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THE NEED FOR DOPPLER COMPENSATION IN THE PHASE UPLINK FOR VSOP AND RADIOASTRON

by

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SUMMARY

Implementing Doppler compensation on the phase uplink for VSOP and RADIOASTRON would add a small amount of complexity and cost to the ground tracking stations. However, it would yield major benefits for the two missions. Uplink Doppler compensation would reduce the S/N loss due to passband mismatch (a saving as large as 6%). It would essentially eliminate the coherence loss due to imperfect transponder operation. This coherence loss would cause a S/N loss as large as 5% if there were no Doppler compensation. More importantly, it would cause calibration errors on the science data of the same magnitude. Therefore, if we do not perform Doppler compensation on the uplink, the calibration errors on the measured correlated flux densities at 22 GHz would increase from 0.5% to 5%. The reduction in the dynamic range of the resulting images would be approximately a factor of 10, with a large degradation in the science return of the mission.

INTRODUCTION

Two space VLBI missions, VSOP and RADIOASTRON, are planned for launch in 1995. Neither mission plans to provide its orbiting radio telescope receiver with an accurate on-board frequency standard (*e.g.* a Hydrogen maser). Therefore, the spacecraft's local oscillator phase (stability) must be determined by a signal transmitted to the spacecraft from the ground (*e.g.* a DSN site).

Synchronization of local oscillator phase (often referred to as phase transfer), by means of a microwave radio link from the ground to the spacecraft, inevitably involves a very significant Doppler shift on the uplink frequency, as received by the spacecraft, due to the spacecraft's instantaneous radial velocity as it orbits the earth. This Doppler shift produces a number of problems allied to the radio astronomy receiving process and the ultimate coherence of the phase transfer reference. For these reasons, it is expedient to perform an operation, called Doppler compensation, wherein the bulk of the expected (predicted) Doppler frequency modulation is removed from both the microwave phase transfer uplink, and the return phase downlink (needed for the measurement of the phase degradation components).

From time to time, the necessity to perform Doppler compensation (at least in the manner that is currently proposed) has been brought into question. This memo therefore addresses the principal issues concerning Doppler compensation, and why real-time Doppler compensation of both uplink and downlink frequencies is appropriate.

TWO POSSIBLE PHASE TRANSFER SCHEMES

It has been questioned whether an uncompensated approach might not be used rather than some "sophisticated" compensated Doppler scheme. In the uncompensated mode a pure tone at a frequency ν_{up} would be broadcast from the ground station and received at the orbiter with a frequency $\nu_{up}\left[1 - v_{true}(t)/c\right]$, where $v_{true}(t)$ is the true orbiter-ground station velocity along the link direction, defined such that $v_{true} > 0$ when the orbiter-ground station distance is increasing. c is the velocity of light. In the Doppler compensated mode the frequency of the transmitted signal would be varied in phase-continuous steps to equal $\nu_{up}(1 + v_{pred}(t)/c)$, where $v_{pred}(t)$ is the orbiter-ground station velocity along the link direction as derived from the predicted ephemeris. The received signal on-board would be

$$\nu_{up}\left[1 + \frac{v_{pred}(t)}{c}\right]\left[1 - \frac{v_{true}(t)}{c}\right] = \nu_{up}\left[1 + \frac{v_{pred}(t) - v_{true}(t)}{c}\right]$$

which is close to the nominal uplink frequency ν_{up}. For simplicity, terms of second and higher orders in v/c have been neglected in this memo.

ROUND TRIP PHASE MEASUREMENT

With either scheme, the deviation of the on-board local oscillator (LO) from its nominal value must be known to better than about 100 mHz at the time of correlation. The most direct and accurate method of determining this deviation is to measure the round trip link phase by sampling and recording it for later use at the correlator. Such sampling and recording means that the bandwidth of the round trip phase, prior to sampling, should be made as small as possible. This requires that the bulk of the Doppler shift be removed by some mechanism. We now examine the two ways by which this may be done. The first approach would be to remove the two-way Doppler only at the ground receiver. A carrier is transmitted from the ground to the spacecraft, where it is coherently received and transponded to the downlink frequency. Doppler alters the frequency received on the ground with respect to a simple transponding-scaled uplink frequency. The received frequency is mixed with its predicted value, and the difference sampled and recorded. (In the following calculations, the acceleration of the ground station during the round trip link time has been neglected). In the uncompensated scheme, the received frequency at the ground $\nu_{rec}(t)$ is

$$\nu_{rec}(t) = \nu_{down}\left[1 - \frac{v_{true}(t)}{c}\right]^2$$

ν_{down} is the nominal downlink (no-Doppler) fequency. The predicted downlink frequency $\nu_{pred}(t)$ is

$$\nu_{pred}(t) = \nu_{down}\left[1 - \frac{v_{pred}(t)}{c}\right]^2$$

The difference $\nu_{diff}(t)$ between the received and the predicted downlink frequency is

$$\nu_{diff}(t) = \nu_{down}\left[\frac{2(v_{pred}(t) - v_{true}(t))}{c}\right]$$

In the Doppler compensated scheme,

$$\nu_{rec}(t) = \nu_{down}\left[1 + \frac{v_{pred}(t) - v_{true}(t)}{c}\right]\left[1 - \frac{v_{true}(t)}{c}\right]$$

$$\nu_{pred}(t) = \nu_{down}\left[1 - \frac{v_{pred}(t)}{c}\right]$$

$$\nu_{diff}(t) = \nu_{down}\left[\frac{2(v_{pred}(t) - v_{true}(t))}{c}\right]$$

The values of ν_{diff} are equal (to first order) for the two schemes. With either one, the term $1 + v_{pred}(t)/c$ must be calculated and used to coherently multiply a monochromatic signal. The first scheme requires a single phase continuous synthesis of the predicted Doppler, and one mixer for removal, while the second requires the same phase continuous synthesis of the predicted Doppler, one mixer to remove uplink Doppler, and a second mixer to remove downlink Doppler. Therefore, the second scheme requires somewhat more hardware, but this, we believe, is fully justified based upon the following considerations.

MISMATCHED PASSBANDS

In any VLBI observation, there will be some mismatch of passbands due to the difference in the LO values at two stations, as measured in an inertial frame. These mismatched LO's will cause a fractional loss $\Delta S/N$ in the signal-to-noise ratio (S/N) of

$$\Delta S/N = \frac{|LO_1 - LO_2|}{\nu_{ch}}$$

where ν_{ch} is the channel bandwidth and LO_1 and LO_2 are the LO's (in an inertial frame) at the two stations of a baseline. If the on-board LO frequency ν_{LO} were equal to its nominal value in the orbiter rest frame (this will be approximately true for the Doppler compensated scheme), the maximum LO offset would be $v_{per}\nu_{LO}/c \approx 0.7$ MHz for either orbiter at 22 GHz observing frequency. v_{per} is the maximum geocentric velocity (*i.e.* velocity with respect to the center of the earth) of the orbiter, which occurs at perigee. $\Delta S/N$ can be as large as 4% for VSOP ($\nu_{ch} = 16$ MHz) and 8% for RADIOASTRON ($\nu_{ch} = 8$ MHz). In the uncompensated case, the LO offset can be as large as $2\cos(\theta_{min}/2)\ v_{per}\nu_{LO}/c$, where θ_{min} is the minimum source-orbiter-telemetry station angle which is allowed by the spacecraft hardware. Current values of θ_{min} are 60° for VSOP and 55° for RADIOASTRON. *Therefore, the additional S/N penalty due to mismatched passbands can be as large as 3% for VSOP and 6% for RADIOASTRON with the uncompensated scheme.*

DATA CORRELATION

With either scheme, round trip phase measurements will determine the deviation of the on-board LO from its nominal value. Polynomial fits to this deviation will be made at the telemetry station and used at the correlator in the orbiter delay model. The reconstructed orbit ephemeris will be used to calculate the delay and phase along the orbiter-radio source direction due to orbital motion. An additional component of delay and phase derived from the round trip link phase measurement must be added to this model. This link phase correction term is just the error in the on-board LO in the rest frame of the orbiter. This term will be small (a few tens of Hz) with the Doppler compensated mode and large (hundreds of kHz) with the uncompensated mode. The link phase correction term will be used at the correlator in the form of polynomial spline fits. For the VLBA correlator, the very large link phase correction term resulting from the uncompensated mode can be accomodated. However, this may not be true of the Canadian and Japanese correlators. The Doppler compensated mode may be much easier to implement for these correlators because it makes the orbiting antenna seem more like a normal VLBI tation, with its local oscillator acting (to first order) like the primary frequency standard is on-board.

The large variation in the on-board LO with the uncompensated scheme can result in a larger delay rate. For the Doppler compensated scheme, the maximum delay rate $\dot{\tau}_{max}$ is $\dot{\tau}_{max} = v_{per}/c = 31\ \mu sec/s$ for VSOP. For the uncompensated scheme, the maximum delay rate is $\dot{\tau}_{max} = 2\cos(\theta_{min}/2)\ v_{per}/c = 53\ \mu sec/s$ for VSOP. With either scheme, the VLBA correlator will need to be modified to handle these large delay rates, and a delay rate of 53 $\mu sec/s$ would be no more difficult to handle than one of 31 $\mu sec/s$.

TRANSPONDER RECEIVER INDUCED COHERENCE LOSS

The spacecraft transponder receiver will be implemented (for both VSOP and RADIOASTRON) using 1) an analog, second-order, phase-locked loop (PLL), and 2) a multiple conversion receiver architecture, based upon LO frequencies derived from the Voltage Controlled Oscillator (VCO) of the PLL. Such implementations are known to produce significant amounts of non-reciprocal phase modulation when signals having large dynamic Doppler are received. Such non-reciprocal phase modulations will result in a coherence loss which can be neither corrected nor calibrated. (The term 'Dynamic Doppler' refers to the temporal frequency character of the received signal, and therefore includes the components referred to as Doppler, Doppler-rate, Doppler-acceleration, etc.).

The PLL tracks the instantaneous received uplink frequency, but does so imperfectly. The resulting error (called 'loop stress') is a function of the received dynamic Doppler. When a non-zero Doppler rate (quadratic phase component) is being tracked, it is accomodated by a second-order PLL only at the expense of a loop phase error which increases with time. Because the phase detector of the PLL has a sinusoidal error characteristic, the loop error can grow to the point where nonlinear operation begins (if the error gets sufficiently large, the loop will lose lock, or 'skip a cycle,' generating a phase jump of nearly 2π). Nonlinearities associated with the phase detector and other receiver circuits are also capable of generating a strong quadratic phase term under large dynamic Doppler conditions. Furthermore, a large instantaneous Doppler value will shift the frequencies within the IF passbands of the tracking receiver away from their nominal values. This will cause a phase modulation due to the phase-versus-frequency characteristics of these IF passbands. The final IF of the tracking receiver typically has a multi-pole filter and therefore large phase variations across the passband. The combination of these effects can contribute significant quadratic (and higher order) phase terms to the phase transfer process when the uncompensated scheme is used. We estimate that the dynamic Doppler rate (quadratic phase term) could cause a coherence loss as large as 5% for observations at 22 GHz.

If the phase modulation introduced by the transponder were highly reciprocal, its effect could be compensated by means of the round trip phase measurement, with the coherence loss eliminated. Unfortunately, this particular type of phase modulation is not at all reciprocal for the uncompensated scheme. This is because the ground PLL receiver will not contribute a 'like' phase modulation (*i.e.* an additional and nearly identical added due to the downlink dynamic Doppler), by reason of its being doppler compensated (see the above discussion under ROUND TRIP PHASE MEASUREMENT). Thus, the phase produced by the spacecraft receiver must be minimized either by design or by the use of uplink Doppler compensation. Moderation of dynamic Doppler effects by design is usually obtained by specifying the receiver IF and PLL to have wide tracking bandwidths and large open-loop gain. However, both the RADIOASTRON and VSOP transponder receiver implementations will not be new devices built especially for space VLBI, but will be based on older, less critical, designs. Since we cannot control the characteristics of the Soviet and Japanese receivers, the only way to eliminate the coherence loss from dynamic Doppler is to implement uplink Doppler compensation at the ground tracking stations.

The 5% coherence loss from an uncompensated Dopler would cause a reduction in S/N of the same magnitude, equivalent to a 5% reduction in the antenna diameter. However, the science loss would be much greater than implied by this S/N loss. S/N loss due to mismatched passbands is a deterministic effect which can be accurately calibrated (at the expense of extra complexity in the post-correlation data reduction process). Therefore, passband mismatch due to Doppler effects would not increase the calibration errors on the science data. *This is not true for the coherence loss resulting from a large Doppler-rate in the PLL. This coherence loss cannot be accurately predicted (or reconstructed) and would cause a calibration error comparable to the S/N loss. A 5% calibration error would violate the mission requirement by a factor of 10. It would cause a serious degradation in the science return (specifically, in the dynamic range of the images made at 22 GHz). To avoid this large science loss, Doppler compensation on the phase uplink is essential.*