Generation of Global Geodetic Networks for GGOS

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Abstract We simulated future networks of VLBI+SLR sites to assess their performance. The objective is to build a global network of geographically well distributed, co-located next-generation sites from each of the space geodetic techniques. The network is being designed to meet the GGOS terrestrial reference frame goals of 1 mm in accuracy and 0.1 mm/yr in stability. We simulated the next generation networks that should be available in five years and in ten years to assess the likelihood that these networks will meet the reference frame goals. Simulations were based on the expectation that 17 broadband VLBI stations will be available in five years and 27 stations in ten years. We also consider the improvement resulting from expanding the network by six additional VLBI sites to improve the global distribution of the network. In the simulations, the networks will operate continuously, but we account for station downtime for maintenance or because of bad weather. We ran SLR+VLBI combination TRF solutions, where site ties were used to connect the two networks in the same way as in combination solutions with observed data. The strengths of VLBI and SLR allows them to provide the necessary reference frame accuracy in scale, geocenter, and orientation. With the +10-year extended network operating for ten years, simulations indicate that scale, origin, and orientation accuracies will be at the level of 0.02 ppb, 0.2 mm, and 6 μas. Combining the +5-year and +10-year network realizations will provide better estimates of accuracy and estimates of stability.

Keywords VLBI, SLR, TRF, GGOS, VGOS

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2. Joint Center for Earth Systems Technology/UMBC

1 Introduction

Progress is already being made on building next generation stations for the geodetic networks for future observing by all of the geodetic techniques. The GGOS terrestrial reference frame goals of 1 mm in accuracy and 0.1 mm/yr in stability impose strong requirements on the geodetic networks. Future networks will contain sites with legacy, next-generation, and mixed equipment. We have performed simulations for the +5-year and the +10-year time frames. The two network designs are based on the existing stations' plans for the future and an extensive database of information for future system deployments collected from proposals submitted to the GGOS Bureau of Networks and Observations (GBNO). Although we have no guarantee that all these proposed plans will materialize exactly as planned, these are the best available information that we can rely upon. As a first step, we have made simulations for the VLBI+SLR combinations. The rationale for this combination is that SLR uniquely provides the origin of the TRF since it is directly sensitive to the geocenter. VLBI provides the reference frame orientation since it can measure orientation relative to the distant quasar reference frame, which provides essentially fixed reference points. Both techniques provide the TRF scale. A next step will be to incorporate GNSS into the combination. GNSS will be available at all sites, including those that have less than the complete ensemble of techniques that would provide a direct tie. With the presence of GNSS these non-core sites are tied to the rest of the network via this third technique.

For our simulations, we assumed that in the +5-year time frame, there would be both legacy and next-generation systems. In the +10-year time frame, VLBI will be assumed to be observing only with next generation broadband networks; the SLR network would be composed of about 50% next-generation systems and 50% legacy systems because the high cost of replacement of many legacy sites is prohibitive.

2 Simulations for Future VLBI + SLR Networks

For the VLBI simulation, next-generation stations will all have broadband (2–14 GHz) receivers. Most of these antennas will be "very fast" being capable of slewing at 12°/s in azimuth and 6°/s in elevation. At present there are five antennas in the "fast" category (GGAO12M at GSFC, three Australian, and one in New Zealand) slewing at 5–6°/s in azimuth and 1–2°/s in elevation. We included the legacy antenna at Westford, which has an azimuth slew rate of 3°/s.

Figure 1 shows the locations of broadband VLBI sites used in our simulations. In five years we expect that there will be 17 sites. It is clear from the map that there are large areas without stations, most notably South America, South Pacific, Africa, and Central Asia. The additional sites we foresee in ten years fill in these holes. NASA Headquarters requested that we extend the +10-year network to include six sites that help to further fill in geographical holes. Figure 2 shows the corresponding map for SLR for the +10-year and +10-year-extended cases. For the purpose of the simulations we did not include a few sites (which we know will have future stations) that are close to our chosen sites because the Calc/Solve analysis software limits the number of sites in a session to a maximum of 32 sites.

Table 1 VLBI observing day comparison.

Session Type	Number of Stations	Site average scans/hr	Range scans/hr	Number of Observations
Weekly R1	8–10	15	12–21	5,100
CONT11	14	16	12–20	10,900
CONT14	17	19	14–24	20,300
+5-year	17	79	58–97	141,800
+10-year	27	76	61–86	274,200

The new VLBI broadband antennas will make far more observations than current operational networks. The large antenna slew rates enable many more observations to be made and the high data rate (16 Gbps)

Fig. 1 Global distribution of future VLBI broadband stations. Stations (at 17 sites) expected in five years (solid black circles), added stations (at ten sites) in ten years (solid red stars), and additional stations (at six sites) in an extended network in ten years (blue diamonds).

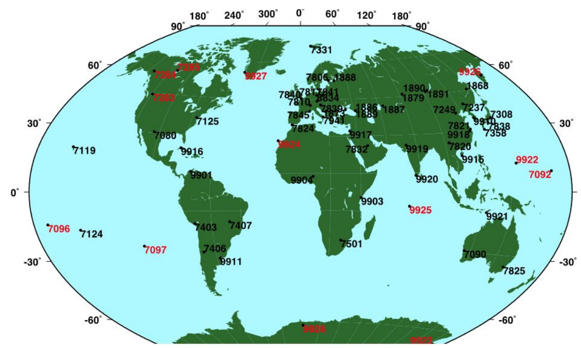

Fig. 2 Global distribution of future SLR stations. Stations expected in ten years (black number codes) and additional stations in an extended network in ten years (red number codes).

allows observation scan times to be short (20–30 s depending on the source flux). Table 1 compares network performance statistics of the weekly R1 operational networks, CONT campaign networks, and the future broadband networks that we have simulated. The big increase (factor of 3 to 4) in the network size and the increase (factor of 5 to 8) in station scans/hour lead to about a factor of more than 50 in the number of observations made by the network in a 24-hour session.

To generate the VLBI input to the combination, we first made an observing schedule for a network of stations with the desired properties (antenna slew rates, data rates, antenna SEFDs). This was done using the scheduling software SKED. The schedule is converted into a simulation database, which can be run with the VLBI analysis software package Calc/Solve. Calc/Solve is set up to generate three VLBI Geodyn input files: 1) observations, 2) solution setup information, and 3) a simulated delay for each observation. For each observation, the observation file gives the epoch, the stations, and the radio source that was observed. The solution setup file contains the a priori station positions and velocities, the parametrization of the estimation of clock and troposphere parameters, and constraint information. Simulated delays consist of three contributions: clock delays, wet tropospheric delays, and observation uncertainty. Clock delays for each station are modeled as the sum of random walk and integrated random processes with the expected (required) clock Allan standard deviation 1×10^{-14}@ 50 minutes. The wet delay contribution is based on a Kolmogorov turbulence delay model, where the model parameters are the effective troposphere height, wind velocity, and site dependent refractive index structure constants C_n. A white noise contribution corresponding to the observation uncertainty is included. The simulation delay model was validated by applying it in the analysis of CONT11 data. Baseline length repeatabilities using simulated delays were compared to repeatabilities from analysis of observed data. Simulated repeatabilities are within about 30% of observed repeatabilities. The average ratio of repeatabilites was close to one (0.97 ± 0.32).

The SLR simulation procedure starts by using GEODYN with a suite of models for gravity, tides, and so on that represent the "true" Earth System, to predict all available passes of LAGEOS and LAGEOS-2 over the network of SLR stations for a year of continuous system operations. Data are then deleted in several steps, to eliminate tracking of two targets simultaneously, to account for other effects including local weather and system downtime. In the next step, the data set is split into daylight and nighttime passes and sampled according to the system capabilities and performance for each site. For legacy sites, the sampling is done to match multi-year performance statistics. For next-generation SGSLR-class sites, 25% and 50% of data is kept for day and night passes, respectively (see Figure 3). In the final step we corrupt the data by adding simulated errors to the observed ranges, using the systematic and random error levels corresponding to each category of sites. For legacy sites, this is based on current performance statistics, while for SGSLR-class systems on the system specifications, using for each pass a random walk error model with a standard deviation of 1 mm plus white noise of 1 mm.

3 VLBI + SLR TRF Combination Solution

Figure 4 provides an overview of the calculation of the combination TRF with the Geodyn software. The first step involves ingesting the simulated observations from VLBI and from SLR. For SLR, GEODYN generates weekly normal equations (Sunday to Saturday). In the case of SLR data, GEODYN uses a slightly inferior set of models for gravity, tides, and so on compared to what was used in generating the "real" data. In this way we include a systematic error component in the reduction process to represent the real situation where the models used in data reductions are only approximations of the "true" Earth models. The difference of the parameters describing each model (true vs. approximate) being commensurate with our best estimate of the uncertainty in the used model. In the case of VLBI the data are processed by GEODYN in sessions (daily) and normal equations are formed. In a second step, we use the companion program to GEODYN, "SOLVE" (not the one associated with Calc), to form a weekly set of normal equations by stacking the appropriate session files. Uncertainties from each weekly solution are scaled to make the chi-square (per degree of freedom) equal to 1. In the next step, SOLVE combines the VLBI and SLR normal equations. In our solution, there were 12 co- located SLR and VLBI sites in the +5-year simulation. For the +10-year and +10-year-extended cases there were 15 and 21 sites, respectively. To account for (model) the ties between the sites, the covariance matrix included the 3-dimensional site-tie covariance. For the current simulation, we assumed a 3D covariance of 3 mm, consistent with an estimate of the quality of ground survey measurements of site ties from Z. Altamimi. Better local site tie vector determination could reduce this below the 1-mm level. We plan further tests using other values for the tie covariance including more pessimistic values.

Table 2 Projection of combined TRF quality results.

Case	σ_{Tx} mm	σ_{Ty} mm	σ_{Tz} mm	σ_{Ds} ppb	σ_{Rx} µas	σ_{Ry} µas	σ_{Rz} µas	σ_{3D} mm
+5 years	0.77	0.79	0.81	0.12	32.2	31.7	30.7	1.37
+10 years	0.66	0.65	0.88	0.10	34.4	37.1	23.5	1.28
+10 years (extended)	0.42	0.41	0.50	0.06	21.4	22.0	15.7	0.77

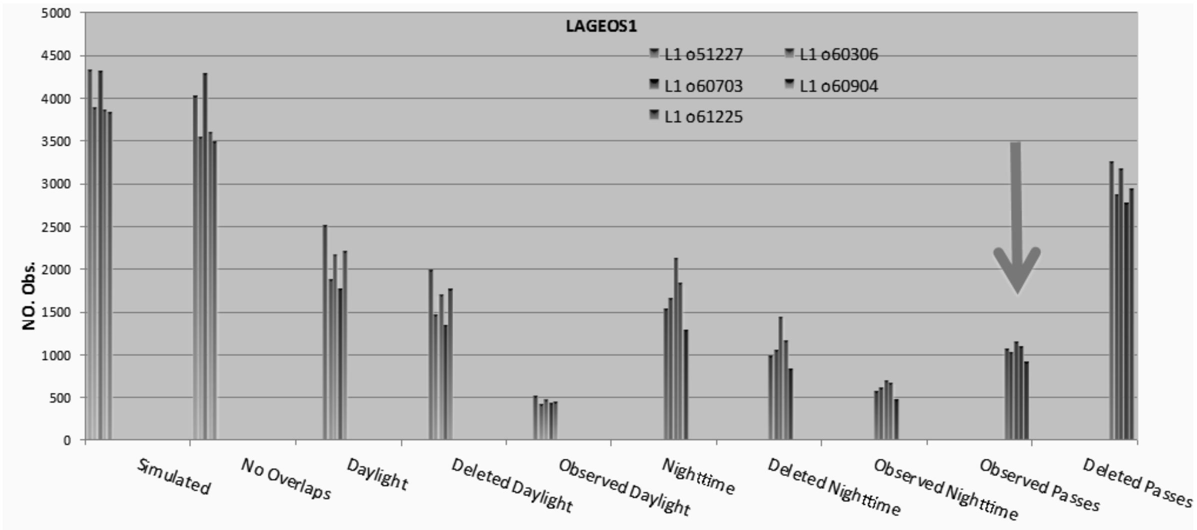

Fig. 3 Five weekly LAGEOS arcs, examples of SLR data going through the preprocessing steps for the generation of a realistic set of observed data: (a) generating all possible data, (b) eliminating the data overlapping with tracking other targets, (c) splitting the data in daytime and nighttime tracking, (d) sub-sampling the data according to the individual system's expected performance. The last two columns indicate the final number of accepted and rejected passes.

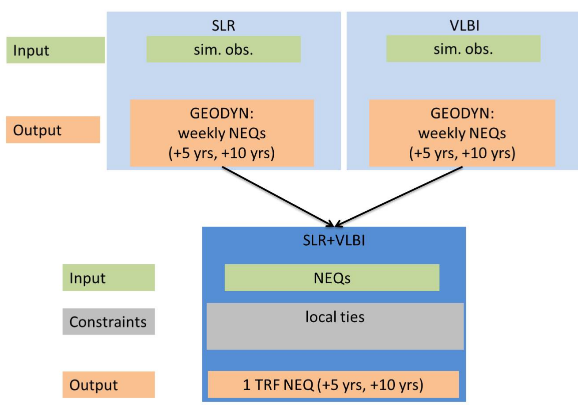

Fig. 4 Overview of the process of combining VLBI and SLR input to produce an SLR+VLBI combined TRF solution.

The quality of the combination TRF is summarized in Table 2. For each network case, the uncertainties of the seven-parameter Helmert transformation parameters are shown. The increase in network size from the +5-year network to the extended network in ten years improved the 3D uncertainties by a factor of 1.78 to 0.77 mm. Scale improved by a factor of 2 to 0.06 ppb (0.38 mm), and orientation by a factor of 1.45 to 22 µas. Even with just one year of continuous observations, the GGOS TRF accuracy goal of 1 mm is met. Of course, at this point we have not considered reference frame stability. To estimate this, we will combine the +5-year and +10-year TRF realizations.

4 Conclusions

We simulated the SLR and VLBI network operations for one year at two different epochs of its future evolution: five years and ten years from present. The predictions for how the networks will "look" like at these two instances are based on the information collected and tabulated by the GGOS Bureau of Networks and Observations. The major differences from previous simulations is that here special care was taken to generate realistic tracking data for the mixed (legacy + next generation) SLR networks and, additionally, the processing of a vast amount of VLBI data generated by an all next-generation broadband system network, compared to the legacy systems that were used in the past. Based on our combined VLBI and SLR TRF realizations, these networks seem to be sufficiently robust in delivering the required accuracy of 1 mm for the origin, scale, and orientation of the TRF, which are the goals of GGOS. If we further assume that the network realization of ten years operates for ten continuous years, we find that a combination of these ten years will lead to a TRF model with an origin (3D) accurate to 0.4 mm, a scale at 0.2 mm, and an orientation at 0.5 mm. At the request of NASA/HQ we also examined an extended network for the period of ten years. This network considers the addition of about a dozen more sites to the standard network, half of which are core sites with colocated SLR and VLBI systems, and these are placed in areas void of sites in the standard network, that is they fill-in gaps. The improved coverage demonstrates the critical importance of establishing uniform networks, as it improves the TRF accuracy delivered by the standard network by about 40%. If such an extended network were to operate for ten years, it would deliver a TRF accurate to 0.2 mm in origin, 0.13 mm in scale and 0.33 mm in orientation. Our immediate plans are the combination of the two networks five years apart (the one after five with the one after ten years from present), which will provide us with a first estimate of the stability that we can expect these two networks to deliver for the TRF models of the very next years.

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