NAVY CALIBRATION OF THE US SPACE SURVEILLANCE NETWORK USING SATELLITE LASER RANGING

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A Special Perturbations Space Object Catalog is currently maintained at Naval Space Command with a weighted batch least squares estimator. The first and second central moments of the satellite observation errors are required by these normal equations in the form of an observation error covariance matrix. Accurate orbits, estimated from satellite laser ranging, provide a suitable reference from which it is possible to estimate the sample moments of the observation errors of the US Space Surveillance Network (managed by the Air Force Space Command) and the NAVSPASUR Fence (managed by the Naval Space Command). In this paper, the sensor calibration mission at Naval Space Command is reviewed with an emphasis on the quality of the SLR-based reference trajectories. Preliminary sensor calibration results are provided on NAVSPASUR Fence performance. Additional benefits of SLR to Space Catalog operations are also discussed.

INTRODUCTION

The US Naval Space Command (NAVSPACECOM) is the Naval component of the joint United States Space Command (USSPACECOM) and the central operations center for processing satellite observations originating from the Naval Space Surveillance System (NAVSPASUR), commonly known as the Fence. NAVSPACECOM is making operational a special perturbations orbit determination processor to increase the overall accuracy of its Space Object Catalog. The NAVSPACECOM is also chartered to provide a redundancy in functionality for the Air Force Space Command (AFSPC) to the US Department of Defense (DoD), where special perturbation catalog operations are also underway.

Schumacher et al. (1998) described a Concept of Operations to provide timely metric calibration of the NAVSPASUR Fence using post-fit ephemerides estimated from Satellite Laser Ranging. The immediate goals discussed in that study included the feasibility of monitoring of short term variability in Fence performance, and long term evaluation of possible systematic Fence errors. However, accurate special perturbations orbit determination for the operational NAVSPACECOM Space Object Catalog requires some level of metric calibration for all contributing sensors, since approximately two-thirds of the satellite observations originate from the US Space Surveillance Network. A brief overview of component networks contributing to the calibration mission follows.

Satellite Laser Ranging Network

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Satellite Laser Ranging (SLR) is an extremely precise method of measuring the distance to the Moon and artificial satellites. The native SLR observation is the two way time-of-flight of an optical pulse between an apparent reflection point on the satellite retro-reflector array and a fiducial point associated with an SLR tracking station on the surface of the Earth. While this raw measurement is highly precise, the optical pulse time-of-flight measurement requires many corrections to be utilized in the orbit determination problem to nearly the same level of accuracy. The orbital ephemeris is a derivative product that is less accurate than the SLR observations being used to estimate the satellite state, due to the uncertainty of the satellite dynamics.

SLR observations originate from an international network of approximately 40 tracking stations (Figure 1). The SLR data are electronically transferred to a central database maintained at the NASA Goddard Space Flight Center (GSFC). Access to the primary SLR database is freely available via the Internet through the Crustal Dynamics Data Information System (CDDIS). More recently, the International Laser Ranging Service (ILRS) was established to coordinate and manage SLR data distribution and analysis. The primary mission of the global SLR tracking network is space-based geodetic and oceanographic research.

![Figure 1. Active SLR Stations Contributing to the CDDIS](image)
(dark symbols indicate stations supported by NASA)

**US Space Surveillance Network (SSN)**

For Space Catalog maintenance, the NAVSPACECOM processes observations electronically transferred from various space surveillance sensors. This network is generally described as the US Space Surveillance Network (SSN). Approximately two dozen sensor systems currently contribute observational data to the NAVSPACECOM for this mission, which makes up about two-thirds of the observational data available for
Space Catalog maintenance by the Navy. In addition to the NAVSPASUR Fence, there are three broad categories of sensors: mechanically steered radars, electronically steered (phased array) radars, and optical imaging systems (Figure 2). Most of the SSN assets are located in the continental United States, Alaska, and Hawaii; however, tracking in the Eastern Hemisphere is supplemented by radars in Great Britain and one optical sensor in Spain. Equatorial tracking coverage is facilitated by sensors located on islands in the Pacific, Atlantic, and Indian Oceans, while polar coverage is facilitated by one site in northern Greenland. The Space-Based Visible (SBV) sensor, an optical system on board the Midcourse Space Experiment (MSX) spacecraft, also contributes.

![Figure 2. Active SSN Sensors Contributing to the NAVSPACECOM Space Catalog](image)

**Naval Space Surveillance System (NAVSPASUR)**
The NAVSPASUR Fence system is a sub-continental, bi-static, continuous wave interferometer consisting of three (3) transmitter stations and six (6) receiver stations located along a great circle arc in a plane inclined at 33.58 degrees with respect to the equator (Figure 3). The effective field of view of this system is about 1/3 of the great circle circumference at altitude. The Fence samples about 170,000 observations of phase and amplitude daily without any \textit{a priori} knowledge of the satellite population. These samples are forwarded in real-time to the NAVSPACECOM for processing.

Figure 3. NAVSPASUR Fence Transmitter and Receiver Locations
Two primary observables are produced for orbit determination from each receiver station: a direction cosine with respect to the perpendicular of the Fence plane (pseudo-North-South), and a direction cosine with respect to the Fence plane along the local receiver horizon (pseudo-East-West). Since the receivers are widely separated, the sighting geometry usually allows a single triangulated position fix to be determined for each pass. These triangulated positions are less accurate than the native cosine measurements and are not used by NAVSPACECOM for catalog maintenance, however, they are requested by AFSPC and other external agencies. A more detailed description of the NAVSPASUR Fence can be found in Schumacher et al. (1998).

SENSOR CALIBRATION REQUIREMENTS

The US Navy's Space Object Catalog is currently maintained with a linearized weighted batch least squares estimator. For the orbit determination problem, the classic normal equations are:

$$x = \left( H^T WH \right)^{-1} H^T Wy$$  

where

- $y$ is the $n \times 1$ vector of observation residuals,
- $W$ is the $n \times n$ matrix of observation weights (the inverse of observation error covariance matrix),

Figure 4. Flow Chart of SLR in the NAVSPACECOM Calibration Task
\( H \) is an \( n \times m \) matrix of partial derivatives, also known as the Jacobian matrix, \( x \) is the estimated update to an initial satellite state \( X \), 
\[(H^T WH)^{-1}\] is the sample covariance of \( x \).

The Navy's calibration mission accomplishes two objectives. The primary task assesses the accuracy of NAVSPASUR Fence observations, identifies observation errors, and corrects those observation errors insofar as possible. A secondary task provides reasonably accurate \textit{a priori} estimates of the first and second central moments of the satellite observation errors in the matrix \( W \) used in the least-squares normal equations (the inverse elements of \( W \) are sometimes known as scalar weights and the first moments are sometimes known as biases). This latter task is a response to requests by NASA to have accurate estimates of satellite state covariance for collision avoidance with the International Space Station (ISS). Figure 4 illustrates the process of how SLR data are used in the computation of the weights and biases.

\textbf{SLR Reference Ephemeris Accuracy Requirements}

The performance of a satellite-observing sensor can be described by a statistical distribution of its observation errors. During calibration, an observation error estimate is obtained by differencing the actual SSN or Fence observation with a computed observation based on a \textit{post priori} estimate of the SLR-based satellite state having a predetermined accuracy much smaller than the suspected instrument error (Figure 4). Specifically, the true errors in the SSN observations are the sum total of all the possible error sources,

\[ \varepsilon_{\text{observed}} = \sum \varepsilon_{\text{station}} + \sum \varepsilon_{\text{atmosphere}} + \sum \varepsilon_{\text{target}} + \sum \varepsilon_{\text{post-processing}} + \mathbb{L} \tag{2} \]

where the different error anomalies may arise from the target, atmospheric propagation, the station, signal post-processing, etc. This sensor residual equation also contains errors sources due to something denoted as “target” effects, where the significant constituent to this part of the error budget includes “skin-track” ranging errors (the difference between the apparent point of RF reflection with respect to the true center-of-mass). The SLR orbit error falls under the category of target uncertainty, because it represents an ambiguity between the estimated center-of-mass and the actual center-of-mass (where the actual center-of-mass is estimated but never actually known). By isolating all other sources of observation error from the SLR-based center-of-mass error, the sensor residual equation reduces to the sum of two random variables:

\[ \varepsilon_{\text{observed}} = \varepsilon_{\text{sensor}} + \varepsilon_{\text{SLR}} \tag{3} \]

where \( \varepsilon_{\text{sensor}} \) represents all the observation error except the SLR trajectory uncertainty. The expected value provides a mean error:
\[ \bar{e}_{\text{observed}} = \bar{e}_{\text{sensor}} + \bar{e}_{\text{SLR}} \]

Presuming the SLR-based satellite state is without bias and knowing the SSN sensor errors are independent of any SLR-based solution, the variance of the expected errors is

\[ \sigma_{\text{sensor}}^2 = \sigma_{\text{observed}}^2 - \sigma_{\text{SLR}}^2 \]

From inspection, a relatively small SLR orbit uncertainty implies that the observed sensor variance approaches the actual sensor error variance. Relative knowledge of the SLR orbit variance is therefore required to determine the degree to which it inflates the noise levels observed during calibration. A desire to identify constituent errors (Equation 2) may place additional demands on the accuracy assessment of the SLR-based computed observations, or at the very least, variance estimates may need to be adjusted to account for SLR orbit uncertainties.

There are sources of noise inherent to SSN observations that will limit the necessary accuracy required from external reference orbits. Skin-track effects can introduce satellite-dependent foreshortening of range measurements, or at least complicate the specular return of a radar pulse on extended targets, possibly resulting in noisier observations. The number of significant digits maintained in the antiquated SSN message formats introduces observation precision loss at the level of several meters RMS. Internal electronic calibration in the present Fence system demonstrates an apparent lower noise threshold of about 10 microradians angular measurement precision (for cosine measurements at zenith), which translates to a alongtrack position uncertainty of about 35 cm at a zenith range of 350 km. In practice, the Fence does not operate at its noise threshold level, and observed Fence cosine errors are closer to 2000 microradians at zenith (or 70 meters alongtrack uncertainty at 350 km).

**SLR Reference Ephemeris Accuracy**

The SLR orbit determination process estimates the state of the satellite center-of-mass relative to the center-of-mass of the Earth. A numerical model for each satellite is required, and a number of empirical parameters are estimated to absorb remaining errors due to an incomplete force model. The most commonly estimated parameters absorb drag and solar radiation pressure effects by scaling certain model coefficients.\(^{10}\) Other estimated quantities include directional accelerations, both constant or periodically varying.\(^{11,12}\) Each of these may be estimated over time intervals that are shorter than the total time of the integrated state estimate, called “subarc” parameterization.\(^{13}\) Depending upon the density of high-quality SLR tracking, the number (or frequency) of these simultaneous state parameters can be slightly augmented to absorb more or less model error. In this calibration effort, a capability exists to provide SLR reference orbits within 72 hours of the time the tracking acquisition. Such an orbit is considered to be a “quicklook” product, meaning it may be of dubious quality by SLR standards. There can be a
substantial delay between the acquisition of the SLR measurements at the remote field sites and their distribution to the CDDIS, which makes routine quick-look SLR orbit determination non-trivial.

The Electro-Optics Technology section of the US Naval Research Laboratory (NRL) has used SLR to generate a series of medium precision orbital ephemerides, creating a database spanning three years. The orbit determination processor is GSFC GEODYN II (version 9903). The modeling of the SLR observation type within the GEODYN software can correct the SLR observation down to the level of the noise of the measurement, on the order of one (1) centimeter. Such corrections include atmospheric delay, retro-reflector to center-of-mass offsets, satellite attitude, station upheaval due to solid tides, retro-reflector array signatures, station specific detector signatures, ocean loading of coastal SLR sites, and relativistic corrections to the two-way time of flight. The SLR state estimates are of sufficient fidelity to be assumed free of large scale bias for SSN and Fence calibration purposes.

There are currently twenty-one (21) SLR satellites contributing to this orbital database, with twenty-two (22) others having been previously tracked (Table 1). Because the NRL process is geared for quick-look results, daily tuning of subarc parameters is not really efficient or necessarily effective. Instead, nominal satellite models are used to provide fairly consistent results under moderate tracking conditions. For the network calibration problem, there is an emphasis on large numbers of quick-look reference solutions for many satellites, rather than a select set of highly precise solutions (i.e., less than 50 cm 3-D RSS).

TABLE 1. SLR AND GPS CALIBRATION REFERENCE TARGETS

<table>
<thead>
<tr>
<th>Active Targets (48)</th>
<th>Inactive Targets (22)</th>
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</thead>
<tbody>
<tr>
<td>Ajisai</td>
<td>DIADEME-1-C,D</td>
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<tr>
<td>BEC</td>
<td>Fizeau</td>
</tr>
<tr>
<td>CHAMP</td>
<td>GEOS-3</td>
</tr>
<tr>
<td>ERS-1.2</td>
<td>GFZ-1</td>
</tr>
<tr>
<td>ETALON-1.2</td>
<td>GLONASS-62,63,64,65,66,67,68,</td>
</tr>
<tr>
<td>GFO-1</td>
<td>69,70,71,74,75,76,77</td>
</tr>
<tr>
<td>GLONASS-72,79,80,81,82</td>
<td>RESURS-1</td>
</tr>
<tr>
<td>LAGEOS-1.2</td>
<td>GPS-14,18</td>
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<tr>
<td>Starlette</td>
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<td>Stella</td>
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<td>TOPEX</td>
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<td>WESTPAC</td>
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GPS-11,13,15,16,17,19,21,22,23,24,25,26,27,29,30,31,32,33,34,35,36,37,38,39,40,43,44,51
The SLR-based ephemeris database has been supplemented with NIMA precise ephemerides for the entire GPS constellation.\textsuperscript{16} Although SLR tracking of the GPS constellation is rather limited, NRL compares corrected SLR range data to the GPS-35 and GPS-36 NIMA products as part of the overall reference ephemeris qualification process. The NIMA fit to the SLR residuals is approximately 6.3 cm RMS overall after removal of a 5.2 cm bias.\textsuperscript{17}

There are currently no formal requirements for reference trajectory accuracy related to SSN calibration, and consequently there are no requirements for the means by which to assess that accuracy. The high quality of the SLR data type with respect to RF skin-track observations has likely obviated the need for some of these formalities. However, “meter level” accuracy in the three dimensions is often informally cited as adequate for RF sensor calibration efforts, since the dominant error sources result from unmodeled ionospheric range delay at the level of several meters in addition to the effects cited earlier.\textsuperscript{18}

Seago et al. (2000) describes an investigation to measure the effectiveness of the NRL accuracy indicators for the SLR reference orbits used in calibration.\textsuperscript{19} Two indicators were used as estimates of quick-look ephemeris uncertainty: SLR measurement residual RMS, and the 3-D RSS of overlapping solutions. Similar indicators have also been adopted by AFSPC for its calibration mission. The SLR measurement residual RMS is the best and most immediate indicator of ephemeris accuracy under dense tracking conditions, but under less favorable circumstances Type II errors are more probable (accepting poor solutions that should be rejected). For the NRL quick-look product, the overlap RSS is a more pessimistic indicator of orbit error prone to causing Type I errors (rejecting acceptable orbits).

The study concluded that the NRL quick-look estimates of 3-D SLR orbital quality are variable enough such that they are inadequate to establish an acceptance-rejection criterion for quick-look reference orbits at the suggested one (1) meter level. Specifically, one could not reject bad orbits without adopting a rejection criterion that resulted in an unacceptably high rejection rate of good reference orbits as well. The probability of rejecting a good orbit was more than 10-30% on average if the probability of accepting a bad orbit was maintained below 2%. However, the rejection criterion could be reasonably employed at the level of 3-5 meter 3-D RSS. In this latter case, the probability of rejecting a good orbit was less than 5% overall while the probability of accepting a bad orbit was less than 1%. This has resulted in the rejection criterion based on quick-look indicators at the 3-5 meter 3-D RSS. This criterion is consistent with an assumption that “meter-level” accuracy might imply an order-of-magnitude definition for orbit quality (50 centimeter to 5 meter 3-D RSS) for all reference trajectories contributing to SSN calibration. In general, this level of reference ephemeris accuracy exceeds any reasonable requirements imposed by the operational Fence performance, and is considered satisfactory for most of the SSN.
EXAMPLES OF CALIBRATION BENEFITS

Several examples now illustrate how SLR-based sensor calibration has benefited catalog maintenance efforts specific to NAVSPACEDCOM.

Fence Background Error Model

Fence direction cosines are determined from phase differences across antenna pairs, and not by any absolute phase determination. The phase differencing tends to cancel many possible systematic phase errors across the antenna field of each receiver station. Moreover, these phase differences are numerically smoothed over the sampling time before the cosines are computed, which compensates for any phase noise present in the original samples. These techniques have yielded metric data of sufficient quality to help maintain the NAVSPACEDCOM satellite catalog for many years.

When a signal is detected by the receiver electronics, phase and amplitude measurements on each antenna are sampled digitally using three separate detection bandwidths centered on the main transmitter frequency of 216.980 MHz. Up to 55 discrete samples constitute the “raw observations” from the Fence system, and are forwarded in real-time (within two seconds) to the Fence Data Reduction (FDR) process at NAVSPACEDCOM. The sampling duration depends on which of the three detection bandwidths yielded the signal. Fast-moving, low-altitude satellites usually have large, fast-changing Doppler shifts. For these signals, the widest detection band of 30 kHz is often necessary. This is the so-called “full Doppler region”, in which signal phase and amplitude are sampled at an effective rate of 55 Hz for a time interval of one second. A narrower 15 kHz detection band, called the “half (1/2) Doppler region”, samples signals over a time interval of 4 seconds at an effective rate of (55÷4) Hz. The narrowest 7.5 kHz band is the “quarter (1/4) Doppler region”, in which signals are sampled for up to 16 seconds at an effective rate of (55÷16) Hz. The narrower detection bands are intended for slow-moving, high-altitude satellites, since the longer integration times accommodate weaker signals.
Figure 5. NAVSPASUR Fence San Diego Receiver Station Cosine Error vs. Elevation (with Fitted Corrections) for Three (3) Separate Transmitters
Figure 6. NAVSPASUR Fence San Diego Receiver Station Cosine Error Distributions (with and without Fitted Corrections) for Three (3) Separate Transmitters
Several error sources have now been confirmed from analyses of Fence direction cosine data spanning almost three years. The most significant error appears as a timing error across all Fence receivers observed as a function of the integrated Doppler region. Because the raw measurements are made up of many discrete samples, an apparent timing error can occur if the observation time tag is not properly associated. Based on calibration results, it is now believed that the site processor reports a time tag that is exactly 1.5 samples from the true observation time. For the “full Doppler region”, where the sampling rate is 55 Hz, the timing error is about 27 milliseconds [i.e. \(1.5 \div (55 \text{ Hz})\)], and proportionately larger for the half- and quarter-Doppler regions. Because most satellites are detected within the “full Doppler region”, the timing bias across most satellite observations averages to approximately 30 milliseconds, which is most accurately seen in the pseudo-North-South direction cosine being perpendicular to the Fence plane.

Another Fence error source is a large scale, systematic skewing of the cosine residuals across the receiver field-of-view. This skewing generates errors that are more positive as the receiver observes toward the east and less positive as the receiver observes toward the west. In addition to this overall skew, a low elevation oscillatory signature had been strongly evident prior to SLR calibration campaign. This low elevation effect has an appearance that is similar to antennae coupling (dipole re-radiation) at low elevations, although the actual cause of this error has not been confirmed. A plot of Fence cosine residuals in Figure 5 illustrates the effect.

The total error signature has appeared as an almost static feature during a three year interval from mid-1998 to mid-2000. It has been proposed that these signatures be removed with a background model as part of the FDR direction cosine generation. Experiments have shown that the signature can be empirically modeled using high order Chebyshev polynomials. The resulting improvement in the distribution of cosine residuals by using such a model is illustrated in Figure 6. However, the repetitive evaluation of such polynomials is not a desirable computational feature, so the operational curve fit is expected to be replaced with a piecewise cubic polynomial (spline) based on fewer interpolation nodes. After removal of these larger scale effects, very small temporal errors persist in the large scale averages of the receiver errors over time scales of months. Models for forecasting these quasi-seasonal effects remains to be developed.

**Confirmation of Sensor Locations**

In October 1999, the COBRA DANE (AN/FPS-108) phased array radar in Shemya, AK was reinstated as a contributing sensor to the SSN. For orbit determination purposes, a calibration campaign was begun to estimate the variance of the sensor by NAVSPACECOM and NRL. During this campaign, a review of historical AFSPC sensor location records showed that the NAVSPACECOM operational geocentric sensor position for COBRA DANE was different than its documented historical value. A
calibrated range bias of approximately -20 meters (with a sample standard deviation of about 17 meters) was observed while using this operational sensor position. Because this estimate demonstrated an error that was greater than expected, a supplemental calibration was performed using the historically published site location. The supplemental calibration provided a much better result consistent with published COBRA DANE performance measurements (0.3 m bias and 2.9 m deviation in range). The results raised questions about the most recently adopted sensor location at NAVSPACECOM.

Further investigation revealed that NAVSPACECOM had received a revised sensor location corresponding with the reinstatement of COBRA DANE where units of station altitude had not been specified. Because the historical documentation was not available for comparison at the time of data entry, it was (erroneously) assumed that the station altitude (in units of kilometers) had been provided in units of meters. The assumption was made because only two digits of numerical significance existed in station height, consistent with most surveys precise to the sub-meter level. The SLR-based calibration was able to discriminate that the updated sensor location had merely been miscommunicated to NAVSPACECOM, and did not intend to represent a survey different from the historical archive. Consequently, the operational site location was changed back to the historically documented survey.

A similar calibration campaign recently evaluated revised surveys of five (5) SSN sensors. All but one of the sensors error budgets remained insensitive to the subtle changes implied by these new survey measurements. The surveyed position of the Moron Optical Space Surveillance System (MOSS) was updated by several hundred meters, and the calibrated RMS scatter of MOSS observation residuals improved by at least 28% after adopting the new survey.

Coordinate Frame Differences

Recently published improvements to SSN optical sensors have indicated that an observational accuracy at few arcsecond level (RMS) is now possible. While improvements have been verified at NAVSPACECOM through subsequent SLR-based calibration campaigns, the estimated observation error variance from the SSN optical sensors had consistently yielded estimates that were larger than the published accuracy. This had been true for both terrestrial and space-based optical observations.

One complication affecting optical sensor calibration arises from the fact that NAVSPACECOM preprocesses all angular observations in Right Ascension and Declination coordinates by rotating the basis into a topocentric azimuth and elevation frame. This preprocessing puts all optical observations in an implicitly similar topocentric frame, reducing the complexity of the orbit determination software. However, the inertial reference frame designators originally accompanying the observations are discarded by this preprocessor. The original raw observation message cannot be completely reconstructed unless assumptions are made regarding the originally reported inertial reference frame. Since the processing of the NAVSPACECOM observations presented an
added step in the NAVSPACECOM orbit determination process, it was investigated to explain suspected increases in the observational error variance.

A careful review of the appropriate AFSPC instructions and Interface Control Documents (ICDs) were ambiguous regarding the specific coordinate frame designation, the frame epoch, and the underlying system of constants as it pertained to the reporting of optical observations. Personnel affiliated with the GEODSS, MOSS, and MSX optical sensors were contacted to determine how these sensors were interpreting these ICDs. These discussions confirmed that the sensor groups each had different interpretations of the same ICDs and were reporting observations with respect to different reference frames.

This confusion has primarily arisen from the fact that the US Space Command adopted for its Space Catalog, many decades ago, an unconventional fiducial direction known as the uniform equinox of date. Until recently, the differences between the true, mean and uniform equinoxes of date were below the error threshold of most SSN optical sensors. To avoid further confusion, and because the concept of equinox was made operationally obsolete for high accuracy applications in 1998 when the International Astronomical Union adopted a celestial reference system independent of any equinox, Seago and Vallado (2000) have recommended that the USSPACECOM support the International Celestial Reference System as a standard reference system for such high accuracy applications as the reporting of high accuracy orbits or observations.22 In the interim, a new NAVSPACECOM preprocessor has been developed that will properly transform these angular observations. Testing and evaluation is ongoing using SLR-based calibration.

Assessment of Proposed SSN Error Models

Barker et al. (1999) partly describes an assessment of ten (10) SSN sensor systems using the trajectories of five (5) SLR reference satellites, estimated from batches of observational data taken from 1994 through 1998.23 The authors of that study concluded that the range errors for most SSN sensors could be reasonably approximated using a function that emulates a two-parameter, elevation-dependent ionospheric refraction model based on “Klobuchar’s formula”. The study also concluded that the range error variance is elevation dependent. The results were based on empirical curve fits to range residuals plotted versus elevation, where the Eglin phased array radar has been the only published example supporting these findings to date. To test the proposed hypothesis, an assessment of Eglin range residuals was conducted by NRL using an extended sample of twenty-five (25) SLR- and GPS-based reference satellites from August 1998 through March 2000. For this analysis, an identical number of observations were used as that of the Barker et al. study, but concentrated over a shorter, nearly continuous time interval.
The NRL results confirmed that the sample variance of the range residuals measurably increased as elevation decreased. Least-squares curve fitting experiments to the proposed Klobuchar function suggested that it could be well approximated using a sixth order polynomial or higher; however, polynomial fits to the Eglin range residuals did not conform well to the proposed Klobuchar function. Based on the NRL analysis, no conclusive elevation-dependent signature could be discerned from the central tendency of the Eglin range residuals averaged over the past three years, as illustrated in Figure 7. The “proposed” curve in the figure conforms to the original curve published in the Barker et al. (1999) article. The “NRL fit” is an optimal trend fitted to the Eglin range residuals plotted, which appears fairly constant in comparison to the proposed function.

CONCLUDING REMARKS

In this paper, the authors have provided an overview of a sensor assessment method at the NAVSPACECOM using orbital ephemerides based on Satellite Laser Ranging, citing specific cases where improvements might be established. Calibration for the entire SSN is an expansion of the original effort to measure Fence performance and possibly improve Fence accuracy. However, calibration results for the SSN by the Navy do not directly contribute toward field calibration of that network (this is the responsibility of the AFSPC which maintains its own SLR calibration effort for that mission). Rather, Navy statistics provide more accurate a priori weighting of the sensors.
for routine Space Catalog maintenance at the NAVSPACECOM. Since the Navy preprocesses SSN observations differently, a process separate from the AFSPC is maintained to monitor the quality of observations contributing to the Navy orbit determination process. Such duplication of effort stems from the charter of the NAVSPACECOM to provide a level of redundant functionality for the DoD regarding Catalog maintenance.

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