VLBI2010: Next generation VLBI system for geodesy and astrometry

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Abstract. The International VLBI Service for Geodesy and Astrometry (IVS) is well on the way to fully defining a next generation VLBI system, called VLBI2010. The goals of the new system are to achieve 1-mm position accuracy over a 24-hour observing session and to carry out continuous observations, with initial results to be delivered within 24 hours after taking the data. These goals require a completely new technical and conceptual design of VLBI measurements. Based on extensive simulation studies, strategies have been developed by the IVS to significantly improve its product accuracy through the use of a network of small (~12-m) fast-slewing antennas, a new method for generating high precision delay measurements, and improved methods for handling biases related to system electronics, deformations of the antenna structures, and radio source structure. To test many of the proposed strategies, NASA is sponsoring a proof-of-concept development effort using IVS antennas near Washington, DC, and Boston, MA. Furthermore, as of Feb. 2009, the construction of ten new VLBI2010 sites has already been funded, which will improve the geographical distribution of geodetic VLBI sites and provide an important step towards a global VLBI2010 network.

Keywords. Geodetic VLBI, VLBI2010, IVS.

1 Introduction

Very Long Baseline Interferometry (VLBI) is an essential technique for the realization of reference frames, both terrestrial and celestial. It owes its significance primarily to the fact that it refers its observations to quasars, which are distant extragalactic radio sources that appear to be nearly fixed in angular position. VLBI determinations of the coordinates of a selected subset of these sources realize the International Celestial Reference Frame (ICRF), and VLBI determinations of the positions and velocities of about 30 globally distributed radio antennas contribute significantly to the realization of the International Terrestrial Reference Frame (ITRF), in particular to the definition of its scale. VLBI also measures the link between the ICRF and ITRF by determining the full set of Earth orientation parameters (EOP) including DUT1 and nutation which are provided uniquely. Because of its dual role with respect to the ICRF and ITRF, the International VLBI Service for Geodesy and Astrometry (IVS), which is the governing body for VLBI, is a joint service of the International Association of Geodesy (IAG) and the International Astronomical Union (IAU) [Schlüter and Behrend, 2007].

The current VLBI system was conceived and constructed mostly in the 1960s and 1970s. Aging antennas, increasing radio frequency interference (RFI) problems, obsolete electronics, and high operating costs make it increasingly difficult to sustain the current levels of accuracy, reliability, and timeliness. In September 2003 the IVS, recognizing the limitations of existing VLBI infrastructure and the increasingly demanding requirements of space geodesy, established Working Group 3 (WG3): VLBI2010 to investigate options for modernization [Behrend et al., 2009].

Guided by emerging space geodesy science and operational needs [Schuh et al., 2002; Plag & Pearlman, 2009], WG3 established challenging goals for the next generation VLBI system:

- 1 mm position and 0.1 mm/year velocity accuracy on global scales,
- continuous measurements for time series of station positions and EOP,
- posting of initial geodetic results less than 24 hours after observations are complete.

In its final report [Niell et al., 2006], WG3 proposed strategies to move toward the unprecedented 1 mm position accuracy target and broad recommendations for a next generation system based on the use of smaller (~12 m) fast-slewing automated antennas. To help make these recommendations more specific, the report additionally suggested a series of 13 studies and development projects.

In order to encourage the realization of the recommendations of WG3, the IVS, in September 2005, established the VLBI2010 Committee (V2C) as a permanent body of the IVS. The V2C takes an integrated view of VLBI and evaluates the effectiveness of proposed system changes based on the degree to which they improve the final products. The V2C work goes hand-in-hand with the gradual establishment of the Global Geodetic Observing System (GGOS) [Plag et al., 2009] of the IAG. To realize the demanding goals for VLBI2010, the following strategies have been investigated by the V2C:

- a reduction of the random component of the delay observable noise, e.g., the measurement error per observation, the stochastic properties of the clocks, and the unmodeled variations in the atmosphere;
- a reduction of the systematic errors, e.g., the thermal and gravitational deflection of the antenna, drifts of the electronics, and radio source structure;
- an increase of the number of antennas for geodetic VLBI and an improvement of their geographic distribution;
- an increase of the observation density, i.e. the number of observations per unit time;
- a reduction of susceptibility to external radio frequency interference.

This paper summarizes the work of the V2C to date, which has been described thoroughly in a recently published progress report [Petrachenko et al., 2009].

2 Monte Carlo Simulators

Making rational design decisions for VLBI2010 requires a realistic understanding of the impacts of new operating modes on final products. These impacts are difficult to evaluate analytically due to complex interactions in the VLBI analysis process and are impractical to evaluate with real data due to the high cost of VLBI systems and operations.

To fill this gap, Monte Carlo simulators based on the two VLBI analysis software packages Calc/Solve and OCCAM and a third simulator based on Precise Point Positioning (PPP) were developed. The concept of a Monte Carlo simulator involves the generation of several sets (typically 25 for the VLBI2010 studies) of input data, with each set driven by different random numbers. All data sets are then processed as if they were from real sessions, and the ensemble of output products is analyzed statistically to produce estimates of the bias and standard deviation of those products. The Monte Carlo simulators are only as realistic as the models used to generate the simulated input data. Efforts continue to improve those models [Nilsson & Haas, 2008; MacMillan, 2008; Wresnik et al., 2008]. The simulators have been used to study the effects of the dominant VLBI random error processes (related to the atmosphere, the reference clocks, and the delay measurement noise) and the benefit of new approaches to reduce them, such as decreasing the source-switching interval and improving analysis and scheduling strategies.

Of particular merit is the strategy to reduce the source-switching interval. Because of the directionality of the parabolic antennas used in VLBI, each antenna can observe only one source at a time. The antenna must then be mechanically redirected to observe the next source. Reducing the average time to complete the observe/redirect cycle was shown to result in a nearly proportionate improvement in station position accuracy (see Fig. 1).

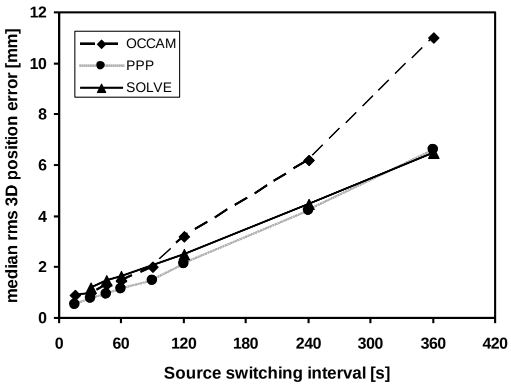

Fig. 1. Median of the rms 3D position errors for uniform sky schedules with regular source-switching intervals ranging from 15 to 360 s. The delay measurement noise is 4 ps per baseline observation, the clock Allan Standard Deviation is $1 \cdot 10^{-14}$@ 50 minutes, and the turbulence parameters are those driven by a turbulence model (Petrachenko et al., 2008).

Regardless of the strategy employed, the simulators confirm that the dominant error source is the atmosphere. Research into better ways to handle the atmosphere will continue to be a priority for the IVS [Petrachenko et al., 2009].

3 System considerations

Based on the Monte Carlo studies, high priority is placed on finding strategies for reducing the source-switching interval. This entails decreasing both the on-source time needed to make a precise delay measurement and the time required to slew between sources. From these two somewhat competing goals, recommendations for the VLBI2010 antennas are emerging, e.g. use either a single 12-m diameter antenna with very high slew rates (e.g., 12°/s in azimuth and 4°/s in elevation) or a pair of 12-m diameter antennas, each with more moderate slew rates (e.g., 5°/s in azimuth and 1.5°/s in elevation) [Petrachenko et al., 2008].

In order to shorten the on-source observing time, it is important to find a means for measuring the delay with the requisite precision even at a modest signal-to-noise ratio. To do this a new approach is being developed in which several widely spaced frequency bands are used to unambiguously resolve the interferometric phase. The new observable is being referred to as the broadband delay. To do this, a four-band system is recommended that uses a broadband feed to span the entire frequency range from 2 to 14 GHz. In order to be able to detect an adequate number of high-quality radio sources, a total instantaneous data rate as high as 32 Gbps and a sustained data storage or transmission rate of 8 Gbps are necessary. Since the broadband delay technique is new and untested, NASA is funding a proof-of-concept development effort to verify that it works and to gain experience with the new VLBI2010 systems.

It is also recognized that reducing systematic errors plays a critical role in improving VLBI accuracy. For minimizing electronic biases, updated calibration systems and processes are being developed. For errors due to source structure, the application of corrections based on images derived directly from the VLBI2010 observations is under study. For antenna deformations, conventional surveying techniques continue to be refined, while the use of a small reference antenna for generating deformation models and establishing site ties is also under consideration [Petrachenko et al., 2009].

The last concept is based on the idea that the reference antenna, being small, can be mechanically and thermally well understood. Connected element interferometry between the small antenna and the primary VLBI antenna can then be done to develop thermal and gravitational deformation models for the primary antenna. The small antenna being parabolic also has a well-defined phase center and experiences minimal multi-path. If it is sensitive to GNSS frequencies, joint observations can be carried out with a co-located GNSS antenna to develop *in situ* models for the GNSS antenna phase center deviations. In the process of carrying out these observations, the effective reference points of both the VLBI and GNSS antennas can be determined relative to the intersection of axes of the small reference antenna, the net result being a site tie not between nominal reference points for the antennas but between the effective reference points as they appear in the context of normal operations. This can be done with minimal complication or risk of misinterpretation compared to more classical approaches.

The system development effort for VLBI2010 is significant. It involves nearly a complete reworking of the current S/X system. To give a feeling for the degree of change, a number of the new VLBI2010 characteristics are listed below:

- The VLBI2010 feed is dual linearly polarized and spans the entire frequency range from 2 to 14 GHz.
- The entire feed structure is cryogenically cooled.

- The phase calibration unit is constructed using digital integrated circuits.
- The amplitude calibration unit will operate in the 80-Hz synchronous mode.
- The radio frequency (RF) signals are transported from vertex to control room via analog fiber optics.
- The RF frequency of four dual-polarized bands can be independently selected using flexible up-down converters (UDC).
- The outputs of the UDCs are high-frequency sampled with at least 8-bit resolution and all back end processing is performed digitally.
- RFI mitigation strategies will be implemented in the digital back ends.
- Data rates of up to 32 Gbps will be burst-mode acquired into RAM while the antenna is on source and will be recorded (or transmitted via eVLBI) at sustained rates of up to 8 Gbps as the antenna slews.
- Correlation will be done in software.

4 Network considerations

It is vital that the ITRF scale provided by VLBI2010 be accurate and be transferred as effectively as possible to the ITRF. A robust transfer requires a large total number of VLBI sites co-located with the other techniques, while a more stable scale estimate requires more frequent observations with a larger network. Although more frequent observations can be expected to improve results through averaging, dense time series of station positions will perhaps more importantly prove valuable for revealing, understanding, and eventually reducing systematic errors.

For CRF a larger, better-distributed global network improves u-v coverage, which is a prerequisite for generating higher quality images of radio sources, and also yields more uniform CRF quality between the northern and southern celestial hemispheres. In addition, a more uniform north-south distribution of stations leads to reduced coupling between global troposphere gradients and estimates of station latitude and source declinations.

For EOP it is necessary that the VLBI2010 estimates be strongly coupled to the ITRF. Experience shows that VLBI EOP estimates include small network dependent biases and that those biases change somewhat with time. The systematic impact of any single station on VLBI EOP determinations can be expected to become smaller as the network size increases, making a larger network more robust against changes in network composition.

It is recommended that a globally distributed network of at least 16 VLBI2010 antennas observe every day to determine EOP, and that other antennas be added as needed for the maintenance of the ICRF and ITRF. A subset of antennas with access to high-speed fiber networks is also required to enable daily delivery of initial IVS products in less than 24 hours. For the observation of faint radio sources for densification of the ICRF at least four large radio telescopes per hemisphere are also recommended. High priority is placed on increasing the number of stations in the southern hemisphere.

5 Operational considerations

The key to developing a fully integrated observing strategy for CRF, TRF, and EOP is to have a correlator capacity that can handle significantly more sites than is needed just for daily determination of EOP. Incorporating the added antennas into integrated observing schedules that overlap with the daily EOP schedules will enhance the connection to the stations that observe on a daily basis and hence have well established locations.

Since IVS products must be delivered without interruption, a transition period to VLBI2010 operations is required in which there will be a mix of antennas with current and next-generation receiving systems. For this period a compatibility mode of operation has been identified and tested to a limited extent with the NASA proof-of-concept system. To preserve continuity in particular with respect to the strength of stable long-term time series of station positions, baseline lengths, and troposphere parameters, among other things, several existing radio telescopes are expected to continue VLBI observations for many years to come.

In order to increase reliability and to reduce the cost of operations, enhanced automation will be introduced both at the stations and in the analysis process. Stations will be monitored centrally to ensure compatible operating modes, to update schedules as required, and to notify station staff when problems occur. Automation of the analysis process will benefit from the work of IVS Working Group 4, which is updating VLBI data structures and modernizing data delivery.

6 Status at the end of 2009

VLBI2010 is now well on the way to the definition of requirements and recommendations for subsystem specifications. This is expected to be complete in 2010.

At the same time, sponsored by NASA, full progenitor VLBI2010 signal paths have already been implemented on two antennas, the 18-m antenna at the Haystack Observatory in Westford, Massachusetts, and the 5-m MV-3 antenna at the NASA Goddard Space Flight Center (GSFC) in Maryland, a baseline of 597 km. The development effort is significant since the VLBI2010 system design involves nearly a complete reworking of the current S/X system. With the new systems, fringes are now routinely detected and the broadband delay technique is currently under test. A 12-m VLBI2010-style antenna has also been acquired for the GSFC site and will soon be installed.

Worldwide, about ten VLBI2010 antennas have been funded and are currently in various stages of implementation. New antennas are coming up in Australia, Korea, New Zealand, Germany (Fig. 2), Spain/Portugal (Fig. 3), and USA. The IVS has been approached by several other countries regarding VLBI2010, and a number of proposals for new sites are in various stages of preparation and approval.

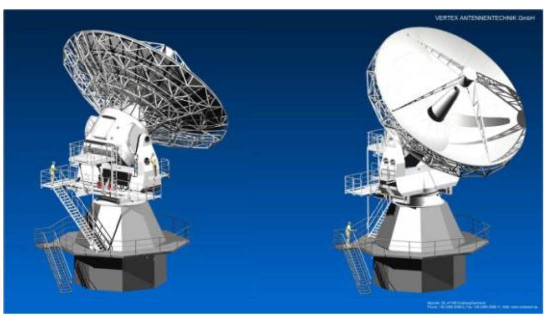

Fig. 2. An artist's conception of the VLBI2010 antenna being designed by Vertex Antennentechnik GmbH. A pair of these antennas will be installed at Wettzell Fundamental Station in Germany as part of the Twin Telescope Wettzell project. These antennas are fully VLBI2010 compliant.

Fig. 3. Proposed locations for antennas of the Spain/Portugal RAEGE Project for studying dynamics at the intersection of the North American, African and Eurasian Plates.

Beyond the NASA development effort, organizations in other countries are involved in system developments potentially applicable to VLBI2010. These include Australia, China, Finland, Germany, Italy, Japan, Norway, Sweden (Fig. 4), and possibly others.

Fig. 4. Prototype of a broadband 2-14 GHz "Eleven" feed for VLBI2010. The feed is being developed at Chalmers University in Sweden.

A small radio antenna that is potentially applicable as a reference antenna for VLBI antenna deformation modeling and site ties is under development in Japan [Ichikawa et al., 2008].

The VLBI2010 concept also needs strategic and political support to be realized. In March 2009 a small VLBI2010 Project Executive Group (V2PEG) was established to move to the next level of defining development and deployment schedules and soliciting contributions.

There are a number of risks to the successful implementation of VLBI2010, the most significant of which follow, together with respective fallback options:

- The higher slew rates and the smaller antennas for the VLBI2010 system will result in a significant increase in data volume and hence higher shipping and/or transmission costs are anticipated. It is expected that future technological advances will reduce these costs. In the interim less data-intensive operating modes may be employed.
- Radio frequency interference (RFI) is an ever increasing problem in the VLBI2010 spectrum. The VLBI2010 system is being designed to be resilient against it.
- The broadband delay technique has not been fully verified. Known risks come from RFI and source structure. The NASA proof-of-concept test is now in the process of testing the concept. In the event that

problems are identified, less attractive but adequate fallback options, such as the use of multiple bands for group delay, have been defined.

7 Next steps

The development, realization, and implementation of the VLBI2010 system will continue in the next several months and years. Major items on the work schedule are:

- Continue the NASA proof-of-concept effort.
- Continue defining subsystem recommendations.
- Improve algorithms for scheduling observations.
- Develop VLBI2010 analysis strategies including automation.
- Promote the expansion of the VLBI2010 network.
- Develop VLBI2010 deployment schedules.

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