminent shutdown of the Bermuda Command site.

III Concept of Operation

The Space-Based Command concept envisions transmitting commands to launch vehicles via satellites (Geosynchronous Earth Orbits {GEO} 37000 km, Low Earth Orbits {LEO} <500 km or Medium Earth Orbits {MEO} 5000 to 15000 km) [1]. Command messages would originate from the ROCC by the FCO responsible for flight safety. To convey commands to the launch vehicle, the messages would first be routed to the satellite ground station via commercial or government lease ground or satellite links. Once the command messages arrive at this station, the ground station would assume responsibility for forwarding them to the vehicle via a satellite. The Forward RF signals transmitted from ground station to satellite for retransmission to customer vehicles would be received by the satellite on the Space-to-Ground-Link (SGL) antenna. This antenna could be either fixed or steerable. If steerable, the Forward RF signals received from the ground station would be retransmitted to a customer vehicle using the SGL. This SGL would be aimed in the direction of the customer vehicle using mechanical gimbals in two axes. If the SGL antenna is fixed, its coverage would be limited to the diameter of the footprint of the antenna.

The possible utilization of a Return link from the user vehicle, back through the same satellite, is under study. Since all launch vehicles currently use a telemetry down link to communicate with launch or tracking facilities, this route may be more appropriate for command verification than a space-based relay satellite would be. However, if the Return link utilization should be elected, the Return data flow would be similar to the Forward service.

An auxiliary concept would be the utilization of a ground site at the Cape to communicate with the launch vehicle on the pad for day-to-day operations and for initial launch support, until the satellite has an uninterrupted view of the vehicle (at approximately 100 seconds.) After 100 seconds, the space-based relay satellite Forward and Return data flow path would be used.

For Space-Based Command operations the coverage requirement would span from day-to-day launch vehicle operations to the minus count (launch pad altitude) to several seconds after the cessation of powered flight. This in-flight coverage span would be vehicle and trajectory dependent, ranging from 124 seconds for Shuttle to 900 seconds for Titan.

IV Message

Before discussing the proposed satellite command and control system, it would be helpful to become familiar with the Command messages [2] to be transmitted. The message format necessary to initiate SAFE, ARM and DESTROY commands are not lengthy, typically on the order of 20 bytes. To maintain standardization, let's assume that the space-based Command messages will be similar. One possible data format could be as follows: A 20 byte message, with eight bits per byte, would have a total message length of 160 bits. For security and encryption purposes, this could yield a total of 1.53×10^{54} different bit combinations, of which only three will be valid. An increase in bit error rate performance and data robustness may be realized if 3/4 rate convolutional encoding [3] is used. This adds an additional 4.7 dB of link margin for a total message length of 280 bits. Adding 20 bits for synchronization brings the total data package to 300 bits. At this size, a single message, including synchronization, could be transmitted at an 8 messages per second (MPS) rate, given the typically available data rate of 2.4 KBPS. The present ground-based secure command destruct system transmits at 5.5 MPS.

The following is a description of the proposed command destruct message path for the space-based system. Once the FCO initiates a request message, the processing elements located inside the ROCC would provide generation of the appropriate message, convolutional encoding, encryption and transmission to the Earth station. To establish, maintain and verify connectivity with the vehicle's receiver, a special "keep alive" or sync message would be sent at a nominal 8 MPS rate. Receipt of this message would be verified by either the satellite return data path, the vehicle's telemetry stream or both.

At the Earth station, a connection with the vehicle's receiver would be initiated through the satellite which is currently servicing that geographical area. Since this service provides for full duplex communications, the return data path could be utilized to verify command receipt, report on bit error rate or provide some other type of link health and status in real time. Once the connection is established, it would be maintained until Range Safety release. As the individual satellites pass from view of the receiver (GEO, LEO or MEO satellite to vehicle connection time: 15 minutes or less), the call would be handed to the next satellite in the orbital plane.

We will examine one each example of GEO, LEO and MEO satellites to see if they will fulfill our concept of operation.

V GEO - TDRSS

The Tracking and Data Relay Satellite System (TDRSS) [4] is a NASA operated communication signal relay system which provides data links between spacecraft and customer con-

trol/data processing facilities.

TDRSS was originally implemented to provide signal relay between the Space Shuttle and NASA facilities minimizing the requirements for ground stations. NASA has expanded the TDRSS coverage and has offered the facilities to non-Shuttle applications on a commercial basis. Current TDRSS customers include Hubble Space Telescope, Landsat, Extreme Ultraviolet Explorer, Upper Atmosphere Research Satellite and International Space Station, just to name a few. Because of the Geosynchronous orbit, extensive area coverage (footprint), redundancy and availability, the TDRSS is a particularly good candidate for the Space Based Command System. (See Figure 1).

Place Figure 1 here

Figure 1. TDRSS and Iridium Constellation

TDRSSs are in Geosynchronous orbits at 37,200 km over the equator, and appear stationary with respect to the earth. The expected usage life is a minimum of ten years. Currently there are six TDRSS in orbit, and several new satellites (TDRSS "H", "I" and "J") will be launched in the future. The current placement of the six existing TDRSS are:

- F-1 (TDS) at 049° west longitude - N of Brazil, operational
- F-3 (TDZ) at 275° west longitude - W of Australia, operational
- F-4 (TDE) at 041° west longitude - NE of Brazil, operational
- F-5 (TDW) at 174° west longitude - SW of Hawaii, operational
- F-6 (RES) at 047° west longitude - In reserve
- F-7 (RES) at 171° west longitude - In reserve

The coverage provided by TDRSS is dependent on the altitude and inclination of the customer spacecraft. NASA states that "a minimum of 85% of the total customer orbit can be realized between two operational satellites". TDRSS geometric Zone Of Exclusion, a zone where TDRSS coverage is not available, is a relatively narrow area located east of the African continent. It stretches from latitude 60° north to 60° south and the area's size is function of the spacecraft's orbital characteristics.

The TDRSS Forward S-Band antenna has a beamwidth of 2.08°, which provides a circular footprint at the 28° latitude (CCAS Launch facilities) of approximately 900 miles in diameter. This footprint will cover the initial phase of powered flight trajectories, however, antenna pointing adjustment will be required by White Sands Complex (WSC) operations to keep the target in the beamwidth during the mid-phase flight. WSC has proved this capability during several Titan/Centaur operations, where the TDRSS has received the vehicle's telemetry data and has down-linked the data back to ROCC.

In contrast, the Forward Ku-Band antenna on the TDRSS has only a 0.27° beamwidth, providing a 110 mile diameter footprint at the launch pads. This smaller coverage requires more frequent and accurate antenna pointing adjustments or requires the optional autotracking feature.

The TDRSS ground support facility is located in the WSC near Los Cruces, New Mexico. It includes two functionally identical satellite ground terminals, named Cacique and Danzante. The ground terminals provide the hardware and the software necessary to ensure uninterrupted com-

munications between the spacecraft and customer control centers. The White Sands Complex Project Office at Goddard Space Flight Center can act as a back-up command and control link to TDRSS.

Other GEO satellites that have been examined are DSCS, and several military communication satellites.

VI LEO/MEO

LEO - Iridium

The Iridium [5] LEO constellation is a multiple satellite system currently being implemented by, among others, Motorola. This system is touted as being able to provide cellular phone type service from any point on the globe utilizing a system of 66 low earth orbiting satellites. These satellites, established in eleven planes of six satellites each, will provide real time voice and low speed data to small user terminals roughly the size of a standard cellular telephone. The satellites themselves will orbit at an altitude of 765 km (413 NM) with an inclination of 90 degrees giving it a polar orbit. Each satellite is, in effect a repeater for both the incoming user data and data received from the four adjacent satellites (see figure 1). The satellite that is within line of site to the closest gateway station will provide the space-ground link.

To provide the necessary frequency re-utilization, each satellite divides its coverage of the earth into 37 separate spot beams which are, in turn, divided into seven different frequency cells. These cells are so arranged as to provide maximum geographical separation between cells operating on the same frequency. Within each cell, multiple access is provided through the use of a combination of Frequency Division and Time Division Multiple Access.

As one satellite passes from line of site of the user, the call in progress is handed off, much in the same manner as a terrestrial cellular phone call is handed-off, from that satellite to the next one in the orbital plane. Should the user travel from one plane to the next, each satellite has data connectivity to it's counterpart in both adjacent planes. This also facilitates an easier hand-off.

The iridium system is unique in that it uses intelligent routing within each satellite to route calls from satellite to satellite until one is located within view of the Earth station. Other LEO systems substitute this routing for a greater number of gateways, thus requiring the satellite in use to be within line of site of a gateway at all times.

Upon liftoff, the vehicle's trajectory will take it through several areas of data hand-off - all of which pose the risk of a dropped call and the cessation of Command data connectivity. The first area of concern is cell to cell. Within each spot beam coming from the satellite, the area covered is divided into seven separate frequency cells. This cellular division is required to allow for maximum reuse of the limited L-band spectrum. Each cell represents a different channel within the allocated spectrum. These are arranged to provide as much geographical separation between areas operating on the same channel. Once the vehicle is in motion, the combination of it's trajectory and the ground trace of the orbiting satellite will cause it to traverse several cells very quickly.

On a slightly larger scale, a moving vehicle will also travel through several spot beams of the same servicing satellite. There are a total of 37 such spot beams within the geographical

coverage area of an Iridium satellite. At worst case, the vehicle would transition through of these spot beams in roughly seconds of time. This places a significant amount of stress on the satellite's hand-off capability.

As the launch vehicle ascends and proceeds down range, it is quickly ascending above the "cone" of the Iridium satellites spot beam antennas and runs the risk of flying through and out of the area of coverage. Should the vehicle pop out of the coverage area of the antennas, it could be several seconds before it appears within the coverage area of another antenna. As the vehicle gains altitude, the amount of coverage area available to it from a particular satellite decreases (Inverse Square Law). On the ground, the swath of coverage is $13.1 \times 10^6 \text{ km}^2$ yet at an altitude of 50 km the coverage area decreases to $3.1 \times 10^6 \text{ km}^2$. The worst case scenario occurs when the vehicle's first motion occurs at a time when it is located at the edge of a coverage area. In this case, the vehicle could travel outside of the coverage swath within seconds of lift off.

Other LEO satellites that have been examined are Ellipso, ECCO, Globalstar, Teldesic and Orbcomm.

MEO - ICO

MEO satellites were initially attractive for the Eastern Range because the higher orbit seemed more likely to provide continuous coverage of high loft trajectories than the LEOs. Especially the ICO system, because the Eastern Range already has operational experience with Inmarsat communications links.

The ICO Globalcom constellation [6] is a satellite communication system designed to provide cellular phone connections on a world wide basis. ICO Global Communications is a commercial spin-off of Inmarsat. Their goal is to provide a combination of satellite-enabled personal mobile global communications and the existing telephone network.

ICO's ground segment (ICONET) will consist of 12 stations, called satellite access nodes (SANs), and the high-capacity terrestrial links between them. The ICONET control center will be located in Japan. There will also be a satellite control station to be located in London. The SANs will provide the connection between the ICO satellite based communication and existing terrestrial phone services. The ICO design uses no inter-satellite links so all intelligence, with regard to routing of calls, will be in the SANs.

The ICO constellation will consist of ten active satellites and two on-orbit spares. The satellites are to be placed in two planes inclined at 45° with a height of 10,355 km. This is expected to provide continuous overlapping coverage of the total Earth surface. ICO believes that their use of the MEO constellation will result in less likelihood of signal blockage and fewer hand-offs between satellites.

The ICO satellites are being built by Hughes Space and Communications and are based on the HS601 geosynchronous satellite bus. Each satellite will provide an S-band (2 GHz) service link, through two 2m antennas, between the satellite and the hand held user terminals. The satellite will also have C-band (5 GHz and 7 GHz) feeder links between the satellite and the SANs. Time-division multiple access will be used to provide for up to 4,500 phone calls per satellite.

The system is being designed to provide a minimum of 8 dB margin for communications with a 0.25 watt hand held unit. The technology used in the hand held units is also being made available for aeronautical units. ICO will not build any terminal units. They intend only to provide

the service and to license the terminal technology to manufacturers.

Odyssey, GPS are the only other satellite systems considered in the MEO constellation group.

VIII Conclusion

In considering any of the three earth orbit satellite constellations for use in the control and destruction of a high speed, high altitude vehicle such as a missile, there are several factors which must be taken into account. It must always be remembered that the original system design for most commercial communication constellations, either proposed or in operation, was for use with slow moving (i.e. typically under 1.0 mach), low altitude or stationary ground terminals. The use of such a constellation for space launches pushes the system design to extremes and requires close scrutiny of a multiplicity of factors. These factors include, but are not limited to, the following: inter-cellular hand-off, inter-satellite hand-off, inter-constellation hand-off, antenna pattern geometry at higher altitudes, Doppler shift effects and single point of failure (SPOF) stipulations.

When using LEO or MEO communication systems it may not be possible to "continuously capture" a receiver on the vehicle. It is likely the encryption of the command message stream will provide adequate protection against unauthorized destruction of a vehicle. It is less clear how the link could be protected against random interference. It may be possible to use a count down timer that would initiate the flight termination charges if a keep alive message was not received for some period of time. However, this has clear mission assurance implications. Technical interchange with LEO or MEO manufacturers will be needed to deal with this issue.

To be useful as a Space-Based Command system, it must provide high availability values. If customers are unable to connect to the service they will quickly switch to alternatives. Reliability is a somewhat different question. A reliability that is perfectly adequate for digital voice may not be adequate for command data. Also the time period required for launch is as much as 13.5 hours which may be long compared to the average cellular phone call. Although Space-Based Command systems probably have estimates or goals for availability and reliability there are no measured values since some of the system are not in service yet. This is a major contrast with TDRSS which has published values based on years of operation. The cost of LEO or MEO service remains as an open question, but it is expected to be very attractive, in the range of \$10 a minute.

IX Summary

At first glance, the LEO or MEO satellite systems look like the best solution to a Space-Based Command system, but as you closely examine the satellite systems you come to a realization that their are numerous draw-backs. The two main problems stem from the doppler shift based on the narrow band widths allocated to the different satellite constellations and the hand-over between adjacent satellites. GEO satellites appears to offer the best solution. The GEO satellites may only require a single hand-off or none at all and they are usually configured to handle doppler shifts such as TDRSS. Even though GEO satellites can cover the launch location and the in-flight coverage, a command ground station combined with the GEO satellites provides the most economical approach to conform to Range Safety guidelines.

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