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VLBI2010: Progress and Challenges

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Abstract

It is now six years since the publication of the final report of IVS Working Group 3 entitled "VLBI2010: Current and Future Requirements for Geodetic VLBI Systems" in which a bold vision for a next generation geodetic VLBI system was put forward. In the intervening years, work towards the realization of that vision has been carried out under the technical leadership of the IVS VLBI2010 Committee. This paper presents an overview of progress towards achieving the VLBI2010 goals and challenges yet to be overcome.

1. Background

In September 2003 the IVS Directing Board established Working Group 3 (WG3) to review all aspects of geodetic VLBI and to make recommendations for future requirements. In their final report [4], WG3 put forward a bold vision for a completely revitalized next generation system called VLBI2010. After the termination of WG3, the IVS initiated the VLBI2010 Committee (V2C) to encourage the realization of VLBI2010, and in 2008 the VLBI2010 Project Executive Group (V2PEG) was established to take strategic leadership of the project. Since 2008, the V2C has focused its activities on technical developments. In 2009 the V2C published a progress report outlining design aspects of the VLBI2010 system [7], and on March 1-2, 2012, the technical specifications for the project were presented at a workshop held in Bad Kötzting, Germany.

2. The VLBI2010 Concept

Three goals were set out for VLBI2010 [4]:

- 1-mm position accuracy globally (based on a 24-hour observing session).
- continuous time series of station positions and Earth orientation parameters.
- turnaround time to initial geodetic results of less than 24 hours.

Achieving 1-mm position accuracy globally is a significant challenge and requires improvements in the handling of both random and systematic errors. For VLBI, the main systematic errors are due to source structure, antenna deformations, and drifts of the electronics; the main random errors are due to delay measurement error, clock drifts, and atmospheric turbulence.

The VLBI2010 plan for reducing systematic errors is to develop designs that are less sensitive to systematic effects and to improve calibration techniques. The situation is not as straightforward for random errors. Beginning in 2006 studies were carried out to test strategies for reducing their impact. The most successful strategy was to increase the number of observations in a session. Achieving this requires both the use of fast antennas to reduce slew time between sources and short on-source times, the latter being achieved both by acquiring data very rapidly while on source, e.g., 16 Gbps, and by using a new technique called broadband delay to resolve the very precise phase delay at modest SNR. Broadband delay involves the reception of four 1-GHz bands optimally spaced in the very wide 2-14 GHz input range.

3. Progress

The introduction of the VLBI2010 broadband concept requires a complete redesign of the VLBI system. Highlights of progress to date are summarized below (see Figure 1):

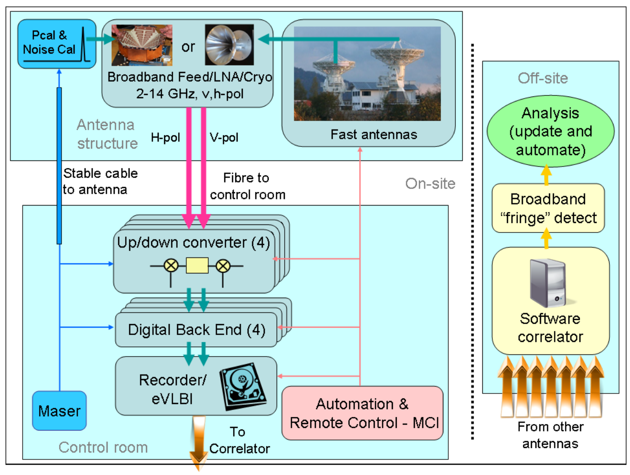

Figure 1. VLBI2010 System.

- *VLBI2010 antenna.* Studies [7] have shown that a 12-m class antenna has adequate sensitivity for VLBI2010 and that slew rates of 12°/s in azimuth and 4°/s in elevation are sufficient to achieve the required number of scans per day. In addition, surface accuracy good to 32 GHz is recommended to support X/Ka observations. It is further recognized that truly continuous observations cannot be realized without multiple antennas at a site so that one antenna at a time can be taken off line for maintenance or repair. There are currently three manufacturers with designs for antennas that meet the VLBI2010 specifications, those being Vertex Antennentechnik GmbH, MT Mechatronics GmbH, and InterTronic Antennas.
- *Broadband feed.* VLBI2010 requires a front end that has high efficiency and low noise in the full 2-14 GHz frequency range. Rapid progress in the past two years has resulted in two feed options that fully meet these specifications [1]. One is the Eleven Feed under development at Chalmers University of Technology and Onsala Observatory. The other is the Quadruple Ridged Flared Horn (QRFH) under development at California Institute of Technology.
- *Phase Calibration (PCAL).* PCAL is required in the broadband system to coherently align bands and for tracking changes in instrumental delay. The PCAL system has been upgraded in three ways: the tunnel diodes, which are now difficult to procure, have been replaced by high speed digital circuits adapted to produce the very narrow PCAL pulses; shielding of the PCAL enclosure is being improved to avoid corruption caused by leaked pulses reflecting

off nearby structures, and PCAL detection is being upgraded to include the capability to simultaneously detect all available PCAL tones.

- *Down-Conversion.* For broadband delay, arbitrary segments of the input 2-14 GHz range must be selected and down-converted to a lower frequency where they can be sampled and processed. For this purpose, an updown converter with frequency range 1-13 GHz, a Nyquist bandwidth of 512 MHz, and frequency resolution of 400 KHz has been developed at Haystack Observatory [9]. For full VLBI2010 compliance, minor modifications are required to shift the frequency range to 2-14 GHz and double the Nyquist bandwidth to 1024 MHz. Recently, development has been underway for a second very different down-converter. The DBBC3 uses direct sampling of the RF input and digital selection of output bands [12]. It is based on a 28 Gsps 8-bit sampler. Although promising for the future, the frequency resolution of band selection is somewhat coarse in the initial implementation.
- *Digital Back End (DBE).* All developments for VLBI back ends are now completely digital, i.e. they sample the IF input immediately and select and process channels digitally. VLBI DBEs have been developed in Italy, the US, Japan, and China. Of the DBEs in existence, two are fully or nearly VLBI2010 compliant. The DBBC VLBI2010 [11] is fully compliant while the RDBE [5] currently operates at half bandwidth, i.e., 512 MHz instead of 1024 MHz.
- *Recorder.* Over the past decade VLBI record capability has benefited from nearly continuous advances in commercial technology. Disks with capacities of 2 TB are now cost effective and routinely available; the Mark 5C data system can now handle sustained record rates of up to 4 Gbps. Recently a next generation VLBI data system is under development and soon will be available to the general VLBI community [13]. The Mark 6 system uses high-performance COTS hardware and open source software, can sustain record rates up to 16 Gbps, and can accommodate up to four disk packs.
- *Correlator.* There are a number of IVS components that have developed software correlators. Only one though has been enhanced to specifically handle features of VLBI2010. It is based on the Distributed FX (DiFX) kernel developed by Adam Deller and is being further developed by an international consortium. Capabilities have been introduced to make it compatible with operational processes used in geodetic VLBI. Correlator outputs for both polarizations and multiple bands can now be combined (fringed) to produce a single cycle-resolved phase delay observation that has been corrected for the ionosphere delay.

4. Challenges

- *Antenna deformations.* A significant problem for Terrestrial Reference Frame (TRF) combinations is non-closure of site ties. The errors are believed to result from offsets between the nominal and effective reference points for the techniques. For VLBI the offset is likely caused by thermal and gravitational deflections of the antenna structure. Careful measurements and analyses have been carried out for gravitational deflection (e.g. [10]) as have real time measurements of thermal deflection (e.g. [3]). Another approach has been proposed that might provide a valuable independent cross-check. It involves the use of a small co-located reference antenna that is sensitive to both GNSS and VLBI frequencies. Since observations are taken in the native mode of each technique, ties are naturally measured between the *effective* reference points of the antennas.

- *Source structure.* The extragalactic radio sources used in geodetic VLBI are not point sources. They have structure, and their structure varies with both time and observing frequency. This is due to phenomena such as core shifts and sub-beam structure [8]. These phenomena result in apparent motions of the sources and make phase resolution in the broadband delay process more complicated. Simulations are underway to study the possible use of structure corrections to mitigate these complications [2]. It will be difficult to evaluate the full extent of source structure problems until the VLBI2010 network is in regular operation.

- *RFI.* The VLBI2010 capability to easily move bands within its broad input frequency range makes it possible to adapt to a changing RFI environment. However, the broad input range also opens the system to potentially catastrophic problems with saturation if strong enough RFI sources appear anywhere in the input range. This must be avoided at all costs. It is urgent that a quantitative RFI survey be carried out at all potential VLBI2010 sites to determine whether or not saturation of the front ends is likely to be a problem.

- *Atmosphere.* Monte Carlo simulations indicate that the neutral atmosphere will remain the dominant error source for VLBI2010 [7]. To make matters worse, there are indications that the atmospheric parameters used in the initial VLBI2010 simulations were optimistic [6]. Improved strategies to handle the atmosphere involving the use of numerical weather models and optimization of elevation angle cut-offs are under way, but improvement is expected to be incremental. Another somewhat radical approach has been proposed that involves the use of an array of GNSS receivers to estimate the azimuthal dependence of the atmosphere and hence reduce its apparent bumpiness (see Figure 2). Studies are however required to evaluate the effectiveness of the approach.

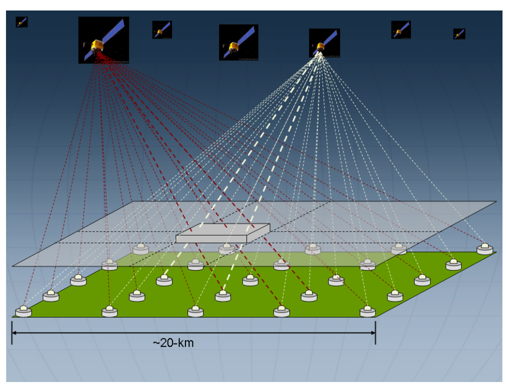

Figure 2. Local GNSS array for estimating the bumpiness of the neutral atmosphere.

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