THEORY AND DEVELOPMENT OF A DYNAMIC HITL AUTOTRACK EVALUATION SYSTEM

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ABSTRACT

Telemetry ground antenna tracking performance evaluation and measurement was previously performed by evaluating only the antenna drive system. The integrated nature of software controlled antenna systems has prompted a need to evaluate the entire tracking antenna system, as a whole. Particularly, the ability of an antenna to remain "locked" on a dynamic target must be able to be evaluated and quantified. This paper presents one method for evaluating the tracking ability of a telemetry antenna system and discusses a likely set of metrics to be used as figures of merit for antenna system tracking performance.

KEY WORDS

Telemetry Autotrack Simulator Antenna Tracking

INTRODUCTION

This paper will present the current state of telemetry system test procedures and the ability of these procedures to accurately determine system level capabilities. A discussion of a potential change to this methodology will be presented. This discussion will be followed by a technical description of a system designed to perform hardware in the loop simulation, providing quantifiable, deterministic results. Finally, potential future development efforts for this system will be presented.

Historically, ground station telemetry antennas are parabolic reflector antennas. The reflector of the antenna focuses the radio frequency (RF) energy at a central location where an RF antenna (feed) is placed. Additionally, the feed creates a tracking signal that is usually modulated on the RF signal. The receiver receives the RF signal from the feed and sends a filtered version of the tracking signal to the Antenna Control Unit (ACU). The ACU interprets the tracking signal and moves the antenna.

Previous generations of antennas performed these tasks using analog circuitry. Modern day antenna designs rely heavily on processor based digital control systems and embedded firmware. This software/firmware determines the drive parameters of the antenna and initiates movement. The analog versions of telemetry antenna systems were fairly easily tested at the component level. Each component could be isolated and stimulated while measuring the response to determine the effectiveness of that particular component. Reasonably accurate assumptions could be made about the ability of the antenna to track a target by making various sub-system or component level measurements. The telemetry antenna as a whole was rarely tested to determine specification compliance or mission acceptability. Recent integration of computing technology into the antenna control loops make isolating components extremely difficult. Also, the previously straightforward assumptions that were made about the effect of component on the entire system are no longer valid, because the newly added software component can apply corrections and alterations at a point after the component function. A significant error or non-linearity in one component potentially could be corrected in the software of the antenna. Additionally, the software itself could cause issues that are only able to be shown by the software developer. As a result of this increase in integration and the addition of computer technology, telemetry antennas must now be tested at a system level to determine mission suitability. This new system level test requirement will create a need for new system level standards, test methods, and hardware.

Previously, the only method of performing a system level operational test was to present the system with an airborne target and have the antenna track a target with the GPS position of the test article and the pointing angle of the antenna (as measured by the antenna) being recorded. Once these two measurements were correlated, a determination of the angle off boresight (antenna pointing error) could be made. This particular test method is very resource intensive and requires access to an instrumented, airborne, test article. Furthermore, the ability of the test to accurately reflect real mission performance is limited by the flight envelope of the representative test article, in relation to the actual mission test article. If, from the viewpoint of the antenna, these do not exhibit similar motion characteristics, a conclusion about the ability of the antenna to track a mission test article can be difficult to reach. In addition to being resource intensive and somewhat limiting in test accuracy, it is very difficult to repeat test points. These limitations make it highly unlikely that flight testing can be used as a long term solution for system level antenna tracking performance measurement, especially when constrained by current budget limitations.

The following sections of this paper present the technical theory and specific hardware used to create hardware in the loop antenna simulation tool that can be used to present repeatable, dynamic tracking scenarios to the antenna at the system level and produce quantifiable measurements of antenna dynamic tracking performance.

SOLUTION THEORY

FIGURE 1 depicts the main component block diagram of a notional telemetry tracking antenna system for this discussion. This antenna system could be a monopulse, e-scan, or conical scan system. All have the same main components shown; an RF feed with reflector, an RF front end and frequency down-convert chain, a receiver to recover a baseband signal, an ACU that takes user commands and/or closes the autonomous antenna pointing loop, and an EL/AZ pedestal servo system to mechanically point the RF reflector with feed.

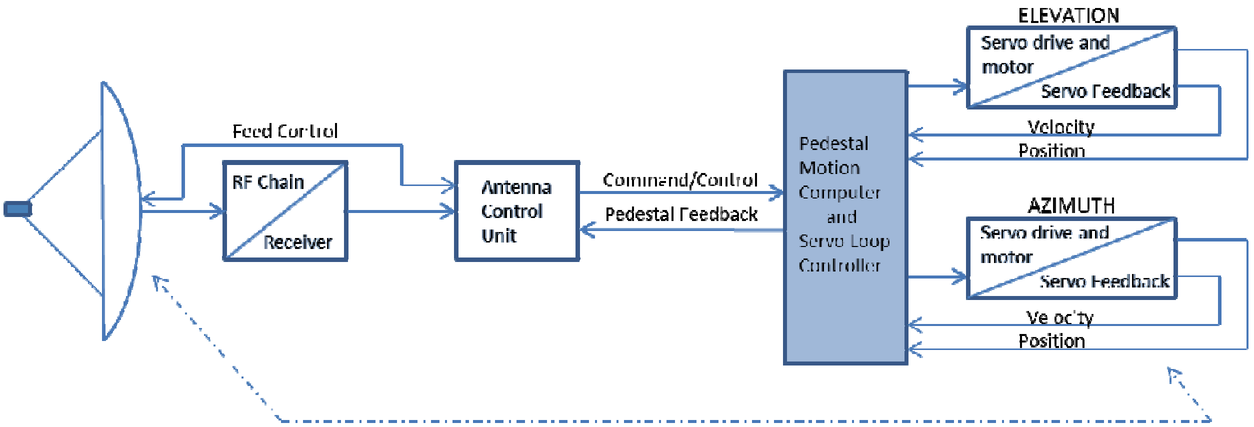

FIGURE 1. Notional Tracking Antenna System

A minimally invasive solution to the problem statement is desirable. The test solution must include as much of the antenna system as possible in order to get an idea of overall tracking performance. The solution approach taken involves attaching an accurate, very low drift and low noise, inertial measurement unit (IMU) to an antenna yoke arm for attitude and attitude rate truth. During actual testing, the boresight camera mount location was used to attach the IMU. The idea is to feed the antenna system a reference trajectory and compare the difference between the commanded trajectory and inertial truth. This difference is used to create a quantifiable tracking error profile, for the given trajectory. Certain conclusions can be made from the collected test data. For example, if the tracking error exceeds the antenna beamwidth, a loss of track would be inferred. This may indicate a shortcoming in the dynamic tracking performance of the antenna system.

One of the concepts that make this approach so attractive is the use of the "stick on" IMU for independent sensing of position and velocity in azimuth and elevation as depicted in FIGURE 2. More will be discussed about the IMU in a later section. For now, recognize it as a sensed motion truth source that can be used on any system whether monopulse, e-scan, or conical scan.

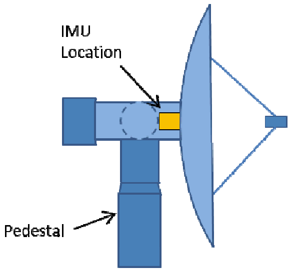

FIGURE 2. Inertial Measurement Unit Mounted in Camera Location

The task at hand is to present a repeatable known target flight trajectory to the tracking system. Having an aircraft, instrumented with the appropriate GPS receiver equipment, fly a predetermined flight path or a series of trajectories may be one way to stimulate the whole system. However, achieving this in a truly deterministic and repeatable way might be precluded due to various technical and logistical reasons, some of which are discussed in the previous section of this paper. Stimulating the antenna RF feed or RF front end with a controlled and synchronized RF signal would be another approach; however, interfacing with the actual antenna reflector-feed interaction to simulate and produce an electrical signal representative and suitable for tracking would be a very challenging task. Potentially, this RF generation simulation method could be a follow on to the research presented in this paper.

For the research presented here, it was deemed more feasible to emulate the baseband signal from the receiver that is input to the ACU. Determining the tracking performance of a conical scan telemetry tracking antenna system was the focus of our effort. The trajectory used for the simulated target can be loaded from a file or real-time trajectory generation equations can be used while the command and control program is running. The output of the custom developed control instrumentation is converted into an analog signal and fed into the ACU as a conical scan signal.

The majority of the actual testing using the Antenna Track Assessment System (A-TAS) system was performed on a conical scan, autotracking reflector telemetry antenna. To fully understand the A-TAS system implementation and the representative results presented, it is important to have a general understand how a conical scan tracking antenna functions. A sufficiently detailed overview of the conical scan function and error signal is beyond the scope of this document. A good explanation of the conical scan theory, as applied to tracking, is given by Skolnik[1]. The basis of the A-TAS system is that it presents an error and top dead center signal, or aligns an error signal to a top dead center signal, so the unit can stimulate the entire antenna control system as if it were the native antenna feed tracking an actual target.

SOLUTION SPECIFICS

The equipment that was developed for the purpose of assessing and characterizing the performance of our telemetry tracking antenna systems is named the Antenna Tracking Assessment System (A-TAS). The main components are a commercially purchased IMU, for determination of inertial angles and angle rates, and a custom developed system control unit housing a National Instrument reconfigurable input/output (cRIO) controller.

Two notable elements stand out that make this approach attractive; the use of a versatile and repeatable digital command track and the use of the “stick on” inertial measurement unit as an external, non-intrusive, truth source. Any desired flight trajectory can be generated to test the dynamic tracking ability of the system. The exact same trajectory can be run any number of times. Alternatively, the antenna pointing angles and angle rates could be taken from the pedestal’s position and velocity sensors, but those are usually not readily available or easily accessible for testing purposes. The external truth source is more attractive since it is an independent truth source. The pedestal’s sensors could, in fact, be part of any performance or tracking issue that may be in question.

Additionally, having the truth source referenced to an earth based reference frame allows for the effects of antenna mount movement (tower sway, vessel movement) to be included in the solution. If the antenna is viewing a distant target, located at the center of the antenna beam (boresight location), and the antenna mount moves; it will appear to the antenna, that the target had moved. A simulator system based on antenna pointing angle sensor feedback would not detect this change, because the antenna has not moved when referenced to itself. The IMU is a truth source that is not referenced to the antenna. It is referenced to an external reference frame. Meaning, when the tower or mount moves, the IMU will detect this movement and generate the appropriate error signal to stimulate the antenna, identical to if the antenna were actually tracking a target.

COMPONENT SELECTION

The inertial measurement unit used for our purpose was actually an inertial navigation unit (INU) from Honeywell Aerospace, the Tactical Advanced Land Inertial Navigator (TALIN^{TM}) 5000. After GPS aided gyro compass alignment at power up, this ring laser gyro (RLG) unit has an attitude pointing accuracy of less than 0.02^{0}, an in-run stability of less than 0.0084 ^{0}/hour. The angular rate dynamic range is given as ±200 °/second.

The reconfigurable flexibility of the cRIO comes from the various input/output modules (analog and digital) that can be easily used in the cRIO chassis. Embedded in the backplane of the chassis is a large field programmable gate array (FPGA) that interfaces with input/output modules to give additional computational and digital logic flexibility. The chassis is mated to a real-time controller having floating point math capability. The cRIO runs in-house developed command and control software written in LabVIEW for the FPGA and real-time controller. LabVIEW is a visual programming language also from National Instruments that is used widely in data acquisition and industrial control applications.

FIGURE 3 shows the block diagram with the A-TAS equipment in place, in the test configuration. The standard communication interface of the TALIN^{TM} is selectable between Mil-Std-1553, RS-422, or RS-232 with output sample/packet rates up to 200 per second. A sample/packet rate of 50 per second (50Hz) was used in our tests to date. A rate of 100 per second will be employed in our final characterization equipment.

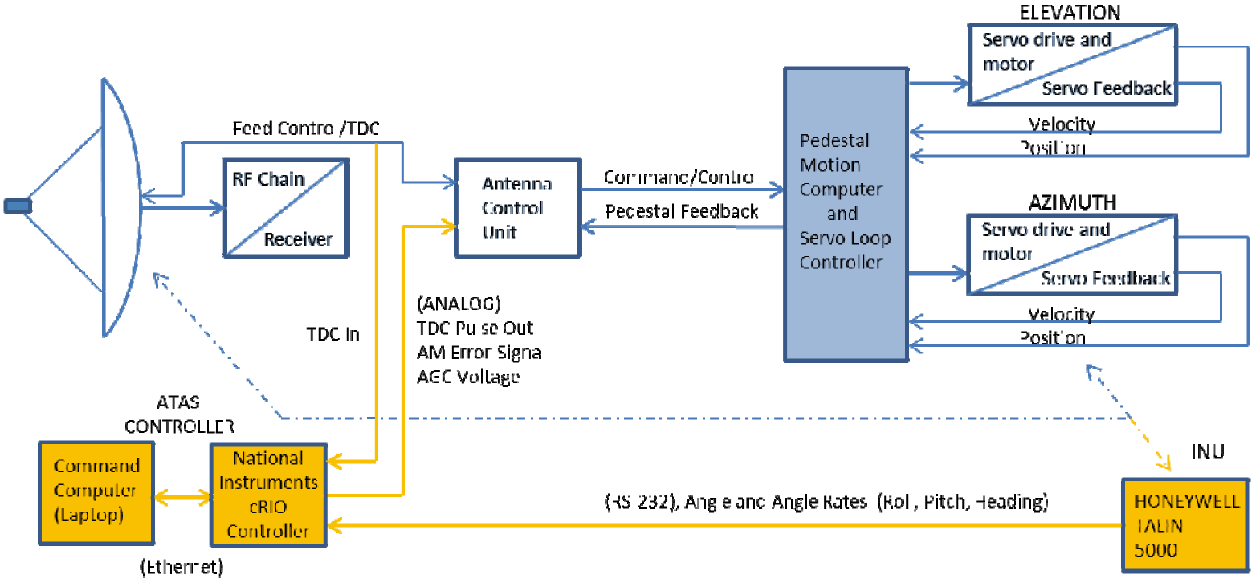

FIGURE 3. A-TAS Equipment in Closed Loop with a Conical Scan ACU

The INU data was sent through an existing RF line through the pedestal rotary joint and down to the antenna control room, where the ACU and custom A-TAS instrumentation were located. RS-232 data format used was used and a high bandwidth 50 Ohm line driver was employed at the INU with very good results. The RS-232 signal looked “textbook” at its destination even after having been pushed over 150 feet down the RF path. The cRIO read and processed the RS-232 INU data in real-time at the stated 50Hz rate.

Once the amplitude and phase of the AM Error Signal are calculated, the parameters were input to a cosine wave generator running in the cRIO chassis backplane FPGA. The output cosine wave generator is, in essence, a numerically controlled oscillator, and was calculated using 32-bit fixed point arithmetic, at an output update rate of 10k samples/second. The cosine wave frequency is the emulated conical scan frequency and could vary from 10Hz to 60Hz as a fixed user input parameter or synchronized to the input TDC pulse.

The A-TAS controller is at the center of the A-TAS equipment. The INU data is input to the cRIO along with the actual feed generated TDC pulse, if needed. The A-TAS controller can generate its own TDC or synchronize to the TDC of the tracking antenna system under test. A computer or laptop PC runs the graphical user interface of the A-TAS controller and communicates via a standard Ethernet connection to the cRIO. The outputs to the ACU are the analog AM Error Signal along with the TDC and an adjustable analog receiver AGC voltage. FIGURE 4 shows how the loop was closed with the INU data.

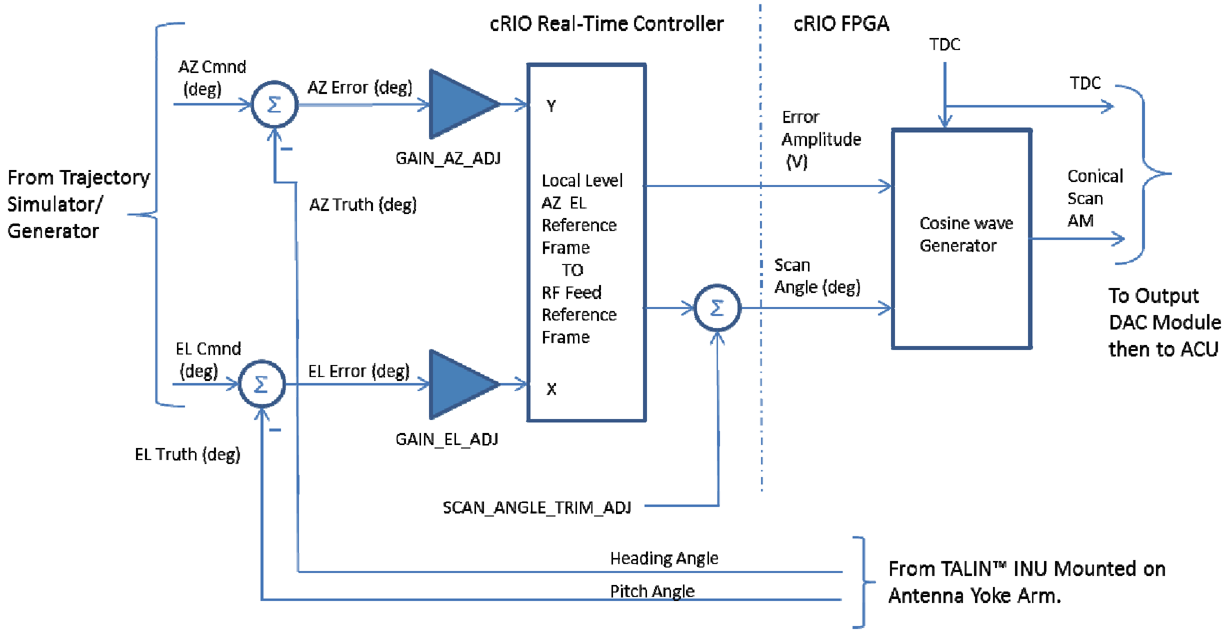

FIGURE 4. Closing the Loop with the INU

ERROR SIGNAL GENERATION AND CALIBRATION

For proper function, the test flight trajectory needs to be decomposed into the local level antenna reference frame azimuth and elevation components to compare with the sensed attitude angles from the inertial navigation unit (INU). The INU mounted on the antenna yoke arm outputs heading, pitch, and roll attitude angles for rates of up to ±200°/sec. An azimuth angle of 0° corresponds to a heading of 0° while an elevation angle of 0° corresponds to a pitch angle of 0°. Azimuth and heading are positive in the same direction, clockwise. Elevation and pitch are positive in the same direction, up from the horizon.

(1)

The error signal, in azimuth and elevation components, was converted to a corresponding AM Error Signal (with phase) by first using a simple rectangular-to-polar conversion. However, the elevation value has to be input as the "X" component and the azimuth value as the "Y" component. This is due to the "zero angle" defined in the standard conversion as being aligned to the X-direction. In conical scan, the zero reference angle is defined in the positive pitch direction that is in the Y-direction graphically speaking. Once the amplitude and phase are found they are used in the simple cosine signal function (Equation 1). The process is given graphically in FIGURE 5.

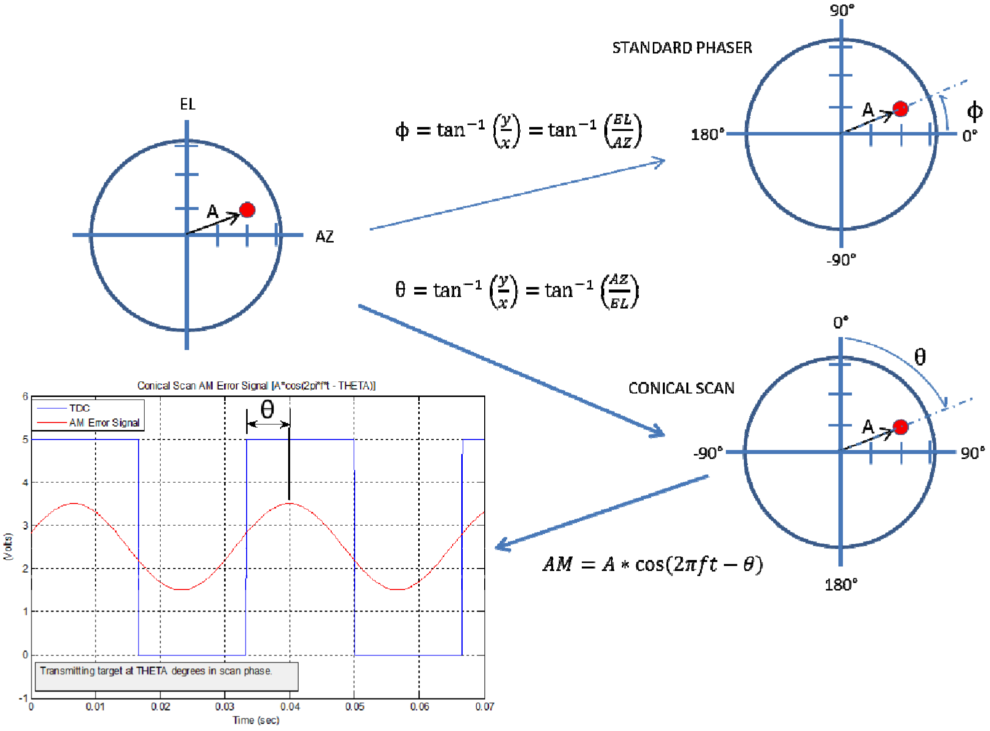

FIGURE 5. AZ EL Conversion to Conical Scan Reference Frame

As mentioned earlier, the peak-to-peak amplitude, A_{pp}, is more intuitive for the vector amplitude parameter since the AM Error Signal is physically created by the difference in received signal strength (Vmax - Vmin). Substituting A_{pp} for A in Equation 1 yields a more appropriate expression for the error signal presented to the ACU. Also, notice from FIGURE 6, that independent AZ and EL gain adjustments, along with a scan angle trim adjustment, was incorporated into the closed loop strategy. These adjustment points were used to calibrate and align the A-TAS equipment with the antenna system under test.

An alignment and calibration was accomplished to confirm that the amplitude (peak-to-peak) and phase (relative to the TDC pulse) the A-TAS controller was outputting, was perceived correctly by the ACU. Basically, while in TRACK mode with servos in STAND-BY, the A-TAS controller error signal was adjusted and trimmed so that a 1° angle off boresight in AZ and/or EL agreed with a 1° angle off boresight in the same direction as perceived by the ACU.

Once calibrated and aligned, a small stimulus signal from the A-TAS controller was presented to the ACU while in TRACK with SERVOS ON to verify the correct phasing of the drive. This was performed with the INU feedback forced to (AZ=0°, EL=0°) in software at the error summing junction so a closed-loop positive feedback could not exist if the phasing happened to be out 180°.

As previously stated, the commanded trajectory ultimately has to be in the local level antenna AZ and EL frame to be compared to the heading (AZ) and pitch (EL) from the INU. The trajectory to be tracked should be generated or sampled with the same sample rate as that of the INU. Using the appropriate rotation sequence, a trajectory can be generated or converted from the (latitude, longitude, altitude) reference frame to the antenna's local level frame, and then decomposed into (AZ, EL, range), in the antenna frame. To obtain quick and intuitive results in the initial effort, the command trajectory used, was generated in the local level AZ and EL frame of the antenna, using simple geometry. The trajectory was straight and level simulating an aircraft flyby at 270 m/sec with a trajectory heading of -90°, flying from east to west. The antenna track started with a northeast pointing angle, tracked through AZ = Heading = 0°. This was primarily done to make the trajectory easy to generate and have the error plots centered about 0° on the X-axis. The simulated trajectory could have taken any azimuth trajectory desired. FIGURE 7 depicts the command trajectory just described.

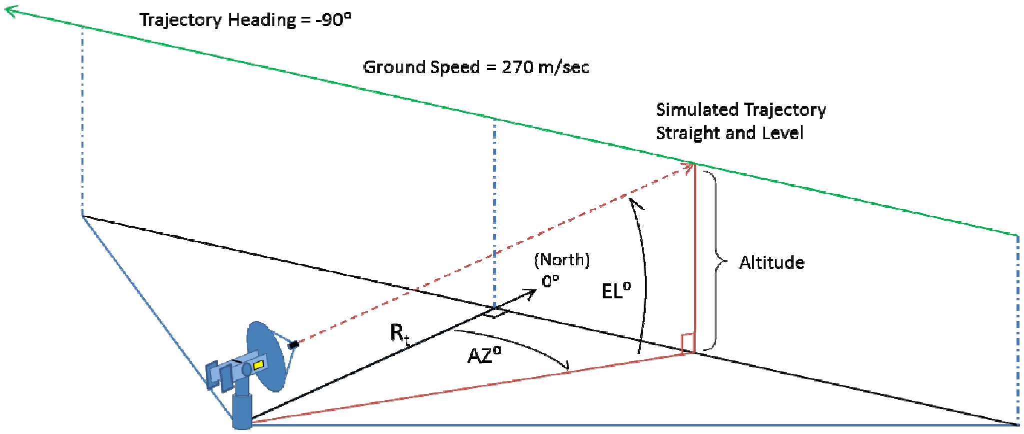

FIGURE 6. Straight and Level Simulated Trajectory

TEST RESULTS

The commanded trajectory based on the straight and level geometry depicted above in Figure 6, is shown in graphical form in FIGURE 7. The trajectory was from east to west passing through AZ = 0° with an altitude of 10,500 ft. The maximum azimuth angular rate was 4.8 °/sec and was reached at the ground projected distance of two statute miles with an elevation pointing angle of 45°.

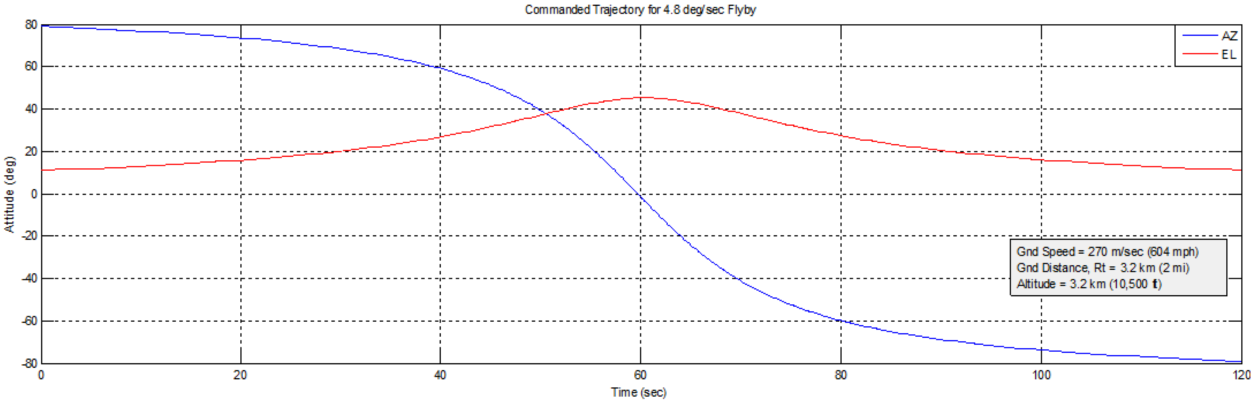

FIGURE 7. Commanded Trajectory for 4.8 (°/sec) in Azimuth Flyby

FIGURE 8 shows a filtered and normalized antenna system pointing error profile over the commanded trajectory for a representative antenna system being assessed. The data shows that the largest error for this simple flyby flight path occurred at the points, in the trajectory, where the angular rates were the greatest. For the azimuth error, this occurred at the closest point of the trajectory relative to the antenna, AZ = 0° north, for this geometry. This analysis data can give insight into the tracking performance of the system. For example, if the actual tracking attitude error is larger than the antenna beamwidth, one would deduce that a loss of track would result and telemetry data would be lost. The A-TAS instrumentation can be used to assess system tracking performance of the entire antenna system to verify specified dynamic performance stated from the antenna system manufacturer.

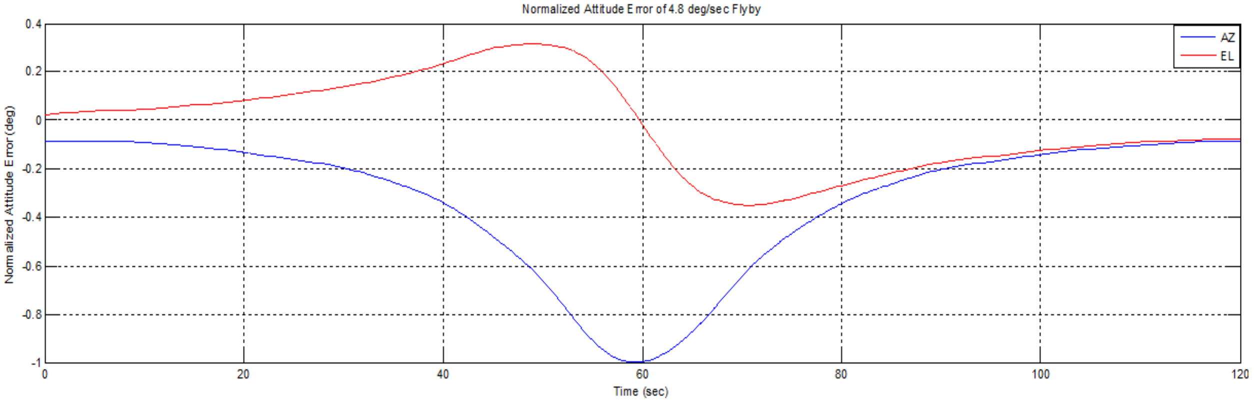

FIGURE 8. Filtered and Normalized Attitude Error for 4.8 (°/sec) in Azimuth Flyby

CONCLUSION

Testing of telemetry systems and the standard measurements associated with those test methods have become largely obsolete. This is primarily because of the complexity added by the inclusion of discrete sensors and digital software in modern telemetry antennas. The inclusion of these components require the majority of testing to be focused on the entire system, specifically focusing on the effectiveness of the integration of mechanical parts with the antenna drive and sensor network, rather than on the performance of each of these individual sub-systems.

For system level tests to be repeatable, standardized, and cost effective, simulators are needed that can stimulate the entire antenna system as if it is tracking a target, while monitoring the antenna motion response. These systems should be able to mimic moving platforms (ship/air borne mount) or detect the resonance and deflection of a tower. Having access to these additional test systems will greatly improve current antenna development tuning and operational calibration. Additionally, these systems can be used to definitively determine what flight profiles pose the greatest probability for the antenna to lose track. These simulators will increase knowledge about the antenna system capability the development and operational environments.

The A-TAS system, as described in the previous sections, has proven to be a very reliable, somewhat easily adapted and very accurate test system. This system and ones like it are prime candidates to fulfill the long term system level test needs presented by the modern telemetry community. These systems could be used to measure system baseline performance and allow maintainers to make informed decisions about overhaul and depot level maintenance timeframes. A system such as A-TAS could be used to determine the suitability of an antenna, or an antenna mount, for migration to an alternate frequency range, such as C-band. Most importantly, simulation/emulation systems can provide a cost effective measurement of antenna performance for specific mission flight scenarios. This quantifiable measurement could lead to more representative specification development and additional test methods and standards required to support the needs of the telemetry community in the new frequency agile environment.

Frequency migration has recently become a major concern for the telemetry community. Particularly, there are several concerns about how well legacy telemetry systems or current iterations of C-band dedicated systems will perform from a tracking/antenna pointing standpoint. Systems such as the A-TAS would be able to aid in assessments of these systems and predict performance at alternate frequency bands. These assessments and predictions could be done long before any expense is spent on modifying the antenna to receive these frequencies.

With growing pressure for the antennas to perform autonomously and the threat of having to track at higher frequencies a better understanding of the telemetry system dynamic tracking performance is a premium concern. Without these necessary tools the telemetry community will continue to incur increased expense and development delays associated with navigating the upcoming technical challenges. The A-TAS system and similar systems can be very powerful tools that the telemetry community can use to produce systems that will meet the challenges posed by current migration efforts and modern telemetry system design. These simulation systems will provide a much needed characterization of current capability and have limitless potential to improve the capability of both current and future antenna system designs.

REFRENCES

Skolnik, Merril, “Tracking Radar”, Radar Handbook, 2nd Edition, McGraw-Hill, Boston, MA, 1990, pp. 18.3-18.8