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Airborne Protected Military Satellite Communications: Analysis of Open-Loop Pointing and Closed-Loop Tracking with Noisy Platform Attitude Information

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Abstract—U.S. military assets' increasing need for secure global communications has led to the design and fabrication of airborne satellite communication terminals that operate under protected security protocol. Protected transmission limits the closed-loop tracking options to eliminate pointing error in the open-loop pointing solution. In an airborne environment, aircraft disturbances and noisy attitude information affect the open-loop pointing performance. This paper analyzes the open-loop pointing and closed-loop tracking performance in the presence of open-loop pointing error and uncertainty in the received signal to assess hardware options relative to performance requirements. Results from the open-loop analysis are characterizations of the pointing error based on plant definition, aircraft motion, the control system, and a non-ideal GPS/INS. The closed-loop tracking analysis shows several results. The distribution of the noise power dominates (over the received signal power) the SNR distribution. The defined step-tracking algorithm reduces pointing error in the open-loop pointing solution for a pedestal experiencing aircraft disturbances and random errors from the GPS/INS. For initial pointing off-boresight, the performance of the step tracking algorithm depends on the antenna aperture size and the GPS/INS unit. The closed-loop tracking performance is primarily a function of the number of SNR samples and is for the most part independent of the hardware selection.

Keywords—satellite communication; airborne; GPS; frequency hopping; tracking

I. INTRODUCTION

The U.S. military has realized the strategic and tactical advantage satellite communication (SATCOM) systems can provide to troops in wartime environments, and has utilized this technology in combat zones since the early 1990's [1, 2]. The Military Strategic and Tactical Relay (MILSTAR) program is a constellation of geosynchronous satellites within the Military Satellite Communications (MILSATCOM) system that provides secure beyond line-of-sight communication and enables sensitive information sharing between the President, the Secretary of Defense, and the U.S. Armed Forces around the globe [3]. MILSTAR is a robust "Nuclear Survivable" system with the ability to avoid, repel, and withstand virtually any enemy attack [4]. The MILSTAR satellites operate in the Extremely High Frequency (EHF) band, with center

frequencies for downlink and uplink at 20 and 44 GHz, respectively. The system utilizes fast frequency hopping to create low probabilities of interception and detection [5]. The MILSTAR satellites operate in a protected protocol, so there is no tracking beacon for adversaries to locate and jam. At the same time, the lack of a beacon makes it difficult for allies to acquire and track the satellite.

Mobile SATCOM terminals point an antenna at an orbiting satellite to secure a communication link based on the satellite's location and the terminal's location and orientation. A gimballed pedestal is a type of inertially stabilized platform that points and stabilizes an antenna [6]. This form of control is defined as open-loop pointing because the solution incorporates no performance feedback to reduce and eliminate errors within the pointing solution [7]. More robust systems utilize closed-loop tracking to improve the pointing performance by feeding back the received signal strength, which is then used to reduce bias errors in the pointing solution and improve the communication link.

This paper defines relevant parameters that affect the terminal's pointing performance and analyzes their impact on a communication link. Section 2 describes the SATCOM terminal architecture. Section 3 describes the open-loop pointing portion of the problem by presenting the open-loop pointing error caused by random errors in the GPS/INS Euler angle information. Section 4 describes the closed-loop tracking portion of the problem and begins by defining the signal-to-noise ratio and modeling its uncertainty. The section continues by presenting a closed-loop tracking algorithm and a simulation that tests the closed-loop tracking performance. The section concludes with an analysis of the simulation results.

II. SATELLITE TERMINAL ARCHITECTURE

This paper focuses on SATCOM terminal communication performance in the presence of non-ideal stabilization and pointing. Stabilization and pointing in the presence of aircraft disturbances are the functions of the Antenna Positioner System (APS). The APS is comprised of an antenna pedestal system, a Global Positioning System (GPS)/Inertial Navigation System (INS), satellite ephemeris, and a pedestal control

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computer. The signal processing system is a separate system that performs the terminal's communication functions. Figure 1 is a block diagram of the components of a SATCOM terminal.

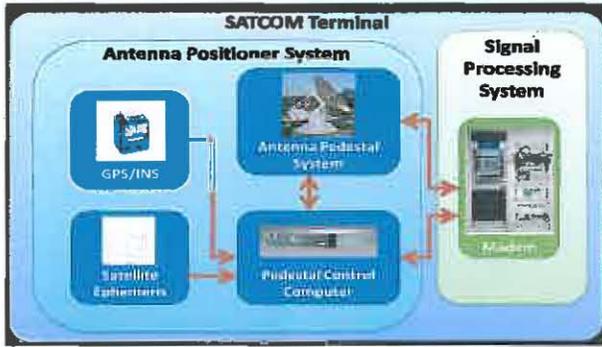


Figure 1. Satellite communications terminal.

The pedestal control computer calculates the open-loop pointing angles for the antenna pedestal system based on the GPS/INS and satellite ephemeris. Errors due to inaccuracies in the satellite ephemeris and the floating point calculations done by the pedestal control computer are neglected. The analysis presented here accounts for pedestal and GPS/INS non-idealities only.

A. Antenna Pedestal System

The antenna pedestal system consists of an antenna and a pedestal that stabilizes and points the antenna. Antenna apertures for EHF SATCOM applications are typically highly directional [8]. However, as the antenna aperture size and transmission frequency increase, the antenna's half-power beamwidth decreases, which translates to tighter pointing requirements [9]. The analysis in this paper focuses on a 0.3 m diameter parabolic dish antenna that receives and transmits on the downlink and uplink at 20 and 44 GHz, respectively. This system requires a multi-axis gimballed pedestal to steer the antenna.

A pedestal with a minimum of two axes of rotation points and stabilizes the antenna in a commanded direction. A gimbal is a collection of motors, bearings, and machined parts that forms a rigid body and allows motion in one axis of rotation [6]. The two-axis gimballed system, assumed for analysis in this paper, is the simplest, cheapest, and sturdiest configuration. The outer gimbal controls the azimuth axis, while the inner gimbal controls the elevation axis. A disadvantage in a two-axis system is the problem of gimbal lock, which occurs at elevation angles approaching zenith, the keyhole region [9]. To avoid the keyhole region, this analysis is restricted to elevation angles less than 80° .

Torque disturbances enter the gimballed pedestal and cause unwanted angular accelerations in the axes of rotation resulting in pointing error [6]. These disturbances are caused by coulomb friction, spring torques, imbalance, vehicle motion coupling, inter-gimbal coupling, internal disturbances, structural flexure, and environmental disturbances [10]. Gyroscopic sensors and angular resolvers measure these unwanted rotations and the pedestal then uses the gimbal motors to cancel out the torque disturbances.

B. GPS/INS

The Global Positioning System/Inertial Navigation System (GPS/INS) subsystem transmits the system's location and orientation to the pedestal control computer. GPS provides an accurate position, but only updates once per second. An INS measures changes in position and orientation at a much higher rate, but accumulates error and drift [11]. Combining the GPS and INS into one system provides position and orientation information [12]. A Kalman filter optimally blends the two systems in the presence of noise and uncertainty.

III. OPEN LOOP POINTING

In open-loop pointing, the pedestal control computer takes the terminal position and orientation data from the GPS/INS and the satellite ephemeris and calculates a pointing solution. Sensors in the pedestal stabilize the gimbals. Several early SATCOM systems performed open-loop pointing with great success [13, 14]. The fundamental problem with open-loop pointing is that there is no way to eliminate errors in the open-loop pointing solution. These errors include

1. Aged satellite ephemeris at the terminal.
2. Misalignment errors between components.
3. Steady-state biasing in pedestal resolvers.
4. Non-orthogonality of INS accelerometers.
5. Noisy GPS/INS position and orientation.

The first four errors in the list are not considered in this analysis. Aged satellite ephemeris causes error in the satellite's estimated position, but once the terminal is connected, it can request updated ephemeris. Misalignment errors between components and steady state biasing in pedestal resolvers can be minimized by careful installation and pre-flight calibration. Non-orthogonality of INS accelerometers is kept at a minimum by careful quality control.

A much more serious error stems from inaccuracies in the GPS/INS solution. GPS/INS hardware specifications define the position and orientation errors as Gaussian random variables with defined variance. While errors in the terminal's position do not cause serious errors, orientation errors directly impact the pointing solution [15].

A. Plant definition

The equations of motion describe the system's response to internal and external forces. The derivation of the equations of motion for a standard rotating rigid body is commonly available [16]. The two-axis gimballed pedestal is not a rigid body because of its two rotation axes about the azimuth and elevation gimbals. The two axes of concern in this application are the pitch and yaw velocities of the inner gimbal because unwanted rotations in these axes correspond to pointing error between the antenna and the satellite. Because the antenna aperture is circularly symmetric, rotation in the roll axis does not impact performance.

Three reference frames describe the orientation of the pedestal components. Rotational transformation matrices define the transition among these frames. Equations of motion

for the two-axis gimballed system are derived by starting with the equations for a rigid body, isolating each axis of interest and applying transformation matrices to define the dynamic interactions within the pedestal as well as external torques that enter through the base of the pedestal. Standard motor dynamics are also incorporated to simulate the DC servomotors within the pedestal. The resulting equations define the equations of motion of the pedestal and define the plant model.

B. Aircraft disturbance data

Lincoln Laboratory operates and maintains the Paul Revere, a heavily modified Boeing 707, as a government sensor and communication systems testbed. Lincoln Laboratory employees tested a mobile SATCOM system on the Paul Revere during June 2009. The onboard GPS/INS recorded the aircraft's position and orientation for the entire flight. The flight data was broken into segments with two distinct flight profiles, racetrack and cruise. These are used to characterize system performance during two distinct aircraft mission profiles. The racetrack data (Fig. 2) simulates an aircraft in a holding pattern over a target area. The cruise data simulates an aircraft performing steady, level flight.

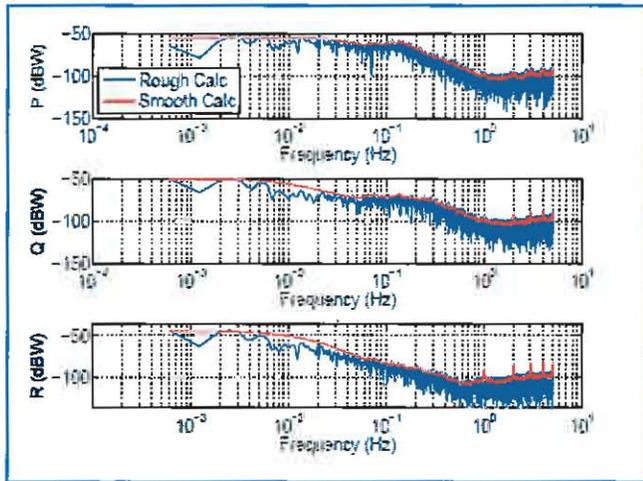


Figure 2. Racetrack raw and filtered spectra for roll, pitch, and yaw.

C. Control system analysis

To define the control law, the derived pedestal and motor dynamics from the plant model are first linearized around an operating point. A simple proportional differential (PD) controller calculates the error between a reference command and the actual output. The error and the derivative of the error are fed into the controller, which then sends control inputs to the plant. The control law maintains the operating point in the presence of aircraft disturbances.

A MATLAB Simulink model simulates the linearized plant to determine proper gain settings for the controller in order to create a stable system that tracks changes in the reference command. The model takes the recorded flight data and simulates how well the system tracks the commanded trajectory.

The PD controller from the linearized model is then tested with the original nonlinear plant in another Simulink model. As indicated by [17], complex models can often be stabilized

by simple controllers and this simulation demonstrates just that. The final controller simplified even further to a proportional controller due to undesirable error accumulation in the differential feedback signal. The end result is a pedestal that tracks the commanded trajectory with a total error remaining below 0.2° the majority of the time, Fig. 3.

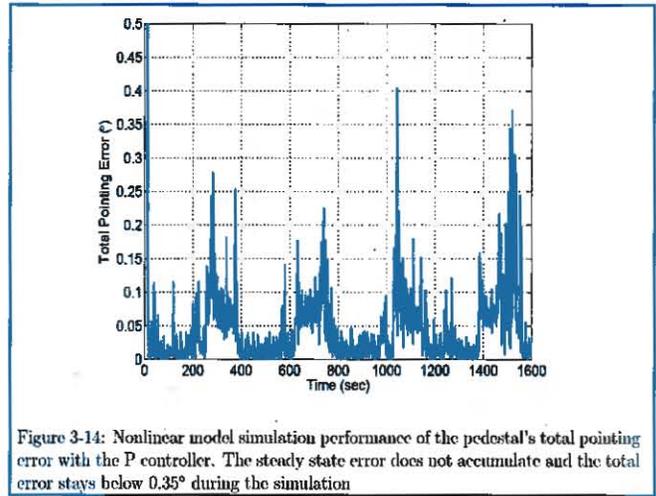


Figure 3-14: Nonlinear model simulation performance of the pedestal's total pointing error with the P controller. The steady state error does not accumulate and the total error stays below 0.35° during the simulation

Figure 3. Pointing error during the course of a single racetrack.

D. Pointing error analysis

A GPS/INS supplies position and orientation information in a specified reference frame. The pedestal computer calculates an inertial pointing vector between the platform and the intended target using the position information. The computer translates the vector into correct reference frame using the aircraft's orientation information. Position errors are trivial due to the distance between antenna and satellite, but orientation errors directly impact system performance. The random errors in each axis are modeled as zero mean, Gaussian random variables with some specified variance determined by the quality and precision of the GPS/INS package. Table I identifies typical values for four different grade GPS/INS units.

TABLE I. STANDARD DEVIATIONS FOR 4 DIFFERENT GRADE GPS/INS PACKAGES

Table 3.1: Standard deviations (1-σ) for 4 different grade GPS/INS packages

	Package 1	Package 2	Package 3	Package 4
Yaw	5 mrad/s	2 mrad/s	1 mrad/s	0.7 mrad/s
Pitch	2.5 mrad/s	1 mrad/s	0.5 mrad/s	0.35 mrad/s
Roll	2.5 mrad/s	1 mrad/s	0.5 mrad/s	0.35 mrad/s

A closed form solution for the pointing errors as a function of GPS/INS and pointing direction could not be found, so a software model in Simulink was developed for the control system to determine how the errors impact the system's pointing performance. Separate simulations are performed for the racetrack and cruise profiles. Figure 4 is the CDF of the total pointing error for each GPS/INS. The magenta data set demonstrates the open-loop pointing performance if a perfect GPS/INS without any random errors existed. The inflection in the line at 0.05 deg is a result of the pedestal's reaction to dynamic changes in the pointing solution while the aircraft is banked during the racetrack.

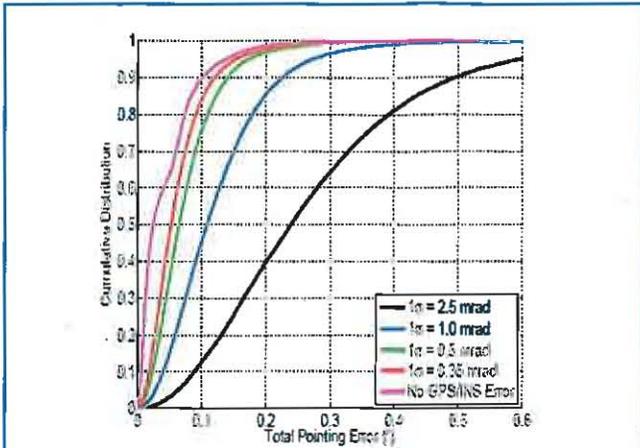


Figure 3-30: Cumulative distribution function of the total pointing error from the open-loop pointing simulation of the racetrack flight data.

Figure 4. Cumulative distribution function of the total pointing error during racetracks.

Figure 5 depicts the performance results of the cruise simulation. The results demonstrate that the total pointing error is less than racetrack pattern.

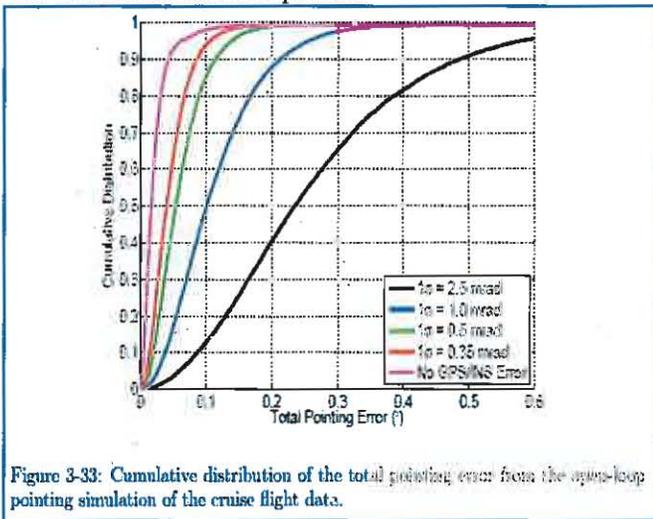


Figure 3-33: Cumulative distribution of the total pointing error from the open-loop pointing simulation of the cruise flight data.

Figure 5. Cumulative distribution function of the total pointing error during cruise.

IV. CLOSED LOOP TRACKING

The pedestal control computer performs closed-loop tracking by calculating the same pointing solution as before and then using the received signal-to-noise ratio to detect any error in the current pointing solution. Three closed-loop tracking strategies are commonly used in radar and communication systems: Monopulse, Conical Scanning, and Step tracking.

Monopulse tracking uses multiple antennas to locate and track a target. The signal levels from the individual antenna feeds are manipulated to determine a pointing offset between the antenna and the target [18]. These systems require advanced hardware, with multiple antenna feeds.

Conical scanning requires only one antenna feed. The antenna is mechanically-steered in a circular motion around the estimated pointing angle. The circular motion causes sinusoidal variations in the received signal power, which are then used to estimate the pointing error [19]. For protected systems, uncertainty in the signal-to-noise ratio degrades the performance and the time off-boresight necessarily means degraded communication performance.

The simplest and least expensive method for closed-loop pointing is step tracking, which has some of the advantages of both monopulse and conscan techniques. Step tracking requires only one feed, taking SNR readings at specific points in a desired pattern to estimate the pointing error. The difference between step tracking and conscan is that step tracking points at a fixed location in the sky and takes enough samples to estimate the SNR rather than continuously scanning the antenna. This paper focuses on step tracking because it is the most practical form of closed-loop tracking for protected MILSATCOM transmission.

A. Effects on Signal-to-Noise Ratio

The signal processing system calculates the signal-to-noise ratio (SNR), which the pedestal control computer uses to estimate the antenna pointing errors. This section examines the variations in SNR to better understand how to implement SNR as a figure of merit for antenna pointing accuracy. The SNR is defined by

$$SNR = \frac{P_R}{N} = \frac{P_T G_T G_R}{N L_{FSP} L_0} = \frac{RIP * G_R}{N} \quad (1)$$

where P_R and P_T are the received and transmitted power respectively, G_R and G_T are the receiver and transmitter antenna gain respectively, N is thermal noise in the receiver, L_{FSP} is the free-space path loss, L_0 is the combination of other losses (atmospheric absorption, rain attenuation, refraction, diffraction, and multipath), and RIP is the received isotropic power.

B. SNR characterization

The signal processing system calculates the signal and noise levels during a portion of the transmission when the system is on a single carrier. These values can be used individually at a fast rate or averaged over many samples to assess the pointing performance. The RIP , receiver antenna gain, and the receiver's thermal noise are the three independent, random components of the SNR as defined by (1). RIP and thermal noise are considered here; changes in antenna gain due to GPS/INS noise is considered in the system simulation in Section IV.C.

RIP is assumed to have a gain across the band that is linear (in dB) between the band edges. Fig. 6 demonstrates that the probability of being within 1 dB of the signal level increases for a larger number of samples (n), but decreases for larger slopes (r). In practice, the slope should not exceed 3 dB, which means the probability of being within 1 dB is extremely high. This demonstrates that the variation in SNR does not depend heavily on the RIP distribution as long as the slope is relatively

small and the pedestal control computer averages SNR over more than 10 samples.

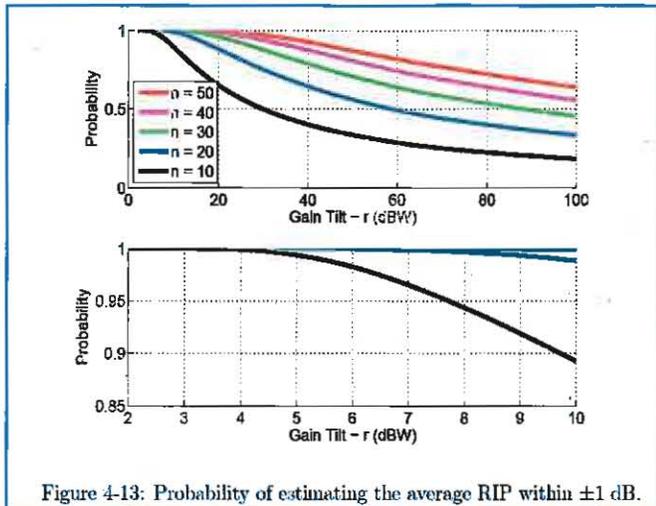


Figure 4-13: Probability of estimating the average RIP within ± 1 dB.

Figure 6. Probability of estimating RIP to within ± 1 dB.

Fig. 7 shows the probability of being within X dB of the average SNR and the average noise power as a function of the number of samples. The lower graph of Fig. 7 is the difference between the two probabilities which demonstrates that the variance of the RIP is insignificant when compared to the variance in the average noise power.

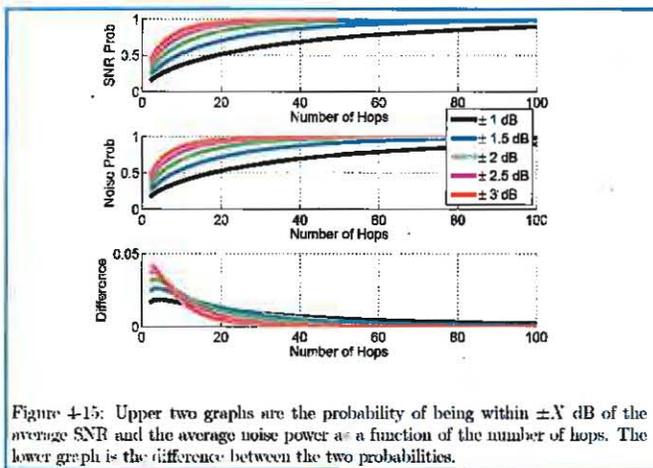


Figure 4-15: Upper two graphs are the probability of being within $\pm X$ dB of the average SNR and the average noise power as a function of the number of hops. The lower graph is the difference between the two probabilities.

Figure 7. Graphs depicting that the variation in thermal noise dominates the variation in SNR.

C. Closed-Loop Pointing

Step tracking is a form of closed-loop tracking used to assess and reduce the pointing error between the terminal's antenna and the satellite. The pedestal control computer commands the pedestal to point the antenna deliberately off-boresight by a predefined angle. The modem processes the received signal over a certain number of samples to estimate the SNR. The computer then assesses the pointing error between the pedestal and satellite. If an error exists, then the pointing solution is updated.

Two different test case scenarios are shown in Fig. 8. The first scenario sets the pedestal on-boresight. The second

scenario sets the pedestal off-boresight. The focus here is on the tracking problem, which means the system has established a link with the satellite. The initial condition for the off-boresight scenario places the satellite on the edge of the antenna's half-power beamwidth (HPBW). It is important to note that the graphs are for a 0.3 m radius antenna aperture and that only the scaling of the cross-elevation and elevation axes change for a different sized apertures.

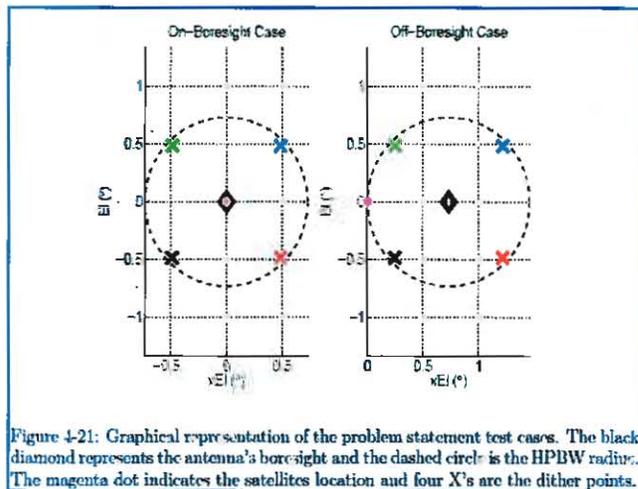


Figure 4-21: Graphical representation of the problem statement test cases. The black diamond represents the antenna's boresight and the dashed circle is the HPBW radius. The magenta dot indicates the satellite's location and four X's are the dither points.

Figure 8. Graphical depiction of problem statement test cases.

The Simulink model for the open-loop pointing simulation is modified to include dithering of the beam and assessing whether a pointing error exists. Both test case scenarios are tested for different grade GPS/INS units and over longer hop sequences.

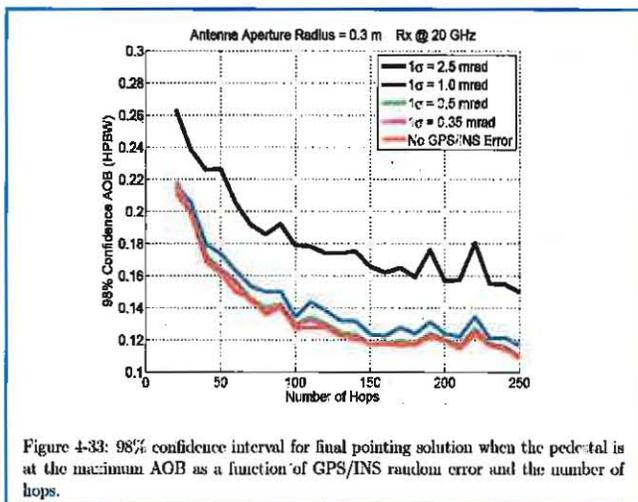


Figure 4-33: 98% confidence interval for final pointing solution when the pedestal is at the maximum AOB as a function of GPS/INS random error and the number of hops.

Figure 9. 98% confidence interval for final pointing solution when the pedestal is off-boresight as a function of GPS/INS random error and the number of samples

As expected, the pedestal performance is nearly identical for all GPS/INS units when the pedestal is on-boresight. However, for the off-boresight case, Fig. 9 demonstrates that the performance varies among GPS/INS units, but all improve at the same rate as the number of samples increases

The preceding results assume 0.3 m radius antenna aperture. In the case of an ideal pedestal, simulation performance is identical for different sized apertures; however, this does not hold when open-loop pointing errors enter the simulation. Results show that for different grade GPS/INS units, the closed-loop tracking performance decreases as the aperture size increases. The reason for this decrease in performance is because the HPBW gets smaller as the aperture increases in size. The performance begins to decrease for larger GPS/INS random errors and larger aperture sizes as the angle off-boresight increases. Despite this difference in performance, closed-loop tracking in each scenario eliminates a significant portion of the pointing error and improves the communication link. For larger apertures or lower grade GPS/INS units, it may take multiple step-tracking iterations to track out a bias, but the pointing solution improves and the error tends toward zero.

Because closed-loop tracking works for each grade GPS/INS and antenna aperture, the design tradeoffs are based on the open-loop pointing performance. The uplink antenna beam pattern has a smaller HPBW than the downlink, so the 44 GHz HPBW determines the pointing requirement for reasonable system performance. Fig. 10 presents the family of CDFs of pointing performance for each grade GPS/INS and compares it to half of the HPBW of each antenna aperture's uplink antenna beam pattern. The figure shows that if the terminal has a design constraint of pointing within the HPBW 95% of the time for a 0.5 m antenna aperture, then the GPS/INS unit must have a 1σ value of no more than 1.0 mrad.

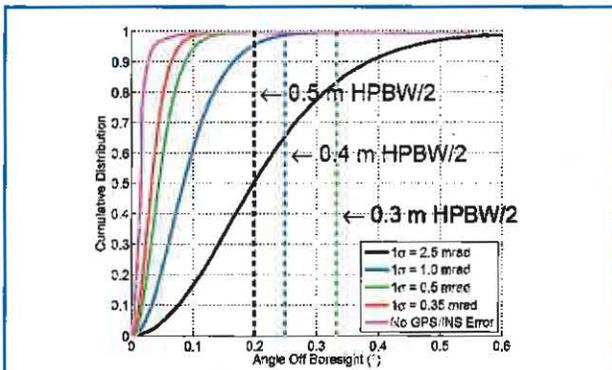


Figure 4-36: Family of cumulative distribution functions of the open-loop pointing performance in reference to uplink 44 GHz antenna aperture HPBW.

Figure 10. Family of cumulative distribution functions of the open-loop pointing performance in reference to uplink 44 GHz antenna aperture HPBW.

V. CONCLUSIONS

For the received isotropic power distributions investigated in Section IV.B, the distribution of the average noise power has a stronger influence than the distribution of the received isotropic power on the signal-to-noise ratio distribution.

The step-tracking algorithm reduces pointing error in the open-loop pointing solution for a pedestal experiencing aircraft disturbances and random errors from the GPS/INS. For the off-boresight case, the performance depends on the antenna

aperture size and GPS/INS unit. For example, the 98% confidence level angle off-boresight decreases by 0.04 half-power beamwidth between the 2.5 and 1.0 mrad GPS/INS units for a 0.3 m antenna aperture.

The overall system performance is bounded by the open-loop pointing solution, which is based on hardware selection. Closed-loop tracking performance is a function of the number of averaged samples and is for the most part independent of the hardware selection.

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