Testing and Verifying the NASA SGSLR system to meet the Projected 1mm Level Performance

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ABSTRACT
NASA Space Geodesy Satellite Laser Ranging (SGSLR) network, presently in its early stage of development, must meet significantly improved ranging performance than the current NASA SLR network. The goal is to achieve 1mm or better normal point data precision, accuracy, and stability as well as support automation. This places significant emphasis on the need for a robust and comprehensive approach for system testing and verification for performance compliance. The system build phase will include conventional approaches to test the hardware and software performance from the modular level to the subsystem level and subsequently to the system level. Upon completion of the standalone system performance testing and verification, NASA intends to use the collocation technique, where a proximity SLR reference system will be used to benchmark the performance via simultaneous ranging to geodetic satellites with precisely known Center of Mass (CoM). The ranging performance comparison is then performed on a pass by pass basis using a combination of geometrical and orbit analysis. This comparison is normally performed over a sufficiently long period to establish adequate satellite pass geometry and to verify the short and long term system stability. This mature approach, which has significantly helped NASA to achieve uniformity and consistency of performance across its global network while minimizing the performance risk across its core sites, will be used for SGSLR also. To further augment the above verification framework, each system or at least the reference system could carry a piggy-backed small aperture auxiliary telescope to simultaneously receive the satellite returns from the other system for cross-correlated range measurements. Details are discussed.

1. INTRODUCTION
As spelled out in the Space Geodesy Project (SGP) requirements [1, 2], there is a compelling need for truly "millimeter" level data in terms of precision, accuracy, and stability. Even though these requirements are imposed primarily by the TRF community, the scientists studying the sea surface topography also need the high accuracy space geodetic data for the altimetry satellite POD and altimeter calibration. The earth CoM knowledge provided through the reference frame is critical to the study of the sea level change. The TRF and sea level change analyses constitute the most demanding SLR data quality requirements for the International Laser Ranging Service (ILRS) stations and hence for the SGSLR system. Even though there are system requirements for data quantity and automation, none of these are as demanding as the millimeter data quality. SGP, using Network simulation of globally distributed ideal stations, has simulated the science requirement for millimeter level data. Such an ideal network of globally distributed 1mm (precision, accuracy, and stability) stations, in simulation, generated <1mm level accuracy for the TRF scale. Amongst the data quality requirements, the verification of data precision is straight forward. However, the testing and verification (T&V) required for establishing the system accuracy and stability at the 1 mm level is a real challenge. The individual station data quality in terms of the precision and stability (short term and long term) are the most pressing demands for the SGSLR system performance testing and verification.

This paper provides an insight into the project's preliminary plan for millimeter level testing and verification. This plan will be refined as the project goes through the life cycle reviews. This document highlights areas of SLR performance that need special attention for test and verification effort for delivering millimeter level performance for a core station such as SGSLR. An attempt is made here to discuss the salient aspects of the system and network level T&V that will become necessary both at the NASA GGAO and the remote deployment sites. Last, but not the least, this paper refers to the challenges, ideas, strategies, and techniques to establish legitimacy of SGSLR millimeter level performance.

2. TESTING AND VERIFICATION
In the commercial industry view, testing and verification is the process of ensuring that a system or product complies with its (1) requirement, (2) specification, (3) regulation, or (4) functional condition. In the case of SGSLR, all of these attributes are rolled into the requirements from levels 3-5. The real challenge is to confine the scope of verification

without compromising the required performance. The T&V plan entails establishing crisp tests, verification, and analyses to establish an overall scope of "what, how, when, where, to what extent, at what level" of the verification to encapsulate the system performance.

Error Estimation and Data Quality

The SLR involves measuring a number of parameters critical to the target range determination. The time of flight (ToF), i.e., the 2-way time to the satellite and back is a function of the various system engineering parameters. To establish the point to point range to the satellite from the telescope invariant point, the measured range needs to be corrected for system electronics and optical path delays, atmospheric refraction, and the range offset to the CoM of the satellite. The range residuals are then computed with respect to an estimated range from an *a priori* known orbit and are subsequently fitted using a polynomial of appropriate order. An iterative 3 sigma filter improves the SNR and the data statistics. The SLR data statistics typically include single shot RMS, NPT RMS, mean, skew, and kurtosis.

The range data obtained by a SLR system is a function of many parameters.
$R = \eta(x_1, x_2 \ldots)$, where x_i = system engineering parameters, external parameters (atmosphere, LRA CoM, models, processing algorithms….) (1)

There are millimeter and/or sub-millimeter errors in the various devices, sensors, and the data pathways used in the system. These need to be quantified through direct measurements wherever possible or using models and/or computations. The quality of the data, thus obtained, is a function of the engineering capability of the system as well as the measurement constraints. Thus,

Data Quality= $\phi(x_1, x_2, y_1, y_2)$; x_i = engineering capability; y_i = constraints of measurement and analysis; 2)

The data and system quality obtained is a measure of the quality of engineering incorporated in the system, which is a function of the expended resources (human and material resources) along with the time expended to establish the desired quality. Thus,

System Quality = $\varphi(x_1, x_2)$, where x_i = invested dollars and actual time spent for design, development, and T&V; (3)

If the small systematic errors are neglected, then these could potentially accumulate and aggregate to several millimeters. Thus, careful scrutiny is needed of the accumulation and aggregation of small errors in the various sensors and devices included in the ranging data loop.

Net Systematic error = $\sum (\Delta x_i)$, where, Δx_i = error of the i^{th} source; (4)

T&V Approach

The overall approach to testing and verification is illustrated in Figure 1. Amongst the SGSLR levels 1-5 requirements, only levels 3-5 applies to SGSLR as a system. Although testing will be done on a continuing basis at multiple levels, the verification will be performed at the highest level possible. The T&V of level 3 and 4 requirements will be an integral part of the subsystem/ system integration efforts, while level 5 verification will address the modular or component level. During the project planning and designing phase, a verification matrix of how each requirement will be verified will be compiled for levels 3-5. This will be embellished with additional details at the conclusion of the design phase. Thus, the verification extends across the system hierarchy, from the system level to the component level. When the design phase ends and before the component level verification begins, a detailed plan for the T&V will be created and captured in the verification matrix. The verification plan will be finalized prior to CDR for the review and approval. The system level benchmarking will involve collocation with an external reference, which will precede the commissioning phase of the system, but will follow the I&T phase. The reference system needs to be a well-stabilized proven system like Moblas 7. The T&V needs to be managed carefully and rigorously through the system life cycle phases and across the various constituents.

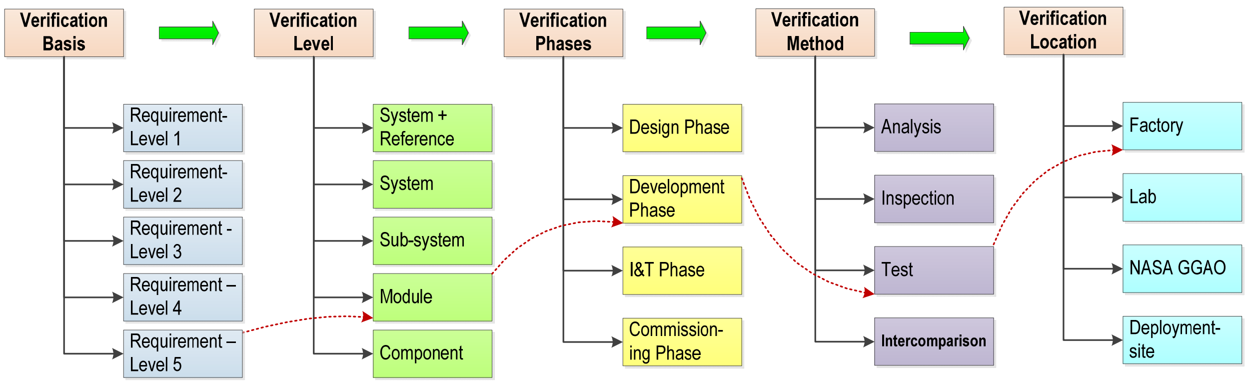

Figure 1: Verification Approach

As can be seen from the above diagram, each requirement (level 3 through 5) will be verified at the right "verification level" during the appropriate "verification phase" of the project using a suitable "verification method" and a "verification location". The methods of verification will include: (1) Inspection, (2) Analysis, (3) Test, and (4) Intercomparison. The tests may be conducted at the factory for commercially procured items as needed, an external lab, NASA or Goddard Geodynamic and Astronomical Observatory (GGAO) lab.

Major subsystems or products, which are procured from a vendor, such as the telescope, will undergo factory acceptance testing. This testing may be performed, as discussed before, across the lifecycle of that product. The dotted lines in figure 1 shows how a test like the telescope absolute imaging quality, which happens to be a "level 5 requirement", will be verified. In this case, the project plans to test the Telescope Optical tube assembly as a "module" using test resources at the "factory". This test will most likely be done during the "development phase" of the telescope. This test will be difficult to perform at the Integration and Test (I&T) site or the deployment site due to "seeing" conditions. Most of the T&V, from the component level to the system level, is expected to take place at NASA labs or GGAO. Additional laboratory capabilities planned for GGAO is expected to meet the short term and long term testing needs. Some of the T&V may not be doable at the deployment site due to the constrained tools and resources base.

Verification Plan and Reporting

The T&V plan and the corresponding report will incorporate the following information:

- Level 3-5 Requirements
- Verification procedure and Success criteria for the Verification
- Tools and Resources Needed, e.g., Analysis tools and Test equipments
- When, where, and who will perform the verification?
- Analysis and archiving of the test results;

Millimeter level Verification – Challenges, Implications, and Capability requirements

The millimeter level geodetic station errors can only be deciphered over a long period after collecting data over 12 months. Since SGSLR systems will become the ILRS core-sites, there is an implied demand on them to be explicitly accurate, while supporting estimation of errors and biases in other non-core stations. Furthermore, when a network is being built based on a replication model of a single system, there is a critical need to minimize/eliminate systematic errors and biases contributing adversely to the data inaccuracy. Thus, the T&V process of SGSLR has a huge impact on the future SGSLR network evolution and its impact on ILRS and the scientific community. A rigorous approach will be used to minimize/ eliminate the ranging error contributions or at least characterize the error contributions fully. While pursuing higher SLR measurement capability, there is also a need for the analysis techniques to mature and become robust to establish the required millimeter legitimacy. Indeed, the rigor of verification executed is paramount to the performance quality achieved by the system on a short and/or long time scales.

Critical Requirements

The key performance requirements are as shown below, which will carry a margin of 50% to accommodate worst case performance. The quality of the data will be assessed under Standard Clear Atmospheric conditions.

- CAL Normal Point Precision: 1mm
- CAL Normal Point Stability: 1mm
- CAL Normal Point Accuracy: 1mm
- SLR Normal Point Precision: 1mm
- SLR Normal Point Stability: 1mm

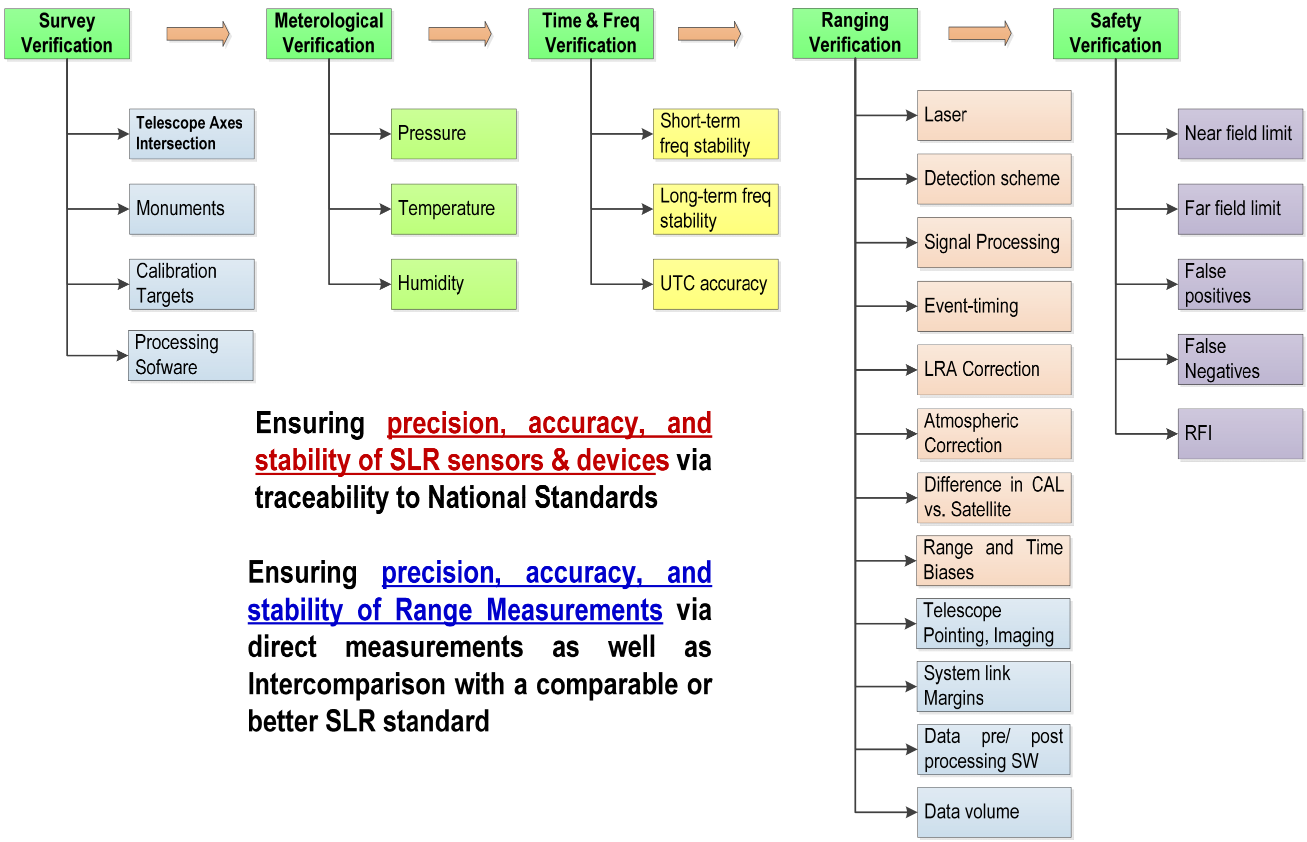

Figure 2: Constituents of the Data quality Space

Critical Areas to Verify to Meet the SGSLR level 3-5 Requirements

Figure 2 highlights the critical areas that need to be characterized to meet the level 3-5 requirements for data quality and quantity. These include: (1) survey measurements, (2) meteorological sensors, (3) frequency and timing instruments, (4) safety subsystem, as well as the (5) ranging data loop that include several subsystems. The systematic and random error contributions to data quality need to be carefully characterized and minimized through T&V so that the aggregate errors in the range measurement are kept to a minimum, well below the desired millimeter performance specifications. The factors affecting data quantity also have to be well characterized to optimize the system performance and thereby the data volume. The survey measurements will be verified only at the SGP level 2. In the case of survey, survey instruments are calibrated to fraction of a millimeter using standard ranges at the National Geodetic Survey. The question remains as to how well we can transfer this level of accuracy to the actual survey measurements for a network of short range monuments and ground targets. The observations to date attest to the fact that the errors seen in actual measurements and analyses are higher than the instrument capability.

The Safety subsystem is paramount for SGSLR operations. The false positives and false negatives (if any) are critical to be characterized fully and if need be fully remedied. The maximum and minimum ranges for the safety system need to be measured and established for aircraft avoidance. The safety margins also have to be verified appropriately. Any zones of exclusion, especially, at the lower ranges need to be clearly understood. All requirements for FAA and ANSI need to be measured, analyzed, and managed from the start and there shall be no exceptions to the enforcement of safety through adequate tests and verification.

The weather sensors are traceable to NIST standards. The critical ones affecting the data quality and hence the accuracy are the Pressure, Temperature, and Humidity. Of these, pressure has the highest impact followed by temperature, and lastly humidity. Meteorological instruments may be evaluated by intercomparison with similar sensors / instruments for stability as well as accuracy. Such intercomparison may be made over a short term or long term as this has direct implications for system level stability and accuracy. The performance of precipitation or wind sensor is not critical to range accuracy, but is invaluable for protecting the telescope. A potential technique for real-time environmental verification involves backscatter from the atmosphere, which can give a measure of the atmospheric visibility and cloud transparency for ranging.

The T&V of the time and frequency instrument needs to be performed for both the short term and long term stability of frequency. A hydrogen maser source may be used for such measurements, which is available in the lab as well as at GGAO. Any potential for drift with temperature needs to be clearly established as part of verification. The entire ranging loop of the optics and electronics needs extensive testing, analysis, and verification. Data quality and data quantity capability are intertwined across multiple subsystems such as the Telescope, Laser, Range receiver, Time and frequency instruments, meteorological sensors, etc. Any system accuracy dependencies on refraction models or CoM models for geodetic satellite need to be fully characterized and verified to obtain millimeter quality data. Equally, the telescope tracking and imaging performance need to be verified for maximizing data quantity. If large range biases are present, then we may fail to acquire the satellite. Indeed, very low range biases (mm) and time biases (<100ns) on geodetic satellites are a must for a core-site. The ranging loop will be verified across the system hierarchy and eventually at the system level to compute the Range Bias (RB) and Time Bias (TB).

Material and Facility Requirements for Testing and Verification

T&V will require laboratory, material, software, and hardware tools. Figure 3 highlights these test requirements. The factory testing may be supported by the vendor's tools and processing capabilities. In some cases, it may be preferable to have SGP's own tools to complement the factory capabilities. Controlled laboratory environment (cleanliness, temperature, and humidity control) will be required for the labs involving laser and optics. Diagnostic tools such as: high speed oscilloscope; DVM; power meter; autocollimator; beam profiler, digitizers, etc., will be required to perform the testing and verification. Additional software tools for data acquisition, processing, and verification data will be required. A database for archiving all the test and verification results and inferences will be maintained for future reference. Anomalies will be maintained and managed separately.

3. SGSLR SYSTEM LEVEL TESTING

The SGSLR system level testing will consist of two modes: (1) Standalone and (2) Intercomparison. Standalone test is defined as a test without the use of a reference system. The intercomparison will be performed using a "known" reference system like the Moblas 7.

SGSLR Standalone Tests

Here the goal is to perform verification without the need for a reference system adjacent to it. This framework is as illustrated in Figure 3, below. As indicated earlier, all T&V efforts, from the component level to the system level, are driven by the corresponding test plan. A battery of tests and/or analysis may be performed with the help of special software, test equipments, etc. and the collected data will be analyzed. All results of data analysis and observations made will be included in a Data Base. Interim verification reports will be generated for reviews. In case, the verification fails, then the test or analysis may have to be repeated. Prior to repeating the T&V, the root cause for failure will be analyzed and remedial effects put in place before re-verifying. This verification approach will be applicable from the component level to the system level.

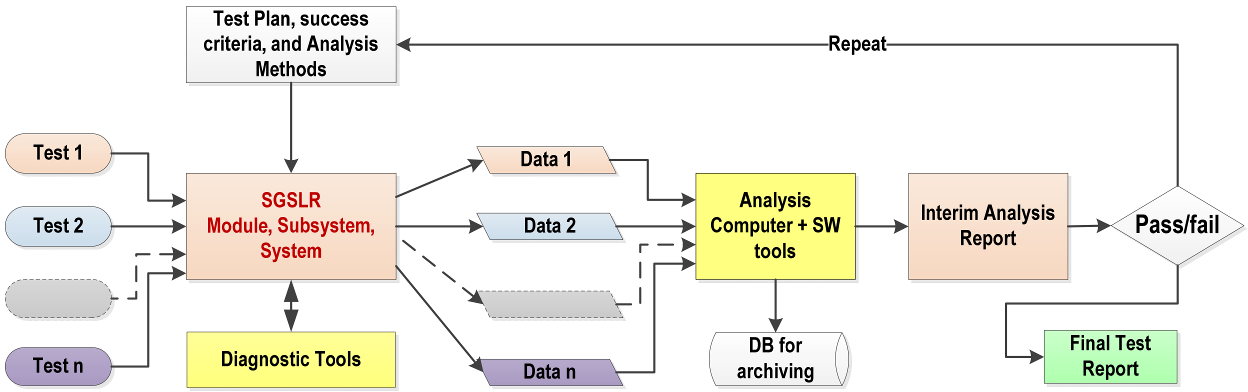

Figure 3: Standalone Verification Scheme

SGSLR Intercomparison Tests

The commercial world uses benchmarking to “known references” to gauge the performance of new products and technologies. Such intercomparison with a reference system enables comparison of performance to a common set of control inputs and measurement constraints. This allows one–on-one comparison. Usually, the “Reference system” in such cases will either match the performance or exceed the performance of the “Test System”. Moblas 7 (M7) has a rich history of collocation at the NASA GGAO. Figure 4 illustrates the M7 collocations at GGAO during 1982 – 2000 and the observed Range Bias in millimeters. NASA stations as well as foreign stations have gone through such intercomparison at GGAO. NGSLR was the last station that went through collocation in 2013. Improved M7 capabilities and performance are expected for the SGSLR collocation.

The purpose of collocation is to leverage the “commonality” on a macro scale to eliminate a variety of potential sources of error such as meteorological measurements, satellite orientation, satellite orbit, ground targets, and monuments for the local datum, atmospheric turbulence, and seeing conditions. By placing a reference system in the proximity of a test system (see Figure -5), we can minimize/ eliminate the “macro scale” differences and their contributions to the range errors. The effects of ground water motion, seasonal effects, etc., are common across the two proximity stations and such effects are normalized. Such an environment allows direct comparison of the engineering and technology embedded in the ranging loop of the reference system with that of the test system, which indeed is the primary objective of the collocation efforts. Thus, a well-conditioned and proven reference system of high quality goes a long way towards verifying the quality of a newly emerging/ developed system.

Along with improvement and refinement in the measurement techniques, the intercomparison analysis needs to be strengthened to make a comparison at the millimeter level. Collocation analysis may be performed using a Geometrical technique or an Orbit based technique using a short arc. In the case of the geometrical technique, the range vectors to the satellite from either of the systems can be “closed” using the vector separating the invariant points of the two telescopes. This technique eliminates any potential errors in the short arc of the orbit from models or ranges of other contributing ILRS stations. On the other hand, orbit techniques allow comparing both the reference and test station’s data against a global reference. In either of these cases, a substantial amount of data will be needed to establish adequate geometry around the stations of both ascending and descending nodes as well as day and night conditions. This is particularly true to pursue millimeter level comparisons and verification. The orbit technique is prone to multi-millimeter level variances in RB from one pass to the next, which demands significant amount of averaging over a longer term to get meaningful millimeter level RB numbers.

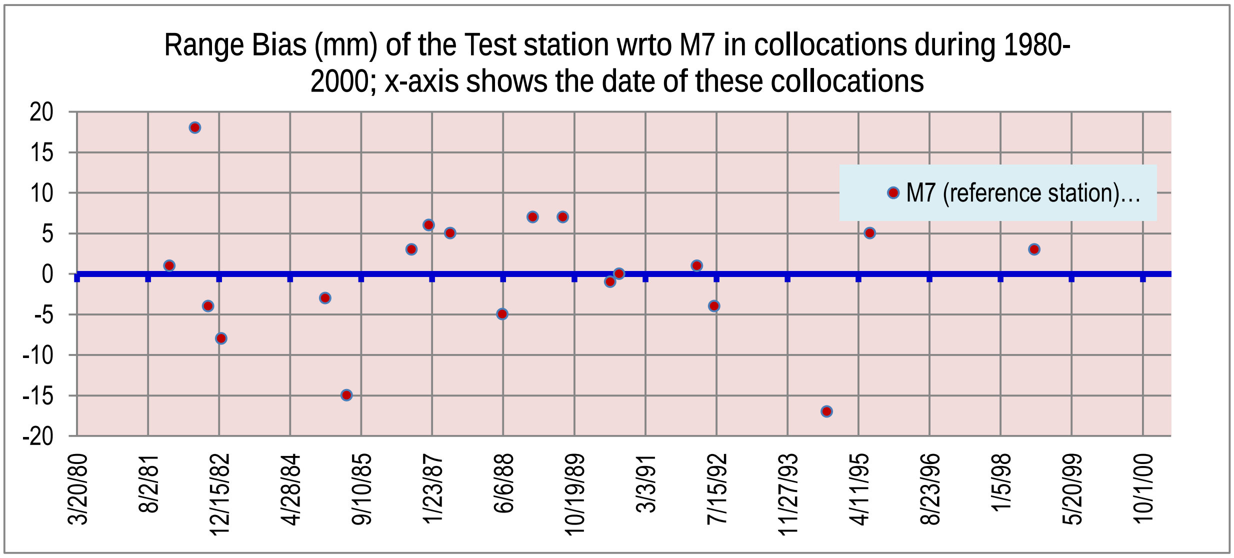

Figure 4: M7 Intercomparison with other stations at GGAO during 1980-2000

In the case of the geometrical techniques, one can even compare the ranges directly. Bypassing the atmospheric refraction correction is equivalent to using the same P, T, H values for the refraction correction. The processed range values are not necessarily immune to the artifacts of the polynomial regression techniques, as the fits are statistics based rather than model based. This can potentially induce errors at the millimeter level for the normal point. Multi-photoelectron level systems can also exhibit amplitude dependence at high signal levels due to the non-linear response of signal processing electronics, which can also be corrected to minimize errors. The satellite impulse response is orientation dependent as well as dependent on the position in the Far Field Diffraction pattern (FFDP).

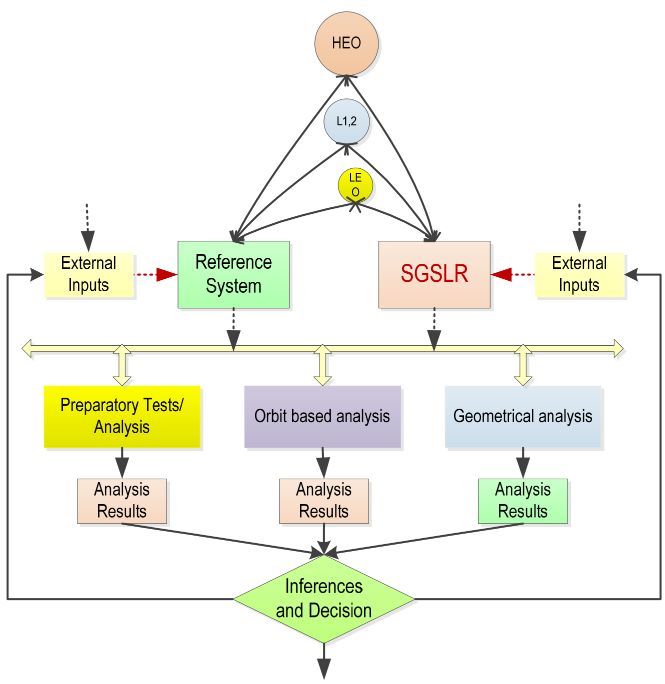

Figure 5: Intercomparison verification scheme

The surveyed accuracy to the individual targets from each station may vary from 1 target to another and can vary from one SLR system to another system. These require very high accuracy survey measurements as well as accurate range measurements from the individual stations. The stability of the station position typically requires 9-12 months of operational data as per ILRS guidelines. Variances in behavior are routinely seen for seasonal effects, satellite pass geometries, and time of the day measurements. All these need to be well characterized by the reference and test systems to enhance mutual agreement. Despite the challenges, it is quite likely that we will achieve the desired results by adhering to a rigorous regimen of testing and verification. The stability of the individual system performances is paramount to achieving the overall objective of meeting the level 3-5 requirements.

As SGSLR stations get rolled out into the global network and eventually, when the new stations form a distinct network around the world, we will need a framework for millimeter level comparisons at the network level. Most likely, the orbital techniques will be used in such cases, unless of course, there is a short baseline between the new SGSLR systems, which supports simultaneous viewing of 2 or more stations. Currently, the orbital technique does not demonstrate the ability to resolve data issues at the 1 millimeter level on a short term scale. Geometrical technique may be the only answer, although both the reference and test system data could be compared against the common reference orbit.

To increase the level of corroboration of the reference and the test system during collocation, additional tests and measurements may be pursued to correlate the range measurement between the 2 stations. Both auto-correlated and cross-correlated range measurements may be pursued to further enhance the direct individual station range measurements on satellites.

4. SUMMARY

Testing and verification has been accorded a significant role in the design, development, and deployment of NASA SGSLR systems pursuing 1 millimeter capability. As the SGSLR CDR phase is currently underway, efforts are continuing to identify the dependencies across the multiple levels of system requirements and develop appropriate tests to fully characterize these across the component, subsystem, and system level with the goal of achieving the desired 1 millimeter level performance.

5. REFERENCES

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