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How and Why to Do VLBI on GPS

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Abstract

In order to establish the position of the center of mass of the Earth in the International Celestial Reference Frame, observations of the Global Positioning Satellite (GPS) constellation using the IVS network are important. With a good frame-tie between the coordinates of the IVS telescopes and nearby GPS receivers, plus a common local oscillator reference signal, it should be possible to observe and record simultaneously signals from the astrometric calibration sources and the GPS satellites. The standard IVS solution would give the atmospheric delay and clock offsets to use in analysis of the GPS data. Correlation of the GPS signals would then give accurate orbital parameters of the satellites **in the ICRF reference frame**, i.e., relative to the positions of the astrometric sources. This is particularly needed to determine motion of the center of mass of the earth along the rotation axis.

1. Background

Methods of observing the Global Positioning System (GPS) satellites with the International Very Long Baseline Interferometry Service for Geodesy and Astrometry (IVS) telescopes have been discussed for more than a decade (Hase 1999 [9], Petrachenko et al. 2004 [12]). The motivation is to measure the orbits of the GPS spacecraft in near-real-time with high precision **directly in the reference frame** defined by the extragalactic radio sources, i.e., the International Celestial Reference Frame (ICRF, Ma 2008 [11], Boboltz et al. 2010 [5]). The challenge of extending the ICRF to the International Terrestrial Reference Frame (ITRF) involves combining data from other sources such as Satellite Laser Ranging (SLR), the Gravity Recovery and Climate Experiment (GRACE), the Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) systems, and measurements using GPS receivers themselves (e.g., Argus et al. 2010 [2], Tregoning et al. 2009 [14]).

A particularly important issue is the motion of the Earth's center of mass (CE). A discrepancy between the ITRF2000 and ITRF2005 suggests that the mass distribution of the Earth is changing in such a way that the CE is moving northward at a rate of 1.8 mm yr^{-1} (Altamimi et al. 2007 [1], Tregoning and Watson 2009 [15]). If this motion were real it would raise problems with other precision measurements such as sea level rise and glacial isostatic adjustment (e.g., Beckley et al. 2007 [4]). The problem is the reference frames themselves. While SLR, GRACE, and DORIS are ultra-sensitive to the Earth's gravitational field, the IVS solutions for the Earth Orientation Parameters (EOPs) are sensitive only to the rotation of the Earth's surface. The frame-tie between the ICRF and the satellite orbits (measured in the ITRF) introduces uncertainty in the CE position at the level of millimeters. This frame-tie could be simplified by correlating the GPS signals along with those from the ICRF-defining quasars as part of the IVS operation.

The CE position could be a sensitive measure of the global average of glacial melting, given the asymmetry of the latitudinal distribution of land and sea between the Northern and Southern Hemispheres. Melting of sea ice has no impact on the CE, but melting of ice caps such as those in

Greenland and Antarctica leads to a redistribution of the mass as the melt water adjusts to follow an equipotential. This glacial melting contributes to sea level rise, and so it has been studied quantitatively (Bahr et al. 2007 [3] and references therein); the mass of ice whose melting gives a rise in the mean sea level of 1 mm is $m_i = 3.3 \cdot 10^{14}$ kg (Dyurgerov and Meier 2005 [7] figure 5 ff). Comparing this to the total Earth mass gives a prediction for the motion of the CE along the axis of rotation of $\dot{z}$:

$$\dot{z} \;=\; -\, R_\oplus \left(\frac{f\; m_i}{2\; M_\oplus}\right) \left(\frac{\dot{s}}{\text{mm yr}^{-1}}\right) \;\simeq\; -0.4 \text{ mm yr}^{-1}$$

where $R_\oplus$ and $M_\oplus$ are the Earth radius and mass, and f is a dimensionless number between -1 and +1 given by the mass-weighted mean of the sine of the latitude where the ice melts. Assuming that $f \sim 1$ gives the value of -0.4 mm yr^{-1} above, with the minus indicating southward motion because most glacial melting is (for now) in the Northern Hemisphere. More accurate measurement of the motion of the CE would be a valuable addition to our knowledge of the effects of global warming (Dickey et al. 2002 [6]). This could be accomplished by determining the orbital parameters of the GPS satellites directly from measurements coupled with routine IVS observations. Combining the two would circumvent the need for a series of techniques, each based on a different observable, to establish the CE together with the ITRF itself. The main advantage of combining IVS and GPS satellite orbit measurement is not improved precision in the measurements, although that might be possible, but rather the direct measurement of satellite orbits relative to the ICRF calibrators.

2. IVS Techniques

The simplest approach (method 1) to measuring GPS signals with the IVS array is to use the radio telescopes themselves to record the GPS signals, and then to correlate these signals to determine the delay on each baseline and hence the position of each satellite as a function of time. The radio telescope beams are narrow, so that the satellites are observed one at a time, and their approximate positions must be tracked using an ephemeris. The main disadvantage of this method is that the GPS signals are in the 1500-1600 MHz and 1200-1300 MHz ranges, which are well below the S-band (2100-2400 MHz) frequencies of the IVS receivers. Thus new, wideband receivers would have to be built for all the network telescopes, in order to accommodate observations of both GPS and the standard IVS calibration sources together.

A more ambitious but ultimately simpler method (method 2, illustrated in Figure 1) is to use a standard, geodetic-quality GPS antenna and receiver near each IVS telescope, using local oscillators locked to the same station clock for the GPS and IVS receivers and simultaneously recording the receiver outputs on separate channels on the same media. A precise frame-tie or survey of the relative positions of the two antennas is also needed. The GPS antennas are nearly omni-directional and so they receive the signals from all satellites that are above the horizon. Correlating the outputs from the GPS receivers should give multiple delay peaks on each baseline, one for each spacecraft. With three or more baselines the positions of all the satellites can be fixed, and their orbital parameters determined from the position vs. time over an extended observation. Note that it is the carrier signal that gives the correlation peak and hence provides the relative delay on each baseline; there is no need to decode the information carried in the modulation of the carrier as for normal GPS operation.

The main advantage of the second method is that the radio telescopes simultaneously carry out normal IVS observing, so that the correlation and position solutions from the ICRF sources

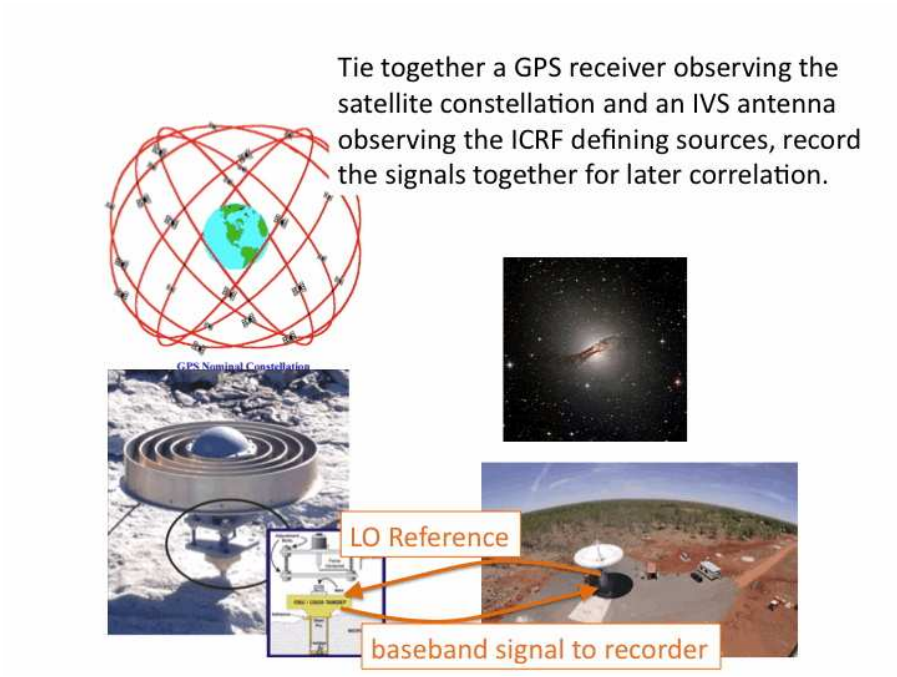

Figure 1. An illustration of the second method for combining observations of the GPS signals with the IVS calibrators. The advantages of recording signals from two antennas simultaneously at each station outweigh the difficulties of measuring the offset between the two, both in position and in the LO/RF round-trip delay.

provide clock offsets, EOPs, and atmospheric delays at all times during the observation. These results can be extended to the frequency of the GPS to predict values for the propagation delay through the neutral and ionized components of the atmosphere. Determination of the clock offsets effectively puts the GPS satellite positions in the reference frame of the astronomical sources. This accomplishes the frame-tie that allows the CE to be **directly measured in the ICRF** with a single technique. Other satellite measurement techniques could still improve the precision of the measured CE position, but the fundamental reference frame of the measurement would become the ICRF rather than the ITRF. This avoids problems with the registration (offset) of one reference frame relative to the other.

3. Applications

Evidence of the need for better long-term monitoring of the GPS orbital elements in the ICRF frame comes from comparison of time series of terrestrial reference positions using GPS and GRACE. Figure 2 from Tregoning and Watson (2009 [15]) shows the time series and resulting power spectrum of a reference point near Darwin, NT. There is strong vertical motion with an annual period resulting from seasonal groundwater variation. Unfortunately, determination of this variation, and hence of the groundwater supply in the region, is confused by another effect with a similar period, the synodic period of the GPS constellation or draconitic period, 351.4 days. The GRACE and GPS positions agree well except for periods between 0.5 and 1.5 years in the vertical direction as seen in Figure 2. This problem could be alleviated by independent measurement of the

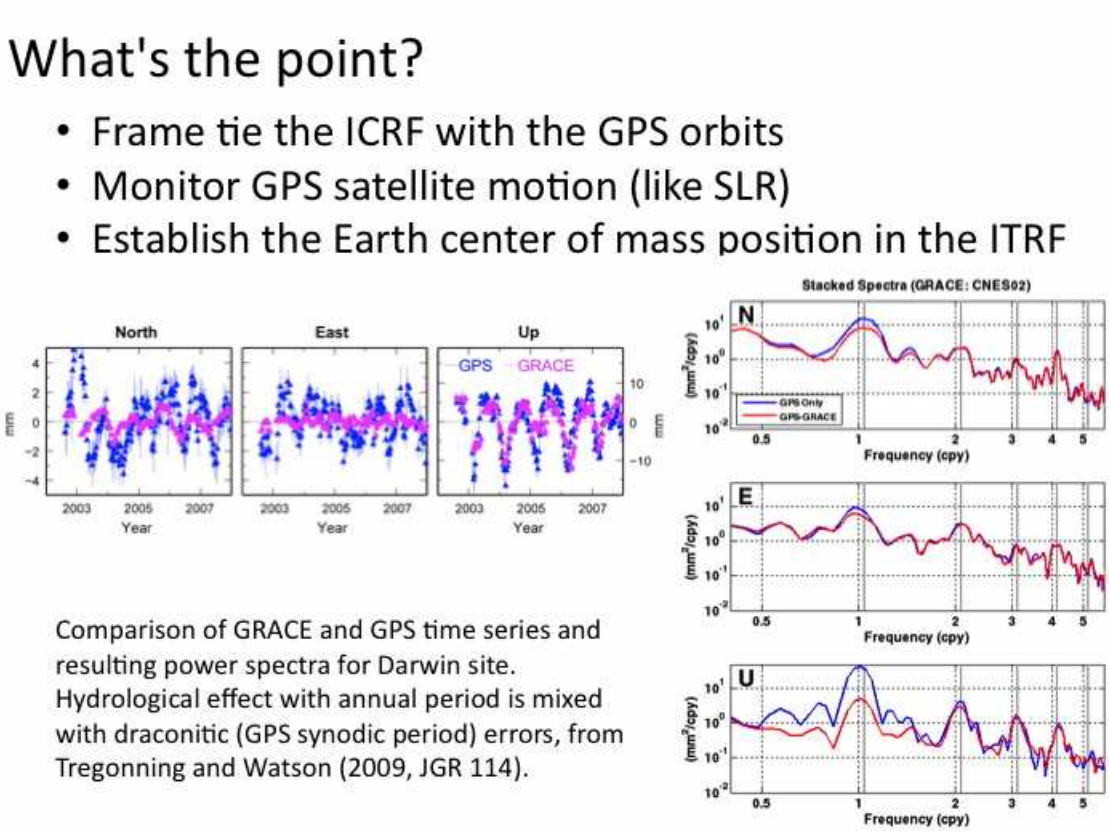

Figure 2. An illustration of the current problem with GPS orbital elements. At the draconitic period of the GPS satellites, i.e. the synodic period of the constellation as a whole, there is a significant discrepancy between position measurements using GRACE and those using GPS. The figures are taken from Tregoning and Watson (2009) [15], who studied time series of positions for a geodetic reference site near Darwin, NT.

GPS satellite positions in the ICRF, that could be provided by the extension of the IVS technique described here.

4. Conclusions

The modest proposal of this contribution is that IVS operations in the future should include recording of one or more bands in the 1.5 GHz range collected from a GPS receiver near the main radio astronomy antenna. The GPS receiver should have its local oscillator phase-locked to the station clock. As a preliminary experiment, three antennas could be equipped in this way for test observations. As an ultimate goal, the GPS signal from each satellite could be decoded to predict the delay expected on each baseline, to save time in the correlation step. Two very important steps toward the operation described here are the pioneering studies by Tornatore and Haas (2010 [13]) and Kwak et al. (2010 [10]) described in this volume.

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References

[1] Altamimi, Z., Sillard, P., and Boucher, C., 2002b, J. Geophys. Res., 107(B10), 2214, doi:10.1029/2001JB000561.

[2] Argus, D.F., Gordon, R.G., Heflin, M.B., Ma, C., et al. 2010, Geophys. Journal International 180, 913-960.

[3] Bahr, D.B., Dyurgerov, M., Meier, M.F., 2009 Geophysical Research Letters, 36, CiteID L03501.

[4] Beckley B. D., F. G. Lemoine, S. B. Luthcke, R. D. Ray, N. P. Zelensky, 2007, Geophys. Res. Lett., 34, L14608, doi:10.1029/2007GL030002.

[5] Boboltz, D.A., Gaume, R.A., Fey, A.L., Ma, C., Gordon, D., IERS/IVS Working Group on ICRF2, 2010, AAS Meeting 215 no. 469.06, BAAS 41, 512.

[6] Dickey, J.O., Marcus, S.L., de Viron, O., and Fukumori, I., 2002 American Geophysical Union abstract U72A-0013.

[7] Dyurgerov, M.B. and Meier, M.F., 2005, Glaciers and the Changing Earth System: A 2004 Snapshot, INSTAAR, Occasional Paper No. 58, (University of Colorado at Boulder: Boulder), ISSN 0069-6145.

[8] Fey, A.L., Ma, C., Arias, E.F., Charlot, P., Feissel-Vernier, M., et al., 2004, A.J. 127, 3587.

[9] Hase, H., 1999, Proceedings of the 13th Working Meeting on European VLBI for Geodesy and Astrometry, pp. 273-277.

[10] Kwak, Y., Kondo, T., Gotoh, T., Amagai, J., Takiguchi, H., et al., 2010, Proceedings of the Sixth General Meeting of the IVS, in press (this volume).

[11] Ma, C. 2008, Proceedings of IAU Symposium 248, p. 337.

[12] Petrachenko, W. et al. 2004, IVS 2004 General Meeting Proceedings, ed. N.R. Vandenberg and K.D. Bavar, NASA/CP-2004-212255, 2004.

[13] Tornatore, V. and Haas, R., 2010, Proceedings of the Sixth General Meeting of the IVS, in press (this volume).

[14] Tregoning, P., Ramillien, G., McQueen, H., and Zwartz, D., 2009, J. Geophys. Res., 114, B06406, doi:10.1029/2008JB006161.

[15] Tregoning, P. and Watson, C.S., 2009, J. Geophys. Res.,, Vol. 114, No. B9, B09403, doi:10.1029/2009JB006344.