# X-33 INTEGRATED TEST FACILITY EXTENDED RANGE SIMULATION

**Ashley Sharma**
**National Aeronautics and Space Administration**
**Dryden Flight Research Center**
**Edwards, California**

## ABSTRACT

In support of the X-33 single-stage-to-orbit program, NASA Dryden Flight Research Center was selected to provide continuous range communications of the X-33 vehicle from launch at Edwards Air Force Base, California, through landing at Malmstrom Air Force Base, Montana, or at Michael Army Air Field, Utah. An extensive real-time range simulation capability is being developed to ensure successful communications with the autonomous X-33 vehicle. This paper provides an overview of the various levels of simulation, integration, and test being developed to support the X-33 extended range subsystems. These subsystems include the flight termination system, L-band command uplink subsystem, and S-band telemetry downlink subsystem.

## KEY WORDS

X-33 Experimental Aircraft, Integration and Test Facility, Range Simulation, Dynamic Ground Station Analysis, Plasma Attenuation, Link Margin

## NOMENCLATURE

| | |
|---|---|
| dB | Decibel |
| dBm | Decibel-milliwatt |
| DES | Data Enhancement System |
| DFRC | Dryden Flight Research Center |
| DGPS | Differential Global Positioning System |
| DGSA | Dynamic Ground Station Analysis |
| EIRP | Effective Isotropic Radiated Power |
| ER | Earth Research |
| FTS | Flight Termination System |
| GPIB | General Purpose Interface Bus |
| IF | Intermediate Frequency |

| | |
|---|---|
| IIP | Instantaneous Impact Prediction |
| ITF | Integration and Test Facility |
| LMCMS | Launch and Mission Control Monitoring System |
| NASA | National Aeronautical and Space Administration |
| NRZ-L | Non-return to Zero-Level |
| OCC | Operations Control Center |
| PCM | Pulse Code Modulation |
| PTP | Programmable Telemetry Processor |
| RCO | Range Control Officer |
| RCVR | Receiver |
| RF | Radio Frequency |
| RS | Radio Standard |
| RSO | Range Safety Officer |
| Rx | Receive |
| TTL | Transitor-Transitor Logic |
| Tx | Transmit |
| VDA | Video Distribution Amplifier |
| VHM | Vehicle Health Monitor |
| VMC | Vehicle Mission Computer |

## INTRODUCTION

The X-33 advanced technology demonstrator launch vehicle is a 50-percent scaled model of the reusable launch vehicle proposed by Lockheed Martin Skunk Works, Palmdale, California. The vehicle will autonomously follow a suborbital flight profile, reenter the atmosphere, and descend for a horizontal landing. When flying an autonomous vehicle at hypersonic speeds and over populated areas, minimizing the risk to public safety is imperative. This reduction in risk can only be achieved with an acceptable degree of confidence by validating the reliability and accuracy of the radar tracking system, telemetered downlink, uplink and flight termination systems (FTS) at every stage of the mission. The X-33 project range requirement for mission safety and success from the time of launch through landing could not be accomplished using the existing resources available at NASA Dryden Flight Research Center (DFRC), Edwards, California. The DFRC was challenged to develop an extended range capability that could track and communicate with the vehicle beyond the airspace at Edwards Air Force Base (EAFB), California, out to either the landing site in Michael Army Airfield, Utah, or in Malstrom Air Force Base, Montana. The technical approach used to address this challenge will be comprised of systematically developing the range system in six incremental phases of integration and test, beginning at the Integration and Test Facility (ITF) at NASA DFRC and ending with a complete end-to-end check of all range systems *in situ*. This paper describes the simulation models developed during the first phase of integration.

Integration of these models to mission hardware during the subsequent phases is also discussed. Use of trade names or names of manufacturers in this document does not constitute an official endorsement of such products or manufacturers, either expressed or implied, by the National Aeronautics and Space Administration.

## X-33 EXTENDED RANGE SIMULATION OVERVIEW

All flight and mission critical vehicle subsystem components, such as the vehicle health monitor, mission computers, flight controls, and traffic on the 1553 bus, are modeled in software to provide an initial assessment of the expected performance of that system. Because the range system will be the sole communications link between the Operations Control Center (OCC) and the vehicle, this system is also deemed mission critical. As such, failure of any component that could affect communication links may endanger the mission and compromise public safety, which is completely unacceptable. It became abundantly clear that as a first step toward the integration and test of the range system, a simulation of the entire range system needed to be developed to provide an initial evaluation.

Figure 1 shows the extended range coverage area. Each circle provides radar coverage for an approximate area of 235 nautical miles.

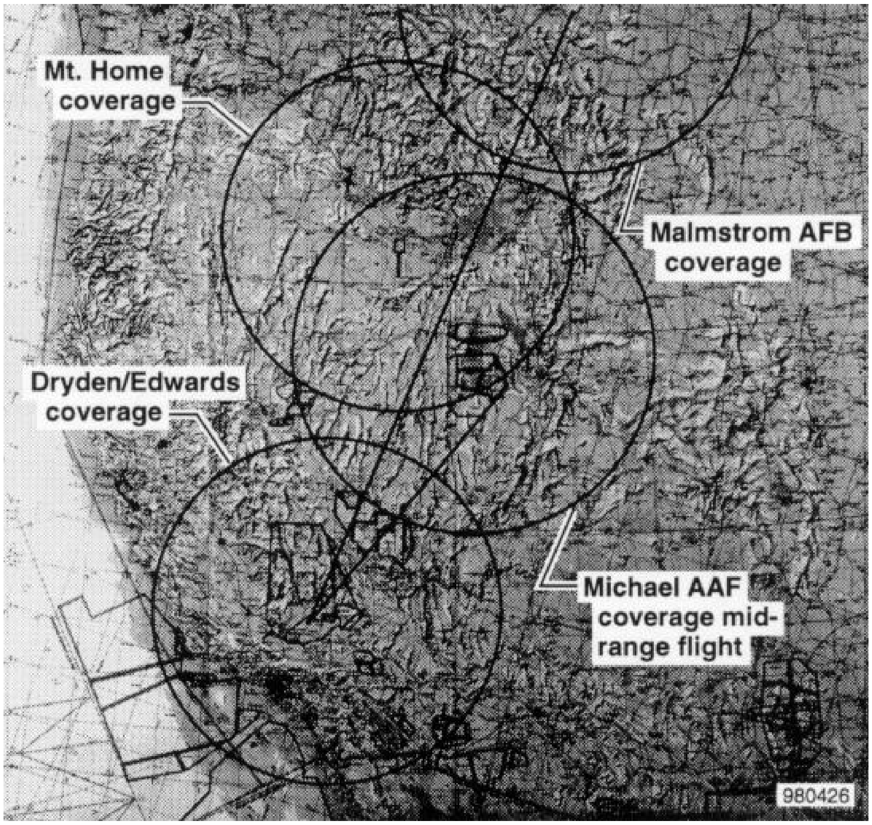

Figure 1. Extended range coverage area,

## Range Simulation

The purpose of the range simulation is to compute the total radio frequency (RF) link margins at each stage of the flight trajectory and to provide intermediate data, such as plasma attenuation, space loss, and ground-to-vehicle and vehicle-to-ground look angles. The simulation has the flexibility of performing both real-time hardware-in-the-loop (HIL) or stand alone operations. It also has the freedom to vary link parameters to optimize the analysis. A specification for bit error rate for digital communications determines the required signal-to-noise ratio to accurately reproduce the transmitted data. A pad or margin above this required signal-to-noise ratio is then used to ensure that a good RF link is maintained between the vehicle and the OCC at all times. In the same manner, a margin above the required signal-to-noise ratio for analog transmission is also specified.

The simulation model determines the vehicle position and attitude and passes this data on to the radar model at an update rate of once every 20 seconds. The Dynamic Ground Station Analysis (DGSA) tool will receive the same data along with supplementary vehicle information at an update rate of once every second. As the vehicle approaches the range tracking limits of the ground radar site, responsibility to track the vehicle is handed over to the next radar site. Handovers between ground sites for the FTS and uplink systems are accomplished by setting maximum attenuation levels for the current site and after a 1-second delay, setting DGSA calculated attenuations for the new site. This test mimics in software, the delays involved in powering down one ground transmitter while bringing up another. It also assists in optimizating ground site handovers during the actual mission.

The DGSA model, which is at the heart of the range simulation system, performs a timepoint-by-timepoint dynamic link margin analysis for spacecraft-to-ground and ground-to-spacecraft RF links. The three links supported are the flight termination, command uplink, and telemetry downlink. A simulation model of the X-33 vehicle for a preprogrammed flight trajectory provides the vehicle position coordinates and look angles in azimuth and elevation for every point in space for a delta time of 1 second. A separate antenna radiation pattern computes the gain of the electromagnetic field, in magnitude and phase, for all 360° of azimuth angles and spanning 180° in elevation. This computation is accomplished by the phasor addition of the electromagnetic fields emanating from the top and bottom antennas. The link margins for the ground-to-vehicle path are defined as the difference between the calculated signal-to-noise ratio in the intermediate frequency (IF) bandwidth to the required IF signal-to-noise ratio. For example,

$$\mathrm{Link}_{\mathrm{margin}} = \mathrm{IF}_{\mathrm{calcsnr}} - \mathrm{If}_{\mathrm{reqsnr}} \tag{1}$$

The required link margins for the uplink and flight termination systems are 3 and 12 dB, respectively. A figure of merit used to determine the actual power received at the vehicle, correcting for thermal noise, is a ratio of the antenna gain (G) divided by thermal noise (T). The Effective Isotropic Radiation Power (EIRP) can be determined by subtracting any passive losses between the transmitter and antenna from the transmitted power. Antenna gain and pointing loss associated with boresite antenna gain must also be taken into account.

$$EIRP = P_t - L_{pass} - L_{point} + G_{gnd} \tag{2}$$

where $P_t$ is the power transmitted by the ground antenna; $L_{pass}$ are passive losses in the cable and through connectors; $L_{point}$ is the pointing loss associated with directing the antenna; and $G_{gnd}$ is the gain of the antenna taking into account the effective area, aperture efficiency, and wavelength.

Losses or attenuation factors that arise during the transmission of an electromagnetic wave through the atmosphere are referred to as channel losses. These losses can be comprised of free space, atmospheric, rain, polarization, and plasma losses. The power incident at the vehicle antenna is the cumulative channel loss subtracted from the EIRP.

$$P_{rec} = EIRP - L_{atmos} - L_{rain} - L_{pol} - L_{plasma} - L_{space} \tag{3}$$

where $P_{rec}$ is the power received at the vehicle antenna; and $L_{atmos}$ are atmospheric losses, which in the absence of any condensation or dust particles is caused by oxygen and water vapor in the atmosphere. Attenuation because of rain, $L_{rain}$, and polarization loss, $L_{pol}$, are assumed to be negligible at this frequency. By far, the greatest uncertainty as far as channel losses are concerned arises from the predictions for the attenuation of electromagnetic waves due to the effects of plasma, $L_{plasma}$, during reentry. Plasma analysis is still in the evolutionary stage and is being conducted by NASA Goddard Space Flight Center, Greenbelt, Maryland. At this point, however, all indications are that affects at ultrahigh frequencies (UHF) will be for a minimal amount of time. Reference 1 provides further details regarding X-33 plasma analysis. The free space dispersion loss, $L_{space}$, is based on the slant range to the vehicle and assumes clear sky conditions.

The vehicle G/T is arrived at by subtracting the passive losses, $L_{pass/veh}$, between the vehicle antenna to the uplink receiver from the gain of the antenna, $G_{veh}$. The system noise density, $N_{sys}$, corrected for thermal noise by way of Boltzman constant K is also taken into consideration.

$$G/T = G_{veh} - L_{pass/veh} - (Nsys - K) \tag{4}$$

With the signal-to-noise ratio in the intermediate frequency bandwidth, $IF_{bw}$, the calculated signal-to-noise ratio, $IF_{snrcalc}$, is given by

$$If_{snrcalc} = P_{rec} + G/T - 10*\log_{10}(lF_{bw}) \qquad (5)$$

## DYNAMIC GROUND STATION ANALYSIS

Figure 2 shows a typical output from DGSA for the command uplink during a simulated flight to Malmstrom AFB. Note the short periods where the limiting margin drops to zero that occur at time 2:24 and approximately 5 minutes into the flight. These periods imply that there is a complete blackout of the RF signal. Further investigation into these periods reveals that the primary cause of attenuation is an anomaly in the plasma attenuation calculations. This anomaly will be corrected in the next update to the algorithm.

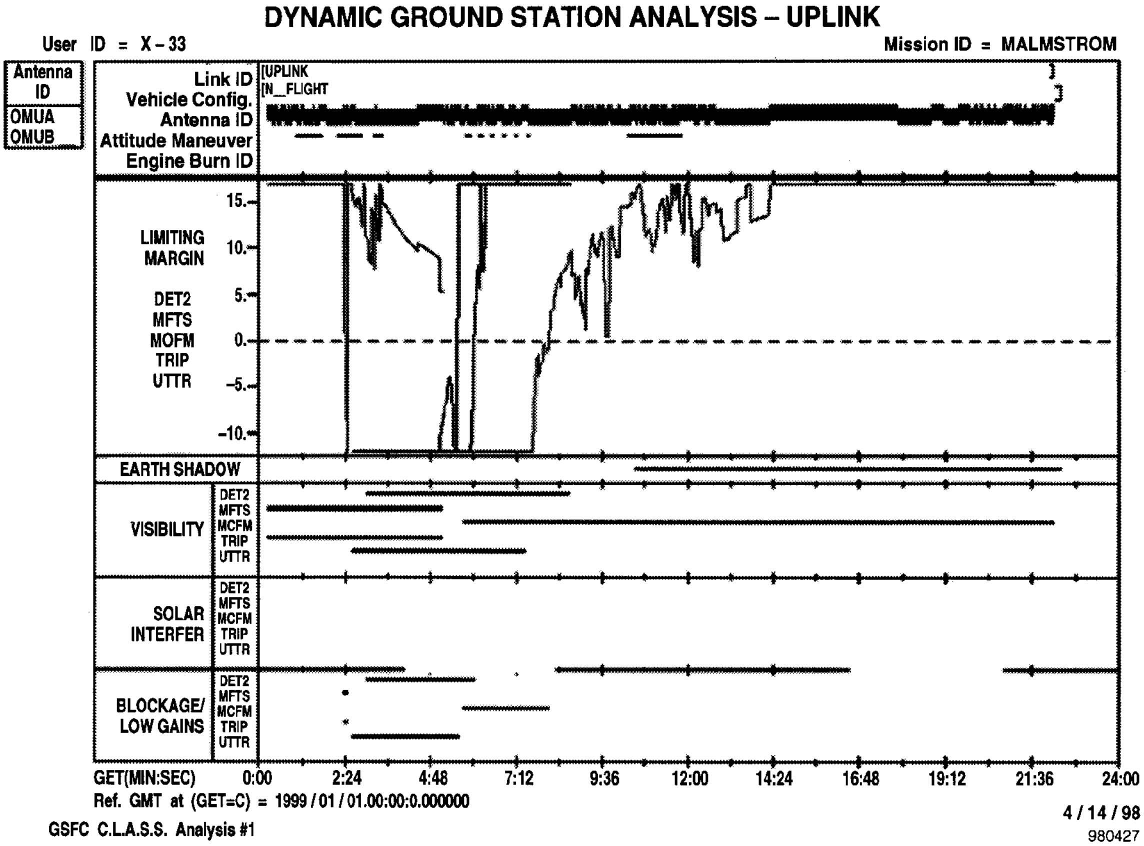

Figure 2. Dynamic Ground Station Analysis output.

## Radar Model

The radar model is accessed by DGSA once each second to determine which ground site is tracking the vehicle. Geodetic coordinates for latitude, longitude, and spheroid height of the vehicle during its trajectory are received from the X-33 flight simulation program.

Radar data from all of the ground sites are sent to the Data Enhancement System (DES) in position information-processing system format, where the nominal trajectory is adjusted to match the current tracking data. The radar simulation program computes the geometric look angles in azimuth and elevation from up to 10 radar sites to the target vehicle. When the range value at any one of these radar sites drops below 235 nautical miles, a range flag is set for that radar. Similarly, when the elevation value rises above 2.5°, an elevation flag is set. With both flags set, the vehicle is within the program-specified tracking limits, and an on track flag is set for that particular radar. Because more than one radar may be on the target at the same time, the radar on track and shortest range to the target is selected as prime and a selection flag is set. The DES then sends best source-adjusted radar data to all of the ground sites.

## Integration Phases

Phase 1 of range integration is based entirely on executing all software models to simulate the flight parameters and to verify that the RF links are within the budgets allocated. This simulation reduces the risk of damage to any hardware during the later phases and will require the implementation of range software to model vehicle antenna radiation patterns. The radar model will provide range to the vehicle for radar tracking purposes along with azimuth and elevation angles. Simulations using the DGSA model are then run for a complete link analysis of each of the three systems. The DGSA model includes the ability to modify some of the ground station parameters, such as antenna gains, aperture, and polarization, providing the flexibility of running *what if* scenarios for a better understanding of how significant the affect of these parameters are on the overall analysis.

Phase 2 will provide the ability to simulate range system operations using actual flight hardware. This operation is accomplished by connecting X-33 flight hardware for the telemetry, uplink, and flight termination systems and by integrating them with the software simulation developed in phase 1. During this time, the DGSA tool controls the power levels at the telemetry, FTS, and uplink receivers based on its internal computations. This tool also performs handoffs to the prescribed ground sites, depending on the vehicle location.

In phase 3, once the RF transmission is validated through a hard link, the next step is to duplicate the same tests by transmitting through space for a more realistic determination of the levels and affects of any electromagnetic interference that may exist. Vehicle antennas are connected to the ITF to transmit and receive from the Aeronautical Test Facility 1 and the DFRC FTS. Figure 3 shows how these systems will be interconnected during this phase.

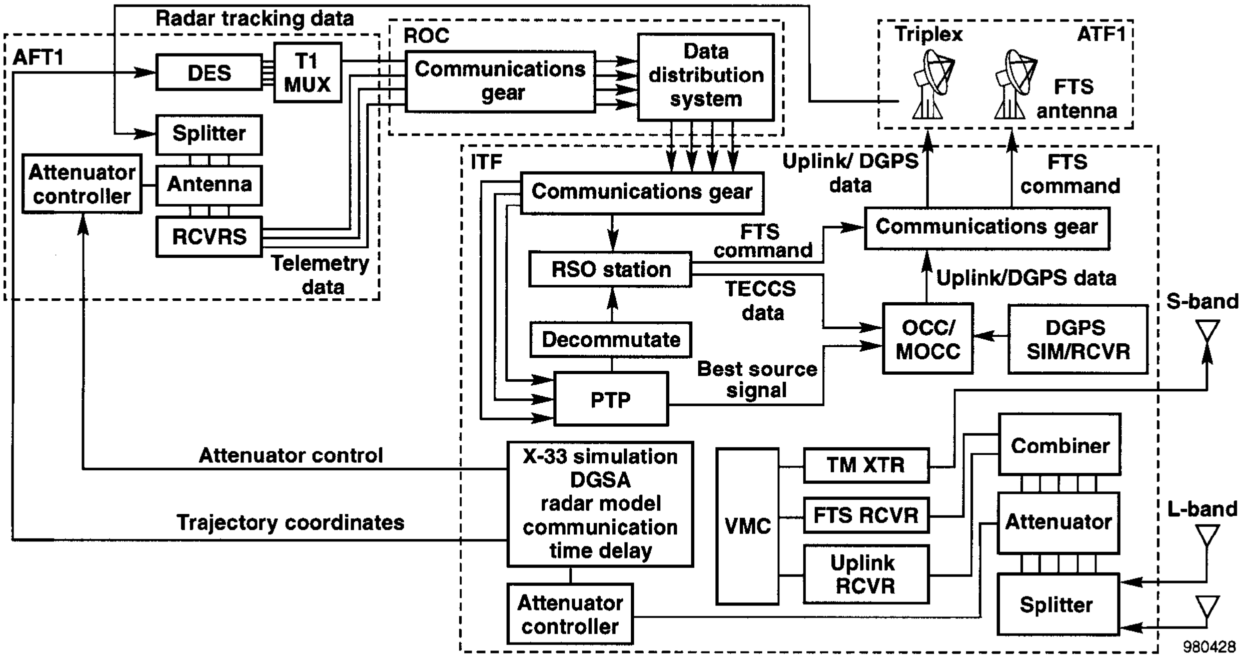

Figure 3. Phase 3 flight hardware and local range.

Phase 4 will bring all the range systems to be deployed at the remote sites to DFRC for an initial system checkout. The primary goal is to ensure that the systems to be located at each remote site are integrated together and can transfer data from system to system before deployment.

Phase 5 will deploy the range systems to support a flight to Malmstrom AFB. The remote systems checked out during phase 4 will be deployed to Mountain Home, Idaho, for over flight and to Malmstrom AFB for landing. The ER-2 flight testbed will be used to check the functionality of the communication systems onboard and the communication links to all of the ground systems.

Phase 6 will deploy range systems to support a flight to Dugway Proving Ground, Utah. Once again, the ER-2 flight testbed will be used to validate the entire range systems operation with each of the ground stations. Communication links between the ground station and the vehicle during the flight will be verified, and a better assessment can be made of the site handovers and where they occur.

## Integration Test Facility Range Simulation Hardware

Although both top and bottom communication antennas on the vehicle are used for simultaneous RF transmission and reception, only one transmitter will be active at any time. For the purpose of integration in the laboratory only, the top antenna has been designated to the S-band transmit path. The transmitter outputs 10 watts or 40 dBm of average power, which for redundancy is divided equally between the two ports at the hybrid coupler. Figure 4 shows the vehicle communications subsystem architecture which includes the RF combiner unit.

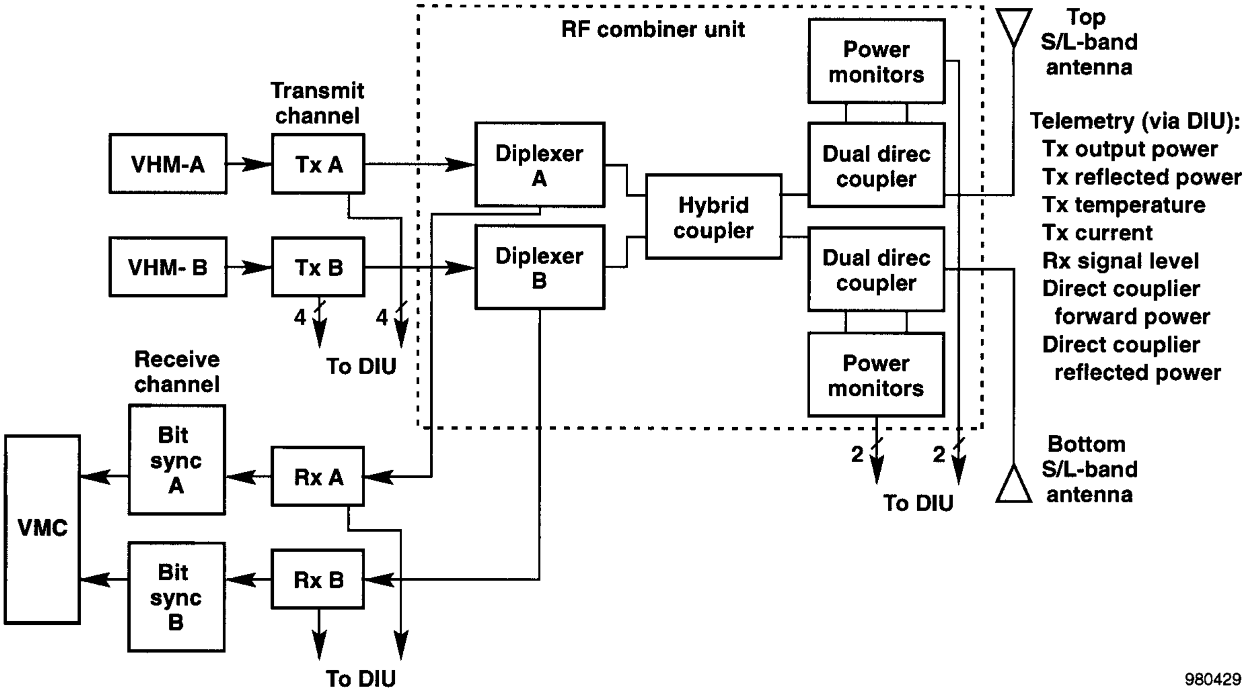

Figure 4. Communications subsystem architecture.

Figure 5 shows an example to illustrate the hardware interconnections for the S-band transmit section. After attenuating the transmitted signal by 60 dB, it is separated into three paths that lead into telemetry receivers resembling three simulated ground sites. Each site is distinguished by the RF power input to the receivers, which in turn controls the attenuation level settings computed by DGSA. The amount of attenuation must be sufficient to completely swamp out all the RF power in order to simulate a complete dropout. At the same time, care must be taken not to saturate the receivers. A programmable telemetry processor takes in derandomized non-return-to-zero-level (NRZ-L) telemetry data from the three pseudosites and determines which of the three contain the most coherent data to be passed on to the Launch and Mission Control Monitoring System (LMCMS). A secondary output from the best source selector is fed into the Range Safety Officer's (RSO) station, where data are decommutated. In addition, the telemetered vehicle parameters are displayed on one of the RSO monitors.*

---

*See Darryl Burkes' paper titled "X-33 Telemetry Best Source Selection, Processing, Display, and Simulation Model Comparison," (also available in these proceedings). This paper provides a detailed discussion of the best source selection and decommutated telemetry display.

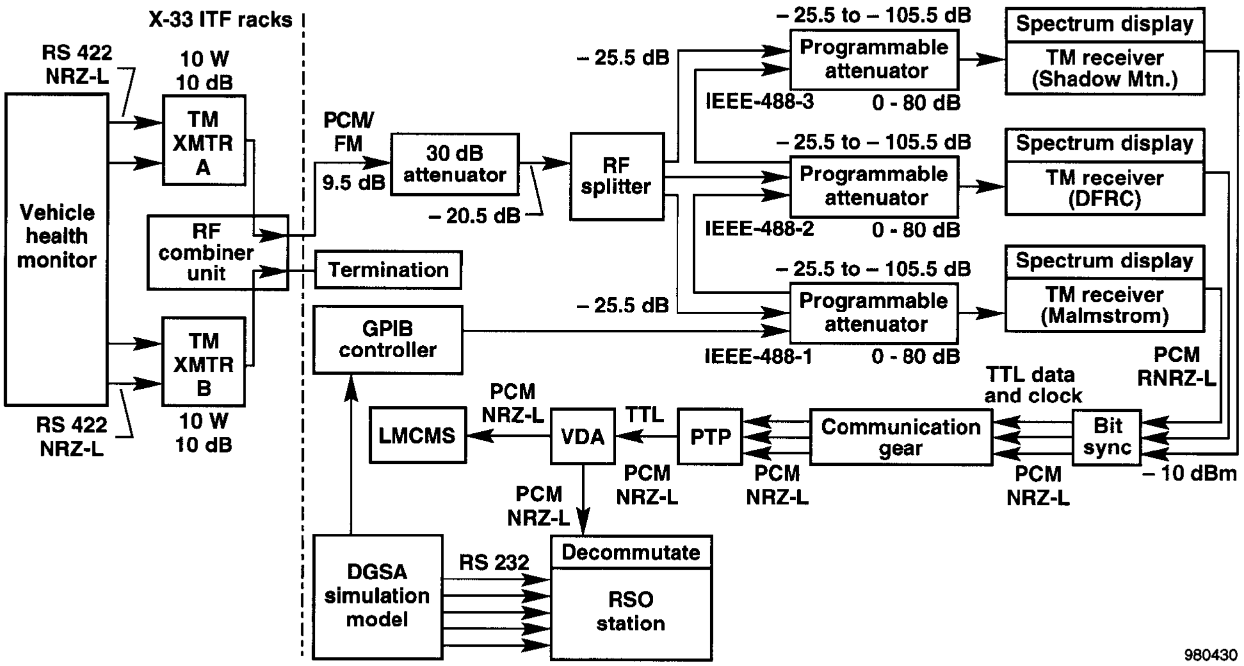

Figure 5. X-33 Integration and Test Facility S-band simulation hardware design.

The bottom antenna port is terminated with a 50-ohm load for the transmit path. This port also connects to receivers and the vehicle mission computer for the uplink path. The uplink data stream is packaged inside the telemetry and range interface processor where the secondary L-band flight termination command and differential GPS corrections are interlaced with the uplink command. Once again, the DGSA model computes the signal power levels expected at the vehicle taking into consideration the position of the vehicle and all the channel losses. A signal generator output power level is then attenuated to this computed value. In addition, the command uplink data stream is frequency modulated onto the uplink carrier. The flight termination command is initiated from the master control panel at the RSO station or from the remote control panel at one of the ground sites. The termination command is then relayed to the LMCMS for secondary L-band transmission. The termination command in the form of open and ground discretes are then tone encoded. As with the command uplink channel, the DGSA model computes the signal power levels expected at the vehicle, taking into consideration the position of the vehicle and the channel losses. A signal generator output power level is then attenuated to this computed value, and the flight termination tones are frequency modulated onto its carrier. The second output from the RF splitter is used to monitor the received RF termination command along with its decoded tones for confirmation that the tones were correctly sent and received.

### Range Safety Officer's Station

The RSO station located in the ITF will be the first of five RSO stations built for the X-33 program. This station will be used to provide training for range control and range safety personnel. The RSO station consists of a stand-alone processing system that displays radar and telemetry data on an instantaneous impact prediction (IIP) system that will be used for the evaluation of X-33 flights. The station includes a system to decommutate the telemetry data, to display critical vehicle parameters, and to output global positioning system (GPS) as well as inertial navigation system (INS) parameters over ethernet to the IIP systems. The IIP system calculates the debris pattern for the vehicle, based upon its location and trajectory. These results will be used to determine suitable locations for a safe flight termination. The RSO station also includes the Test and Evaluation Command and Control System which is used by the Range Control Officer to display Federal Aviation Administration data.

## CONCLUSION

The X-33 range requirements to provide continuous communications between the vehicle and ground stations will be verified by using an innovative approach to provide real-time simulations, analysis, and tests. The risk to public safety will have been greatly reduced by this analysis, along with results obtained from the flight testbed missions. The extended range will support X-33 flights with a great confidence of mission success.

## ACKNOWLEDGEMENTS

Much of the specialized information presented was provided by members of the Extended Test Range Alliance, Darryl Burkes, Rey Garza, Debra Randall, and Dale Mackall, to whom I wish to extend considerable thanks. I would also like to thank David Wampler of NASA Goddard Space Flight Center, Greenbelt, Maryland, for his contributions on Dynamic Ground Station Analysis. The work described in this paper was NASA supported through cooperative agreement NCC8-115 with Lockheed Martin Skunk Works, Palmdale, California.

## REFERENCES

1. Mackall, Dale, Sakahara, Robert, Kremer, Steve, "The Extended Flight Test Range," NASA/TM-1998-206557, 1998.