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Improved geodesy with GNSS and VLBI combined at the obervation level

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Contents

1 Executive Summary

We will process GNSS and VLBI data combined at the observation level over ten years using the same geodetic software. That includes unification of data reduction procedures and development of sophisticated methods of parameter estimation tuned for processing a combined dataset. We will process a dataset of collocated VLBI and GNSS sites for 10 years applying the data reduction models and the parameter estimation procedure implemented in the same code for both techniques. We will investigate the impact of estimating common atmospheric parameters at collocated sites and common Earth Orientation Parameters (EOP) from a combined dataset and the impact of fixing the scale parameter of the GNSS network to the VLBI scale. We will perform an in depth comparison of the performance of the combined solution with respect to those solutions that use VLBI and GNSS data independentely for estimation of the EOP and site positions by comparing metrics of the solutions. We expect the combined use of GNSS and VLBI data on the observational level will provide more accurate estimates of UT1 and site positions because of improved sampling of the atmosphere, more stable scale, and ties of GNSS orbits to an interial celestial coordinate systen based on extragalactic sources when data from both techniques are combined.

2 Introduction

Addressing the challenges listed in NASA's Challenges and Opportunities for Research in ESI (CORE) Report (2016), *1. What is the nature of deformation associated with plate boundaries and what are the implications for earthquakes, tsunamis, and other related natural hazards? 2. How do tectonic processes and climate variability interact to shape Earth's surface and create natural hazards? 3. How does the solid Earth respond to climate-driven exchange of water among Earth systems and what are the implications for sea-level change?* rely on the terrestrial reference frame that is accurate at 1 mm and stable at 0.1 mm/year level. As it is stressed in section 3.2 of this document, in order to achieve that goal the space geodesy community needs to

> Develop means to improve geodetic reference frame accuracy through novel combinations of geodetic data types and by collocation of geodetic systems on Earth and in space [page 44].

We address this challenge verbatim and propose a research that will enable capabilities to process a combination of space geodesy data at the observational level, which is essential to advancing the ESI science objectives. It was realized over 20 years ago that a combination of all space geodesy techniques will provide the most accurate results (Altamimi et al., 2002; Coulot et al., 2007; Thaller et al., 2007; Teke et al., 2011; Diamantidis et al., 2021). A simplified approach: to request analysis centers that process data of the specific technique to provide loosely constrained solutions with full covariance matrices for their consequent analysis had a limited success mainly because it turned out difficult to enforce the consistency between solutions made by loosely interacting groups. It became clear that analysis should be performed with the same software. Pilot studies of Kwak and Cho (2013); Hobiger et al. (2014); Hobiger and Otsubo (2014); Wang et al. (2022) based on processing several weeks of data from several techniques performed with the same software showed very encouraging signs of improvements. We aim to follow that route but processing **two orders of magnitude** more observing sessions and using a sophisticated parameter estimation approach designed for processing combined data.

3 Problem statement

Observations at collocated GNSS and VLBI sites sense the same atmosphere. The advantage of GNSS is that several satellites are observed quasi-continuously. Using a directional antenna, VLBI is immune to multi-path and can observe as low as at 3°. The disadvantage of VLBI is that it can observe only one source at once. VLBI one hour Intensive observations can provide very accurate UT1, but have a relatively poor sampling of the atmosphere. UT1 estimates from GNSS are affected by systematic errors due to imprecise modeling of non-radial forces, but provide a much better sampling of the atmosphere. VLBI observations provide very stable scale estimate, while GNSS scale shows variations due to systematic errors of orbits in radial direction.

We suggest to exploit the synergism of VLBI and GNSS techniques and combine VLBI and GNSS data from collocated sites at the observation level. The focus of the study is

- to develop a technique for adjusting atmosphere parameters, common for VLBI and GNSS, in a manner that is expected to reduce its impact on site positions and EOP estimates. We will exploit here the fact the atmospheric path delay at both sites is the same.
- to develop a technique that will compute the EOP in a form of set of B-spline coefficients from both VLBI and GNSS. We will exploit here the fact that both VLBI and GNSS stations have the same motion in the inertial space due to Earth's rotation.
- to develop a technique that will use VLBI stable scale to stabilize GNSS site positions and the orbits.

We will investigate in depth two important cases:

- Estimation of EOP from the so-called one hour long single baseline VLBI Intensive campaigns that run several times a day. The metric of the success: improvement in EOP estimates.
- Estimation of site positions at 36 collocated VLBI/GNSS sites. The metric of the success: reduction of a scatter in time series of vertical and horizontal components of site positions.

4 Proposed Methodology

It is critically important to enforce the uniformity of data analysis between GNSS and VLBI data. Even small discrepancies in the data reduction and the parameter estimation procedure, if not accounted for, can drive us to a wrong conclusion. We do not see a reliable practical way to proof there is no differences in GNSS and VLBI solutions because of differences software other than to process the data using one software package that supports both techniques. Our team will use GEODYN software. The GEODYN orbit determination and geodetic parameter estimation software Putney et al. (1990) has been under continuous maintenance and development by our group at NASA/GSFC for over 50 years. GEODYN has high fidelity mathematical models for satellite forces and for a wide range of geodetic measurement models for satellite tracking observations and for VLBI observations. GEODYN has been used by various universities and

Figure 1: Collocated VLBI/GNSS site Pie Town, New Mexico. The permanent GNSS station PIE1 is in the low right corner.

research groups conducting research for NASA (see, for instance, Lucchesi et al., 2015; Pardini et al., 2017; Ciufolini et al., 2019). GEODYN has played an important role in many NASA Earth orbiting and planetary missions (see, for instance, Haines et al., 1990; Lejba and Schillak, 2011; Kim et al., 2015; Goossens et al., 2020). Currently, GEODYN is used to produce high precision orbits from GPS data for the Jason-1, ICESat-2 (Luthcke et al., 2003; Luthcke et al., 2021; Thomas et al., 2021), and GEDI missions. GEODYN was recently used in the OSRIS-Rex asteroid mission to make a geodetic survey of the Bennu asteroid Mazarico et al. (2017); Goossens et al. (2020) before the touch and go maneuver. GEODYN's VLBI capability was used in OSIRIS-Rex to process Delta DOR observations.

We have dedicated VLBI software PIMA/pSolve (see, for instance, Petrov et al., 2011; Petrov, 2021) that processes VLBI data at Level 1, i.e. the time series of auto- and cross- spectra of the correlation function between voltage dataset recorded at observations sessions. The VLBI data analysis pipeline involves a number of steps that can be viewed as pre-processing. At the very end it generates the final dataset of group delays cleaned for outliers, with updated weights, and determined epochs of clock function breaks in rare events when data records have discontinuities, f.e. due to power outages.

Our approach is to use VLBI dedicated software for performing preprocessing steps and then export a clean data to GEODYN for a final geodetic analysis. Although VLBI preprocessing software uses the data reduction and parameter estimation procedures that may differ from those used by GEODYN, they do not have any impact on the subsequent solution since we will re-run computation of theoretical GNSS ranges and VLBI path delays in GEODYN from scratch and then perform parameter estimation of the combined VLBI+GNSS dataset.

4.1 Data reduction

The data reduction model used for processing takes IERS Conventions (Petit and Luzum, 2010) as the basis and provides a number of enhancements. The most important are inclusion of all mass loadings and the use of a priori atmospheric path delay derived from the output of numerical weather model.

We will use atmospheric (Petrov and Boy, 2004), land-water storage, and non-tidal loading time series provided by the International Mass Loading Service (Petrov, 2015b) and derived from NASA GEOS-FPIT numerical model (Reichle et al., 2011; Molod et al., 2012; Rienecker et al., 2018), and MPIOM6 model (Jungclaus et al., 2013; Dobslaw et al., 2017) respectively. Loading are computed by the spherical harmonic expansion approach. We use degree/order 2700 and apply the land-sea mask with a resolution of 460 m.

The a priori slant path delay in the moist atmosphere is computed by a direct integration of equations of wave propagation in the heterogeneous 3D media using the refractivity field (Petrov, 2015a) derived from the output of the GEOS-FPIT numerical weather model. Accuracy of the path delay derived from processing of numerical weather models is roughly 1 cm for the zenith direction equivalent (Petrov, 2015a). This is not sufficient to reach the requirements for space geodesy that needs a factor of 2–5 higher accuracy. Therefore, we will be estimating residual atmospheric path delay. We will compute mapping function from our estimates of slant atmospheric path delay at different elevations.The main advantage of our approach to use the most precise a priori slant path delay model for data reduction is that the impact of errors of the mapping function is diluted because the residual estimates of the atmospheric path delay is about several centimeters.

In the course of this study for some purposes we may use GNSS orbits that have been computed by the IGS. When using pre-computed orbits we have the capability to use both GPS and Galileo satellites. For some purposes we will need to estimate GNSS orbits. We will estimate only the orbits of GPS satellites. For GPS satellites we have the complete force models required for precision orbit determination. For solar radiation modeling we use the adjustable box-wing model for solar radiation pressure and albedo from the Technical University of Munich (TUMSOL) (Rodriguez-Solano et al., 2012). GPS antenna thrust is also modeled. Our GEODYN software has a very complete range of force models that apply to all satellites including ocean and Earth tides as well as static and time variable gravity (including both long and short period time variable gravity).

We process doubly differenced GPS phase data that is formed from a combination of L1 and L2 signals to remove the first order contribution of the ionosphere. This means that that our doubly differenced range data require ambiguity bias parameters. For most of the biases we will be able to find the integer number of cycles in L1 and L2 phase that comprise the bias.

We will pay special attention to eclipsing satellites. We have models for the midnight and noon maneuvers for each block of GPS satellites. We may have to omit certain eclipsing satellites, especially Block II satellites which will be present in the early years of our study. It is important to remember that it not our goal to provide a trajectory for every satellite. What we want is a very good set of orbits for Earth orientation and atmospheric parameter estimation.

4.2 Parameter estimation

The parametric model of adjusted parameters consists of estimation of VLBI source parameters, GNSS specific parameters and common parameters. VLBI specific parameters are source coordinates, VLBI station positions, and VLBI clock function. Note that for GNSS, we process passes of doubly differenced combinations of L1 and L2 phase data. GNSS specific parameters are GNSS site positions, GNSS force model parameters and some phase ambiguity parameters that our pre-processing procedure does not succeed at fixing at integer cycles in L1 and L2. GNSS force model parameters include initial state vectors, time correlated empirical acceleration parameters and some parameters of the Technical University of Munich Solar radiation Model

Common parameters are the Earth Orientation Parameters, residual atmospheric path delay in zenith direction, and two angles of the common tilt of the symmetry axis of the atmospheric refractivity field at a given site, also known as atmospheric horizontal gradients. In this scheme we assume VLBI-GNSS ties are not known with the desired accuracy (better than 2 mm). Therefore, the main physical parameters that "tie" GNSS and VLBI stations are the atmospheric path delay and the Earth's rotation. Since the difference in height between GNSS and VLBI is always known better than 0.1 meter, the systematic bias in differences in atmospheric path delay is taken into account during computation of a priori path delay because a differnece in heights 0.1 meter cause a bias in atmospheric path delay 0.03 mm. Therefore, the only source of systematic differences in the atmosphere sensed by VLBI and GNSS is spatial gradients in the atmosphere at distances of GNSS-VLBI site separation.

The parametric model of the residual atmosphere and tilt directions is described in a general form as an expansion in the B-spline basis of degree *m* at equi-distant knots. The traditional choice used for processing VLBI observations is degree 1 and the span between knots is 20 minutes for zenith path delay and 6 hours for tilts. Constraints on time derivative are imposed. We will vary the degree of the spline, span between knots, and constrain weight to find the optimal combination for processing GNSS+VLBI data.

4.2.1 UT1 estimates from GNSS+VLBI

Combined processing GNSS and VLBI data from collocating observations for estimation of UT1 has a significant advantage. GNSS observes continuously, but the contribution of imprecisely modeled non-gravitational forces results in a drift of the nodes of the orbits and corresponding drift in UT1 estimates. Although precision of UT1 determination from GNSS for a short period of time (less than 5 days) is high, accuracy for longer period of time is poor. Our approach is to estimate UT1 in a form of an expansion over the B-spline basis of the 3rd degree with applying constraints in the 1st and 2nd time derivatives following the method we have developed and successfully demonstrated in the past (Petrov, 2007). Both VLBI and GNSS will contribute to the estimation of B-spline expansion coefficients. We are well aware of the problems that other encountered when tried to combined UT1 from VLBI with UT1 or LOD from GNSS (for instance, Bizouard et al., 2018). **Therefore, in addition, we will estimate a bias between UT1 from GNSS and VLBI also in a form of a B-spline of the 3rd degree with applying constraints in the 1st and 2nd time derivative:**

$$
\begin{array}{lllllll}
\Delta\tau(\mathrm{VLBI}) & = & \ldots & + & \displaystyle\sum_{i=k-m}^{i=k} B_i^m(t)\frac{\partial\tau}{\partial\mathrm{UT1}} & + & 0 & + & \ldots \\
\Delta r(\mathrm{GNSS}) & = & \ldots & + & \displaystyle\sum_{i=k-m}^{i=j} B_i^m(t)\frac{\partial r}{\partial\mathrm{UT1}} & + & \displaystyle\sum_{j=l-m}^{j=l} B_j^m(t)\frac{\partial r}{\partial b} & + & \ldots
\end{array}
\qquad (1)
$$

Here $\Delta\tau(\text{VLBI})$ and Δr are VLBI path delay and GNSS range reduced for the theoretical model, B^m is the B-spline of the m-th degree, i and j are knots of the B-spline for UT1 and bias b for which $B^m(t)$ is not zero.

If the time span between knots of the B-splines for UT1 and GNSS UT1 bias were the same and the weights of constraints were also the same, no improvement with respect to UT1 from VLBI only solution could be achieved, because the contribution of GNSS will be entirely absorbed in bias estimates. In that case VLBI would have contributed to UT1 and GNSS to the UT1 bias which has a physical meaning of residual rotation of the nodes of the GNSS constellation along the Z-axis of the terrestrial coordinate system.

Prior work of Kammeyer (2000); Gambis and Luzum (2011); Capitaine (2017) demonstrated that UT1 GNSS bias caused by mismodeled drift of GNSS satellite nodes is significantly less variable then UT1. In particular, according to Capitaine (2017), the orbital systematic errors remain limited at scales up to about 20 days, Therefore, using a longer time span for B-spline that models GNSS UT1 bias estimation and stronger constraints with respect to UT1 estimation, we will let GNSS to contribute to short variations of UT1 but anchor long-term UT1 variations to VLBI. Therefore, separation of UT1 from GNSS UT1 biase that is the residual node rotation is made on the basis of stochastic properties of these process. We will impose a strong constraint on the UT1 bias to zero at the reference epoch to avoid degeneracy.

VLBI observations that run 1 to 3 times a day for 1 hour anchor UT1 to the coordinate system based on remote active galactic nuclea. GNSS observations that run 24/7 densify the dataset and improve the sensitivity to UT1 variations at short scales. Combined processing VLBI and GNSS anchors the satellite constellation orbits to the coordinate system based on remote active galactic nuclea because both VLBI and GNSS stations have a common motion in the inertial space due to Earth's rotation and they are assumed not to move with respect to each other at collocated sites. Considering that the accuracy of UT1 from 1 hour observing campaigns 0.02 ms, which corresponds to 4 cm at the GNSS orbit, the orbits will be calibrated with the accuracy at the level. In addition to UT1, drift of GNSS orbits along z axis will be estimated as a nuisance parameter.

For completeness, we will estimate polar motion the same way as UT1 in a form of B-spline expansion, but we do not expect an improvement in polar motion estimation with respect to using GNSS only data. Estimates of UT1 from processing one hour VLBI Intensive observations using VLBI data alone strongly depend on polar motion taken as a prioi. Estimating polar motion from both VLBI and GNSS observations will ensure no biases in UT1 estimates due to the inconsistent use of the a priori polar motion.

4.3 Estimating station positions

We will be estimating GNSS and VLBI station positions for common epochs of observations. Following the traditional scheme (Collilieux et al., 2011; Chatzinikos and Kotsakis, 2017), positions of ith station $x^i(t)$ from a daily or weekly solution at epoch t_0 are related to station positions at the reference frame x_r through a Helmert transformation

$$x^i(t) = T(t) \ + \ (1+S(t))[x^i_r(t_0) - \dot{x}_r \cdot (t-t_0)] \ + \ R(t) \times [x^i_r(t0) + \dot{x}^i_r \cdot (t-t_0)] \ + \ \varepsilon^i \tag{2}$$

with translation vector $T(t)$, rotation vector $R(t)$, and scaling factor $S(t)$. Here ε^i denotes the noise. These seven parameters are estimated using least squares. Strictly speaking, the scale of the coordinate system is determined by the speed of light, f.e. fixed. And, indeed, processing of VLBI observations shows that the scaling factor estimate $S(T)$ statistically insignificantly deviates from 0. In processing GNSS observations the scaling factor estimate absorbs the contribution of orbit errors and in lesser extent, contribution of unaccounted mass loading crustal deformations (Collilieux et al., 2011).

We will keep the scaling factor of the GNSS+VLBI network fixed to that of the VLBI network. This will be achieved by downweighting GNSS observations in solving eq. 2 for $T(t), R(t)$, and $S(t)$. Adding VLBI data to analysis will stabilize our solution. One can consider VLBI measurements as a scale calibrator. Calibration of scale will contribute to estimates of the orbit. We expect that scale calibration will improve the orbit and thus, will improve the overall solution quality.

4.4 Estimating GNSS orbits

Our preprocessing procedure is able to "fix" about most of the ambiguity biases. The other biases need to be estimated in our orbit solutions along with initial state vectors, several parameters of the TUMSOL box wing model and empirical accelerations. The empirical accelerations are estimated in the along track and cross track components. Each component is estimated as a pair of periodic parameters with the period being once per revolution. Each pair of parameters is re-estimated every quarter of a revolution and pairs of parameters in the same component are tied together with time correlation constraints (Luthcke et al., 2003). This compensates for orbit error arising from an imperfect force model and characterizes the error as a once per revolution phenomenon that is slowly evolving in phase and amplitude.

In an orbit solution for GNSS satellites treatment of clock errors (double differencing in our case) means that the orbit quality of one satellite affects all other satellites. Every solution will have some eclipsing satellites, so the decision of how to treat these satellites will be important. It is likely that eclipsing Block II satellites will be omitted. At the very least data during maneuvers may need to be down-weighted or even omitted. We will use orbit quality metrics (see below) to guide these decisions.

4.5 Observing campaigns

In order to keep the efforts focused on achieving well defined goals and staying within budget, we will limit data analysis to two cases: processing of so-called one-hour Intensive VLBI campaigns aimed at determination of UT1 and twenty-four hour observing sessions aimed at determination of station positions, nutation offset angles, polar motion, and UT1. Both campaigns are run by a consortium of institutions, including NASA, and are coordinates by the International VLBI Services for Geodesy and Astrometry.

4.5.1 One-hour Intensive VLBI observing campaigns

One hour VLBI Intensive programs run on a daily basis, primarily at a single baseline with the goal of rapid determination of UT1 (Nothnagel et al., 1994; Nilsson et al., 2011; Haas et al., 2021). There are several campaigns that run concurrently. For instance, 816 experiments are scheduled in 2022. All VLBI stations that participate in Intensive campaign have a collocated GNSS station within 300 meters. Sensitivity of VLBI to UT1 is proportional to the equatorial baseline projection length. Therefore, these observations are made at baselines with a length of 6,000 to 10,000 km. A constraint that a source should be above the horizon at both sites shrinks the zone of mutual visibilities that is limited to low elevations and a restricted azimuth range at both stations (See Figure 2). The longer baseline, the smaller mutual visibility zone, the lower elevations. Simple geometrical considerations show the closer an observed source to the equatorial plane, the higher sensitivity of a given observation to UT1. From the other hand, in order to estimate the residual atmospheric path delay precisely, observations at low and high elevations should be included within a short time interval. Requirements to provide the best sensitivity to UT1 and requirements to provide the best sensitivity to the atmospheric path delay, and therefore, mitigate its impact on results, are not compatible: we can schedule the sources that would reduce random errors in UT1 determination by expense of less precise estimation of the residual atmospheric parameters, which will increase the contribution of atmosphere-driven systematic errors (Gipson and Baver, 2016; Nilsson et al., 2017; Corbin et al., 2020; Schartner et al., 2021). Or we can schedule the sources that would improve estimation of the residual atmospheric parameters by expense of an increase of random errors.

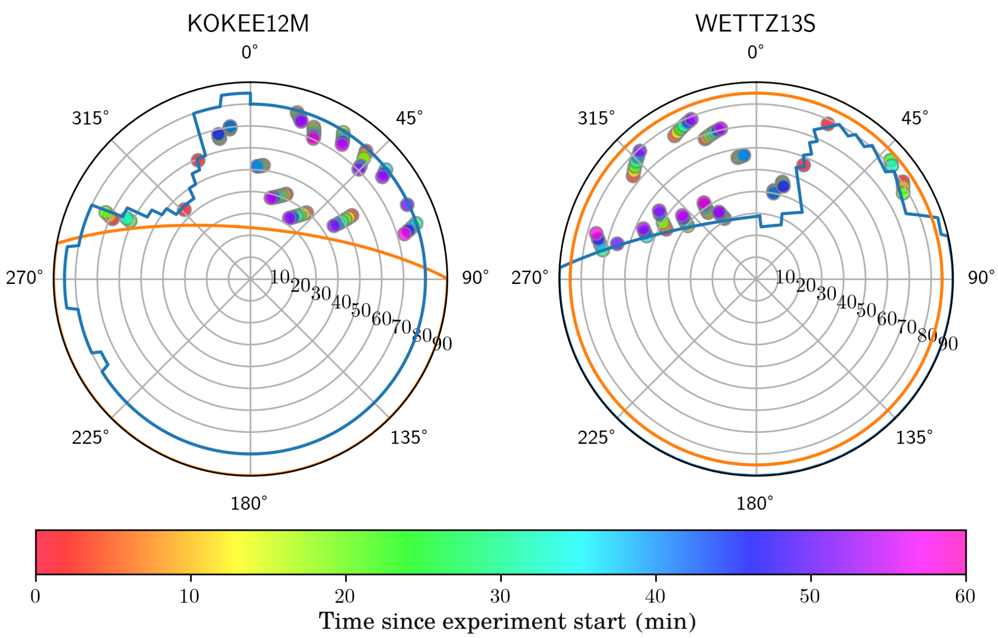

Figure 2: Azimuth-elevation diagram at 10,357 km long KOKEE/WETTZELL baseline. The physical horzonont mask is shopwn with blue line. The mutual vizibility zone abve 5° is shown with a red line.

Adding GNSS observations into analysis will change the balance. In particular, in order to observe sources at high elevations at a long baseline, sources with high declinations have to be included. Observations of these sources have a low sensitivity to UT1. Using GNSS observations at high elevations in a combined analysis allows us to observe other sources, typically at lower elevations. This will provide better UT1 estimates.

4.5.2 Twenty-four hour VLBI observing campaigns

In addition to one hour long Intensive experiments, there are about 150 twenty four hour observing sessions per year at different networks (Robertson et al., 1985; Gambis and Luzum, 2011) (See Figure 3. Not all networking stations have a collocated GNSS receiver, but most of them do. We will select for our analysis approximately 120 experiments per year from the networks that involve only sites with collocated VLBI/GNSS stations. We will be analyzing them the same way as for processing one hour VLBI experiments: we will estimate common residual atmospheric path delays in zenith direction, tilts of the refractivity fields, polar motion and UT1, and GNSS biases of the EOP with respect to VLBI. Estimates of the polar motion GNSS bias with respect to VLBI is expected to be statistically insignificant, but if not, this will provide and important diagnostic of systematic errors that will be investigated. The advantage of the approach of modeling EOP in a form of an expansion over the B-spline basis is that it is universal and suitable for any experiment design without modification.

We will be using these observing campaigns for estimating GNSS and VLBI station positions in these solutions for common epochs. VLBI data will be available approximately for 120 days a year while GNSS data will be available for 365 days per year. The goal of processing of these experiments is to a) investigate the impact of estimating the same atmospheric parameters, and in a lesser extent common EOP, on site positions; b) investigate the impact of calibrating the scale of GNSS subnetwork to that of VLBI subnetwork.

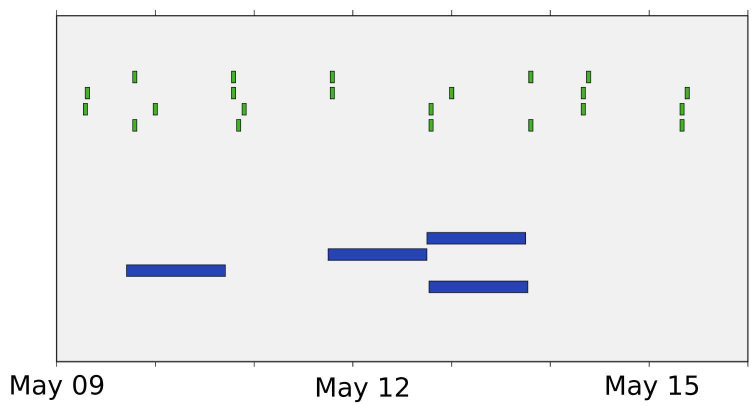

Figure 3: The schedule of geodetic VLBI observations for a week in May 2022. Green small boxes at the top of the plot demonstrate durations of one hour Intensive experiments. Blue long boxes at the bttom of the plot demonstrate durations of twenty four hour experiments. NB: a number of experiments are running concurrently at different sub-networks.

4.6 Data processing

We plan to process all the data since 2016 from 36 VLBI/GNSS collocated sites (See Figure 4). We consider two stations collocated if the distance between them is less than 300 meters. We restrict out analysis with sites that remained operational in 2022. Since a given site may have more than one GNSS or VLBI station, we will be processing data from 43 VLBI stations and 57 GNSS stations. Since the distribution of collocated is sparse and not uniform, we will process 35 extra GNSS sites used by Thomas et al. (2021) for orbit determination. These stations are not collocated, and their use in data analysis can result in biases in orbit that we would like to avoid. To mitigate this problem, we will downweight data from these stations. We will run several solutions and vary downweight factors in a range from 1.0 (normal weights) to 0.0 (data from extra GNSS sites are effecitively excluded).

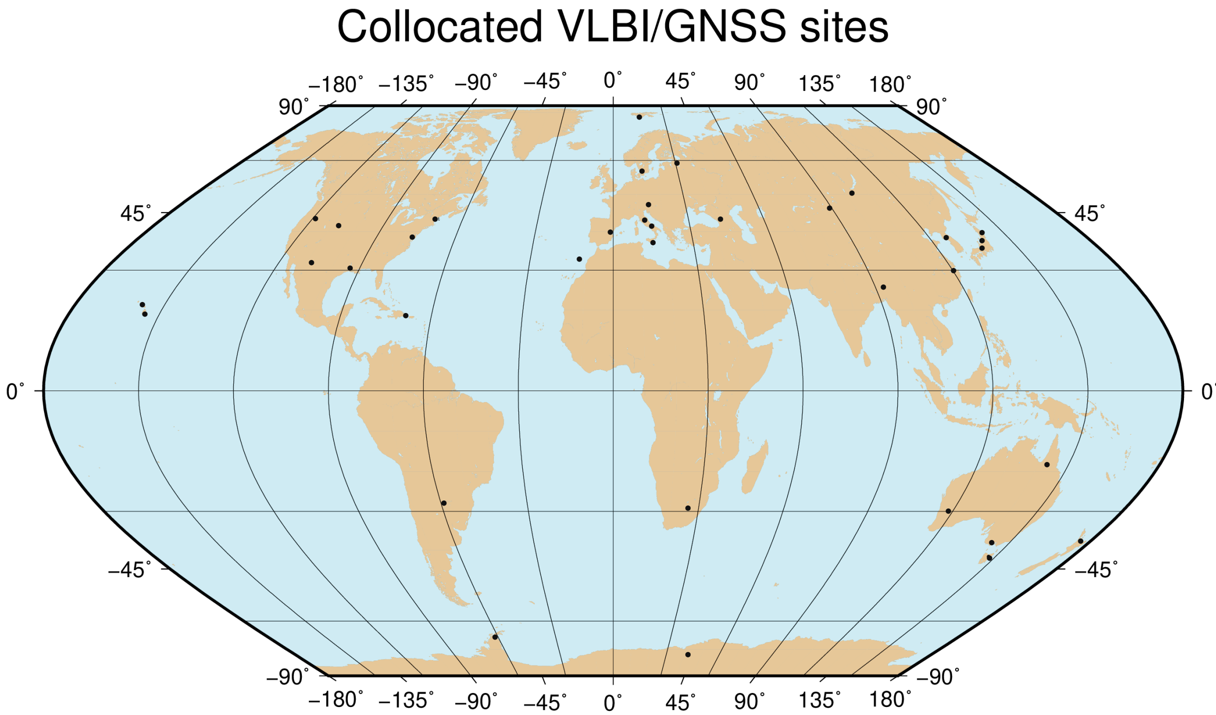

Figure 4: The distribution of 36 collocated VLBI/GNSS sites with stations that were operational in 2022.

We will run solutions of three types: GNSS+VLBI with normal weights, VLBI only solution with GNSS data down-weighted by a factor of 100, and GNSS only solution with VLBI data down-weighted by a factor of 100. We will be examining differences in site position time series and residual atmospheric path delays.

We will examine the impact of a selection of time span of the B-spline for the atmospheric parameters, tilts, and EOP and weight of constraints on the first and second derivatives on results.

5 Prior work

We have develop and maintain VLBI data analysis software packages PIMA and pSolve that process VLBI data from visibility level and provide estimates of station positions (Petrov et al., 2009), Earth Orientation Parameters (Petrov, 2007), and source coordinates (Petrov, 2021). We are maintaining the International Mass Loading Service (Petrov, 2015b) that computes atmospheric, land-water, tidal and non-tidal loading at a $2' \times 2'$ grid and 1278 space geodesy sites, including all the sites with data we will use for our study. We also have developed and maintained the service for computation of slant path delay for all VLBI sites (Petrov, 2015a).

In 2004–2006 we developed the capabilities to process VLBI data with GEODYN in the framework of the project aimed at mean sea level study. The data reduction library, VTD (VLBI Time Delay), developed during these efforts was integrated into GEODYN. This library replaced the old code in VLBI software pSolve and since 2007 is used for operational data analysis and maintained. Therefore, the data reduction part for combined analysis of VLBI and GNSS is already implemented.

We have computed orbits at centimeter level of accuracy for radar altimeter satellites from GNSS data as in Luthcke et al. (2003). For the last few years our group has determined the orbits of ICESat-2 using GPS phase data (Thomas et al., 2021) and GPS satellite orbits fixed to IGS provided trajectories. Analysis of independent satellite laser ranging (SLR) observations of ICESat-2 confirmed that our ICESat-2 orbits have accuracy better than 2 cm radially (Thomas et al., 2021).

6 Proposed work

We will do following tasks:

- Preprocess VLBI data from all the stations fro all geodetic experiments since 2016 through now. That includes editing for outliers, finding all clock break, and weight update.

- Preprocess GNSS data from 57 collocated stations since 2016 through now. We will leverage the fact that our group produces the precise orbits for the ICESat-2 and GEDI missions (Luthcke et al., 2003). These are two altimeter missions where the satellite requires precise orbits from GPS phase data collected on board the altimeter satellite and from a complete set of ground stations. As part of our ICESat-2 and GEDI work we have already preprocessed ground station RINEX data from a complete set of stations since 2018. This also means that we have the infrastructure to preprocess data before these missions.

  Our software eliminates stations and GNSS satellites that are performing poorly during a given orbit solution. We also identify which satellites are eclipsing and when the maneuvers occur. Changes in station eccentricities such as antennae are tracked. We process phase data in the form of double differences. This eliminates the first order effect of clock error from GNSS satellites, but only removes the first order effects of receiver clock error. At the preprocessing stage we remove the second order effect of receiver clock error (time tag error) by using approximate GNSS satellite positions and pseudo ranges. Our procedure removes time tag error to the microsecond level. We have software that forms double differences of combinations of L1 and L2 phase data from time tag corrected RINEX files.

- Test the data reduction model for VLBI and GNSS and check that exactly the same data reductions are applied to VLBI and GNSS data. The data reduction model includes all loadings and an interface to the output of slant path delay computation.

- Implement in GEODYN parameter estimation of atmospheric zenith path delay adjustment, atmospheric tilts, clock, and EOP in a form of B-spline with equidistant knots and constraints on derivatives. That includes code update and testing against pSolve package that has this parameterization already implemented. We will re-use most of the code developed for VLBI processing.

- Prepare three reference solutions with given parameters of spline and with constraints. The reference solutions will differ by the length of the dataset: one month, one year, and all the data.

- Develop algorithms for computation of metrics of solutions and implement them in software (see next subsection).

- Develop code that allows to run the GNSS+VLBI geodetic solution with given settings, parse the solution listing, and compute metrics of the solution in a totally automatic, thread safe mode.
- Run a set of test solutions with varying
  - relative weight of GNSS to VLBI. That includes three cases:
    a) normal weights
    b) VLBI data are downweighted by a factor of 100
    c) GNSS data are downweighted by a factor of 100
  - time span between knots of B-spline
  - weights of constraints on the first and second derivative of atmospheric path delay, EOP, and UT1 bias;
- Identify parameters of the solution such as time span between knots and constraint weights that provides the best metric of the solution.

6.1 Solution metrics

The overarching goal of our project is to improve quality of geodetic data products, namely EOP series to and station positions. The National Academy of Sciences (NAS) Decadal Survey, Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space (2018) defines among others the following objective:

> Objective S-3a: *Quantify the rates of sea-level change and its driving processes at global, regional, and local scales, with uncertainty* < 0.1 *mm/yr for global mean sea-level equivalent and* < 0.5 *mm/yr sea-level equivalent at resolution of 10 km.*

The National Academy of Sciences report Evolving the Geodetic Infrastructure to Meet New Scientific Needs (2020) emphasizes that in order to reach this objective, ‘‘*the sea-level science questions require a TRF accuracy of 1 mm and drift in the origin of the TRF of less than 0.1 mm/yr (or less than 0.02 ppb/yr in scale rate equivalent).*” Our project proposes development of new capabilities advancing towards these goals by combining GNSS and VLBI data at the observation level. In order to evaluate the proposed methodology has indeed led to improvement of results, we will evaluate solution metrics.

We will characterize quality of our solution the following way.

- The rms of the scatter in vertical and horizontal site position time series. Reduction of the scatter will be interpreted as an improvement.
- Baseline length repeatability. Baseline length is invariant with respect to an arbitrary translation and rotation. We will fit a linear regression into baseline length time series, with discontinuities at epoch known a priori, and compute the rms of the residual scatter. Reduction of the scatter will be interpreted as an improvement.

- Since UT1 from VLBI are the most accurate, evaluation of improvement in UT1 estimation poses a challenge. There is a number of VLBI twenty four hour experiments that run concurrently at two networks. For instance, 37 such observing sessions in 2021 and there will be 56 sessions in 2022. We will be running two solutions that use only one of the concurrently running VLBI experiment and compute a bias and the rms in UT1 estimates of these two solutions among these experiments. The reduction of biases and rms of the differences will be considered as a measure of improvement.
- Most of VLBI twenty four hour observing sessions overlap with one hour Intensive experiments. We will run a solution with 25%, 50%, 75% and 100% twenty four hour experiments downweighted and compute biases and rms between these solutions. The reduction of UT1 biases and rms of the differences will be considered as a measure of improvement if processing Intensive experiments.
- In order to investigate to which extent the use of GNSS data improves UT1, we will split the interval of time we have data into N sub-intervals, 24, 36, 48, 60, and 72 hour long. We will downweight by a factor of 100 all the data within odd subintervals keeping data within even subintervals. We will compute rms and biases in UT1 differences with respect to the reference solution that uses all the data. The reduction of biases and rms of the differences will be considered as a measure of improvement.
- In order to judge orbit quality, we will compute orbit overlaps between successive overlapping arcs. The scatter in overlaps will be considered a measure of improvement.
- We will also leverage our precision orbit determination in support of the ICESat-2 mission (Thomas et al., 2021). Our ICESat-2 trajectories begin in 2018. Our ICESat-2 orbit solutions are based on doubly differenced phase data collected by the ICESat-2 GPS receiver. We will run two solutons. In the first soluition we will fix GPS orbits. In the second solution we will use the GPS orbit from our solution and compute a new ICESat-2 orbit. As a measure of the resulting ICESat-2 orbit quality, we look at how well SLR that have not been used in the solution (independent data) are fit by our ICESat-2 trajectory. We will consider the reduction of the scatter in ICESat-2 SLR data with respect to its trajectroy deterimined in two solutions as a measure of improvement.
- We will split residuals into elevation bins from 0 to 90° with a step of 10 ○ and compute rms of residual at each elevation bin. Excessive rms in residual bins at low elevation is a measure of unaccounted errors in modeling atmospheric path delay. Reduction of the excessive rms is a measure of solution improvement.
- Scatter in residual atmospheric path delay in zenith direction estimates. Physical processes governs variability of zenith path delay. Too large scatter in residual atmospheric path delay estimates is an indication of solution instability. Too small scatter may happen with the constraints on the time derivative was too strong. We will compute the mean and rms of the scatter of residual atmospheric path delay in zenith direction and tilts.
- We will compare GNSS/VLBI positions offsets from our solution against the local ties determined with geodetic measurements when this information available. We will identify stations with anomaluous differences in tie vectors.

7 Deliverables and outcomes

The main outcome of the proposed research will be the technology of combined processing of GNSS and VLBI data, assessment of the improvement, evaluation of problems that one may encounter in combined analysis, and approaches for solving these problems. The findings will be summarize in a major publication in Journal of Geodesy. New capabilities in GEODYN and the user manual that describes all steps needed for reproducing our results will be documented and published in NASA Technical memorandum. We will provide recommendations for adoption of the developed technology for operational analysis of GNSS and VLBI data.

In addition to documenting our findings, we will deliver

- EOP time series from the combined analysis;
- Time series of GNSS and VLBI site positions;
- Orbits of GNSS satellites used in our solution;
- Source code of the updated GEODYN package;

8 Adherence to open-source principles

GEODYN software is already released as open source (See https://space-geodesy.nasa.gov/techniques/tools/GEODYN/GEODYN.html). The documentation is available from this web site. There is a user community around GEODYN who uses it for decades. GEODYN code is compiled with open-source compilers gfortran, gcc, and Python. All GEODYN dependencies are open source. Our team has already implemented open source principles in our work. We will continue to develop GEODYN under these principles in a full compliance with NASA SMD Policy Document SPD-41 and Open Source Software Policy Options for NASA Earth and Space Sciences[1]. Specifically, 1) updated version of GEODYN will be made available to the user community at GEODYN web site; 2) no dependencies to a non-open source software will be made; 3) new capabilities will be documented following the standards that have already been adopted by the GEODYN support team; 4) the GEODYN user community will be notified about new GEODYN capabilities and invited to make their own builds and test them; 5) we will be using for our work **only publicly available data** hosted at the Crustal Dynamics Data Information System (CDDIS)[2])

9 Management plan and milestones

The Principal Investigator, Leonid Petrov (NASA GSFC), will manage the project. He will be responsible for preprocessing VLBI data. He will be testing data reduction in GEODYN. He will develop the architecture of new capabilities for parameter estimation in GEODYN and participate in code development and testing. Leonid Petrov will organize monthly regular meetings. Leonid Petrov and co-Is will participate in biennial ESI team meetings.

The co-I Scott Scott B. Luthcke is a Geophysicist in NASA GSFC's Geodesy and Geophysics Laboratory with over 30 years of satellite tracking data analysis for geophysical studies. Scott

[1] See https://nap.nationalacademies.org/download/25217

[2] https://cddis.nasa.gov

Table 1: Schedule chart

Activity name	PY1	PY2	PY3
Upgrade of data reduction in GEODYN	•		
Upgrade of data parameter estimation in GEODYN	•		
Preprocessing VLBI data	•	•	
Preprocessing GNSS data		•	
Get a satisfactory reference solution		•	•
Run exploratory solutions		•	•
Writing papers and reports			•

is the POD and overall geolocation lead for both ICESat-2 and GEDI. Scott will lead the GNSS data reduction and analysis leveraging the software, algorithms, processes, and data currently computing the POD for both GEDI and ICESat-2. Scott will focus on GNSS solution optimization and performance assessment.

The co-I Frank Lemoine, geophysicist at NASA GSFC Code 61A, will be responsible for estimation of time series of site positions from GNSS and VLBI and assessment of improvement due to atmosphere ties and fixing GNSS scale to VLBI scale.

The collaborator, David Rownlads at NASA GSFC Code 61A will consult the team about implementaton in GEODYN existing models and methods of data analysis.

The software developer, TBD, will work with Leonid Petrov, Scott Lutchke, and Frank Lemoine on code development and testing.

All teams members will be contributing in writing a technical memorandum and the journal paper.

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11 Data management plan

We will be using in our work only the publicly accessible data available from the Crustal Dynamics Data Information System (CDDIS) https://cddis.nasa.gov/archive. These data holding includes VLBI level 2 data as well as VLBI station logs and GNSS data in RINEX format.

Source code developed under this project will be adhere the open source license and we will continue to make it available at https://space-geodesy.nasa.gov/techniques/tools/GEODYN/GEODYN.html). The PI will take responsibility to acquiring the approval for the source code releases in accordance with NASA regulations and depositing source code releases to this web site.

The project will generate relatively small output dataset, less than 10 GB. This includes a) EOP time series; b) station position time series; c) time series of estimates of atmospheric path delay in zenith direction; d) GNSS orbits; e) time series of estimates of atmosphere symmetry axis tilts; f) control files for GEODYN; g) editing files; h) weight update files. We will create a simple database that will archive these datasets for each trial run, but this database will be mainly for our internal use and tracking our work. We will provide an interface from the project web site to 5–10 final solutions that support out conclusions. The web site will provide format description of deposited sets. When possible, we will be using the same data format adopted by CDDIS for data product submission (data products from (a) to (d)).

All electronic tables and data used for plots in publication will be submitted as online material for publications.

12 An inclusion plan

Work performed under this project will be conducted at the Goddard Space flight Center. We will follow the the *"Policy Statement on Diversity, Equity, Inclusion, and Accessibility for NASA's Workforce and Workplaces"* signed by the acting NASA Administrator Stephen G. Jurczyk on 9/28/2021.

NASA is entirely committed to the full participation and empowerment of a wide variety of people, organizations, capabilities, and assets because we know this best enables us to access everyone and everything we need to best accomplish our missions.

NASA definitions of diversity and inclusion apply to and embrace the full variety of environmental, organizational, and individual dynamics and characteristics — including the commonalities that connect organizations and individuals, as well as the different cultures, histories, traits, skills, knowledge, capabilities, and thinking of organizations and individuals that are so unique and vital for our mission success. Our definition of diversity specifically encompasses the full variety of communities, identities, races, ethnicities, backgrounds, abilities, cultures, and beliefs of all people, including those from underserved communities (i.e., populations and geographic communities, sharing a particular characteristic, that have been systematically denied a full opportunity to participate in aspects of economic, social, and civic life). NASA definition of inclusion also specifically involves the recognition, appreciation, and use of the talents and skills of employees of all backgrounds.

NASA is also fully committed to equity for all employees and in all our workplaces. We define equity as "the consistent and systematic provision of fair, just, and impartial treatment to all individuals, including individuals who belong to underserved communities that have been denied such treatment."

NASA strictly prohibits discrimination based on race, color, religion, national origin, sex, gender identity, sexual orientation, pregnancy, status as a parent, marital status, age, disability (physical or mental), family medical history or genetic information, political affiliation, military service, or any other non-merit-based factor. These protections extend to all employment policies, practices, and actions, including but not limited to: recruitment and hiring; job assignments; performance management; rewards; promotions; training and development; reassignments; discipline; and removals.

Furthermore, NASA is fully committed to assuring the safety and effectiveness of our workforce and our missions. Consequently, NASA strictly prohibits harassment and is fully committed to providing a safe and harassment-free work environment. We define harassment as any "conduct that is unwelcome, verbal or physical, regardless of whether it is based on an individual's race, color, sex (sexual orientation, pregnancy, and gender identity), national origin, religion, age, disability, status as a parent, genetic information, or retaliation, when: (a) the behavior can reasonably be considered to adversely affect the work environment, or (b) an employment decision affecting the employee is based upon the employee's acceptance or rejection of such conduct." Examples of such conduct include, but are not limited to, offensive jokes, slurs, name calling, physical threats, intimidation, and insults.

We will follow NASA management directives concerning diversity and inclusion, identifying barriers to creating a positive and inclusive working environment. The team members, including support personnel, know each other more than 5 years and since then we are engaged in at least weekly personal interaction. Thefore, if initial barriers might have existed, we believe they have been vanished due to the course of prior work together as a team. No hiring decisions related to the proposed investigation will be made. At the same time, we will be diligent to address any concerns if they arise. We will encourage all team members to speak at monthly meeting and address any concerns either to the group or to individual team members.

During monthly meetings we will encourage all team members to make suggestions how work can be done more efficiently. This includes suggestions from the team to ensure that every team member is fully involved in the proposed research.

The role of the PI in training and development of a diverse and inclusive scientific workforce will be putting an open discussion about diversity and inclusion in the agenda during monthly team meetings. The role of all team members is to discuss these issues, provide suggestions, and seek for consensus.

13 Biographical Sketches

Leonid Petrov (PI)

Present position:

Geophysicist at NASA GSFC in Geodesy & Geophysics Laboratory at NASA GSFC, VLBI Lead Scientist.

Professional experience:

Since 1988 Leonid Petrov has been working in data analysis of space geodesy and remote sensing data, development of data processing algorithms with the highest accuracy, systems and tools aimed to improvement of the terrestrial and celestial reference frames and Earth orientation parameters. He has developed algorithms and implemented them into software for VLBI scheduling, VLBI post-correlation processing based on cross-spectrum, for computation of theoretical VLBI delay, and for geodetic and astrometric VLBI data analysis based on group delays. He has processed all publicly available VLBI observations suitable for astrometry and geodesy.

Leonid Petrov NASA worked at Goddard Earth Sciences Data and Information Services Center for support of the infrastructure for visualization, analyzing, and access of vast amounts of Earth science remote sensing data. During his carrier has has developed over one million line of code for various scientific applications.

Leonid Petrov has been working on development of advanced methods for processing space geodesy, remote sensing data, and numerical models. He has been working on development and maintenance of the pipeline for prepossessing, analysis, and interpretation of VLBI geodetic experiments that was adopted by the International VLBI Service. He also worked on development and maintenance of the International Mass Loading Service, the International Path Delay Service, the Atmospheric Angular Momentum Service, and the Network Earth Rotation Service.

Management experience:

Managed twenty nine projects under various astronomy programs at the National Radio Astronomy Observatory, the European VLBI Network, Australian National Telescope Facility, East Asian VLBI Network, National Astronomical Observatory of Japan, Korea Astronomy and Space Science.

Managed seven projects under NASA Earth Surface and Interior program and one project under NASA Global Navigation Satellite System Remote Sensing Science Team as a principal investigator.

Education:

Ph.D. of Russian Academy of Sciences, 1995, Astronomy
M.S. of Leningrad National University, 1988, Astronomy

Selected publications

1. **Petrov, L.**, "The wide-field VLBA calibrator survey – WFCS", (2021), Astronomical Journal, 161(1), 15 (25pp). doi: 10.3847/1538-3881/abc4e1

2. **Petrov, L.**, (2016), "The International Mass Loading Service", International Association of Geodesy Symposia, Springer, vol 146, 79–83. doi: 10.1007/1345_2015_218

3. **Petrov, L.**, T. Natusch, S. Weston, J. McCallum, S. Ellingsen, S. Gulyaev, (2015). "First scientific VLBI observations using New Zealand 30 meter radio telescope WARK30M", Publications of the Astronomical Society of the Pacific, 127, 516–522

4. **Petrov, L.**, (2015), Modeling of path delay in the neutral atmosphere: a paradigm shift, to appear in the Proceedings of the 12th European VLBI Network Symposium and Users Meeting, 7-10 October 2014 Cagliari, Italy http://arxiv.org/abs/1502.06678

5. P. Sarti, C. Abbondanza, **L. Petrov**, M. Negusini, (2010) "Effect of antenna gravity deformations on VLBI estimates of site positions", Jour. of Geodesy, DOI: 10.1007/s00190-010-0410-6.

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8. **Petrov, L.**, C. Phillips, A. Bertarini, A. Deller, S. Pogrebenko, A. Mujunen, (2009) "The use of the Long Baseline Array in Australia for precise geodesy and absolute astrometry", Publications of the Astronomical Society of Australia, 26(1), 75-84.

9. **Petrov, L.**, J.-P. Boy, (2004) "Study of the atmospheric pressure loading signal in VLBI observations", Journal of Geophysical Research, 10.1029/2003JB002500, vol. 109, No. B03405.

10. **Petrov, L.**, C. Ma, (2003) "Study of harmonic site position variations determined by VLBI", Journal of Geophysical Research, vol. 108, No. B4, 2190.

11. **Petrov, L.**, O. Volvach, N. Nesterov, "Measurements of horizontal motion of the station Simeiz using VLBI", (2001) Kinematic and Physics of Celestial Bodies, Vol. 17, N5, p. 424–436.

There are 59 peer reviewed works with a total of 2509 citations. Hirsch index 26.

Scott Luthcke (Co-I)

Scott B. Luthcke

NASA Goddard Space Flight Center
Planetary Geodynamics Laboratory, Code 698
Greenbelt, MD 20771 USA
Scott.B.Luthcke@nasa.gov
Tel: (301) 614-61123
Fax: (301) 614-6522

RESEARCH AREAS: Satellite geodesy, ice sheet and glacier mass balance and evolution from satellite gravity, and satellite/airborne altimetry; time variable and static gravity recovery from satellite tracking including inter-satellite observations; satellite and airborne laser and radar altimeter analysis for cryosphere, oceans, hydrology and eco-systems research; satellite tracking data analysis, satellite accelerometry and attitude data analysis, satellite measurement and force modeling, satellite and airborne precise positioning and attitude determination.

Current Mission Responsibilities

- GEDI Co-investigator, POD/PPD/Geolocation Lead, and Science Operations Center Lead
- ICESat-2 POD/PPD/Geolocation Lead

Selected Publications

Luthcke, S.B., Thomas, T.C., Pennington, T.A., Rebold, T.W., Nicholas, J.B., Rowlands, D.D., Gardner, A.S. and Bae, S., (2021). ICESat-2 pointing calibration and geolocation performance. *Earth and Space Science*, *8*(3), https://doi.org/10.1029/2020EA001494.

Thomas, T. C., S. B. Luthcke, T. A. Pennington, J. B. Nicholas, and D. D. Rowlands. "ICESat-2 Precision Orbit Determination." *Earth and Space Science* 8, no. 4 (2021): https://doi.org/10.1029/2020EA001496.

Dubayah, R., Blair, J.B., Goetz, S., Fatoyinbo, L., Hansen, M., Healey, S., Hofton, M., Hurtt, G., Kellner, J., Luthcke, S. and Armston, J., (2020). The Global Ecosystem Dynamics Investigation: High-resolution laser ranging of the Earth's forests and topography. *Science of remote sensing*, *1*, p.100002. https://doi.org/10.1016/j.srs.2020.100002.

Markus, T., Neumann, T., Martino, A., Abdalati, W., Brunt, K., Csatho, B., Farrell, S., Fricker, H., Gardner, A., Harding, D. and Jasinsk, M., Kwok, R., Magruder, L., Lubin, D., Luthcke, S., Morison, J., Nelson, R., Neuenschwander, A., Palm, S., Popescu, S., Shum, C., Schutz, B., Smith, B., Yang, Y., Zwally, J. (2017). The Ice, Cloud, and land Elevation Satellite-2 (ICESat-2): Science requirements, concept, and implementation. *Remote Sensing of Environment*, *190*, pp.260-273.

Luthcke, S.B., H.J. Zwally, W. Abdalati, D.D. Rowlands, R.D. Ray, R.S. Nerem, F.G. Lemoine, J.J. McCarthy and D.S. Chinn (2006), Recent Greenland Ice Mass Loss by Drainage System from Satellite Gravity Observations, *Science* 314, 1286 (10.1126/science.1130776).

Luthcke, S.B., D.D. Rowlands, T.A. Williams, M. Sirota,"Calibration and reduction of ICESat geolocation errors and the impact on ice sheet elevation change detection," *Geophys. Res. Lett.,* VOL. 32, L21S05, doi:10.1029/2005GL023689, 2005.

Luthcke, S.B., N.P. Zelensky, D.D. Rowlands, F.G. Lemoine and T.A. Williams (2003), The 1-centimeter Orbit: Jason-1 Precision Orbit Determination Using GPS, SLR, DORIS and Altimeter data, *Marine Geodesy,* Special Issue on Jason-1 Calibration/Validation, Part 1, Vol. 26, No. 3-4, pp. 399-421.

Frank Lemoine (Co-I)

Frank G. Lemoine

https://science.gsfc.nasa.gov/sed/bio/frank.g.lemoine

NASA Goddard Space Flight Center Frank.G.Lemoine@nasa.gov
Geodesy & Geophysics Laboratory, Code 61A Tel: (301) 614-6109
Greenbelt, MD 20771 U.S.A. Fax: (301) 614-6522

CURRENT POSITION: 1995 — present: Geophysicist, NASA GSFC.

RESEARCH AREAS: Satellite geodesy; The determination and maintenance of the terrestrial reference frame; Determination of changes in Mean sea level; Precise orbit determination for artificial satellites; Mapping of the static and time-variable gravity field of the Earth and planets from satellite tracking data; Analysis of laser altimeter data.

EDUCATION:

1984,	B.S.E.	Princeton University.
1986	M.S.	University of Colorado, Boulder.
1992	Ph.D.	University of Colorado, Boulder.

PROFESSIONAL ACTIVITIES

• Project Scientist, NASA Space Geodesy Project (Oct. 2018 – Present).
• Co-I Lunar Orbiter Laser Altimeter, Lunar Reconnaissance Orbiter (2008 – Present).
• Co-chair, POD Team for Jason-2 & Jason-3, 2008 – Present.
• Chair & Member Governing Board, International DORIS Service (IDS), 2017 – 2024.
• Director of GSC DORIS Analysis Center, providing weekly SINEX series, and full reprocessing of DORIS satellite data for ITRF2008, ITRF2014, and ITRF2020.
• Member, Central Bureau, International Laser Ranging Service (ILRS).
• Co-I Gravity Recovery and Interior Laboratory (GRAIL), NASA Discovery mission.

SELECTED PUBLICATIONS

Belli, A., N.P. Zelensky, **F.G. Lemoine**, and D.S. Chinn. (2021). "Impact of Jason-2/T2L2 Ultra-Stable-Oscillator Frequency Model on DORIS stations coordinates and Earth Orientation Parameters." *Adv. Space Res.*, **67 (3):** 930-944 doi:10.1016/j.asr.2020.11.034.

Lemoine, F. G. (2020). "The Role of SLR: Science from Satellite Laser Ranging." *International Laser Ranging Service (ILRS) 2016-2019 Report edited by C. Noll and M. Pearlman, NASA/TP-20205008530, NASA Goddard Space Flight Center, Greenbelt, MD, USA, 2020 (https://ilrs.gsfc.nasa.gov/docs/2020/ilrsreport_2016_section2.pdf)*

Pearlman, M.R., C. E. Noll, E.C. Pavlis, **F.G. Lemoine**, et al**.** (2019**).** "The ILRS: approaching 20 years and planning for the future." J. Geodesy, doi:10.1007/s00190-019-01241-1.

Lemoine, F.G., D.S. Chinn, N.P. Zelensky, et al. (2016), "The development of the GSFC DORIS Contribution to ITRF2014," *Adv. Space Res*., doi:10.1016/j.asr.2015.12.043.

Genova, A., S. Goossens, **F.G. Lemoine**, et al. (2015), "Long-term variability of CO2 and O in the Mars upper atmosphere from MRO radio science data," *J. Geophys. Res.-Planets, 120(5), 849–868*, doi: 10.1002/2014JE004770.

Lemoine, F.G., S. Goossens, T.J. Sabaka, et al. (2014), "GRGM900C: A degree 900 lunar gravity model from GRAIL primary and extended mission data", *Geophys. Res. Lett., 41(10),* 3382-3389, doi:10.1002/2014GL060027.

Lemoine, F.G., S. Goossens, T.J. Sabaka, et al. (2013), "High-degree gravity models from GRAIL primary mission data", *J. Geophys. Res.-Planets, 118(8)*, 1676-1698, doi:10.1002/jgre.20118.

Lemoine, F.G., N.P. Zelensky, D.S. Chinn, et al. (2010), "Towards development of a consistent orbit series for TOPEX, Jason-1, and Jason-2", *Adv. Space Res*, 46(12).

Mazarico, E., **F.G. Lemoine**, S.C. Han and D.E. Smith (2010), "GLGM-3: A degree-150 lunar gravity model from the historical tracking data of NASA Moon orbiters", *J. Geophys. Res-Planets, 115(E05001),* doi: 0.1029/2009JE003472.

14 Work efforts table

TABLE OF WORK EFFORT

		Commitment (months per year)											
		Year 1			*Year 2*			*Year 3*			*Sum*		
		This Project		*Other Funded Projects*	*This Project*		*Other Funded Projects*	*This Project*		*Other Funded Projects*	*This Project*		*Other Funded Projects*
Name	**Role**	*NASA Support*	*Total*		*NASA Support*	*Total*		*NASA Support*	*Total*		*NASA Support*	*Total*	
Leonid Petrov	PI	2.4	2.4	9.5	2.4	2.4	8.4	2.4	2.4	8.4	7.2	7.2	26.3
Scott Luthcke	Co-I	2.4	2.4	8.0	2.4	2.4	8.0	2.4	2.4	8.0	7.2	77.2	24.0
Frank Lemoine	Co-I	1.2	1.2	10.4	1.2	1.2	10.4	1.2	1.2	9.2	3.6	3.6	30.0
David Rowlands	Collaborator	0.0	0.0	6.0	0.0	0.0	6.0	0.0	0.0	6.0	0.0	0.0	18.0
TBD	Support	2.4	2.4	0.0	2.4	2.4	0.0	2.4	2.4	0.0	7.2	7.2	0.0
Sum of work effort:		**8.4**	**8.4**	**33.9**	**8.4**	**8.40**	**32.8**	**8.40**	**8.40**	**31.6**	**25.2**	**25.2**	**98.3**
Comments:													

Total - The total number of months that will be committed to this project by the team member (including time not funded by this proposal and time funded by this proposal).
NASA Support - The number of months committed to this project that will actually be funded by this proposal.
Other Funded Projects - The number of months that are committed to other currently funded proposals.