Use of a Closed-Loop Tracking Algorithm for Orientation Bias Determination of an S-Band Ground Station

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***Abstract*—The Space Communications and Navigation (SCaN) Testbed project completed installation and checkout testing of a new S-Band ground station at the NASA Glenn Research Center in Cleveland, Ohio in 2015. As with all ground stations, a key alignment process must be conducted to obtain offset angles in azimuth (AZ) and elevation (EL). In telescopes with AZ-EL gimbals, this is normally done with a two-star alignment process, where telescope-based pointing vectors are derived from catalogued locations with the AZ-EL bias angles derived from the pointing vector difference. For an antenna, the process is complicated without an optical asset. For the present study, the solution was to utilize the gimbal control algorithm's closed-loop tracking capability to acquire the peak received power signal automatically from two distinct NASA Tracking and Data Relay Satellite (TDRS) spacecraft, without a human making the pointing adjustments. Briefly, the TDRS satellite acts as a simulated optical source and the alignment process proceeds exactly the same way as a one-star alignment. The data reduction process, which will be discussed in the paper, results in two bias angles which are retained for future pointing determination. Finally, the paper compares the test results and provides lessons learned from the activity.**

I. Introduction

In 2015, the Space Communication and Navigation (SCaN) Testbed Project completed installation and checkout testing of a new S-Band Ground Station at the NASA Glenn Research Center in Cleveland, Ohio. One aspect of checkout testing the GRC Ground Station (GRC-GS) was the derivation of misalignment angles associated with the installation of the gimbal to its roof-mounted pedestal.

The gimbal associated with the GRC-GS is a two-axis Elevation (EL) over Azimuth (AZ) gimbal with motion constrained to prevent a roll axis, which is mounted on a roof-top platform pedestal to physically secure the system. Ideally, the gimbal is mounted such that a) its internally defined AZ axis 0° angle location is co-located with the vector direction of true North and b) the EL 0° location is co-located with zenith. However, there are several limitations that prevent mounting the gimbal in an ideal configuration. These include platform orientation mounting locations on the gimbal base, and roof slope. These limitations create bias angles that must be understood to accurately point the antenna. Therefore, it is essential to precisely define the bias angles as they relate to the gimbal's AZ 0° position with true North, as well as the EL 0° position with zenith, as illustrated in Figure 1. Determining these angles must be completed to declare the ground station operational.

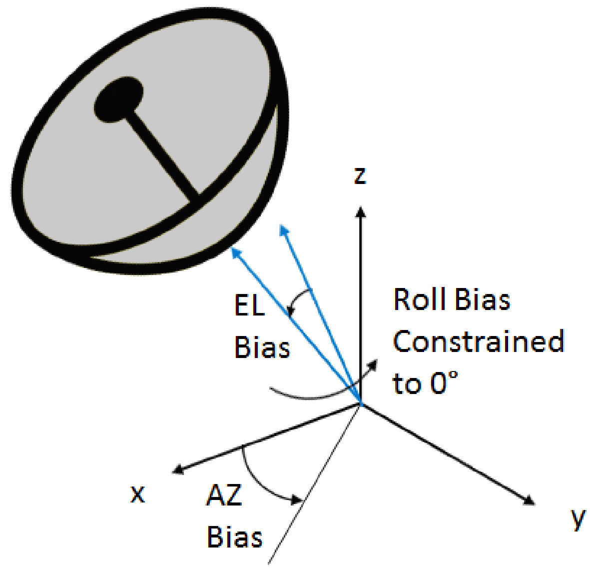

Figure 1. GRC-GS Antenna Bias Angles of Interest

II. GRC-GS Description

The GRC-GS built at the NASA Glenn Research Center is a multi-node system with the antenna located on the rooftop of the Space Experiments Laboratory and the control location at Power Systems Facility Telescience Support Center, as shown in Figure 2 on the right and left sides of the aerial view, respectively. This was done to optimize coverage contacts to its primary target, the SCAN Testbed payload onboard the International Space Station (ISS), while operating from a control location shared with the SCAN Testbed operators.

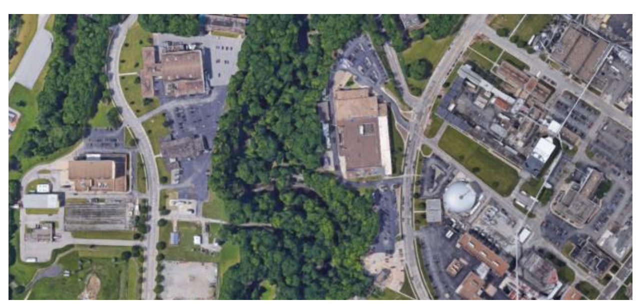

Figure 2. GRC-GS Locations on the GRC Campus

The Space Experiments Laboratory rooftop location for the gimbal/antenna was selected to provide a vantage point that was relatively free of obstructions such as other buildings and tree-lines, while providing rooftop access via stairwells. Figure 3 shows the view from the platform on the roof.

Eastward View

Westward View

Figure 3. Views from GRC-GS Platform

The equipment located at the platform for the GRC-GS in total is the gimbal, antenna, weather station, GPS receiver, cameras, Radio Frequency (RF) Transmit (TX) enclosure, and an RF Receive (RX) enclosure, as shown in Figure 4. The weather station provides pertinent temperature and wind data at the platform location, while the GPS receiver is used to pull time information for synchronizing the GRC-GS computers at each location. The RF TX enclosure houses the diplexer, power amplifier, and diplexer switch, which allows the GRC-GS to swap the frequency function of the system to allow transmission to either the payload or the NASA Tracking and Data Relay System (TDRS) satellites. The RF RX enclosure houses the first Low-Noise Amplifier in the RX signal chain, as well as a debug system loop-back switch [1].

Figure 4. GRC-GS Platform

The primary equipment of interest for this discussion is the gimbal and the antenna. The gimbal is a Moog QPT-500 Positioner which has 420° AZ range of motion and 180° EL range of motion. It can run up to 20°/s in AZ and 4°/s in EL, which is very useful due to the high slew rates associated with tracking the ISS.

The antenna, which is mounted to the gimbal, is a 2.4m General Dynamics parabolic dish using a QPar left hand circular polarized feed. At the S-Band frequencies between 2 GHz and 2.4 GHz, the antenna has a full half-power beamwidth of roughly 3.9°. The antenna, as seen in Figure 4, is mounted to be co-aligned with the gimbal. Previous testing in the GRC Near-Field was performed with the GRC-GS antenna mounted to the gimbal. This was done both to characterize the antenna pattern, as well as to determine if the center-fed parabolic antenna showed any misalignments in peak antenna gain direction, due to mounting and/or deformation. Results of that testing showed that the main beam was not skewed in AZ or EL [1]. This eliminates a single source of alignment error from the overall alignment problem as shown in Figure 1 and simplifies a portion of the overall challenge of determining bias angles.

III. Alignment Processes

A common tool telescope-mounted gimbal manufacturers build into their control software is the ability to take GPS measurements, to provide the gimbal location and a timestamp, and then perform a routine called a two-star alignment. This is a process where the telescope searches for two distinct stars, to determine the necessary Roll, Pitch, and Yaw angle offsets needed to reference built-in star-maps. These maps are used whenever the telescope gimbal is commanded to point to a particular star [2]. The generic pointing problem should solve for bias angles in all three Cartesian rotation dimensions, however many telescope-mounted gimbal manufacturers also constrain the pointing problem to an EL over AZ setup, as is the case for the GRC-GS gimbal, as any pointing vector can be defined via two pointing angles, AZ and EL. The usage of additional stars allows for further reduction in the error while calculating the bias angles, in the same manner that incorporating additional measurements to a Kalman filter estimator improves the measurement uncertainty. For best performance, the stars are selected to be in distinctly different regions of the gimbal space, so the delta view angle between the stars is much larger in scope than the measurement error.

Alternatively, telescope-mounted gimbals can also perform a one-star alignment. This process focuses on one star, typically the North Star in the northern hemisphere, where the goal is primarily to determine the AZ offset only [3], as the process is constrained by the number of measurements available. For this type of alignment, it is assumed that the gimbal is mounted level to the ground and the telescope-mounted gimbal does not allow for Roll axis motion. The solution process can only numerically resolve a single error vector, and thus constraining the solution error to a single axis allows for a direct solution of the bias angle in that axis. This means the levelness of the mounting location must be independently verified before using a one star alignment process to limit the determined offset to be properly treated as the AZ bias solution. This one-star alignment problem is shown in Figure 5.

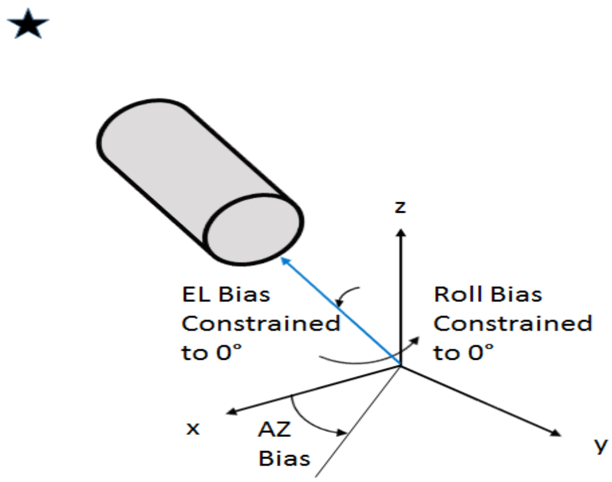

Figure 5. One-Star Alignment Example

IV. RF ALIGNMENT VIA TDRS

The alignment process used for the GRC-GS is similar in nature to the one-star alignment process. However the process was completed using numerous sources to try and minimize solution error, as is done in the process of the two-star (or more) alignment. Unlike telescopes, the GRC-GS would not observe stars as it is not an optical station. Instead it would use RF signals provided by the two TDRS spacecraft located in the TDRS East and TDRS Spare orbital slots off the US East Coast, with pointing command being driven by a Standard General Perturbations Satellite Orbit Model 4 (SGP4) propagator derived from TDRS Two-Line Element (TLE) information [4]. Use of these two spacecraft was not ideal in terms of pointing diversity, but provided two distinct opportunities to solve the bias angles, conceptually illustrated in Figure 6. Solving for the same angles using multiple sources is vital in reducing error as discussed above.

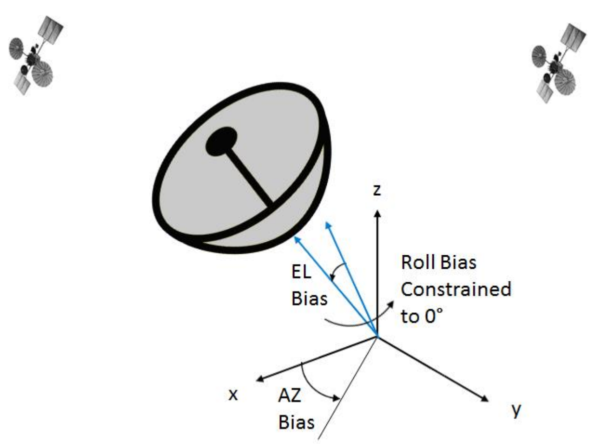

Figure 6. RF Two-Source Alignment Process

The measurements made by the GRC-GS were received power level measurements from the RX chain by a Spectrum Analyzer controlled as a power meter. These measurements are directly integrated into the closed-loop tracking algorithm that is part of the gimbal controller, where the closed-loop control is based on maximizing the RF signal obtained. The risk with this type of amplitude based response is that the closed-loop system can achieve false lock, such as if the gimbal locks onto the source while pointing to it via a side-lobe. To avoid such circumstances, it is important to know the predicted power levels of both the main lobe, as well as the maximum side lobes, such that a reasonable transition level can be set as the threshold, derived from link budget calculations of the TDRS transmit power and gain, path loss, GRC-GS received gain, and RX chain gains and losses in the path to the Spectrum Analyzer.

For the GRC-GS, the closed-loop controller operates in two distinct modes, based on the received power indicator measurement and the threshold point setting. The first mode is a spiral track search mode. This controls gimbal motion off the nominal trajectory in a rate/width controlled spiral motion. The rate controller parameter dictates the rate of speed along the track of the growing spiral, while the width controller parameter dictates the angular spacing between consecutive spiral laps. The spiral track search mode will continue to grow as long as the received power indicator is below the transition threshold, or will restart if the received power indicator transitions from above the transition threshold to below the transition threshold. Note that slightly different transition thresholds are used in each case so that mode changes are not inadvertently triggered. For example, the transition to go from spiral track to auto track is higher than the reverse transition.

The second closed-loop mode occurs when the received power level is above the transition point. This auto track mode commands two-axis dither motion on top of a nominal profile. The two-axis dither process is a small sinusoidal oscillation occurring on a single axis at a time while the second axis is held, on a predefined dither period, and then continues via alternating axes. The auto track mode goal is to maximize the received power level feedback, by moving the gimbal in the dither axis direction where the feedback response is larger. This tracking mode should result in the gimbal pointing the antenna so it is fully “peaked up” towards the source, and no improvements can be made in either direction [5].

The expected level of accuracy of the measurement process is based on several factors, root-sum-square combined to determine the overall performance error. The individual errors [6, 7] and resultant accuracy are listed in Table I.

TABLE I. RF ALIGNMENT MEASUREMENT UNCERTAINTY

Error Source	*Cartesian Error*	*Angular Error*	*Total Error*
TDRS Position	50m	7.16E-5°	---
SGP4 GEO Error	910m	1.30E-3°	---
Gimbal Step Size	---	0.01°	---
Wind Oscillation	---	0.02°	---
Cumulative Error	---	---	2.23E-2°

For the purpose of completing this alignment characterization, tests were performed in 2014 with both TDRS 6 and TDRS 9, at the orbital slots of TDRS-Spare (TDS) and TDRS-East (TDE), respectively, on the dates and times listed in Table II.

TABLE II. RF ALIGNMENT TESTS

Event	*Year*	*Day of Year*	*Source*	*Start Time*	*Stop Time*
1	2014	211	TDE	19:17:00	20:01:12
2	2014	212	TDS	16:44:20	17:24:59

Event 1 acted as the first one-star alignment process. Once completed, its results were used as a baseline which could be augmented with the results of the follow-up testing. Figure 7 illustrates the stability of the closed-loop tracking on the peak source, after initial spiral track acquisition is obtained.

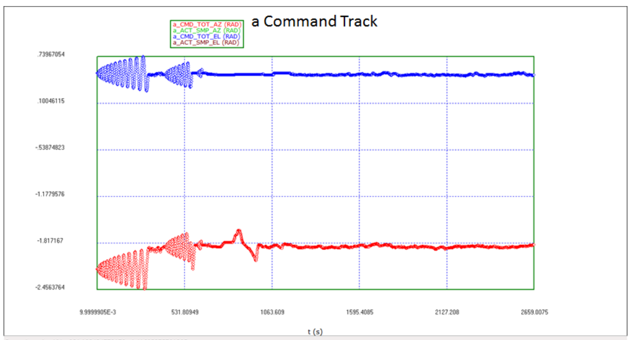

Figure 7. Event 1 Gimbal Command Angles

As the source is at the stationary point in the sky, the initial command angles would nominally be held constant through auto track if the bias angles were zero. However, as the bias angle in azimuth was not zero, shown via the red line in Figure 7, the auto track reached a stable location offset of the initial command location. Figure 8 shows a histogram of the auto track calculated AZ bias, where the solution converges to an average AZ bias calculated as 17.9°.

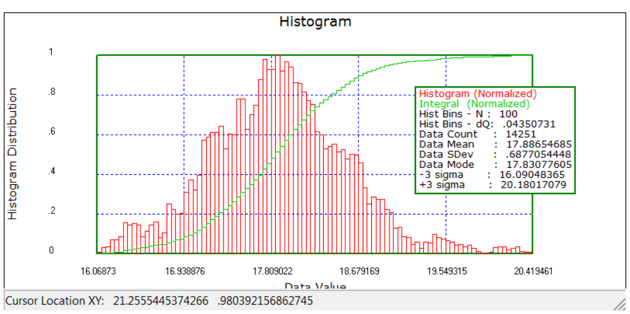

Figure 8. Event 1 AZ Bias Histogram

Figure 9 shows a histogram of the auto track calculated EL bias, where the solution converges to the known/constrained value of 0.0°.

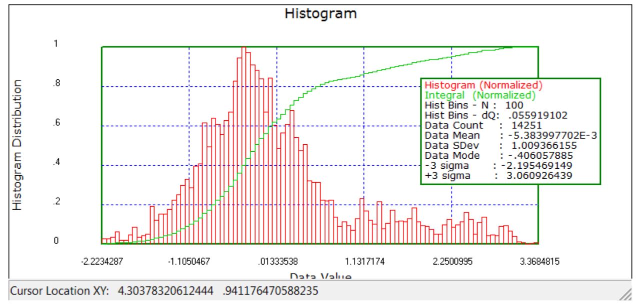

Figure 9. Event 1 EL Bias Histogram

The results of Event 1 showed a convergence of the AZ and EL bias angles. Subsequently, testing for Event 2 utilized these offset values commanded upon start of the event, while also testing the ability of the algorithm to reacquire to the same location many times throughout the event duration. Figure 10 plots the gimbal command angle response throughout.

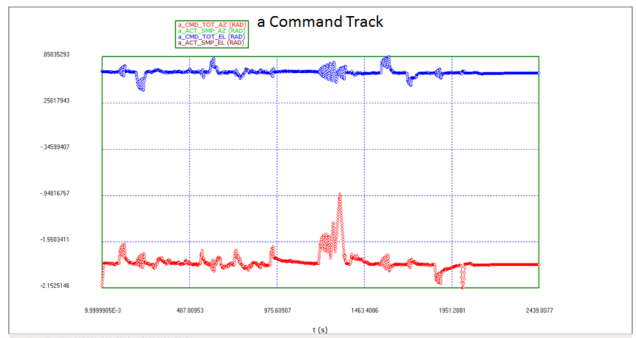

Figure 10. Event 2 Gimbal Command Angles

The results of Event 2 demonstrated the resultant bias angles determined in Event 1 and used during software initialization were accurate for the GRC-GS, throughout all the special tests where lock was broken to force reacquisition of the signal, as the reacquired peak response gimbal angles were consistent with the resultant bias angles from Event 1.

V. CONCLUSIONS AND LESSONS LEARNED

Results of the two test events used to characterize the bias angles of the GRC-GS showed a common resultant solution, whereas results from the first event were used as an input to the second event, with the second event's bias being near zero. This shows that the methodology of using a stationary RF source for antenna alignment is equivalent to using a one-star alignment for telescopes. This is an important aspect for the development of ground stations, as it allows for an alternative to using site surveys to determine the alignment of the platform and ground station gimbal through the use of a known source.

The methodology does have several dependencies for the process to function properly, else an auto track process will not converge to an accurate solution. First, the RF source location needs to be very stable and well known, both a priori for baseline gimbal command position predictions, but more importantly, for a posteriori solution assessments in comparing the auto track solution to the updated gimbal position prediction assessment of baseline pointing using more timely Two-Line Element data. Errors in the known position of the truth model of the source will propagate directly into the solution for the bias angles. Also, the error magnitude in the truth model of the source will be the lower bound on the solution for the bias angles in this approach.

Second, the closed-loop auto track methodology needs to behave in a very stable manner. There are several factors that play into this, which include feedback measurement stability, platform stability, RF environment, and auto track algorithm parameters. Feedback provided by the spectrum analyzer needs to be linear with the actual received power measurement. Therefore, using a carrier wave signal as an RF source is the simplest input. Modulated signals can also be tracked, though bandwidth settings must be understood so that all the signal power is adequately captured. Platform stability is another vital element, as any motion on the antenna position needs to be driven by the gimbal, and motion acting upon the gimbal should be limited. Wind loading is of particular concern when designing a ground station so as to limit the wind impact on platform stability. Ideally the RF environment should not contain extraneous RF emissions as these can corrupt the received power measurements used in the feedback process. This criteria is especially difficult in the frequency band being used by the GRC-GS, as the S-Band frequency received from the TDRS spacecraft at 2041.027 MHz is part of the frequency band used by local area broadcasters for mobile vehicle communications.

Finally, the auto track algorithm parameters dictate an important aspect of the solution process. Spiral track width needs to be set to less than half of the width of the main beam covered above the transition threshold. Meanwhile, rates should be set to maximize the amount of search space covered during the event while remaining below the maximum gimbal rate limit. The auto track dither needs to be related to the antenna beamwidth, while the auto track rates need to be proportional to the auto track dither magnitude and dither repetition frequency. The closed-loop algorithm needs to be properly simulated to understand prior to testing how stable the algorithm will perform with the various noise sources under different spiral and auto track parameter values.

ACKNOWLEDGEMENT

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