W.T. Petrachenko et al.: Multi-Beam VLBI, IVS 2002 General Meeting Proceedings, p.162–166
http://ivscc.gsfc.nasa.gov/publications/gm2002/petrachenko

Multi-Beam VLBI

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Abstract

In comparison to GPS, VLBI, as it is typically practised today, suffers from the fact that at any location only one source can be observed at a time. In this paper, we ask the audience to consider a world in which each VLBI reference location is equipped with a cluster of small antennas. Fringe detection limitations experienced by the small antenna pairs can be overcome by using large antennas for SNR enhancement and then mathematically forming the cluster-cluster observables after the fact. The resulting network, if the co-located antennas are carefully tied together, could perform multi-beam VLBI. By having multiple beams in different directions, parameter correlations could be reduced and parameters of interest could be determined more quickly and accurately. Taking advantage of new developments in the astronomical community, inexpensive antennas may be available to make this dream a reality. Advantages and limitations of this approach will be considered. The resulting advancement in geodetic VLBI science may be significantly more cost-effective than simply increasing the recording bandwidth. This presentation is intended to generate further discussion and lateral thinking about the future of geodetic VLBI.

1. Introduction

Ever since the first successful demonstration of VLBI, recording technology has been a dominant focus of VLBI development. However, with the advent of low cost high capacity off the shelf discs and the anticipation of low cost global fiber/optic connections, simple economical solutions to VLBI's data transmission problem can at long last be envisioned. With the data transmission problem in principle solved, now is an opportune time for IVS Technology Development Centers to turn their focus to the many other factors that limit VLBI and to work out a comprehensive technological vision for the future that addresses as many of these factors as possible.

It is in this spirit that we embarked on the present investigation. It eventually led us to consider an innovative implementation of the concept of "multi-beam" VLBI. "Multi-beam" VLBI refers to the ability of an interferometer baseline to observe more than one source at a time. Technologically this can be achieved a number of different ways such as with multi-beam phased arrays or Lunenberg lenses. However, the most obvious approach, the one considered here, is to use multiple antennas at each station. Although the concept is not new [1], and its benefits are widely understood, it has never been implemented due to the excessive cost of clusters of large antennas. The challenge of this paper will be to show that there is in fact an affordable solution to the problem that uses clusters of small low cost antennas in conjunction with a few large antennas for sensitivity enhancement. In fact, it will be shown that the cost of each cluster can be reduced to the extent that significantly larger geodetic VLBI networks can be considered.

2. Search for a Low Cost Geodetic VLBI Antenna

Although geodetic VLBI has a potential performance advantage over other space geodetic techniques due to its use of the stable quasar reference frame it is not currently fulfilling this promise. This results at least partially from the high capital and operating costs associated with the large antennas used to collect the weak quasar signals. These high costs, in turn, result in VLBI networks that are undersized and observations that are comparatively infrequent. This investigation began with a desire to see whether the "commercial off the shelf" (COTS) principle, already used to such good advantage in recording technology, could be extended to the design of a complete low cost geodetic VLBI station. In particular, a solution was considered involving widely available commercial satellite technology. News of progress being made on the Allen Telescope Array (ATA) to apply this principle to the development of a low cost radio antenna with large collecting area provided further encouragement.

The ATA is a joint project of the SETI Institute and the University of California, Berkeley. The purpose of the project is to design and build a one-hectare microwave collecting area for less than $26,000,000 US. First light for the instrument is expected some time around 2005. It is one of five competing technologies for the Square Kilometer Array.

Loosely speaking, the ATA can be described as a field of phased satellite antennas, with the current design employing 350 6.1m antennas. Although the antennas take their inspiration from the satellite industry, their projected performance far exceeds that of a typical backyard satellite dish as can be seen in the specifications summary in Table 1. The projected cost for an antenna including pier, pedestal, positioner, reflector, feed, LNA, fiber optic transmission system and RF-to-IF converter is about $50,000 when produced in large quantities.

Table 1. Projected ATA Antenna Specifications

Diameter	6.1m
Focus	Offset Gregorian
F/D	0.4
Efficiency	63%
Positioner	Alt-Az
Feed	Pyramidal log periodic
Polarization	Dual linear
Tsys goal	35K
RF Band	0.5 to 11 GHz

One interesting characteristic of the ATA antenna that is worth mention in the context of geodetic VLBI is that the antenna, feed, LNA and RF-to-IF electronics can all handle the full continuous frequency band from 0.5 to 11 GHz. This is an essential specification for the ATA to avoid the need to change 350 "front-ends" every time a new frequency band is selected. For geodetic VLBI, it has the benefit of enabling phase connection across more than 10 GHz. This, in turn, enables the use of the phase delay observable even for modest SNR observations. This is important since it represents more than an order of magnitude improvement in delay measurement precision; and to make matters even better, this is coupled with a proportional decrease in the effect of systematic phase biases on the delay observable. Furthermore, continuous frequency coverage from 0.5 to 11 GHz provides access to the higher order ionospheric terms.

3. Baseline Sensitivity with an ATA Antenna

Whenever considering the effectiveness of a small antenna, the most obvious issue is one of sensitivity. Fortunately, the sensitivity of an interferometer baseline is proportional to the geometric mean of the diameters of its two antennas. Hence, a small antenna can achieve adequate baseline sensitivity provided that its partner antenna is sufficiently large.

In geodetic VLBI, the question of sensitivity has two facets. First, is the signal strong enough to determine delay and delay rate with sufficient accuracy; and second, can enough sources be detected at that SNR to provide the geometric strength to produce a well-conditioned parameter inversion? Based on these two considerations, a reasonable sensitivity criterion for an ATA-style antenna could be stated as follows: *A large fraction of the usual geodetic VLBI candidate sources must be detectable, with SNR >20, when the ATA antenna forms baselines with other IVS network antennas.* To see whether the ATA antenna meets this criterion, a list of 18 IVS antennas with SEFD <3500 and a list of 92 typical geodetic candidate sources were considered. A record rate of 1 Gbit/s and a scan length of 300s were assumed. For all 18 antennas, at least 95% of the sources achieve SNR=20 or better.

It is clear that an ATA-style antenna has more than adequate sensitivity when it observes along with any of the above 18 IVS antennas. However, using the same assumptions as above, it is also interesting to note that for a baseline that has ATA antennas at both ends, 71% of the 92 candidate sources are detectable at SNR=20. In short, a network, made up entirely of ATA-style antennas, is useable but probably not optimum until data rates beyond 1 Gbit/s become affordable.

4. A New Low Cost Geodetic VLBI Station

So far, we have been considering the antenna subsystems in isolation. However, there is more to a geodetic VLBI station than the antenna, e.g. hydrogen maser, data acquisition system (DAS), data recorder, monitor/control and ancillary data systems, and infrastructure such as power and shelter. Given that the maser and DAS are themselves costly items, it is not likely that a complete station can be constructed for less than $500,000 if traditional VLBI solutions are assumed. However, the application of a combination of innovation, modern technology and the COTS/MOTS principle to the design of these subsystems promises to greatly reduce their cost. In the case of the DAS, some examples of applying these approaches might include the use of low cost commercial satellite components, the use of high speed samplers coupled with a completely digital back-end, or perhaps the use of a single wide-bandwidth baseband channel along with a frequency switched local oscillator. In the case of the maser, it might be possible to replace it entirely with a lower performance clock and then achieve coherence through, for example, VLBI phase referencing to geostationary satellites.

5. "Multi-beam" VLBI

A small antenna paired with a large antenna for sensitivity enhancement is not a new idea in geodetic VLBI. In fact, it was this principle that made the use of the small mobile MV antennas practical during the Crustal Dynamics Project (CDP). However, in the CDP, a single small antenna was used in an array of large antennas. Here we consider the opposite, a network with a single large antenna and numerous small antennas. The main attraction of this network architecture is that the incremental cost of adding new VLBI stations is greatly reduced, making larger networks affordable. Although the performance of the new low cost geodetic VLBI stations and the proposed network architecture is promising, with an additional twist to the configuration, the potential for performance improvement is even more impressive.

Since antenna cost is low, the idea is to equip each station with more than one antenna, each observing a different source, i.e. multi-beam VLBI. This mode of operation has two important benefits. First, because of the multiple antennas used, significantly more scans can be acquired per day. This is an important figure-of-merit with respect to improving the conditioning of VLBI parameter inversions. Second, since the hydrogen maser reference oscillator is common to all antennas in the cluster, its corrupting effect disappears when data is differenced between antennas. Removal of clock terms from the parameter list also greatly improves the conditioning of the parameter inversion.

The procedure that enables the use of clusters of *small* antennas is simple. For sensitivity enhancement, each of the small antennas in a cluster observes along with one large antenna. In other words, if there are four antennas in each cluster, then a total of four large antennas will be required. Antenna number 1 in each cluster will observe with the first large antenna; antenna number 2 in each cluster will observe with the second large antenna; and so on. Fringes are only detected on baselines that include one small and one large antenna. Observables on the baselines between pairs of small antennas, although often too weak to be detected, are determined mathematically after the fact through differencing.

6. A Vision for the Future of Geodetic VLBI

In this final section, we challenge the reader to consider the following list of performance benefits of a new IVS reality that includes a network of identical low-cost multi-beam VLBI stations.

1. **Larger networks.** With the greatly reduced incremental cost of adding VLBI stations, much larger networks become affordable. A larger network has the potential of adding accuracy and robustness to VLBI solutions.

2. **Improved site selection.** For practical reasons, early VLBI stations were often acquired on an “as is, where is” basis. Assuming that a new large VLBI network is being planned, station locations can be selected according to merit, based on, for example: achieving uniform global coverage; occurrence of benign tropospheric conditions; accessibility to infrastructure such as power, advanced communications networks and personnel; geological stability; accessibility of bedrock; lack of interference; nearness to other fundamental geodetic measurements; etc.

3. **More scans per day.** Obviously, if several antennas are observing simultaneously at each station, more scans can be acquired per day. This tendency is further augmented by the fact that, with multiple antennas, each antenna can be assigned a different region of the sky, which significantly reduces slew distances. Finally, it is also easier to implement high slew rates on small antennas. This will have a more significant impact when data rates become high enough that the large antennas will not be required for SNR enhancement and can be eliminated entirely.

4. **Simultaneous scans and the removal of clock terms.** With a multi-beam VLBI station, scans on different antennas can be arranged to be simultaneous. Since the H maser clock is common to each antenna, its effect then disappears when observables are differenced between

antennas. The ability to remove clock terms from parameter adjustments may have a profound effect on performance. A simulation of a typical NEOS observation, with and without the inclusion of clock terms in the adjustment, showed that a factor of 3-4 improvement in EOP precision could be achieved when the clock terms were removed.

5. **Increased Data Rate.** Current trends indicate that disc capacities and fiber/optic data rates and costs, with their huge commercial drivers, will continue to improve at a rapid and exponential rate into the foreseeable future. Geodetic VLBI as it is currently practised does not stand to reap significant benefits from these industry advances since typical schedules are already slew time dominated. The multi-beam proposal, with its bias towards low sensitivity, stands to benefit from increased data rates well into the future. If data rates continue to increase, the obvious next step for multi-beam VLBI is to operate without the assistance of the large antennas used for sensitivity enhancement.

6. **Unattended operation.** The current state of communication systems, antenna controllers and record systems is such that automatic operation of a modern VLBI site is an attainable goal. In fact, it is probably a necessary goal if regular operations with a large network are to be practical. With the exception of trouble-shooting, routine maintenance, and shipping of record media, it should be possible to design stations to be robust and to operate completely unattended.

7. **Spanned bandwidth enhancement.** With the technologies used in the ATA antenna system, continuous bandwidth coverage in the range 0.5 to 11 GHz can be achieved. This opens up the possibility of using phase delay observables even for modest SNR observations. This will result in more than an order of magnitude improvement in delay observable precision and a proportional reduction in contributions of phase biases. The wide continuous frequency coverage also opens up the possibility of a higher order ionospheric correction.

8. **Stiffer antennas.** Small antennas tend to be stiffer than large antennas. This eases the requirements for modeling gravitational deformation. Thermal deformations are also smaller.

9. **Better survey ties.** It is assumed that it would be easier with a small antenna to implement a design for efficient and accurate survey ties to local networks.

10. **Efficient station development.** Assuming that a new large VLBI network is being planned, the opportunity exists to deploy identical stations at each site. This would allow funds to be focused on the design of an optimized station, with development costs being amortized among all the network stations. A coherent station design would also improve maintenance efficiency.

References

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