IVS/IGS/ILRS Working Group on GPS Phase Center Mapping

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Abstract

A joint working group composed of representatives from the IVS, IGS, and ILRS is investigating the feasibility of using VLBI observations of GPS satellites to measure the phase center locations of the satellite transmitter antennas. This report describes the motivation behind the investigation, the organization of the working group, and some key points from the initial discussions.

1. Motivation for establishing working group

Accurate knowledge of the location of the phase center of each GPS satellite transmitter antenna is essential in high-accuracy GPS geodesy. Estimates of the scale of the terrestrial reference frame (TRF) and of station zenith tropospheric delays are particularly sensitive to the phase center z-component, along the direction from the satellite toward the geocenter. A change of 1 meter in the assumed z-component for all satellites causes a change in the terrestrial scale of $\sim$8 ppb (50 mm in station height) and a change in zenith delay of $\sim$5 mm.

Several related pieces of evidence point to significant errors in the phase center locations assumed in most GPS geodetic analyses. The instantaneous location of each satellite is normally set equal to the vector sum of (1) the instantaneous position of the satellite center of mass, which is believed to be known to < 10 cm in all three dimensions from GPS orbital solutions and from SLR rangings on selected satellites, and (2) the nominal offset between the phase center and the center of mass. When global GPS data sets are analyzed with these phase center locations and with absolute phase patterns for the GPS receiving antennas, the scale of the GPS TRF is found to differ from the scale of the VLBI and SLR TRF's by $\sim$15 ppb, or 10 cm in station height [1, 2]. An adjustment of the z-component of the phase center offsets by 2 m brings the scale of the GPS TRF into agreement with VLBI and SLR. Furthermore, if the phase center z-component offsets are estimated from the GPS data, differences from the nominal offsets of 1–2 m are found [1, 2].

The immediate impetus for the formation of the IVS/IGS/ILRS joint working group (WG) on GPS phase center mapping was a series of discussions at the IGS Analysis Center Workshop at the Scripps Institution of Oceanography in 1999 regarding the uncertainty in the location of the phase centers of the GPS satellite transmitters. It was suggested at the workshop that VLBI observations of the satellites could provide independent information on the phase center locations, including perhaps the relative locations for the 12 individual radiating elements in the phased array transmitters. An informal request was made to the IVS to lead an investigation of the feasibility of such observations.

2. Establishment and organization of working group

At the second IVS Directing Board meeting in July 1999, the board decided to establish a working group on this matter and to invite the IVS, IGS, and ILRS chairs to nominate representatives to serve on it. The charge to the working group was to study the feasibility of the proposed VLBI observations, the equipment and time required, and the expected accuracy of the phase center location estimates.

Following the nomination of members from the three services, the WG was officially established under the rules of the IVS at the third IVS Directing Board meeting on 20 Feburary 2000. The members of the WG are:

Graham Appleby	ILRS-nominated representative
Richard Biancale	ILRS-nominated representative
Brian Corey	IVS-nominated representative and WG chair
Tom Herring	IGS-nominated representative
Ed Himwich	IVS-nominated representative
Axel Nothnagel	IVS analysis coordinator, *ex officio*
Wolfgang Schlüter	IVS chair, *ex officio*
Tim Springer	IGS-nominated representative
Nancy Vandenberg	IVS coordinating center director, *ex officio*

The initial meeting of the WG was held on 23 February 2000 in Kötzting, Germany, during the first IVS General Meeting. The purpose of the meeting was primarily organizational, but some technical issues regarding the phase center estimates from GPS observations and the proposed VLBI measurements were also discussed.

3. Initial working group activities

A WG web site was set up in March 2000 at

`http://ivscc.gsfc.nasa.gov/WG/wg1`

Background information on the phase center problem, general information on the WG, and a WG email archive are available on the web site.

Following official notification of the IGS and ILRS chairs by the IVS chair that the WG had been established, a general email announcement was distributed to the IGS, ILRS, and IVS communities to inform them of the existence and purpose of the WG. The announcement included an invitation for interested individuals with expertise in relevant fields to participate in the WG studies. In response to this invitation, the following IVS members have joined in the WG discussions: Wayne Cannon, Hayo Hase, Maria Rioja, David Shaffer, and Vincenza Tornatore.

4. Summary of technical discussions in 2000

There are two related goals to the proposed VLBI observations:

A. Measure the mean phase center location of the full, 12-element phased array on each satellite.

B. Measure the relative signal phase and drive level of the 12 individual radiating elements in each array.

The results of A could be compared directly against the GPS estimates, while the results of B might provide clues to help understand the GPS and VLBI mean phase center results. The key questions to be answered regarding both types of measurements are what the potential accuracy is and what the technical roadblocks are to observing the satellites with a VLBI network, correlating the VLBI data, and analyzing the results. The investigations to date have concentrated on assessing the limitations on accuracy.

4.1. Measuring the mean phase center location

VLBI phase center measurements will likely employ an observing strategy similar to narrow-field VLBI astrometry, in which the VLBI antennas alternately observe a target source (in this case, a GPS satellite) and one or more extragalactic reference sources of accurately known position that lie near the line of sight to the target. The small angular separation between target and reference is intended to minimize errors from propagation media effects and from uncertainties in various global parameters such as station locations. The nature of the GPS orbits sets two different types of limits on how small the target-reference separation can be made:

- With an orbital period of 12 hours, a satellite moves 1° every 2 minutes. A reference source that lies right on the path of a satellite will remain within 5° of the satellite for only 20 minutes, or a few antenna nodding cycles between satellite and reference.
- For a 5000-km baseline transverse to the satellite nadir direction, the parallax on the satellite between the two ends of the baseline is 14°. If a reference source is coincident in direction with a satellite at one station, it will be 14° from the satellite at the other station.

In order to measure the phase center z-component to 20 cm accuracy (5σ over 1 m), say, the differential range from satellite to ground between nadir and Earth limb (which is 14° away from nadir) must be measured to an accuracy of $(20\text{ cm}) \times (\cos 0^\circ - \cos 14^\circ) = 6$ mm, or 11° phase at the GPS L1 frequency of 1575 MHz. All error sources that affect the VLBI phase or delay must be accounted for, to this level of accuracy. These error sources, which are currently under investigation, include:

- Reference source positions — The L-band positions of the reference sources in the global celestial reference frame must be known to $\sim$0.2 mas to achieve the accuracy goal. Global S/X-band astrometry on compact sources can achieve such small uncertainties, but reaching this level at L-band may be difficult.
- Ionosphere — The typical differential L-band ionospheric delay between two directions 5° apart is 1–2 orders of magnitude larger than the error budget, so the ionospheric delay between satellite and reference sources must be either measured or modeled. Ionospheric total electron content models derived from global GPS data appear to be too inaccurate [3]. The best approach may be to use the VLBI observations on the satellite and reference sources to estimate the differential ionospheric delay directly from the fringe phase difference between the GPS frequencies L1 and L2, in a manner similar to a technique developed for L-band pulsar astrometry [4].
- Troposphere — The tropospheric delay can be estimated from GPS measurements with colocated geodetic GPS receivers. Systematic errors in the estimates of the differential tropospheric delay across 5° should be $\sim$3 mm.
- Instrumentation — When pointing at a GPS satellite, the antenna temperature for a 20-m antenna is of order 20,000 K over 20 MHz. Such high levels may cause problems with saturation and distortion in the electronics, particularly in the VLBI baseband converters.

4.2. Mapping the satellite phased array

The second goal of the VLBI observations, which is equivalent to measuring the aperture field distribution of the phased array, will almost certainly be more difficult to achieve than the first.

The applicable technique is microwave holography, in which the far-field amplitude and phase pattern of the test antenna (the GPS transmitter, in this case) is measured over a grid of points spaced wavelength/(aperture size) radians apart; the Fourier transform of the pattern gives the aperture distribution. For the GPS phased array, the grid spacing is 13°, so Earth-bound observers can measure the far-field pattern at only a few grid points, and the resolution on the aperture field map will be very poor – only slightly better (*i.e.*, smaller) than the overall size of the array itself. Super-resolution techniques can sometimes be employed to improve the resolution, but they typically require very accurate phase and/or amplitude measurements, which the error sources noted above may well preclude.

References

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[4] Brisken, W.F., *et al.*, "Measurement of the parallax of PSR B0950+08 using the VLBA," Astrophys. J., **541**, pp. 959-962, 2000.