Bill Petrachenko: Achieving a Quantum Leap in Observation Density, IVS 2006 General Meeting Proceedings, p.67–71
http://ivscc.gsfc.nasa.gov/publications/gm2006/petrachenko

Achieving a Quantum Leap in Observation Density

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Abstract

It is a general rule of thumb in geodetic VLBI that performance improves as the observation density (number of scans per day) increases. An acquisition system and observing strategy will be described for increasing the number of scans per day by roughly an order of magnitude. This will be achieved at a sensitivity that allows nearly all ICRF sources to be observed each day. Resulting benefits will be discussed.

1. Introduction

The purpose of this study is to investigate if it will be technically feasible by 2010 to increase the number of observations per day at each station by roughly an order of magnitude. Today, each site typically makes 200 to 450 observations per day. The goal here is to achieve one observation every 30 s, or 2880 observations per day. Two factors are needed to increase the observation density: shorter integration times, and shorter switching times between sources. Both factors will be addressed in more detail in the following sections, along with a discussion of related risks and benefits.

In order to maximize the advantage of increasing the observation density, additional performance-related targets need to be considered, e.g.:

- The system (antenna, electronics, etc) should be capable of achieving the VLBI2010 delay precision target of 4 ps for most observations.
- The system should have enough sensitivity to detect most ICRF sources at a level where the VLBI2010 delay precision target can be met.
- The system should have low enough capital and operating costs to encourage the establishment of 20-40 globally distributed stations of uniform design.
- The system should have high enough performance in other aspects to ensure that the benefits of the new VLBI2010 delay precision target will not be masked. For example, it must have high enough electrical, mechanical and geological stability, and it must have the ability to model and calibrate the troposphere at a high level.

2. Benefits of Increased Observation Density

Increasing observation density has the potential to improve performance in the following ways:

- The troposphere can be sampled more uniformly.
- The troposphere can be modeled with more temporal and spatial structure.

- The reference oscillators can be modeled with more temporal structure.
- The number of degrees of freedom can be increased, leading to *improved robustness of solutions and increased precision due to averaging.*
- A monolithic observing strategy can be developed to fulfill all IVS goals simultaneously, leading to *Increased internal consistency of products.*
- More sources can be observed each day, leading to *Improved connection to the ICRF.*
- More scans per day can be acquired per source, leading to *An improved ability to use internally acquired geodetic VLBI data to map sources and make source structure corrections.*
- Sensitivity to sub-daily geophysical processes would be enhanced.

3. Phase Delay

As stated in Section 1, one of the two factors required to increase observation density is the use of short integration times. Unfortunately, in the current geodetic VLBI mode of operation (which uses group delays at S and X-band), short integrations are difficult to achieve while still maintaining a capability for both high delay precision and access to most sources in the ICRF—in particular, if a lower cost antenna system is desired. As the phase delay is very precise, relative to the group delay, using it might provide the key to resolving this dilemma. Unfortunately, the phase delay is corrupted by an integer cycle ambiguity. With present systems, the phase ambiguity can, in fact, be resolved, but only at high signal-to-noise ratio (SNR). This defeats the purpose, because a high SNR is not compatible with either a lower-cost antenna system or the use of weaker sources. In this section, a system will be proposed where phase ambiguities can be resolved, even at low SNR. This innovation is key to achieving the targets laid out in Section 1.

Unlike the two-band S/X systems currently in use, the system proposed here uses a much larger number of IF bands. Technologically, this is enabled by the use of broadband feeds like the ones being developed at Chalmers University [1] for the SKA. Analytically, the process for combining the data to resolve RF phase involves three steps. First, the group delays are determined. Next, those group delays are used to resolve (in sequence from easiest-to-resolve pair to hardest-to-resolve pair) the phase differences between all pairs of adjacent bands. Finally, using the group delays from the first step and the phase differences from the second, an attempt can be made to resolve the RF phase ambiguities.

An analysis was made to determine the number of IF bands which make it possible to resolve RF phase at the lowest SNR. In the considered examples, the number of bands ranged from two to eleven, and, in each case, the broadband frequency range was 2-13 GHz. It was assumed that the IF bands had a uniformly filled 1 GHz bandwidth and that there was equal signal strength in each band. Phase resolution was achieved at a 5-sigma confidence level. For each system, the band frequencies were varied in 0.25 GHz steps across the full 2-13 GHz range, taking care to ensure that the bands did not overlap.

The results are summarized in Table 1. As can be seen, the system that exhibited the best performance (with respect to minimum overall SNR required to resolve RF phase) was the one that used five bands. Although not shown in the table, each of the systems was capable of achieving a delay of better than 2.5 ps at the minimum useable SNR, i.e. they were all capable of achieving the VLBI2010 delay precision target.

Table 1. Number of IF bands (NoB) vs. the minimum overall SNR required for phase resolution.

No. of IF Bands	2	3	4	5	6	7	8	9	10	11
Overall SNR	35.84	17.01	12.72	11.61	11.83	12.20	12.50	13.11	13.76	14.39

4. Sensitivity Considerations

As stated in Section 1, one of the secondary goals of this study is to be able to detect most of the ICRF sources with sufficient sensitivity to achieve the VLBI2010 delay precision target.

In a survey performed by Fey and Charlot in 2000 [2], the VLBA observed 225 ICRF sources. As part of the analysis, Gaussian component models were fitted to the uv data. The percentile distributions of the S and X-band principle component fluxes from the survey are displayed in Table 2. To the extent that the 225 sources of the survey are representative of the ICRF, these numbers provide a good estimate of the flux limits required to use the majority of ICRF sources—although, for the poorer ICRF sources, correlated flux degrades quickly as baseline length increases.

Table 2. Percentile distribution of the S/X-band principle component fluxes for 225 ICRF sources [2].

Percentile (sources)	0	5	10	20	30	40	50	60	70	80	90
S-band flux (mJy)	170	260	310	400	480	570	670	850	990	1190	1730
X-band flux (mJy)	110	160	190	230	290	350	440	510	610	760	1250

Next, consider the performance of an interferometer with the following characteristics: antenna diameter, 12 m; antenna efficiency, 50%; Tsys, 50 deg K; and, VLBI processing factor, 0.7. The system will have six optimally positioned IF bands, each with a completely filled 1 GHz bandwidth, two polarizations and 2-bit sampling. An integration time of 5 s will be assumed. Using the minimum SNR required to resolve phase when using six bands (see Table 1), it can be shown that the above system can resolve phase using a source as weak as 120 mJy. Given that the minimum principle component flux of the above survey was 110 mJy, it should be possible (in the absence of complications due to RFI, source structure, or dispersive electronics) to use that system to achieve the VLBI2010 delay precision target for nearly all sources of the ICRF.

5. Data Rate Considerations

With the exception of data rate, the system described above is very conservative with respect to cost and feasibility. However, it does produce a total data rate of 48 Gbits/s. Fortunately, with the low and decreasing cost of RAM, it is no longer necessary to record the entire bandwidth in real time. For example, 5 s of data acquired at 48 Gbits/s could be stored temporarily in a 30 Gbyte RAM buffer and then written to disk at 8 Gbits/s over a 30 s period. An extrapolation performed in 2004 [3] (along with current trends) indicates that disk capacity and rate will advance to the point that, by 2010, it will be possible, using a single pack of 16 disks, to sustain an 8 Gbits/s data rate for 24 hours.

6. Slew Rate Considerations

Thus far, a practical system has been described that, under perfect conditions, has the capability of achieving the VLBI2010 delay precision target of 4 ps for virtually all sources in the ICRF. A source dwell time of no longer than 5 s is required, along with a 25 s period to write the remaining data to disk and simultaneously to slew. In order to achieve the goal of acquiring one source every 30s, it only remains to define the antenna slew parameters required to perform a full end-to-end slew within 25 s. In the calculation, the time needed for the antenna to accelerate/decelerate between stationary and full speed isassumed to be 5 s. Two variations of an alt-az drive will be considered, both being capable of full sky coverage. One uses 360 degrees of azimuth motion and 90 degrees of elevation motion (i.e. the elevation motion is from horizon to zenith), and the other uses 180 degrees of azimuth motion and 180 degrees of elevation motion (i.e. the elevation motion is from horizon to horizon). For the first option, a speed and acceleration of 18 deg/s and 3.6 deg/s^2 respectively are required for the azimuth drive and 4.5 deg/s and 0.9 deg/s^2 for the elevation drive. For the second option, a speed and acceleration of 9 deg/s and 1.8 deg/s/s respectively are required for both axes.

The calculation of the above speeds is based on the assumption that each source change will require a full end-to-end slew. This allows complete flexibility in sheduling. However, depending on the optimization criteria, real schedules may, in fact, require significantly shorter average slew distances and hence tolerate slower slew rates while still achieving an average of one observation every 30 s.

7. Observing Scenarios

When an order-of-magnitude increase in observing density (proposed in this paper) is coupled with the VLBI2010 recommendation for a 20 to 40-station network observing continuously, it is possible to envision very powerful observing scenarios. In a straightforward example, a global network could be used to observe all 717 sources of the ICRF at least eight times each day. Although very powerful and unified by today's standards, this scenario might not be optimum, due to the uniform weighting of sources. Other scenarios might begin by selecting a number (perhaps 200) of the best ICRF sources. A large fraction of a session could then be dedicated to observing those sources with the remainder of the session dedicated to monitoring, on a rotating basis, other candidate sources, either from the ICRF or astronomical calibrator lists.

Regardless of the details, any of these scenarios will be very powerful for source structure corrections. If maps for the primary (e.g. 200 best) sources are generated once per week, and a 20 to 40-station network operates daily, thousands of uv points will be available for each map. With this amount of data, it should be possible to make effective structure corrections relative to the stable AGN cores, making it possible to define the ICRF axes very precisely relative to that frame. This will have obvious benefits for the ICRF, ITRF and EOP.

8. Risks

Known risks are discussed below:

- **Source Structure.** It has been assumed that sources have no structure. In the real world, this is not true. The degree to which source structure affects both sensitivity requirements and the ability to resolve phase ambiguities needs to be studied. The feasability of mapping (or modeling) sources and then correcting for the structure also needs to be considered.

- **Dispersive Electronics.** Electronics have been assumed to be perfectly linear. In the real world, this is not true. An attempt should be made to reduce the problem through careful design, but some self-calibration will almost certainly still be required. Temporal stability of the electronics will then become a larger issue.
- **RFI.** It has been assumed here that there is no RFI. In reality, RFI is a growing problem. Electronics need to be designed to be (at least) RFI tolerant, and further investigation is required to determine the degree to which the sensitivity conclusions of this paper need to be scaled to account for the presence of RFI.
- **Data rate.** It has been assumed that a practical sustained data rate of 8 Gbits/s can be achieved by the year 2010. State-of-the-art disk and data transmission performance needs to be monitored on a regular basis to verify the validity of that prediction.
- **Slew rate.** Currently, the fastest antenna involved in regular IVS observations (TIGO) has a slew rate of 6 degrees per second. The mechanical and cost implications of using faster slew rates need to be investigated.
- **Sensitivity.** Increased sensitivity could help reduce a number of the above risk factors. To anticipate that possibility, antennas larger than 12m could be considered, cooled feeds could be used to reduce Tsys, or larger existing antennas could be used in conjunction with the 12 m atennas to produce baselines with enhanced sensitivity.

9. Conclusion

It has been shown that, in the absence of known risk factors, it should be feasible by 2010 to build practical systems that will allow observation density to increase by an order of magnitude. Potential benefits have been discussed. To proceed beyond this point, a thorough theoretical examination of all known risks needs to be carried out. After that, if warranted, performance tests should begin using a prototype system.

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