Radeus Labs

Series 9000 Antenna Control System

Description and Monopulse Tracking Test Results

ABSTRACT

The Radeus Labs Model 9000 Antenna Control System (ACS) is a modern, state of the art antenna control system for use in high end satellite tracking antennas, particularly with narrow -3dB beamwidths. Typical systems would include two or more motors per primary axis which must be torque managed and also typically include monopulse tracking capability. This paper provides a background and overview of the actual monopulse tracking performance for a 13-meter, C-band antenna system fielded in the spring of 2021 using the 9000 ACS. Tracking results are provided for three separate satellites, confirming the tracking capabilities of the Radeus Labs Model 9000 ACS.

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Monopulse Background

Monopulse Radar Background

The terminology *monopulse tracking* used for satellite communications actually comes from a target tracking method developed for pointing radar antennas. The term *monopulse* refers to a method of transmitting a single pulse of RF energy and then waiting for the echo return of that pulse at the receivers. The receiving system would consist of 4 horns which would combine the received signal in such a way that from the single return pulse the tracking system could determine both direction and distance to the target.

Monopulse for SatCom

For monopulse in satellite communications there is no transmitted pulse, only a received signal transmitted from the satellite, but the name *monopulse* is still used to represent the tracking methodology. The 4 or 5 horn configuration is valid for satellite communications.

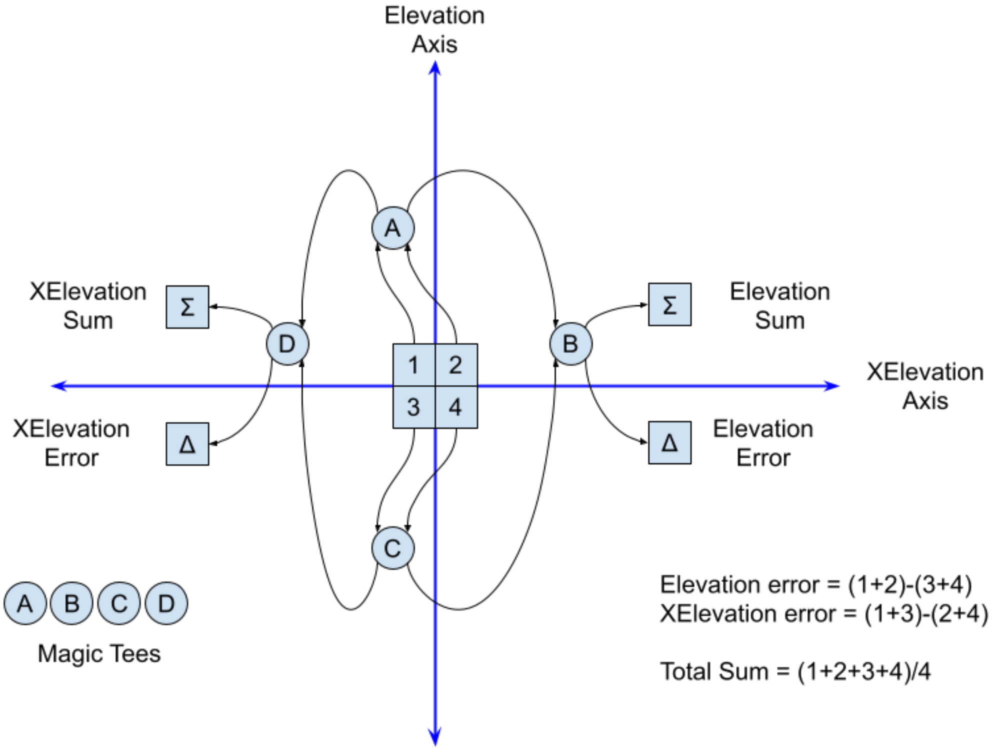

Figure 1: Monopulse 4-Horn Feed

A second common approach used for monopulse tracking in satellite communications is to add a TE21 coupler to the communications (COMM) feed network. There are other types of couplers that can be utilized for monopulse but the TE21 with 8 coupling slots is most common as it provides good results for tracking both Circular and Linear polarized downlink signals. Tracking is performed similarly to the 4 horn while minimizing the loss of signal on the comm channel.

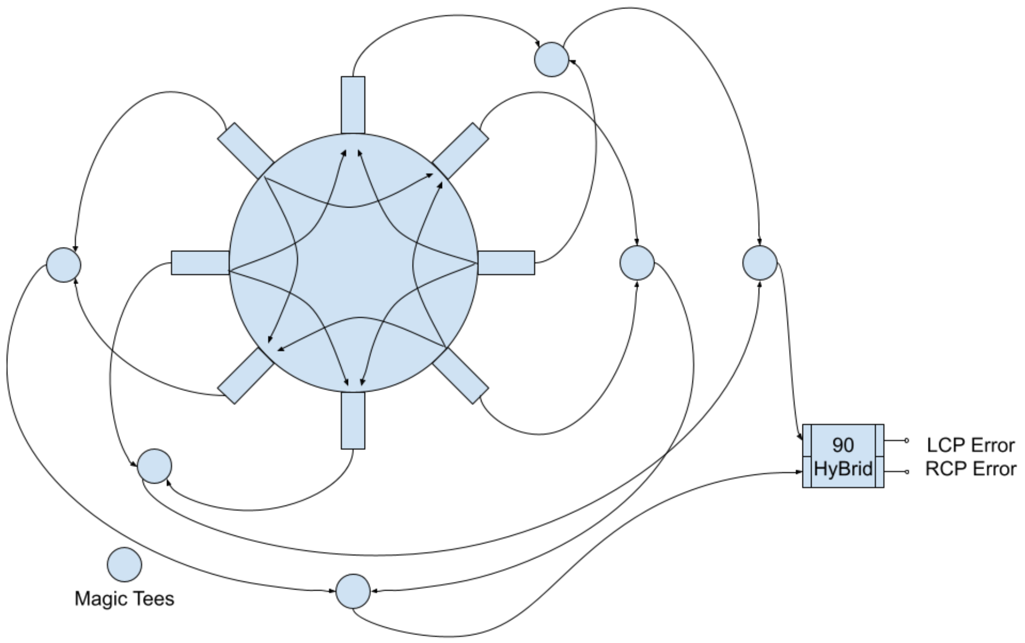

Figure 2: Monopulse TE21 Coupler

The TE21 hardware is a circular device. It can be utilized for receiving both Linear and Circular polarized signals from a satellite. When used for tracking a linear polarized signal (Horizontal or Vertical) both signals will be accessible on either "error" port from the 90 degree Hybrid. However when tracking Circular polarization then one port will be Left Hand CP and the other will be Right Hand CP. It is always important to verify that the error ports are properly identified.

When the feed system consisted of 4 horns for reception the horns were often mounted to align with the Elevation and X-elevation axis. The nice result of this is the two error signals come out exactly on the EL axis and the XEL axis.

With the TE21 coupler that alignment is lost. It is possible to configure (rotate) the coupler into a position where the output errors are aligned with EL and XEL moment but it is not always practical. For one the error coupler is often large and heavy. The other issue is the alignment will change with a frequency change. So most of the time the error coupler is fixed and only the feed horn moves if the signals are linear and Horizontal/ Vertical polarization adjustment is required to optimize signal levels. This means that a means to calibrate the tracking signal errors to the axis motion is needed in the control system.

Monopulse Tracking Signals

The goal of the TE21 coupler network is to create an "error" channel pattern. That is a pattern that is nulled exactly below the peak of the sum (reference) channel pattern.

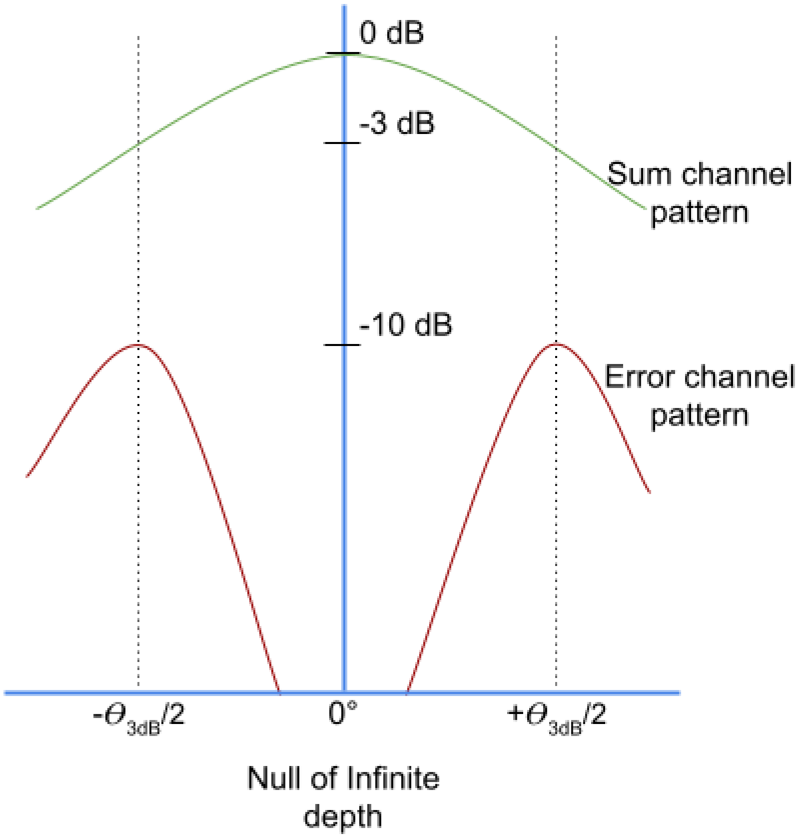

Figure 3: Monopulse tracking error channel null (RF power in dB)

In operation as the horn aperture becomes larger, the “reference” (sum) channel pattern becomes narrower, and the “error” channel pattern peaks come closer together. As such the slope of the pattern toward the axis will become steeper. The sensitivity of the error pattern will increase as the slope into the null increases. The logarithmic “db - scale” would theoretically show an on-axis null of infinite depth with respect to the 0 dB reference pattern maximum. In practice the on axis value for the null will reach a measured depth of only 40 or 50 db below the reference pattern peak.

The error pattern is interpreted by the monopulse tracking receiver as a voltage pattern for use as a tracking reference. As the target moves off axis the receiver generates the relative error voltage used by the drive system to return the antenna to the “on target” position. The error pattern passes through zero volts at the null and changes sign. Thus a monopulse tracking system is not actually tracking to the peak of the reference (or Sum) signal, it is tracking to the null of the error signal as represented by the zero voltage point. The depth and location of the null of the error signal will vary depending on the accuracy of construction of the feed. Sometimes the null is shifted slightly off of the reference peak. The feed test data should indicate this shift and magnitude.

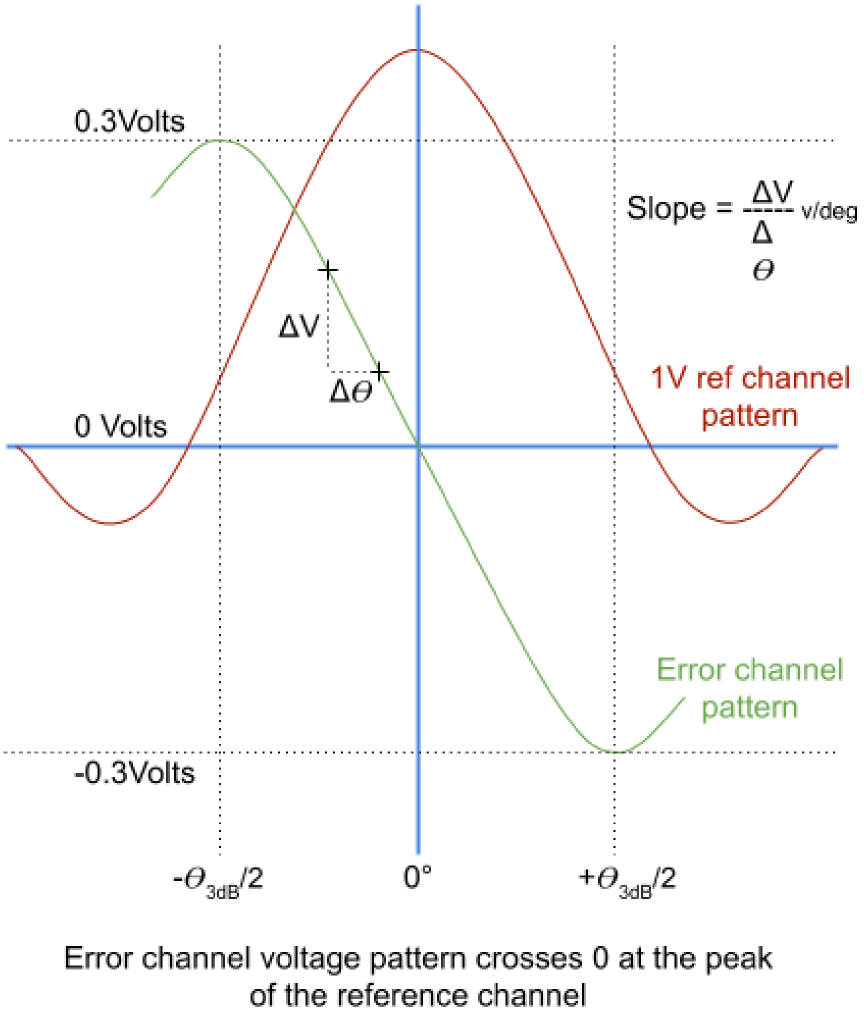

Figure 4: Tracking signal in Volts

Two Channel vs. Single Channel

There are two approaches generally available in the market to create tracking information from the sum and error outputs. The 9000 monopulse system supports both approaches.

The older approach is to use two receivers, one for each signal sum and error. Depending on who you talk with this approach is "Monopulse" or also known as "Two Channel Monopulse" tracking. The second approach is to combine the sum and error signals, while manipulating the error signal with a phase shifter and then only use one receiver to recover the signal. This approach has been called "Pseudo-Monopulse" or "Single Channel Monopulse". From a performance point of view the single channel can have a slower update rate but often tracking accuracy to null is comparable with the two-channel receiver tracking. Both approaches can utilize the TE21 coupler.

Two Channel Monopulse

The two channel receiver is a term that indicates that at a minimum there is a receiver for the reference signal and a separate receiver for the error signal. There may be more receivers as there are often two reference signals available. It is also possible to “track” polarization in a linear system when the target is in inclined operation.

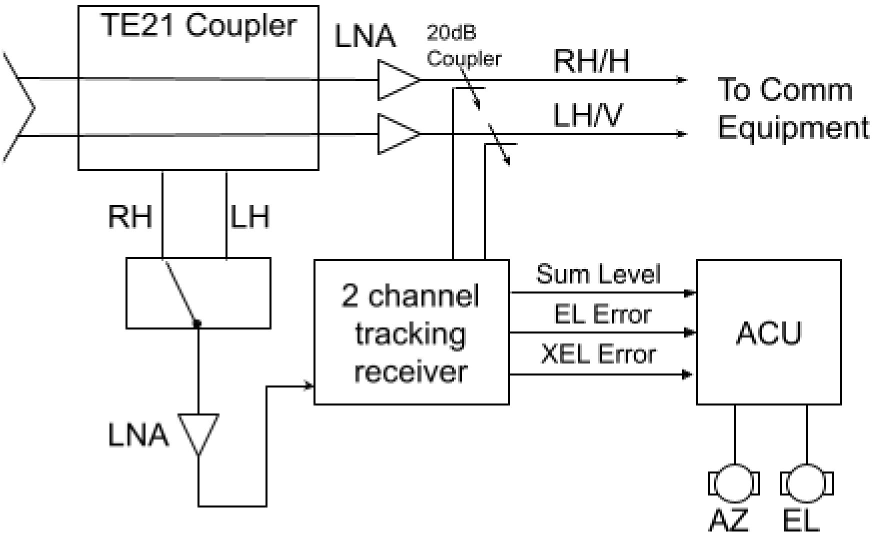

Figure 5: 2-Channel Monopulse System Diagram

In a two channel system the error channel receiver must be able to output a signal level at very low input power levels. For example if the input Sum level is -90 dBm power input levels the error signal at “null” could be about -140 dBm. Normally a very narrow resolution bandwidth will be needed to achieve these measurements along with a very low residual FM. With the receiver operating with a narrow resolution bandwidth (<1kHz) for a very low signal any drift of signal frequency could cause the signal to be lost - and the error recovery would not be able to detect it. Normally the lock of the receiver on the reference signal is used to also drive the tuning of the error receiver.

For two channel tracking the tracking slope is defined by the output of the TE21 coupler. Because of that the tracking slope is fixed. The manufacture of the monopulse tracking receiver defines the method of calibrating the receiver to the feed for operation.

Generally, it consists of:

1. pointing the antenna at a target which could be a bore site tower or a satellite with minimal motion.
2. peak the reference signal to get near to error signal null.
3. then adjust pointing to minimize error signal - this becomes the reference peak location
4. Move the dish off target in one axis only a prescribed distance - this sets signal level change to distance and also sign adjustment.
5. Return to ref peak location
6. Move dish off in the alternate axis a prescribed distance - set signal level change for distance for second axis along with sign adjustment.

Single Channel Monopulse

For single channel monopulse there is only one operational receiver that will be recovering signal power from a combined “synthetic” beam.

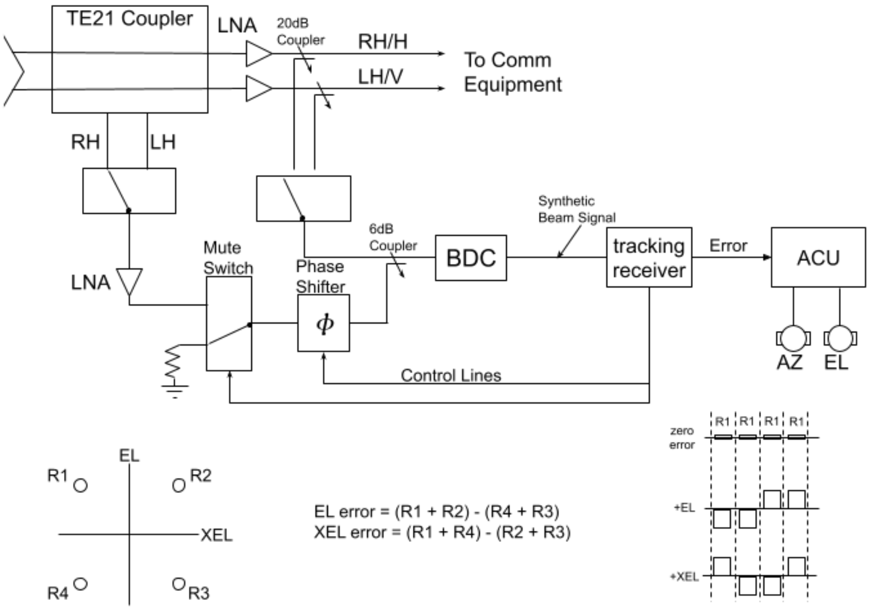

Figure 6: 1-Channel Monopulse System Diagram

The monopulse tracking feed is equipped with a TE21 mode coupler to supply error pattern signals to a track channel. This coupler produces an error output signal with amplitude proportional (to the magnitude of the arrival angle of the signal) and relative to the line of sight of the antenna beam. The phase of the error signal relative to the phase of the sum signal is proportional to the direction of this arrival angle relative to the rotation position of the feed. For example, with proper phasing, the error signal can be made to be in phase with the sum signal for an AZ error to the right and it will be 180 degrees out of phase for an AZ error to the left. At the same phasing, the difference might be 90 degrees for an "up" error and 270 degrees for a "down" error.

If the error signal is phase shifted and combined with the sum signal, the peak of the composite signal is shifted relative to the antenna line of sight in the direction where the error signal and the sum signal are in phase. The phase shifter affects this direction. With the phase shifter commanded to zero phase shift, the rotation direction of the peak is determined by the net phase shift between the sum channel path and the error channel path. This net phase shift is referred to as the reference phase.

For monopulse tracking utilizing this arrangement, the tracking receiver will command the phase shifter through repetitive cycles of 0, 90, 180, and 270 (and back to 0) degrees. This action generates a (synchronously modulated) scan pattern; the pattern is a square in the plane normal to the antenna line of sight. The sum and difference patterns and the relative gain between the sum and difference channels determine the size of the square. So by changing attenuation in the sum path before combining with the error path the tracking slope can be adjusted. The orientation of the pattern in rotation about the line of sight is determined by the reference phase defined above.

It can be shown that the reference phase establishes the rotation of the scan pattern about the line of sight, e.g., a given reference phase might place the beam position with the 0 degree output at 37.5 degrees CCW from horizontal to the right. A 100-degree change in the reference phase would then place the beam at 137.5 degrees CCW from horizontal or at 62.5 degrees CW from horizontal. Accordingly, the correction for the reference phase is simply a coordinate rotation that is a function of the front-end configuration and the track signal frequency.

A calibration procedure (which can be performed while the communication system is on-line) is needed to determine the value of the reference phase correction and the effective scan pattern size for each configuration. The calibration results should be stored in the ACU in a database that also logs RF path and tracking frequency. Calibrations are unique to each frequency/RF path configuration.

Synchronous demodulation of the signal level variations produced by the scanning of the synthetic beam is performed in the tracking receiver. This demodulation process not only provides the required two orthogonal error signals, it also performs a very effective filtering (signal variations with a frequency significantly different from the scan frequency will have little effect). The demodulation process is performed by software after application of the corrections described above for both net gains between the sum and difference channels and the loss variations from the phase shifter. After the demodulation, the coordinate rotation for reference phase and the secant correction of the AZ error signal is performed and the results are routed to the ACU for AZ and EL antenna corrections.

Monopulse Tracking vs. Step Tracking

The most commonly used method for tracking geostationary satellites is step tracking, not monopulse, due to its relatively low cost.

Step tracking is a simple, and intuitive, approach to periodically peaking the antenna on the target using relative RF signal level measurements. In a step track system, the antenna controller moves the antenna by a known step size, measures the relative signal level delta before and after the step, and uses the approximate shape of the antenna beam to calculate the target location. The step tracking method trades off the complexity and cost of the monopulse system for a relatively simple and inexpensive system at the expense of tracking accuracy, increased signal loss and more stringent target limitations.

Step tracking provides lower accuracy compared to monopulse tracking for two reasons:

1) The RF measurements in a step track system are made off of the main signal beam (the sum signal of a monopulse system). Unfortunately, the sum signal has a very flat curve close to the peak and often the signal noise level exceeds the relative measurements that the step track system can make for calculation of the target location. This is in sharp contrast to the high tracking slope of the monopulse receiver, all the way into the exact peak of the target.

2) The step track operates slowly and only on intervals. Due to antenna dynamics, signal noise levels and other system design factors, step track systems typically operate slowly. It can take a minute or more for a step track cycle to complete and arrive at the approximate peak location of the target system. Additionally, since the step track algorithm necessarily must step off of the peak to make measurements, the tracking process itself creates the very signal loss that it is attempting to minimize. Due to this tracking

loss, steptrack systems generally wait several minutes at least between peaking algorithms. By contrast, a monopulse system operates on a much faster, approaching continuous, update rate and does not require deliberately moving away from the target to maintain an accurate peak position.

Due to these factors a step track system is typically offered with a stated accuracy of 10% RMS of the 3dB beamwidth compared to a typical monopulse accuracy specification of 3% RMS. Additionally, the 10% accuracy is limited to relatively slow targets and benign wind conditions while the monopulse tracking system can maintain good accuracy for fast moving targets in the presence of wind induced antenna deflections.

In addition to the monopulse RF system, a more advanced control system than is typically found on step track systems is needed to take advantage of the accuracy and speed gains of the monopulse tracking approach. The 9000 series control system is designed to get the most out of the capabilities of antennas fitted with monopulse RF systems.

Series 9000 System Overview

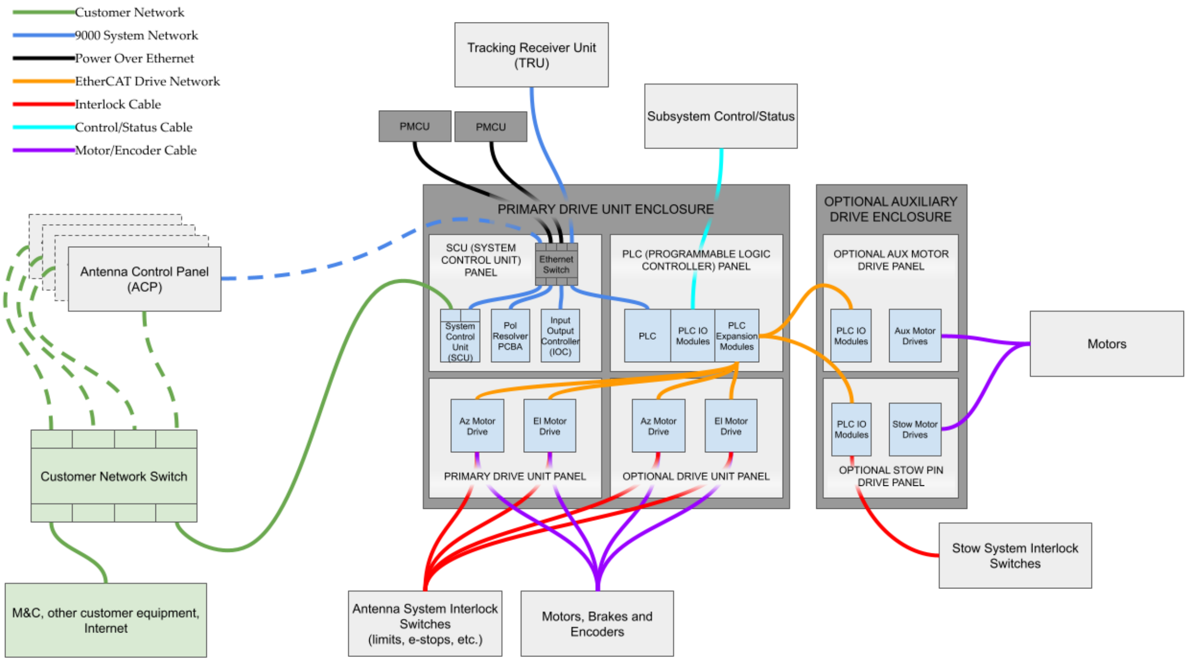

Figure 8: 9000 System Diagram

Antenna Control Panel (ACP)

The ACP is the primary control interface for the 9000 system. It is a graphical user interface with a touchscreen and optional keyboard and mouse. The ACP is provided in a rack mounted configuration for easy integration into the customer's control center.

Up to 4 ACP's may be connected to the system for control and monitor points at convenient locations on the customer's network.

System Control Unit (SCU)

The SCU is the primary control unit in the system running most of the tracking logic as well as monitor and control of the various control subsystems.

Antenna Control Unit (ACU)

ACU is a legacy term, there is no single device in the 9000 system known as the antenna control unit, however, ACU is sometimes still used to refer to the system as a whole or parts of it.

Drive Unit

The 9000 Series Drive Unit is designed based on modular panels that can be mounted in a standard control cabinet style or a rack mount style. A standard Drive Unit contains 3 or more standard panels:

- SCU (System Control Unit) Panel – contains interfaces for the system wiring, the main system circuit breaker, contactors for 3-phase power cutoff, Ethernet switches, DC power supplies and circuit boards.
- PLC (Programmable Logic Controller) Panel – Contains interfaces for the system wiring, the Pol Motor and Warning Horn/Light circuit breakers, DC power supply, relays for safety logic, and a PLC with IO modules for controlling the motors and IO functions.
- Drive Panel 1 – Contains an Azimuth and Elevation servo motor drive unit along with associated circuitry.
- Drive Panel 2+ - Contain optional additional servo drive circuits for Azimuth and/or Elevation.

Servo Motor Control

Servo Control vs. Bang-Bang Control

Step track control systems often have what is known as a bang-bang control system. What this means is that the motors are either on or off but there is no variable control of the motor speed or direct control of the motor shaft position. A bang-bang control system must operate at relatively low motor speeds to achieve accurate position and thus a trade off is necessary between operational effectiveness and pointing accuracy. If the motor speed is too slow and the controller will not be able to make necessary motions in a reasonable time but if the motor speed is too fast then the controller will not be able to achieve the necessary accuracy for the system. The resulting compromise is generally suitable for step track systems up to a limit of accuracy, frequency, size and speed but once these limits have been surpassed a true servo motor control system is needed.

The 9000 system utilizes a feedback control system (servo motor control) for precise position and velocity control of the antenna’s Az and El motors. In a feedback control system the motors are equipped with encoders mounted directly on their shaft allowing the shaft position and velocity to be accurately measured and controlled by an advanced control system. This motor shaft control is in addition to the position feedback used to control the actual position of the antenna axis. The 9000 system utilizes proportional-integral control loops in the PLC for both the position and velocity control. Torque control is managed within the motor drive unit itself.

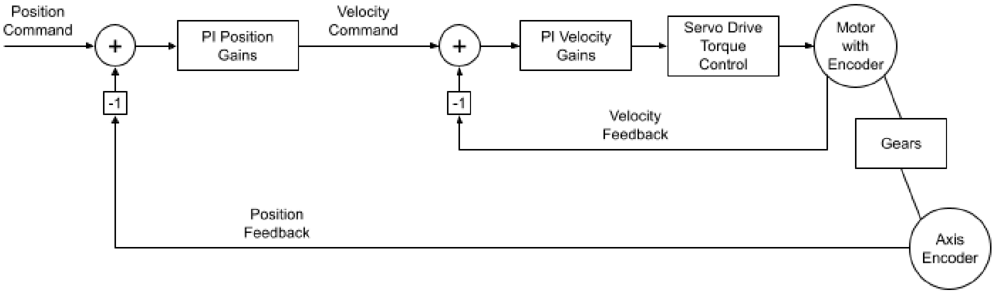

Figure 9: Simple Servo Control

Dual Motor Servo Control

The simplified diagram shown in Figure 9 works well for systems that require limited accuracy but due to errors introduced by the gears (primarily backlash and wind up) the system cannot translate the precise motor velocity control into precise axis control. In order to solve this problem for antennas requiring high accuracy the antenna is often fitted with a set (or more) of two motors in a torque biased configuration. Torque biasing on the final drive gear allows the system to eliminate most of the inaccuracies introduced by the gears.

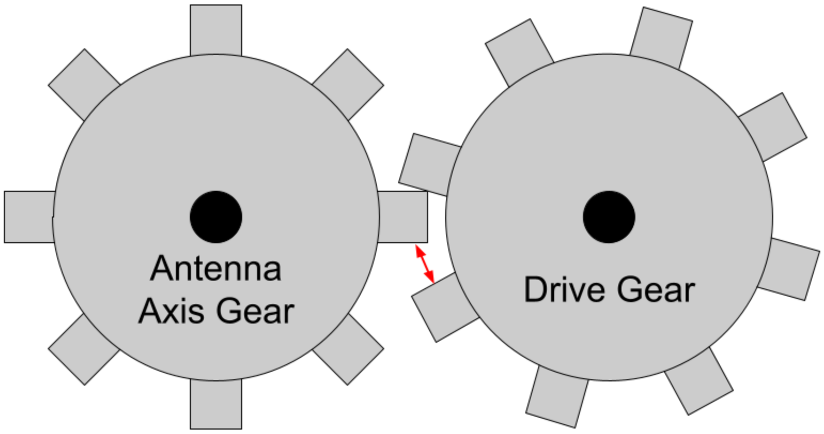

Figure 10: Single Motor Backlash Illustration

In a drive system with backlash the drive gear has a gap on one side of the teeth when meshed with the axis gear. This causes the axis gear to not be driven when the drive gear is changing directions. It also allows the antenna gear to coast or be moved by external disturbances in the direction toward the backlash in a way that the drive gear cannot control. The result is that the accuracy of the motor controller in positioning the drive gear cannot translate fully to accuracy on the axis.

To accommodate this backlash, a single motor system uses a position deadband that is larger than the gear backlash so that the control loop gain is reduced when within the deadband of the target position. This prevents the phenomenon of limit-cycling which is when a control system oscillates back and forth across a non-linearity in the system, in this case the gear backlash.

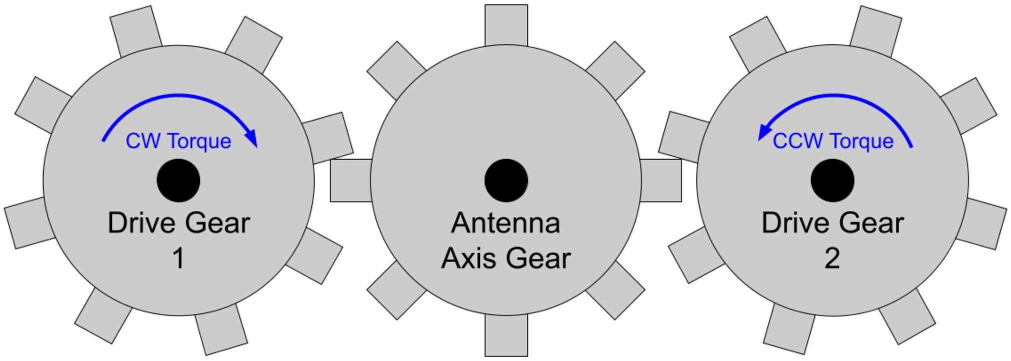

Figure 11: Dual Motor, Backlash Elimination Method

In a dual motor drive system a second drive gear is added. The control system applies a torque to the second gear that is biased against the torque applied by the first gear. This means that there is direct contact from the antenna gear to one drive gear or the other in both directions of rotation. This biasing effectively eliminates the backlash of the gear system allowing for highly accurate control of the axis gear by the motor control.

The position deadband in a dual motor system is set significantly lower than in a single motor system and is used more to establish the reasonable limit of control accuracy than to prevent limit cycling. In a typical system the position feedback resolution is 0.001 degrees and it is not necessary to control the position much more accurately than this. However, the deadband can still be set to lower numbers if required by the application.

In order to control the two motor system, the control system must become more complex when compared with a single motor system.

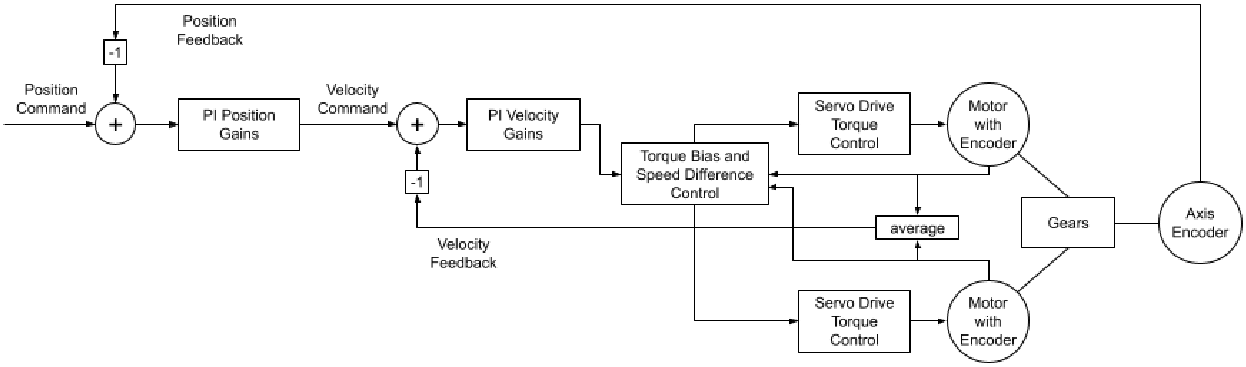

Figure 12: Dual Motor Servo Control

The design for controlling two motors still includes a single position command and velocity command with their associated PI loops but now it requires a torque bias and speed difference controller as well as using the average motor velocity as the velocity feedback. The torque bias and speed difference controller ensures that a bias is maintained to eliminate backlash and that the two motors drive in a stable manner, not fighting each other or resonating energy between them through the gear coupling.

Monopulse Tracking Receiver

The 9000 system supports the use of a newly installed monopulse system from ECA, the CTR-70 with Tracking Downconverter.

The 9000 system can also be tailored to support many legacy systems with existing monopulse receivers provided the interface data is available to interoperate with the existing equipment.

Monopulse Tracking Design

Monopulse Target Acquisition

Tracking a monopulse target consists of acquisition, peak detection, autophase adjustment, and tracking:

- Acquisition of a monopulse target can be performed using Move to Look Angles, Move to Longitude, TLE (SGP4, or IESS.
- Peak detection is performed using a cross scan to minimize the monopulse error vectors.
- Autophase adjustment is performed using the built-in feature of the monopulse tracking receiver, if equipped, or by adjusting receiver parameters to minimize phase errors that could degrade monopulse tracking performance due to temperature changes at the ground station.
- Tracking is performed by following the error vectors received from the tracking receiver to continually maintain a peaked condition on the target.

Monopulse Target Tracking

For all of the complexity that goes into receiving, transforming, acquiring, phase adjusting and calibrating the monopulse tracking signal – once it is complete the actual tracking is surprisingly simple. The tracking error signals represent the distance from the current angle on each axis to the peak location. Due to noise and other errors in the system this is only an estimate and requires filtering.

The 9000 monopulse position estimation function consists of two filters:

- Error Vector Filter
- Estimated Position Filter

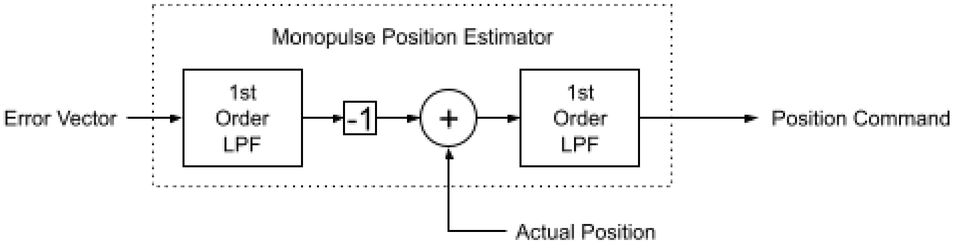

Figure 13: Monopulse Position Estimator

Filtering the error vector reduces noise but will increase pointing errors due to decorrelating the vector from the actual pointing angles in time. Note that the error vector filter is applied before the error vector is subtracted from the actual position. Due to this, a relatively high cutoff frequency is recommended, typically 1-2 Hz.

The estimated position filter is applied after the error vector is subtracted from the actual position so it is correlated to the position signal and does not cause the same pointing errors as the vector filter, however it will cause the estimated position to lag behind the actual target so it should be set with the expected target velocity in mind. Typically 0.5-1.0 Hz is a good value.

These are both single order low pass filters of user selectable cutoff frequency. The cutoff frequency represents the frequency where the input signal is attenuated by 3dB. Frequencies above will be attenuated further. In time, the cutoff frequency (Fc) corresponds to what is called a time constant (Tc): Fc(Hz) = 1/(2πTc(s)). The time constant, in practical terms, is the time the output takes to rise to 63% of the input value in a step function. The output reaches 95% of the input value after three time constants.

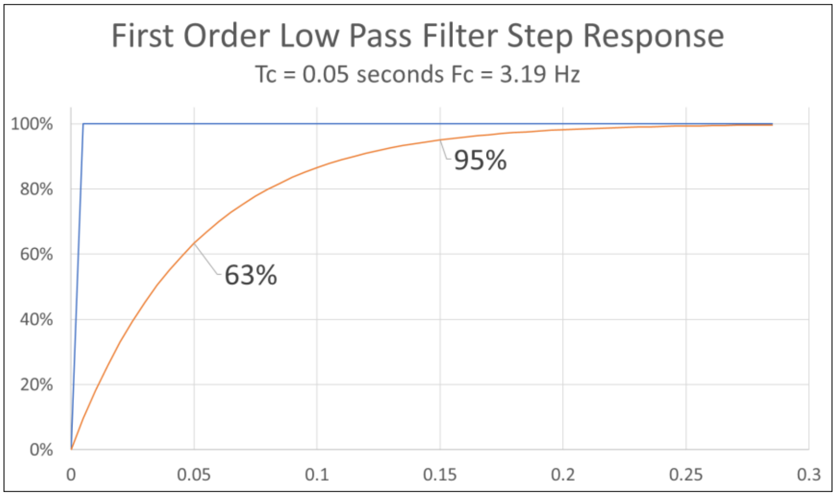

Figure 14: 1st Order Low Pass Response

When setting the value of the estimated position filter the operator should consider how fast the target is moving, the noise level in the measurements and how much tracking error is acceptable. Often it is easiest to determine the optimal values by experimentation.

First Order Low Pass Filter as an Optimal Estimator

Reference *Tutorial on a very simple yet useful filter : the first order IIR filter*.

Monopulse Tracking Test Methodology

Monopulse Tracking Test Objectives

The objective of the tests discussed in this paper is to establish the tracking accuracy performance of the 9000 series control system in monopulse mode. There is no discussion of errors introduced by the antenna itself because the antenna performance is not what is under discussion. Therefore, errors strictly existing in the construction of the antenna are not considered such as misalignment between the error channel null and the sum channel peak, orthogonality of the azimuth and elevation axes, non-linearity in the position encoder’s pickoff point, etc.

The monopulse tracking accuracy requirement is 3% RMS in 45 mph winds gusting to 60 mph. Since the test is performed on a live system, as opposed to simulation, the actual wind conditions are not under control of the test and assumed to be relatively benign.

Monopulse Receiver Used in the Test

The monopulse tracking receiver used in these tests was a CTR-70 with a C-Band Tracking Downconverter from ECA.

Antenna System Used In the Test

The monopulse results discussed in this paper were obtained using a 13 meter C-Band antenna in Vernon Valley, New Jersey. The antenna system was originally installed in 1998, the motors and gearboxes are old and not in ideal condition, however, the antenna is equipped with two motors on azimuth and elevation so is a good candidate for monopulse testing. The 3dB beamwidth is approximately 0.384°. The position deadband on the antenna is set to 0.0005° which is 0.13% of the beamwidth so will have negligible impact on the tracking performance relative to the 3% RMS accuracy target.

Test Variable

The test variable for the test is the monopulse error vector transformed into axis degrees. The monopulse error vector is a voltage which represents the monopulse error channel null power position when it is at 0 volts. The null position and conversion to voltage are assumed to be ideal for the analysis as they are not under the control of the system under test, namely the 9000 control system. In practical terms there will be some non-zero alignment error in the feed construction that may cause the error null to be misaligned with the peak of the sum signal. Similarly, there may be some non-zero bias in the voltage produced to cause an error from the actual error channel null. However, these errors tend to be very small and do not reflect on the accuracy of the 9000 system tracking.

The monopulse error vectors are converted from voltage to axis degrees empirically by measuring the relationship as a scan is performed across the signal peak in each axis.

AMC-1 Monopulse Tracking Results

Tracking Results

AMC-1 was tracked in monopulse mode for 86 hours. During that time the monopulse error vectors and signal level were logged each second to make the plot in Figure 15. The tracking beacon was 4.1995 GHz which corresponds to approximately 0.384° for the 3dB beamwidth. The error limit for the test based on the 3% limit was 0.011520° which is represented by the red horizontal line in Figure 15. The RMS level of the Beam Radial Error (BRE) over the full test duration was 0.00244° which is represented by the green horizontal line in Figure 15. This corresponds to 0.64% of the 3dB beamwidth, well within the 3% limit.

The BRE peak exceeds the 3% limit a few times corresponding to approximately 15.8 minutes through the course of the 86 hour test. These peak deviations, amounting to 0.3% of the test time, do not affect the test results since the 3% criteria is RMS error, not peak error.

A 10 minute moving average of the BRE is shown on the chart in black to help with distinguishing the nominal tracking performance from the instantaneous BRE calculations shown in light gray since the instantaneous levels include a significant amount of noise.

The tracking error margin from these results was 0.00908° or 78.8% better than the 0.011520° error budget. The BRE RMS value of 0.64% is well below the 3% tracking error limit.

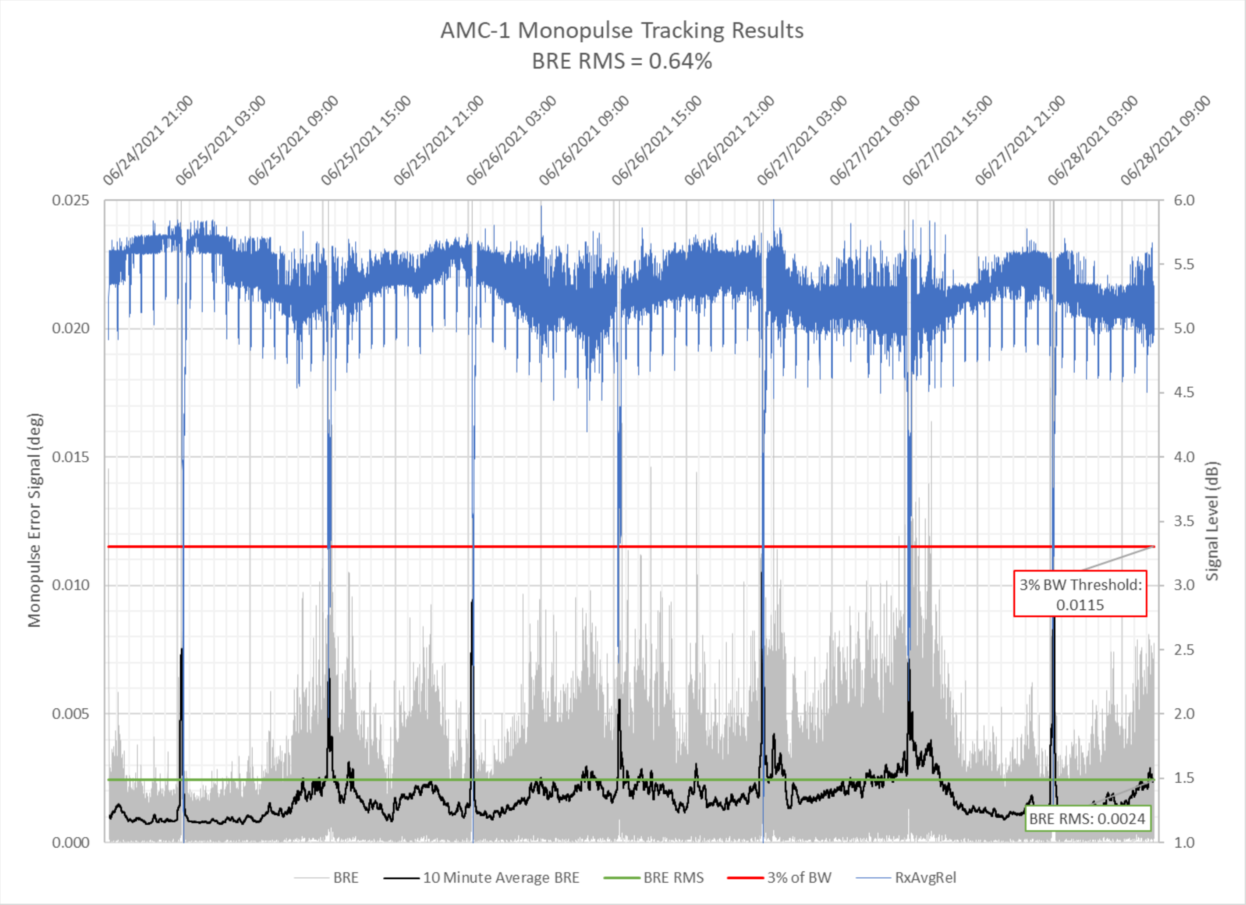

Figure 15: AMC-1 Tracking Results

Beacon Modulation

A regular drop in beacon level is apparent due to modulation for ranging performed on the beacon every hour. The beacon ranging does not have any noticeable effect on the monopulse tracking.

Signal Anomaly

There is an anomaly in the RF signal that occurs with AMC-1 twice every day around 03:00 and 15:00 hours. Figure 15 shows that the signal drop does not coincide with the elevated monopulse error signal, indicating that the drop is not caused by a true position error. Additionally, Figures 16 and 17 show that there is no significant deviation to the pointing angles of the antenna during this signal drop. Thus the signal drop must be caused by the satellite operator.

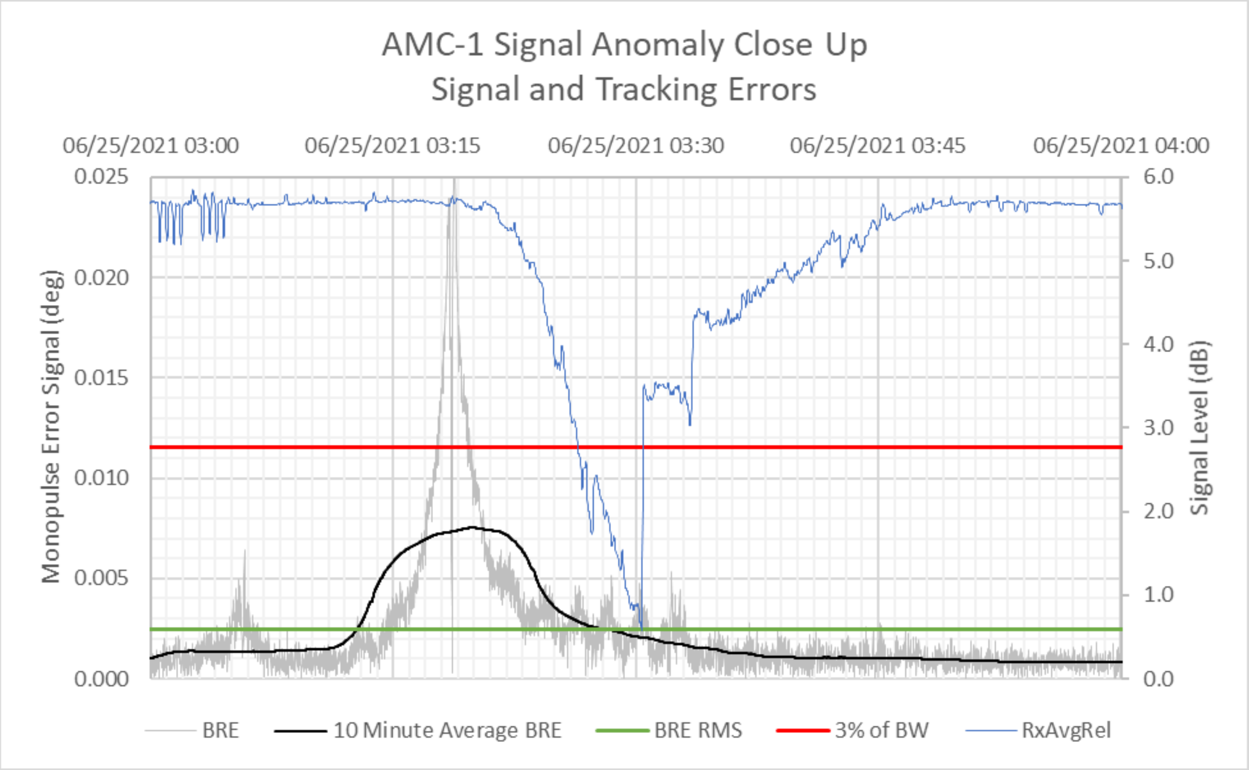

Figure 16: Signal Anomaly with Tracking Error

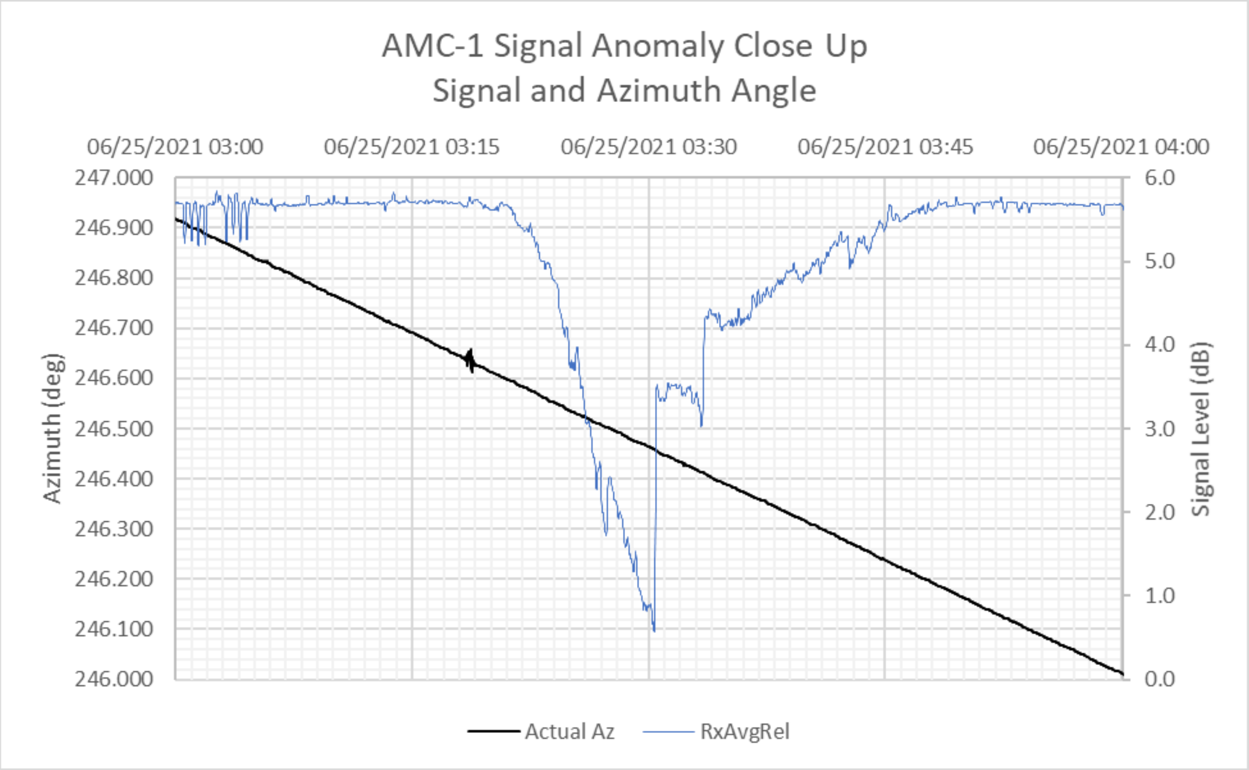

Figure 17: Signal Anomaly with Azimuth Angles

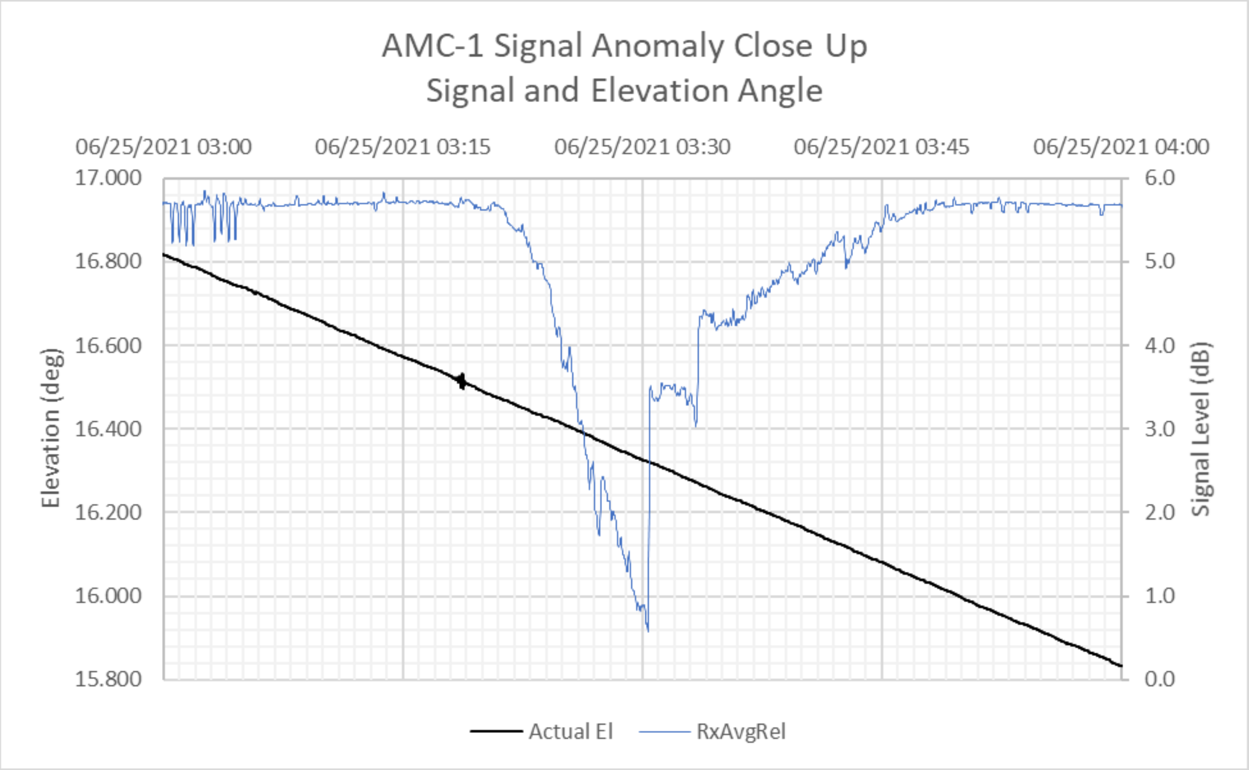

Figure 18: Signal Anomaly with Elevation Errors

Figure 19 and Figure 20 are plots of the TLE data for AMC-1 and AMC-11. They show that AMC-1 passes very close (within 0.1° to 0.2°) to AMC-11 at this same time every day. It is hypothesized that the operator of AMC-1 is dropping the transmit power to avoid interference with AMC-11.

This proximity also explains the rise in monopulse error shown in Figure 16 as the satellites pass close to each other. AMC-1 and AMC-11 both have beacons at the tracking frequency of 4.1995 GHz but on opposite horizontal polarities. The polarity difference prevents the beacon from interfering with the linear polarized sum channel of the monopulse tracking receiver but since the error channel of the monopulse feed is circular polarized it does not distinguish between the beacons of the two satellites when they are so close to each other. This means that the error channel is causing the monopulse error vector to deviate from the true location of AMC-1 as it begins to read the signal from AMC-11.

Due to the circular polarization of the error channel in the monopulse feed we would not recommend using it to track a target that moves within such close proximity to an interfering signal if the tracking signal is linear polarized. However, the AMC-1 tracking test demonstrates nonetheless that the 9000 system maintained the correct tracking trajectory in the presence of both the proximity of AMC-11 and the signal anomaly and thus proves to be quite robust.

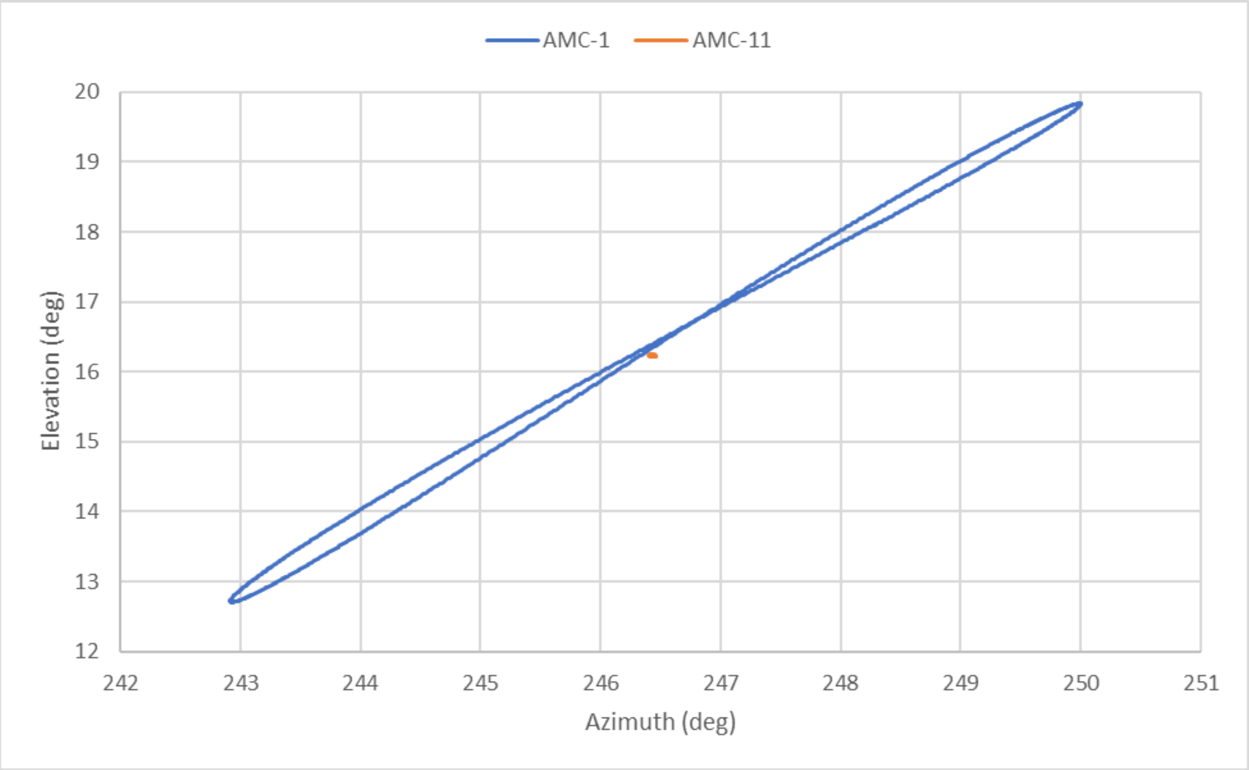

Figure 19: AMC-1 and AMC-11 Orbits

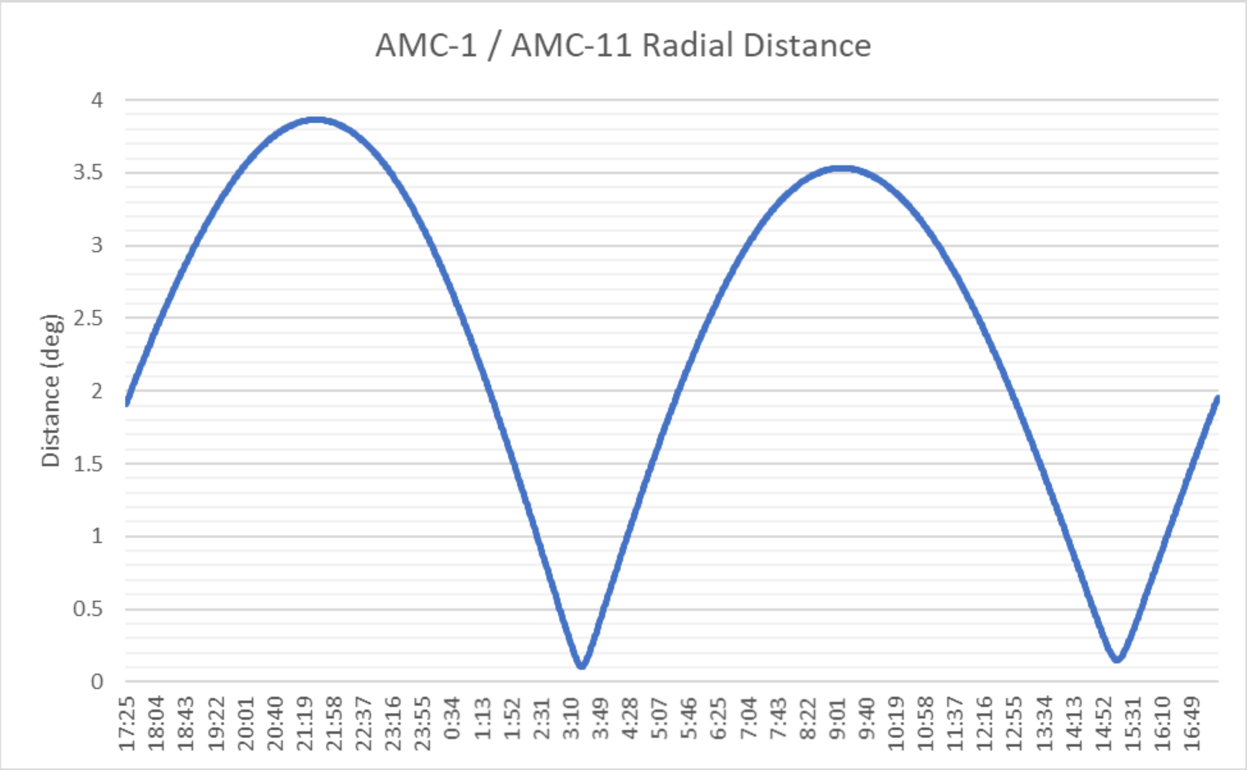

Figure 20: AMC-1 and AMC-11 Radial Distance

Weather

Historic weather data shows no significant precipitation or wind during the course of this test.

Tracking Parameters

Error vector filter cutoff frequency : 0.5 Hz
Estimated position filter cutoff frequency : 1 Hz

Orbit

Elevation Travel: 7.27°
Azimuth Travel: 7.27°

Figure 21 is provided for reference only to give a view of the orbital path for the tracking test.

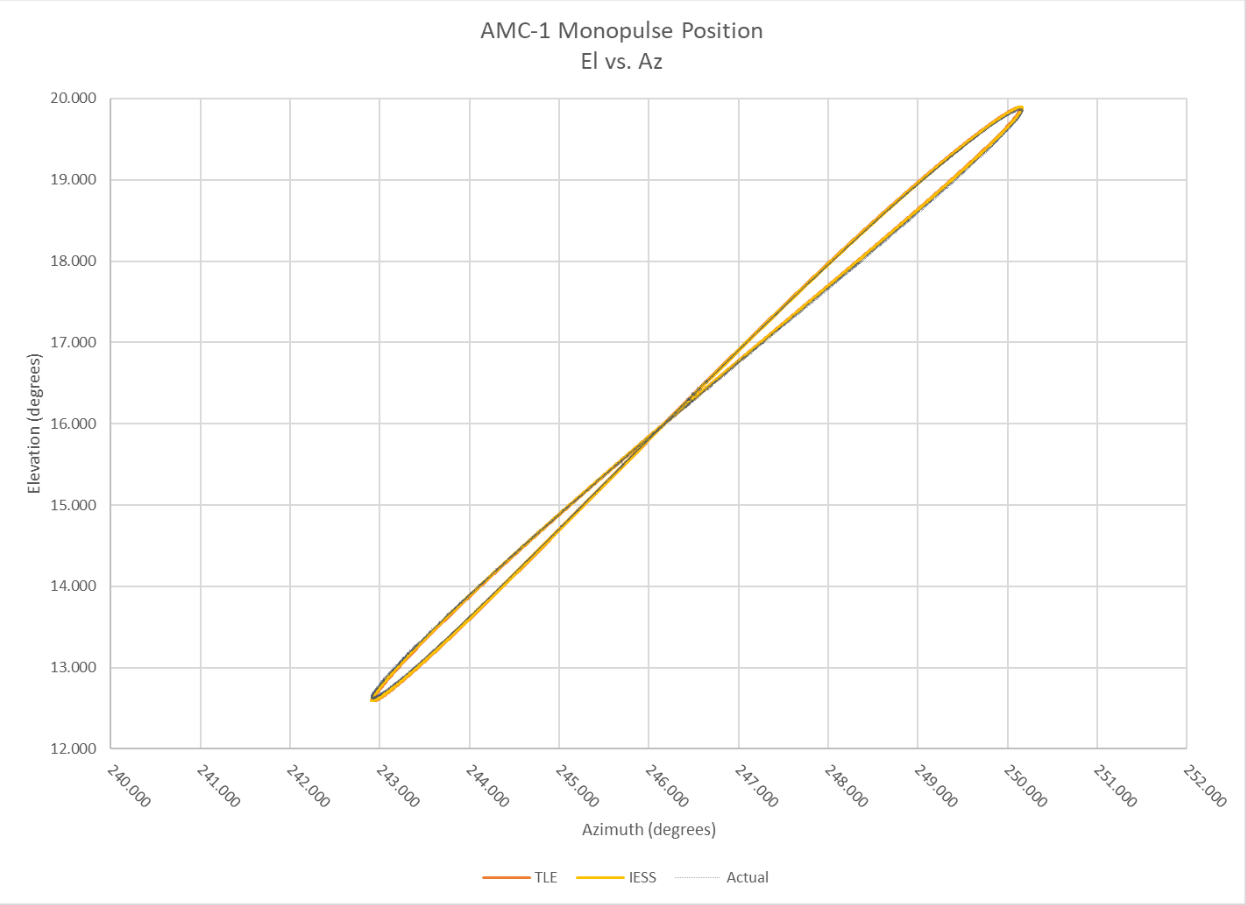

Figure 21: AMC-1 Orbit

AMC-3 Monopulse Tracking Results

Tracking Results

AMC-3 was tracked in monopulse mode for 71 hours. During that time the monopulse error vectors and signal level were logged each second to make the plot in Figure 19. The tracking beacon was 4.1995 GHz which corresponds to approximately 0.384° for the 3dB beamwidth. The error limit for the test based on the 3% limit was 0.011520° which is represented by the red horizontal line. The RMS level of the Beam Radial Error (BRE) over the full test duration was 0.00234° which is represented by the green horizontal line. This corresponds to 0.61% of the 3dB beamwidth, well within the 3% limit.

A 10 minute moving average of the BRE is shown on the chart in black to help with distinguishing the nominal tracking performance from the instantaneous BRE calculations shown in light gray since the instantaneous levels include a significant amount of noise.

The tracking error margin was 0.009182° or 79.7% better than the 0.011520° error budget. The BRE RMS value of 0.61% is well below the 3% tracking error limit.

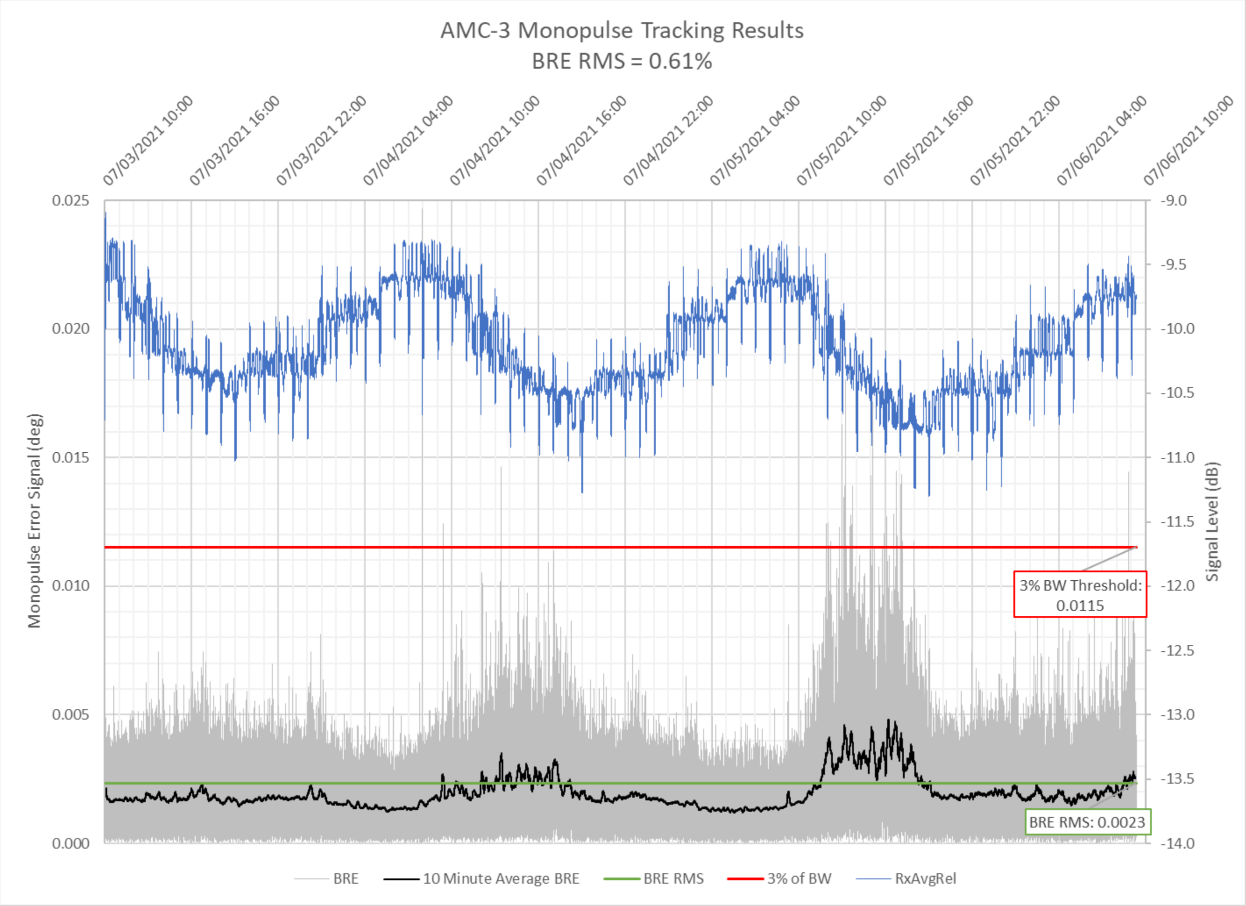

Figure 22: AMC-3 Tracking Results

Beacon Modulation

A regular drop in beacon level is apparent due to modulation for ranging performed on the beacon every hour. The beacon ranging does not have any noticeable effect on the monopulse tracking.

Weather

Historic weather data shows no significant precipitation or wind during the course of this test.

Tracking Parameters

Error vector filter cutoff frequency : 0.5 Hz
Estimated position filter cutoff frequency : 0.1 Hz

Orbit

Elevation Travel: 8.24°
Azimuth Travel: 0.76°

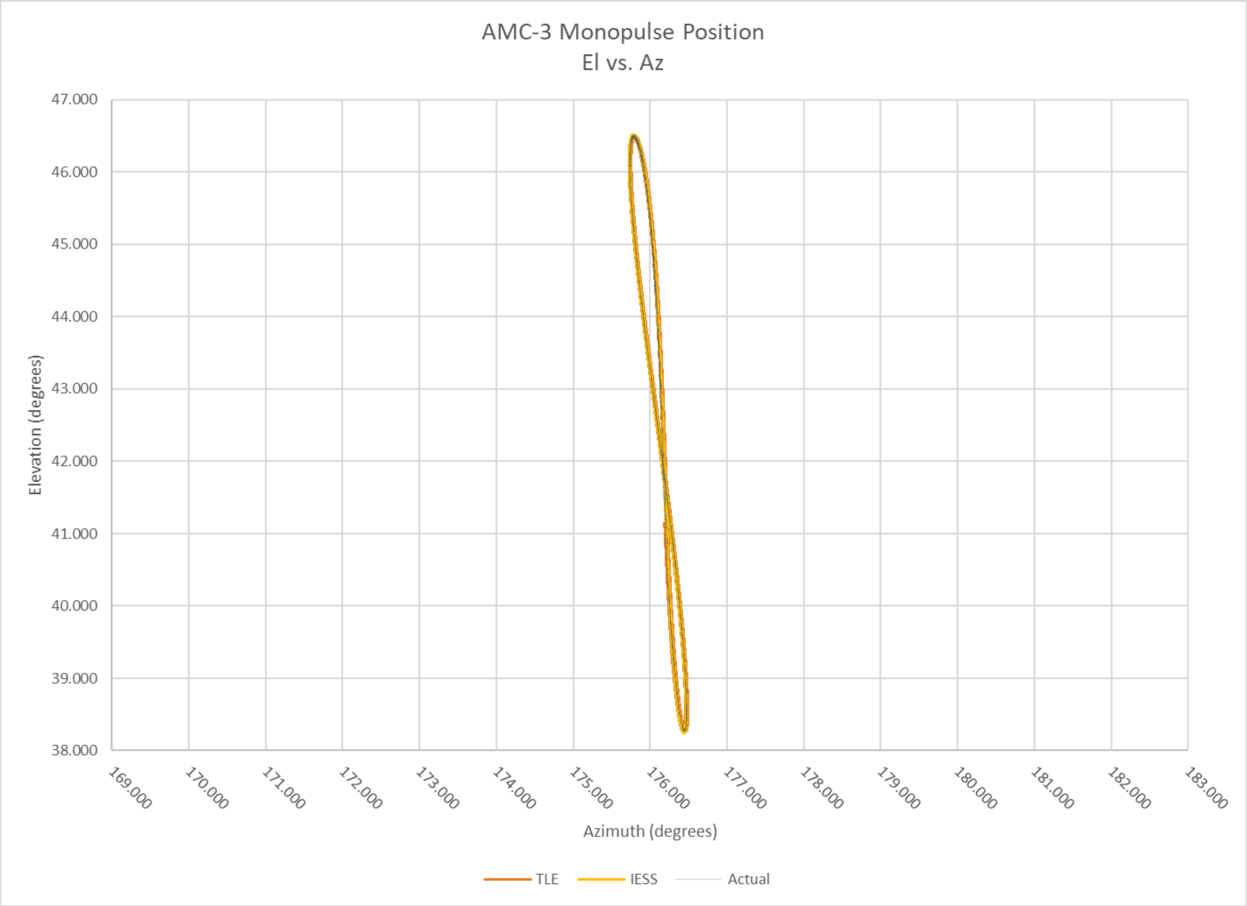

Figure 23: AMC-3 Orbit

Figure 23 is provided for reference only to give a view of the orbital path for the tracking test.

AMC-18 Monopulse Tracking Results

Tracking Results

AMC-18 was tracked in monopulse mode for 37 hours. During that time the monopulse error vectors and signal level were logged each second to make the plot in Figure 17. The tracking beacon was 4.1995 GHz which corresponds to approximately 0.384° for the 3dB beamwidth. The error limit for the test based on the 3% limit was 0.011520° which is represented by the red horizontal line in Figure 17. The RMS level of the Beam Radial Error (BRE) over the full test duration was 0.00148° which is represented by the green horizontal line in Figure 17. This corresponds to 0.39% of the 3dB beamwidth, well within the 3% limit.

A 10 minute moving average of the BRE is shown on the chart in black to help with distinguishing the nominal tracking performance from the instantaneous BRE calculations shown in light gray since the instantaneous levels include a significant amount of noise.

The tracking error margin was 0.010038° or 87.1% better than the 0.011520° error budget. The BRE RMS value of 0.39% is well below the 3% tracking error limit.

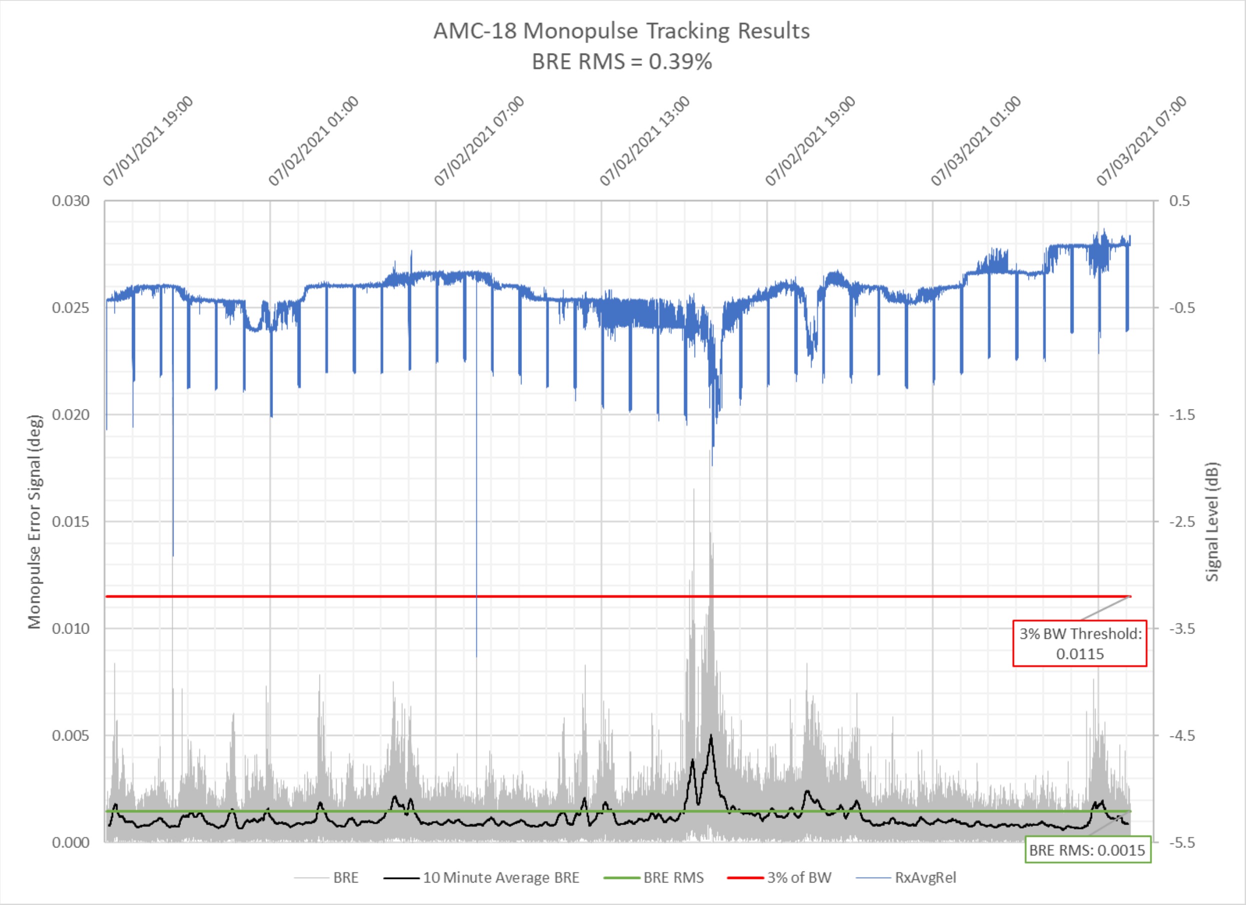

Figure 24: AMC-18 Tracking Results

Beacon Modulation

A regular drop in beacon level is apparent due to modulation for ranging performed on the beacon every hour. The beacon ranging does not have any noticeable effect on the monopulse tracking.

Weather Impacts

The signal level chart shows three potential impacts from weather:

1. 7/2 at 00:30
2. 7/2 at 17:00
3. 7/2 at 20:30

Looking up historical weather data for the site location confirms these weather events.

Data from: https://gis.ncdc.noaa.gov/maps/ncei/radar/radar

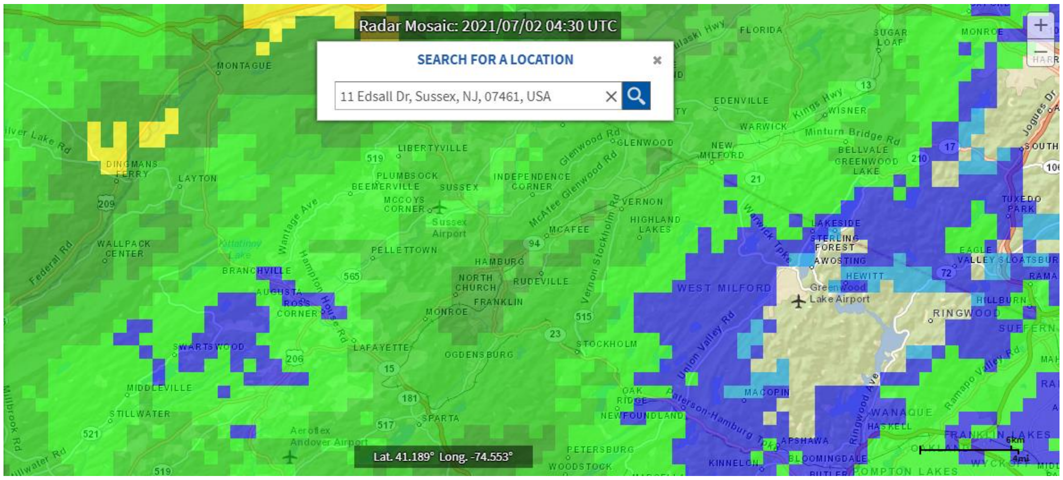

Figure 25: Doppler Weather Radar Chart 7/2/2021 00:30 EDT (04:30 UTC)

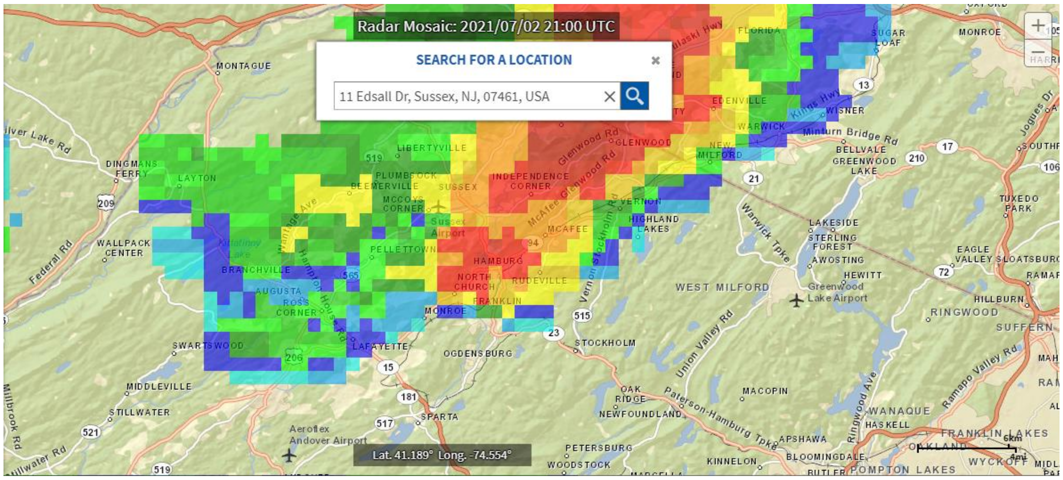

Figure 26: Doppler Weather Radar Chart 7/2/2021 17:00 EDT (21:00 UTC)

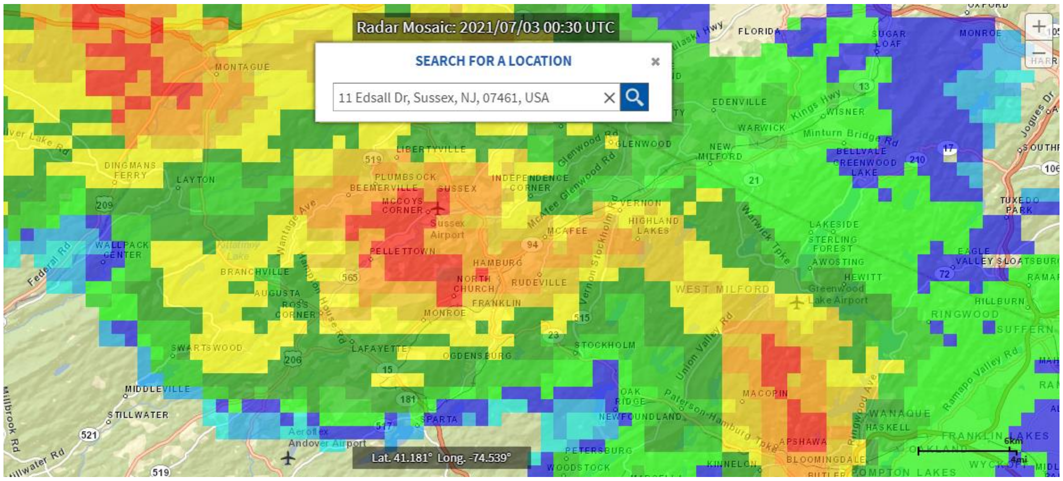

Figure 27: **Doppler Weather Radar Chart 7/2/2021 20:30 EDT (7/3/2021 00:30 UTC)**

Tracking Parameters

Error vector filter cutoff frequency : 0.5 Hz
Estimated position filter cutoff frequency : 1 Hz

Orbit

Elevation Travel: 0.07°
Azimuth Travel: 0.09°

Figure 28 is provided for reference only to give a view of the orbital path for the tracking test.

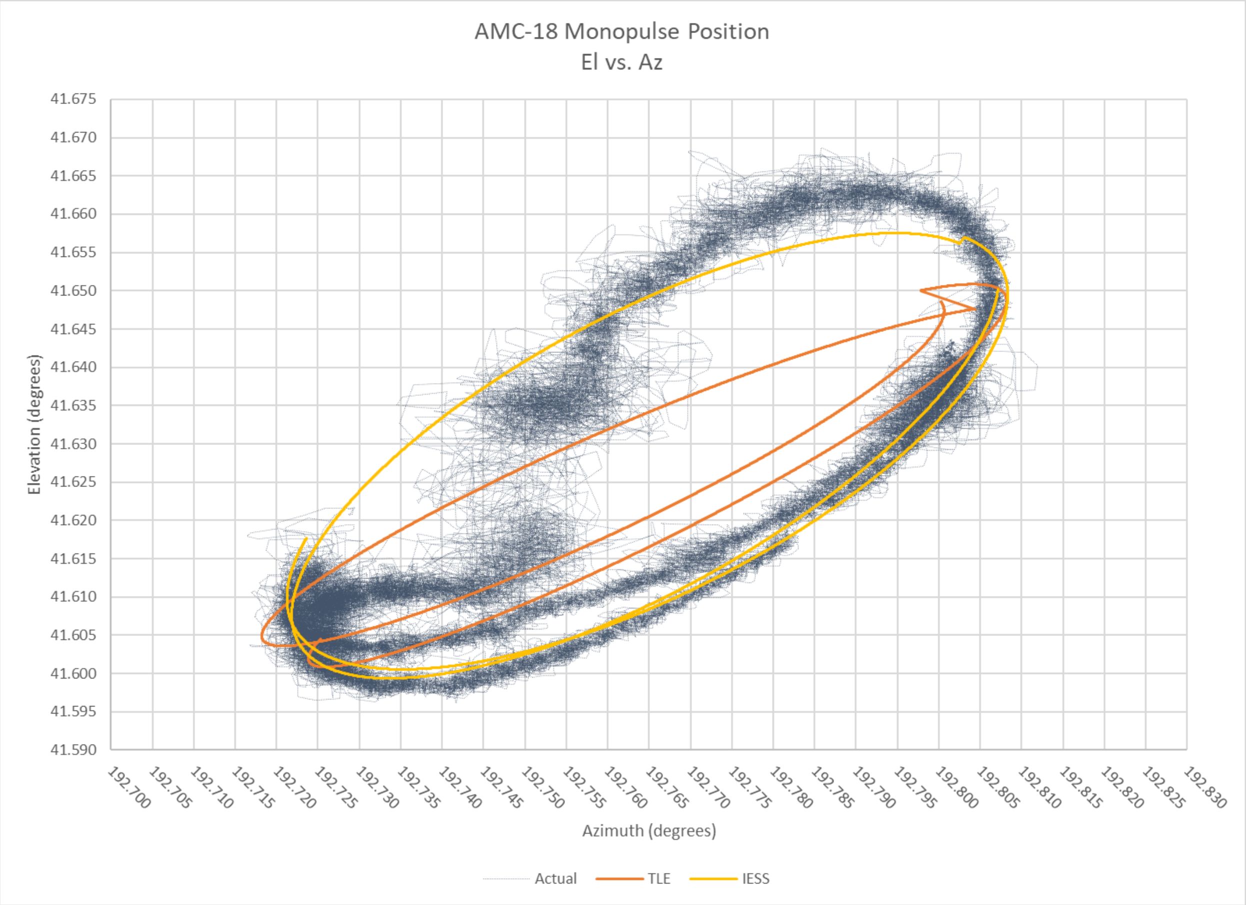

Figure 28: AMC-18 Orbit

Summary

The Radeus Labs Model 9000 ACS provides a sophisticated approach as a retrofit option for existing monopulse tracking systems or for new antennas. The system leverages current, state of the art motor and drive technologies to provide velocity and torque management of multi-motor per axis antennas. The system offers a variety of I/O options to manage lockouts, estops and position feedback devices. The monopulse system can also work with either single or dual channel systems, offering flexibility as a retrofit option for ageing legacy systems. The tracking tests for a RL9000 ACS deployed in the fall of 2020 show a robust tracking performance in 3 separate tracking tests. Tracking test results for AMC-1 (0.64% BRE RMS), AMC-3 (0.61% BRE RMS) and AMC-18 (0.39% BRE RMS) show that the system provides robust tracking performance far exceeding the 3% BRE required for robust tracking applications. These results validate the design and implementation of the RL9000 solution as a replacement for existing monopulse systems.