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The feasibility study of the use of ngVLA for space geodesy

Submitted in response to Research Opportunities in Space and Earth Sciences (ROSES) — 2019 Solicitation: NNH19ZDA001N-ESI, program A. 27. Earth Surface and Interior, section 2.2

Contents

1 Executive Summary

The goal of the proposed research is to explore the feasibility of the use of planned network of radio telescopes ngVLA for space geodesy as a complement to VLBI Global Observing Stations (VGOS). This will be done through simulation. We will assess performance of such a network for space geodesy applications under different observing modes.

2 Motivation

As part of its mandate as a national observatory, the National Radio Astronomy Observatory (NRAO) is looking toward the longrange future of radio astronomy and fostering the long-term growth of the U.S. and global astronomical community. Based on input solicited from the astronomical community, the concept of the next generation very large array (ngVLA) is defined. The array will consist of 244 18m antennas distributed quasi-randomly at all scales from 100m to 8860 km. The array will operate at the frequency range from 1.2 to 116 GHz.

The science objectives of the new instrument include astrophysics, heliophysics, solar system exploration, space navigation, astrometry, cosmology and fundamental physics, but do not include space geodesy. Although this instrument that is planned to start early science program in 2028 and achieve full operation in 2034 is not designed for space geodesy, the data flow generated during observations under non-geodetic programs will, certainly, be useful for space geodesy. This prompted us to investigate in detail to what extent ngVLA data can contribute to space geodesy.

3 Introduction

3.1 ngVLA configuration

In order to optimize image fidelity, ngVLA sites are distributed highly non-uniformly (See Figure 1). The array has four levels of hierarchy. At the first level, ngVLA configuration resembles the Very Long Baseline Array (VLBA) configuration (Petrov et al., 2009), although each ngVLA site has multiple antennas. In case of Maunakea, HI and Saint Croix, VI additional antennas are located at distances of hundreds of kilometers. There will be a GNSS receiver in the vicinity of each antenna. Each ngVLA antenna will be equipped with a water vapor radiometer. The long baseline part of the array consists of 30 antennas. The second level of hierarchy, spread over Texas, Arizona, New Mexico, and northern Mexico, consists of 46 antennas at distances 36–1000 km. The third level of the array hierarchy consists of 74 antennas at distances 1.3–73 km, and the 4th level consists of 94 antennas at distances up to 1.3 km (Selina et al., 2018). The network of 76 antennas of the 1st and 2nd levels, hereafter called an outer array is the main interest for space geodesy. For comparison, in total, 57 antennas participate in geodetic VLBI observations in 2019. Therefore, **the outer part of ngVLA will have more antennas than all existing and planned geodetic VLBI sites combined**.

3.2 Space geodesy from astronomy VLBI observations

Can astronomy VLBI observations be used for space geodesy? There are several factors that adversely affects the accuracy of geodetic parameter estimates. Firstly, in the past, astronomy observations selected the frequency allocation that covered the continuous band, while geodesy observations spread allocated frequencies over as wide bandwidth as possible. That affects the uncertainties of group delay. For example, the formal uncertainty of group delay with signal to noise ratio (SNR) 10 at the geodetic setup spread over 736 MHz spanned bandwidth used for regular geodetic VLBI experiments dedicated for the Earth orientation parameter determination is 53 ps. The uncertainty of group delay in astronomy experiment gc034a with the same SNR, with the same recorded bit rate, but with different frequency allocation is 863 ps. Secondly, the observing schedules of astronomy VLBI campaigns are not optimized for space geodesy, and therefore, accuracy of site positions and the Earth orientation parameters will be somewhat compromised. To what extent?

Petrov and Taylor (2011) have demonstrated that re-analysis of the astronomical program VLBI Image and Polarimetry Survey (VIPS) at 5 GHz using the geodetic VLBI data analysis pipeline provided precise astrometry with additional noise in quadrature 0.23 mas. Typical uncertainty in positions of VLBA sites achieved over 11 hour long experiments was 4–5 mm in horizontal and 25–30 mm vertical. These experiments used the frequency allocation spanned over 494 MHz in order to calibrate for the polarization leakage. Accuracy of these results is only $\sim$50% below the level of accuracy of results under dedicated regular VLBA geodesy program rdv (Petrov et al., 2009) made at approximately the same time with the same recorded bit rate.

We recently conducted two imaging VLBA experiments of the peculiar radiogalaxy 3C48 at 24 GHz. The frequency channels were allocated over 480 MHz spanned bandwidth. Each experiment lasted 7 hours. Processing the experiments using the geodesy VLBI data analysis pipeline provided the position uncertainty of VLBA stations at a level 2–3 mm in horizontal and 8–12 mm in vertical components; whereas estimates of X pole coordinate, Y pole coordinate and UT1 had uncertainties 110, 150 μas, and 9 μsec respectively. These errors are a factor of 3 lower than from 24 hour VLBA experiments dedicated for geodesy, but after re-scaling for the duration of an experiment ($\sqrt{24/7} = 1.9$), the differences are at a level of 50%.

These examples demonstrate that although geodetic scheduling algorithms provide superior results, processing astronomy experiments via the geodetic pipeline can provide results with accuracies that are only 50% lower than accuracies of results of dedicated VLBI experiments. We should stress that **usable space geodesy data from regular ngVLA astronomical observations will be available for the geodetic community virtually for free**, not counting efforts for their analysis.

4 Problem statement

We will address the question to what extent ngVLA can be used for space geodesy. The goal of our project is

- **to investigate feasibility of using regular ngVLA data for geodetic applications** as commensal science mutually benefiting the geodetic and astronomy communities. In a typical astronomical experiment bright sources are scheduled every 1–3 minutes for being used as calibrators. The SNR of such observations is above 10. Analysis of group delays from observations of bright calibrators in regular ngVLA astronomical experiments at 3,000 baselines of the outer array looks very promising for determination of the Earth orientation parameters (EOPs), and establishing a precise reference frame.

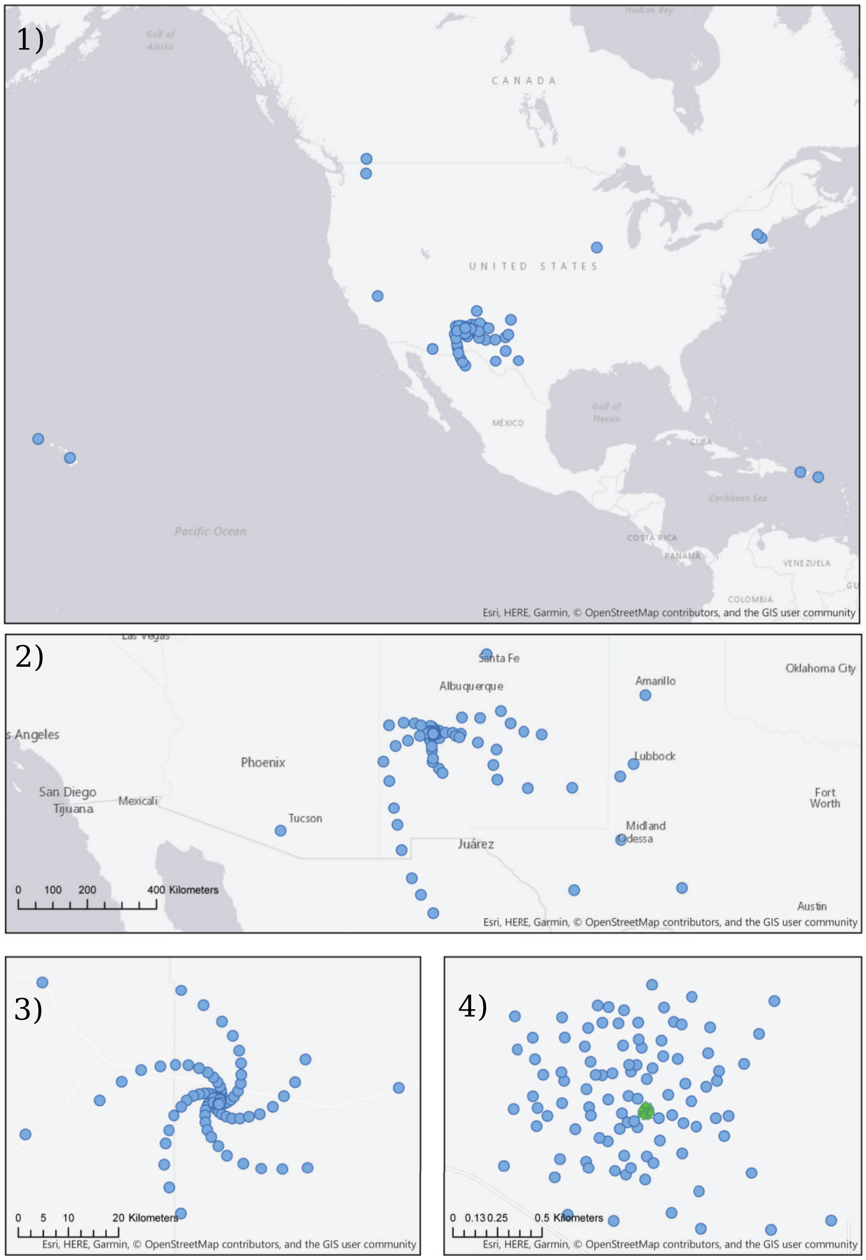

Figure 1: ngVLA array configuration at four levels of hierarchy. Multiple antennas located at each site are not shown at levels 1 and 2. Reproduced from Selina et al. (2018).

- **to assess what resources may be needed for achieving geodesy-grade results using ngVLA.** In particular, we propose to investigate requirements for GNSS receivers near the stations, requirements for establishing local geodetic networks for GNSS–VLBI ties, requirements for delay calibration, measurements of phase calibration, clock offsets, and other factors that may not be essential for astronomy observations, but have to be accounted carefully for obtaining high quality geodesy results. It is worth pointing out that by conducting this study before ngVLA is built there may be opportunities for modifications that may substantially improve the capabilities for space geodesy.

- **to investigate geodetic requirements of ngVLA.** Astrometry is one of the key science goals of the proposed instrument. We expect that precise astrometry at 86 GHz requires sub-cm accuracy of instantaneous positions of array elements and we will evaluate these requirements rigorously.

5 Proposed methodologies

We will be investigating quality of geodetic results using simulated ngVLA datasets from the outer array. For this study we will ignore the inner array at the area of 73 km. Although recorded bandwidth 20 GHz is planned for observations at high frequencies, we will use a more conservative low limit 8 GHz of the recorded bandwidth for our work. Simple calculations based on expected ngVLA sensitivity (Selina et al., 2018) that will be comparable to the VLBA sensitivity show that when phase delay τ_{ph} and group delay τ_{gr} are estimated over 8 GHz bandwidth, dual polarization, the uncertainty of group delay is 5 ps, or 1 mm for observations with SNR=10. At frequencies above 20 GHz, modeling the ionosphere contribution using Total Electron Contents (TEC) maps derived from GNSS observations is adequate. At lower frequencies, the TEC is fitted to the cross-correlation spectrum, and three parameters are estimated:

$$\varphi(\omega) = \tau_{\mathrm{ph}}\,\omega_0 + \tau_{\mathrm{gr}}\,(\omega - \omega_0) + \mathrm{TEC}\,\frac{\kappa}{\omega}, \tag{1}$$

where ω is the angular frequency of the cross-spectrum, ω is the reference frequency, and κ is a scaling parameter. Estimating the 3rd parameter increases statistical uncertainty to 8 ps when the lower frequency is 3.5 GHz and to 12 ps when the lower frequency is 12 GHz. SNR equal to 10 for calibrator observations is rather a lower limit: observing a source with flux density 3–4 mJy for 40 seconds will result in SNR=10 at frequencies below 50 GHz at a given ngVLA baseline. Typically, the calibrator sources are brighter, 10–50 mJy. Shortening the calibrator integration time below 20 sec is not practical, since slewing time will take longer. Observation of a 20 mJy calibrator for 20 s over 8 GHz bandwidth with 64 Gbps recording rate will result in SNR=35 and formal uncertainty of group delay 1 ps, or 0.3 mm. Therefore, accuracy of group delays from these observations will be limited by systematic errors, f.e. path delay in the atmosphere, with measurement errors being negligible.

5.1 Simulation of ngVLA observations

First, we consider how accurately geodetic parameters can be estimated using **regular astronomical observations**.

- We will analyze the ngVLA science cases as they are known to date and prepare a list of observing modes. We will assess the expected share of observing time of every observing mode. We will analyze the VLA and VLBA archives for the current use of this instrument and make an educated guess how the share of the current observing modes will be changed in the future as a result of a change in priorities and as a result of new capabilities ngVLA will offer to users.

- Then for each observing mode we will run a battery of trial schedules using the ngVLA toolbox and scheduling software SCHED maintained by NRAO. We will vary experiment duration, flux density of calibrator and target sources, their declinations, and observing frequencies.
- These schedule files will be transformed to simulated database files in the format that VLBI data analysis software Solve maintained by the Geodesy & Geophysics Laboratory supports. We will add correlated noise to the simulated observables. The covariance matrix of noise is computed with including off-diagonal terms derived assuming Kolmogorov's atmosphere turbulence model according to rigorous approaches developed in Nilsson and Haas (2010) and Pany et al. (2011).

  Results of simulation runs, such as the Earth orientation parameters and site positions will be stored for further analysis.
- A subset of the representative schedules will be passed through multiple ngVLA configurations in order to understand the benefits of including additional antennas beyond the standard configuration.
- Based on the expected time share of each observing mode, we will generate time series of expected results over ten years. The results will include pole coordinates, UT1, nutation angle offsets, site positions. Using these time series and their full variance-covariance matrices, we will compute station positions averaged over one day, one week, one month and their uncertainties, as well as amplitudes of harmonic site position variations at seasonal periods.

Simulated delays are and applied in a usual Solve solutions. We will be using the approaches similar to that used by the IVS (International VLBI Service for Geodesy and Astrometry) VLBI2010 Working Group that investigated tradeoffs in the performance of a future global network of broadband antennas, specifically the precision of estimated geodetic parameters. The VLBI2010 WG used the formalism of Treuhaft and Lanyi (1987) for accounting for random turbulent fluctuation of wet troposphere refractivity, as wells as others turbulence models (e.g., Davis, 1992; Lanyi, 1998). Since a rigorous treatment of the atmospheric contribution is crucial for getting realistic error estimates, we present here our approach in more detail.

The spatial statistics of differences in the wet tropospheric refractive index n at positions r and $r+R$ are described by a Kolmogorov structure function,

$$D_n(r,R) = < (n(r+R)-n(r))^2 > = C_n^2\, R^{2/3}, \qquad (2)$$

where the brackets indicate a mean ensemble average and C_n^2 is a constant. The refractivity field is assumed to be homogeneous and isotropic, where D_n depends only on $|R|$. The structure constant C_n characterizes the "strength" or "rockiness" of the spatial fluctuations.

Wet delay is the integral of the wet troposphere refractivity over the ray path toward a radio source. This "slant" path delay can be expressed as the product of the zenith delay an elevation dependent mapping function $m(e_i)$. For each station in the ngVLA network, we will compute a simulated series of equivalent wet zenith delays corresponding to each observation following the method of Nilsson and Haas (2010). To do this, we compute the covariance matrix between all of the scheduled observations. The covariance between equivalent wet zenith delays for each pair of observations involves differences between the refractivities along the delay paths toward the sources of the two observations. One can express these differences in the form of structure functions between elements of refractivity along the two raypaths. If the above Kolmogorov assumption is made, then these structure functions can be evaluated. We can then compute the double integrations along the two observation paths numerically for all pairs of observations. Once the covariance matrix C is generated, it can be decomposed with a Cholesky algorithm

$$C = AA^T. \tag{3}$$

Based on this covariance matrix, one can then derive a series of simulated wet zenith delays driven by Gaussian random noise. A series of equivalent wet zenith delays at the observation epochs can be generated as components of the vector

$$\tau^z = \tau^z_0 + A\,w, \tag{4}$$

where τ^z_0 is an a priori initial equivalent wet zenith delay and w is a vector of zero mean Gaussian random numbers of unit variance. These simulated delays are correlated according to the Kolmogorov fluctuation model. Simulated tropospheric delays in the source direction are then

$$\tau_i = m(e_i)\,\tau^z_i. \tag{5}$$

For each Monte Carlo realization of simulated delays, we will generate a new Gaussian random noise vector with length equal to the number of session observations and computes the resulting series of equivalent wet zenith delays. We will compute C_n from GNSS derived time series of zenith wet path delays from nearby IGS sites following the approach of Nilsson and Haas (2010) that was validated by Nilsson et al. (2014). Once the simulated delays are computed, we will apply them in a Solve solution in which parameters of interest such as Earth orientation parameters or station positions are estimated for many Monte Carlo repetitions. The parameter estimates will be stored for further analysis. We will compute parameter precision, which is given by the repeatability of the estimated parameters.

5.2 Evaluation of geodetic requirements for ngVLA

Among key science cases of ngVLA are indirect detection of exoplanets through astrometry (Butler and Matthews, 2018), measuring Galaxy dynamics and evolution through highly accurate astrometric measurements (Loinard and Reid, 2018), extragalactic proper motions: gravitational waves and cosmology (Darling et al., 2018), and others (Reid et al., 2018; Patil et al., 2018; Rujopakarn et al., 2018; Taylor and Simon, 2018; Lister et al., 2018; Kirkpatrick et al., 2018; Bower et al., 2018). The use of precise astrometry with precision down to 10 μas sets strict requirements on accuracy of site positions. One milliarcsecond at the Earth's surface corresponds to 30 mm. Therefore, 10 μas accuracy in source positions roughly requires a 0.3 mm level of accuracy in site positions. Accounting for systematic errors is especially important: some applications can tolerate random errors significantly higher than 10 μas for an individual observing session, but systematic bias at that level may be highly undesirable. In order to reach absolute astrometry with such accuracy, site positions should be known with sub-millimeter accuracy. The contribution of site positions errors to source position estimates derived using differential astrometry is diluted by approximately the angular distance between the target and the calibrator. With a typical target/calibrator separation 2.5°, position errors 7 mm will contribute to the error budget at a level comparable with random measurement errors.

We will investigate in detail the contribution of site position errors to results of precise absolute and differential astrometry. We will run a set of simulations using scenarios used for absolute and differential astrometry in past VLBA observing campaigns. We will add random and systematic noise to station positions and investigate its impact on source position estimates. For modeling systematic errors we will consider a) partly correlated noise with correlations exponentially decaying with antenna separations; b) harmonic signal with partly coherent amplitudes. The latter effect will account for the contribution of mismodeled mass loading and atmosphere path delays that are partly correlated at scales up to several thousand kilometers (Petrov and Boy, 2004).

Although ngVLA project assumes that a GNSS receiver within one hundred meters of each ngVLA antenna site will be installed, anticipated accuracy of local ties between GNSS receivers and a radiotelescopes is expected at a level of 1–2 cm (Combrinck and Merry, 1997; Ray and Altamimi, 2005; Abbondanza et al., 2009; Ning et al., 2015; Glaser et al., 2019), which is insufficient to meet requirements not only for absolute astrometry but for differential astrometry as well. Therefore, we will consider a program of dedicated VLBI observations to improve site positions. We will generate a set of simulated geodetic schedules using the geodetic scheduling software package `sked`. We will add the correlated noise generated by the method described in the previous subsection to right hand sides of simulated observational equations and estimate parameters using the VLBI analysis package `Solve`. We will generate a set of schedules of 6, 12, and 24 hour long for observations that will run every day within one year and estimate accuracy of positions averaged over 1 day, 7 days, one month, and one year, as well as amplitudes of harmonic site position variations. We will consider including all available VGOS stations in these simulations. Then we will decimate the observing schedules keeping one experiment per a given time interval, for instance, one per month, or six time a year, and evaluate degradation of accuracy.

Then we repeat this decimation test by combining simulation results of dedicated geodetic VLBI observations at the ngVLA network and regular astronomical observations. The purpose of these simulations is twofold:

1. to answer the question how often dedicated geodetic VLBI observations at the ngVLA should be performed to support a) differential astrometry and b) absolute astrometry and what should be a duration of such experiments;

2. to assess the impact of these observations for improvement of the global terrestrial coordinate system and assess what kind of benefits these new observations will bring to the geodetic community. We will run TRF-style global solutions with including simulated ngVLA dedicated observations into the dataset and evaluate changes in stability of the reference frame, stability of the scale factor, robustness of the global solution to mismodeled episodic site motions due to including 76 outer ngVLA sites.

5.3 Evaluation of requirements for ngVLA stations to provide high quality geodetic results

We will be investigating the requirements for ngVLA stations to provide high quality geodetic results. In particular,

- Each ngVLA site will have a GNSS receiver. The primary purpose of the installing GNSS receivers is to provide estimates of zenith path delay and be incorporated in computation of the TEC for reduction of astronomical observations. We will evaluate whether any changes in design are desirable and estimate associated costs to ensure these receivers will be compliant with IGS guidelines.

- We will investigate feasibility of making VLBI-GNSS ties. That work includes recommendations for location of pillars for local surveys and placements of retro-reflectors on the antennas to conduct surveys.

- We will investigate requirements for VLBI system to ensure geodetic quality of results. That includes cable calibrations and phase calibrations. We will re-analyze a number of wide-band VGOS experiments with and without phase and cable calibration to evaluate an impact of omission of cable and phase calibration on group delay, and on estimates of site positions and the Earth orientation parameters.

6 Anticipated scientific value of ngVLA geodetic results

Geometrically, ngVLA can be considered as an extension of the VLBA array in the context of space geodesy. The main differences relevant to space geodesy are:

1. ngVLA adds additional stations with baselines 50–500 km near the outmost VLBA sites MK-VLBA, SC-VLBA, HN-VLBA, BR-VLBA;
2. Among ngVLA sites, there will be antennas within 1000 meters of VGOS stations KOKEE12M and WESTWORD and within 10 km of the new VGOS station MCDONALD;
3. ngVLA densifies the network in the vicinity of the VLBA inner core;
4. all ngVLA sites have a collocated GPS receiver within a hundred meters;
5. all ngVLA sites will have a waver vapor radiometer (WVR).

- As we showed in Petrov et al. (2009), VLBA geodetic results are excellent: baseline length repeatability is on a par with the repeatability derived from observations at dedicated geodetic networks. Accuracy of the Earth orientation parameters derived from analysis of VLBA data was only 10–15% lower than accuracy from data analysis of the dedicated IVS global network R1.

  Since two ngVLA sites are collocated with VGOS stations, this will enable us to use very precise phase delay observables that usually provide sub-millimeter repeatability in a baseline between stations within several kilometers. The ngVLA is frequency compatible with the VGOS network that at the moment has 6 operating stations and will have 25 stations by 2028, when ngVLA is expected to have first light. Therefore, VGOS+ngVLA observations

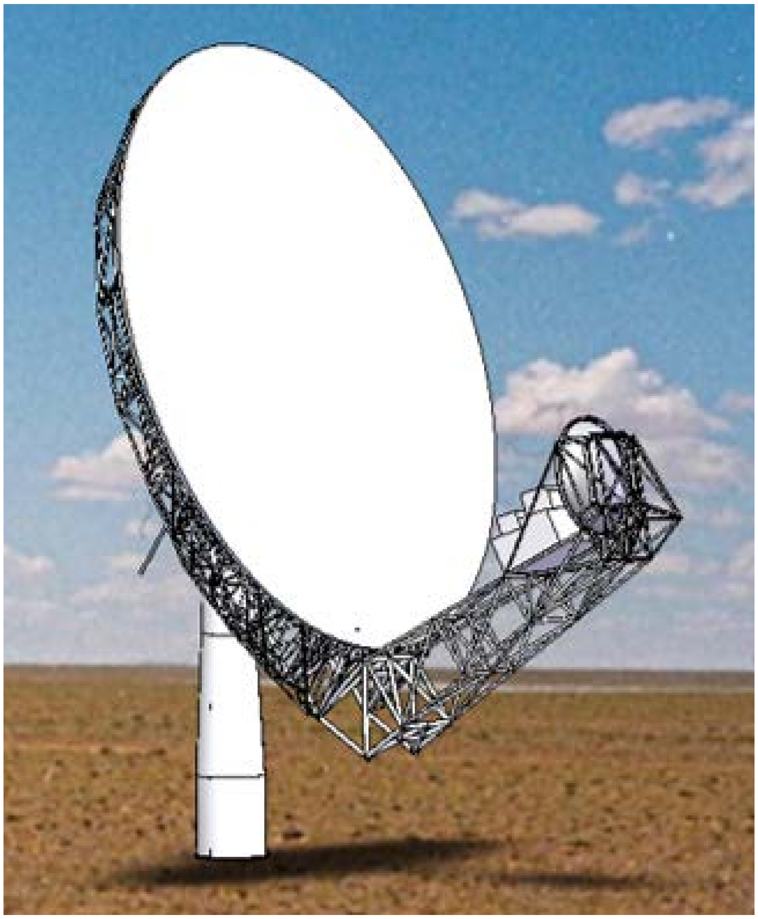

Figure 2: Front view of the General Dynamics mission systems 18m reference design antenna whose network we wish to exploit for space geodesy as a complement to the global VGOS network.

will easily align ngVLA stations to the ITRF. Therefore, all geodetic results achieved at the VLBA are expected to be achieved at ngVLA as well. We will investigate through simulations of regular and dedicated ngVLA observations how many observations are needed to reach ngVLA position accuracy at a level of 5, 3, and 1 mm.

But we anticipate ngVLA will provide space geodesy results well beyond that have been obtained with VLBA. Each ngVLA site that is equivalent to VLBA sites will have several antennas within 1000 m of each other. We will be in a position to exploit such geometry for distinguishing local site motion from global. Petrov et al. (2001, 2009) reported a tilt of the azimuthal axis that is changing with time for several stations, namely PIETOWN and CRIMEA. Analysis of observations with historic VLBI site HRAS 085, within 300 m of FD-VLBA antenna revealed a pattern of peculiar motion that was not fully understood. It was attributed to local motion or possibly to some antenna pointing error. Plots of the HRAS 085 baseline length vector time series in Ryan et al. (1993) indicate that the magnitude of this motion was as large 40–50 mm.

A cluster of 2–4 stations with relative positions known with sub-mm accuracy via phase delay VLBI, will allows us to isolate a station with a peculiar motion that is not caused by mass loading or other large-scale geophysical process and therefore, improve robustness of the TRF.

A part of the ngVLA at the third level of the hierarchy with 74 antennas at distances 1.3–73 km (Figure 1 part 3) provides an exciting opportunity to study differential atmospheric path delay at these scales. Although resolving phase delay ambiguities at distance 73 km may not work, we are confident that we can resolve phase delay ambiguities at baselines 1–3 km at frequencies below 20 GHz – we were always successful in the past. Phase delays can be measured with sub-millimeter precision. Such observations provided sub-millimeter baseline length repeatabilities (Petrov, 1999). Therefore, observations at this sub-network will allow us to monitor relative motions of these antennas with sub-millimeter accuracies. We do not know what will be the outcome of such monitoring. We surmise three possibilities: 1) no statistically significant motion, i.e. we will find that the sub-array of 74 antenna is stable; 2) incoherent noise-like motion, i.e. we will find the sub-array is unstable; 3) a pattern of coherent motion of the sub-array. The latter two cases will require a research for understanding what is their cause.

- Observations at that array will also allow us to study in detail effects of atmosphere turbulence on path delay at scales 1–73 km. Using VLBI observations of different sources at the inner subarray, we will determine differential path delay at $74 \times (74-1)/2 = 2701$ baselines. Using these data, we will be in a position to perform tomography of the refractivity coefficients over the subarray area and estimate corrections to a priori refractivity in volume elements (voxels). This will help us to improve geodetic results at this subarray by better modeling the contribution of the neutral atmosphere to path delay, and a study of 4D tomography will allow us to investigate statistical properties of refractivity fluctuations that may help us to improve modeling atmospheric path delay in general by incorporating advanced stochastic mode in the parameter estimation procedure.

  We will run a simulation with the 4D refractivity field taken from NASA GMAO Nature Run model with 7 km and higher resolutions (Putman, 2015). We will use the contribution to path delay computed by integration of the original refractivity field from that model for computation of right hand sides of the simulation. For data reduction of simulated data, we will use the same refractivity field but heavily smoothed that will remove most of the high-resolution features. We will estimate residual path delays at voxels and compare these estimates with the path delays computed from known refractivity field of the NASA GMAO Nature Run model. We will vary the size of voxels and investigated what kind of features of 4D refractivity field can be recovered. We should note that a part of this research for handling NASA GMAO Nature Run output and computation of path delay from that model is already funded by the on-going 18-ESI18-0057 project "*Development of the Optimal Strategy for Scheduling Geodetic VLBI Observations*" (PI: Leonid Petrov). Will just use results of this work.

- VLBI and GNSS observations at a dense inner ngVLA subarray will be useful for comparison with InSAR results. We will evaluate how often ngVLA can observe astronomical experiments in a mode suitable for space geodesy during flyby time of current and future InSAR missions, such as NISAR (Hoffman et al., 2016) and what will be accuracy of such concurrent observations. Baseline lengths in the inner subarray determined using phase delay data can be considered as the ground truth for InSAR. We will evaluate accuracy of such ngVLA observations by running simulations.

- Forty six new ngVLA antennas that form the second level of the ngVLA hierarchy, spread over TX, AZ, NM, and northern Mexico (Figure 1, part 2) at distances 36–1000 km provide a substantial densification of the existing VLBI network. We anticipate that including these stations located at the tectonically stable part of the United States into a global TRF solution will improve its robustness. The level of improvement will be assessed by running a simulation in a similar way as we did it in the past for evaluation of the VGOS network (MacMillan et al., 2016).

  Data analysis of 46 collocated VLBI/GNSS sites within distances 36–1000 km will allow us to assess a level of systematic errors of GNSS and VLBI. Geophysical signal, such as loading or crustal deformation caused by water pumping is supposed to be common at collocated GNSS and VLBI networks. However, errors caused by modeling the atmosphere path delay and instrumental effects are supposed to be at large uncorrelated between stations. The differences in position time series of 46 stations will provide us a substantial new material for useful statistics. In our simulations we will assess the formal uncertainties of VLBI station positions. This will allow is to judge of what level of magnitude of statistically significant differences in VLBI and GNSS site positions ngVLA observations can provide us.

7 Relevance to the program elements

The ESI program under section 2.2 Solid-Earth Observational Strategies

> "…welcomes …modeling, and analysis efforts that explore the tradeoffs between different data collection strategies, and the viability of those schemes for capturing specific solid-Earth processes of interest."

We address this solicitation by proposing to explore the feasibility of using ngVLA for space geodesy by exploring the tradeoffs between processing regular astronomical observations and dedicated geodetic VLBI observations for improvement of the terrestrial reference frame, densification of the EOP series, capturing crustal deformation, and inter-comparison of VLBI and GNSS results at new numerous collocated sites. The ESI program solicitation lays out the strategy:

> "Proposals to conduct Observing System Simulation Experiments (OSSE) that consider real and simulated observations and errors associated with solid-Earth science questions, …are also encouraged. Such studies may address the development of future remote-sensing and geodetic observational systems …"

We address this solicitation by proposing to run extended simulations for exploring the feasibility of using the future network of GNSS sensors and VLBI antennas as a geodetic observational system. The outcome of the proposed research will provide us realistic estimates of site position and EOP errors at different time scales scales in order to provide a **quantitative** measure of the performance of the network that is developed for goals different from Earth sciences.

The National Academy of Sciences (NAS) Decadal Survey, "Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space (2018)" warns in pages 179–180:

> "Reference systems that enable quality observations are often forgotten or neglected during observing system development, as they generally play more of a supporting role to those missions built primarily to observe geophysical variables. . . . A substantial amount of science reliant on the ITRF is at risk if the ITRF is not properly maintained and advanced."

and our proposal is a direct response to this concern. We propose to provide a quantitative assessment of the ability of the ngVLA mission built primarily to observe astrophysical variables to provide maintenance and advancement of the International Terrestrial Reference Frame (ITRF), as well as to contribute to Earth sciences. We hope that results of such a study will help us to raise awareness and prevent neglecting these issues during ngVLA development.

8 Previous work and risk assessment

PI L. Petrov has processed virtually all VLBI experiments usable for geodesy and absolute astrometry, including those originally scheduled as astronomy campaigns (Petrov, 2011, 2013; Petrov et al., 2012; Petrov and Taylor, 2011). Successful use of non-geodetic VLBI observations for geodesy gives us confidence that we will be able to overcome challenges in processing simulated ngVLA experiments.

Co-I D. MacMillan was a member of the IVS VLBI2010 Working Group that investigated the performance of a future global network of broadband VGOS antennas (MacMillan et al., 2016). We will be using the methods developed by the Working Group. D. MacMillan maintains software for simulation of VLBI networks, and we will adapt it software for simulation of the ngVLA network rather than develop new from scratch. We have validated the simulation modeling by comparing the precision of parameters estimated from observed data versus from simulated data (MacMillan, 2017). As an example, we consider a VLBI CONT11 observing campaign that consisted of a series of fifteen 24-hour continuously observed sessions in September 2011. We compared the observed versus the simulated baseline length repeatabilities and got the differences within 5%. Similarly, there was a reasonable agreement (10–25%) between simulated and observed EOP (polar motion and length of day) precision. The observed precision was based on the weighted root mean square (wrms) difference between VLBI and GNSS estimates and simulated precision is defined as the repeatability of EOP estimates from the Monte-Carlo simulation.

Figure 3 shows the results of a comparison of observed versus simulated baseline length repeatabilities from the CONT11 campaign. The mean ratio of simulated to observed wrms repeatability was 0.97 and the standard deviation of this ratio was 0.32. We stress the importance of the fact that the simulated results are close the observed. The uncertainties from our simulations are a realistic measure of precision as opposed to simply the formal uncertainties based only on observation delay uncertainties.

Co-I G. Taylor, the director of the Long Wave Array (LWA) performed extensive simulations

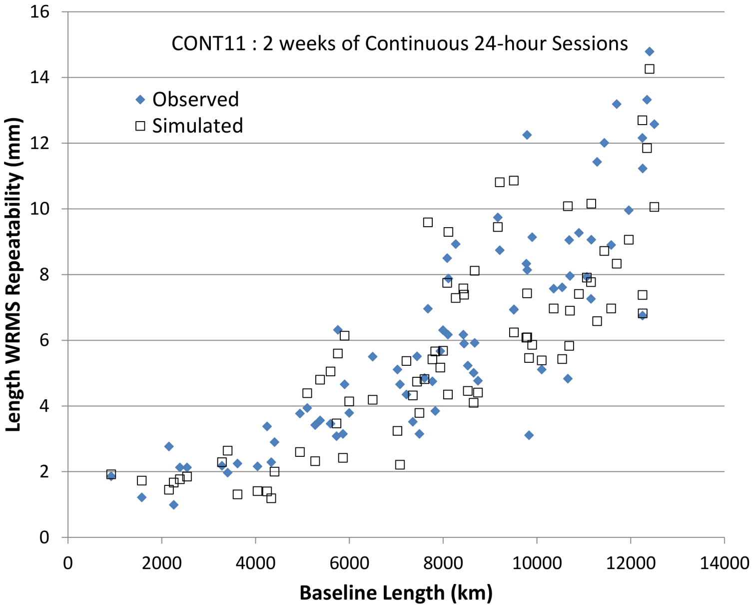

Figure 3: Wrms baseline length repeatabilities from the simulated (open squares) and observed (**Blue diamonds**) 15-day CONT11 campaign. The validity of simulation methodology is confirmed by the close agreement we show here between the simulated and observed results of this campaign.

of this facility for typical astronomical observing campaigns. Gregory Taylor has attended many of the ngVLA planning workshops and conferences.

Collaborator J. Long has over 40 years of experience in geodesy, including design of VGOS sites, performing local surveys for determination of tie vectors between techniques and processing GNSS data.

9 Deliverables and Outcomes

The main deliverable of the project will be a peer reviewed paper with results of the simulation for both regular astronomical and dedicated geodetic VLBI experiments. We also plan to write a NASA Technical Memorandum and provide other details of simulations that are beyond the scope of a publication in a refereed journal. We will make publicly available developed new tools or adaptations of existing tools.

The major outcome of the proposed research will be **a quantitative assessment** of the usability of ngVLA for space geodesy under both regular astronomy and dedicated geodesy programs. Such an assessment will facilitate decision making.

10 Management plan and milestones

The chart below shows the schedule for implementing the tasks. The schedule is arranged to give an approximately uniform deployment of effort for the team.

The Principal Investigator, Leonid Petrov, civil servant in Geodesy & Geophysics Laboratory at NASA GSFC will manage the project. He will coordinate the efforts of the team. Leonid

Table 1: Schedule chart

Activity name	PY1 Q1	PY1 Q2	PY1 Q3	PY1 Q4
Simulating ngVLA science program	●			
Generating simulation schedule files	●	●		
Running geodetic simulation		●	●	
Writing papers and reports				●

Petrov will run simulation schedules of dedicated geodetic observations at the ngVLA. He will process results of simulation runs, analyze the results of individual runs, and systematize them.

Greg Taylor (co-I, University of New Mexico (UNM)) will oversee the efforts at UNM, oversee the development of observing modes, and coordinate with NRAO and NASA GSFC.

Jayce Dowell (support, University of New Mexico) will assist with the installation of the NRAO ngVLA tools, its configuration, deployment, and their use for simulation of the data through realistic astronomical schedules.

A graduate student at UNM will assist with (1) evaluation of the standard astronomical observing modes expected for the ngVLA; (2) creation of realistic astronomical observing schedules; (3) generating simulated data sets from various configurations.

Daniel MacMillan (co-I, NVI Inc.) will convert simulation schedule files in the form suitable for geodetic analysis, run parameter estimation of simulated datasets using NASA geodetic VLBI software, and adapt Solve for analysis ngVLA simulations when needed.

Anthony Beasley (co-I, NRAO) will be the ngVLA liaison, providing the input of the planned ngVLA observing program, evaluate the share of individual program elements, and review the additional requirements for ngVLA sites to provide high quality space geodesy results.

James Long (collaborator, NASA GSFC) will consult the PI on issues related to GNSS antennas, on measurements of local ties between VLBI and GNSS antennas, and on site design that meets the goals of space geodesy based on his experience for design of VGOS sites.

All team members will contribute to writing the refereed paper and reports.

10.1 Data sharing plan

The major results of this project will be accessible in publications. We will make publicly available in a form of machine-readable tables as a supplementary material of publications the following information

- Source code of simulation tools that we use beyond those that are already publicly available;
- Uncertainties of site positions for each observing mode of ngVLA from a given simulation;
- Uncertainties of site positions for each observing mode averaged over 1 day, 7 days, 1 month, and 1 year;
- Uncertainties of site velocities, amplitude of seasonal harmonic variations and in the Earth orientation parameters.

11 References

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Taylor, S. R. and J. Simon (2018), "From Megaparsecs To Milliparsecs: Galaxy Evolution and Supermassive Black Holes with NANOGrav and the ngVLA." In *Science with a Next Generation Very Large Array* (Eric Murphy, ed.), vol. 517 of *Astronomical Society of the Pacific Conference Series*, 611.

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12 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 (over 140,000 hours).

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 three projects under various astronomy programs at the NRAO, ATNF, EVN, NAOJ, KASI.

Managed seven projects under NASA Earth Surface and Interior program as a principal investigator.

Education:

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

Selected publications: peer reviewed works

1. **Petrov, L.**, Kovalev, Y.Y., "Observational consequences of optical range milliarcsecond-scale structure in active galactic nuclei discovered by Gaia", Monthly Notices of the Royal Astronomical Society, 471, 3775–3787, 2017.

2. **L. Petrov**, (2016), "The International Mass Loading Service", International Association of Geodesy Symposia, Springer, vol 146, 79–83. doi: 10.1007/1345_2015_218
3. **L. Petrov**, T. Natusch, S. Weston, J. McCallum, S. Ellingsen, S. Gulyaev, First scientific VLBI observations using New Zealand 30 meter radio telescope WARK30M, Publications of the Astronomical Society of the Pacific, 2015, 127, 516–522
4. **L. Petrov**, (2012) The EVN Galactic Plane Survey — EGaPS, Mon. Not. Roy. Astron. Soc., 419(2), 1097–1105
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.
6. **L. Petrov**, D. Gordon, J. Gipson, D. MacMillan, C. Ma, E. Fomalont, R. C. Walker, C. Carabajal, (2009) "Precise geodesy with the Very Long Baseline Array", Journal of Geodesy, vol. 83(9), 859.
7. **L. Petrov**, (2007) "The empirical Earth rotation model from VLBI observations", Astronomy and Astrophysics, vol. 467, p. 359.
8. **L. Petrov**, 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. **L. Petrov**, 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. **L. Petrov**, 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 47 peer reviewed works with a total of 1402 citations. Hirsch index 20.

Greg Taylor (Co-I)

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Professional Preparation

B.S. in Physics/Computer Science 1986 from Duke University
M.S. in Astronomy 1988 from University of California, Los Angeles
Ph.D. in Astronomy 1991 from University of California, Los Angeles
Postdoc at Arcetri Observatory (1991-1992) in Radio Astronomy
Postdoc at Caltech (1992-1995) in the VLBI Group

Appointments

Distinguished Professor of Physics and Astronomy, Univ. of New Mexico (2018 - present)
Director for the Center for Astrophysical Research and Technology (2015 - present)
Director for the Long Wavelength Array (2005 - present)
Adjunct Scientist at the National Radio Astronomy Observatory (2005 - present)
Professor of Physics and Astronomy, University of New Mexico (2013 - 2018)
Associate Professor of Physics and Astronomy, University of New Mexico (2005 - 2013)
Visiting Scientist at KIPAC/Stanford (2004-2005)
Division Head for Scientific Services at NRAO (2001-2005)
Scientist at the National Radio Astronomy Observatory (2001-2005)
Associate Scientist at the National Radio Astronomy Observatory (1999-2001)
Adjunct Professor in the Physics Department of NMIMT (1999-2009)
Assistant Scientist at the National Radio Astronomy Observatory (1995-1998)

Scientific, Technical and Management Experience on Relevant Prior Research Efforts

- *PI for numerous funding proposals to support the Long Wavelength Array.*
- *Author of over 270 refereed scientific publications.*
- *Chair of NASA review panel, member of NSF, NASA, and DFG (Germany) review panels. Member of SNF review panel, Chair LANL CSES external advisory committee 2015-2019.*
- *Organization of the NRAO Synthesis Imaging Schools in Radio Astronomy (2020, 2018, 2016, ...). I have led or assisted with the schools since 1998.*
- *Served on Chandra, IGPP and CSES External Committees, NRAO Visiting Committee, MPIfR Scientific Advisory Board*

Daniel MacMillan (Co-I)

Present position: Principal Scientist, NVI Inc. at NASA GSFC, Greenbelt, MD

Education: M.S. 1978, Ph. D. Physics, University of Maryland,

Professional experience: Since 1990, Daniel MacMillan has worked on improving the analysis of space geodetic data. He demonstrated the importance of modeling the azimuthal dependence of tropospheric delay by estimation of troposphere gradients in geodetic analysis and in determining the terrestrial and celestial reference frames. He also investigated improvements in tropospheric delay modeling using raytracing of numerical weather model atmospheres. He was a principal investigator on the Jason altimeter science working team using used GPS and VLBI tropospheric delay estimates to calibrate altimeter microwave radiometer drifts. As a member of IVS Working Group 3, he used simulations to determine the specifications for the next generation VLBI2010 (VGOS) antennas. He was a primary contributor to the development of the 2nd Realization of the International Celestial Reference Frame by Very Long Baseline Interferometry.

Selected relevant peer reviewed publications:

MacMillan, D.S., 2017. "EOP and scale from continuous VLBI observing: CONT campaigns to future VGOS networks." *J. Geodesy*, 91 **(7):** 819-829 [10.1007/s00190-017-1003-4]

Fey, A.L., Gordon, D., Jacobs, C.S., et al., 2015. "The Second Realization of the International Celestial Reference Frame by Very Long Baseline Interferometry." *The Astronomical Journal*, 150 (2): 58 [10.1088/0004-6256/150/2/58]

Eriksson, D., MacMillan, D.S., and Gipson, J.M., 2014. "Tropospheric delay ray tracing applied in VLBI analysis." *Journal of Geophysical Research: Solid Earth*, 119 (12)**:** 9156-9170 [10.1002/2014jb011552]

Petrov, L., Gordon, D., Gipson, J.M. et al., 2009. "Precise geodesy with the Very Long Baseline Array." *Journal of Geodesy*, 83 (9): 859-876 [10.1007/s00190-009-0304-7]

MacMillan, D.S., Fang, P., and Beckley, B.D., 2004. "Monitoring the TOPEX and Jason-1 microwave radiometers with GPS and VLBI wet zenith path delays." *Marine Geodesy*, **27** (3-4): 703-716 [10.1080/01490410490904780]

MacMillan, D.S., and Ma, C., 1997. "Atmospheric gradients and the VLBI terrestrial and celestial reference frames." *Geophysical Research Letters*, 24 (4)**:** 453-456 [10.1029/97GL00143]

MacMillan, D.S., 1995. “Atmospheric gradients from very long baseline interferometry observations,” *Geophysical Research Letters*, 22 (9): 1041-1044.

MacMillan, D.S. and Ma, C., 1994. "Evaluation of very long baseline interferometry atmospheric modeling improvements." *Journal of Geophysical Research*, 99 (B1)**:** 637-651 [10.1029/93JB02162]

Anthony Beasley (Co-I)

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EDUCATION

1983 - 1986	University of Sydney, Australia, B.SC. with first-class honors (School of Physics).
1987 - 1991	University of Sydney, Ph.D. in Astrophysics, Prof. L.E. Cram supervisor, "The Evolution of Magnetic Activity in Post Main-Sequence Stars."

PROFESSIONAL EXPERIENCE

1991 - 1994	Postdoctoral Fellow – US National Radio Astronomy Observatory, Very Long Baseline Array.
1995 - 1997	Staff Scientist – US National Radio Astronomy Observatory.
1997 - 1998	Deputy Assistant Director – US National Radio Astronomy Observatory, Head of VLA/VLBA Operations & Computing and the Astronomical Image Processing System (AIPS) Software Project.
1998 - 2000	Assistant Director – US National Radio Astronomy Observatory; Adjunct Associate Professor, University of Virginia.
2000 - 2004	Project Manager – Combined Array for Research in Millimeter-wave Astronomy (CARMA).
2004 - 2008	International Project Manager – Atacama Large Millimeter Array Project (ALMA), Assistant Director – US National Radio Astronomy Observatory.
2008 - 2012	Chief Operating Officer – NEON, Inc., Project Manager – National Ecological Observatory Network (NEON).
2012 -	**Director, US National Radio Astronomy Observatory;** Research Professor, University of Virginia.
2016 -	**Vice President for Radio Astronomy Operations,** Associated Universities Inc.

RECENT PUBLICATIONS

Roshi, A. et al, (2018)
'Performance of a Highly Sensitive, 19-element, Dual-polarization, Cryogenic L-band Phased-array Feed on the Green Bank Telescope',
AJ, 155, 202.

Bastian, T. S.; Villadsen, J.; Maps, A.; Hallinan, G.; Beasley, A. J. (2018)
'Radio Emission from the Exoplanetary System ε Eridani',
ApJ, 857, 133.

Liszt, H; Gerin, M; Beasley, A.; Pety, J. (2018)
'Chemical Complexity in Local Diffuse and Translucent Clouds: Ubiquitous Linear C3H and CH3CN, a Detection of HC3N and an Upper Limit on the Abundance of CH2CN',
ApJ, 856, 151.

13 Summary of Work Effort

TABLE OF WORK EFFORT

Name	Role	Commitment (months per year)													
		Institution Support	*Institution Research Time*	***Year 1***			***Year 2***			***Year 3***			***Sum***		
				This Project		*Other Projects*	*This Project*		*Other Projects*	*This Project*		*Other Projects*	*This Project*		*Other Projects*
				NASA Support	*Total*		*NASA Support*	*Total*		*NASA Support*	*Total*		*NASA Support*	*Total*	
Leonid Petrov	PI	12	4.92	3	3	1.92	0	0	0	0	0	0	3	3	1.92
Greg Tailor	Co-I	12	3	0.5	0.5	2.5	0	0	0	0	0	0	0.5	0.5	2.5
James Long	Collaborator	12	0.35	0	0.35	0	0	0	0	0	0	0	0	0.35	0.35
Daniel MacMillan	Co-I	12	1.2	1.2	1.2	0	0	0	0	0	0	0	0	1.2	1.2
Anthony Beasley	Co-I	12	2.6	0	0.6	2	0	0	0	0	0	0	0	0.6	2
Jayce Dowell	Support	12	1	1	1	0	0	0	0	0	0	0	1	1	0
Graduate Student	Support	7.5	7.5	7.5	7.5	0	0	0	0	0	0	0	7.5	7.5	0
Sum of work effort:		**79.5**	**20.57**	**13.2**	**14.15**	**6.42**	**0**	**0**	**0**	**0**	**0**	**0**	**13.2**	**14.15**	**6.42**
Comments:															

Institution Support – The total number of months this individual is supported by their institution (for all tasks, not just this project).
Institution Research Time – The number of months institution support is allocated toward all research (less than or equal to *Institution Support*).
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 Projects - The number of months that are committed to other currently funded proposals.

14 Current and pending support

Current and pending support of PI, Leonid Petrov

Current and Pending Support

The following information should be provided for each investigator and other senior personnel. Failure to provide this information may delay consideration of this proposal.

Investigator: Leonid Petrov

Other agencies (including NASA) to which this proposal has been/will be submitted.

Support: ☒ Current ☐ Pending
Project/Proposal Title:
Excitation and dissipation of the free core nutation
Source of Support: NASA, Earth Surface and Interior program
Total Award Period Covered: March 2019 --- February 2021
Person-Months Per Year Committed to the Project: PY 2019: 0.72 months ; PY 2020 0.96 months

Support: ☒ Current ☐ Pending
Project/Proposal Title: **Optimal strategy for scheduling geodetic VLBI observations**

Source of Support: NASA, Earth Surface and Interior program
Total Award Period Covered: March 2019 --- February 2021
Person-Months Per Year Committed to the Project: PY 2019: 0.96 months ; PY 2020 0.96 months

Current and pending support of co-I Daniel MacMillan

None

15 Budget Justification (narrative) including facilities and equipment

15.1 NASA GSFC budget justification

Budget Justification: Narrative and Details

Budget Justification: Narrative

NASA Center Funding
Procurement and Travel Only

Per ROSES solicitation instructions, all labor dollars are redacted from budgets in Proposal Documents.

http://science.nasa.gov/researchers/sara/how-to-guide/nspires-CSlabor/
NASA Center Funding By Program Year

	PY 1 Cost	Total Cost
NASA/GSFC	23,897	23,897
Total:	23,897	23,897

GSFC Civil Servant Roles and Cost Basis:

LEONID PETROV, PI, will manage the project. He will coordinate the efforts of the team. Leonid Petrov will generate simulation schedules of dedicated geodetic observations at the ngVLA. He will process results of simulation runs, analyze the results of individual runs, and systematize them.

JAMES LONG, collaborator, will consult the PI on issues related to GNSS antennas, on measurements of local ties between VLBI and GNSS antennas, and on site design that meets the goals of space geodesy based on his experience for design of VGOS sites. No funds is requested for him. He is fully covered by other projects.

The civil servants included in this budget are proposed at the following skill levels:

GSFC Civil Servant Name	Budgeted Skill Title
LEONID PETROV	Scientist-Tier 2

GSFC proposal budgets are based on four Scientist skill levels with Scientist-Tier 1 reflecting the experience level equivalent to GS-13-Step 6 and Scientist Tier-4 the experience level of GS-15-Step 10.

The cost of the labor (salary and fringe) is based on GSFC's established salary rates for the skill levels shown in the above table. GSFC fringe dollars are based on a percent applied to salary dollars using GSFC established rates per year.

GSFC On-Site/Near-Site Contractor Roles and Cost Basis:

The following on-site contractors are needed. The cost estimates are based on currently established loaded rates for the contracts that already exist at GSFC.

DANIEL MACMILLAN, will create simulated database files, run them through VLBI data analysis with Solve, and adapt Solve analysis for ngVLA simulations. He will be working 1.2 months (0.1 FTE). These costs are based on fully loaded cost estimates provided under the terms of established contract in place at NASA GSFC.

Other Direct Costs

GSFC Off-Site Subcontracts / Subaward:

The basis of estimate and detailed budgets for off-site institutions are provided in the Budget Details section below.

Non-US Government Recipient: University of New Mexico

Description of the Work: determination of observing modes of ngvla; construction of realistic schedules; investigation into configurations.

Reason for subcontracting: professor Taylor and Dr. Dowell have considerable experience with interferometry and simulations and with using the VLA. Prof. Taylor has attended many of the ngVLA planning workshops and conferences. Greg Taylor led similar efforts for simulation of the Long Wavelength Array.

Materials and Supplies (ie, < $5K per unit; otherwise, see Equipment)

This table reflects GSFC's budget for materials and supplies which to cover consumables, replacement of failed hardware, such as harddrives, power supplies etc. We make an allowance for purchase of replacement disks for our RAID arrays. We have noted failure rates on our arrays of up to two per annum. Cost estimates are based on procurement initiated by GSFC and recent quotes from local vendors.

Item	PY 1	Total
Material/Supplies/Consumables	2,800	2,800
Total:	2,800	2,800

Travel

The budget includes travel as shown below based on the following cost assumptions:

- Estimated airfare and auto rental costs were obtained from either NASA's customary source or from other airfare estimating search engines (ie, Travelocity, etc.); also, per diem costs were obtained from http://www.gsa.gov/
- Inflation of 3% per year is applied for annual occurrences.

Cost Details
Trip 1

	Lodging	MI&E or Per Diem	Airfare	Ground Trans	Auto Rental	Conf Fee	Fuel	Parking	Tolls	Other	Total	
Rate	94	55	500	50	70	0	0	0	0	0		
Nbr of People	1	1	1	1								
Nbr of Days	2	2			2							
Total	188	110	500	50	140	0	0	0	0	0	988	PY 1
											988	Total

Purpose of Trip: To meet with co-investigators
Depart From: Washington, DC
Arrive To: Albuquerque, NM

Trip 2

	Lodging	MI&E or Per Diem	Airfare	Ground Trans	Auto Rental	Conf Fee	Fuel	Parking	Tolls	Other	Total	
Rate	247	94	650	50	0	685	0	0	0	50		
Nbr of People	1	1	1	1								
Nbr of Days	6	6			6							
Total	1,482	564	650	50	0	685	0	0	0	50	3,481	PY 1
											3,481	Total

Purpose of Trip: Presentation at the AGU
Depart From: Washington Dc
Arrive To: San Francisco

Trip 3

	Lodging	**MI&E or Per Diem**	**Airfare**	**Ground Trans**	**Auto Rental**	**Conf Fee**	**Fuel**	**Parking**	**Tolls**	**Other**	**Total**	
Rate	132	71	0	150	0	0	0	0	0	0		
Nbr of People	1	1	1	1								
Nbr of Days	2	2			2							
Total	264	142	0	150	0	0	0	0	0	0	556	PY 1
											556	Total

Purpose of Trip: To meet with a collaborator
Depart From: Washington DC
Arrive To: Charlottesville, VA

PI Leonid Petrov and co-I Daniel MacMillan will be attending an annual two-day NASA solid-Earth team meeting to be held in the Washington, D.C. area. No funds are requested for this meeting, since the meeting will be held in less than 25 miles of their duty stations.

Summary of Travel Budget Requirements

Domestic/Foreign; Purpose	**PY 1**	**Total**
Domestic; To meet with co-investigators	988	988
Domestic; Presentation at the AGU	3,481	3,481
Domestic; To meet with a collaborator	556	556
Total:	5,025	5,025

Other

Publications – We plan to submit a paper with results of work to the Journal of Geodesy to disseminate results to the scientific community. The Journal of Geodesy charges $3,000 for the open access publication. The source of the cost estimate: https://support.springer.com/support/solutions/articles/6000137677-are-there-fees-for-publishing-in-an-open-choice-journal-

Item	**PY 1**	**Total**
Open Access page charges in Journal of Geodesy	3,000	3,000
Total:	3,000	3,000

Other Direct Costs, SED - These costs, as discussed in NASA financial regulations, are for services to support the research effort that go beyond the standard costs considered under Center Management and Operations (Center Overhead), and are not incurred elsewhere within GSFC. Within the Sciences and Exploration Directorate these costs cover system administration for the complex information technology services required to support the proposed research activities, administrative and resource analysis support, and supplies to support the research effort.

Facilities and Administrative (F&A) Costs, GSFC

NASA CM&O (Center Management and Operations) is managed from Headquarters and is therefore excluded from this proposal.

Cost Sharing

n/a

<u>Description of Required Facilities and Equipment</u>

Existing Facilities and Equipment for Which Funding is Not Requested

The existing facilities and equipment needed to carry out the proposed research are available at the proposer's institution, NASA/Goddard Space Flight Center. These include: computer Xeon Gold 6148, 40-cores and 84 Tb raid at the Geodesy and Geophysics Lab (Code 61A).

The facilities and equipment of the proposed subaward recipient, University of New Mexico, include a general purpose desktop computer. Based on their prior experience for simulation of the Long Wave Array, this equipment is sufficient for the proposed work.

Budget Justification: Details

Below is the total budget for the items described in the Budget Narrative. Also below are any supporting budgets.

Per ROSES solicitation instructions, all labor dollars are redacted from budgets in Proposal Documents.

15.2 NASA GSFC budet details

COMPETITION SENSITIVE - FOR PROPOSAL SUBMISSION & PANEL REVIEW ONLY
Budget by Program Year

Solicitation: NNH19ZDA001N-ESI, Earth Surface and Interior , A.27
GSFC Proposer Name: Leonid Petrov

Proposal Title: The feasibility study of the use of ngVLA for space geodesy

Total Excluding Labor Dollars and Indirect Costs: $23,897
Proposal Start Date: 01/01/2020
Proposal End Date: 12/31/2020

Description	PY 1 FTE	PY 1 Cost	Total FTE	Total Cost
A. Senior / Key Personnel (CS Only)				
Scientist-Tier 2	0.25		0.25	
Subtotal	0.25		0.25	
B.1.a-c Other Personnel (Civil Servants Not Named as Co-I in Proposal)				
Subtotal				
Subtotal GSFC Civil Servants	0.25		0.25	
Other Personnel (Non-Civil Servants)				
B.2.a On-Site Contractors	0.10		0.10	
B.2.b On-Site Cooperative Agreements				
B.2.c On-Site, Test & Fab Pool				
C. Off-Site Subawards / Subcontracts :				
[GSFC Funded] University of New Mexico	0.75	5,931	0.75	5,931
Subtotal Other Personnel	0.85	5,931	0.85	5,931
Subtotal Labor-Redacted Cost	1.10	5,931	1.10	5,931
Travel Total		5,025		5,025
Other Costs				
Equipment				
Materials and Supplies		2,800		2,800
Publications		3,000		3,000
Consultant Services				
ADP/Computer Services				
Rental/User Fees				
Alterations and Renovations				
Mission Design Center				
Test Services Non GSFC				
Fab Services Non GSFC				
Other Costs				
Other Direct Costs, SED		7,141		7,141
Subtotal Other Cost		12,941		12,941
Indirect CM&O				
Total Labor-Redacted Proposal Costs	1.10	23,897	1.10	23,897

Summary

	PY 1 FTE	PY 1 Cost	Total FTE	Total Cost
Civil Servant, GSFC	0.25		0.25	
Contractor, On-Site	0.10		0.10	
Subawards / Off-Site	0.75	5,931	0.75	5,931
Other Costs, Direct		17,966		17,966
Other Costs, CM&O				
Total Labor-Redacted Proposal Costs	1.10	23,897	1.10	23,897

Funds Distribution

	PY 1 FTE	PY 1 Cost	Total FTE	Total Cost
Other NASA Centers and JPL				
GSFC	1.10	23,897	1.10	23,897
Total Labor-Redacted Proposal Costs	1.10	23,897	1.10	23,897

(Labor Dollars Redacted)

CS Labor Distribution by FY

	FY 2020 FTE		FY 2021 FTE	
Civil Servant, GSFC	0.19		0.06	

15.3 University of New Mexico budget justification

A part of the cost is subawarded to the University of New Mexico, because the Co-I, professor Greg Taylor and his team are uniquely qualified for the proposed work. They have important prior experience of a similar work.

BUDGET JUSTIFICATION

Organization: The University of New Mexico
PI: Gregory Taylor
Department: Physics and Astronomy
Project Title: Feasibility Study of the Use of the ngVLA for Space Geodesy

PERSONNEL:

- 0.5 months of faculty summer salary support is requested for the PI (1.0 FTE)
- 1 months of faculty salary support is requested for Research Assistant Professor Jayce Dowell (1.0 FTE)
- Salary is requested for one graduate student to work 4.5 academic months (0.5 FTE), and 3 summer months

TUITION: $5,931
Tuition is requested for the graduate student to take 12 regular graduate credits in the fall semester, and 3 credits in the summer semester, at $395/credit in Year 1, and totaling $5,931 for the period of performance.

Per ROSES solicitation instructions, all labor dollars are redacted from budgets in Proposal Documents.

15.4 University of New Mexico budget details

Cost Proposal to GSFC		**19-030**		
Organization: University of New Mexico				
Title: Feasibility Study of the Use of the ngVLA for Space Geodesy				
Principal Investigator: Greg Taylor				
ROSES2019		**FY20**	Proposed	1-Jan-20
Period of Performance: 1/1/20 - 12/31/20			Period	31-Dec-20
Cayuse SP No. 19-1079				
		Base period		**Period 1**
A. Senior Personnel		Person Mos	$/mo	(12 mos)
( ) Principal Investigator		0.00		
(1) Principal Investigator (Summer salary for 9 mo faculty		0.50		
(1) Total Senior Personnel		**0.50**		
B. Other Personnel		Calendar Mos.	$/mo	
(1) Faculty 2		1.00		
( ) Graduate Research Ass'ts.	50% FTE Academic	4.50		
( ) Graduate Research Ass'ts.	100% FTE Summer	3.00		
Tuition - No F&A		# of student credits or semesters		
Grad Student Tuition (Individual Credits - Fall Semester)		12	$395	4,745
Grad Student Tuition (Individual Credits - Spring Semeste		0	$395	0
Grad Student Tuition (Individual Summer Credits)		3	$395	1,186
Grad Student Tuition (Semesters - Dissertation Credits)		0	$847	0
Total Graduate Student Tuition				**5,931**
Total Salaries and Wages (A+B)				
C. Fringe Benefits				
Faculty (Summer salary only for 9 mo faculty)				
Faculty				
Staff				
Postdocs				
Students				
Student Health Insurance - Fall				
Student Health Insurance - Spring/Summer				
Student Health Insurance - Summer Only				
Subtotal Fringe Benefits				
Total Salaries, Wages, and Fringe Benefits (A+B+C)				
D. Capital Equipment (>$5,000/unit)				
Total Equipment				
E. Travel	1. Domestic In-State			
	2. Domestic Out-of-State			
	3. Foreign			
F. Participant Support Costs				
Subtotal Participant Support Costs				
G. Other Direct Costs				
Laboratory supplies				
Total Other Direct Costs				
Modified Total Direct Costs				
H. Total Direct Costs				
I. Indirect Costs				
Rate:				
Base:				
Total Indirect Costs				
J. Total Direct and Indirect Costs (H+I) ***[Total Program Cost]***				
L. Total Program Cost to the Agency				

15.5 National Radio Astronomical Observatory funding

No funds are requested for National Radio Astronomical Observatory. Work of co-I Anthony Beasley on the project is funded by his institution.