2013-09

Standardization in performance assessment of telemetry tracking systems

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Monterey, California: Naval Postgraduate School

https://hdl.handle.net/10945/37667

NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

JOINT APPLIED PROJECT

Standardization in Performance Assessment of Telemetry Tracking Systems

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September 2013

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REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704–0188*

1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** September 2013	**3. REPORT TYPE AND DATES COVERED** Joint Applied Project

4. TITLE AND SUBTITLE STANDARDIZATION IN PERFORMANCE ASSESSMENT OF TELEMETRY TRACKING SYSTEMS	**5. FUNDING NUMBERS**
6. AUTHOR(S) Florencio Marquez	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943–5000	**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A	**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB Protocol number _______N/A________.

12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited	**12b. DISTRIBUTION CODE**

13. ABSTRACT (maximum 200 words)

In the world of missile testing, telemetry plays a vital role in the evaluation of these weapon systems. Telemetry is defined as the process of taking measurements from a distance, or remote location. As measurements are made within the missile, the data is packetized and transmitted down to ground stations in real time. Once the data is accumulated, analysts review the data and evaluate the results of the missile test.

Launching a missile is a major test event that requires significant coordination and a considerable amount of funding. Collecting as much data as possible is crucial and always a fundamental requirement. Therefore, the telemetry tracking ground stations receiving the data play just as an important role as the missile itself. The ground stations must be reliable systems, where periodic maintenance and technical refreshing are key elements in the risk management of the receiving system.

This paper explores the effectiveness of predicting system failures by carefully analyzing antenna data metrics already made available to system users. By establishing a standard for evaluating these tracking systems, variances in the performance metrics over time may predict future system failures. By addressing potential issues preemptively, last-minute critical failures can be significantly reduced while making the system's availability and reliability much higher.

14. SUBJECT TERMS Telemetry, tracking systems, performance assessment, system risk management			**15. NUMBER OF PAGES** 69
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540–01–280–5500

Standard Form 298 (Rev. 2–89)
Prescribed by ANSI Std. 239–18

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STANDARDIZATION IN PERFORMANCE ASSESSMENT OF TELEMETRY TRACKING SYSTEMS

Florencio Marquez, Systems Engineer, WSMR Range Operations Directorate

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN PROGRAM MANAGEMENT

from the

NAVAL POSTGRADUATE SCHOOL
September 2013

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ABSTRACT

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LIST OF ACRONYMS AND ABBREVIATIONS

ACU	Antenna Control Unit
AGC	Automatic Gain Control
AHW-01	Advanced Hypersonic Weapon mission event #1
AOS	Acquisition of Signal
BMDS	Ballistic Missile Defense System
BVT-01	Booster Vehicle Test mission event #1
CSF	Conical Scan Feed
CSV	Comma Separated Variable
DSL	Data Support Limitation
DTR	Directorate of Test Resources
EKV	Exo-Atmospheric Kill Vehicle
G/T	Ratio of Gain over Temperature, a system sensitivity metric
GUI	Graphical User Interface
Hz	Hertz
ICBM	Inter-Continental Ballistic Missile
ITC	International Telemetry Conference
LNA	Low Noise Amplifier
LOS	Loss of Signal
FTG-06A	Flight Test Ground-Based Interceptor mission event #6, 2nd test
FTI-01	Flight Test Integrated mission event #1
Mbps	Mega bits per second – one million bits per second
MDA	Missile Defense Agency
MFPG	Machinery Failure Prevention Technology society
M.V.	Motor Vessel
RCC	Range Commander’s Council
RF	Radio Frequency
RTS	Ronald Reagan Test Site
SBSS	Space-Based Space Surveillance satellite rocket launch
SCM	Single Channel Monopulse
SDI	Strategic Defense Initiative

S.S.	Steam Ship
TM	Telemetry
TSZ	Test Support Zone
TTS	Transportable Telemetry System
VAFB	Vandenberg Air Force Base
WSMR	White Sands Missile Range

ACKNOWLEDGMENTS

I would like to thank Mr. Mike Winstead for always finding the time to explain things, and endorsing my decision to embark on earning a post-graduate degree. Working side by side with Mike has always been an adventure.

I am also thankful to have been witness to the birth of the Transportable Telemetry Systems at White Sands Missile Range. Working with Mr. Moises Pedroza as an intern, as he designed these systems on paper, proved to be of invaluable experience.

I want to thank the faculty and staff of the Naval Postgraduate School's Department of Business and Public Policy, especially my JAP advisor Professor Mike Boudreau. His commitment to supporting me even after having to go back to the drawing board is priceless.

To Mr. Antonio Cardoso from the Naval Surface Warfare Center, Corona Division, and my JAP technical advisor, thanks for all the support even in the face of all the inundating workload you always seem to carry.

Many thanks to all my TTS shipmates and team members for continuously inspiring me to achieve greater things. Thanks for the support.

Lastly, and most importantly, to my ever-understanding and supportive wife, Azalia, who has been by my side through the rough ride of being a full-time student and a full-time employee on the road. Thank you for all the love, support, and encouragement, even when our beautiful newborn baby, Mia Victoria, did not feel like cooperating.

Thank you all.

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I. INTRODUCTION

"The goal is to turn data into information, and information into insight."

— Carly Fiorina, former executive, president,
and chair of Hewlett-Packard Co

Like the quote implies, successful management and interpretation of data can become an accurate means for truly understanding what is going on, under any circumstance. In this case, the focus is on data relating to the performance and health of telemetry tracking antennas used for missile defense testing. It is the author's hypothesis that by collecting and analyzing relevant data made available by these telemetry systems in the form of log files, operators will be able to establish performance trends over time and identify symptoms that may point to potential failures. Furthermore, by standardizing the way these metrics are organized and reported, it will be much easier to gauge and compare performance of telemetry receiving tracking systems across the world.

A. PURPOSE

The purpose of this paper is to identify pertinent parameters for evaluating the performance and health status of telemetry tracking systems. By studying the data produced by two specific ship-based telemetry tracking systems, data metrics and known past failures will be time aligned so that trends and/or symptoms pronounced in the data can be identified. Once these trends, or symptoms, are characterized, they can be better detected in the future and allow operators to resolve the source of the problem preemptively, before a critical failure occurs.

B. BENEFITS

The benefits of this study extend to all users of telemetry tracking systems, and some relevance may exist for radar as well as optics tracking systems. Operators and test range engineers will have better insight as to the health and status of their tracking systems. Additionally, by identifying concerning data trends and/or symptoms, catastrophic failures can be avoided. This will, in turn, reduce system down-time and the number of data support limitations, also known as DSL's, a test range has to issue to its customers.

For the missile programs utilizing the range for testing purposes, they can count on data collection systems with better reliability and availability figures. Again, this translates to less last-minute critical failures and thus a more manageable mission schedule.

C. SCOPE AND LIMITATIONS

The scope of this project focuses on two sea-based telemetry tracking systems employed by the Missile Defense Agency (MDA). Each system consists of two 24 ft. dish tracking antennas and corresponding telemetry instrumentation, such as receivers, recorders, and communications infrastructure. Of more importance are the Antenna Control Units (ACUs) that are linked to each antenna. These units provide the graphical user interface (GUI) necessary for controlling the antenna and its configuration. These entire systems are deployed to various locations in the Pacific Ocean to collect missile data for tests relating to the Ballistic Missile Defense System (BMDS).

This research paper dissects the post-mission data logs produced by the ACUs for the two aforementioned systems. Additionally, only data from 6 missions will be analyzed, spanning the period from January 2010 through June 2011. Known failures that occurred during this timeframe were identified and documented. The mission data leading up to these failures, and post repairs, will be analyzed for trends and/or symptoms in the data that went unnoticed before. The goal is to identify specific trends or symptoms in the data that will point to specific problems beginning to show within the system.

D. SIGNIFICANCE

The implication of this study is important because by linking certain emerging patterns in the data to specific failures, there is a significant chance that similar systems may show similar symptoms prior to failure. By collecting and sharing this information, ranges across the country can, in essence, create a database of different data patterns and corresponding failures that everyone can share and have access to.

II. BACKGROUND

A. EVOLUTION OF MISSILE DEFENSE

Since the dawn of the missile age in 1944, during World War II, the United States has recognized the need for a defense system against ballistic missiles (Kaplan, 2008). Back then the threat was realized by Germany's V-2 rocket, the world's first ballistic missile. In the late 1970s, the Soviet Union's continued growth in the quantity and quality of its inter-continental ballistic missiles, or ICBMs, forced strategic defense planners to examine methods of instituting a ballistic defense system.

In a nationally televised speech in 1983, President Ronald Reagan challenged the scientific community to develop antiballistic missile technologies by launching a new program, the Strategic Defense Initiative (SDI) (MDA, 2013). The president desired a strategic alternative to the mutual assured destruction involved with engaging an enemy with nuclear weapons. This is the same program that became widely identified as the "Star Wars" program thanks to a critical comment from Senator Edward M. Kennedy of Massachusetts (Kaplan, 2008).

"It is the policy of the United States to deploy as soon as is technologically possible an effective National Missile Defense system capable of defending the territory of the United States against limited ballistic missile attack (whether accidental, unauthorized, or deliberate) with funding subject to the annual authorization of appropriations and the annual appropriation of funds for National Missile Defense." The preceding statement is taken from the National Missile Defense Act of 1999 (Public Law 106–38). This act not only provided clear direction, it effectively made it official policy for the United States Government to pursue missile defense (Thielmann, 2009).

Throughout the years, missile defense agencies have taken on different names and have focused on different threats depending on real world events. Additionally, technology has advanced at an exponential rate that has allowed significant improvements in missile defense. Today, President Barrack Obama's administration is continuing to evolve an integrated and global ballistic missile defense capability

(Hildreth & Woolf, 2010). Although the attention has shifted to more current and evolving threats such as Iran and North Korea (DoD, 2010), the objective remains the same.

B. THE MISSILE DEFENSE AGENCY

The Missile Defense Agency (MDA) is currently the research, development, and acquisition agency within the Department of Defense (DoD) that is responsible for developing a layered defense against limited ballistic missile attack. The MDA's mission is to develop a defense system to defend the U.S., our deployed troops, and our Allies from ballistic missile attacks (Testing, 2009). "Ballistic missile" is a term that refers to "any missile that does not rely upon aerodynamic surfaces to produce lift and consequently follows a ballistic trajectory when thrust is terminated" (Lash, 2010). The Ballistic Missile Defense System (BMDS), as described in Figure 1, is a sophisticated architecture of networked sensors necessary to detect and track enemy targets, ground and sea-based interceptor missiles to destroy the enemy targets, and a communications infrastructure providing operational commanders with the necessary links to manage and activate all available capabilities (MDA, 2013). In essence, MDA is responsible for developing, testing, and integrating a grand system of systems in order to engage and destroy the threat of ballistic missiles.

The MDA is a vast organization that breaks down into several directorates and branches, each focusing on unique responsibilities. The MDA's Directorate for Test (DT) executes BMDS test policy, manages the BMDS Test Baseline, and provides programmatic and technical direction and oversight of the test program and test resources (MDA Fact Sheet, 2013). Missile Defense flight tests are designed to provide the BMDS with test scenarios meant to simulate hostile conditions in order to evaluate BMDS against the threat. These test scenarios typically involve a target missile launch toward the BMDS in a manner that would best simulate an actual enemy engagement (Lash, 2010). Ground and flight tests offer DT an opportunity to provide valuable data for advanced modeling and simulation processes that measure and predict future performance of all missile defense technologies (MDA Fact Sheet, 2013). It is this data that demonstrates the performance of the BMDS and its elements. Because test and evaluation is so important to the evolution and growth of the BMDS, MDA placed great emphasis on testing in 2008 and produced notable accomplishments (Testing, 2009).

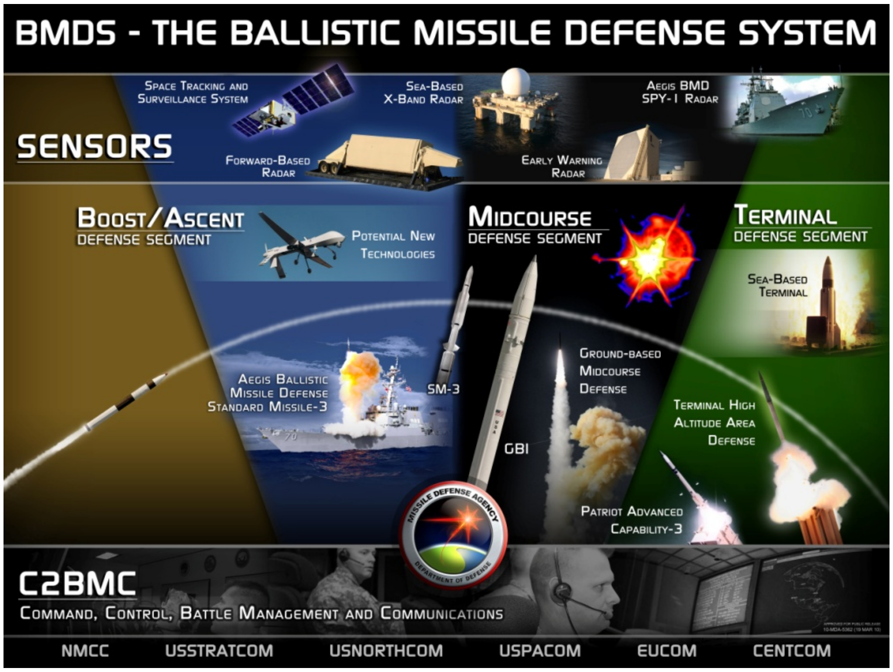


Figure 1. The Ballistic Missile Defense System

C. TRANSPORTABLE TELEMETRY SYSTEMS

Within the Directorate of Test (DT), the Test Resources Directorate (DTR) is responsible for managing some of the assets whose primary purpose is to collect test data during flight test missions. The Transportable Telemetry Systems (TTS) are such assets and they are dedicated to collecting missile telemetry (TM) data. In 2003, the first TTS systems (TTS-1 and TTS-2) were developed by MDA/DTR to support BMDS testing in the Pacific and, when necessary, support out of any land-based range within the continental United States. The primary purpose of these systems was to collect data from missiles flying in their midcourse and terminal phases while requiring minimal to no infrastructure for maintaining effective operations.

Early MDA intercept tests consisted of target missiles, emulating enemy ballistic missiles, launched from Vandenberg Air Force Base (VAFB), in California, toward the

Ronald Reagan Ballistic Missile Defense Test Site (RTS) located on the Kwajalein Atoll in the Marshall Islands (Lash, 2010). More recently, the roles have been reversed and Exo-atmospheric Kill Vehicle (EKV) interceptors have been launched out of VAFB while the targets come from RTS. The distance between VAFB and RTS is nearly 5,600 km (Lash, 2010). This broad ocean-occupied distance creates line-of-sight issues, and serious data collection limitations, for land-based assets. In turn, this creates data coverage gaps along the trajectories of the missiles. It is this gap that motivated the requirement for ship-based data collection assets (Lash, 2010). Thus, TTS-1 found a permanent home aboard the M.V. Pacific Collector in 2006 and TTS-2 aboard the S.S. Pacific Tracker in 2011, both depicted in Figures 2 and 3.

Figure 2. TTS-1 aboard the M.V. Pacific Collector

Figure 3. TTS-2 aboard the S.S. Pacific Tracker

The TTS systems are fully redundant stand-alone telemetry tracking systems that are capable of deploying to anywhere in the Pacific Ocean in order to maximize data collection efforts for MDA mission flight tests. These systems consist of two 24 ft. antennas each, SeaTel antennas for satellite communications for real-time telemetry transmission, and a robust set of back-end instrumentation capable of receiving, processing, and recording up to 12 streams of TM data redundantly (MDA, 2003). These antennas, being sea-based, also utilize a third axis, or the roll axis, to compensate for the rolls of the sea. Therefore, the three axes include the azimuth axis (side to side motion), the elevation axis (up and down motion), and the roll axis at the base of the dish antenna. Figure 4 illustrates the three antenna axes.

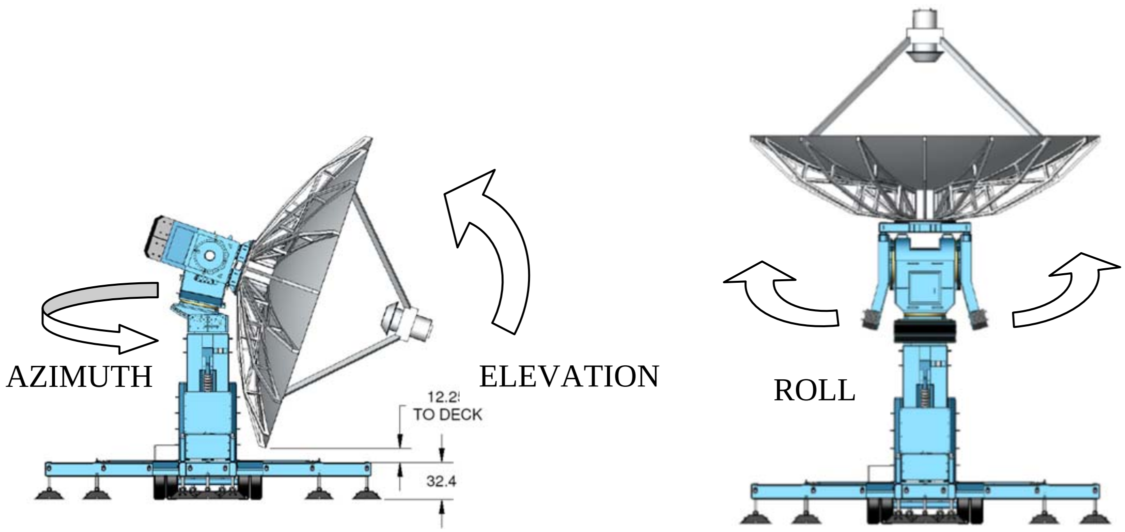


Figure 4. Azimuth, Elevation, and Roll axis of TTS antenna

The types of flight test missions the TTS systems support require numerous test assets that include other types of data collection, such as weather, radar, and optics. All these systems need to be well-coordinated, synchronized, and operational for the count-down to reach zero, and have a missile launch. For this reason, it is critical that all systems be as reliable as possible. TTS failures during an operation could potentially bring the entire schedule to a grinding halt. The TTS systems loiter in the Pacific Ocean as they await a launch and are the only assets that can collect data during certain sections of the trajectory. Therefore, these sea assets are mandatory and a launch will not occur without their participation. Thus, the reliability and health of these systems play a key role in how these complex flight test missions are executed.

D. COLLECTING MISSILE TELEMETRY DATA

The word telemetry is derived from the Greek roots: *tele* = remote, and *metron* = measure. In the case of missile testing, telemetry is the process by which a missile's characteristics are measured (such as velocity, spin rate, or system health), converted to digital signals, modulated, and then transmitted down to a receiving ground station where the TM stream is demodulated and the missile data is displayed, recorded, and analyzed (L-3, n.d.). For a typical flight test mission, the TTS systems are assigned to a Test Support Zone (TSZ) in the Pacific Ocean where they loiter while the mission clock counts down. At T-0, or the moment of missile launch, land-based sensors with line-of-sight to the launch pad track the missile and provide the TTS systems, via the communications infrastructure, cuing information in real-time so that they know where to expect the missile when it breaks horizon. Prior to horizon break, TTS operators maintain the antennas in slave mode, which means the antennas orient themselves to azimuth and elevation angle commands based on pointing cues provided by the sensors that are actively tracking the missile. Once the missile breaks horizon for the ships, the telemetry tracking antennas begin receiving the radio frequency (RF) signals directly from the missile. At this point the receiving antennas deliver the RF signals to the TM instrumentation that processes, demodulates, and records all the data. Additionally, once the antennas have line-of-sight and have a successful acquisition of signal (AOS), antenna operators configure the antennas to operate in auto-track mode, where the antenna locks onto the missile and tracks it based on the RF coming in and auto-tracking errors generated at the feed of the antenna.

III. ANTENNA TRACKING SYSTEMS

A. PARABOLIC ANTENNA BASICS

Prior to any missile test, the missile itself is outfitted with RF transmitters that radiate data measurements made inside the missile while in flight, much like radio stations radiate music over certain frequencies via their antenna towers. The only difference is that instead of music, missiles transmit the data in the form of high bit-rate one's and zero's (typically ranging from 1 to 20 Mbps). Additionally, missiles are highly dynamic and limited in how much space and power can be allocated for these transmitters. Therefore, the signals transmitted are not strong and robust like the ones radio stations transmit from their towers. Therefore, specialized antennas and radio receivers are required to capture these signals and extract the data being transmitted.

In the case of the TTS systems, 7.3 meter parabolic antennas are used as the source for tracking and receiving signals transmitted by targets under test. Each of these antennas comes equipped with its own pedestal that houses the servo control electronics and the servo amplifiers that provide the high currents needed to energize the antenna-moving motors. Figure 5 illustrates the TTS tracking antennas aboard one of the sea vessels, the M.V. Pacific Collector.

Figure 5. The two 7.3m tracking antennas (with radomes removed) utilized by TTS-1

These antennas make use of a dish-shaped reflector that follows a parabolic contour. This shape provides reflective properties such that all RF energy illuminating the dish is reflected and focused at one specific point, known as the focal point of the antenna. Figure 5 illustrates this concept. The RF energy, depicted by the lines Q1, Q2, and Q3, illuminates the parabolic dish at points P1, P2, and P3. The parabolic dish then reflects all this energy onto the focal point, point F. The feed of the antenna, which encloses or houses the actual elements energized by this received energy, is carefully located as close to the focal point as possible so as to receive the most amplified version of the signal being transmitted.

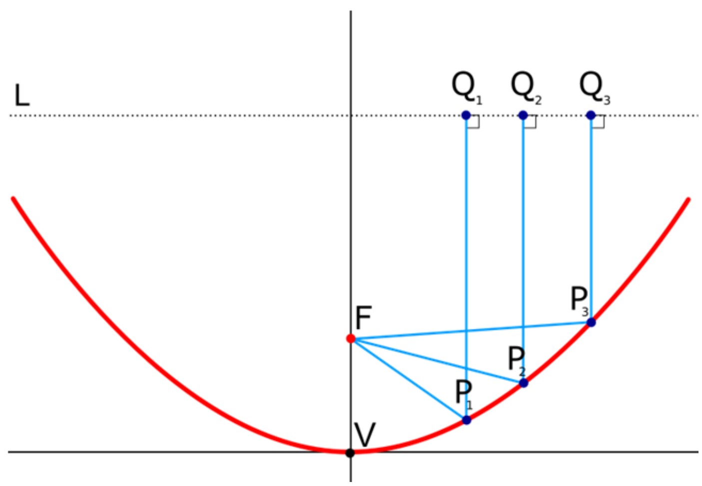


Figure 6. Reflective properties of a parabolic dish antenna

B. AUTO-TRACKING SYSTEMS

A parabolic antenna is an effective means of receiving a weak signal when the antenna is aligned and pointing directly toward the transmitting object, along its bore sight. However, there is little reason to test a missile that is static and not flying off into the sky. Therefore, a parabolic antenna must be able to maintain track, or keep a direct line-of-sight to the target, in order for the receiving system to be of any value. There are two ways of maintaining a parabolic dish pointed directly at a moving target: (1) by configuring the system to track in slave mode and have outside cuing data tell the antenna where to point, or (2) by outfitting the antenna system with a feed subsystem capable of auto-tracking the transmitting source as it flies into the sky, off the launch-pad.

The first method will work so long as there is cuing data coming in from other systems tracking the missile. However, a receiving station is of little value if it cannot track a target, and collect its data, once other sensors can no longer see it. A tracking antenna should be able to lock on to the signal it is receiving and track the target throughout its trajectory based on tracking errors generated at the feed. Therefore, a self-sufficient TM receiving station must be able to auto-track any missile radiating TM that is within its frequency and link margin range.

In an auto-tracking system, the purpose of the feed is twofold, to receive the RF signal from the target being tracked and to produce error signals that control the current, and thus torque, to the azimuth and elevation drive motors that move the antenna enabling it to follow the source of the transmitted signal automatically. There are three basic methods for auto-tracking a target and each employs its own unique tracking feed assembly. These feed assemblies include the conical scan feed (CSF), the single channel monopulse (SCM), and the electronically scanned feed (RCC, 2008).

The CSF method involves a rotating antenna element within the feed, also known as a nutator, which creates a cone-shaped scan due to its “wobble” in order to generate tracking errors based on the amplitude of the incoming target’s signal. The SCM generates tracking errors by scanning the feed dipoles and comparing phase angle differences of incoming signals using a diode-switching system. Lastly, the electronically scanned feed combines the best features of the previous two methods to generate tracking errors (RCC, 2008). It has been found that electronically scanned feed subsystems have a superior auto-tracking performance overall (Goswami, Sucharita, & Arya, 2003). For the purposes of this paper, we will focus on the electronically scanned feed assembly because the TTS antennas being analyzed for this paper utilize this type of feed assembly system.

Figure 7 depicts a representation of what an electronically scanned feed, along with its five dual linear dipole antennas, looks like when it is facing the dish antenna. The feed generates a sequence of scanned beams around the bore-sight axis. These beams are sequentially scanned to four positions in space: beam right, beam down, beam left, and beam up (Viasat, 2005). The difference channels provide samples of the received energy in the four different quadrants while the sum channel is aligned with the antenna's center axis line, or bore sight, and receives the maximum amount of RF energy off the antenna reflector. When the antenna is pointing directly at its target, the amplitude and phase of the frequency received at all the difference channels is the same. As the target moves away from the antenna bore sight, the feed generates tracking error signals by comparing phase and amplitude differences between the four difference channels (Mahafza, 2000).

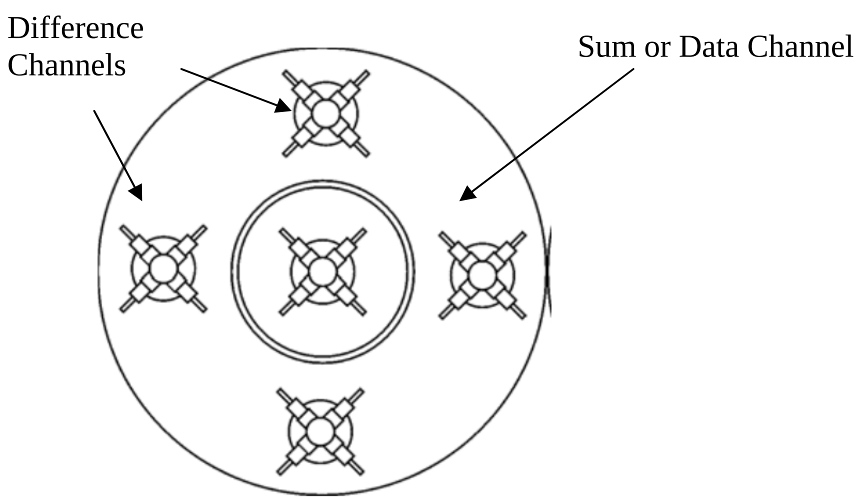


Figure 7. Front panel (faces antenna dish) of an electronically scanned feed subsystem

For the TTS antennas, the ESCAN is the microwave integrated circuit within the feed that carries out the computing and switching required for generating the four scanned beams. By carefully activating different sets of difference channels, the feed is able to create the four different beams. The ESCAN then uses amplitude modulation of the received RF to resolve in what direction the antenna needs to move in order to align itself to the target. For example, in Figure 8 the ESCAN produces a tracking beam up configuration followed by a tracking beam down. The target is clearly above the bore sight axis of the antenna and therefore a higher power level, or amplitude, of RF will reach the antenna when the feed is in the tracking beam up configuration. Tracking error pulses are generated at the ESCAN and then fed to the antenna control unit (ACU). Additional processing instructs the antenna's servo system to move the antenna up in elevation in order to become aligned to the target so that the data channel receives the maximum amount of RF again. The phase length of the data channel is matched to the phase length of the tracking channel, ensuring that the tracking and data channels are combined correctly to form the scanned beams (ViaSat, 2005).

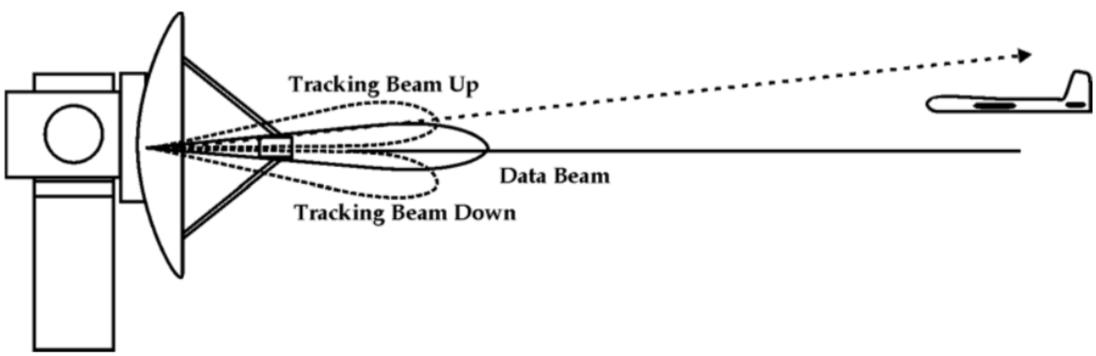


Figure 8. Example of tracking beams, elevation only

C. ANTENNA SYSTEM EVALUATION PARAMETERS

There are multiple methods of evaluating the health of an antenna tracking system. Figure of merit, or a G/T measurement, is defined as the sensitivity of the front end antenna. This measurement is a ratio of system gain (G) over system temperature (T) in dB/K and basically measures how weak a signal the antenna could still receive. Bit-error rate (BER) tests provide a precise indication of the health of the telemetry receiving equipment, such as the receivers, by measuring the number of bits in error during a certain time interval given a certain power level of signal. Ultimately, there are multiple tests that have been documented in telemetry handbooks meant to qualify a system as operational and in top condition. However, this paper focuses on other metrics made available by data recordings made by the antenna control unit of a tracking system. Parameters such as antenna angular velocity, acceleration, and auto-track errors are typically not a major focus when it comes to overall antenna assessment when the track is nominal, i.e., operating normally.

D. ANTENNA CONTROL UNIT (ACU)

A major component of any antenna tracking system is the antenna control unit (ACU), shown in Figure 9. For the TTS systems, this is the touch-screen computer that runs the graphical user interface (GUI) that operators use to control the antenna. The ACU allows operators to move and configure the antenna per the mission requirements. The ACU is also equipped with internal built-in tests to verify system specifications and provides data log files with detailed antenna parameter measurements for every track (given the operator configures for it appropriately).

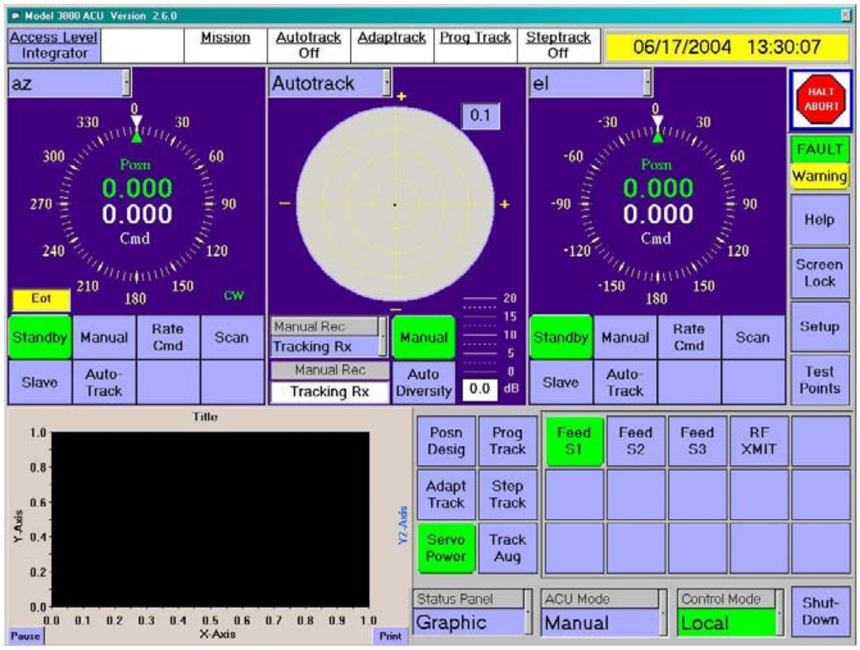


Figure 9. ACU graphical user interface

In effect, the ACU is the "brain" of the entire antenna system. For a mission requiring a mid-range track, one where the tracking asset does not have line of sight to the missile on the launch pad, the antenna will require pointing cues from outside sources so that the antenna knows where the missile in flight will break horizon. The ACU is able to process these pointing cues and point the antenna where it is being told to point. As the elevation look angle to the missile rises shortly after horizon break, the operator must decide when to go from a slave track to auto track. Auto-tracking a target will always maximize the amount of power received at the feed because the antenna system is moving based on the RF coming directly from the target. Pointing cues will always have inaccuracies due to system discrepancies and time latencies inherent in the communications infrastructure. During the auto-track, the ACU processes the error signals coming from the feed and controls the servo motors so that the antenna continually follows the missile flying across the sky.

The ACU system has the capability to record log files, also known as tab files, for each and every track. These log files record a multitude of parameters inherent to the antenna system, such as antenna angular velocity, acceleration, and angular positions, at a rate of 10 Hz onto a CSV (comma separated variable) file. It also records the various states that the ACU was in (standby, manual, slave, auto-track, etc.) due to operator manual input.

The following is a list of applicable parameters recorded by the ACU tab file:

Parameters:	Time:	Time from an outside source (GPS timing unit)
	Actual:	Actual position angle in extended position degrees for each axis.
	Commanded:	Actual commanded angle in extended position degrees for each axis.
	Offset:	Dynamic position offset in degrees.
	Mode:	Axis mode (0= standby, 1 = manual, 2 = slave, 81 = manual mode pending, 82 = slave mode pending)
	Upper:	Upper limit (“F” 1 = End of travel, 2 = Soft, 4 = Primary, 8 = Secondary)
	Lower:	Lower limit (“F” 1 = End of travel, 2 = Soft, 4 = Primary, 8 = Secondary)
	Interlock:	Interlock summary (0 = OK, 1 =set)
	Velocity	Axis velocity in deg/sec for azimuth, elevation, and roll
	Acceleration	Axis acceleration in deg/sec^2 for azimuth, elevation, and roll
	Position Error:	The difference between actual position and commanded position
	Overspeed:	Overspeed status (0 = OK, 1 = overspeed)

	axis_stowed:	Axis stowed = 1,
		`Axis not stowed = 0,`
		`Axis Stow/Unstow Operation in progress = 2`
		`Axis Failed to Stow = -1`

	autotrack_stat:	Autotrack status (-1=Fault, 0=Not Selected, 1=Acquisition, 2= Track (this axis is selected and tracking), 3= Re-Acquisition, 4 = Force Track, 5 = autotrack currently disabled by the Autotrack Mask function)

Tracking State Values	Tracking State Indication
-1	Fault
0	Not Active
1	Acquisition
2	Track
3	Re-Acquisition
4	Force Track
5	Autotrack Disabled by Mask

Table 1. Auto-track status values

slave_cmd:	The command angle from the slave data port. The ACU can receive slave commands at any time, but they will be ignored unless at least one axis is in slave mode.
Sys_mode:	Current system mode (0 = manual, 1 = mission, 2 = reserved, 3 = test, 4 = slave, 5 = stow, 6 = safe mode)
az_auto_error:	Azimuth auto-track error in volts (voltage measurement of feed displacement from bore sight or target, i.e., the farther away the feed is from bore sight, the greater the voltage signal)
el_auto_error:	Elevation auto-track error in volts (voltage measurement of feed displacement from bore sight or target, i.e., the farther away the feed is from bore sight, the greater the voltage signal)
tr1_sig:	Tracking receiver 1 signal strength in dB.
tr2_sig:	Tracking receiver 2 signal strength in dB.
tr3_sig:	Tracking receiver 3 signal strength in dB.
tr4_sig:	Tracking receiver 4 signal strength in dB.
select:	Selected receiver signal strength in dB.

The focus of this paper revolves around these tab files and the wealth of information that they hold. Typically, these files remain unobserved until a failure occurs, and a root cause investigation begins. By carefully analyzing pertinent parameters within these tab files following completion of every mission, it is the hypothesis of the author that telemetry engineers and technicians may be able to identify the symptoms of an oncoming failure. By preemptively assessing the symptoms, preventive maintenance and/or an early replacement of a part would effectively eliminate the risk of a critical failure.

IV. ANALYSIS

A. DIAGNOSIS AND PROGNOSIS

> "Mechanical failures are a pervasive fact of life in our society. Ranging from the failure of small items that all of us have experienced and that many of us take for granted, to the failure of a large complex structure that often becomes front page news, they have undesirable consequences for our society. The large ones many times cause loss of life or cause serious injury to many people. The minor ones sometimes also cause loss of life or injury, and they always cause frustration and anger on the part of the one to whom they occur. Always they cause loss of valuable material, and have undesirable social and economic consequences."
>
> —Elio Passaglia, executive secretary, MFPG, 1976
> (Pusey & Howard, 2008)

Diagnosis is the act of identifying a condition from its signs or symptoms, while prognosis is the act of predicting a future condition on the basis of present signs and symptoms (Pusey & Howard, 2008). The goal is to establish a method for identifying patterns within the data that will provide telemetry operators a better means to achieve an accurate prognosis when evaluating a TM system. Too often, tabulation file data is simply not analyzed. Unless a specific need arises or a catastrophic failure occurs during the support of an event, the tab file is archived and stored away. This chapter will provide actual data from past events and demonstrate why analysis of this data should become standard operating procedure for every event a tracking system supports.

B. OIL ANALYSIS–THE IMPORTANCE OF DATA ANALYSIS

Lubrication inspection has been used to help diagnose the internal condition of oil-wetted components for many years. Most machinery involving moving parts requires some sort of lubrication to reduce wear. This includes internal combustion and diesel engines, along with their components such as gearboxes and transmissions. In 1946, the Denver and Rio Grande Railroad research laboratory successfully linked diesel engine problems to certain properties found in its used oil (Smith, 2008). By 1955, oil analysis had matured to the point that it had gained the interest of the United States Naval Bureau of Weapons. A major research program, the Joint Oil Analysis Program, was initiated involving all the branches of the U.S. Armed Forces and early results proved conclusively that increases in component wear could be confirmed by detecting corresponding increases in metal content in the used oil (Smith, 2008). Additionally, in 1958, the program gained traction with two positive results. An oil sample from an R-1340-AN airplane engine displayed abnormally high levels of iron, copper, and aluminum. Tear-down of the engine revealed the front impeller bearing had completely failed (Pusey & Howard, 2008). Months later, a failed cam drive gear in an R-985 airplane was discovered using the same oil inspection techniques (Pusey & Howard, 2008).

Although the oil analysis program was thought of primarily as an engine condition monitor, the program also discovered that the same technique could identify potential issues with other components such as gearboxes and transmissions. With time, it was found that for transmissions and gearboxes it was relatively easy to predict condition (Pusey & Howard, 2008). Like the same way that human diseases show up in blood analysis, it was proven that certain malfunctioning parts will manifest themselves as changes in the properties of a mechanical system's oil (Pusey & Howard, 2008).

The TTS antennas are electro-mechanical systems with no oil running through them. Nonetheless, the same concept can be applied to this system by analyzing the various metrics made available by the ACU's tab files. By paying close attention to data fluctuations, TM operators should be able to identify potential problems.

The remainder of this chapter will focus on two failures experienced by each sea-based TTS system. TTS-1 encountered anomalies during the actual launch-day mission track of the FTG-06A event. By analyzing ACU tab files for this event, and the prior two (BVT-01 and SBSS), signs of an oncoming failure will be looked for in the data plots. Similarly, a year later, the TTS-2 system suffered a critical failure after supporting the FTI-01 event. Again, ACU tab files for that mission and the one before (AHW-01) will be analyzed for unforeseen symptoms of a potential problem.

The goal is to prove that over time, with enough historical data, predicting certain failures could become a very realistic scenario like in the case of the Navy's airplane transmissions and gearboxes. The focus will be on raw ACU data from past mission support events. With the advantage of hindsight, we will be able to lay out a timeline of past anomalies and focus on tab file data leading up to these failures. The expectation is that we will find indicators, or symptoms, in the data leading up to the system malfunction.

C. DATA ANALYSIS FOR FAILURE #1

Back in 2010, the TTS-1 system, aboard the M.V. Pacific Collector, had a busy and rigorous timetable of mission support. Its schedule called for it to support five events that year, where each event took at least six weeks from planning to execution. Table 2 illustrates the timeline of events for that year.

Mission Event	Launch Date
FTG-06	February 2, 2010
HTV-2A	April 20, 2010
BVT-01	June 6, 2010
SBSS	October 2, 2010
FTG-06A	December 15, 2010

Table 2. Timeline of mission events in 2010

During the execution of FTG-06A, the last mission of the year, a failure occurred with Antenna A during the track of the missile. The roll axis suddenly froze and the antenna was struggling in auto-track mode, which is usually an indicator that something is wrong with the antenna feed. The system was designed to be completely redundant for these types of failures and Antenna B was able to collect all the data without a problem. Nonetheless, it was a concern that such a problem would sneak up and affect the track at the last minute since practice runs and daily checkouts found the antenna to be operational with no exceptions.

The following plots present a subset of all the data made available by the ACU tab files for both antennas. These plots will illustrate that Antenna A clearly experienced problems throughout the track and although telemetry data was collected, the quality fell below expectations. Additionally, since the problem with the antenna seemed mechanical in nature, the focus was on data such as auto-tracking state, auto-tracking errors, and variation in axis accelerations. Since both antennas are identical and had identical tracking assignments, any significant difference between the two in performance data would be of interest.

Figure 10 clearly illustrates that antenna A was having difficulty maintaining track during the trajectory. The tracking state for antenna A shows that the system lost auto-track at least six times during the track. When a system drops out of auto-track mode, the antenna automatically slaves to an outside cueing source for pointing information. Once the antenna reacquires the RF signal, the ACU will try to auto-track again. Antenna B, on the other hand, had the kind of track expected of a system operating in perfect condition. Once the system switched to auto-track mode, the antenna maintained a clean track throughout the flight. The auto-tracking error plot for antenna A shows significant deviations from zero, meaning the antenna was having trouble maintaining accurate pointing. The farther from the bore-sight axis the antenna is, the higher the voltage for the error plot. Alternatively, antenna B had a stable plot for its auto-tracking errors, meaning that the feed pointed accurately and was aligned to the missile in flight. It should also be noted, that errors on these types of plots are expected at the beginning and end of a track due to the multipath and RF reflections off the ocean experienced when the antennas are pointed at low elevations as the target breaks, or falls below, the horizon.

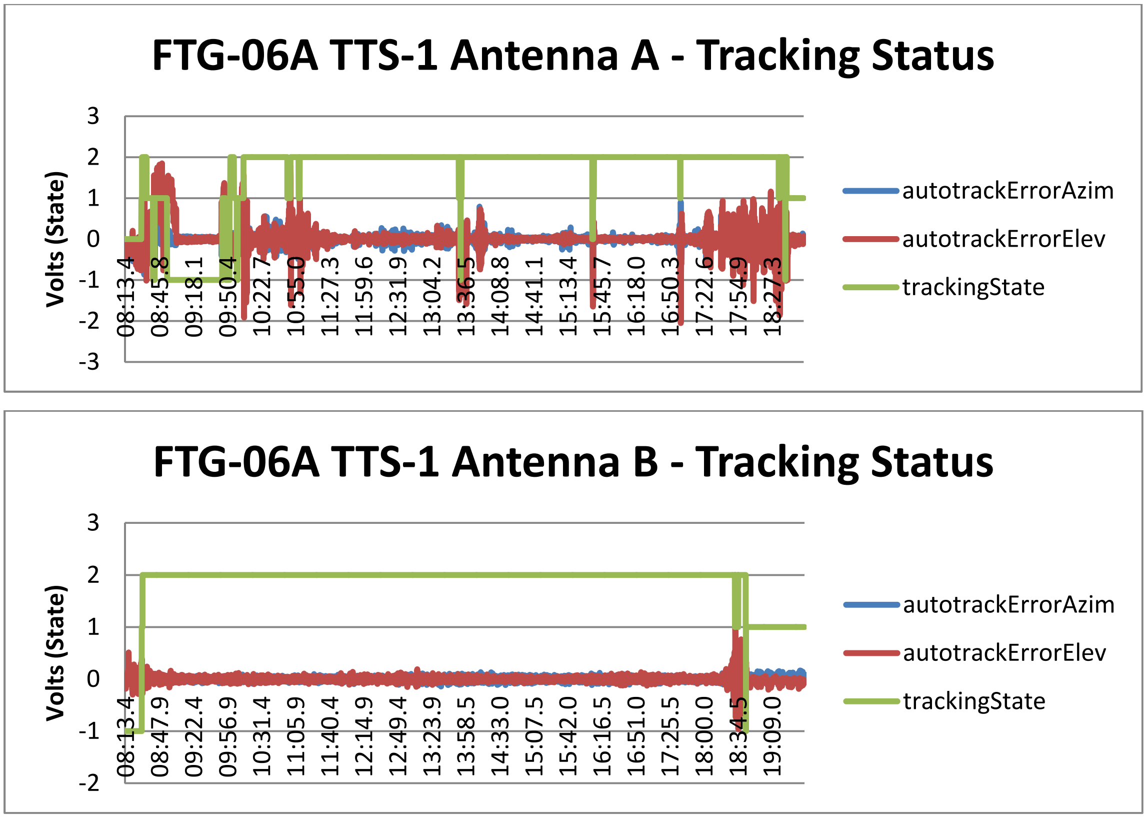


Figure 10. Antenna A and B tracking status during FTG-06A support (From TTS-1, Dec 2010)

Figure 11, displayed below, illustrates the difference in antenna performance in relation to the antenna acceleration along the azimuth and elevation axis. As was noted in Figure 10, here we also see that antenna A was having difficulty maintaining a smooth track. The antenna axis acceleration magnifies the subtle changes in antenna velocity. Therefore, if an antenna is moving at a constant velocity, such as during a smooth track, the acceleration is a flat line at zero. Alternatively, if the antenna is jittering or gears are jamming at periodic intervals, the acceleration data will show spikes in the plots. Typically, antenna movement anomalies are not observable to the naked eye. However, these plots provide detailed insight as to the overall performance of the motors, gearboxes, torque limiters, and any other mechanical part involved in the motion of the antenna.

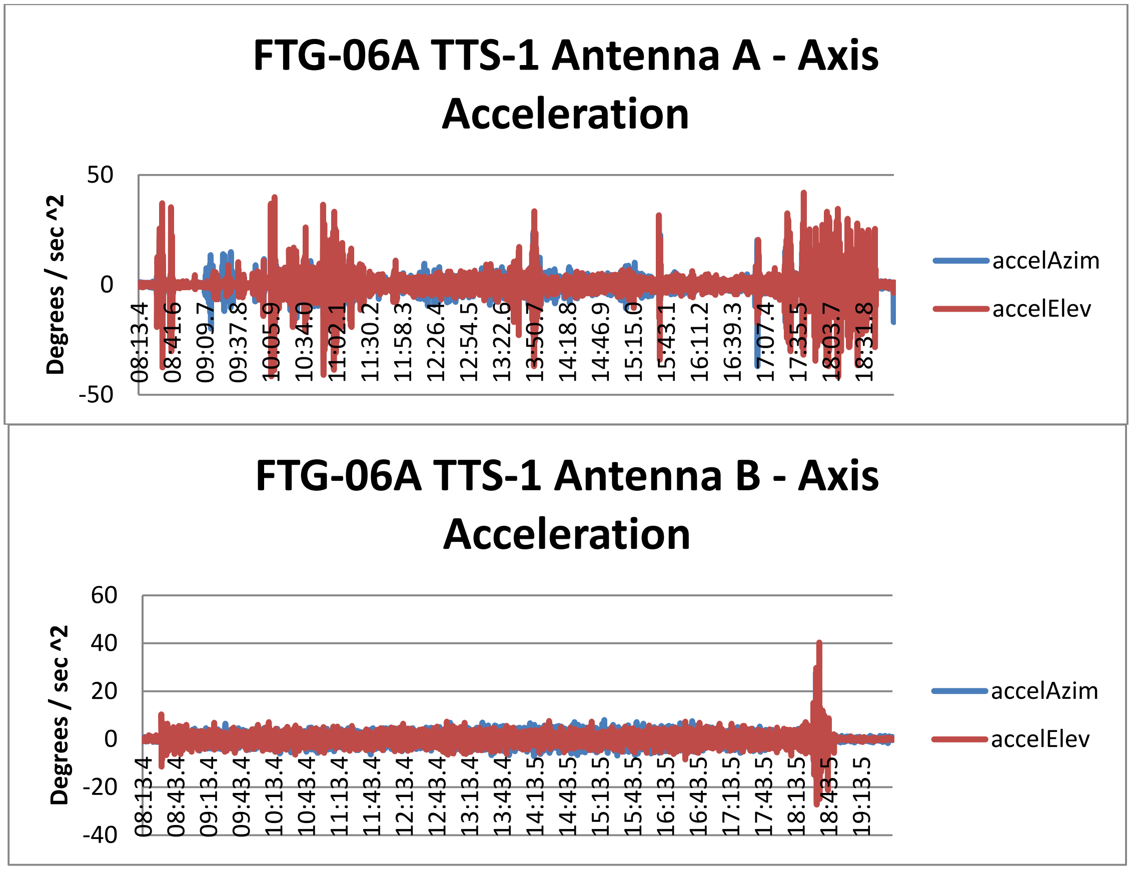
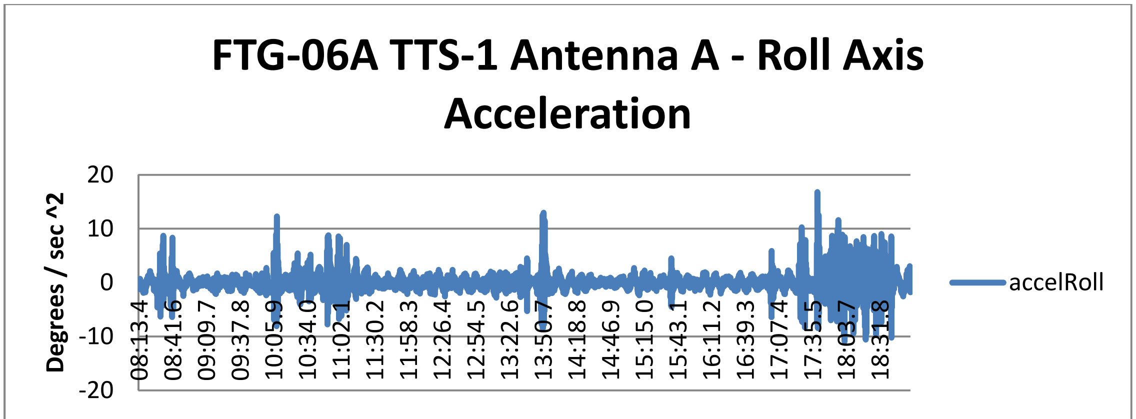


Figure 11. Antenna A and B azimuth and elevation accelerations (From TTS-1, Dec 2010)

Figure 12 illustrates the plots of the antenna roll axis accelerations during the track. As expected, antenna A depicts signs of a problem due to the inconsistent and irregular motion of the antenna along that axis in a couple instances. Again, antenna B data shows sign of a smooth and stable track, indicating an optimally performing antenna system.



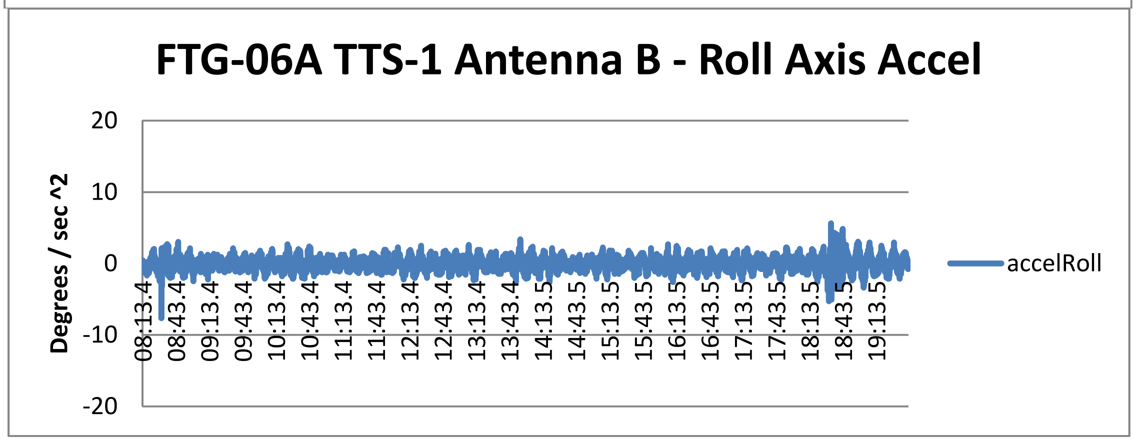


Figure 12. Antenna A and B roll axis acceleration during the track (From TTS-1, Dec 2010)

Figure 13 represents the signal strength received for both antenna systems. This metric is sometimes also known as AGC (automatic gain control) data because of the circuitry found inside the telemetry receivers that automatically control the gain of the signal received. Therefore, if a signal is weak more gain is applied and the AGC level is high. If a signal is strong, then the AGC level is low. The inverted AGC level then becomes a good representation of the signal strength received by the telemetry receiving system. Figure 13 clearly shows that the signal strength received by antenna B is lower than antenna A. We now have four plots suggesting that indeed antenna A, although functional, was not operating at an optimal state.

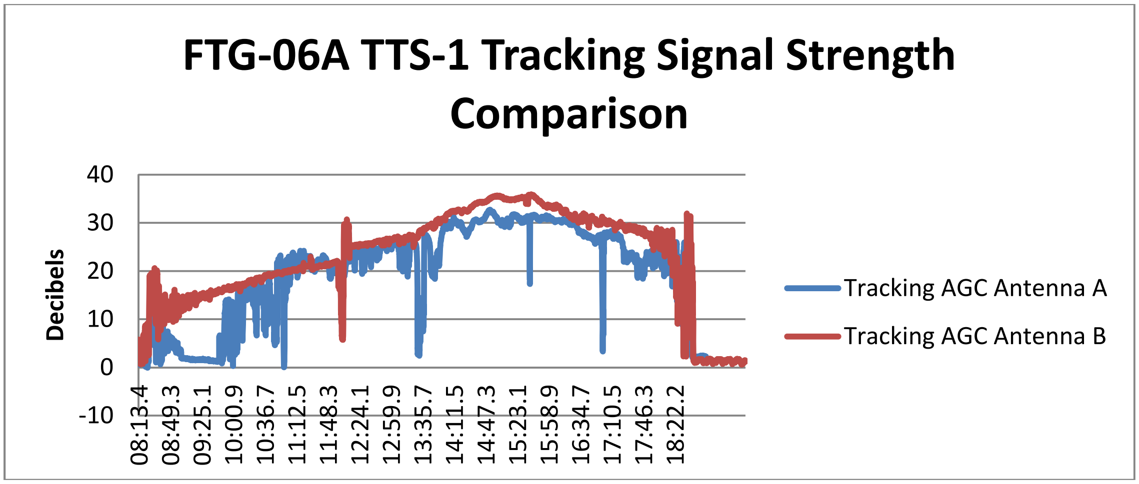


Figure 13. Antenna A showing less signal than Antenna B (From TTS-1, Dec 2010)

After a root cause investigation, it was found that the antenna system experienced an issue when it was powered down and back up the day of the track. Once the system booted up, the roll axis was having trouble aligning itself to zero degrees and therefore was introducing an offset in the antenna position. Additionally, a low noise amplifier (LNA) within the feed was found to performing below specification. This caused the signal levels received by the antenna to be lower than expected, as seen in the signal strength recordings in Figure 13.

This failure occurred in December of 2010. Previous missions supported by this system took place without a problem reported by the telemetry operators. Data quality numbers derived by counting frame sync pattern locks (once the data is demodulated and digitized) for the previous events showed that data collection was a success.

The next step is to plot and analyze data for the missions before FTG-06A and hunt for potential signs of an oncoming system anomaly. The focus will now be on the BVT-01 and SBSS mission events supported by the TTS-1 system prior to FTG-06A. Data metrics such as auto-tracking errors, acceleration of antenna axes, and signal strength (AGC) will be presented next, in Figures 14 through 17.

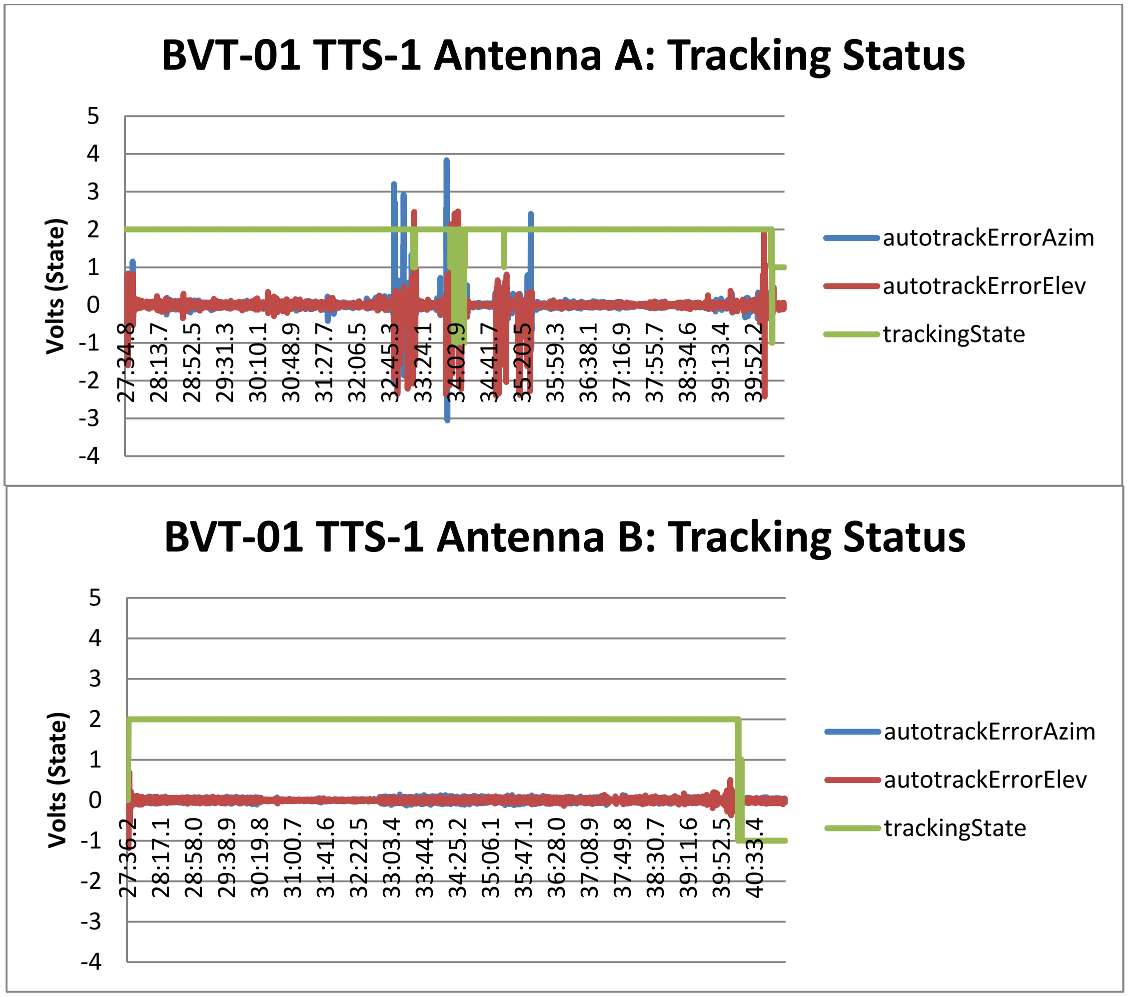


Figure 14. Antenna A having trouble maintaining track prior to the FTG-06A event (From TTS-1, Jun 2010)

Not much effort is required to conclude that antenna A was having trouble maintaining track midway through the missile's trajectory as illustrated by Figure 14. Unfortunately, these types of plots were never analyzed post-mission due to the fact that the customer reported a nominal data collect. Additional plots will be presented for further comparison.

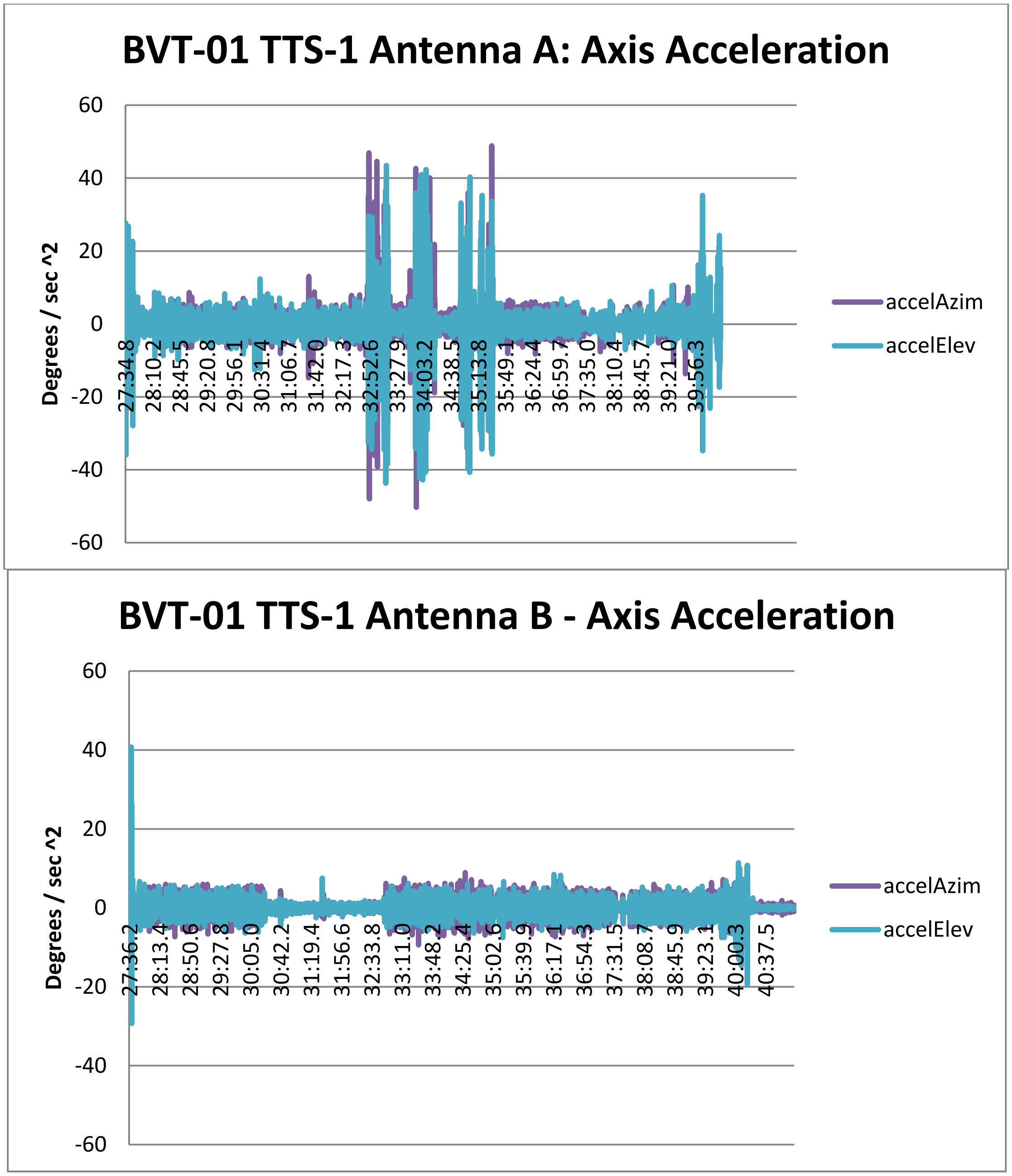
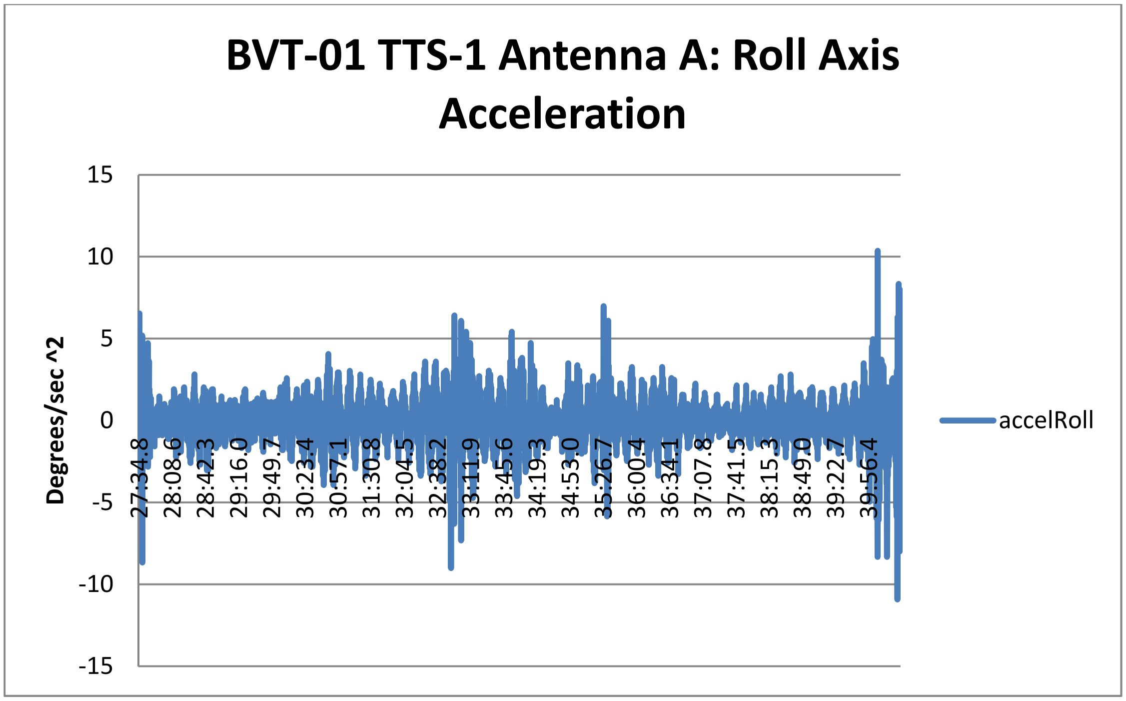


Figure 15. Comparison plots of axis acceleration during the BVT-01 event (From TTS-1, Jun 2010)



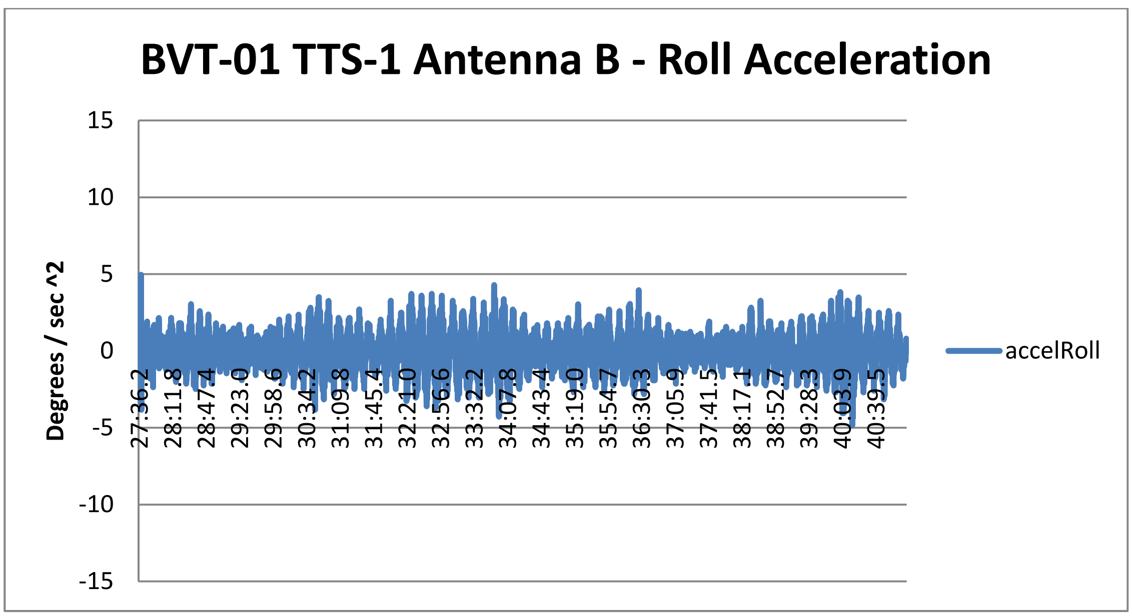


Figure 16. Comparison plots of roll axis acceleration during the BVT-01 event (From TTS-1, Jun 2010)

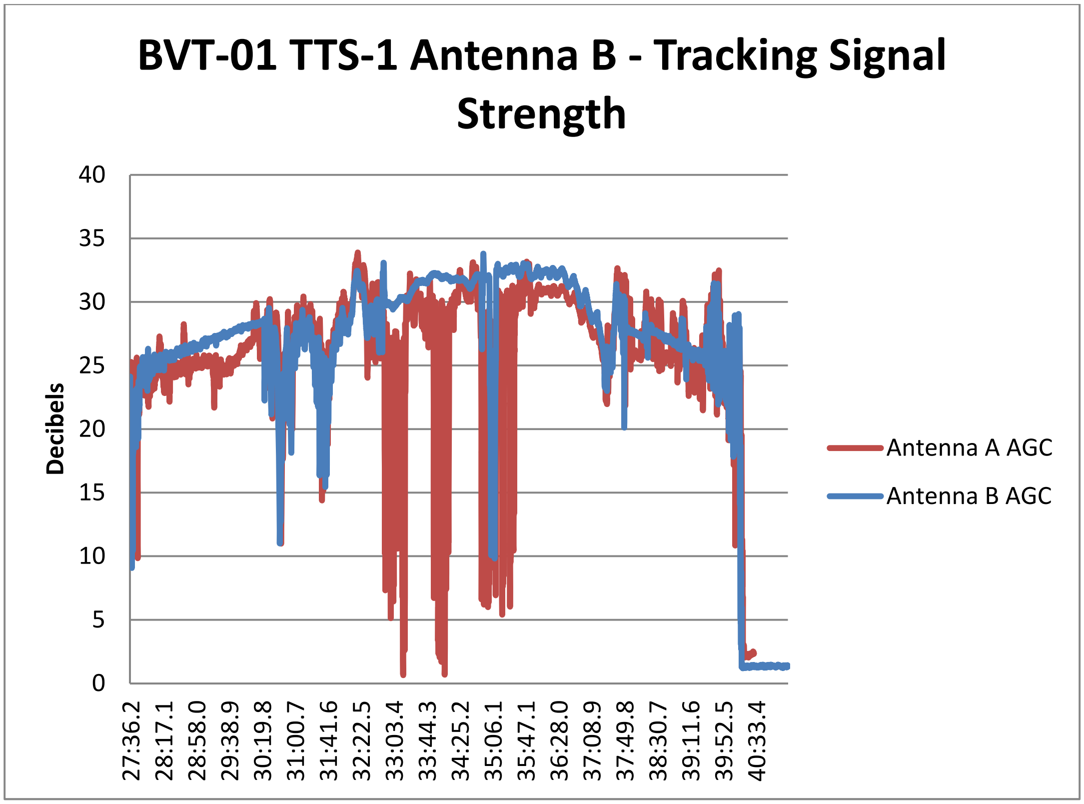
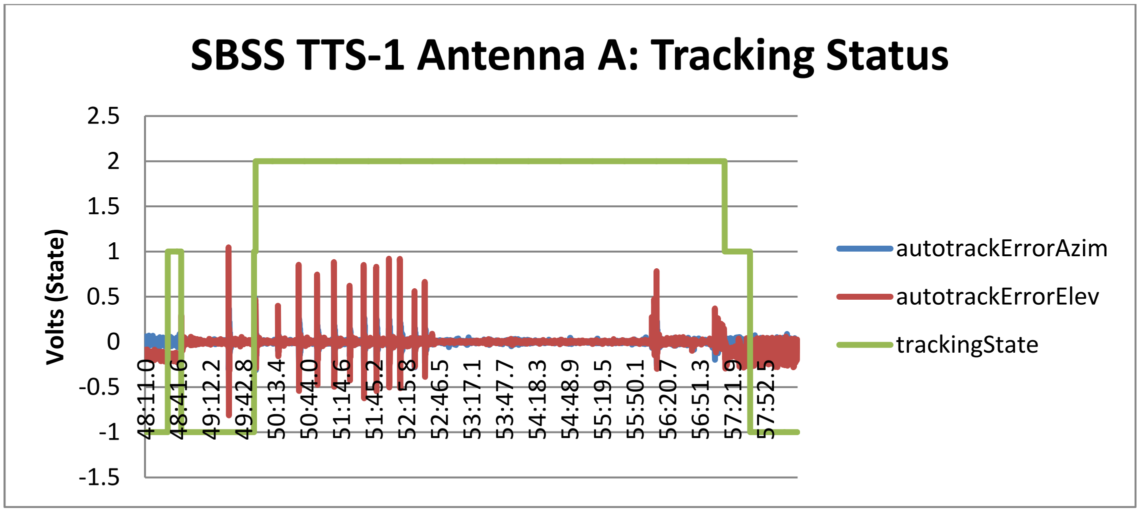


Figure 17. Tracking signal strength of both antennas during the BVT-01 event (From TTS-1, Jun 2010)

Every plot hints at the fact that something with Antenna A was not right. Nonetheless, the systems were believed to be in good working condition due to the nominal readings operators were finding using the usual system checks. Next, we will examine similar plots but for that of the SBSS event, the one prior to FTG-06A.

The SBSS mission took place in October of 2010. The data analysts reported "pristine" data, and again the system was thought to be in perfect working condition. The following plots, Figures 18 through 21, provide a more revealing story when the two TTS-1 antennas are compared to each other.



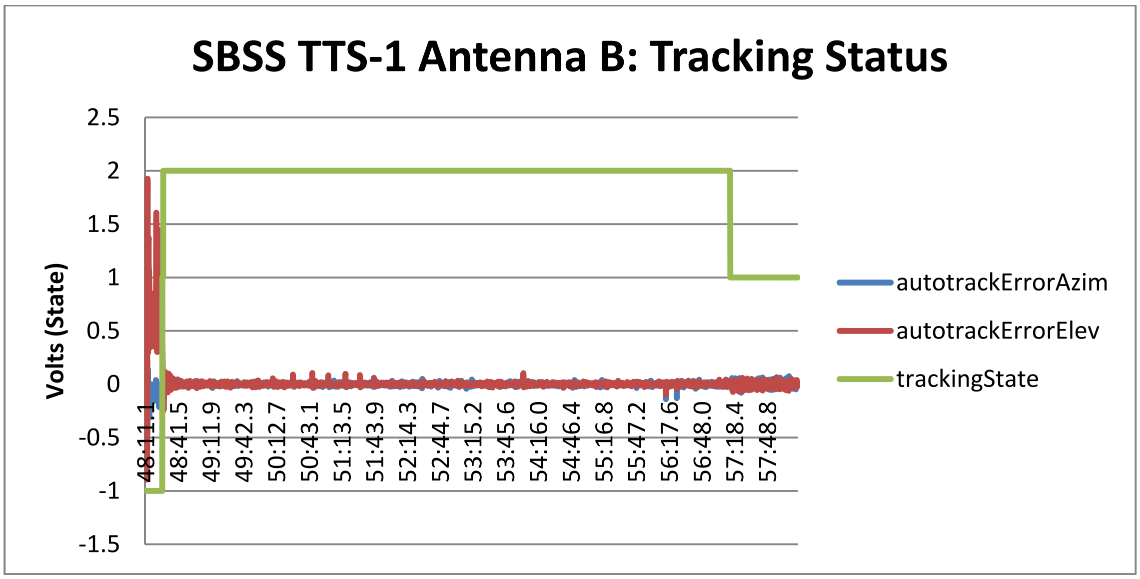
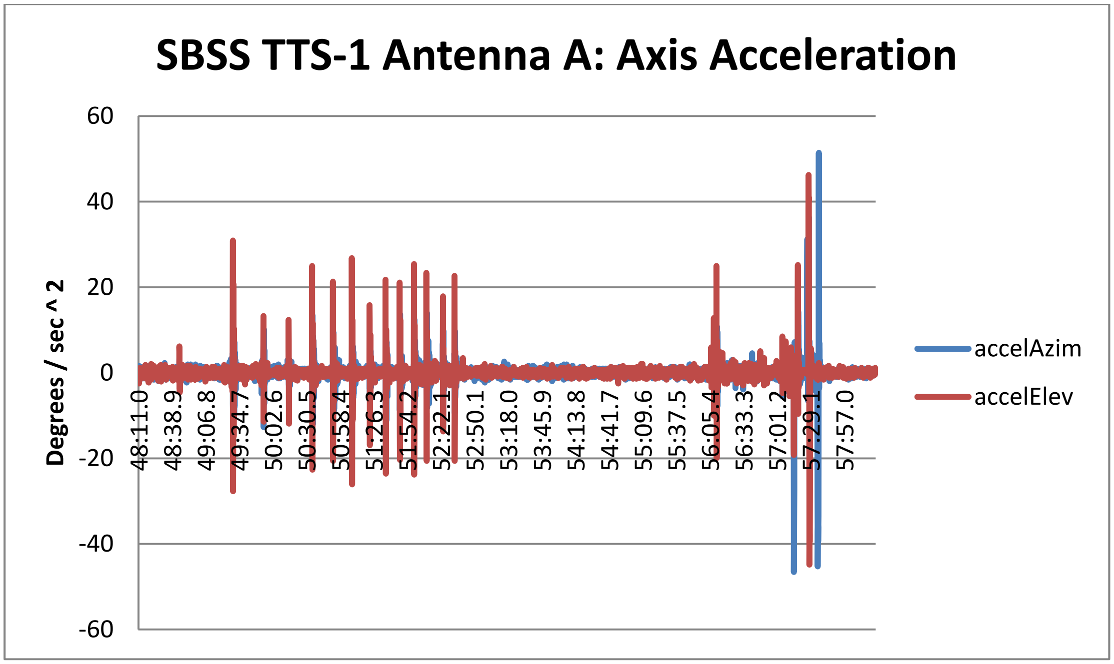


Figure 18. Tracking status plots for the SBSS mission event (From TTS-1, Oct 2010)

Figure 18 shows that both antennas had a solid track throughout the missile flight once they both switched to auto-track mode. However, antenna A showed signs of struggle even though it never lost track once the target was acquired. This can happen when the antenna is slightly off bore sight, yet maintaining the target within its main beam width. Therefore, the antenna will still collect good quality data even though it was slightly off at times.



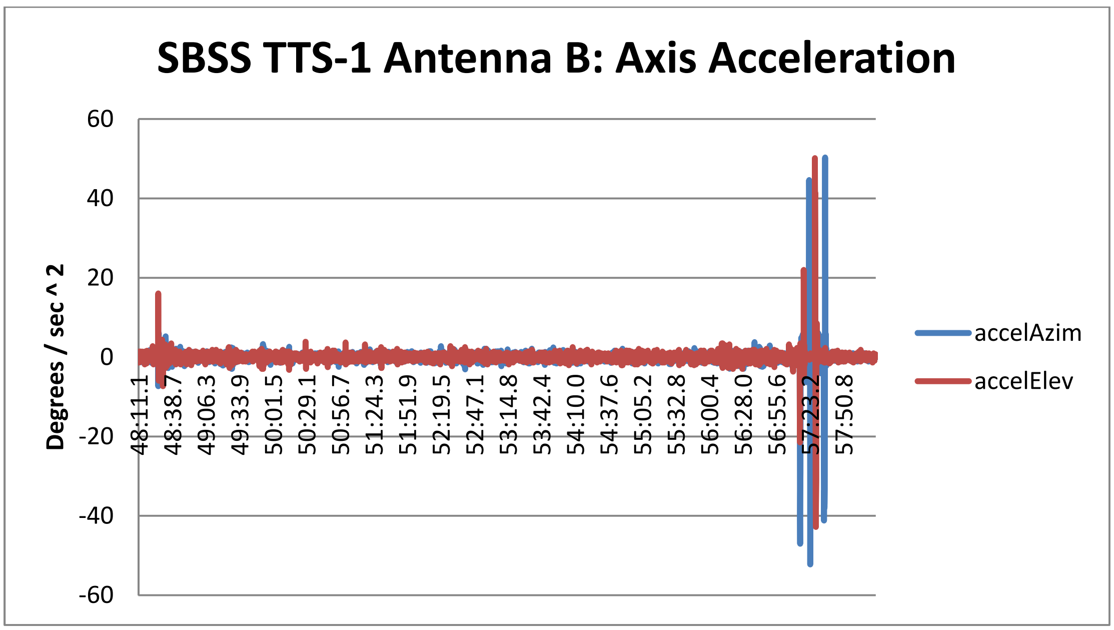
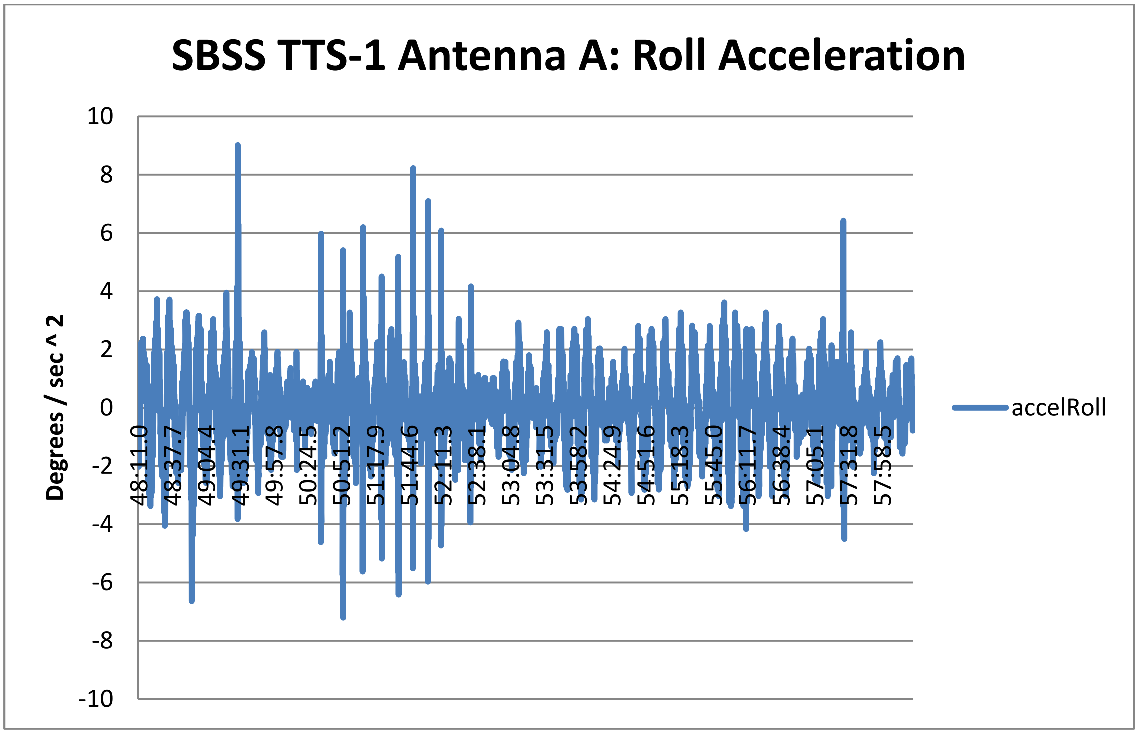


Figure 19. Axis acceleration plots for the SBSS mission event (From TTS-1, Oct 2010)



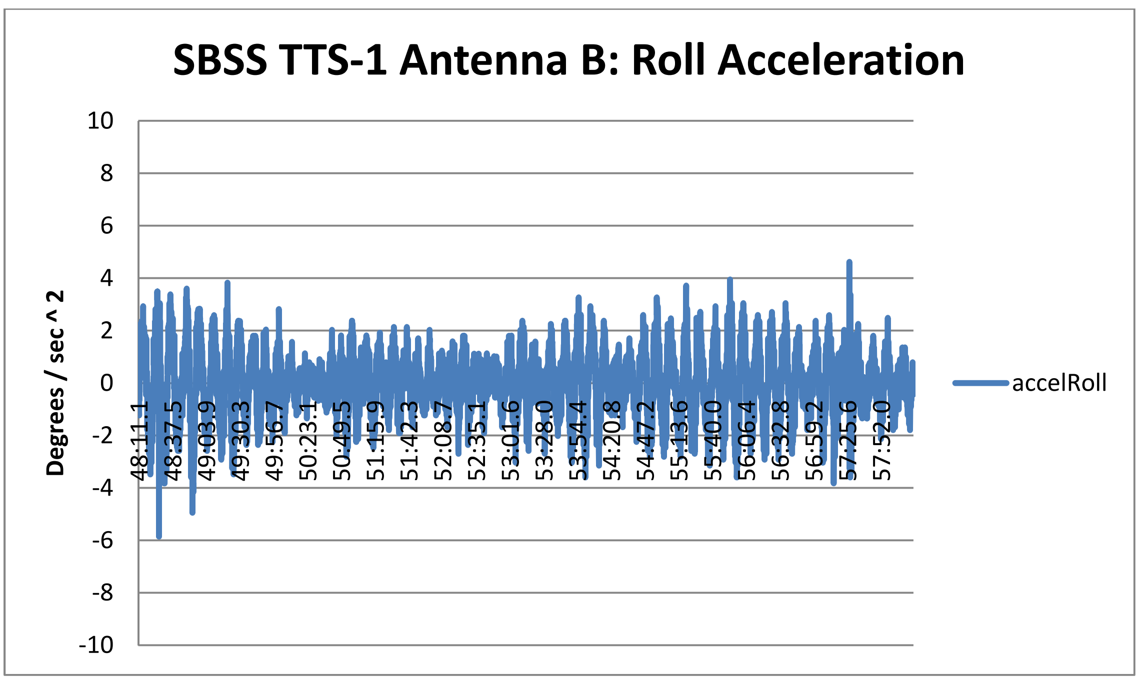


Figure 20. Roll axis acceleration plots for the SBSS mission event (From TTS-1, Oct 2010)

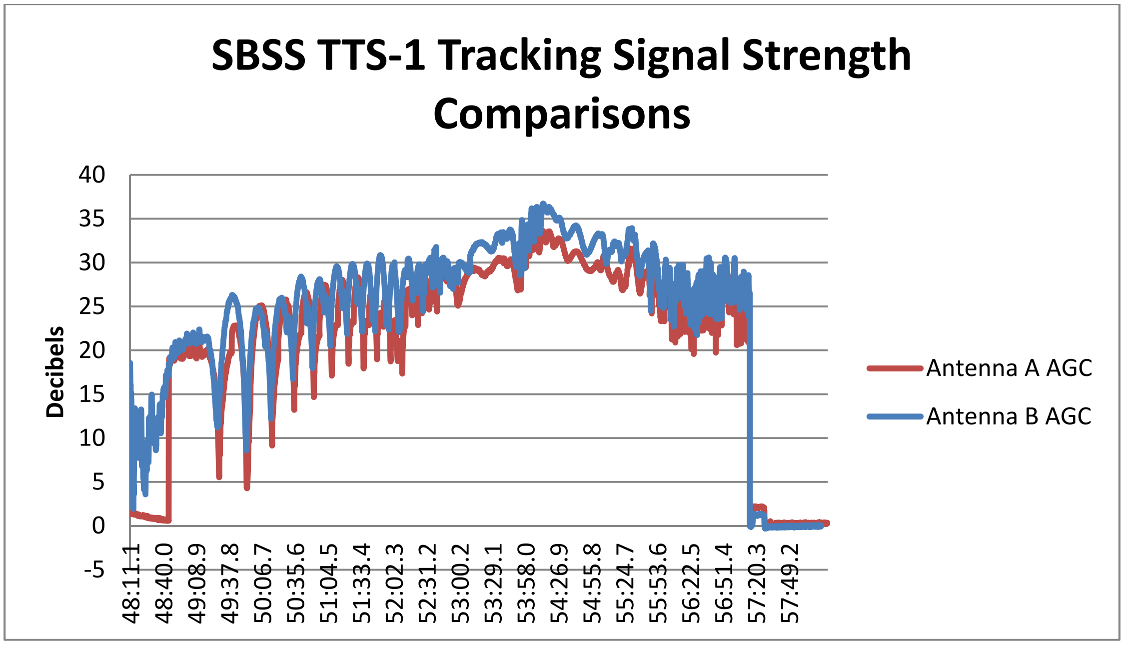


Figure 21. Tracking signal strength comparisons for the SBSS mission event (From TTS-1, Oct 2010)

Like in the case of the BVT-01 mission, SBSS displayed similar results. Antenna A was showing signs, or symptoms, of an anomaly. The periodic glitches seen in the auto-track errors are signs of something mechanical starting to jam. Antenna A was also showing lower levels of signal strength that could have been related to a faulty LNA inside the feed or a direct result of the antenna struggling to maintain accurate pointing to the missile in flight. Clearly, this is valuable information that telemetry operators could have used at the time to begin a troubleshooting investigation as to why the performance of antenna A was degraded.

D. TIMELINE AND DATA ANALYSIS FOR FAILURE #2

Let us now focus on the TTS-2 system, which is identical to TTS-1, but on a different ship, the S. S. Pacific Tracker. Table 3 describes the timeline of missions supported by TTS-2.

Mission Event	Launch Date
AHW-01	November 16, 2011
FTI-01	October 11, 2012

Table 3. Timeline of mission events in 2011–2012

For every mission both sea-based systems support, the ships they reside on still have to voyage back to port once the missile has been tracked and data collected. This can take anywhere from a few days to a couple weeks. While en route, the TM operators run post-mission checks on the systems by performing solar calibrations and tracking available satellites. Once the ships arrive in port, hard copies of data deliverables are shipped out and post-mission maintenance begins. The TM operators wash down the antennas, lubricate them when necessary, and perform every system check again to ensure that the systems are in good health, operational, and ready for the next mission.

While TTS-2 was sailing back to port after supporting FTI-01, a problem was discovered during the post-mission checkouts. During solar calibrations, the antenna was not pointing at the sun when instructed to. It was off by a few degrees. After some troubleshooting, it was discovered that the roll axis was slipping and not allowing the antenna to compensate for the ship's roll movement due to the ocean. Further root-cause investigations had to wait until the ship arrived in port.

Once in port, personnel discovered that a gear in the roll axis gearbox had cracked. When the motor tried moving the roll axis via its gearbox, the shaft simply rotated in place. The cracked gear could hold no torque and therefore the roll axis was not going to move. It was fortunate that this occurred after mission support, which gave the team the time to find a solution to the problem. Like in the previous section, this paper will analyze ACU tab file data from events leading up to this failure and see if symptoms are apparent.

Data from the AHW and FTI-01 missions will be analyzed. These two missions were supported without a record of any problems having occurred and data collection was successful. The goal here is to identify a pattern in the data that would have been able to alert TM operators of an oncoming failure.

Figure 22 shows that the tracking status plots for both antennas look very similar and have no significant difference. Both antennas seem to have tracked rather well throughout the trajectory. As stated previously, these kinds of plots will tend to be noisy to some degree early on and late in the track. This is due to the fact that at low elevation angles, the antennas will be affected by multi-path, or RF reflections, off the ocean that will interfere with the actual signal.

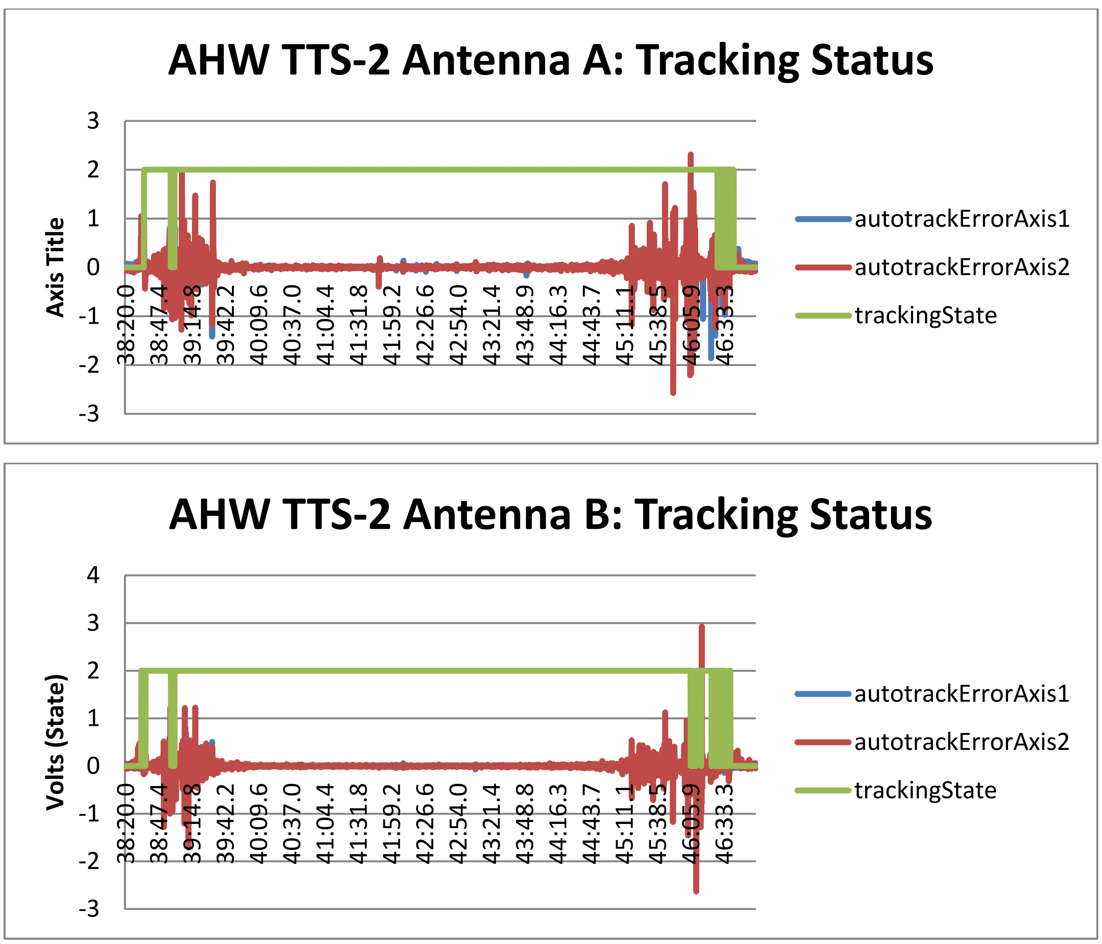
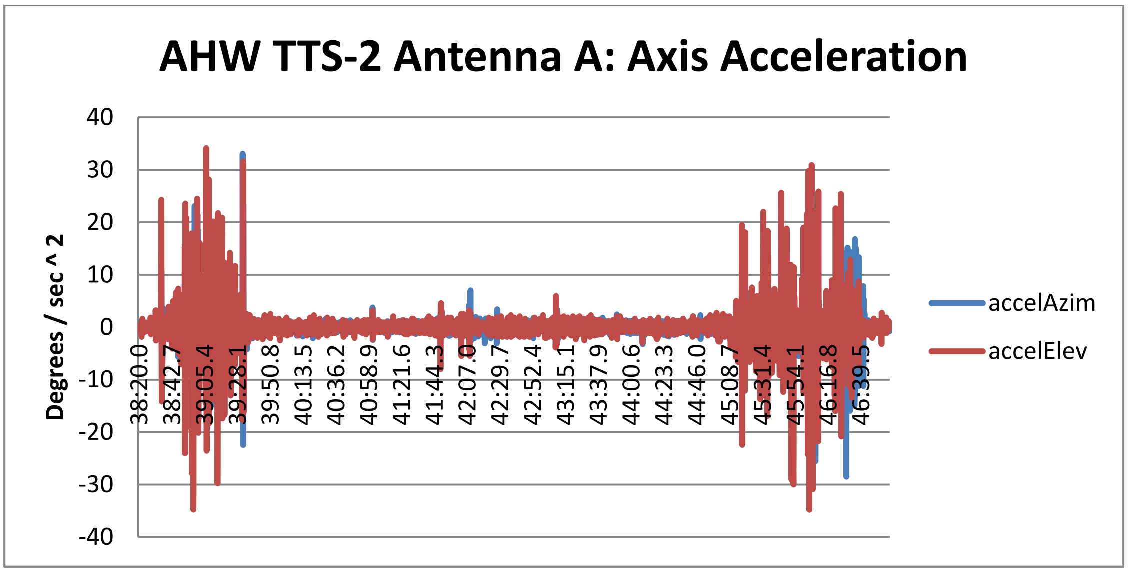


Figure 22. Tracking status comparisons for the AHW mission event (From TTS-2, 2011)

The axis acceleration plots, shown in Figure 23, also provide no proof of a grave symptom lurking around. Although antenna A seems to be a bit noisier, it is nothing significant and both antennas seem to have had a smooth track along the azimuth and elevation axes. The plots for tracking signal strength (not shown) are also very similar and have no significant differences between the two antennas. The next plots will focus on the roll axis, which is the antenna part that experienced the failure.



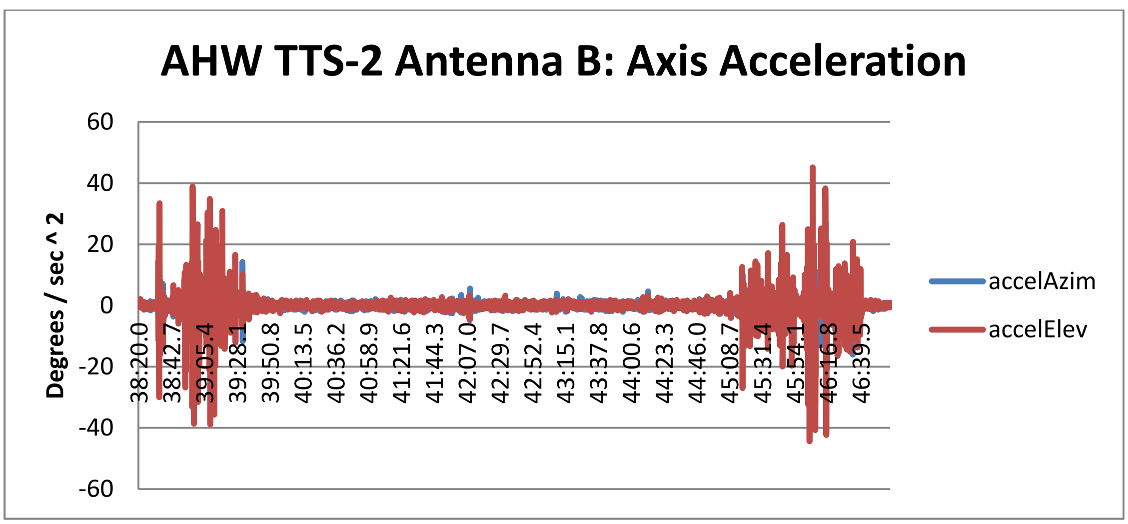
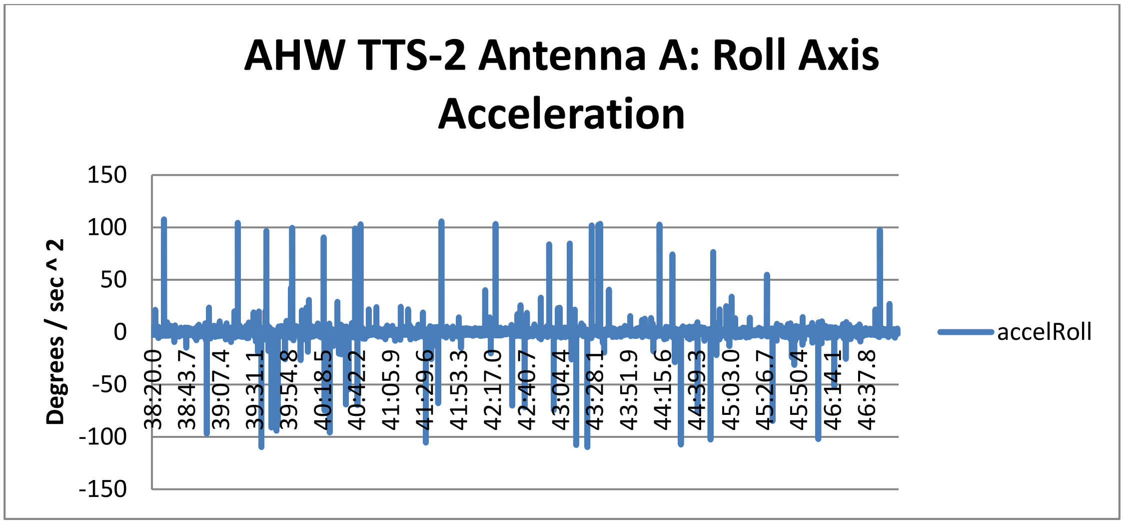


Figure 23. Azimuth and Elevation axis acceleration comparisons for the AHW mission event (From TTS-2, 2011)

Contrary to what the previous plots have shown, the roll acceleration plots in Figure 24 display a significant difference between antennas A and B. There is clearly something going on with the roll axis of Antenna A, which is where the failed gearbox came from almost a year later.



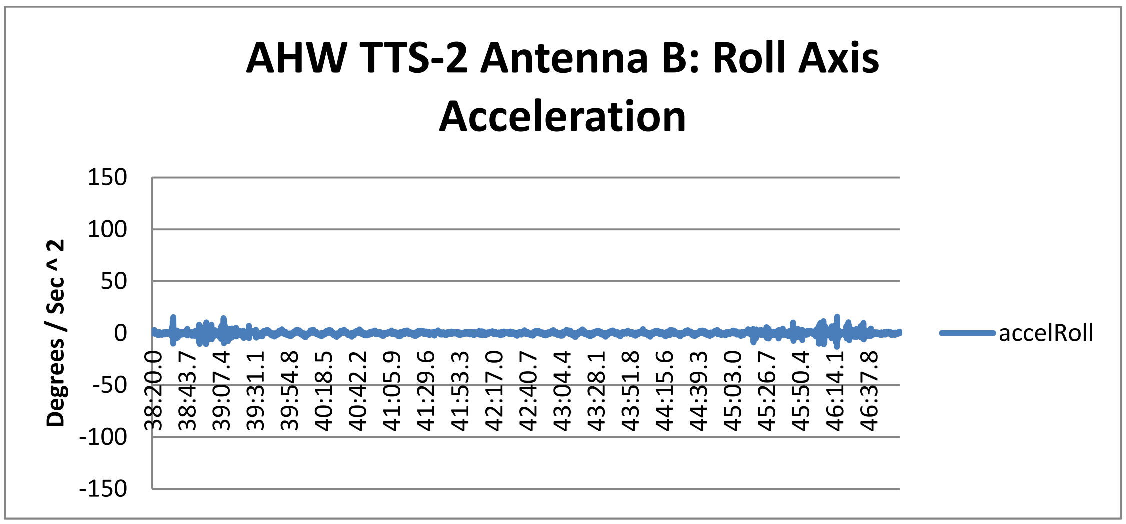


Figure 24. Roll axis acceleration comparisons for the AHW mission event (From TTS-2, 2011)

This is an exciting find that lines up with the hypothesis being presented in this paper. With this type of advanced warning, TM operators can begin investigating what the source of the symptom is. At the very least, spare parts can be ordered and made available in anticipation of a failure.

Next, similar plots will be presented in Figures 25 through 27 for the FTI-01 mission, which is the event TTS-2 supported just before experiencing the failure with the roll axis on antenna A.

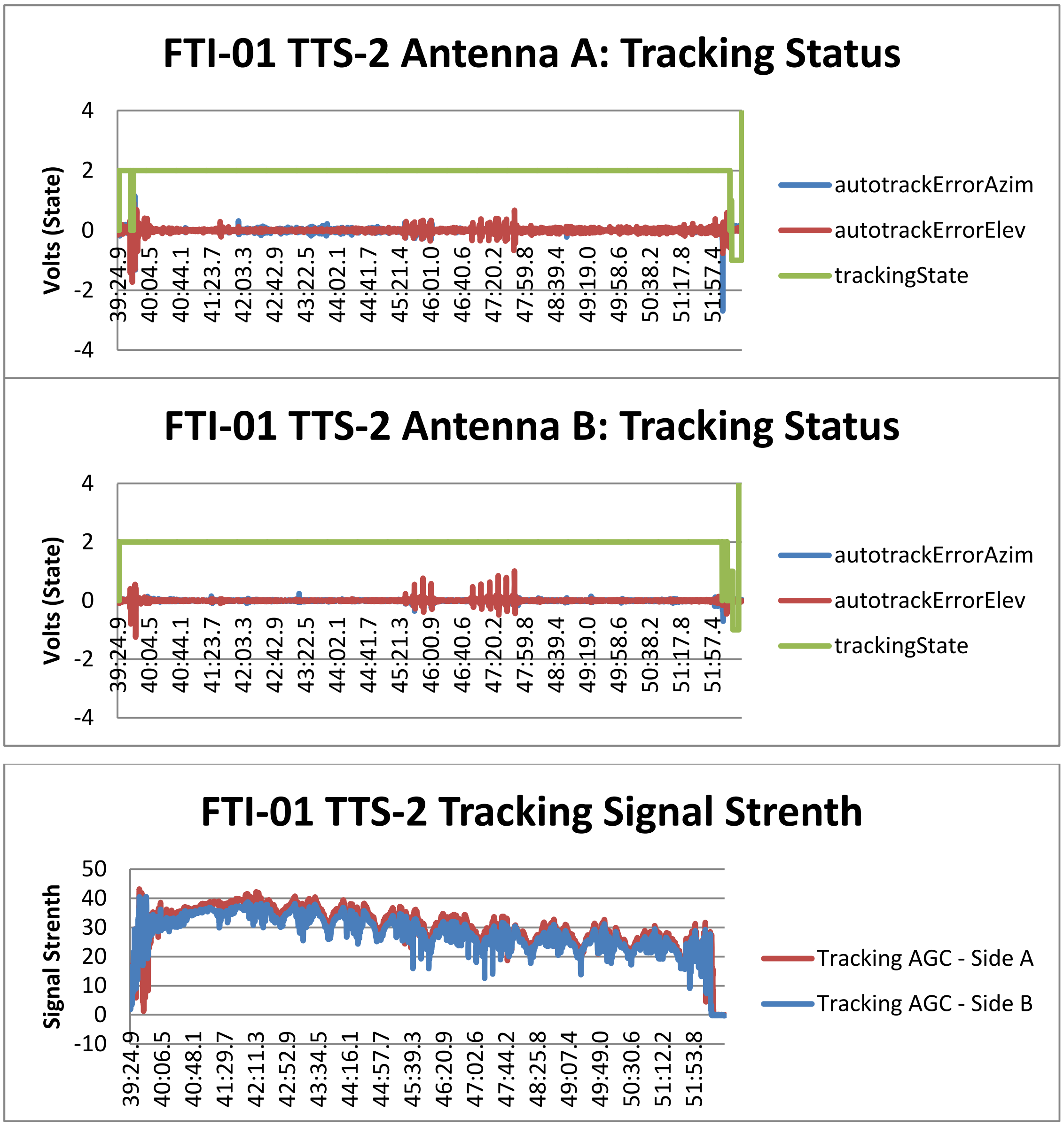


Figure 25. Side by side comparison of tracking status and RF signal strength for the FTI-01 mission event (From TTS-2, 2012)

After reviewing the previous plots for FTI-01, both antennas seemed to have performed well with no significant difference between the two. We will continue with the remaining plots to see if the results match what was found in the data from the AHW mission.

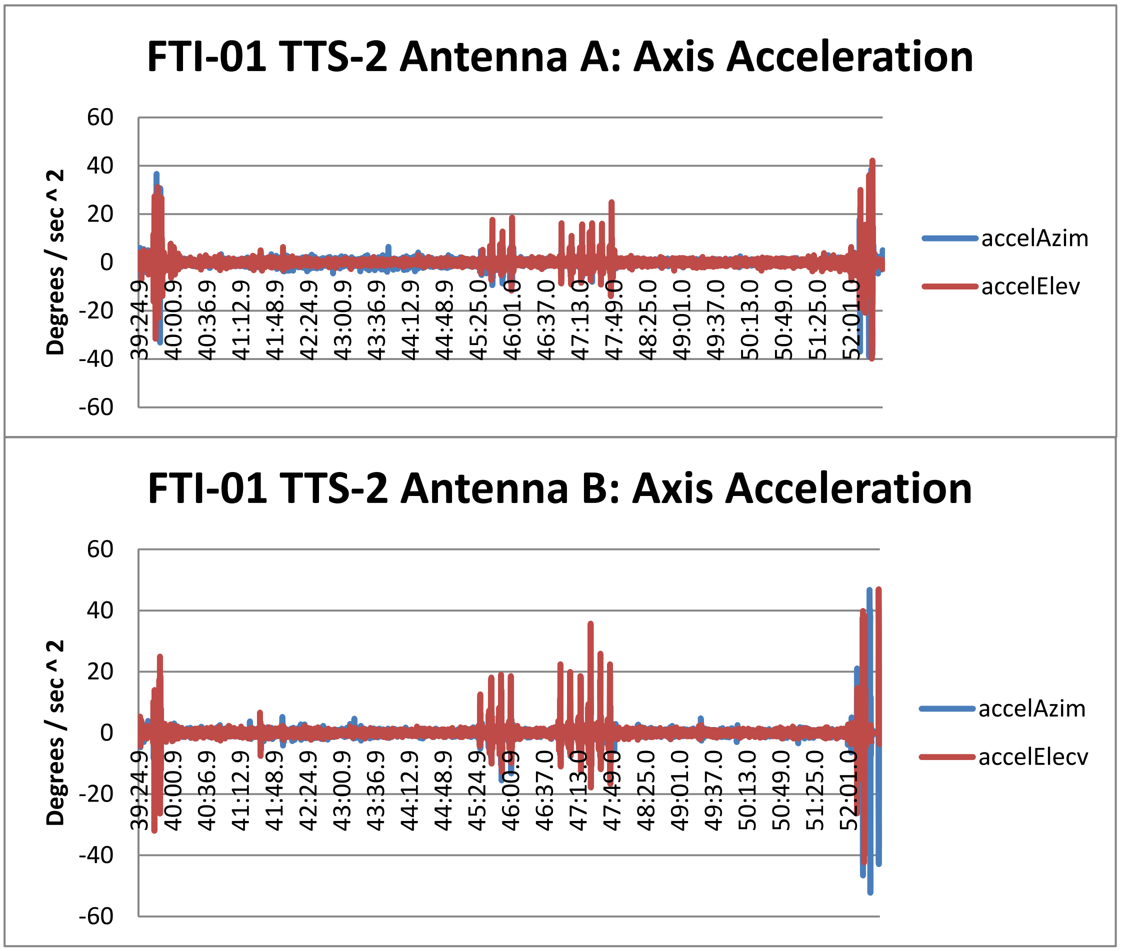


Figure 26. Axis acceleration comparisons for the FTI-01 mission event (From TTS-2, 2012)

The axis acceleration plots do not show much difference in performance between the two antennas. The two instances where the acceleration goes unstable coincide with the auto-tracking errors displayed in Figure 25. This occurrence seems to be more of an RF disturbance coming from the source, most likely due to the spin of the missile than a mechanical issue with the antenna.

Thus far, all the FTI data depicts two healthy antennas performing a mission track with no anomalies. The next plots in Figure 27 will be the ones depicting the roll axis acceleration.

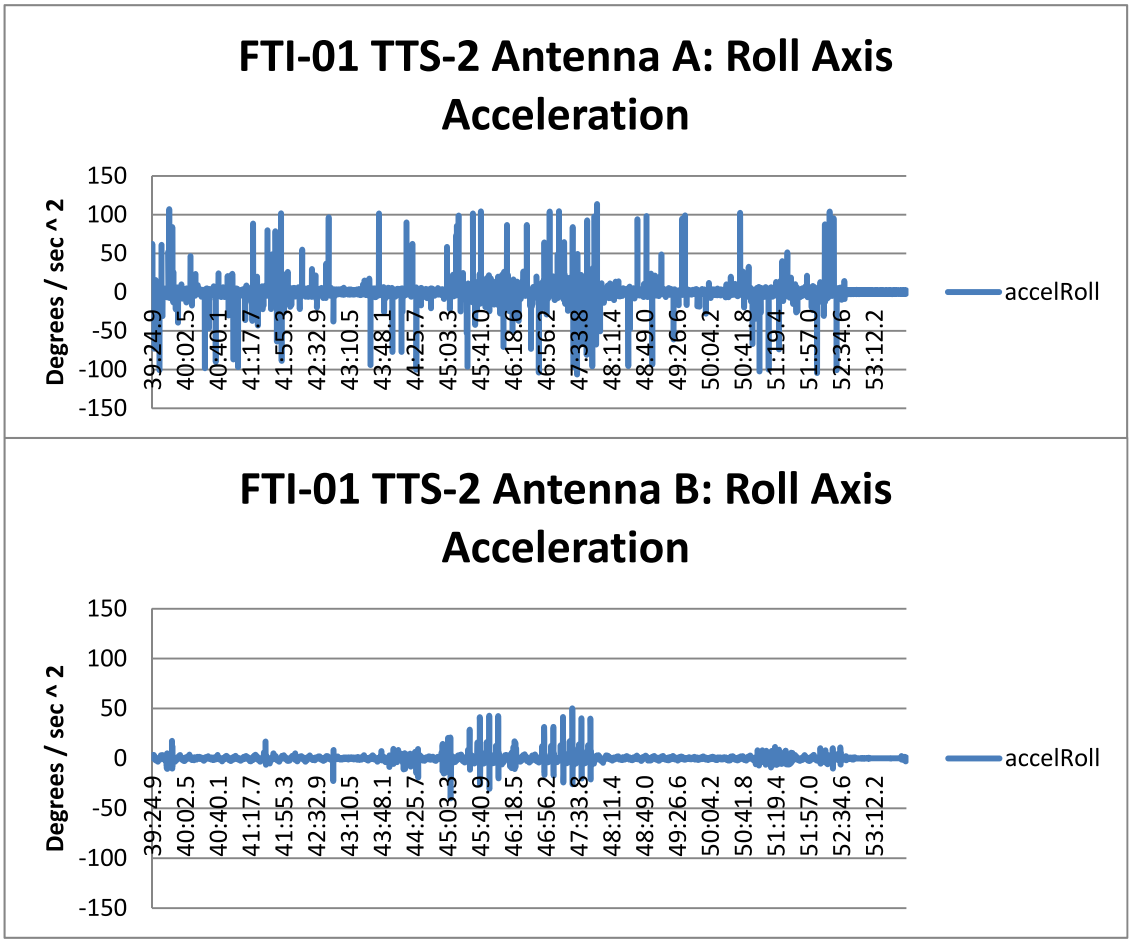


Figure 27. Roll axis acceleration comparisons for the FTI-01 mission (From TTS-2, 2012)

The roll axis acceleration plots once again provide a clear indication that something is not right with the roll axis on antenna A. The results are almost identical to what was seen in the data for the AHW mission. As stated before, shortly after the FTI-01 mission the roll axis on antenna A suffered a critical failure and the interesting fact is that there were warnings in the data pinpointing the symptoms all along. This is another example where careful analysis of the ACU tab files could have better prepared the TM operators for this occurrence.

E. MISSION PERFORMANCE STANDARDIZATION

The previous two sections broke down two past critical failures in the history of TTS support, one happening to each sea-based system. After analyzing the tab file data produced prior to each failure, evidence was found that symptoms did exist prior to the actual failure. By taking advantage of the fact that we have two identical antennas per system performing the same exact tasks, this allows us to make valuable side-by-side comparisons that would be impossible with any other single antenna system. Over time, data patterns for certain failures can be identified and used for developing accurate prognosis for different telemetry trackers everywhere.

The next step is to standardize the way the data is presented so that historical trends can be more easily identified. This may also assist in assessing the performance of a telemetry system when it supports mission events. As the TTS program manager at White Sands Missile Range (WSMR), I will implement a plan for performing tab file analysis for every event each system supports. For this to be useful, a standard way of presenting the analysis will have to be devised. The following pages will describe the method that the TTS team at WSMR will use to present the tab file data collected.

Each system mission lead will now have the responsibility of collecting, analyzing, and presenting tab file results to the rest of the team. The types of plots that will be presented at these meetings will be identified below. By maintaining the same format, along with detailed notes of observations, lessons learned, and anomalies, identifying trends in the long run should become a more feasible task. Every tab file analysis will be archived for future reference.

Random sample data will be used below for illustrative purposes to show how a power point presentation will be prepared and organized in the future. This will represent the tab file analysis document that will be archived.

TAB File Data Analysis Presentation

1. Introduction slide - Text
2. Mission description and TTS system objectives - Text
3. Observations and anomalies - Text
4. Antenna A & B tracking AGC (Signal Strength) on same chart, as shown in Figure 28.

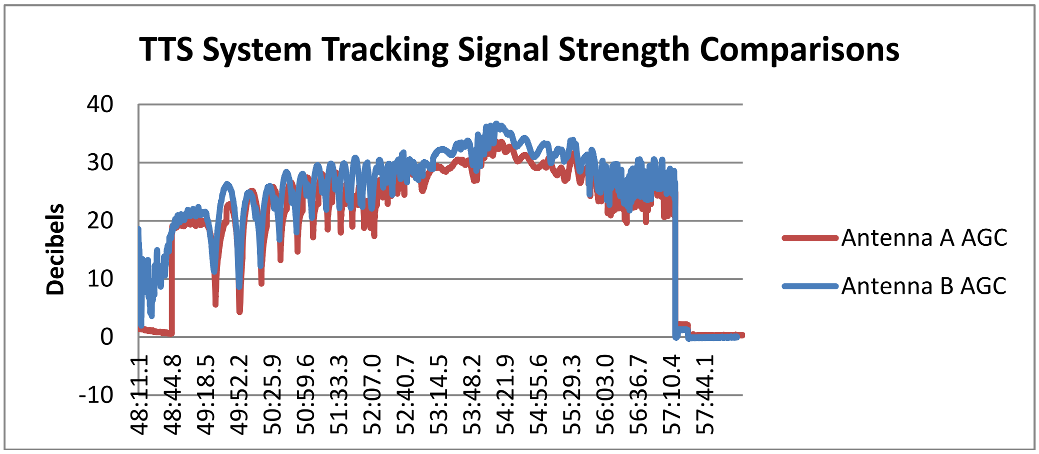


Figure 28. Tracking signal strength comparisons will provide a side-by-side look at how much RF energy the antenna was able to capture during the track of the target.

5. Mission track antenna pointing angles for both antenna A and B, as shown in Figure 29.

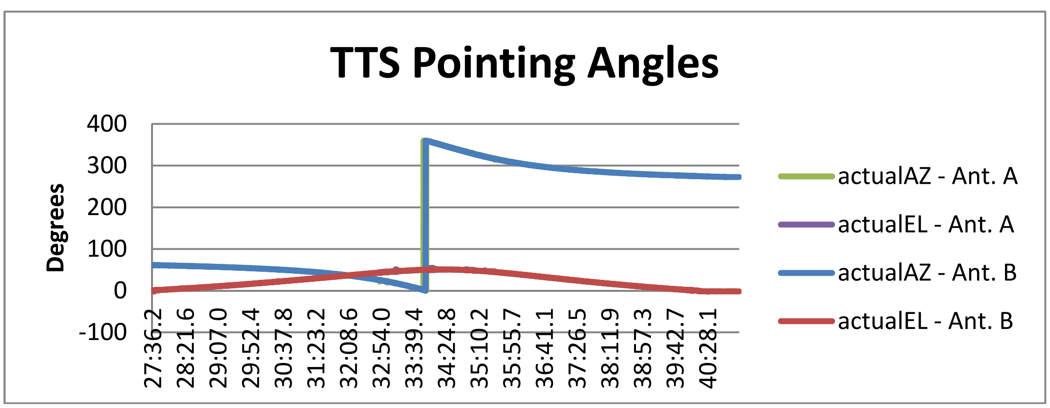


Figure 29. Pointing angles for both antennas verifies that both antennas tracked in an identical pattern.

6. Antenna A tracking errors and auto-track state, as shown in Figure 30.

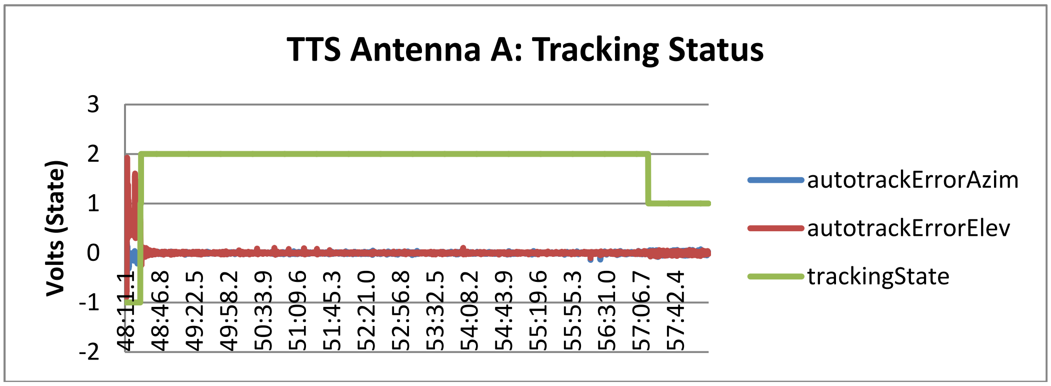


Figure 30. Tracking status will provide data on how accurately the antenna pointed to the target. This plot will also show whether or not the antenna was able to maintain auto-track.

7. Antenna B tracking errors and auto-track state

- Same as #6 but for antenna B

8. Antenna A azimuth and elevation axis accelerations, as shown in Figure 31.

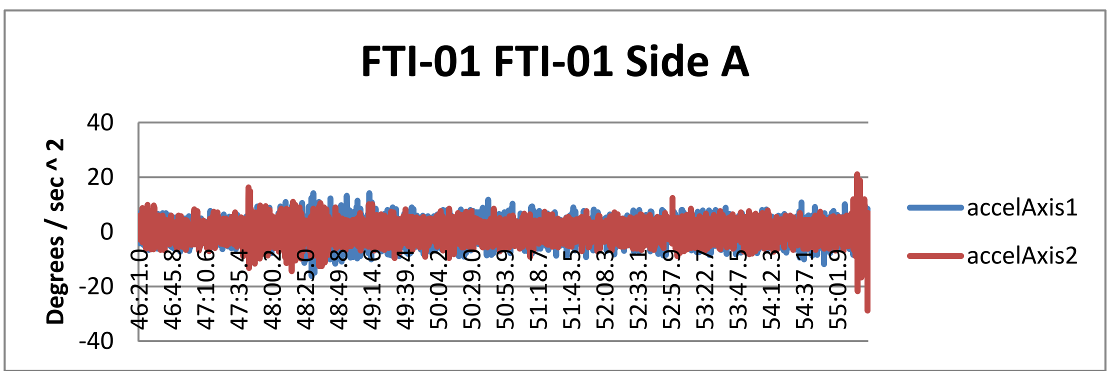


Figure 31. This plot will provide azimuth and elevation axis accelerations for antenna A

9. Antenna B azimuth and elevation axis accelerations

- Same as #8 but for antenna B

10. Antenna A roll axis acceleration, as shown in Figure 32.

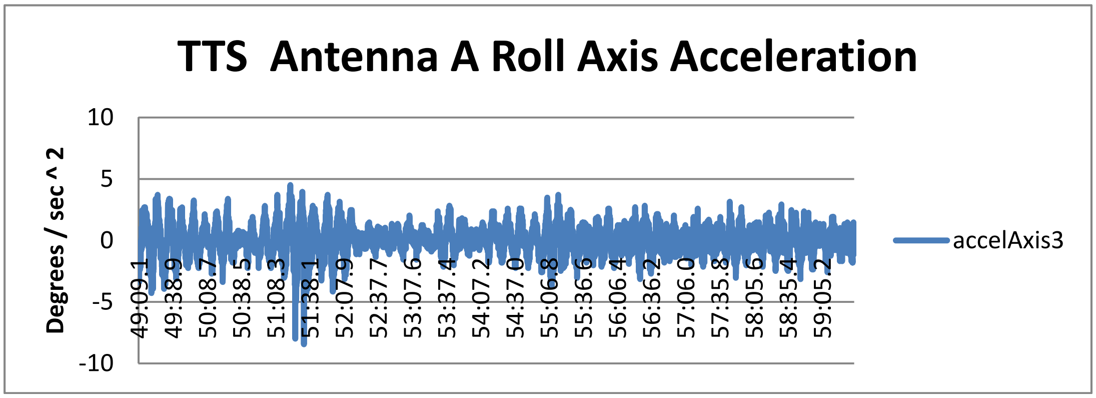


Figure 32. TTS Antenna Roll Axis Accelerations will provide roll axis accelerations for antenna A

11. Antenna B roll axis acceleration

- Same as #10 but for antenna B

12. Ship's roll (can be taken from either antenna's file), as shown in Figure 33.

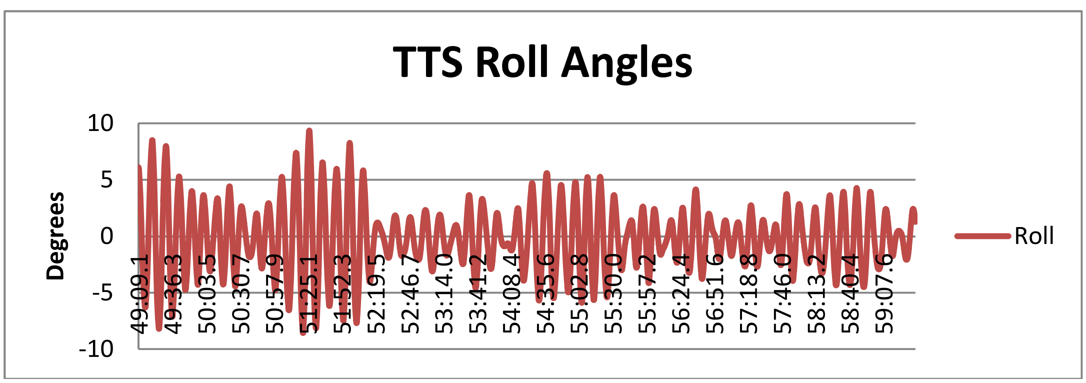


Figure 33. TTS roll angles will provide insight as to the ocean's conditions endured during the mission track by the antennas and support personnel.

13. Interpretations and conclusions (text)

The format described above, by which the data will be organized and presented, may change and evolve over time, depending on future findings and/or if better methods are discovered. With time, as TTS engineers and operators become more familiar with the data plots, anomalies will become easier to spot providing clues to the true health of the system. So long as the data is analyzed and interpreted on a continuous basis, the potential will always exist to find patterns in the data that match up to certain part failures.

V. CONCLUSION

A. HYPOTHESIS

The hypothesis outlined in this paper states that the great majority of tracking system failures exhibit symptoms prior to a complete system breakdown. The ACU tab file data presented here confirms that for the two scenarios described, indications in the data of an oncoming failure were evident. Although two specific failure events do not provide a sufficient sample size to characterize all telemetry trackers, the potential for isolating problematic components by analyzing historical tab file data is very real. Performing this type of analysis is nonintrusive and has no negative impacts. This can only provide benefits and additional detail about the performance of the system.

By identifying potential issues in the early phases, symptoms can be isolated and resolved before they become critical and/or catastrophic failures. By continually analyzing the tab files for each antenna system, historical data trends can become more easily identifiable by applying continuous process improvement techniques. Over time, symptoms of potential failures can be more easily recognized, remediated in advance, and overall system downtime will be reduced.

B. RECOMMENDATIONS

This paper described two particular cases in the history of the sea-based TTS systems. This is hardly the sample size necessary to make conclusive matches between data patterns and system failures. Nonetheless, the data presented here did prove that symptoms of an underlying problem can make a presence in the tab files. If this type of data analysis became a standard amongst test ranges utilizing tracking systems, much more data would become available.

If multiple ranges began documenting critical failures and performing tab file analysis on data leading up to that anomaly, much more insight would be gained as to the relationship between the data patterns and the failures. The question now is, "How do we get all these ranges to sign up for this?" It is the author's intent to one day submit a paper and present this topic at the International Telemetry Conference (ITC). This conference is the perfect forum for disseminating these ideas effectively to ranges utilizing similar systems. The TTS program at WSMR will begin to implement this type of analysis, as described in Chapter IV, and discuss this idea with colleagues as opportunities permit.

C. FINAL THOUGHTS

Test ranges, such as White Sands Missile Range, typically employ multiple telemetry tracking systems several times a week for testing various Department of Defense (DoD) weapons programs. Very few, if any, perform ACU tab file analysis on a continuous basis. In an effort to reduce system down-time, test ranges have the opportunity to strive toward a maintenance strategy that encourages proactive measures over reactive ones. It is a consensus that it is not cost efficient to wait for a system to fail before addressing any concerns and tab file analysis is an excellent method for identifying issues in the making. This paper has presented data analysis supporting the fact that ACU tab file analysis can assist in detecting issues and critical failures much in advance, providing supporting personnel with valuable time to do something about it. As this type of analysis becomes standard operating procedure within the TTS program, the expectation is that system performance will be better characterized as system downtime becomes a less frequent event.

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