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ABSTRACT

Development of an extended test range, with range instrumentation providing continuous vehicle communications, is required to flight-test the X-33, a scaled version of a reusable launch vehicle. The extended test range provides vehicle communications coverage from California to landing at Montana or Utah. This paper provides an overview of the approaches used to meet X-33 program requirements, including using multiple ground stations, and methods to reduce problems caused by reentry plasma radio frequency blackout. The advances used to develop the extended test range show other hypersonic and access-to-space programs can benefit from the development of the extended test range.

KEY WORDS

X-33, Reusable Launch Vehicle, Extended test range, Radio frequency communications, Reentry plasma blackout.

NOMENCLATURE

| | |
|---------|--|
| AFB | Air Force Base |
| AFFTC | Air Force Flight Test Center |
| CFD | computational fluid dynamics |
| DET2 | Detachment 2, deployables of the Space and Missiles Systems Center |
| DGSA | Dynamic Ground Station Analysis |
| DoD | Department of Defense |
| ExTRA | Extended Test Range Alliance |
| FTS | flight termination system |
| GPS/INS | global positioning system/inertial navigation system |
| MOF | Mobile Operations Facility |
| NASA | National Aeronautics and Space Administration |
| RIR | Range Instrumentation Radar |
| TTR | Tonopah Test Range |
| UHF | ultrahigh frequency |
| U. S. | United States |
| UTTR | Utah Test and Training Range |
| WFF | Wallops Flight Facility |

INTRODUCTION

On July 1, 1996, the National Aeronautics and Space Administration (NASA) signed a cooperative agreement, number NCC8-115, with Lockheed Martin Skunk Works (Palmdale, California) to develop and flight-test the autonomous X-33 vehicle, a scaled version of the next-generation single-stage-to-orbit reusable launch vehicle. This cooperative agreement approach gives Lockheed Martin primary responsibility for the X-33 program. When additional government help was required, Lockheed Martin “subcontracted” to NASA centers and the United States (U. S.) Department of Defense (DoD) for specific work. Through this mechanism, NASA Dryden Flight Research Center (Edwards, California) became responsible for the extended test range.

This paper describes the management approach to accomplishing the X-33 objectives, mainly the formation of the Extended Test Range Alliance (ExTRA), a unique team of government and industry personnel and range assets established to resolve design issues and accomplish the X-33 extended test range and support other programs as required. Extended test range requirements, derived from range safety and the X-33 program, are also detailed.

The range safety requirements were the most challenging to define and meet. The X-33 vehicle is an autonomous vehicle that launches like a rocket, reenters the atmosphere, and lands horizontally like an

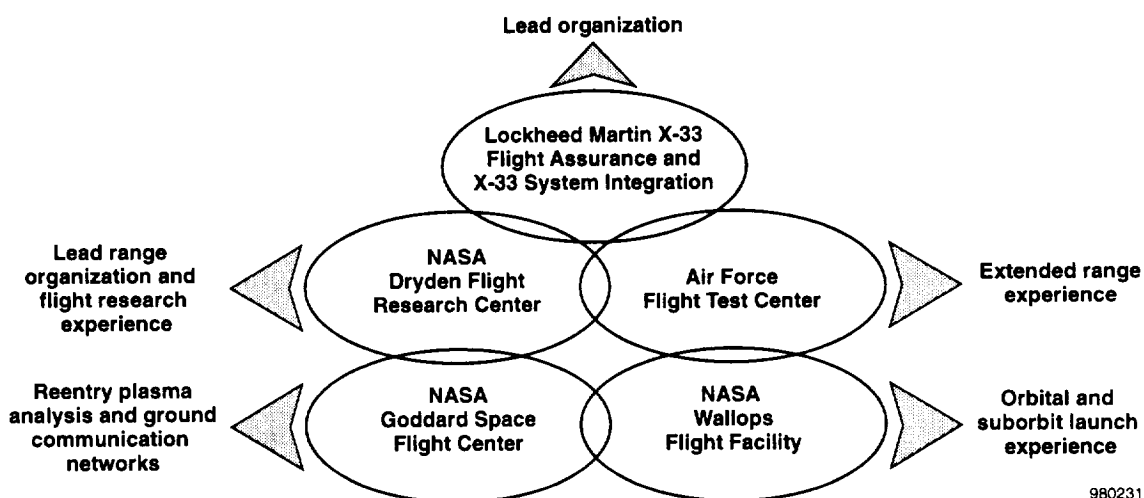
aircraft. Historically, rockets have been launched over the oceans to allow failed rockets to be destroyed using explosive devices. The X-33 vehicle will fly over scarcely populated areas and use remote lakebeds for emergency landings.

Numerous range requirements come from the X-33 program for interface definitions with the vehicle communication subsystems and the need for multiple ground stations to provide continuous coverage of the flight. Another area that can affect communications coverage, the reentry plasma shield that causes a “blackout” of radio frequency signals such as range safety commands, will also be discussed. A cooperative team of experts from across the country has analyzed and modeled the blackout problem.

ESTABLISHING THE EXTENDED TEST RANGE ALLIANCE

The X-33 vehicle behaves like a vertical launch vehicle for the first few minutes of flight, then becomes a reentry vehicle, and finally lands like an aircraft. Developing a team with expertise in all three areas was essential. Soon after the X-33 cooperative agreement was signed, NASA Dryden began gathering the expertise to accomplish the extended test range effort, including using other agencies and contractors. A recent agreement to share capabilities between the U. S. Air Force Flight Test Center (AFFTC) at Edwards Air Force Base (AFB) (California) and NASA Dryden led to the use of AFFTC range engineers. The AFFTC engineers have considerable expertise in telemetry systems, range safety systems, and data communications. With this agreement, the ExTRA first began.

Unfortunately, the ExTRA still lacked launch vehicle and reentry expertise. To cover the launch vehicle arena, the team identified and assigned a chief engineer from the NASA Goddard Space Flight Center (Greenbelt, Maryland) Wallops Flight Facility (WFF) (Wallops Island, Virginia). The WFF is experienced in launch support of suborbital sounding rockets and orbital launch vehicles, and NASA Goddard is providing support of reentry analysis and data communication network services. The ExTRA team (fig. 1) was now ready to build the X-33 extended flight test range in order to perform the range tracking and command and telemetry data acquisition for the X-33 program.



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Figure 1. The extended test range alliance for the X-33 program.

X-33 EXTENDED TEST RANGE REQUIREMENTS

The X-33 range requirements originate from numerous program documents and government organizations, such as the Range Commanders Council. Figure 2 shows the flow of program requirements that determined the range requirements. These documents cover topics such as range safety, ground support system automation and information, vehicle-to-ground radio frequency interfaces, vehicle flight test plans, operational television plans, operational intercom plans, meteorological plans, site operations plans, flight assurance plans, "launch commit" criteria, flight rules, and more (refs. 1-3).

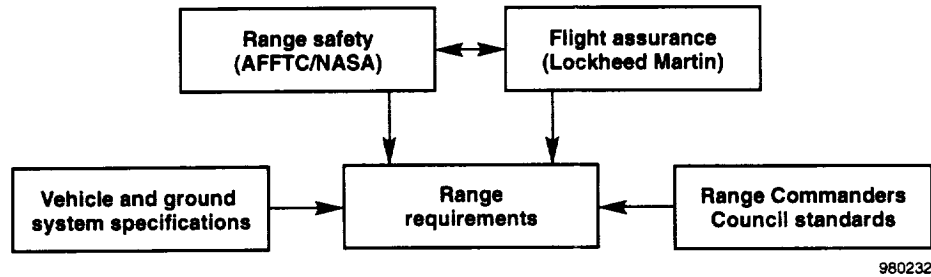


Figure 2. Requirements flow down.

The X-33 vehicle presents unique tracking requirements because of the need to continuously track the vehicle from California to Montana through the atmospheric reentry flight profile (fig. 3). The vehicle will reach a maximum altitude of 300,000 ft and fly at speeds approaching Mach 15. In order to provide the ground tracking coverage, the range team identified sites at the AFFTC, the U. S. Army Dugway Proving Grounds at the U. S. Air Force Utah Test and Training Range (UTTR) (Utah), Mountain Home AFB (Idaho), and Malmstrom AFB (Montana). As is evident by the number of sites, a diverse range network is being implemented to successfully meet the program requirements.

The primary high-level requirement that the range is to meet comes from Lockheed Martin proprietary documents: "The X-33 operations and support shall provide the capability to uplink commands and receive downlink telemetry data during vehicle test and flight operations."* To ensure the requirement is met, the range is implementing a system that will provide complete command uplink and telemetry coverage from launch through wheel stop for all test and flight operations. Range systems will be placed at strategic locations throughout the flightpath of the vehicle to allow overlapping coverage with a maximum range of 235 nmi for each site. The range system will include a communications link from the range operations center (detailed by Karla Shy and Cynthia Norman in the report "The X-33 Range Operations Control Center") at NASA Dryden to all launch, overflight, and landing sites for uplink commands and downlink telemetry data.

Several high-level requirements originate from the AFFTC Range Safety Requirements Document, (ref. 1):

...all reasonable precautions shall be taken to minimize these risks with respect to life, health, and property.

*Lockheed Martin Skunk Works, "X-33 Systems Requirements Document," 604D007 (Revision), Sept. 1996.

All range critical systems shall be designed to ensure that no single point of failure, including software, will deny the capability to monitor and terminate, or result in the inadvertent termination, of the X-33 vehicle.

The overall tracking systems shall be robust, highly fault tolerant, allow for catastrophic failure in a single system without loss of tracking data, and provide for graceful degradation of the system under multiple component failures.

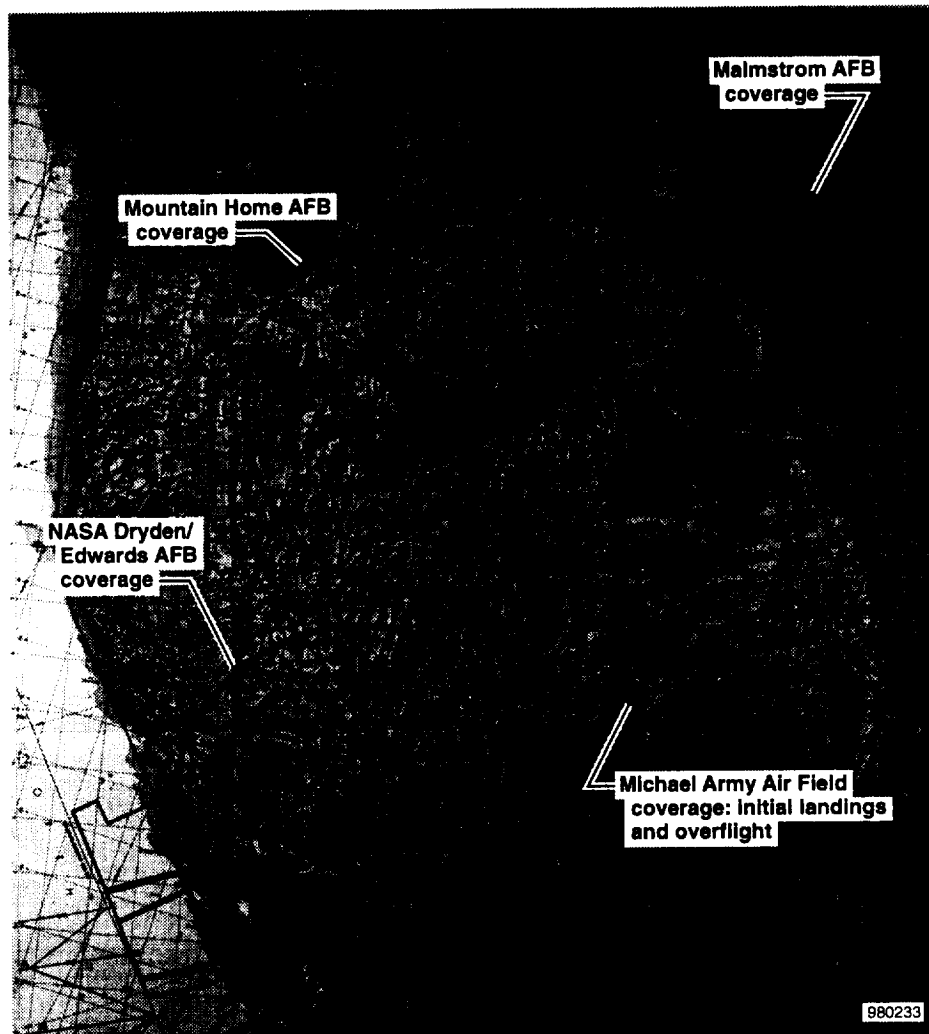


Figure 3. Range coverage circles.

The extended range has arranged for the use of numerous mobile and fixed systems from other ranges throughout the country. Table 1 shows the systems to be used in flights to the Dugway Proving Grounds. Systems, antenna type, and antenna diameter that will provide coverage at the launch site and during downrange flight and landing are given. Table 2 shows the same information for flights to Malmstrom AFB and describes overflight sites. These systems have proven reliability, and the flight termination systems (FTSes) are fully redundant. The range systems chosen are currently used to support NASA, DoD, and commercial suborbital and orbital programs.

Table 1. Ground systems and sites for Dugway Proving Grounds flights.

| System | Coverage | |
|-----------|---|-----------------------|
| | Edwards AFB | UTTR |
| Radar | Transponder test set (LSC) | WFF system (L) |
| | NASA Dryden RIR no. 1; 16 ft (FC) | |
| Telemetry | AFFTC 8 ft (LSC) | NASA Dryden 30 ft (L) |
| | NASA Dryden triplex; 23 ft (FC) | MOF no. 1; 6 ft (L) |
| Uplink | Omni antenna (LSC) | NASA Dryden 30 ft (L) |
| | NASA Dryden triplex; 23 ft (FC) | MOF no. 1; 6 ft (L) |
| FTS | NASA Dryden directional antenna; 15 ft (FC) | WFF FTS no. 1 (L) |

Key: FC Flight coverage
L Landing
LSC Launch site coverage

Table 2. Ground systems and sites for Malmstrom AFB flights.

| System | Coverage | | | |
|-----------|---|-----------------------|-------------------|---------------------|
| | Edwards AFB | UTTR | Mountain Home AFB | Malmstrom AFB |
| Radar | Transponder test set (LSC) | UTTR TPQ-39 (O) | TTR mobile (O) | WFF system (L) |
| | NASA Dryden RIR no. 1; 16 ft (FC) | | | |
| Telemetry | AFFTC 8 ft (LSC) | NASA Dryden 30 ft (O) | DET2; 23 ft (O) | WFF 18 ft (L) |
| | NASA Dryden triplex; 23 ft (FC) | | | MOF no. 1; 6 ft (L) |
| Uplink | Omni antenna (LSC) | NASA Dryden 30 ft (O) | DET2; 23 ft (O) | WFF 10 ft (L) |
| | NASA Dryden triplex; 23 ft (FC) | | | MOF no. 1; 6 ft (L) |
| FTS | NASA Dryden directional antenna; 15 ft (FC) | UTTR system (O) | WFF FTS no. 2 (O) | WFF FTS no. 1 (L) |

Key: FC Flight coverage
L Landing
LSC Launch site coverage
O Overflight

The range has implemented a fully independent communications path for the two sources of tracking data used by the range safety officer. The two sources are the global positioning system/inertial navigation system (GPS/INS) data and radar tracking data. A range safety officer will be at each tracking site to provide local assessment of vehicle safety in the event of a range-wide communications failure. The range systems will also be positioned to allow for spatial diversity to facilitate an additional means of redundancy throughout the range. Completely redundant systems will be used at launch and landing sites to meet the single-system catastrophic failure requirement. The sites will also include redundant power sources that allow for instantaneous switchover and graceful degradation, as required.

Continuous Coverage and Public Safety

An experimental flight test vehicle flying over populated land areas is an important range safety concern. Maximizing the flight vehicle tracking coverage is an important aspect of minimizing flight safety risks. Public safety is the top priority for the X-33 program, and the range systems are designed with this task in mind. Steps taken to minimize the risk to public safety include redundant ground hardware subsystems within each tracking and command system, completely redundant tracking and command antennas at the launch and landing tracking sites, and geographically located tracking sites that allow for ideal overlap of coverage with other sites (fig. 3).

Independent Data Communication Paths

In addition to having overlapping coverage and redundant tracking systems, the range data communications network was designed to allow for independent paths of critical vehicle position data. These critical vehicle position data are being generated by two sources: the ground radar systems tracking the X-33 vehicle; and the GPS/INS data that are embedded in the telemetry downlink. These two sources of vehicle position data are independently routed to the range safety officers throughout the range. The report "Extended Range Communications Support for the X-33" by Brian Eslinger and Reynaldo Garza describes the redundant data communications network in detail.

Approach and Results of the Reentry Plasma Blackout Analysis

Because of a lack of new reentry vehicle designs, little work had been performed on evaluating reentry plasma blackout of radio frequencies since the early days of the Space Shuttle program. Fortunately, NASA Goddard and the NASA Langley Research Center (Hampton, Virginia) had personnel able to perform such analysis. Because communications with the X-33 vehicle for monitoring and control are essential to the success of the flight test program, understanding the level of attenuation and the associated time period for loss of signal is critical.

The approach to the plasma analysis was to first look at Space Shuttle flight data and use the data as a truth model against the analysis techniques. Figure 4 shows an overview of the approach used. First, old Shuttle computational fluid dynamics (CFD) data were recovered, and the resultant CFD data were used in the NASA Goddard and NASA Langley attenuation calculations. The results of the models were then compared to the small amount of Space Shuttle flight data available from the tracking ground stations. Initial NASA Goddard analysis resulted in lower attenuation levels than flight and was adjusted to match. The NASA Langley analysis techniques generally resulted in larger attenuation levels than flight. These data established a "bracket of results" defining best- and worst-case conditions for the attenuation levels.

The results of the two different analysis methods were most evident in the L-band case. The NASA Langley results indicated a maximum attenuation of 114 dB; NASA Goddard results indicated a value of 10 dB. Range safety requires that worst-case results be used when making program decisions.

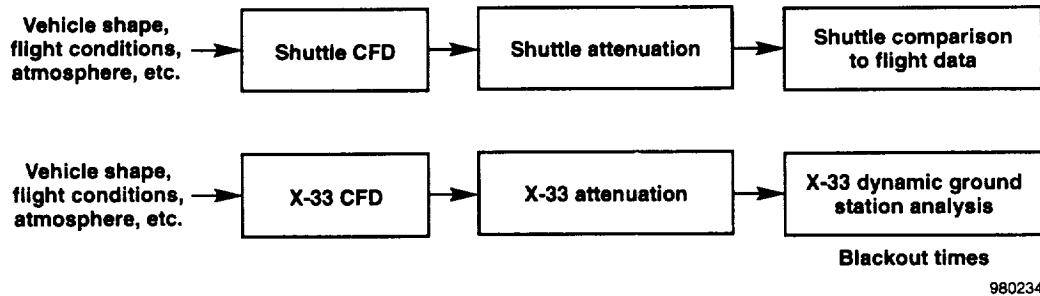


Figure 4. Approach to X-33 plasma analysis.

Both analysis methods provide an attenuation level perpendicular to the vehicle antenna. Because the communication signal vector is usually at an acute angle and continuously changing, a model that includes angular dependencies is required. Using ray tracing methods through the plasma field, NASA Goddard developed an algorithm to calculate attenuation as a function of altitude and communication vector angles. Figure 5 shows a command signal penetrating the dense plasma at the vehicle nose, having a high attenuation level, and a signal penetrating through a thinner plasma region at the rear of the vehicle. The NASA Goddard and NASA Langley normal attenuation values were adjusted using the function for the communication vector angles.

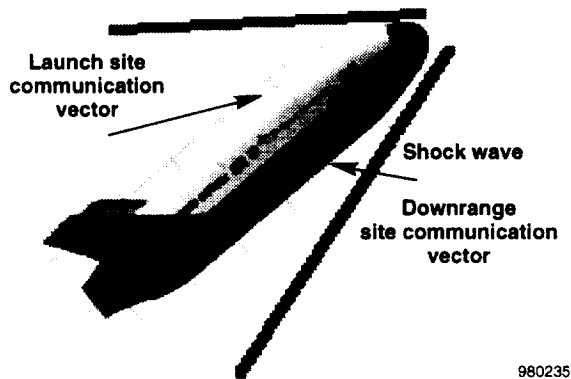


Figure 5. Communication vectors and plasma.

Both plasma models were integrated into an existing Dynamic Ground Station Analysis (DGSA) program developed at NASA Goddard. The program previously included all attenuation factors affecting vehicle communication, except plasma. Some of the factors included were frequency, polarization, path loss (distance), transmitter and receiver characteristics, and physical location of the ground stations. The DGSA program uses vehicle trajectory and attitude data, and provides signal attenuation for all frequencies and from all ground stations. The blackout time period was then calculated for each signal path.

Figure 6 shows the blackout time period for the NASA Goddard and NASA Langley attenuation values. The range safety signal in the ultrahigh frequency (UHF) frequency band is completely lost for 74 sec in both cases. The command uplink signal in the L-band range is completely attenuated for 30 sec, but only when using the NASA Langley attenuation model. A program decision was made to use the L-band communication to provide flight termination capability, thereby shortening the command blackout time from the UHF FTS (see the discussion below). The telemetry S-band signal is completely attenuated at all ground stations for 6 sec when using the NASA Langley values.

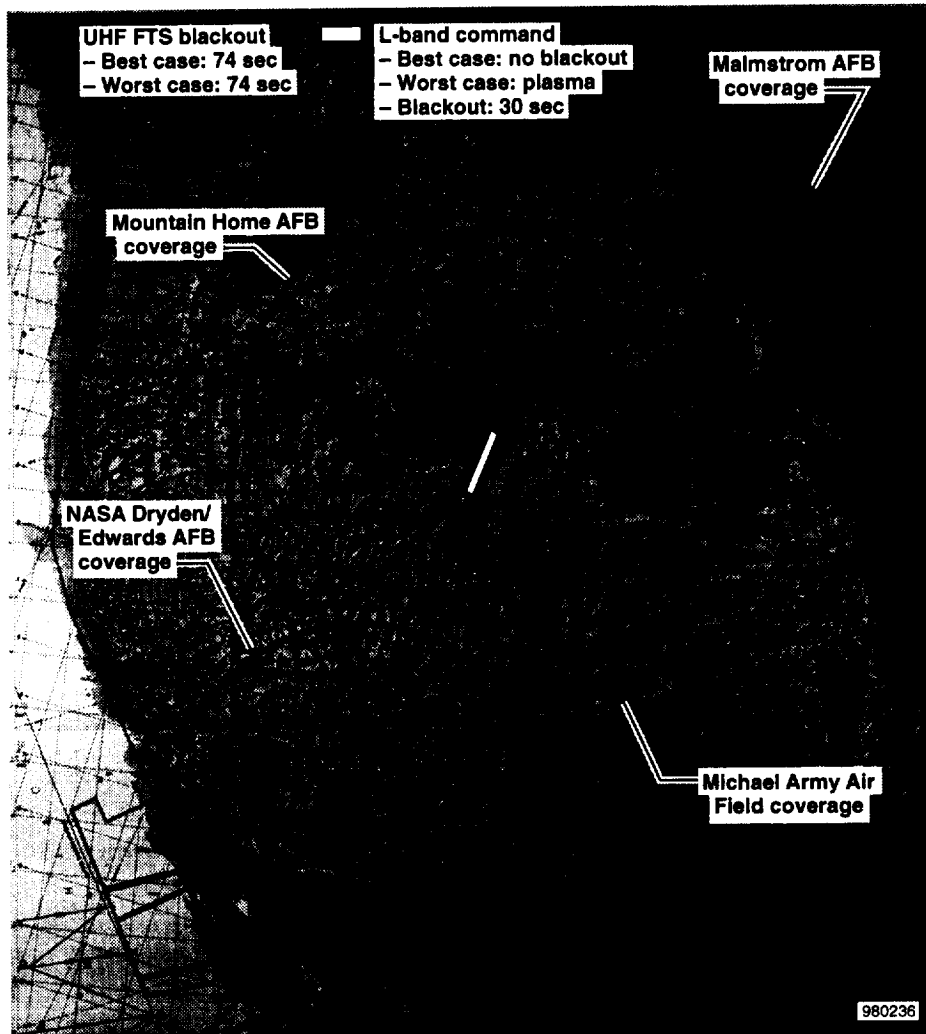


Figure 6. Blackout time periods.

Independent L-Band Flight Termination Capability

As described earlier, when the X-33 vehicle reenters Earth atmosphere, the vehicle will encounter extreme plasma heating conditions. During these periods of extreme heating, radio frequency attenuation levels will increase dramatically. To minimize the time period of radio frequency blackout, high-gain

antennas are required. The current flight profiles define the maximum blackout period to be over the Dugway Proving Grounds and the Mountain Home AFB tracking sites. Placing systems with higher gain antennas at these locations will minimize the radio frequency blackout period. In addition, because of the drastic blackout occurring at UHF frequencies for flight termination, the program proposed a design that would allow the L-band command uplink path to the vehicle to be used as a range safety flight termination medium.

X-33 EXTENDED TEST RANGE ADVANCES

Historically, NASA Dryden and the DoD have used flight corridors from California to Utah for missile testing, and in the 1960's, the X-15 vehicle flew from Northern Utah to Edwards AFB. Yet, the X-33 program poses new challenges because of the vehicle and range safety requirements of an autonomous vehicle. Continuous coverage of the vehicle from launch to landing requires the use of multiple range sites. This concept is not new, but the manner of implementation will ensure that the data are reliably transmitted and received by the customer.

The telemetry stream downlinked from the vehicle will be received by multiple telemetry antennas to ensure the continuous coverage. These multiple streams will be processed by a programmable telemetry processor to automatically select the best telemetry source. Darryl Burkes discusses the approach taken to ensure that the correct stream is chosen in the report, "X-33 Telemetry Best Source Selection, Processing, Display, and Simulation Model Comparison."

Advances in analysis methods were required to determine placement of antenna systems in locations that would ensure required coverage of the vehicle during flight. A software package from NASA Goddard, the DGSA software, was improved using the comprehensive plasma model to provide information. Given the vehicle trajectory and the location of antenna systems, link margins can be calculated to ensure coverage. Ashley Sharma discusses DGSA and the range simulation in the report, "X-33 Integrated Test Facility, Extended Range Simulation."

Another advance is the use of various NASA and DoD mobile and fixed range systems. Telemetry, radar, uplink, flight termination, and differential GPSes from different organizations were evaluated to determine if the systems could meet X-33 requirements. In addition to meeting technical requirements, system availability and cost were also factors used in selecting the systems. Because these systems have different missions and use different data formats, their integration is challenging. The challenge was met by having an integration period allowing identification of potential problems at Edwards AFB before deploying the systems to remote sites.

CONCLUSION

The range requirements to safely perform flight test of the X-33 vehicle over the western United States have been presented. The formation of a unique alliance of national experts to meet the challenges of the X-33 range include United States Department of Defense and NASA personnel and assets. The technical challenges of the X-33 range were accomplished using advanced communication and range system designs, as well as complex plasma blackout analysis methods, previously undeveloped.

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