A Low Cost, Quick Reaction TM Acquisition System Solution for Deployed Testing

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ABSTRACT

Design, development, fabrication, and deployment of an austere, deployable telemetry (TM) system, in only 3 1/2 weeks, will be discussed. This austere approach will be compared to a standard approach. TM candidate systems will be discussed along with exigencies and limitations (test geometry, link analysis, multiple test areas, schedule, cost, fabrication ...) that shaped their selection. Utilization of existing Radio Frequency (RF) systems in "unintended" applications will be discussed. System setup and BER testing with a simulated 'aircraft' will be presented, including observed multipath effects during testing, versus actual performance. Finally, benefits and test efficiencies garnered by having vehicle TM, real- time TM acquisition, processing and display, while deployed to a test area with no range instrumentation, will be presented.

KEY WORDS

Telemetry Receive System
Real-Time Processing and Display
MCS/IADS
Mobile Telemetry Link Simulator

INTRODUCTION

This paper describes the very short planning, design, fabrication, integration and testing of an austere real-time telemetry receive /re-radiation system (TMR/R to support deployed testing in Alaska. This system provided real-time TM data acquisition to “feed“ a real-time processing and display system that enabled safe and efficient testing. This paper also describes the benefits of the broad resources available at a major test center like the Air Force Flight Test Center (AFFTC) at Edwards Air Force Base (EAFB) that enabled a very quick response at a low cost. The short time period was driven by test planning decisions that altered the plan from doing only post-test processing to requiring a full real-time capability only three and one half weeks (24 calendar days) prior to equipment deployment!

Background: In early 2007, work was started on planning of testing of an F-22 aircraft on icy runways, to determine/validate ground handling qualities and stopping distances on icy runways (low Runway Condition Report (RCR), in order to validate Technical Order Data. Originally this was to be a deployment of the test aircraft and support team with an instrumented aircraft that was to make the ground test runs and utilize on- board recording and post-mission processing only, to review and analyze test results for a subsequent report. Emphasis was on minimizing the test program costs, while finishing the testing prior to that aircraft type being deployed to Alaska (See SETP referenced paper). Eliminating real-time TM capability was initially viewed as one of the ways to reduce cost, both for equipment purchase and transport and for deployed personnel.

The author's experience with the high value-added of real-time TM data acquisition processing and display, to support safe, efficient and effective testing, led him to strongly recommend that real-time TM acquisition, processing and display be employed. This recommendation was driven both by the unique limitations and impacts of operating in a very cold (-10 deg F to -40 deg F) environment. While acknowledging the value of this real-time capability, project management planned only for onboard acquisition and recording of data, with post test maneuver processing. However instrumentation and data processing personnel were included in the test survey team that deployed to the test location in the summer of 2007, to determine if real-time TM was feasible, in case it were needed. Thus candidate locations to do real-time TM support were garnered, but no other funds were authorized to pursue an implementation and work on a real-time TMR/R system halted.

Exigencies that supported a real-time capability were as follows. The core Flight Test Instrumentation (FTI) package on board the test aircraft was in the main weapons bay. In order to access the solid state recorder data cartridge for post-test processing, one would have to open the bay, remove the cartridge access cover, remove the cartridge, dub the data, process enough data to validate the data so that the cartridge could be reused, reload the recorder, close the bay. In order to do another test run (especially if the results of the run were required to "clear" the next test condition), data would have to be quick-look analyzed prior to clearing the next test. However, the cold conditions that were required for icy runway (and taxiway) testing most likely would have prohibited opening the weapons bay outside. Therefore the test aircraft would have to taxi roughly a mile into a hangar. In the same cold conditions, the hangar doors could only remain open 10-20 minutes without freezing up and becoming inoperable. This sequence of events could have taken up to several hours. Having to follow this lengthily sequence, to finish a test point and move on to the next, could have severely limited test execution rates.

Additionally test discipline engineers were concerned first about getting actual icing conditions that would satisfy test points, and next maintaining these condition long enough to be able to conduct multiple test points. Again, missing out on available weather conditions required for testing due to the lengthily post-test sequence could have severely slowed test execution. As test planning proceeded with formal test plans and test cards, technical and safety review boards determined real-time TM was required, albeit only 24 days prior to needing an integrated, tested TM acquisition system ready for shipping. The challenge was to meet an aggressive schedule while minimizing costs of equipment and implementation, minimizing additional deployed personnel and meeting all technical requirements. Equally paramount was making the system flexible enough, after deployment, to meet pop-up requirements, which inevitably occur.

SYSTEM DESIGN

When the "green light" was given to proceed with a real-time TM capability, there were only 24 days to design, procure, fabricate, integrate, test, calibrate and pack the system for shipping on the “ice truck” to Alaska! Additionally while the real-time processing and display system would be resident at the test site when the rest of the test team and equipment were deployed on a tanker aircraft, the real-time TM receive and distribution system had to be tested and validated at the deployed location, prior to the tanker arriving.

The biggest drivers to system design were the slant-ranges and azimuth angle range from the TMR/R system to the three candidate test locations (The relative receive location and ranges to the test areas on ramps, taxiways and runways, as well as TM distribution (re-rad) to test force facilities where the ground station and control room were located. See Figure 1. Candidate systems were investigated, the first being traditional ground station telemetry receivers/bit syncs/tracking antennas for TM acquisition. However the constraints of locating these system either outside in the elements or having to provide a climate controlled enclosure (either a container or a TM van) were vetoed as unfeasible given the time remaining and due to the cost of deployment. Similarly a standard range portable microwave link was considered to get the data stream from the tower to the Test Force building for processing. The only suitable location for the TM receive antenna was on the catwalk of the base control tower in order to have adequate field of view of all the candidate test areas. An alternative of locating this equipment inside the control tower was considered, but thought to be too intrusive to control tower operations. So alternatives were investigated. For the tower location, there were also potential electromagnetic compatibility (EMC) concerns regarding interaction of the TM re-rad high power source and control tower RF UHF and VHF radio systems. Conversely there also were concerns about these high power UHF and VHF radios interfering with TM reception. These EMC concerns would have to be worked during design integration and testing of the TMR/R system.

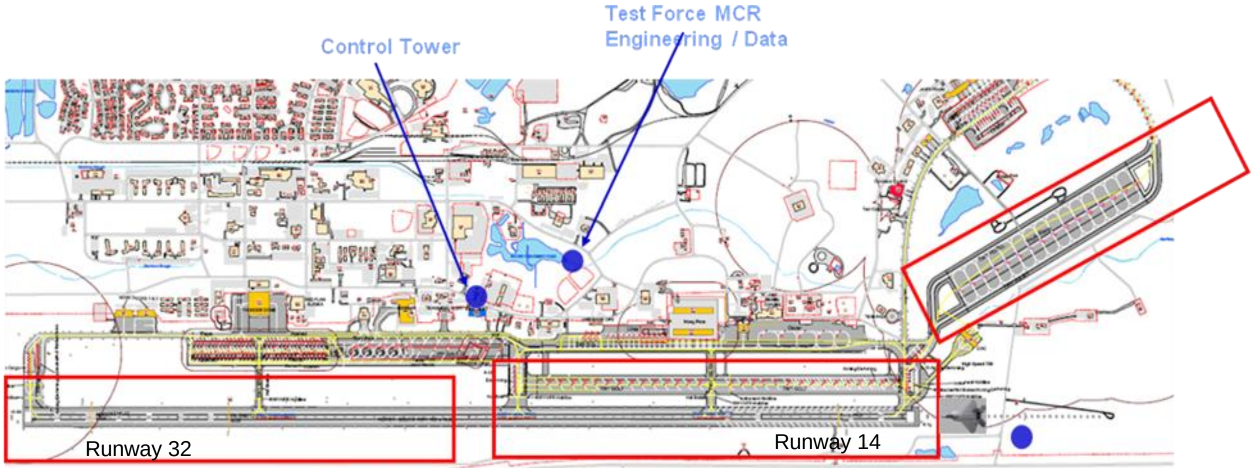

Figure 1: Relative locations of test areas (red shapes), TM receive location (Control Tower) and Test Force MCR.

Since using traditional range receive systems were undesirable, test aircraft on-board re-rad systems were reviewed. Many test aircraft with weapons bays require telemetry to be re-radiated out of the bay through external RF apertures on the test aircraft. The author had designed and worked with many of these. In general the components comprising these TM Receive/Re-radiation systems are designed to work in the harsh environments of the test aircraft weapons bays, and so were thought to be suitable for working in a minimally sheltered environment on the tower catwalk. Additionally, the components utilize 28 VDC as a power source, which would be safer to route from the control tower interior (even if external power receptacles had been available. Putting a 110 VAC to 28 VDC supply outside was deemed unwise. Plans were made to assemble the small, airborne environment capable components to make up the TMR/R system, placing them outside on the tower catwalk, with the 110 VAC to 28 VDC supply housed inside the tower.

The next phase of design was driven by the geometry of the candidate test areas (slant range, azimuth to be covered) and the TM antenna pattern and Effective Isotropic Radiated Power (EIRP) of the test aircraft. These geometries had to be analyzed to determine the required receive system performance, including the receive system components and the associated antenna system. Dimensioned drawings of the planned test areas, control tower locations and Test Force facilities were secured. Azimuths and elevations were determined for each candidate area. For the stacked antenna receive system, a 38 deg azimuth yielded an antenna plus coupler gain of 1.5 dB. Link analyses were performed. Worst case margins for 1×10^{-5} bit error rate was 1 dB, so the systems would theoretically just meet requirements. Thus, the required receive sensitivity and re-transmit power of the TMR/R system, were determined, and candidate airborne re-rad systems could be reviewed. The bomber re-rad system, that was selected, met the requirements and was available (including spare components) for the planned test period and will be discussed later.

ANTENNA SYSTEM DESIGN

Another big limiting factor was that the extensive sheet metal, welding, and machine shops normally available to support instrumentation system fabrication were completely tied up supporting higher priority projects. Only very minimal, simple fabrication could be supported for the antenna mounting system. Thus, no complex antenna mounting/pointing system could be designed and fabricated in the short time available. Additionally, size and type of available antennae were limited to those available on hand. Steps were taken to try and eliminate azimuth and elevation tracking during test runs, but field of regard of the antenna systems were potentially too small to cover the candidate test areas (although repositioning of the antennae was allowable between runs, since most testing would be limited to one candidate area for a group of test runs). Omni-directional antenna gains were too low to provide the link margin required. There were also concerns about the test areas changing and multipath reflections off of the tower was and catwalk fence interfering with the TM reception. So the receive antenna mounting system had to provide a back-up manual “tracking” capability. The smallest relatively high gain antennae on hand were cylindrical stacked-dipole antennae with about a 5 dB gain over ~20 deg azimuth angle. The manufacturer of the antenna was contacted and queried about broadening the effective azimuth angle by combining multiple antennae. Guidance was to space the antennae vertically roughly two wavelengths, and to stagger where they were pointed in azimuth. This would minimize azimuth nulling, with the risk of some elevation nulls. However the relative elevation changes during a test run were small and the elevation nulls were not a limiting factor.

Plans were made to test the antenna system after the mounts and the coupling/cabling were fabricated, if time allowed. An available 3 dB-90 degree hybrid coupler was used to couple the two receive antennae. Cables to connect the antennae were purchased pre-fabricated, with appropriate connectors, to minimize bend radius problems and shorten the build time.

There was still a big hurdle to get a suitable antenna mount. We again canvassed other test forces and organizations at the AFFTC and found that some personnel at Edwards had utilized tripod mounted antennae for some relatively static testing. We looked at available tripods and determined that the weight of the antenna system and the precision pointing requirements dictated buying new tripods. A big benefit of the tripods was that they had azimuth and elevation protractors and panning capability. The protractors also aided pointing reconfiguration for the different test area. They were relatively inexpensive (~$500 for tripod and head). A simple method had to be designed to mount the antennae, using minimal fabrication shop support. While looking through the tripod catalogues and after conferring with the CTF photographers, a lighting clamp called a "Super Clamp"™ (see Figure 2) was found. This clamp had a 1/4-20 threaded hole for a standard tripod-to-camera mounting screw. It clamped to rods from 1/2" to 2" in diameter. The heavy duty tripods and heads that were purchased would support 27 pound loads and accepted a heavy duty hexagonal quick disconnect mounting plate that had a 3/8-16 screw and lock nut. 1/4-20 screw/lock nut mounting plates were also available. Both were ordered, with the assumption that in order to hold the rod firmly to the mounting plate, the larger 3/8-16 screw might be superior. The tripod/Super Clamp/rod design did minimize fabrication requirements. One inch diameter rods were fabricated with both sets of holes (at opposite ends). On a lighter note, the Edward's shops only had 3/8 fine taps (3/8-20) so a test team member bought a 3/8-16 Helicoil™ kit, drilled tapped and installed the require Helicoils™ for the 3/8 end at his home. The only other fabrication was a small flat plate with a few holes for the antennae coupling and individual antenna mount to the Super Clamps. The cylindrical stacked dipole antennae had four mounting holes with the RF type N connector mounted on a raised metal block in the center. Small "hat" sections were designed to pick up these holes and clear the connector block and to mount the antenna to the Super Clamp and thus to the pole. Thus the total fabrication took very few man-hours. The clamps allowed adjusting the receive antennae vertical spacing and relative azimuth. The assembled antennae, couplers and cables could be mounted on the quick-disconnect pole, and then onto the tripods. This enabled the system to be broken down for shipping. The tripods were kept closed. The flat side created by two of the tripod legs were put up against the tower chain link railing and clamped with spring clamps, another simple installation. The re-rad antenna was located on another side of the tower railing with another tripod assembly and pointed at the test force building (see Figure 3 for antenna locations/installations). There was not time to quantitatively test the antenna system at Edwards. However, functional tests were done with the integrated system as described later.

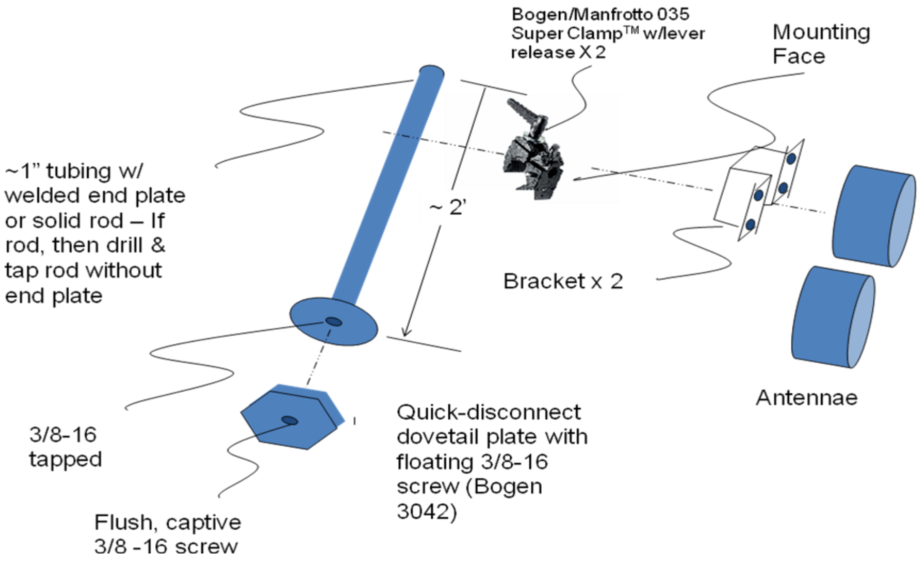

Figure 2. Antenna mounting design

Figure 3. Antenna Installations.

RECEIVE/RE-RAD SYSTEM SELECTION

With the antenna system selected, the available receive and re-rad systems were sought. Again, the AFFTC organizations were canvassed. With limited fabrication capacity available, a "pre-packaged" system was sought that could work in the cold Alaska environment. The various Combined Test Force (CTF) lead flight test instrumentation engineers were canvassed and the Global Power Bomber CTF had integrated receive/re-rad systems that were designed to operate in bomber weapons bay environments. These systems contained all the components to tune to and receive S-band TM (that was on the test aircraft), process the baseband signal through a bit synchronizer and provide data and clock to a Nova multimode digital re-rad transmitter (See Figure 4). Had an analog transmitter been used, a pre-modulation filter would have been required. All components were programmable via RS-232 interfaces. However, since this system was intended to receive data from stores in the weapons bays in close proximity and only for a short separation distance in tens of feet, they were normally run with extra attenuation in the receive path to prevent saturation of the receiver front end. These re-rad systems had not been calibrated for sensitivity. In order to have the data required to perform a link analysis and determine suitability of the B-1 receive/re-rad "box" to support the deployed testing, the system was taken into the RF lab that supported the Advanced Range Telemetry (ARTM) developments. Sophisticated RF signal generation equipment was utilized to model the test aircraft TM data (5 Mbps), control signal strength and model noise effects. The system sensitivity was measured at -95 dBm which was adequate for the Alaska test scenarios. Note that although the B-1 receive/re-rad box was meant to be in a weapons bay, it was not sealed. Ventilation holes were cut into a spare foot-locker to keep water/ice from accumulating on the non sealed system.

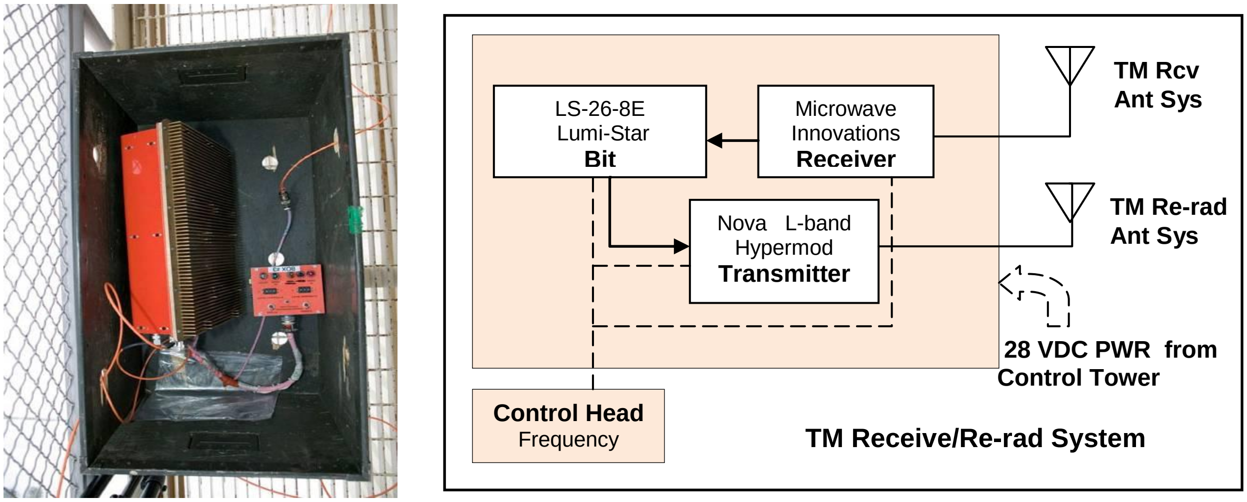

Figure 4. B-1 Receive/Re-rad System in Footlocker and Block Diagram.

An additional benefit of this testing was to identify some operational idiosyncrasies of the selected re-rad system as well as limitations to monitoring the system intermediate outputs while conducting the sensitivity tests. One should never attempt to use any range instrumentation system without testing and calibrating it, especially if it is to be deployed to a remote location where telemetry technical support resources may be very limited. The anomalous operation of the system discovered, was a sequence of events that resulted in the system being inoperative. One had to power up the system without an input PCM stream. If an input signal was present, the bit synchronizer would lock up and not process the TM stream output by the receiver. This limitation was thoroughly tested for repeatability, and a turn-on sequence was devised. Fortunately, there were individual circuit breakers for each component on the bomber re-rad system, so one could ensure that the TM receiver was "OFF" by pulling the receiver breaker. Then one could power up the rest of the system. After a few seconds from "power-up" the receiver circuit breaker could be pushed “IN” and the system was fully operational. If this problem had not been discovered and a fix had not been developed before deployment, it is doubtful that the cause of the problem could have been identified in the field. While reach-back to technical support at Edwards might have solved the problem, the personnel that would have had to support the troubleshooting would have had to drop other work, which would have been unacceptable. Start of testing would have been delayed until the system was operational.

While the technical performance of the receive portion of the TM Receive/Re-rad System was critical for TM reception, the re-rad performance requirements were very benign. The slant-range from the Control Tower to the Test Force building where standard ground TM receivers would be placed was less than 1000 ft. With a nominal five watt (37 dBm) transmitter, two of the 5 dB gain, cylindrical antennae, were used for the re-rad link, one on the tower to transmit and one outside the Test force facility to receive. A two stage step attenuator was included in the equipment to provide attenuation if the signal were too strong. Putting the antennae off bore-sight would also have reduced signal, but might have caused a multipath problem. In-line attenuators could have also been used.

As stated earlier, the ground TM receivers and processing and display system were not scheduled to arrive until one or two days prior to the testing beginning. Therefore, a way to validate the TMR/R system had to be devised. Bit Error Rate (BER) testing was chosen because it provided quantitative data on Bit Error Probability versus energy per bit (E_b/N_o) and is relatable to signal-to-noise ratio (SNR). This SNR can be used to estimate receiver carrier-to-noise ratio and thus validate the link analysis and operational suitability at each test location. While standard rack-mount BER Test Sets (BERTS) were available at the Combined Test Force, they had not been used regularly, and had to be tested for functionality. Only one of two BERTS was operable. A spare was located an added to the "inventory" to be shipped.

TELEMETRY SIMULATOR DETAILS

A data source was now required to provide the pseudo-random code compatible with the BERTS. Again the resources of the RF lab were instrumental in supporting this requirement. The lab engineer had integrated a small pallet (~4" by 10") see Figure 5) with a TM transmitter, heat sink, ducting and cooling fan. In previous requirements gathering during the ARTM and other flight test efforts, the requirement for TM transmitters to have a test signal generation capability had been identified and was subsequently realize in the TM transmitters that ARTM developed. Thus the TM transmitter was capable of generating a 2^{11} -1 pseudo-random sequence compatible with the BERTS. Even better, the transmitter on the pallet generated a native 5 Mbps pseudo-random sequence, which exactly matched the test aircraft data rate. A plan was developed to mount the transmitter into a truck, build an antenna mast and drive the truck in the candidate test area and measure BER performance along each leg at various intervals. The runways and taxiways have marked distances on signs, so we could repeat the testing accurately. Two hurdles had to be overcome to complete the BER test setup for the truck. One was to secure a source of 28 VDC to power the transmitter pallet. The other was to design/build an antenna mast for the truck. There were several 12 VDC to 28 VDC power supplies that were commercially available, but most were open frame and would have had to be integrated into a box with cabling. The time to identify and procure a supply was inadequate, as was fabricating an enclosure. Fortunately, the test team met regularly to discuss challenges problems. At one session, the lead maintenance NCO at the CTF suggested using the power supply for an AN/ARC-164 UHF radio used in vehicles. This unit had a cable that plugged into a standard automotive 12 VDC receptacle. However this power supply was made to mate with the back of the radio, so the 7 socket connector was not a standard receptacle that one could find a mate for. For expediency, the required cable was made with pins to fit the connector sockets. The exposed back of the pins were insulated and the cable was string-tied to the power supply. The TM simulator antenna mount proved to also be problematical. We had envisioned using a mast with a ground plane and a blade antenna that would fit in the square hole in a pick-up bed. We thought we might scrounge one from a similar mast design for the UHF radio. However most truck antennae were not mast mounted anymore. We could not find a commercial source, so we borrowed an extant small square plate, from the Instrumentation Division RF Lab, that had a S-band blade, and decided to work the mounting approach in the field. Note that attenuation was also provided to more accurately simulate the low gain conformal TM antennae on the test aircraft (-11 dB gain). Subsequently we cut slits in the plate, put a nylon strap that had a ratchet tensioner through the slits and mounted the antenna onto the top of a truck cab (see figures 5 and 6 for the mobile TM test source and BER test setup pictures). Test runs were made on the candidate test areas. Reception was error free in all areas except for one 500 ft stretch in a critical braking area. The test conductor was informed of the issue and alternate test areas were devised. We suspected that multi-path interference was the culprit, caused by reflections off of the runway and the relative elevation angles for that area. However, since this was a small program it was relatively easy to have the test aircraft directed to taxi to all candidate test locations, when it arrived, so that reception and data quality could be checked to better characterize the severity of the problem. It turned out that there was very adequate signal strength in all test areas (the link analysis proved very conservative which was a good thing) and no multi-path interference. Evidently, the top of the truck caused the multi-path problem. We did the tests with a single receive antenna as the worst case, determined that it was very easy to use the protractors on the tripods to preposition antenna azimuth and elevation and to hand track the test aircraft, keeping the antenna pointed directly at it, maximizing gain. In retrospect, some sighting references should have been developed and mounted on each antenna to aid pointing. However drawing lines on the antenna side, front to back, and using a piece of cardboard as a template to "drop" the antenna azimuth to the tripod protractor, gave us the cues needed to be able to point the antenna effectively. If the link margin had been lower, precision pointing (via manual tracking) may have become critical.

Figure 5. Mobile TM Test Source

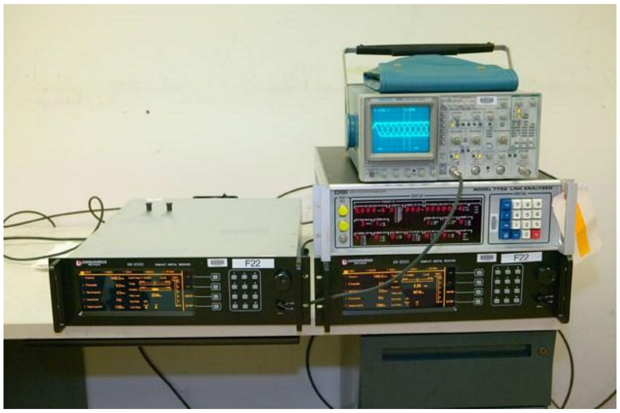

Figure 6. BER Test Equipment Setup.

SPARING AND GENERAL TEST EQUIPMENT

All of the above design and system selection was included consideration of adequate spare components to accommodate system failures. Enough general purpose test equipment (oscilloscope, spectrum analyzer, digital voltmeter …) must be secured and available at the deployed site to troubleshooting in order to isolate component failures and make use of the spares viable. This test equipment complemented the equipment deployed to do quantitative performance testing of the TTR/R system.

SYSTEM CHECKOUT/TEST

After all the assemblies and components were received there were only two days left before the items had to be inventoried, packed and put on the "ice truck" where they would arrive in time to be there for the advance party to arrive. Initial plans were to take one technician/operator to run the post-test processing and analysis station. Only one additional person was required to set-up and test and operate the TMR/R system. However the entire system had to be set-up and tested prior to packing. On packing day -2, the system was set up in two rooms with windows that overlooked the CTF compound. Across the ramp from these windows were a test aircraft with TM and an Instrumentation ground support unit (GSU) Van with steerable antenna, a TM receive system and processing/display capability. The Receive side of the system to be deployed was put in one room. The re-rad tripod/antenna was put in the room next-door. A open air, closed-loop test was performed by receiving the aircraft TM, and re-transmitting to the TM van as the surrogate Test Force processing and display facility. However, the slant range was only 250 feet and the elevation of the system was only ~20ft compared with over a hundred feet for the Alaska tower. So on packing day – 1, the entire system was set up on the Edwards AFB control tower. Technicians that supported the control tower electronics/radios participated in this testing. A test aircraft on the active runway was tracked and the signal re-radiated to an instrumentation van. Distances of this test were actually greater than those required for Alaska, but the effective azimuth traversed was less than the longest Alaska run. This testing was done without hand tracking the test aircraft. Data quality was good and the azimuth range tracked, was satisfactory.

EMC of the tower electronics and the TMR/R were confirmed to be acceptable, eliminating any technical obstacle to placing the system in the tower.

SYSTEM FLEXIBILITY

After deployment and setup of the TMR/R system, the test areas were modified. A new area was added that was farther away than any of the original three candidate systems, with some potentially obstructive trees between the test aircraft and the TMR/R system. However, the azimuth range for these tests, were very narrow. The performance of the TMR/R system was good enough to support this new area, and the tripod azimuth adjustment capability enabled proper pointing to optimize antenna gain. Additional flexibility of real-time TM monitoring was also crucial to the test support. The real-time processing and display system utilized was one already integrated into a ~48 inch high rack on casters. This was a small instance of the MCS/IADS systems, which are also used as core processing/display system in some of the AFFTC mission control rooms (MCRs). While only four work stations were required for four discipline flight test engineers to monitor the single PCM data stream data, the MCS/IADS system had all the capacity and flexibility required to support larger, more complex requirements. Thus test engineers at Alaska had the same analysis and display capability of the new MCRs at the Center. Part of the pacing items for test point execution rates was having to check test aircraft brake temperatures. After a test run, the tests aircraft would taxi back to the start point for another run. The original planning had included utilizing handheld contact pyrometers for monitoring brake temperature and ensuring it was within limits, before beginning another run. The contact units did not function well in the cold. Since the test aircraft brakes were instrumented, the TM already contained accurate brake measurands. The MCS/IADS configuration files were revised in a few minutes to enable display of the brake temperatures, thus allowing test runs to begin immediately upon brakes cooling to within limits (ref. SETP paper) speeding test execution. This again demonstrated the value of a flexible real-time TM system capability.

Testing was completed in approximately five weeks. In the paper given on this project at the 2008 Society of Experimental Test Pilots International Symposium (see reference), real-time TM was touted in a lesson learned number nine as, “Telemetry is a vital test efficiency and safety multiplier in any brake test program. Use of telemetry was credited in cutting the testing period by a factor of 2! Given the large cost savings accrued, it is noteworthy that the entire cost of designing and assembling the real-time TMR/R system was under 5,000 dollars! The extra TM person deployed for only 11 days, after which the technician operating the processing and display system was also able to setup and operate the TMR/R system, again saving funds. Also note that upon initial TMR/R testing in the field, there was one failure of an airborne receiver, but adequate sparing and test equipment enabled repair of the system.

CONCLUSIONS

A low-cost, austere TM Receive and Re-radiate system can be assembled, tested and deployed successfully in a very short time if one had broad test range resource to draw from. Using existing Radio Frequency (RF) TM systems in "unintended" applications may be the key to a successful system integration. One must follow systematic design methods to identify key performance parameters in order to provide a viable solution. One must functionally and quantitatively test as much of the system as possible prior to deployment and at the deployed location to ensure adequate system performance. Thus one must also design and implement deployable test systems required to stimulate TMR/R system. In retrospect, having limited fabrication capacity at the time of design and limited time to deliver the system was a benefit, as it drove a “Keep It Simple Stupid” (KISS) approach. The ripple effect of this KISS approach definitely reduced cost of the TMR/R system greatly and also contributed to a supportable system once deployed. Finally the resulting system must provide flexibility to meet new requirements after deployment.

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