Limits to the Stability of Phase Transfer from Ground to Space

by

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ABSTRACT

An alternative to having a primary frequency standard on board a spacecraft is to phase lock a simple oscillator on the spacecraft to a microwave tone transmitted from the ground. The received tone is transponder and rebroadcast to the ground. The round trip phase is measured, and used to correct for effects on timescales longer than the round trip light travel time. This method is used with the TDRSS relay satellites, and will be used for the Japanese space VLBI mission VSOP. There are several sources of error introduced by this process.

The most important error source is a loss of the on board standard for all times that the satellite is out of contact with a ground tracking station. The fractional loss will be > 10% for almost any orbit, even with a network of several ground tracking stations, and it will be considerably worse for a low earth orbit. Only a geostationary orbit can eliminate this problem.

Another error source is connected to the previous one. Round trip phase tracking can remove, after the fact, link effects during a tracking pass on timescales greater than the round trip light travel time. However, there will be a jump in the spacecraft clock when multiple passes are connected (e.g. when the spacecraft is reacquired after passing out of sight). These jumps will be equal in magnitude (except for a geometrical factor) to the accuracy with which the spacecraft orbit is known. With a GPS receiver and GPS-like beacon on a spacecraft, the orbit can be known to a few cm, giving timing jumps on the order of 100 picosecond. Even with a geostationary orbit, these jumps would occur any time the link was interrupted due to mechanical or electrical problems.

I. BACKGROUND

Flying an on board, high precision clock will introduce cost, mass, and power penalties to a mission. Therefore, it is useful to consider the option of phase transfer from a primary clock on the ground. Such a process is used for space VLBI, in which a radio telescope in earth orbit observes simultaneously with a network of ground radio telescopes. Space VLBI observations were successfully conducted using an antenna on a TDRSS satellite in 1986-1988 (Levy *et al.*, 1986), and they are planned for the VSOP mission, scheduled for launch in Feb. 1997 (Hirabayashi, 1991). VLBI observations (Burke, 1969) require excellent

(Hydrogen maser quality) frequency stability on timescales up to $\sim$ 5(IO s, but are relativel$_y$ insensitive to variations on longer timescales.

II. PHASE TRANSFER FOR SPACE VLBI

For the TDRSS space VLBI observations, an existing (non optimized) system was used (Levy *et al.*, 1989). For VSOP, a customized phase transfer system has been designed, with link frequencies in the 15 GHz band (Springett, 1992). A predicted spacecraft orbit (based on tracking measurements over the previous week) is used to generate an uplink signal. If the predicted orbit were perfect, the received on board signal would be monochromatic (ignoring media effects) at the nominal frequency. The 6 hour elliptical orbit of VSOP involves spacecraft velocities, relative to a ground tracking station, of up to ± 9 km/s. The predicted orbit will be accurate to $\sim$ 1 m/s @stefan, Christensen, and Ellis, 1991).

The uplink signal is used to phase lock an on board oscillator that has good stability on timescales < 1 s. This oscillator is then used 1) to mix the amplified signal from a radio source to baseband before it is sampled and digitized, 2) to generate a clock to time tag these samples before they are transmitted to the ground, and 3) to generate a downlink signal coherent with the uplink.

The phase of this downlink signal is measured, and compared against the value expected from the predicted orbit. The residual phase (Measured-Predicted) is used during VLBI data correlation to correct the on board oscillator 'after the fact.' Any non dispersive error source on timescales significantly greater than the round trip light travel time ($\leq$ 0.19 s for VSOP) will be corrected. Orbit prediction errors and static troposphere delays fall into this category. Analysis has been clone on the effect of the earth's ionosphere (Linfield, 1996b) and on fluct uat ions in the cart h's troposphere (Linfield, 1996a). The conclusion is that the coherence of the phase transfer, after correction with round trip measurements, will be > 99.5% at 22 GHz (the highest observing frequency of VSOP) over t imescales < 1000 s (see Thompson, Moran, and Swenson, 1986 for a definition of coherence as applied to VLBI). This is much better than the coherence of a hydrogen maser, so that the overall coherence of the orbiting telescope will be limited by the ground frequency standard.

III. ADVANTAGES AND DRAWBACKS

Using a phase transfer system instead of a precise on board clock on a earth orbiting spacecraft would save significant mass, power, complexity, and cost on the spacecraft. The on board mass and power requirements for phase transfer are likely to be in the 10 kg and 10 W range. However, there are some serious drawbacks for most applications.

The most serious drawback is that the on board clock can only operate intermittently, because it requires two-way communication with a ground tracking station. For the elliptical orbit of VSOP (1000 km perigee; 20,000 km apogee), a global network of 5 ground tracking stations will allow tracking $\approx$ 80% of the time. For a geostationary orbit, one ground station could provide 100% coverage; for a low cart h orbit, the fractional coverage would be quite small with any plausible ground network. In addition, the cost of tracking station time may be a significant issue for phase transfer.

For space VLBI, these two issues are not a concern. The data rate generated during VLBI observations is so large (128 Mbit/s for VSOP) that on board storage is not feasible. Therefore, a real time downlink to a sizable ($\geq$ 10 m diameter) ground tracking station is required for observations, even with an on board clock.

When the round trip link is reestablished after a break (such as that due to the spacecraft dropping below the horizon at a tracking station), there will be a clock jump, due to the uncertainty in the one way light travel time along the spacecraft-tracking station direction. With on board GPS receivers and G PS-like beacons, the reconstructed (after the fact) orbit error can be as small as $\sim$ 5 cm for a VSOP-like orbit (Wu and Malla, 1994), giving a clock jump of $\sim$ 170 picosec.

A final limitation is that some effects of science interest (e.g., gravitational redshift) require a primary frequency standard on board as well as one on the ground, and cannot be measured using round trip phase.

REFERENCES

B. F. Burke, "Long Baseline Interferometry," *Physics Today*, vol. 22, No. 7, pp. 54-63, 1969.

J. Estefan, C. Christensen, and J. Ellis, "Japanese and DSN Orbit Prediction Capability for the VSOP Mission," July 1, 1991, JPL Space VLBI Memo #72, available electronically at
http://sgra.jpl.nasa.gov/mosaic_v0.0/JPL_Project_dir/Library_dir/memo/y91/91_72.txt

H. Hirabayashi, "Introduction to the VSOP Mission and Its Scientific Goals," *COSPAR: Adv. Space Res.*, vol. 11, No. 2, p. 173, 1991.

G. S. Levy *et al.*, "Very Long Baseline Interferometric Observations Made With an Orbiting Radio Telescope," Science, vol. 234, pp. 187-189, 1986.

G. S. Levy *et al.*, "VLBI Using a Telescope in Earth Orbit. I. The Observations," *The Astrophysical Journal*, vol. *336*, pp. 1098-1104, 1989.

R. Linfield, "Tropospheric Coherence in the Space VLBI phase Transfer Process. II. Inclusion of a Nonzero Phase Averaging Interval," April 2, 1996, available electronically at http://sgra.jpl.nasa.gov/mosaic_v0.0/JPL_Project_dir/Library_dir/memo/y96 (1996a).

R. Linfield, " Ionospheric Coherence Loss in the Space VLBI Phase Transfer Process," April 29, 1996, JPL Space VLBI Memo #288, available electronically at http://sgra.jpl.nasa.gov/mosaic_v0.0/JPL_Project_dir/Library_dir/memo/y96 (1996b).

J. C. Springett, "Phase Stable Frequency Transfer for Orbiting VLBI Radio Telescopes", NeoComm Systems, Inc. document, October 15, 1992.

A. R. Thompson, J. M. Moran, and G. W. Swenson, Jr. "Interferometry and Synthesis in Radio Astronomy,", pp. 277-278, John Wiley & Sons, New York, 1986.

S. C. Wu and R. P. Malla, "GPS-Based Precision Determination of Highly Elliptical Orbits for Orbiting VLBI Applications" *JPL Interoffice Memorandum, 335.8–94–004,* March 29, 1994.