# MULTIPLE USES FOR MULTIPLE TELEMETRY ANTENNAS

Barbara Carlson, Michael Diehl, Edgar Hurtado, Jason Swain, Tab Wilcox
Air Combat Systems Directorate, United States (U.S.) Army Yuma Proving Ground (YPG),
Yuma AZ 85365-9498

## ABSTRACT

An increasing number of munition programs are integrating telemetry (TM) into their artillery rounds. Due to their small size and high speed, tracking munitions brings with it challenges typically not seen with aviation. Tracking with multiple TM antennas provides a more complete data collection event across the extended ranges, demonstrated in modern artillery, and provides advantages as a result of spatial diversity. Traditional munition testing usually incorporates radar and camera mounts that track the munition throughout its flight. TM has the benefit of the telemetered stream aiding in acquisition; however, given the size and speed of the munition, initial radar or camera acquisition can be very challenging without access to an external pointing source. The YPG conducted a series of flight tests using multiple TM antennas to explore the ways TM can help provide pointing as well as to further its integration of best source selection into its TM infrastructure.

Keywords: Best Source Selector (BSS), Data Quality Encapsulation (DQE)

## INTRODUCTION

YPG is a subordinate command of the U.S. Army Test and Evaluation Command and is one of the largest military installations in the world. Located in southwestern Arizona, it encompasses 1,308 square miles. YPG personnel conduct tests on nearly every weapon system or piece of military equipment in the ground combat arsenal. With a mission to provide premier test services to the U.S. Government and its allies, YPG conducts, reports, and supports developmental tests, experiments, production tests, integrated developmental/operational tests, as well as provides training support.

In recent years the Army has sought to significantly increase the accuracy and range of its ground-fired munitions. This emphasis has resulted in a significant increase in the number of munitions utilizing TM to support their development. As the munitions become more sophisticated, the importance of the data being telemetered has grown as well. When compared to typical aviation programs, the speed, duration of flight, the ability to record onboard, and the ability to reuse onboard instrumentation is noticeably different. These differences bring with them challenges typically not seen with aviation. Fortunately, the efforts to improve TM capability in support of aviation testing, such as Telemetry over Internet Protocol (TMoIP), BSS, and DQE coincide nicely with support needed for munitions, especially for the extended range munitions.

The primary instruments used to support munitions testing are radar and camera mounts, which in order to provide the required data need to track a munition throughout its flight. Although the radars used are capable of tracking on their own, both the radars and camera systems can benefit from having access to initial pointing information. Telemetry can also benefit from pointing, but it has the advantage of tracking a cooperative target thanks to the radio frequency (RF) signal being transmitted. In order to ensure that the customer is provided all the required data, YPG is always looking to provide fault-tolerant support and to unify the various instrumentation systems employed to support large test efforts. By looking at ways to combine the various instrumentation systems to have a system of systems support approach, both of these goals are possible.

Recently, YPG planned and conducted a series of flight tests to gather the necessary data to evaluate both new equipment and capabilities that are being brought online. This paper will briefly describe the flight testing and look at both the ability to generate usable real-time pointing data from multiple TM antenna and the resulting performance gains from the utilization of a BSS.

Flight Testing: An organic Cessna 208 Caravan was configured to act as the surrogate test item. Experience with this aircraft has shown that the best TM link availability is achieved with a Space Time Coding (STC)/Low Density Parity Check (LPDC) configuration; however, in this case, a less robust TM link that more closely emulated the test items was desired.

The Caravan was configured with a commercial off-the-shelf (COTS) Embedded GPS/INS (EGI), an encryptor, and associated hardware to provide telemetered information similar to emulate test munitions. A Differential GPS (DGPS) was installed to be utilized as an independent truth source for the aircraft position.

In addition to these items, an additional telemetry transmitter was installed and a PN11 Pseudorandom Bit Stream (PRBS) was transmitted as the reference signal which allowed bit errors to be evaluated. Both signals used a single antenna, and both antennas were located in close proximity to each other on the bottom centerline of the Caravan. Both transmitters were matched in output power and the appropriate RF isolation was used to allow adjacent frequencies to maximize commonality of signal path. The Caravan configuration is shown in figure 1.

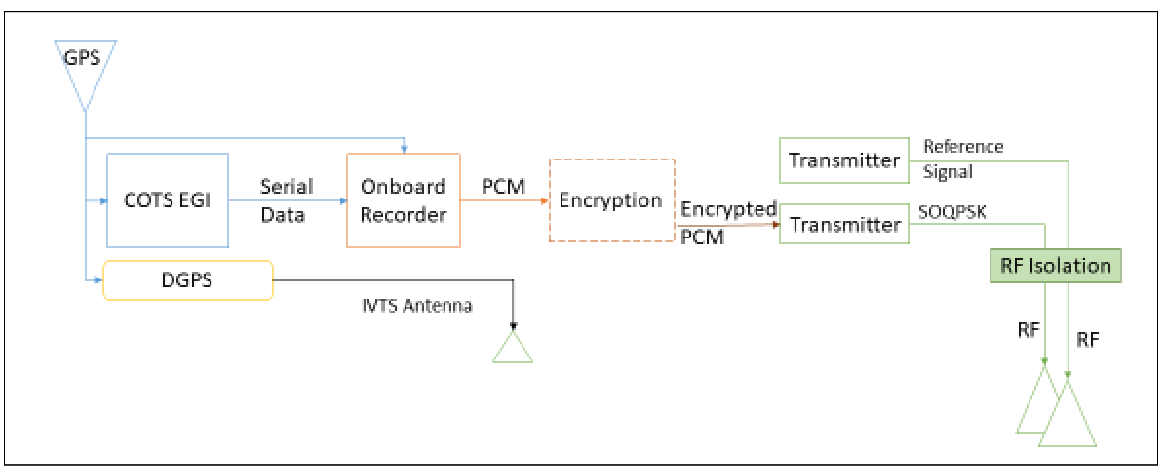


**Figure 1. Caravan Surrogate Test Item Configuration**

Flight testing was conducted in restricted airspace.  In order to evaluate the real-time pointing, changes in azimuth (AZ) and elevation (EL) at longer ranges with respect to the TM antennas were desired.  Flying in the restricted airspace allowed for ranges between 40 to 80 kilometers.  A triangular flight path was laid out and various legs were flown as required.  One flight leg (A) was flown straight and level and the remaining two legs (B and C) featured climbing and descending profiles to provide the desired AZ and EL changes.

Four fixed antennas (Ant-1, Ant-2, Ant-3, and Ant-4) were used to track the Caravan through the flight test.  A mobile TM van was used to receive any available pointing.  The flight profile and antenna sites are shown in figure 2.

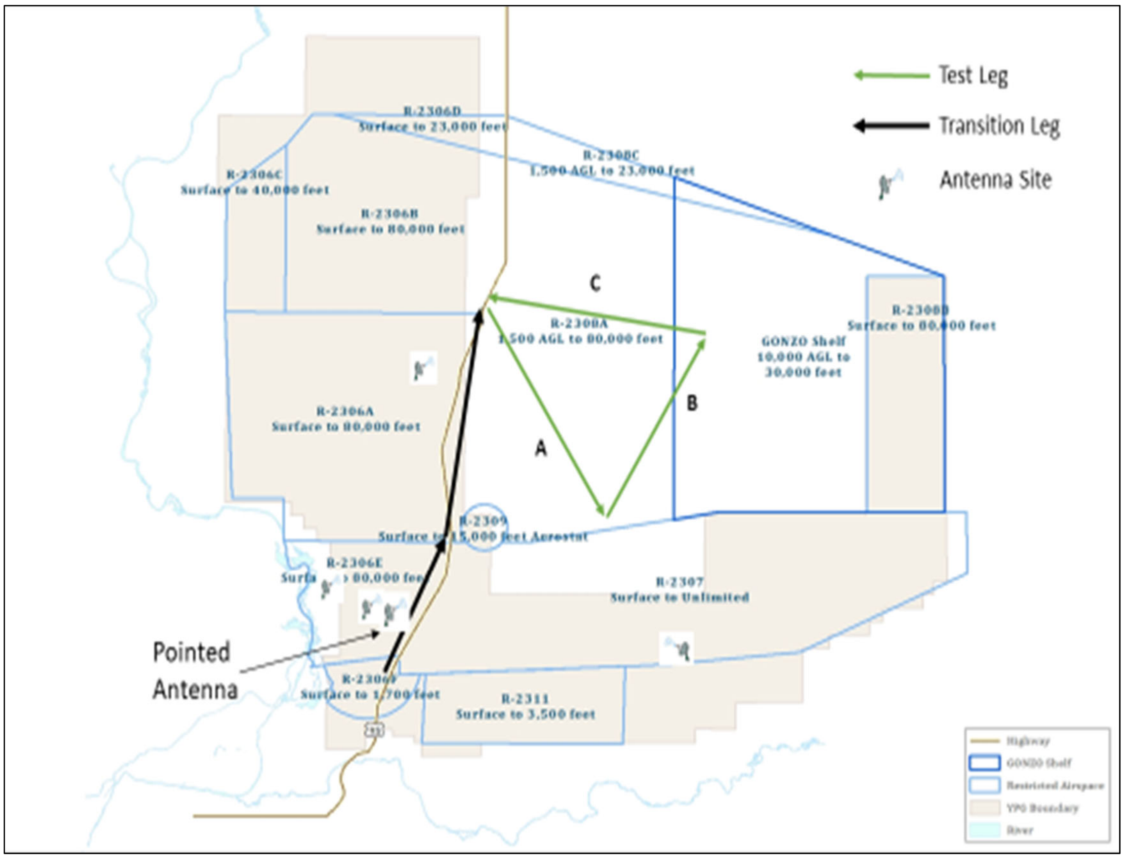


**Figure 2.  Caravan Flight Profile**

Initial flight testing was conducted on 5 May 2021, and additional flight testing was conducted on 8 June 2021.  A summary of the flights conducted is presented in table 1.

**Table 1.  Flight Summary**

| Date | Event | Start Time | Stop Time | Comments |
|---|---|---|---|---|
| 5 May 2021 | Flight 1 | 16:23:57 | 17:42:58 | Data and PN11, 1-mbps, ~ 1 watt |
| 5 May 2021 | Flight 2 | 19:43:17 | 20:12:51 | PN11 only, 10-mbps, < 1 watt |
| 8 June 2021 | Flight 3 | 19:36:52 | 19:54:00 | Data only, 1-mbps, < 1watt |

## MULTIPLE TM ANTENNA-DERIVED TIME-SPACE-POSITION INFORMATION (TSPI)

Acquisition and tracking of a long range munition has been and continues to be a challenging task. As a result, since the late 80's, YPG has included in its infrastructure the ability to provide pointing to different instruments. Originally, Mission Control, with its mainframe computer cluster, was the central hub for pointing. Instruments (radar, tracking cameras, etc.) were linked to Mission Control via multiple bi-directional microwave links and could either contribute to the pointing solution or receive pointing. The real-time engine utilized would ingest relevant TSPI information from the various field instruments, apply any known biases, account for transmission delays, develop a state vector, and output a custom pointing solution, extrapolated to current time for each instrument. Although unique to each instrument, the pointing solution format was standardized to facilitate the incorporation of new instruments.

This infrastructure has evolved considerably over the last 30+ years. The mainframe computers and microwave links are now gone. Currently, the Mission Real-Time Engine (MRTE) serves as the real-time engine and the Range Digital Transmission System (RDTS) fiber network provides links to Mission Control from hundreds of points on the range. Both the legacy format and a newer Ethernet-centric format are used to provide pointing messages.

With this latest iteration, the TM antennas are treated as an instrument, meaning that they can be provided pointing, but also their pointing angles could be ingested into MRTE. If three or more antennas are used, the MRTE can derive TSPI for the object being tracked based solely on TM tracking. Further, given the available infrastructure, this means that the TM antenna-based TSPI can be used to point radar, optical tracking mounts, or other instruments. This potential feature has grown in importance recently as the active telemetry signal has allowed TM antennas to successfully track longer range munitions when other instruments have at times struggled.

One of the objectives of the flight testing performed was to gather data to evaluate the TM antenna-derived TSPI and determine what, if any, improvements were needed for the TM antennas to provide quality TSPI measurements. Attempting TM antenna-based TSPI showed once again why it is always best to test out a new capability prior to use.

Several problems were noted during Flights 1 and 2 (5 May). The first was an incorrect coordinate used in the Ant-2 antenna control unit (ACU). The ACUs are interchangeable and, for this particular ACU, which had been previously used for a different antenna location, the coordinates had not been updated. The second problem was the use of different coordinates in the ACU and MRTE for each antenna site. This occurred because survey information is periodically updated and, when verifying the antenna locations, each group used a different version. The coordinates were close but not exact. The final problem, with respect to the analysis of the resulting TSPI, was that the transmitted signal was intentionally made to be less robust to create a challenging environment for the BSS testing being done in conjunction with this test. The coordinate issues were resolved prior to Flight 3 (8 June). The output power of the transmitted signal was also raised, but not to the maximum level as this flight was also being performed for BSS data collection.

The data used for the analysis was the ACU data sent to the MRTE in real-time from the five antenna sites, (Ant-1, Ant-2, Ant-3, Ant-4, and the mobile van). The data sent from each ACU was time-tagged AZ and EL. During all flights, real-time pointing from the MTRE Kalman solution was sent to the mobile van via the legacy format, and the antenna was setup to receive pointing for the entire flight. The antenna operator was instructed only to intervene with the automated pointing when necessary to prevent damage. Although different sources for pointing were used (including TM antenna-based TSPI), the operator reported that the antenna operated smoothly and well within its limits.

The first step in the post-flight analysis was the correction of coordinate errors in the data to the greatest extent possible for Flight 2. Next, the Best Estimate of Trajectory (BET), a post flight Kalman filter, was utilized to process the data and produce a TSPI solution for Flights 2 and 3. These solutions were to compare with DGPS truth source onboard the Caravan being tracked. Evaluation of the residuals produced by the BET indicated that AZ and EL biases exist for all four telemetry sites, and that the biases observed on both Flights 2 and 3 were quite the same. Similar biases on different days are indicative of a constant bias, which could be accounted for. Flight 3 had longer periods of a valid track making the estimated bias accuracy slightly better. The biases for each site were estimated for Flight 3 and then the BET was rerun using these biases. The estimated biases and remaining residual are shown in table 2.

**Table 2. Estimated Antenna Biases for 8 June 2021**

| Site | Estimated Biases | | Residual After Inclusion of Estimated Biases | |
|---|---|---|---|---|
| | Azimuth (degrees) | Elevation (degrees) | Azimuth (degrees) | Elevation (degrees) |
| Ant-1 | 0.954337 | 1.523177 | -0.040821 | -0.012631 |
| Ant-2 | -0.463295 | -2.298401 | 0.238059 | -0.226985 |
| Ant-3 | -0.658404 | 0.434014 | 0.040407 | 0.063456 |
| Ant-4 | -0.094892 | -0.570000 | -0.009790 | 0.138753 |

These residuals indicate that Ant-2 (AZ and EL), along with the EL from Ant-4 still have slight biases. There is a probability that due to lesser than optimal signal strength, the measurement noise may be masking some of the measurement biases.

To assess pointing potential, the BET solution produced for Flight 3 was output relative to the van location. Similarly, the truth (DGPS) was also produced relative to the van location. The data between 19:25:14 and 19:35:19 was used for comparison since, during this time, the tracking performance of the different antennas was good.

The comparison showed the mean difference between the slant ranges was 54 meters and the median difference was 41 meters. The maximum difference was 321 meters, and a minimum difference of 0.05 meters. Comparing the AZ differences from the van to the Caravan, the mean and median differences were 1.7 and 0.1 degrees. The EL differences were 0.59 and 0.12 degrees, respectively. A small period of time (24 seconds) exists where both the AZ and EL from the telemetry had errors up to 12 degrees. This was possibly caused by track quality due to signal strength. The spike shown in Figure 3, just after 70000 seconds, illustrates where this happened.

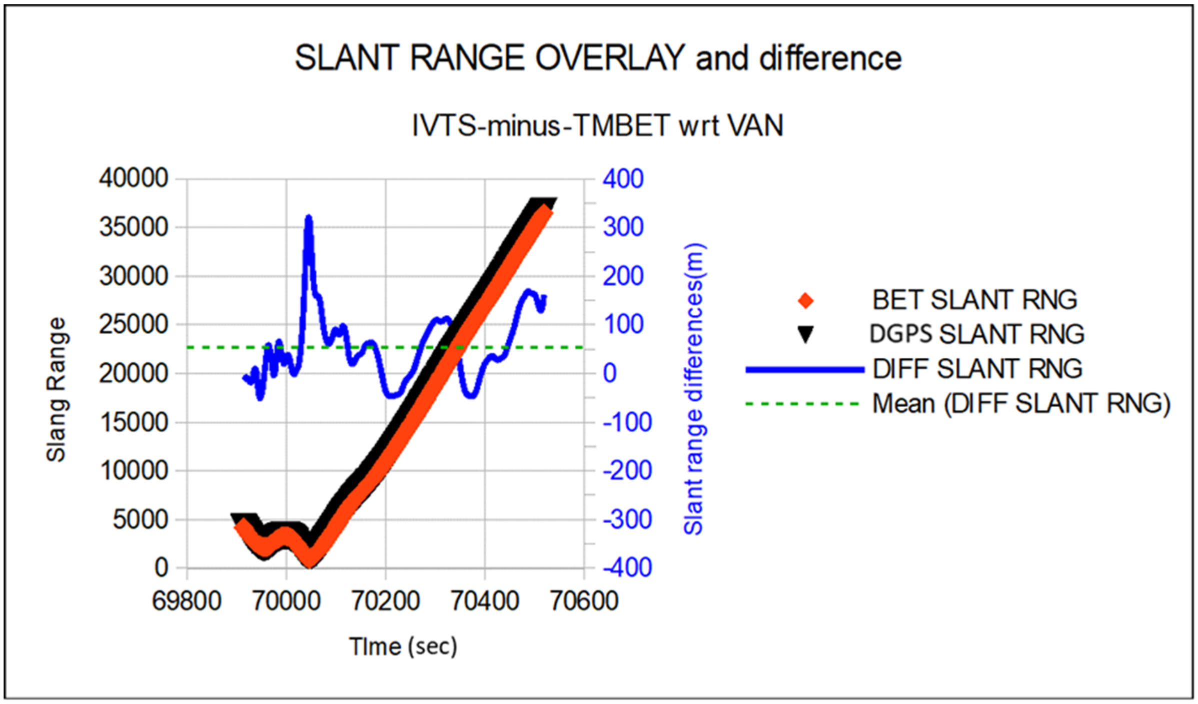


**Figure 3. Pointing Comparison**

A quick comparison was made between the post-processed BET solution and the MRTE Kalman solution. Differences were observed; however, due to incorrect surveyed coordinates, inability to see filter parameter settings used in the MRTE, and Mission Control's inability to calculate or apply biases to the raw measurements, a final determination cannot be made as to the source of these differences and the overall impact to a pointing solution. Time constraints for this paper did not allow for a comparison between the pointing data and where the van actually looked since that was not the primary goal of the test.

Recommendations for moving forward:

1. Develop method to calibrate antenna and apply biases to measurement (AZ, EL) at the ACU.

2. Modify Mission Control/MRTE process to include additional measurements such as the DGPS or other on-board measurements for use in the Kalman solution.

3. Modify Mission Control's real-time output to include a report of the filter settings, coordinates used, any time offsets are applied, and delivery method for pointing to instruments (legacy, new).

4. Work to develop test support procedures for the use of TM antennas as TSPI sources.

## BSS PERFORMANCE

The use of multiple TM antennas to support a test effort also affords the benefit that comes from the spatial diversity. The large geographical difference in antenna locations greatly minimizes the chances that all of the antennas will experience adverse effects such as antenna masking or multipath. To fully realize these benefits, the primary signal must be smartly selected with the optimum methodology being a maximum likelihood bit detector scheme (ref. Rice and Perrins). For the past several years YPG has been increasingly using a BSS to support testing with good results, but did not have a quantifiable measurement of the performance gained from doing so.

As a result, gathering the data needed to quantify BSS performance was an objective of this flight test. In this case, a scenario where the signal received at the various sites would vary in quality was desired to increase the possibilities for the selection of different sites to achieve the "best" signal. To achieve this, a flight path with terrain features that would likely promote multipath was chosen. Furthermore, the transmitter setup of SOQPSK modulation without Low Density Parity Check, using low power and a single antenna, was intentionally chosen to provide a weaker link than possible to increase the likelihood of bit errors.

For this paper, the results from Flight 2 are presented. This flight utilized a PRBS PN11 bit stream transmitted at 10 megabits per second (mbps) and the transmitter power was intentionally reduced from that of Flight 1 to less than one watt to introduce more bit errors. Flight 2 was only flown along Leg A, which had shown the greatest degradation to signal quality of the three legs flown during Flight 1. The net result of all these changes was a very challenging set of input signals being presented to the BSS.

Two sources of data were used to analyze BSS performance. The first was bit error for each antenna site as provided by the receiver loggers. The second was bit error rate of the output of the BSS as logged on a stand-alone Bit Error Rate Tester (BERT). Both of these data sources logged data at a 1-hertz (Hz) rate.

The first thing done was to characterize each individual site by computing the Link Availability (LA) and comparing it to the LA of the BSS output. The LA equation (Eq. 1) used (ref. Temple) was:

$$LA = [(T_M - (\sum SES + LT))/T_M] * (100\%) \qquad \text{(Eq. 1)}$$

Where: TM = measurement period

SES = Severely Errored Second, a one second interval in which the number of bit errors equal or exceed $1x10^{-5}$ as if these errors were random

LT = Lost Time, number of bit periods in the measurement period that are not included in the SES attributed to synchronization loss, BERT overload
NOTE: LT does not include tracking error for this analysis

For Flight 2, given the 10 mbps transmission rate, any one second period that was received with more than 99 bit errors was counted as a SES. During this flight, four events were conducted, where an event was either Leg A being flown from the north to the south (LA) or Leg A being flown from the south to the north (LAR). After conducting the first two events it was determined that, given all the factors at play, the signal strength was too low for consistent tracking. The signal strength was increased but still remained less than one watt.

The BSS selector used has several selectable modes for best source decisions. The primary mode utilized for this effort was the DQE mode. This mode utilizes the Data Quality Metric (DQM) that is determined in the telemetry receiver and encapsulated in its output via DQE for each 4096 bits sent. The DQM is the average quality for all 4096 bits and, given the 10-mbps rate, there are 2441 DQM values per second being sent by each of the five sites utilized. Figure 4 shows the LA for each antenna site as well as the LA for the BSS utilizing DQM.

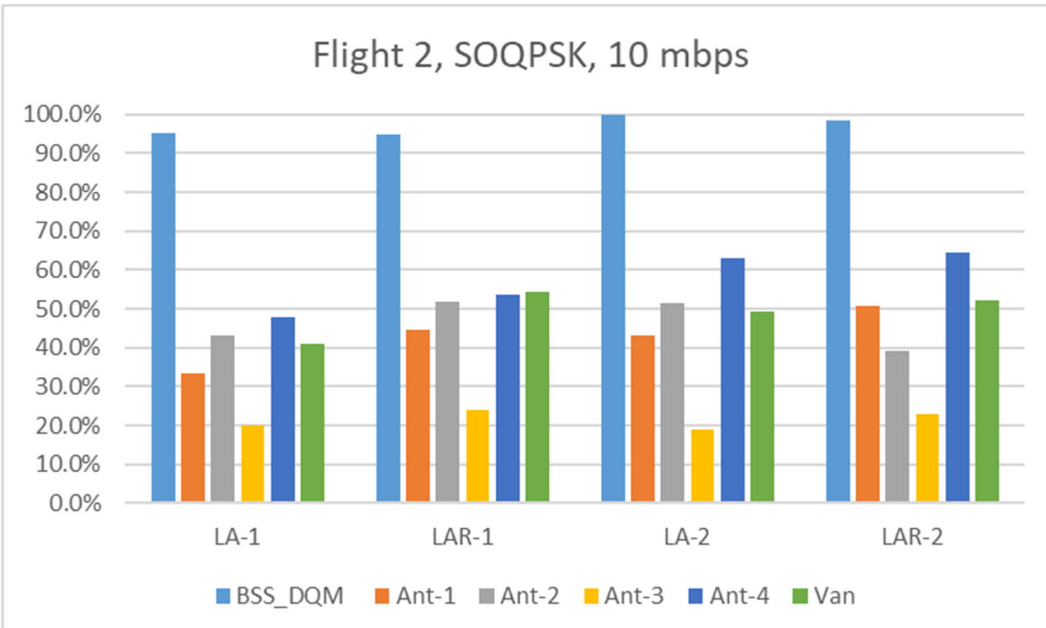


**Figure 4. Link Availability Comparison**

Although the benefits of the BSS to improve link availability was known and had already been put into limited practice, the performance gains demonstrated on this flight showed its tremendous potential. Allowing for the fact that this test had been intentionally constructed to create an extremely challenging signal, the BSS showed a maximum improvement over the best single site of any leg of 47 percent and a minimum of 34 percent. This performance gain would transform an actual test event from a poor quality TM link to an extremely high quality one. For the LA-2 event, a 100 percent LA was achieved by the BSS (a 37 percent improvement over the best single site) using inputs from the various sites that averaged 45 percent LA. The obvious conclusion is to use a BSS and multiple geographically-diverse antennas whenever possible.

Given that the BSS was able to produce outstanding results, the question could be asked if it gave the best possible output? The "best" possible output can be difficult to determine, especially since the truth data was logged at a 1-Hz rate while the BSS was utilizing 2441 DQM values per site per second to make its decision. Still, the advantage of being able to look at the quality of all the sites based on the actual bit errors after the fact and then picking the best site allows for a meaningful comparison of the actual LA of the BSS to the LA based on a post-flight "best source." The results are shown in table-3.

| **Table 3. Real-time BSS versus Post Flight BSS** | | | | |
|---|---|---|---|---|
| Which BSS | LA-1 | LAR-1 | LA-2 | LAR-2 |
| Post Flight Best Source Link Availability | 94.9% | 94.9% | 98.4% | 97.9% |
| Actual BSS/DQM Link Availability | 95.2% | 94.7% | 100.0% | 98.3% |
| **Difference** | **-0.31%** | **0.23%** | **-1.55%** | **-0.37%** |

BSS Input Quality: The next step taken to look deeper into the BSS performance, was to analyze the quality of the input signals going into the BSS. Quality, in this case, is concerned with the actual signal, but only to the extent that the corresponding DQM values accurately reflects the signal quality. This accuracy is of paramount importance since the BSS selection decisions are based directly on these values. For this effort, the use of a PRBS and the receiver loggers provided actual bit errors as well as the estimated bit error probability (BEP) and DQM value at one-second intervals. Using this data, the signal quality could be determined in terms of the actual bit error rate and compared to the BEP for each site. Comparing these two values allowed an assessment of DQM performance since DQM is defined as the log likelihood ratio of the BEP (ref RCC Document IRIG 106).

The approach taken to examine input quality was to plot the actual bit error rate (x-axis) versus the receiver's estimated BEP (y-axis) for each site for each event conducted during Flight 2. These plots show good linear correlation between actual and estimated bit errors. Next, a line of best fit (regression line) was constructed for each set of plotted data and the resulting equation and statistics examined. The ideal case would be a good fitting line, that had a slope of one and a y-intercept of zero as these values would indicate a one-to-one correlation between the actual and estimated bit errors. In order to judge the quality of the regression line, the resulting R-squared ($R^2$) and Root Mean Square Error (RMSE) were examined. The $R^2$ value can range between zero and one and is a statistical measure of how close the data are to the fitted line. The RMSE value is the measure of spread of the resulting residuals, so a smaller RMSE is desired. For all 20 data sets the $R^2$ value was greater than 0.988 and the RMSE was less than or equal to 0.01 indicating excellent fitting lines for all of the cases. The resulting slopes and y-intercepts are shown in table 4.

| **Table 4. Regression Lines Coefficients** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | LA-1 | | LAR-1 | | LA-2 | | LAR-2 | |
| Site | Slope | Y-inter | Slope | Y-inter | Slope | Y-inter | Slope | Y-inter |
| Ant-1 | 0.933 | 0.005 | 0.970 | 0.003 | 0.948 | 0.003 | 0.949 | 0.002 |
| Ant-2 | 1.053 | -0.003 | 1.068 | -0.002 | 1.046 | -0.002 | 1.072 | -0.003 |
| Ant-3 | 0.927 | 0.007 | 0.953 | 0.005 | 0.960 | 0.004 | 0.973 | 0.004 |
| Ant-4 | 0.935 | 0.004 | 0.954 | 0.003 | 1.005 | 0.001 | 1.019 | 0.001 |
| Van | 0.958 | 0.004 | 0.971 | 0.002 | 0.980 | 0.002 | 0.985 | 0.002 |

The resulting coefficients show that the receivers did an excellent job determining a BEP. Remembering that a degraded signal was used, flight profiles were chosen to induce multipath, and that tracking at times was extremely difficult, all of the resulting coefficients were very close to the ideal values. Although not perfect, the results indicate that the DQM values provided with the data bit did a very good job characterizing the signals being input into the BSS. This, combined with the BSS, effectively shows why the LA was so dramatically improved during this test flight.

## SUMMARY

1. A TM antenna-based TSPI solution is possible. Although not designed as TSPI instruments, the utilized TM antennas provided enough precise information to develop a usable solution. More work is needed but the potential is there.

2. Use a BSS and multiple geographically-diverse antennas whenever possible. In addition to the radio frequency benefits provided from the spatial diversity, the BSS helped minimize the adverse effects of different tracking skill levels. Individual skill, availability and other factors will always impact the support that is available for a test program. Use of a BSS can help in these areas as well.

3. Even though a TM antenna-based TSPI solution would be extremely beneficial for test support, this idea should be expanded to include other instruments as well as TSPI information from the test item. Integrated correctly, this source of TSPI pointing would be more robust than any single instrument and would likely be more available as well.

Acknowledgements:

It would have been impossible to conduct the data collection effort that produced this paper without a great deal of help. To the entire YPG team of people responsible for the successful execution of this effort, thank you! There are far too many of you to list, but your hard work and dedication is greatly appreciated. A special thanks to our friends outside of YPG, especially: Kip, Bob, Steve, Roger, Bob, and Terry.

References:

1. Rice, M., & Perrins, E. Maximum likelihood detection from multiple bit sources.

2. Secretariat, Range Commander Council (RCC). Standards for data quality metrics, and data quality encapsulation. RCC Document IRIG 106, Chapter 2, Appendix 2-G.

3. Temple, K. Low density parity check forward error correction for your telemetry link, International Telemetry Conference Proceedings, October 2020.