# DEMONSTRATION OF A LOW-COST MOBILE LAUNCH RANGE SAFETY SYSTEM

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## ABSTRACT

The Ballistic Missile Range Safety Technology (BMRST) program developed and demonstrated a low-cost, rapidly reconfigurable, launch range tracking and safety system. The system is comprised of both an on-board tracking unit and a ground based telemetry acquisition and control system. The on-board unit is based on an integrated GPS/INS unit with an embedded S-band telemetry transmitter. The ground system is comprised of fully redundant telemetry acquisition systems, telemetry processing computers, tracking computers, and secure/IRIG UHF command destruct transmission systems. This paper provides an overview of the system architecture and describes telemetry system design trades in particular. The paper describes how aircraft and satellite testing supports verification of system tracking capability. The paper closes by presenting data from the Quick Reaction Launch Vehicle (QRLV) flight test in Kodiak, Alaska.

## KEY WORDS

Range Safety, GPS Range Tracking, Telemetry, Command Destruct, Mobile Control Systems

## INTRODUCTION

There is a need for domestic missile and space launch ranges to be operated more efficiently to improve the ability of launch ranges and launch companies to compete globally. Key elements of the overall range operations cost are the cost to maintain and operate the aging radar tracking infrastructure, the poor reliability of the existing infrastructure as it relates to supporting on-time launches, and the inflexibility of fixed range systems. The BMRST program was created to specifically address each of these needs. The BMRST program primary goals are to demonstrate the feasibility of using GPS based range tracking systems, using new high reliability commercial hardware and software, and providing a highly mobile and flexible system. A key part of this is demonstrating a ground systems infrastructure that could be deployed to support range tracking in a more reliable and affordable manner than is presently done without relaxing current range safety standards.

## SYSTEM OVERVIEW

The BMRST system is comprised of a mobile operations center, redundant mobile antenna platforms, and a GPS/INS Tracking Unit (GITU). The GITU is mounted on-board the launch vehicle and includes a 12 channel GPS receiver coupled with a navigation quality inertial navigation unit, and an embedded 5-watt S-band telemetry transmitter that provides for a dedicated S-band telemetry downlink. When interfaced to patch or ring-style GPS and S-band antennas and a dedicated power supply, the GITU meets the range safety requirements as an independent source of tracking data. The GITU serves as the primary source of tracking data, thereby replacing or augmenting radar derived data, while the vehicle Telemetered Inertial Guidance (TMIG) data serves as the secondary source.

Each ground based mobile antenna platform captures the GITU and TMIG data streams from the vehicle. With each antenna platform capturing both sources of metric tracking information, the two tracking antenna platforms comprise the required level of redundancy. Each antenna sends the captured downlinks into the mobile operations center where the Radio Frequency (RF) streams are fed into the RF section of the Front End Data System (FEDS).

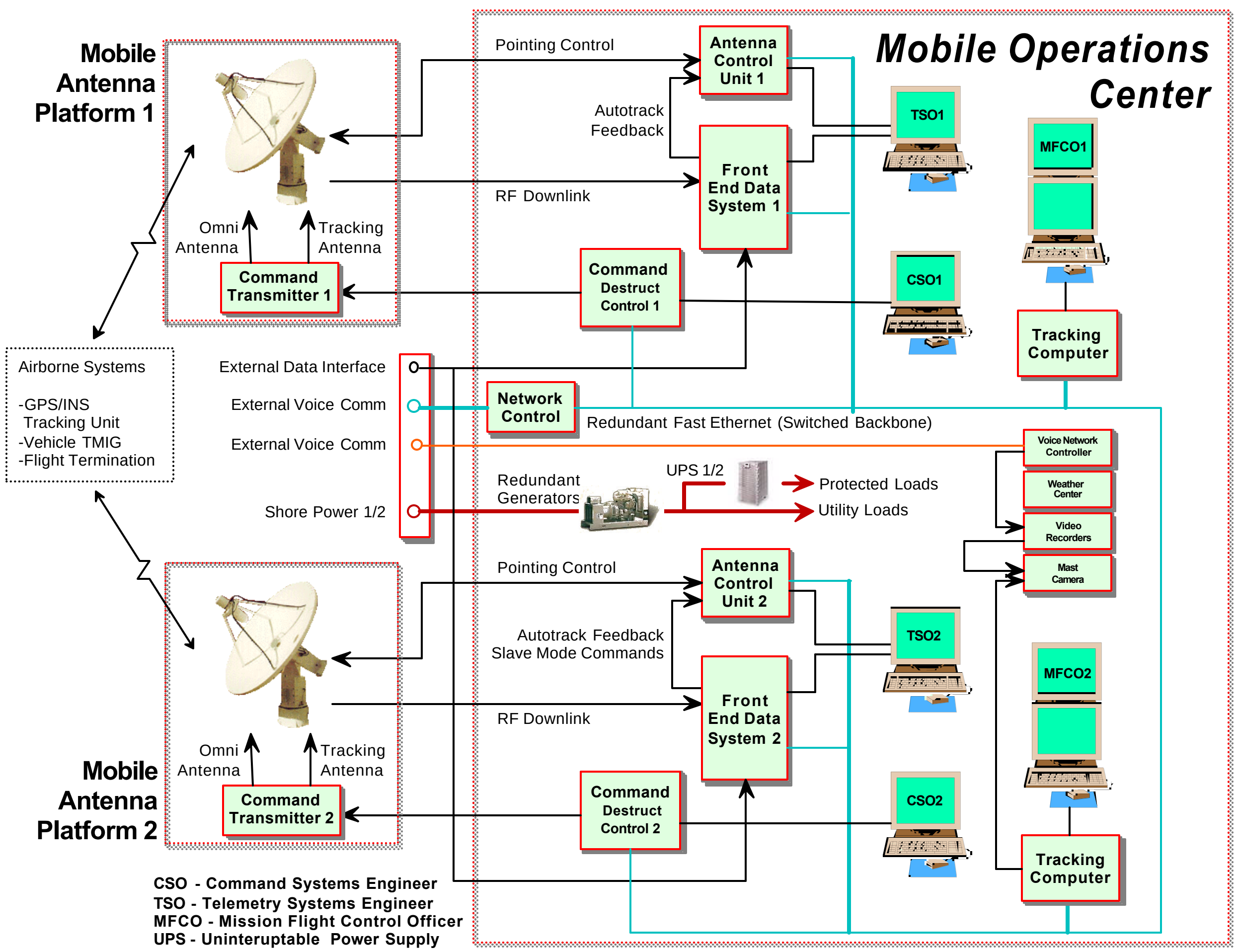


Figure 1. BMRST System Architecture

Antenna platform 1 sends its RF streams to FEDS 1 while antenna platform 2 sends its RF streams to FEDS 2. Each FEDS contains the necessary telemetry receivers, diversity combiners, telemetry bit synchronizers, and telemetry decommutators to process the incoming data streams. The FEDS implements internal cross strapping between antenna sites to enhance system fault tolerance. The FEDS also includes the real-time command and measurement servers that provide processed telemetry data throughout the BMRST network and implement automated configuration and control of all BMRST ground assets.

Each FEDS Command and Measurement Server (CMS) computer interfaces to an antenna control unit to implement direct control of the attached antenna platforms. FEDS CMS 1 controls antenna platform one while FEDS CMS 2 controls antenna platform 2. Each CMS provides real-time vehicle position information to the redundant Tracking Computers (TCs). Each TC processes this information into present position and instantaneous impact position that is then displayed to the Mission Flight Control Officers (MFCOs). Each TC maintains the theoretical trajectory that is also displayed to the MFCO along with impact limit lines and other information. The TCs also compute pointing solutions from any of the available tracking sources for pointing the antennas in a slave mode should autotrack capability ever be lost, or when the system is used in a downrange mode where vehicle acquisition must be accomplished.

High Power Amplifiers (HPA) are co-located with the antenna subsystem on the antenna trailer platform and provide the command destruct uplink. The tone sequencers, encoders, and exciters are located in the mobile operations center. The output of the exciter drives the HPA. An antenna switching system is employed to select among the high gain UHF transmit antenna (embedded in the S-band antenna feed), omni-directional UHF transmit antenna (for near range destruct), and a dummy load. Verification receivers and both secure and IRIG tone encoders are included in the mobile operations center.

Figure 3. Operations Console


Figure 4. MFCO Console

The Mobile Operations Center (MOC) contains several support systems including a redundant switched Fast Ethernet, redundant GPS time receivers, extensive data, voice and video record and playback, and redundant voice network interfaces. The MOC includes a 42-foot telescoping antenna mast mounted on the mobile operations center. This mast carries a video camera that is slaved to the tracking solution, a weather station with wind-speed, wind direction, temperature, and lightning sensors, and a DGPS receive antenna. The MOC also accepts several incoming video streams that can be routed throughout the vehicle. Finally the MOC is capable of redundantly generating all of the power required to run the system and includes Uninterruptible Power Supplies for all critical loads.

## KEY SYSTEM TRADES and TESTS

The design of the ground system required that system trades be performed to maximize performance. Several of the key parameters identified in these trades were validated via testing. System trades are a valuable tool throughout the program life-cycle. In the development phase, they provide key inputs for the product performance requirements documents. As the system is built and deployed, these trades continue to provide guidance for testing, siting, and operations. The key BMRST ground system trades are telemetry bandwidths and peak deviation selection, RF link and siting analyses, and diversity combining.

### Telemetry Bandwidths and Peak Deviation Selection Trade

Telemetry bandwidths are optimized for the communication systems based on system data rates and system modulation. Biphase frequency modulation/pulse code modulation (FM/PCM) was selected as the method to communicate the GITU digital data over the transmission link. The telemetry bandwidths selection (refer to table 1) includes the premodulation filtering, receiver IF bandwidth, and postdetection bandwidth. Parameters required for selecting telemetry bandwidths include peak deviation, IF bandwidth to bit rate ratio, bit-error-rate (BER) performance, and incidental frequency modulation (IFM) level.

Fortunately the Telemetry Applications Handbook Document 119-88[1] provides detailed guidelines on the selection of optimal telemetry bandwidths. In addition, telemetry technical articles (e.g., Gene Law papers) provide critical information. For example, the IFM factor was taken from a paper[2] that provided guidance on determining transmitter IFM degradation in BER. The requirement for the GITU transmitter was specified in accordance with these limits.

### RF Link and Siting Analyses Trade

RF link analysis allows the system architecture developer to integrate communications requirements (e.g., data rates, communication range) with the antenna diameter and system G/T. With a large antenna; the communication link is achievable over long distances. Unfortunately, larger antennas have limited mobility and higher costs. The RF link analysis provides the developer with a tool to optimize communications performance with equipment capabilities.

Honeywell has developed the Antenna Siting Analysis Tool (ASAT) that enables mission planners to both develop the telemetry receiving subsystem and to evaluate locations for antenna systems. The ASAT takes in the launch vehicle theoretical trajectory that includes information

| Requirement | Inputs | Calculation | Result |
|---|---|---|---|
| **1. Total IF BW Calculation** | | | |
| Doppler Frequency (kHz) @ 25000 feet/sec | 60.96 | 60.96 | 60.96 |
| Transmitter Frequency Uncertainty (kHz) @ ±0.001% Accuracy | 24.00 | 2 x 24.00 | 48.00 |
| Receiver Frequency Drift (kHz) @ ±0.00015% Drift | 3.60 | 2 x 3.60 | 7.20 |
| GITU Data Rate (kbps) | 50.00 | 2 x 50 | 100.00 |
| Total IF BW (kHz) | | | **216.16** |
| Receiver (Microdyne PCR-2000) IF Bandwidth (kHz) | | | 250.00 |
| **2. Peak Deviation (kHz) @ Mod Index 0.65** | | .65 x 50 kbps | **32.50** |
| **3. Allowable Peak IFM (kHz) @ IFM Factor 0.05** | | .05 x 32.5 kHz | **1.63** |
| **4. Post-Detection BW (kHz) @ Post-detection Factor 2.0** | | 2.0 x 50 kbps | **100.00** |
| **5. Premod Filter BW (kHz) @ Premod Filter Factor 1.4** | | 1.4 x 50 kbps | **70.00** |

Table 1. BMRST Telemetry Bandwidth Calculations

required by the link analysis equations such as range, elevation angle, azimuth angle, antenna clocking angle, and radiator angle. The ASAT implements S-band telemetry downlink and UHF command destruct uplink analyses. The tool has antenna models that include the UHF Omni command destruct, the UHF directional command destruct, the S-band directional telemetry, and the flight telemetry.

The tool also allows the developer to evaluate different plume models while observing the Intermediate Frequency (IF) carrier-to-noise (CNR) to ensure that it stays above the FM capture range. All vehicle plumes result in some attenuation of RF signals due to plume effects. The plume interferes with the RF signal because it contains free electrons and ions that are produced by thermal ionization of alkali metal impurities in the propellant. Vehicles using solid based boosters are much greater contributors to this problem due to the high metal content in the exhaust plume. The plume model used for the QRLV is shown in figure 5.

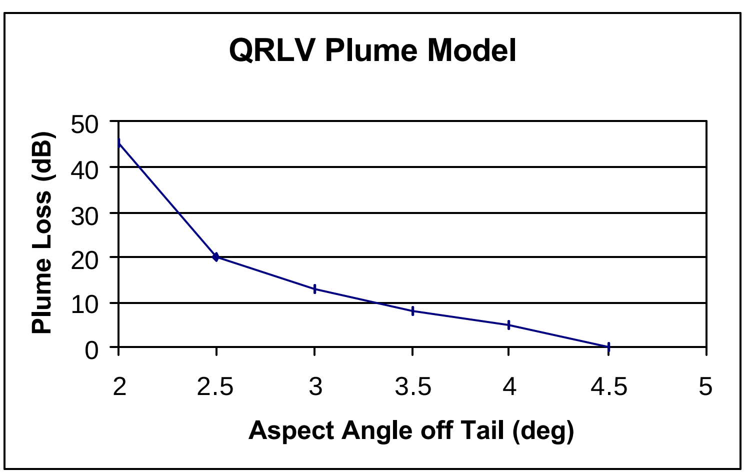


Figure 5. QRLV Plume Model

During the BMRST development phase, the ASAT helped determine that a 4.3 meter dish with a minimum G/T of 15 dB-Hz was required to track vehicles for 2000 km. For the BMRST deployment to Kodiak, the ASAT was used to model the QRLV trajectory (see figure below). This analysis showed that only one ground station located at the launch site was required for range safety coverage throughout flight. Figure 6 shows an ASAT output for the QRLV mission. Note that for both the GITU and TMIG S-band telemetry downlinks that there is sufficient link margin while the antenna elevation angle is above the horizon. The GITU downlink, used for steering the antenna, has a link margin near 40 dB at motor burnout and 30 dB near the end of the flight.

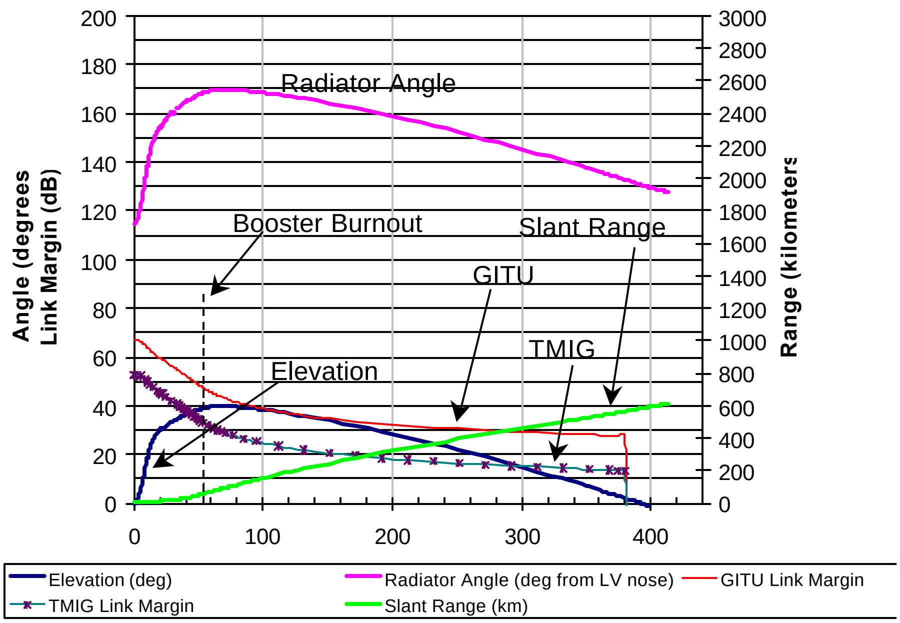


Figure 6. Kodiak S-band Telemetry Link Analysis

<u>Diversity Combiner Trade</u>

When RF signals travel from the missile to the telemetry subsystem, they experience several anomalies that result in fading and polarization changes. If the subsystem is not designed with diversity combiners to compensate for these signal changes, then the quality of the received data is reduced.

A trade study showed that BMRST required pre-detection diversity combiners for polarization diversity and post-detection diversity combiners for space diversity. The pre-detection diversity combiners are placed at the IF output of the RHCP and LHCP telemetry receivers. Theoretically a 3 dB signal-to-noise (SNR) ratio improvement is achievable if the two input signals are in phase and of equal amplitude. This happens because the signals add coherently and the noise adds as the sum of the square roots. However, this condition of two equal signals seldom occurs because the signals are experiencing random phase and amplitude changes. This is where the real advantage of the pre-detection diversity combiner comes to the front. For example, if the RF telemetry subsystem were only designed to receive the RHCP signal and this signal experiences a deep null, then the telemetry data would be lost. In

BMRST, the pre-diversity combiner examines both the RHCP and LHCP signals and then processes the combined signal based on weighting of the telemetry receiver Automatic Gain Control (AGC) voltage. The IF combiner output has an improved SNR that enables the telemetry subsystem to operate above the FM threshold region (about +12 dB CNR). The ASAT link analysis displays the IF CNR, allowing the developer to ensure that the CNR does not drop below the +12 dB threshold.

In the BMRST post-detection combining architecture, the video output from each FEDS channel is fed to post-detection diversity combiners. Due to the spacing between the two BMRST antennas, one antenna might be momentarily in a deep fade. Under these conditions, the post-detection diversity combiner acts like a combiner/switch, using the AGC voltages from the system 1 and 2 demodulators as weighting factors. The outputs from the post-detection diversity combiners are then fed into the FEDS bit synchronizers and decommutators for baseband signal processing.

In order to validate the trades, several tests were conducted at both the Cape Canaveral Air Force Station (CCAFS) and the launch facility in Kodiak. While located at CCAFS, BMRST tracked satellites and conducted a controlled aircraft test. Although these tests validated several of the BMRST critical requirements, they did identify that the antenna's autotracking velocity and acceleration performance was not adequate. Fortunately these results paved the way for improving the antenna's performance in Kodiak. The following test results were measured in Kodiak.

<u>Telemetry Receiver AGC Testing</u>

The telemetry receiver's AGC voltage is used by the Antenna Control Unit (ACU) and the diversity combiners to provide weighting factors on the relative signal strengths of received S-band telemetry signals. In order for the ACU and combiners to operate efficiently, the AGC voltage must have a high degree of linearity. Figure 7 shows that the telemetry receiver's AGC voltage is operating within its linearity requirement of ± 2 dB over a 30 dB range.

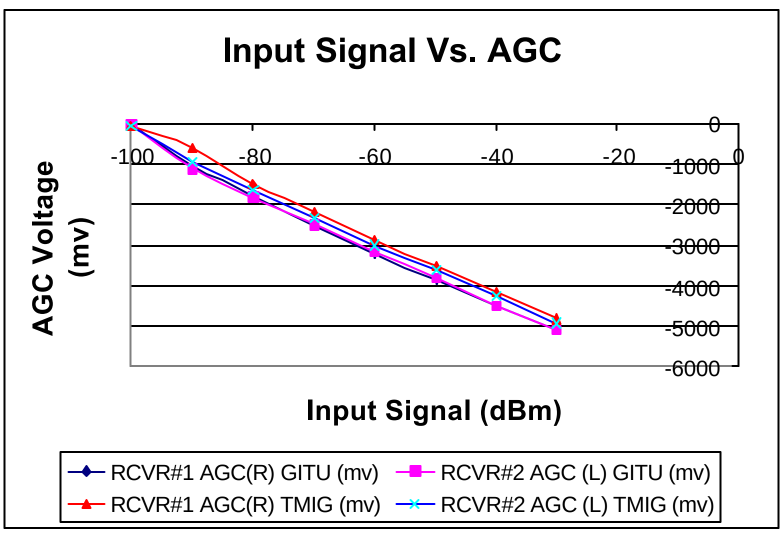


Figure 7. Telemetry Receiver AGC Linearity Measurement

Satellite and Aircraft Tracking Tests

Satellite and aircraft tracking provides an excellent vehicle to measure the antenna's autotracking velocity and acceleration performance. In order for the antenna to be capable of autotracking the dynamics of the QRLV mission trajectory, the antenna subsystem must be able to track at velocities of 4 deg/sec and accelerations of 0.3 deg/sec$^2$.

Tracking tests performed at CCAFS revealed that the tracking velocity and accelerations were not adequate to track the QRLV. Upgrades were made in Kodiak to the antenna's servo control circuits and boresite testing was performed to align the antenna tracking systems This paved the way for new satellite and aircraft tracking tests in Kodiak.

Specific LANDSAT and IRS-1A high elevation satellite passes were chosen because these passes present very high angular rates in the azimuth axis. Figure 8 shows the tracking data for one such LANDSAT pass. The left hand plot shows that this particular high elevation pass required a rapid change in azimuth velocity. The satellite elements were used to determine that the predicted maximum velocity would be 5.5 deg/sec while the predicted maximum acceleration would be 0.33 deg/sec$^2$. As can be seen in the right hand plot, the antenna subsystem autotracking performance was very good. The maximum velocity reached was approximately 5 deg/sec while the maximum acceleration was just at the required 0.3 deg/sec$^2$ value. This satellite testing provided a good level of confidence that the antenna subsystem could autotrack the QRLV.

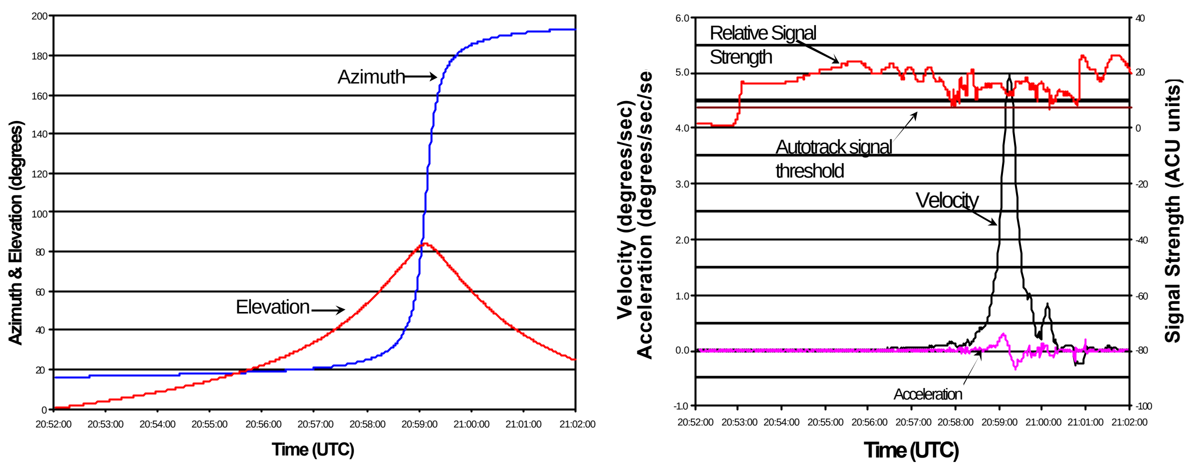


Figure 8. Antenna Subsystem Performance while Tracking LANDSAT

The aircraft test evaluates the antenna subsystem autotracking velocity and acceleration performances at lower elevation angles more comparable to a missile launch. Although the aircraft only tested the azimuth axis performance, the performance of the elevation axis should be similar because both the azimuth and elevation servo constants are similar.

The Kodiak aircraft test placed a signal generator and antenna on a light aircraft which was flown in patterns above the antenna, causing the antenna to track primarily in azimuth. The plane flew at an altitude of approximately 1000 feet on several flight paths that provided antenna rates inversely proportional to the distance to the aircraft ground track from the antenna. Aircraft testing demonstrated that the antenna subsystem could autotrack at rates over 6 degs/sec and at accelerations greater than 1.0 deg/sec$^2$. The antenna equipment was now ready to autotrack the QRLV.

## TEST RESULTS

The satellite and aircraft tracking experiences reinforced the tracking strategy for the QRLV. The primary tracking mode would be to autotrack off of the downlinked RF signal. In the autotrack mode, the system transitions to autotrack when a received telemetry signal exceeds a controlled signal threshold level. If during flight the GITU signal should be received at a level below the autotracking threshold due to transmission fades, vehicle antenna nulls, or high levels of plume, the system transitions back to slave track mode. In the slave track mode the tracking computer primary position source is used to drive the antenna pointing in a closed loop fashion until the autotrack acquisition threshold is again reached. The system design is such that the primary position source could be any valid source of vehicle position data including the GITU, vehicle TMIG, external pointing data, theoretical trajectory or updated theoretical trajectory.

Thirty-five minutes prior to launch, the GITU was turned on and the antenna subsystem received the GITU S-band signal at a sufficient level to exceed the ACU signal threshold level, causing the ACU to transition to autotrack. From launch to 8 seconds from splashdown, both antenna subsystems 1 and 2 stayed in autotrack mode while flawlessly tracking the QRLV.

Tracking data was collected to determine how closely the antenna subsystem was able to track the QRLV. Figure 9 shows the ACU tracking errors in elevation and azimuth. This error is derived by the ACU when it compares where the antenna is pointing versus where the antenna is commanded to point. When the vehicle is moving, this error value is processed by the ACU to point the antenna. The errors developed in elevation or azimuth must stay within the antenna's 2° beamwidth. Note that the maximum elevation error was only 0.38° during liftoff.

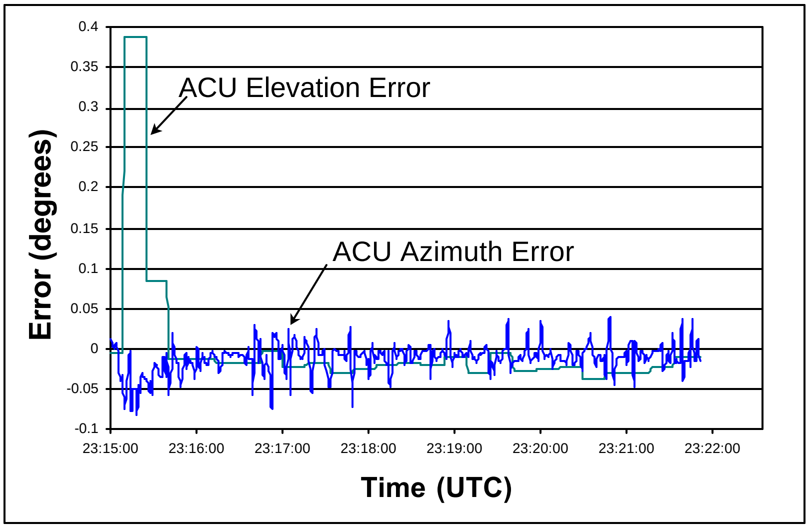


Figure 9. ACU Tracking Error

The best measure of the antenna subsystem's performance is measuring how well the antenna pointed towards the QRLV throughout flight. Figure 10 shows the antenna azimuth and elevation compared to the QRLV actual position as determined from the GITU navigation data. Note in both the azimuth and elevation figures that the GITU data validates that the antenna's pointing error is negligible. Furthermore figure 11 shows that the GITU position knowledge was excellent when compared to the post-mission truth reference.

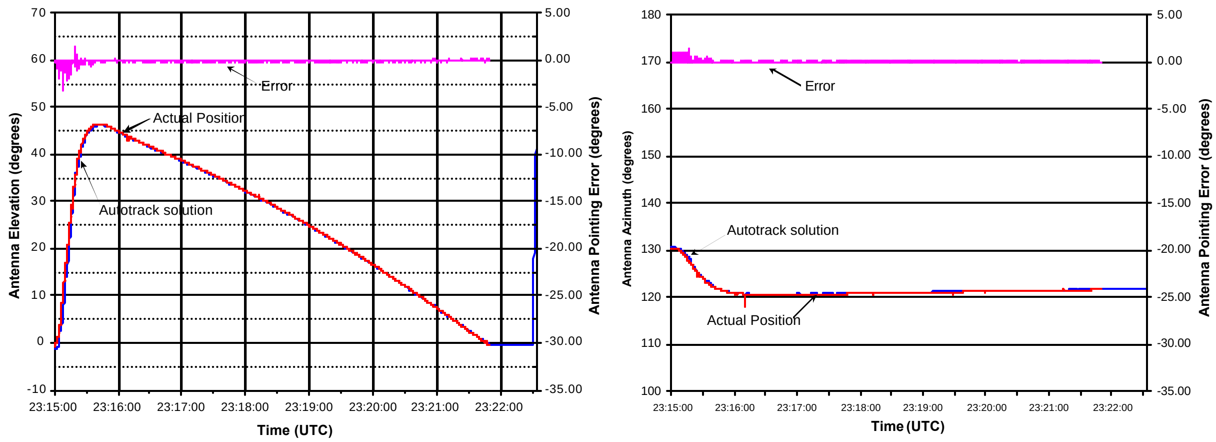


Figure 10. Antenna Autotrack Solution as Compared to GITU Data

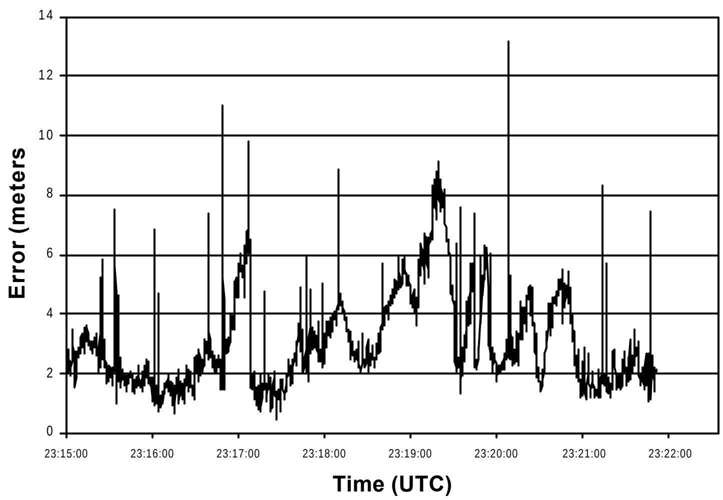


Figure 11. GITU Tracking Performance

Figure 12. BMRST System Stationed at Kodiak Launch Complex

## CONCLUSION

The BMRST program has demonstrated its primary goals showing that GPS based tracking for range safety is feasible, commercial hardware and software can be used to implement a reliable range safety system and a rapidly reconfigurable, highly mobile, range safety system is possible. Trade studies were used throughout the program life cycle to optimize the architecture to multiple missions. Early aircraft and satellite tracking tests further validated the architecture and provided important operational insights. The performance of the system in deploying to Kodiak Alaska was excellent. The performance of the GPS/INS flight system was excellent with better than 10 meter accuracy maintained throughout the mission. The optimization of the overall system design including flight and ground components resulted in an exceptional performance in tracking the QRLV with negligible data loss up until a few seconds from vehicle splashdown.

## REFERENCES

1. Telemetry Applications Handbook Document 119-88, February 1988.
2. Gene Law, Don Whiteman, IFM Effects on PCM/FM Telemetry Systems, International Telemetering Conference 1998.