# VLBI geodesy with sub-millimeter accuracies

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# 1 Executive Summary

We propose to establish a fully automated VLBI measurement system at sites with twin radiotelescopes that will generate dense time series of the baseline vector using phase delays. The baseline vector will be determined with accuracies 1 mm over one hour and 0.2 mm over one day. Three characteristics of these proposed observations: (1) dense observations, (2) phase delay observations (as opposed to group delays) and (3) short baselines (< 2 km) will yield a very precise data set that is almost free of atmospheric error sources. We formulate the hypothesis that such measurements will allow us to assess stability of VLBI reference points at a sub-millimeter level of accuracy and assess instrumental errors of group delays that are the backbone of VLBI's contribution to the ITRF. This will have important implications for all VLBI data analyses. Such a system is necessary for evaluation of realistic errors of the ITRF that contributes to the error budget of the estimates of rates of the sea-level change.

# 2 Introduction

Reaching accuracy 1 mm and maintaining it on a scale of a decade is a tough challenge. A golden standard of accuracy assessment of a given measurement is to compare it with something that is even more accurate. In the absence of direct measurements, indirect accuracy assessment is used. A general approach to perform such an assessment is to evaluate thoroughly the error budget. In a case of space geodesy, the major factors that affect accuracy are uncertainties in modeling the path delay in the atmosphere and uncertainties in satellite orbits (source structure in a case of VLBI). Indirect approaches to assess the contribution of these factors are varying atmospheric models, running solutions with different elevation cutoffs, varying models of satellite forcing, changing program sources for VLBI, etc or comparing results of independent techniques. All indirect methods for accuracy assessment have their limitations. They are based on assumptions which validity is not firmly established. Separation of contributions of different factors that affect accuracy is always problematic. There is a tendency to assign all errors to the factor that is declared the major, f.e. atmosphere because of the difficulties in an assessment of the contribution of other factors that *seem* minor.

A realistic estimate of an uncertainty of a given measurement is critically important when a scientific problem is formulated in a form of a statistical hypothesis. An incorrect uncertainty estimate results in an incorrect statistical test evaluation and therefore, may lead to an incorrect statistical inference. Rigorous, hypothesis-driven scientific research becomes problematic. That highlights the importance of evaluation of errors.

Is it possible to implement a golden standard of accuracy in space geodesy? We argue there is a special case when this is possible with certain limitations: measurements of baselines shorter than 2000 m with VLBI. Processing the correlator output provides us a phase delay that is the ratio of fringe phase to the reference frequency, fringe amplitude, and group delay that is a derivative of fringe phase over recorded bandwidth. Phase delay is one and half order of magnitude more precise than group delay, however is determined with $2\pi$ ambiguity with spacings $\sim$ 3 cm. The mismodeled contribution of atmospheric path delay prevents robust resolution of ambiguities with such tiny spacings. Group delays have much wider ambiguity spacings that are easily resolved and for this reason they are almost exclusively used in geodetic VLBI. At short baselines resolving phase delay ambiguities is always possible (Rogers et al., 1978; Fomalont, 1995; Martí-Vidal et al., 2010), the atmospheric path delay is virtually canceled, and the contribution of source structure becomes negligible. We formulate the hypothesis: the use of phase delays that are over one order of magnitude more accurate than group delays will allow us 1) to assess stability of the VLBI reference point and 2) to evaluate systematic instrumental error in group delays that are used for processing VLBI data at long baselines. In the rest of the proposal we outline our approach for development of a technique that unleashes the full power of this method.

## 3 Problem statement

We propose an innovative technique that allows to implement a golden standard of accuracy assessment for investigation of the stability of the VLBI reference point. We will compute extended time series of the 3D baseline vector of short baselines 30–500 m long with a precision better 0.2 mm over a 24 hour period.

The following factors affect accuracy of VLBI results based on analysis of group delays:

1. Residual errors of path delay in the **neutral atmosphere**. The current approach is to compute slant path delay using the output of NASA numerical weather models such as GEOS-FPIT or MERRA2 (Gelaro et al., 2017) and estimate the coefficients of the expansion of the residual path delay and the inclination of the atmosphere symmetry axis over the B-spline basis. This approach implicitly assumes the atmospheric path delay at a given station is axially symmetric and at a given moment of time it is described with three parameters: zenith path delay, east and north gradients that are proportional to the inclination axis of the atmosphere axial symmetry. Deviation of the path delay from the symmetry, errors in mapping function, and short-term variations in path delay lead to systematic errors.

2. The presence of **source structure** causes radio waves that coming from different parts of a source to interfere. That affects phase and amplitude of visibilities and therefore, affects group delay. At present, this effect is not modeled and its contribution causes systematic errors (Xu et al., 2017; Anderson and Xu, 2018; Xu et al., 2021a,c).

3. **Instability of the reference point**. The VLBI reference point is defined as a point of projection of the moving antenna elevation axis to the fixed azimuthal axis. Thermal variations cause vertical motion of the reference point (Lösler et al., 2013, 2016). The current data reduction model assumes that the azimuthal axis is aligned with the local plumb line, the elevation axis is strictly orthogonal to the azimuthal axes, its offset is fixed, and the axes are absolutely rigid. These assumptions are correct at the centimeter level of accuracy — otherwise, the antenna would not be able to freely move, but validity of these assumptions at a 1 mm level has not been checked. Violation of these assumptions results in systematic errors that are difficult to trace using group delays.

Figure 1: Two VLBI stations at Kokee Park, Hawaii: 20 m KOKEE and KOKEE12M that are 31 meters apart. The height difference of movable elevation axes is 8 meters.

4. **Gravity deformation** changes path delay. This effect is modeled only for several antennas that have been measured (Bergstrand et al., 2019; Nothnagel et al., 2019; Lösler et al., 2019). Unaccounted, gravity deformations cause biases in vertical site positions (Sarti et al., 2011).
5. **Instrumental errors**. Variable delays in VLBI hardware that are not traced by phase calibration result in systematic errors (see f.e., Xu et al., 2021b).
6. **Correlator errors**. The coarseness of the phase tracking model during correlation causes additional errors that are poorly understood.

Observations at short baselines reduce atmospheric errors and the contribution of source structure to a negligible level. Therefore, these observations allow us to investigate all other factors that affect accuracy. The most important factor is the stability of the VLBI reference point. A VLBI antenna has size of several tens of meters. It moves during observations and deforms. This causes a jitter in the position estimate of the reference point. **The main objective of our project is to develop a new and innovative method that will enable us to provide long time series of positions of the antenna reference point in the absence of tropospheric errors and errors caused by source structure with accuracies at a sub-millimeter level over one day. Such time series will allow us to assess the accuracy of modeling mechanical and instrumental errors and to measure stability of the VLBI reference point at scales from hour to decades.** Such measurements will establishing firm ties of new stations with the old stations and with the ITRF and will result in improvement of future releases of the ITRF (Böckmann et al., 2010; Seitz et al., 2012; Altamimi et al., 2016; Soja et al., 2016; Abbondanza et al., 2017; Glaser et al., 2019).

**We formulate the hypothesis:** dense time series of VLBI observations with weighted root mean square (wrms) of phase delay postfit residuals at a sub-millimeter level will allow us to investigate in full detail remaining systematic errors related to the stability of VLBI reference points and the contribution of instrumental errors to estimates of station positions. Knowledge of these systematic errors paves a path to further model improvements. This study is necessary, though not sufficient, to reach the objective set by the National Academy of Science for the terrestrial reference range accuracy: 1 mm for reference site positions and 0.1 mm/yr for accuracy of their velocities.

Since almost all the sources at short baselines can be considered as point-like, processing of properly calibrated data at short baselines will allow us to determine total flux densities of observed sources without will be required. Continuous observations of given source will provide us a light curves. This has been done previously at $\sim 100$ km long baselines (Koyama et al., 2001). Changes the in total flux densities are associated with the activity near the the core of the active galactic nuclei (AGN). Monitoring of the AGN observed in geodetic programs is important for adjusting scheduling parameters. Sudden changes in flux density indicates changes in source structure changes and are used as an alert for dedicated observations that will derive images. Sources are images are required for both scheduling and data analysis. Therefore, such a monitoring program would provide data that are required for improving quality of observing schedules and data analysis. However, dense light curves have a significant scientific value per se. They trace the processes in the close vicinity of AGN central engines (Lister et al., 2019), interstellar medium (Koay et al., 2019), or micro gravitational lensing (Vedantham et al., 2017). This work will be complimentary to the Ovens Valley monitoring program (Richards et al., 2011) conducted with a 40 m radio telescope at 15 GHz. Multifrequency light curves will help to probe opacity of the plasma surrounding the black holes.

## 4 Previous work

The power of phase delay measurements was discovered a long time ago. Rogers et al. (1978) reported results of the first phase delay VLBI observations at short baseline HAYSTACK/WESTFORD. Biases in baseline length estimates from these observations were evaluated by Carter et al. (1980). It was found that these measurements were able to reveal the contribution of antenna gravity deformation. Herring (1992) reanalyzed VLBI data at that baseline for a 15 years and examined the scatter in baseline lengths.

Later, Hase and Petrov (1999) ran six experiments at a 59 m long baseline WETTZELL/TIGOWTZL as a commissioning test of the transportable TIGO antenna. Millimeter level repeatability was found from processing phase delays. In March 2016, a 22 hour experiment at a 31 m long KOKEE12/KOKEE baseline was performed as well as several shorter experiments (Niell et al., 2021). Independently, Varenius et al. (2021) ran a number of diurnal experiments at three stations ONSALA60, ONSA13NE, ONSA13SW with baseline lengths in a range of 75 to 470 meters in 2019–2020. Halsig et al. (2019) processed six experiments at short baseline at Wettzell, but used only group delays in their analysis.

Main findings of these studies:

- the wrms of postfit phase delay residuals are 3–8 times lower than the wrms postfit

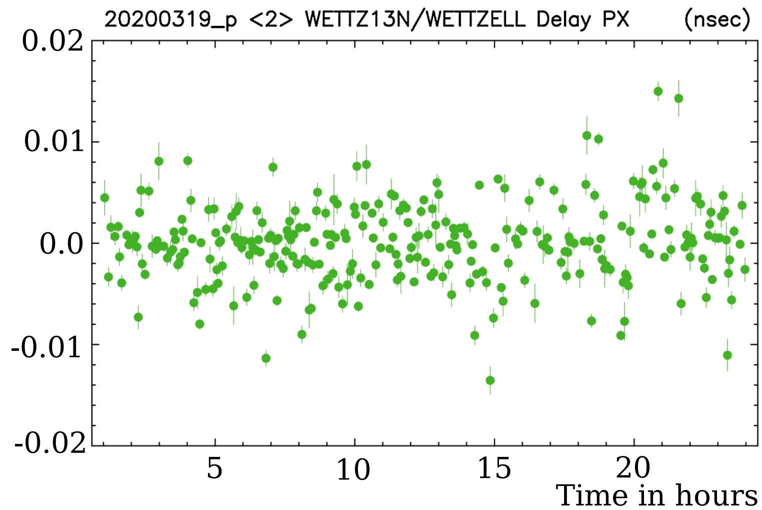


Figure 2: Phase delay postfit residuals at 249 m long baseline between two VLBI stations at Wettzell.

of group delay residuals;

- the wrms of phase delay postfit residuals is significantly higher, up to a factor of 10 than the intrinsic uncertainties of determination of fringe phases. Statistics of phase misclosures defined as $\varphi_{12} - \varphi_{13} + \varphi_{23}$, where indices 1,2,3 run over stations show that uncertainties in fringe phases are underestimated by a factor of 1.2–1.5, but not a factor of 10. This means there is a station-based signal of unknown origin. (See Figure 2).
- Formal uncertainties of baseline vector determination are in a range of 0.03–0.2 mm, but baseline length repeatabilities are one order of magnitude higher.
- Differences between group and phase delays show systematic patterns and biases (See Figure 3). Baseline lengths from phase and group delays are different at a millimeter level of accuracy.

All these findings highlight the richness of VLBI data at short baselines and their potential for improving the quality of geodetic data products.

## 5 Proposed methodologies

We propose to establish quasi-continuous VLBI observations at a short baseline KOKEE12/KOKEE between the legacy 20 m VLBI antenna that operates since 1994 and the 12 m VLBI Geodetic Observing System (VGOS) antenna of a new generation that had first VLBI observations in 2016 and started operating regularly in 2019. We propose to set up a high-end server computer that will be used for correlation of the data acquired at that baseline using the open source DiFX software (Deller et al., 2007, 2011).

We expect we will be able to run these observations for 22 hours a day, starting with one day a week and then gradually intensify cadence. Scheduling, observing, and data analysis will be totally automated. Dense series of phase observations at this baseline will establish

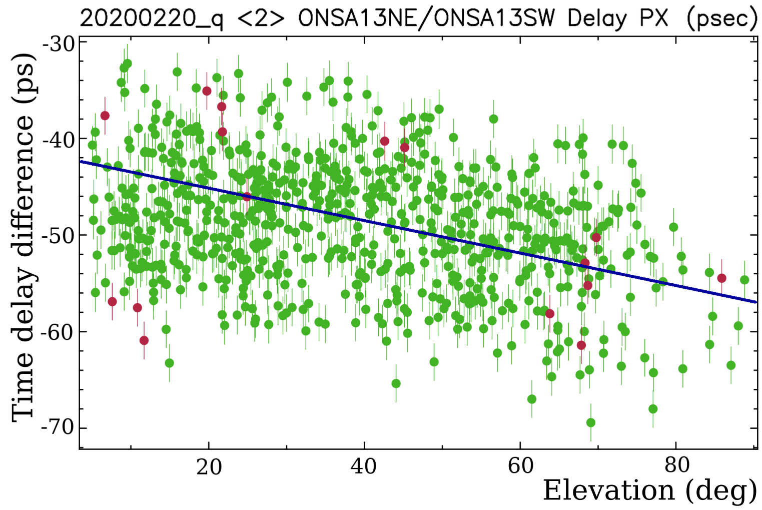


Figure 3: Elevation dependence of the differences between group delay and phase delay at a 75 m long baseline between two VGOS VLBI antennas in Onsala.

the reference that can be considered as a measure of performance of geodetic VLBI using group delay over long baselines.

### 5.1 Proposed observations

Since KOKEE is participating in one hour long VLBI experiments under the IVS Intensive program every day, the proposed observations will be 22 hour long and start half an hour after an the IVS Intensive experiment and will end half an hour before the next experiment. If either KOKEE or KOKEE12M antenna participates in another IVS experiment or is under maintenance, the experiment will be skipped. The entire pipeline from experiment scheduling to submission of results of data analysis will be automated. The pipeline includes correlation, visibility analysis, and geodetic data analysis.

The older legacy KOKEE antenna records right circular polarization R, while the VGOS antenna KOKEE12M records linear polarizations H and V. Due to a number of hardware restrictions, KOKEE is able to record 16 intermediate frequencies of 16 MHz in R polarization each while KOKEE12M will record 16 intermediate frequencies 32 MHz each in linear polarizations in two bands, c and d. Only 8 of them will be fully matching, and one intermediate frequency will be partially matching. In total, matching 256 MHz bandwidth at 2 bit sampling within 8252.4–8780.4 MHz will be processed.

### 5.2 Automated scheduling

A VLBI schedule consists of a table with entries called scans that define for each station

- start time slewing to a program source;
- start time for the pre-observation procedure;
- start time for recording baseband data that are digitized voltage from the receiver;
- start time for the post-observational procedure.

Duration of the pre-observation and post-observation procedures is fixed (typically 2–5 seconds), duration of observation depends on source flux density and varies from 15 seconds to 2 minutes for program sources and 2 to to 5 minute for calibrator sources. Slewing time in a range of 10–100 seconds depends on an arc distance between consecutive sources. During a given 22 hour observing session, 700–1000 scans will be observed. The pool of radio sources used for geodesy observations has 486 objects and it is changed several times a year. Data are recorded in a local raid and are sent via network to a dedicated server that can be either on site or on campus.

The schedule will be optimized to provide the best estimates of the vertical baseline projection. We will develop an automated scheduling algorithm based on existing scheduling software. The parameter estimation model consists of estimation of the Up, East, and North components of the baseline vector between stations and parameters of the B-spline of the 1st degree for the clock of one of the stations, and optionally, parameters of the B-spline of the 1st degree for the atmosphere path delay at one of the stations. The span of the B-spline will vary from 20 to 60 minutes for clock and 20 minutes to 22 hours for the residual atmospheric parameter. The scheduling will be designed in such a way that baseline vector could be determined for 1 hour of observations, i.e. site positions and parameters of the clock function decorrelate within 1 hour. The scheduling algorithm will minimize the covariance of the estimate of the Up component of the baseline vector within a one hour segment. Observations for 2–5 minutes of a strong unpolarized source are added every hour for bandpass calibration in both polarizations.

In general, the scheduling algorithm checks all the sources from the input pool consecutively and computes the score. The source with the highest score is selected for the next scan, and the process is repeated. The score is the weighted sum of contributing factors. One of the contributing factors is the reduction of the variance for the Up baseline vector coordinate. To compute the variance, the scheduling software will be running Kalman filter to perform simulation over observations of the last two hours. The scheduling software will strongly down-score observations of the same source if it was observed within the specified interval of time in the past (default setting: 8 hours). This will force the scheduling to pick up different sources and make the source coverage over azimuth and elevation uniform.

### 5.3 Automated operational data analysis

Baseband data data that are voltage from KOKEE and KOKEE12M antennas will be written into a Mark-6 custom raid. We will develop an automated procedure for correlation of baseband data with an open-source community supported software correlator DiFX. The procedure will start correlation upon arrival data of a given scan. Coarse visibility analysis of a given scan is performed immediately upon correlation using the NASA VLBI analysis software package $\mathcal{PIMA}$ (Petrov et al., 2011). The purpose of the coarse visibility analysis is to check whether a source was detected and evaluate the coarse clock offset. If no source was detected in three scans in a row or the coarse clock offset was found beyond the range, a corrective procedure is invoked (see subsection 5.4). After baseband data of a given scan are correlated and checked, they are cleaned from the raid.

Visibility analysis starts after the last scan of a given experiment is correlated. Calibration scans of strong unpolarized sources are identified, fringe and amplitude is evaluated, and the polarization bandpass is computed. Using these calibration bandpass, the cross-polarizations visibility data between circular and linear polarizations RH, and RV will be transformed to the circular cross-polarization product RR, and the fine fringe fitting procedure for computation of phase and group delays will be performed using software package $\mathcal{PIMA}$. Total group and phase delays will be computed and converted to geodetic database files.

Observations at short baselines are affected by local radio interference (RFI) in a much greater extent since local RFI are decorrelated at long baselines due to Earth rotation. We will develop an advanced RFI filtering algorithm based on analysis of autcorrelations that the correlator produces. We will adapt an open-source RFI filtering software AOFlagger (Offringa, 2010) for our needs.

Geodetic VLBI database files will be processed with the NASA VLBI data analysis software package pSolve/VTD. We will develop an automated pipeline that will execute the following procedures. First, a coarse parameter estimation model will be used that contains estimation clock function in a form of quadratic polynomials used keeping all other parameters fixed. Group delays will be used for parameter estimation using an L1 norm estimator (see, f.e., Farebrother, 2013). Outliers caused by local RFI will be eliminated. Then the Kalman filter procedure will run with the goal of finding clock breaks. Clock breaks, if found, will be used in the final clock model. The final clock model consists of a sum of the quadratic polynomial and a B-spline of the 1st degree. In the presence of clock breaks, the knots of the B-spline coincide with clock break epochs and have multiplicity 1. The span of B-spline in the operational solution will be fixed to 30 minutes. The procedure of the final least square solution using group delays for adjusting the baseline vector and parameters of a refined clock model will run, outliers will be eliminated, and an additive variance will be added to the a priori uncertainties in quadrature to form the $\chi^2$ per degree of freedom close to unity.

At the next step, visibility analysis of the observations marked as outliers will be reprocessed with a narrow fringe fitting window, and the data analysis procedure will be repeated.

After the final group delay solution is produced, the refined clock model and adjustments to station positions will be applied to phase delay, and phase delay ambiguities will be resolved. The least square solution but this time using much more precise phase delays will be repeated, outliers will be eliminated, and the model will be refined. The parameters of the the clock function, outlier elimination flags, weight update parameters, and baseline vector estimates will be stored. The dataset with visibilities and the geodetic database with results of automated data analysis will be submitted to the IVS public archive. Data analysis will be finished within two hours upon the end of observations.

### 5.4 Self-correction of the automated data analysis

If the automated data analysis procedure does not detect a source after processing three scans, it enters a self-correcting mode. The automated pipeline stops processing of the prepared schedule and starts observation of a strong calibrator with expected signal to noise ratio (SNR) over 200. If it does not detect that calibrator, it expands the fringe search window and tries again. If it still cannot detect a source, it sends a message to the

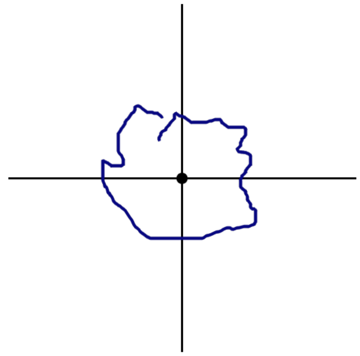

Figure 4: Realistic mechanical motion of the antenna reference point in the horizontal and vertical planes with the respect to the nominal reference point at the center. The mechanical motion may reach several millimeters.

station manager, and stops observations. This is an indication of a serious hardware failure that requires manual trouble shooting. It it detects a source, it adjusts the a priori clock and resumes observations of the prepared schedule.

### 5.5 Refined data analysis

The automated pipeline will produce a dataset of phase delays cleaned for outliers and clock jumps as well as the time series of estimates of Up, East, and North components of the baseline vector. Expected formal uncertainties of the baseline vector estimates based on processing prior similar observations are better than 1 mm over 1 hour and 0.2 mm over one day. The dataset of phase delays will be used for investigation of the remaining systematic errors. In particular, we will do the following:

- We will investigate variations of the VLBI reference points associated with thermal expansion. KOKEE and KOKEE12M antennas have different designs and different dimensions. Therefore, position variations of the reference points will be different and they will affect estimates of Up component of the baseline vector. Both antennas have thermal sensors that measure temperature of concrete and steel constructions. We will develop a model of dependence of the reference point position on temperature $T$ in a form $aT(t-l)$, where $t$ is time, $l$ is a time lag, and $a$ is a coefficient and estimate these parameters using phase delay data.

- We will investigate mechanical stability of the antennas. When we solve for antenna axis offset parameters, we often get values within ±1–5 mm, while the antenna design assumes a zero offset. In addition to the excessive scatter of phase delay residuals, this is another indirect evidence that the antenna reference point may be "flexible" at a level of several millimeters (See Figure 4). We will estimate the variable axis offset with respect to the reference point as a function of azimuth and elevation, investigate significance of the estimates, and develop a mathematical model of the offset motion.

- We will compute the Allan variance of residuals and compare it with the Allan variance

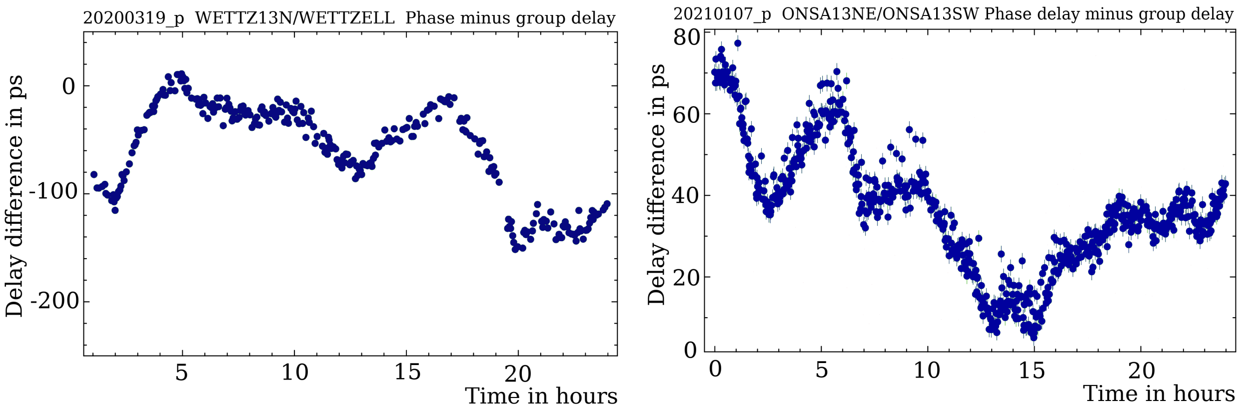


Figure 5: Systematic differences between phase and group delay at a short baseline between two antennas. Left at Wettzell, right at Onsala. This differences should be zero for an ideal system.

of Hydrogen clock. This comparison will help us to understand the contribution of the Hydrogen clock instability to the phase delay error budget.

- We will investigate the residual atmospheric contribution. Unlike observations at long baselines, atmospheric path delay at short baselines has a minor impact on results because only the differences in path delay at scales of tens of meters will affect the differential path delay. The height difference of antennas at Kokee Park is 8 meters, therefore the stride in the path trajectory varies from 31 meters when antennas look at zenith to 8 meters when antennas observe at low elevations. Systematic atmospheric path delay bias due to height differences is easily computed using in situ meteorological parameters, but the stochastic contribution, being elevation dependent, can be separated from clock variations.

- We will investigate the impact of instrumental error that affect group delays. Theoretically, phase delay may differ from group delay only due to ionosphere scintillations that are supposed to be under the picosecond level at a short baseline (1 ps corresponds to 0.3mm). Figure 5 shows systematic differences at a level of tens picoseconds. Their origin is not understood but we assume it is related to VLBI instrumentation (Ray and Corey, 1991), for instance to dispersiveness of cables that bring radio signal to the backend. Considering phase delay as the ground truth, we can characterize systematic errors in group delays. Group delays are used for VLBI geodetic applications at long baselines (Sovers et al., 1998; Thompson et al., 2001). Therefore, characterization of the systematic group delays, establishing their origin, and possibly mitigation, will have a substantial impact on geodetic applications (Petrov, 1999).

  We will investigate in detail the differences in phase and group delays. In particular, we will insert temperature sensors at various part of VLBI hardware: the Hydrogen maser, the reference clock distributor, and the digital baseband converter board.

- We will investigate the impact of the correlator errors on group delay. We will re-correlated some experiments varying the input correlator model and investigate the impact of the digital noise incurred in the correlator in phase and group delay. Characterization of the noise introduced by the digital correlator is poorly understood. Large series of phase and group delays will allow us to accumulate a large realization of the correlator noise and investigate its impact on estimates of baseline vector from phase and group delays.

## 6 Proposed work

The elements of the proposed work were tried before. Short baseline experiments were conducted in the past, and in some experiments phase delays have been used. However, these efforts required substantial manual work and were limited to single experiments. We propose the following work:

- **We will create an automated system that will run without a human intervention and generate two order of magnitude more data than in prior experiments.** Although elements of the VLBI observation pipeline are known, they do not form a system. We will create such a system. Difficulties with tape or disk shipment with baseband data required manual work impeded development of the automated pipeline in the past. Since the correlator will use a network for data transfer, this kind of problems will be gone.

  The automated pipeline will be governed by the master control file that specifies start and stop dates and a number of secondary template control files for various components of the pipeline. They include template control files for scheduling, observation, correlation, visibility analysis, and geodetic analysis. The main VLBI operation program will create the schedule file, initiate the observing queue, send the schedule file to software that controls the antenna, and initiate the messaging bus. A message about completion of a scan will trigger correlation. A message about completion of the daily observing schedule will trigger visibility analysis. A message about completion of the visibility analysis will trigger geodetic analysis and then upload results of correlation, visibility analysis and geodetic analysis to the data archive.

  We will develop comprehensive procedures for quality control of each step. Results of the quality control procedures will be logged. If the quality control procedure identifies a problem, the main VLBI operation program will launch a self-recovery procedure. Self-recovery will amend a control file and will run data observations or analysis in a more extensive way. For instance, it will increase the search window for correlation if a source is not detected, it will select alternative calibrator, if bandpass calibration failed, it will change parameters of the procedure for outliers elimination if the number of outliers exceeded the threshold, etc. The self-recovery procedure will run additional tests for filtering out RFI. If the self-recovery will fail, the system will send a email to the engineer on duty pointing out log files and quit.

  Development of such a system will be a pathfinder for development of a totally automated VLBI observations at long baselines.

- **We will analyze phase delays** that are more than one order of magnitude more precise than group delays. We formulate a hypothesis that phase delays that allow us to determine the baseline vector at baselines shorter than one kilometer with an accuracy of 1 mm over one hour and 0.2 mm over one day and provide the ground truth for precise geodesy. We will create the measuring system that will run over the course of the project and beyond. Such an observing system will be used as a gauge of the VLBI measurement system. It will provide evidence that VLBI system indeed reached a desired level of accuracy and stability (1 mm and 0.1 mm/yr respectively).

- We will investigate advanced methods of data analysis of phase delays and **develop an empirical model of motion of the the realistic reference point** with respect to its nominal position and evaluate statistical significance of parameters of such a model. We will perform statistical tests that would establish that no residual motion of the VLBI reference point with respect to that model above the defined level takes place.

- We will develop procedures for **processing time series of baseline vector estimates** with a step of one hour and one day. We will correlate the time series with readings of temperature sensors and investigate temperature stability of the reference points of radio telescopes. We will investigate dependence of position variations with respect to the average on geometric parameters, such as azimuth and elevation and environmental parameters. We will compute the spectrum of the residuals, structure and autocorrelation functions.

- We will develop procedures for **analysis of the differences between group and phase delays** from results of proposed observations. We will focus our investigation on determining the origin of systematics. In particular, we will correlate the differences with respect to numerous sensors at the antenna and the VLBI data acquisition system, as well as against azimuth, elevation, and other parameters.

- We will develop the procedures for **an automatic amplitude calibration**. These procedures include filtration for outliers in raw TPI measurements and evaluation of the scatter in calibrated cross-correlation amplitudes.

- We will develop the procedures for **an automatic amplitude calibration**. These procedures include filtration for outliers in raw TPI measurements and evaluation of the scatter in calibrated cross-correlation amplitudes.

- We will coordinate with Owens Valley blazar monitoring team the list of common sources and use it for comparison of flux densities for evaluation of possible biases in light curves. This will help us to provide **realistic assessment of accuracy of flux densities** derived from observations at short baselines.

## 7 Broader scope of the project

The scope of our work is broader. Together with international partners from Wettzell, Onsala, Yebes, and Ny Alesund observatories that host twin telescopes at baselines 100–1500 meters, we form a virtual self-managed team. All five partners have their own funding, their own schedules, but share the same goal as outlined in this proposal. The virtual team exchanges data, ideas, and software. Delay of work of one team members will not derail or delay work of other team members. However, progress of one team member will facilitate progress of the entire team.

The team will have regular monthly meetings and ad hoc meetings when needed. Twin telescopes at all observatories are different. Kokee Park twin telescopes form the shortest baseline. Yebes telescopes are the most sensitive. Onsala and Wettzell observatories have three telescopes what allows to check phase delay closures. Wettzell observatory has a high accurate clock comparison system. The diversity of baseline geometries and VLBI hardware strengthens interpretation of baseline length time series analysis, since this allows us to differentiate problems specific to a given baseline to general problems that affect every baseline, such as generic instrumental errors in group delay.

Though KOKEE and KOKEE12M have only 8.2–8.9 GHz common bandwidth, telescopes at Yebes, Wettzell, and Onsala have wider bandwidth: 4–9 and 3–15 GHz respectively. We will run experiments at different frequency bands to explore frequency dependence of instrumental errors and to compute correlated flux density of observed sources at different frequencies.

Some of the program sources will be the same at all short baselines. Comparison of flux densities from different baselines will provides us information about quality of amplitude calibration. In a case of significant biases, we will investigate the reason and develop mitigation approaches.

Wettzell, Onsala, and Yebes will correlate on site with sending data only within the local network. This will facilitate testing near-real time processing capabilities. At Kokee Park and Ny Alesund the correlator will be initially put off-site and then later it is expected to be moved on site after logistical problems will be solved.

## 8 Commensal outcome: RFI monitoring

The algorithm that filters visibility data for RFI will provide information about their frequency, location, and duration. Analysis of this information will allow us to develop an empirical model of RFI and use it for mitigation of VLBI observations, including those at long baselines, by adding new constraints in the schedule to bypass areas of sky and time ranges most affected by the RFI.

## 9 Deliverables and expected outcomes

We will deliver

- time-series of baseline positions with steps of one hour and one day at 31 m long baseline KOKEE/KOKEE12M as well as visibility data and geodetic database;

- software for end-to-end automation of single baseline observations starting from scheduling and ending to uploading time series baseline vectors to the data archive;
- results of statistical analysis of the baseline length vector;
- results of statistical analysis of phase delay residuals;
- results of statistical analysis of differences between group and phase delay;
- time series of the total flux densities of observed sources.

The outcome of the proposed research will be

— estimates of the stability of the VLBI reference point at a sub-millimeter level of accuracy at scales from hourly to interannual;

— an improved model of VLBI observables that accounts for fine mechanical motion, thermal expansion, antenna flexibility, and instrumental delay variations;

— a stochastic model of the contribution of residual instrumental errors to group delay;

— establishing of firm ties of new VGOS stations to the ITRF at a sub-millimeter level.

## 10 Risk management

Risks associated with the project:

- Risk: wear and tear of radiotelescopes from intensive uses. Although new VGOS antennas were designed for 24/7 use, at the moment these antennas are idle most of the time, and antennas were not tested for intensive use. **Mitigation:** We will start with once per week observing program and gradually increase the cadence of observations twice per week and then intensify the schedule further examining antennas for signs of wear and tear. The Co-I Christian Coughlin has an intensive experience of overseeing weekly, monthly, and semi-annual maintenance works. He has a several decade long baseline for what is considered normal wear and tear.

- Risk: presence of local RFI will affect VLBI observables. **Mitigation:** we will develop a subsystem of RFI filtering based on analysis of autocorrelation. We will observe at different frequencies to isolate frequency dependent RFI.

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