The Extended HANDS Characterization and Analysis of Metric Biases

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ABSTRACT

The Extended High Accuracy Network Determination System (Extended HANDS) consists of a network of low cost, high accuracy optical telescopes designed to support space surveillance and development of space object characterization technologies. Comprising off-the-shelf components, the telescopes are designed to provide sub arc-second astrometric accuracy. The design and analysis team are in the process of characterizing the system through development of an error allocation tree whose assessment is supported by simulation, data analysis, and calibration tests. The metric calibration process has revealed 1-2 arc-second biases in the right ascension and declination measurements of reference satellite position, and these have been observed to have fairly distinct characteristics that appear to have some dependence on orbit geometry and tracking rates. The work presented here outlines error models developed to aid in development of the system error budget, and examines characteristic errors (biases, time dependence, etc.) that might be present in each of the relevant system elements used in the data collection and processing, including the metric calibration processing. The relevant reference frames are identified, and include the sensor (CCD camera) reference frame, Earth-fixed topocentric frame, topocentric inertial reference frame, and the geocentric inertial reference frame. The errors modeled in each of these reference frames, when mapped into the topocentric inertial measurement frame, reveal how errors might manifest themselves through the calibration process. The error analysis results that are presented use satellite-sensor geometries taken from periods where actual measurements were collected, and reveal how modeled errors manifest themselves over those specific time periods. These results are compared to the real calibration metric data (right ascension and declination residuals), and sources of the bias are hypothesized. In turn, the actual right ascension and declination calibration residuals are also mapped to other relevant reference frames in an attempt to validate the source of the bias errors. These results will serve as the basis for more focused investigation into specific components embedded in the system and system processes that might contain the source of the observed biases.

1. INTRODUCTION AND BACKGROUND

The Extended High Accuracy Network Determination System (Extended HANDS) consists of a network of low cost, high accuracy optical telescopes designed to support space surveillance and development of space object characterization technologies [1]. One of the major capabilities of HANDS is to produce high-accuracy space-track metric data. Comprising off-the-shelf components, each telescope system in the network is designed to provide sub arc-second astrometric accuracy. The system operational concept, depicted in Fig. 1, is that each telescope, or HANDS Ground Station (HGS), is provided with tasking to collect metric tracking data; the image data are astrometrically processed at the HGS to produce right ascension (RA) and declination (Dec) measurements. These measurements are transferred to the HANDS Control Center (HCC), where they are correlated and processed to produce and/or update the orbits of the tracked objects.

The metric observational data on occasion exhibit unexplained systematic errors when calibrated against well known reference orbits. The monitoring and assessment of metric accuracy is of interest as measurement biases map directly into orbit error, and diminish the resulting orbit determination (OD) and prediction accuracies. To better understand the sensitivity of the metric accuracy to errors in various parts of the HANDS system, a System Characterization Analysis Tool (SCAT) was developed in MATLAB which allows analysis of the system performance as a function of system errors.

The purpose of the work presented in this paper is to gain an understanding of the system errors, and in the context of systems engineering, determine how each error, singly and in combination, contributes to the total error to affect the performance of a "typical" optical metric sensor system. The work is on-going, and so the focus is on the process that is being established, and some details of the models and analysis done so far. The second section of this paper provides some details of the HANDS system and the calibration process. Two actual data examples of metric calibration performance are presented. Section three provides details of the error analysis tool (SCAT) and its implementation in the analysis process. The error analysis results based on simulated reference satellites are presented in section four, where the sensitivity of the system metrics to input errors is examined, and the results of the simulation are compared to actual results. The fifth and final section provides some conclusions to date about the system performance, and the focus of future work.

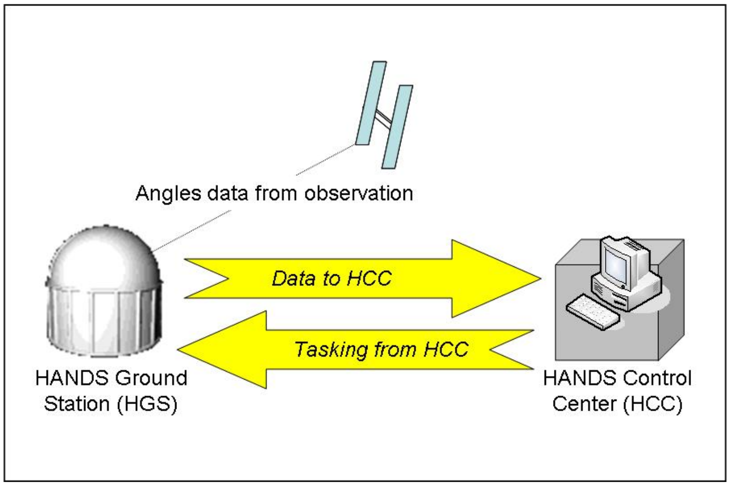

Fig. 1. Extended HANDS Operational Concept

2. METRIC BIASES AND SYSTEMATIC ERRORS

It is well known that biases in optical measurements translate into biases in the orbit determination solutions and subsequent predictions. Fig. 2 shows how metric errors translate into orbit positional and along-track orbit errors for several orbit regimes. As an example, a 1 arc-second bias in GEO tracking measurements results in a measurement bias of 200 meters, and an along-track error growth of 75 meters per hour.

Prior work has been done to examine biases in optical metric data, and also to compensate in the orbit determination process through bias estimation. However, these have only addressed error sources singly, and as uncorrelated from other potential sources. The process and simulation tool presented in this paper provides a systematic approach to identifying the primary contributors to over all bias in the metrics. By appropriate mathematically modeling component biases, the sensitivity of metric measurements to input errors can be determined, in addition to the net effect of combined errors in the overall when numerous error sources might be contributors.

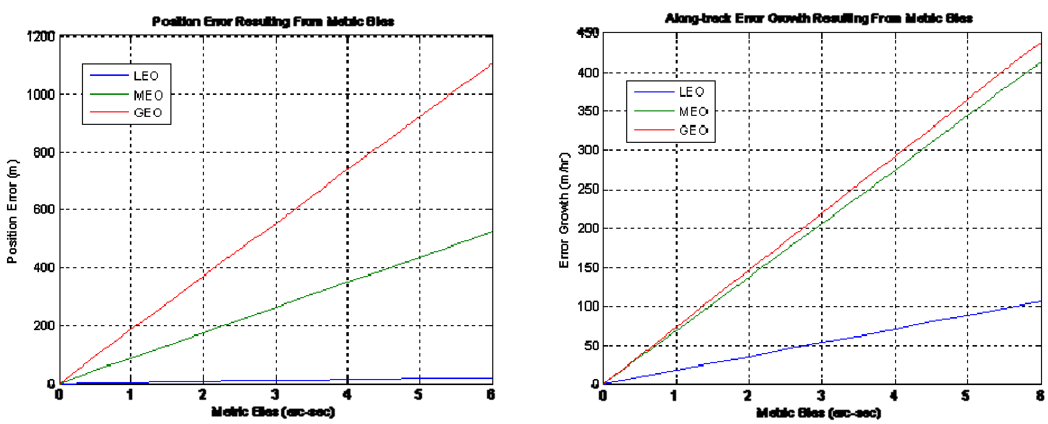

Fig. 2. Position and Along-track Orbit Error from Metric Biases

The potential sources of error that contribute to an optical metric sensor are depicted in Fig. 3, where the two primary components that go into producing metrics are the telescope system and the image processing system. The telescope system consists of the optical and mechanical components, in addition to the CCD camera, telescope dome, GPS clock and weather sensors. The image processing system is primarily software based; for HANDS, "AstroGraph" is the astrometric processing tool which requires parameters such as site location, a star catalog and *a priori* orbit information (e.g., a "TLE," or two-line element set) for tasked objects.

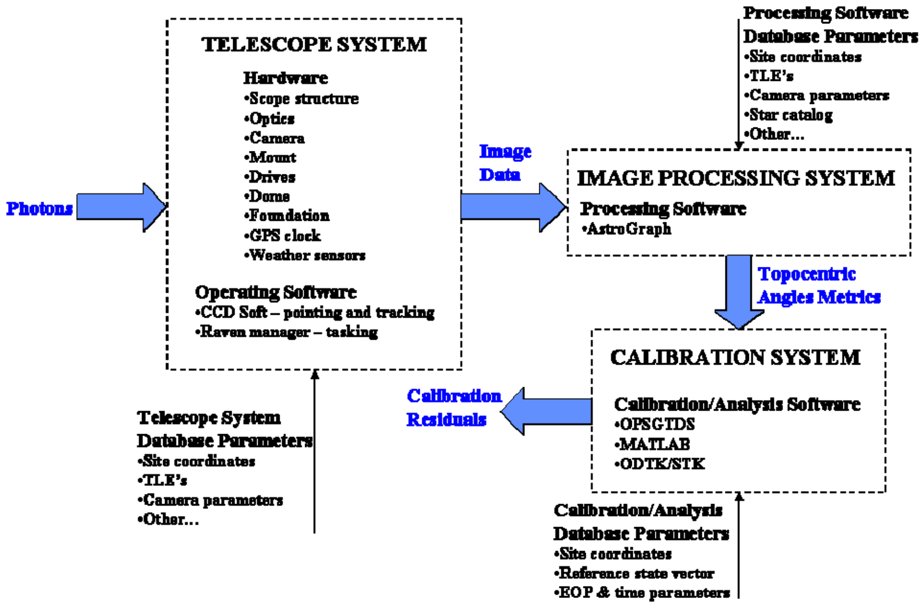

Fig. 3. Optical Metric Sensor System Elements

To establish metric performance, a metric calibration process is also needed. Since the calibration components can contribute to the assessed performance, it needs to be considered in development of a system error budget. The calibration process is depicted in Fig. 4 where a "high accuracy" reference orbit is used to generate reference RA and Dec values at the measurement times. These "computed" values are used as a reference for comparison to the "observed" RA and Dec values. The resulting differences, or residuals, are a measure of RA and Dec performance.

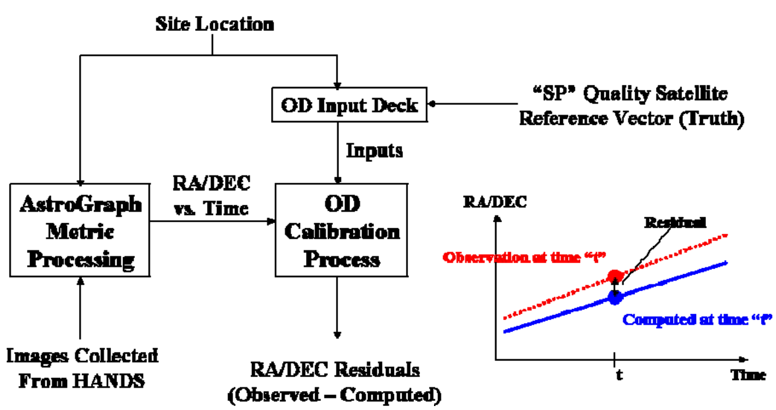

Fig. 4. System Calibration Process

In the calibration process, the HANDS system under test tracks "reference" satellites whose ephemerides are accurately known. Two classes of reference satellites that are typically used are satellites from the Tracking Data and Relay System (TDRS) and the Global Positioning System (GPS). Their reference orbits can be obtained from the web sites provided in the reference section of the paper [2, 3].

Two actual data examples, one from each of the TDRS and GPS classes of reference satellites, are provided. The data were collected on September 12 of 2007 from the HGS known as Unit2 located at the Remote Maui Experiment (RME) site located near sea level on the south side of Maui. The statistics for both sets of metric accuracy data are summarized in Table 1.

Table 1. HANDS Calibration Data for Two Reference Satellites

	RA Mean (arcseconds)	RA Std Dev (arcseconds)	Dec Mean (arcseconds)	Dec Std Dev (arcseconds)
TDRS-5	-0.10	0.65	0.29	-0.39
GPS PRN-22	0.21	0.78	1.15	1.10

Metric calibration data for the TDRS-5 satellite are shown in Fig. 5. The data covers a period of several hours. Though this particular data exhibits fairly small biases, less than 1 arc-second, some systematic behavior can be observed. Data taken on other TDRS reference satellites have, on occasion, exhibited biases on the order of several arc-seconds. The source of these errors is yet to fully be explained.

Metric data for GPS PRN-22 was also collected from the same system on September 12, 2007, at RME, and those calibration residuals are shown in Fig 6. In this example, much larger errors on the order of several arc-seconds can be observed over this period. The error does not appear to be fixed, but varies as a function of time, though this could also be a function of geometry, or any number of other spatial or temporal variables.

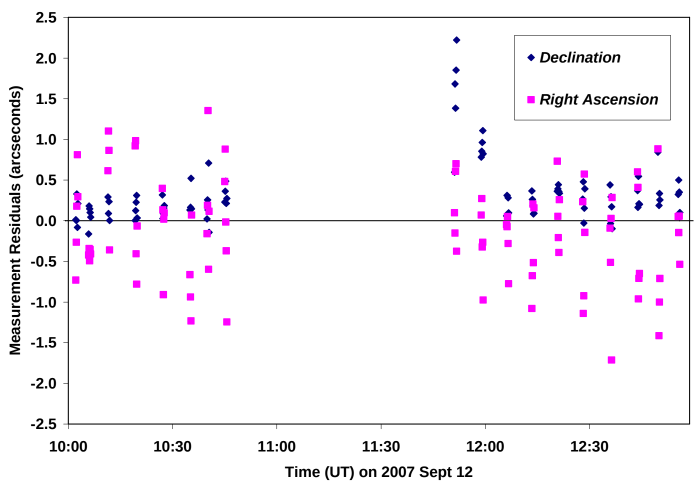

Fig. 5. TDRS-5 HANDS Calibration Data for 12 Sep 2007

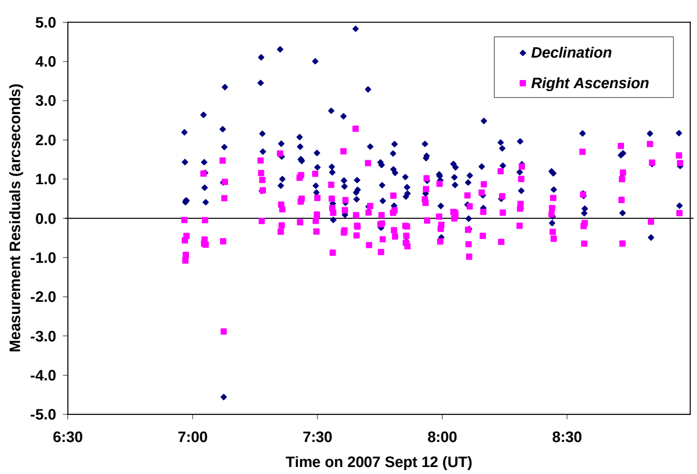

Fig. 6. GPS PRN-22 HANDS Calibration Data for 12 Sep 2007

3. ANALYSIS TOOL AND MODEL DEVELOPMENT

Because the metric calibration process only provides a "net" measure of system performance, a more detailed look at the elements of the system is required to understand their individual contribution to the overall metric accuracy. To guide the systems engineering analysis, an error analysis tool (SCAT) is being developed to provide insight into how each component might contribute. SCAT is a time domain based analysis tool where geometric and other time-dependent attributes of the system can be examined. Its value is in identifying which errors have the largest impact, their characteristics and magnitude of contribution, thus providing guidance for development of testing requirements. When fully developed, the tool can also be used to develop a system error budget designed to meet specific customer requirements.

A schematic of the SCAT simulation and analysis processing is provided in Fig. 7, where key functions are shown in the boxes, and data flow depicted by the arrowed lines. The error analysis is accomplished through a "truth" set of metrics which are generated based on the same reference orbit ephemerides that are used in the calibration. Together with the site coordinates, system noise parameters, transformation parameters, etc., a time history of reference RA and Dec values over a user specified period and time intervals is generated. This "truth" data path is shown in blue in Fig. 7. One or more error sources can be modeled at appropriate points in the simulation to assess the affect on the overall metric accuracy, either one at a time or in combination. These data paths are depicted in red in Fig.7. All specific (e.g., Earth orientation) and general transformation equations and parameters, can be found in several useful references, for example [4].

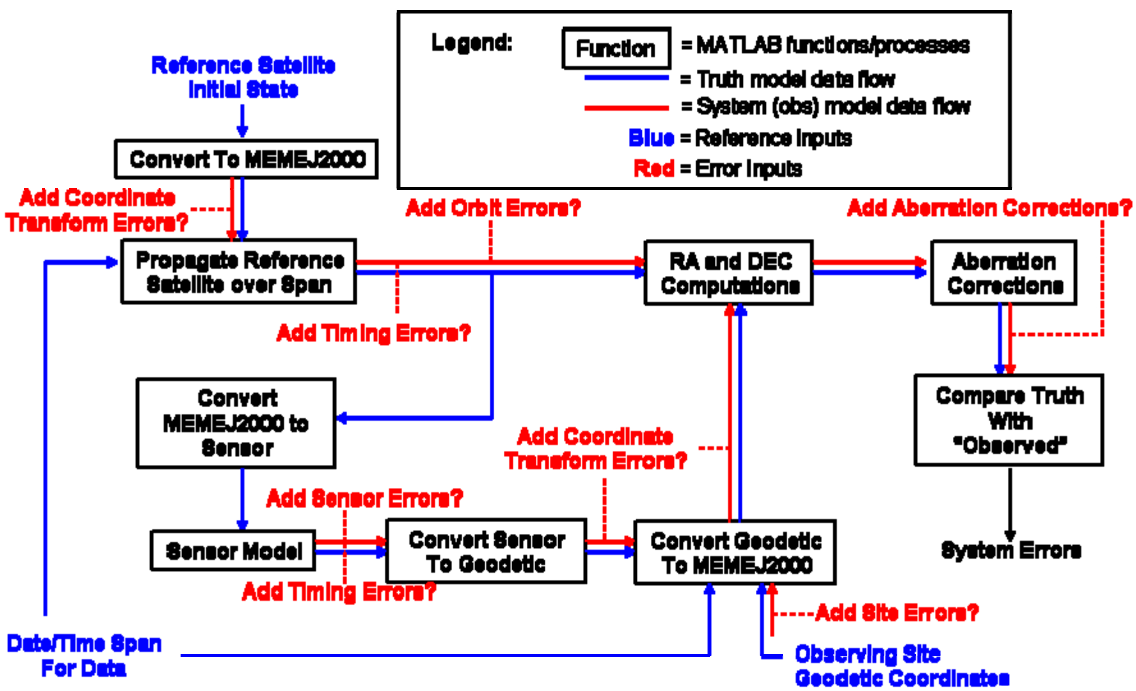

Fig. 7. Simulation Analysis Processing

For this "top down" approach to the error analysis, the errors are categorized as being associated with the "reference" (calibration) component, or the sensor (telescope/image processing) system. The specific reference component errors include the reference satellite orbit errors, site coordinate errors, coordinate transformation and light time correction related errors. The sensor component errors include measurement timing, noise, and astrometric reduction errors. This last source can potentially comprise many sources of error, though the net result is an error applied to the inertial, topocentric RA and Dec. Though more detailed error modeling of the elements of astrometric processing may be done in a future phase of this work, it suffices for now to model the astrometric errors as a composite of several possible error characteristics. This includes noise, bias, linearly time-dependent, and periodic errors which can be modeled separately or in combination.

4. SIMULATED SYSTEM ERROR ANALYSIS RESULTS

As part of the development and validation process, the SCAT analysis code was exercised with the error models that have been incorporated to date. The errors that have been modeled at this initial stage are listed in the first column of Table 2. To exercise the code, the initial state vectors for the TDRS-5 and GPS PRN-22 reference satellites, coincident with the HANDS observations of those satellites on September 12, 2007, were generated for use in the simulation. A set of "baseline" errors was established for each analysis scenario, and both the individual RA and Dec errors and the total errors were assessed over an 8-hour period.

A summary of the simulated TDRS-5 results is presented in Table 2, where the nominal values assigned to each error source are listed, and the mean and standard deviation for each of the resulting RA and Dec errors given. The "nominal" is an estimate (at this stage) of what the expectation is for the given system error. With these estimated errors as inputs, the largest contributor to the metric calibration error appears to be the reference orbit bias, followed by the site coordinate errors and timing bias. The root sum squared (RSS) of all modeled errors is also given, and for this case is around the 0.25 arc-second level for both the mean and the standard deviation. A plot of the simulated metric errors for the case where all error sources are combined is shown in Fig. 8, where it can be seen by comparison of the mean and standard deviations with the RSS that some additive and/or negating effects are possible when the errors are combined.

Sensitivity to the omission of light time correction and Earth orientation transformations was also examined for this TDRS-5 scenario. The bottom of Table 2 summarizes these results, where it can be seen that omission of the precession transformation is potentially the largest impact on the metric errors, followed by the light time correction, nutation and polar motion. Omission of the sidereal time was not examined as it was felt that this transformation is so fundamental as to make its absence obvious.

A summary of the simulated nominal GPS PRN-22 results is presented in Table 3, where the nominal values for each error source are listed, and the mean and standard deviation for each of the resulting RA and Dec errors given. The largest contributor to the metric calibration error in this case appears to be the site coordinate errors, followed by the sensor noise, timing bias and orbit errors. Note, the GPS orbit accuracy is advertised to be an order of magnitude better than that of the TDRS reference orbits. The root sum squared (RSS) of all modeled errors is also given, and for this case is around the 0.3 arc-second level for both the mean and the standard deviation. A plot of the metric errors for the case where all error sources are combined is shown in Fig. 9, where it can again be seen by comparison of the mean and standard deviations with the RSS that some additive and/or negating effects are possible when the errors are combined.

Table 2. TRDS-5 Nominal Input Errors and Simulated Metric Errors for 12 Sep 2007

Metric Error Source	Nominal Error Value	TDRS-5 RA Metric Bias (as)	TDRS-5 RA Metric Std (as)	TDRS-5 Dec Metric Bias (as)	TDRS-5 Dec Metric Std (as)
Reference Orbit Bias	50 m, 50 m, 50 m (radial, along-track, cross-track)	0.233000	0.003790	0.198000	0.006290
Timing Bias	-0.005 s	-0.074900	0.000345	0.007910	0.001510
Timing Drift	1.0e-9 ppm	0.000215	0.000128	-0.000023	0.000013
Sensor Noise (inertial)	0.3 arc-sec	0.016400	0.263000	-0.041700	0.277000
Site Coordinate Errors	10 m, 10 m, 50 m (east, north, up)	0.084300	0.000619	-0.109000	0.012600
Polar Motion Transformation Error	0.001 arc-sec (per x, y axes)	0.000055	0.000000	-0.000066	0.000002
Sidereal Time Transformation Error	0.01 arc-sec	0.001220	0.000003	-0.000012	0.000020
Nutation Transformation Error	0.1 arc-sec (per x, y, z axes)	0.006910	0.001430	-0.007550	0.008830
Precession Transformation Error	0.1 arc-sec (per x, y, z axes)	0.006910	0.001430	-0.007520	0.008840
Total (RSS)		**0.259560**	**0.263036**	**0.230217**	**0.277643**
Light Time Correction	No correction	2.110000	0.011100	-0.250000	0.047800
Polar Motion Correction	No correction	0.023500	0.000063	-0.003290	0.000452
Nutation Correction	No correction	0.725000	0.236000	-0.987000	0.183000
Precession Correction	No correction	48.400000	2.030000	-4.480000	9.460000

The bottom of Table 3 summarizes the omission of the light time correction and transformations, where it can be seen that omission errors are comparable to those of the nominal TDRS-5 scenario. One noteworthy difference with TDRS-5 results is that of the timing bias and light time correction. The GPS orbital velocities relative to TDRS (Geosynchronous) orbits make their calibration performance more sensitive to timing related errors.

To gauge the sensitivity to changes in errors for each of the calibration scenarios, an “anomalous” case was examined for each of the reference satellites over the same 8-hour period on September 12, 2007. In each case, the nominal input errors were increased by an order of magnitude (factor of 10), and the error statistics re-computed. As can be seen in the summary tables for TDRS-5 and GPS PRN-22, Table 4 and 5 respectively, the resulting individual contribution to the RA and Dec metric calibration errors scales linearly; i.e., the root sum square (RSS) metric errors increase by a factor of 10. However, if one examines total combined errors as a function of a scalar increase in the input errors, the total combined (correlated) errors do not necessarily scale linearly with the input errors.

Table 3. GPS PRN-22 Nominal Input Errors and Simulated Metric Errors for 12 Sep 2007

Metric Error Source	Nominal Error Value	PRN-22 RA Metric Bias (as)	PRN-22 RA Metric Std (as)	PRN-22 Dec Metric Bias (as)	PRN-22 Dec Metric Std (as)
Reference Orbit Bias	5 m, 5 m, 5 m (radial, along-track, cross-track)	0.026600	0.024100	0.022900	0.021200
Timing Bias	-0.005 s	-0.127000	0.045200	0.011600	0.091300
Timing Drift	1.0e-9 ppm	0.000368	0.000216	0.000113	0.000268
Sensor Noise (inertial)	0.3 arc-sec	-0.037300	0.292000	-0.035500	0.284000
Site Coordinate Errors	10 m, 10 m, 50 m (east, north, up)	0.252000	0.136000	-0.095800	0.094400
Polar Motion Transformation Error	0.001 arc-sec (per x, y axes)	0.000049	0.000053	-0.000114	0.000024
Sidereal Time Transformation Error	0.01 arc-sec	0.001510	0.000761	-0.000316	0.000567
Nutation Transformation Error	0.1 arc-sec (per x, y, z axes)	0.009420	0.005550	-0.012000	0.013900
Precession Transformation Error	0.1 arc-sec (per x, y, z axes)	0.009440	0.005540	-0.012000	0.013900
Total (RSS)		**0.286203**	**0.326261**	**0.106700**	**0.314228**
Light Time Correction	No correction	2.330000	0.894000	-0.049100	1.800000
Polar Motion Correction	No correction	0.028400	0.015500	-0.010800	0.010900
Nutation Correction	No correction	0.715000	0.050000	-1.680000	0.503000
Precession Correction	No correction	56.800000	36.300000	-20.100000	28.000000

Table 4. TRDS-5 Anomalous Input Errors and Simulated Metric Errors for 12 Sep 2007

Metric Error Source	Anomalous Error Value	TDRS-5 RA Metric Bias (as)	TDRS-5 RA Metric Std (as)	TDRS-5 Dec Metric Bias (as)	TDRS-5 Dec Metric Std (as)
Reference Orbit Bias	500 m, 500 m, 500 m (radial, along-trck, cross-trck)	2.330000	0.037900	1.980000	0.062900
Timing Bias	-0.05 s	-0.749000	0.003450	0.079100	0.015100
Timing Drift	1.0e-8 ppm	0.002150	0.001270	-0.000233	0.000128
Sensor Noise (inertial)	3.0 arc-sec	0.148000	2.670000	0.142000	2.980000
Site Coordinate Errors	100 m, 100 m, 500 m (east, north, up)	0.843000	0.006190	-1.090000	0.126000
Polar Motion Transformation Error	0.01 arc-sec (per x, y axes)	0.000547	0.000002	-0.000656	0.000022
Sidereal Time Transformation Error	0.1 arc-sec	0.012200	0.000031	-0.000123	0.000201
Nutation Transformation Error	1.0 arc-sec (per x, y, z axes)	0.069100	0.014300	-0.075500	0.088300
Precession Transformation Error	1.0 arc-sec (per x, y, z axes)	0.069100	0.014300	-0.075500	0.088300
Total (RSS)		**2.594640**	**2.670355**	**2.268551**	**2.985976**
Light Time Correction	No correction	2.110000	0.011100	-0.250000	0.047800
Polar Motion Correction	No correction	0.023500	0.000063	-0.003290	0.000452
Nutation Correction	No correction	0.725000	0.236000	-0.987000	0.183000
Precession Correction	No correction	48.400000	2.030000	-4.480000	9.460000

Table 5. GPS PRN-22 Anomalous Input Errors and Simulated Metric Errors for 12 Sep 2007

Metric Error Source	Anomalous Error Value	PRN-22 RA Metric Bias (as)	PRN-22 RA Metric Std (as)	PRN-22 Dec Metric Bias (as)	PRN-22 Dec Metric Std (as)
Reference Orbit Bias	50 m, 50 m, 50 m (radial, along-track, cross-track)	0.266000	0.241000	0.229000	0.212000
Timing Bias	-0.05 s	-1.270000	0.452000	0.116000	0.013000
Timing Drift	1.0e-8 ppm	0.003680	0.002150	0.001130	0.002680
Sensor Noise (inertial)	3.0 arc-sec	-0.319000	2.810000	0.161000	3.090000
Site Coordinate Errors	100 m, 100 m, 500 m (east, north, up)	2.520000	1.360000	-0.958000	0.944000
Polar Motion Transformation Error	0.01 arc-sec (per x, y axes)	0.000490	0.000530	-0.001140	0.000244
Sidereal Time Transformation Error	0.1 arc-sec	0.015100	0.007610	-0.003160	0.005670
Nutation Transformation Error	1.0 arc-sec (per x, y, z axes)	0.094200	0.055500	-0.120000	0.139000
Precession Transformation Error	1.0 arc-sec (per x, y, z axes)	0.094400	0.055400	-0.120000	0.139000
Total (RSS)		**2.855494**	**3.164537**	**1.019016**	**3.243922**
Light Time Correction	No correction	2.330000	0.894000	-0.049100	1.800000
Polar Motion Correction	No correction	0.028400	0.015500	-0.010800	0.010900
Nutation Correction	No correction	0.715000	0.050000	-1.680000	0.503000
Precession Correction	No correction	56.800000	36.300000	-20.100000	28.000000

The RSS and combined errors as a function of the “nominal” errors scaled by factors of 1, 2, 5 and 10 are shown in Figs. 10 and 11 for TDRS-5 and GPS PRN-22, respectively. There is apparently an addition and/or negation of errors where parameters associated with each of the errors are correlated. This underscores the need for an analysis tool which appropriately models the combination of errors when comparing with actual data results.

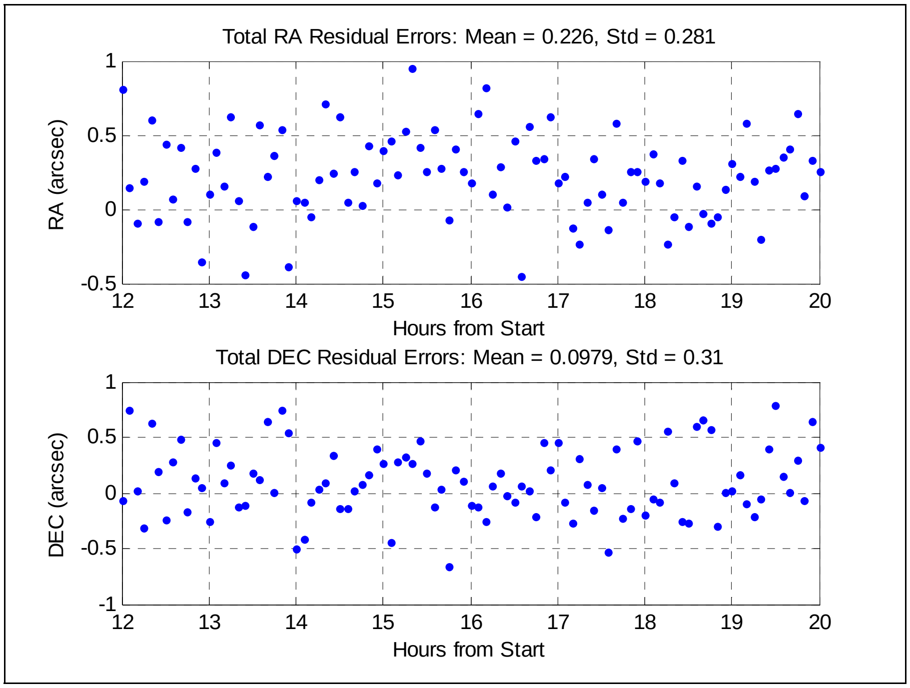

Fig. 8. TDRS-5 Simulated Model Errors with Nominal Input Errors for 12 Sep 2007

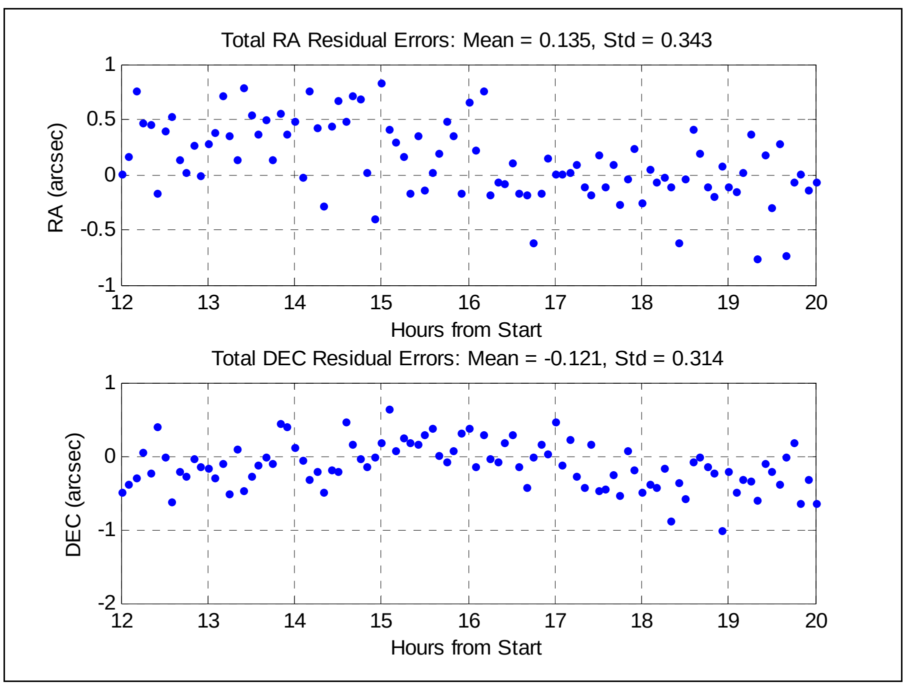

Fig. 9. GPS PRN-22 Simulated Model Errors with Nominal Input Errors for 12 Sep 2007.

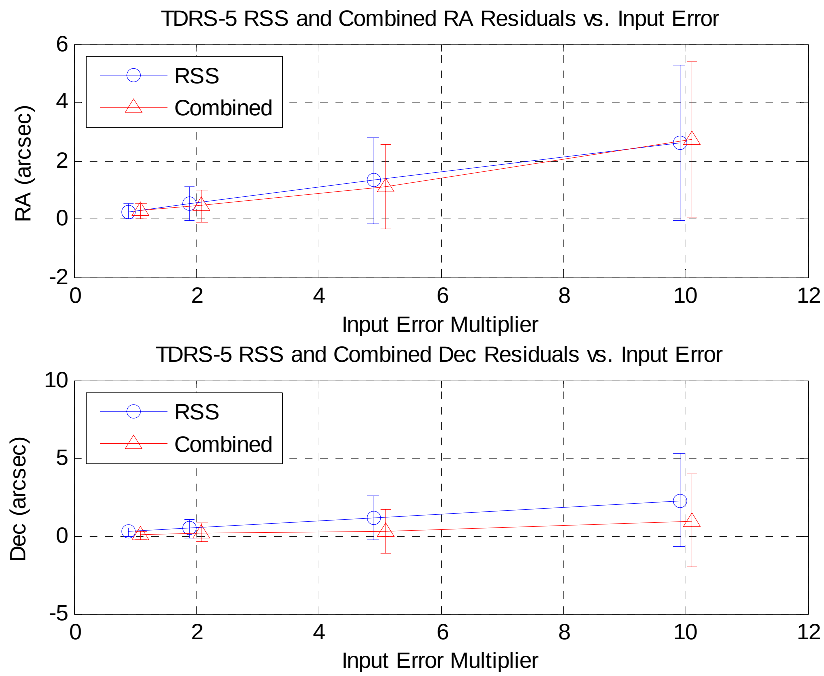

Fig. 10. TDRS-5 Simulated RSS and Combined Errors as a Function of Input Errors for 12 Sep 2007

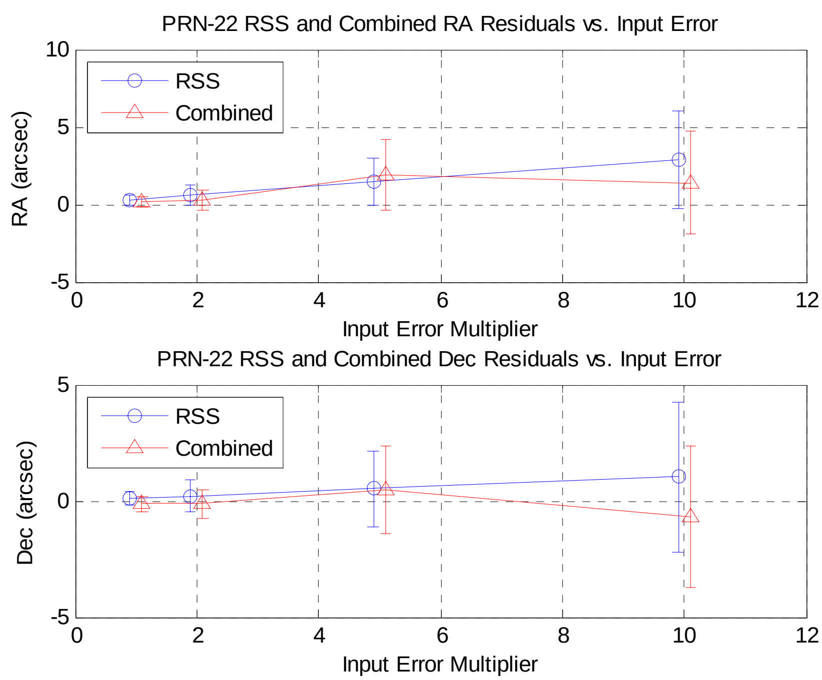

Fig. 11. GPS PRN-22 Simulated RSS and Combined Errors as a Function of Input Errors for 12 Sep 2007

Next we compare results from SCAT to actual results from observations of GPS PRN-22 over a two-hour time span on September 12, 2007. The input errors modeled in the simulator are the nominal errors of Table 3, except for the differences noted in Table 6.

Table 6. Input Errors for Simulation of Residuals for GPS PRN-22.

Metric Error Source	***Input Error Value***
Reference Orbit Bias	5 m, 50 m, 100 m (radial, along-track, cross-track)
Timing Bias	0.033 s
Sensor Noise (inertial)	0.5 arcsec (RA) 0.8 arcsec (Dec)
Site Coordinate Errors	10 m, 10 m, 50 m (east, north, up)

The plots in Figure 12 compare the actual residuals on the left-hand plot to the simulated residuals shown on the right. The largest contributions to the RA and Dec bias in the simulated case come from the Reference Orbit Bias, the Site Coordinate Errors, and the Timing Bias. The spread is due primarily to the correlated Sensor Noise. Are the errors modeled in the simulation responsible for the errors observed in the actual data? The simulation results, in this example, present a plausible hypothesis that can be used to test and validate the performance of specific components of the system to help answer the question. It is notable that not any single error source, but a combination of errors is needed to replicate the actual data errors.

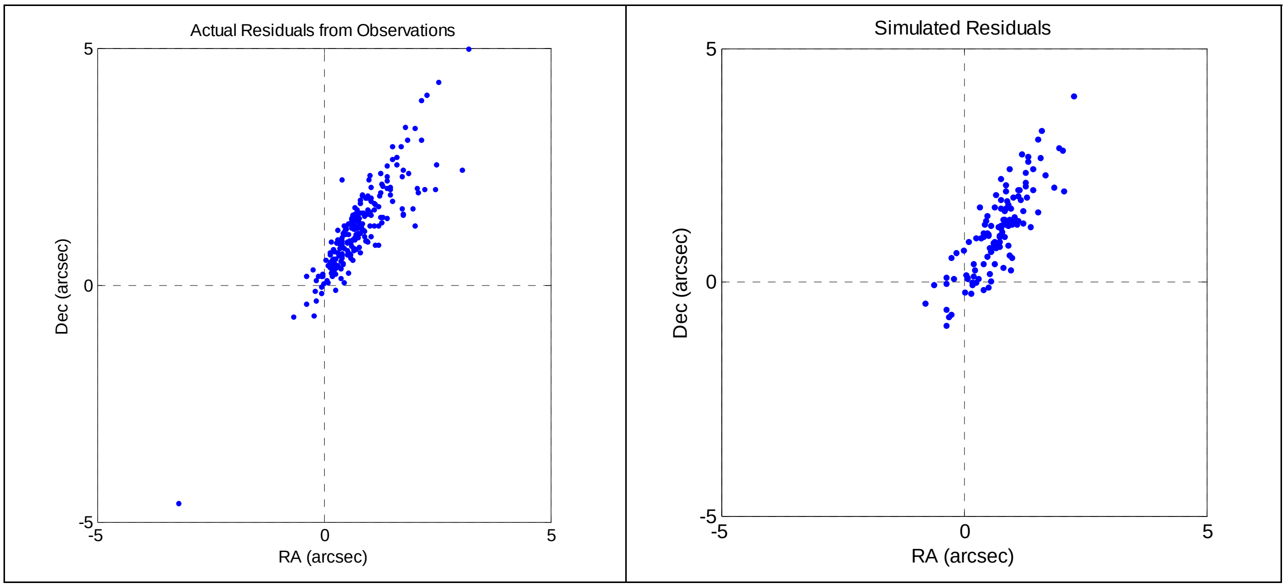

Fig. 12. Comparison of Actual Results (left) to Simulated Results (right) for GPS PRN-22.

5. SUMMARY, CONCLUSIONS AND FUTURE WORK

A process is being established that will allow development of the Extended HANDS system requirements. To support this, a system characterization simulation tool is under development that will permit analysis to assess the errors in system components, and how they combine to impact the overall system performance. A “top level” approach has been adopted, and some of the more fundamental errors have been incorporated into the tool by way of establishing a baseline from which higher fidelity models of system elements can be developed and incorporated. The significant results so far are summarized here.

The preliminary results show that omission of Earth orientation transformations result in significant and obvious errors. However, small errors in the transformation parameters, when applied, contribute errors on the order of fractions of an arc-second.

Reference orbit biases that are representative of the advertised orbit accuracy for TDRS (50 m) and GPS (5 m) do indeed result in metric errors on the order of fractions of an arc-second. However, increases by an order of magnitude of these reference orbit errors result in metric errors on the order of one or more arc-seconds.

Measurement timing errors on the order of tens of milliseconds contribute little to the TDRS metric accuracy. However, timing errors of this magnitude do contribute significant errors to the metrics for GPS. The higher orbital velocity makes GPS metrics more sensitive to timing errors.

Multiple error sources do not combine linearly. Errors can be either additive or negate each other, and which of these occurs is a complex function of the orbit-observation geometry. The value of identifying significant contributions to the overall metric error in the simulation, and attributing it to a specific component of the process, is that if consistent with observed error characteristics, it can provide guidance for test and validation of specific components to improve the overall accuracy of the system.

SCAT continues to be refined with plans to further develop the error models, specifically, to develop detailed models of the astrometric processing. Planned future work includes automation of the incorporation of Earth orientation parameters to accommodate improvements to actual data comparisons, and implementation of code to check the visibility of the satellite during the period of interest. The development of a Graphical User Interface for convenience of the analyst is desired.

The value of the simulated error analysis tool has been demonstrated in the early stages of the system characterization work, and will be an integral part of a broader effort. A more detailed audit of system components, currently underway, will lead to further refinement of the models and the incorporation of new sources of error. For example, the timing error that is currently modeled with bias, drift, and noise may actually arise from a variety of sources, including finite shutter activation time and error due to tracking at a constant rate the satellite whose velocity is not constant. As the system is further detailed, simulation of errors with SCAT will help establish the baseline system requirements and point to key contributors among the error sources. Experiments can then be defined for testing and calibrating the individual components of the system. While the development of SCAT was motivated by its use for HANDS, the use of the simulation tool should also be of interest for anyone developing requirements for an optically based sensor system.

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7. REFERENCES

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