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Demonstration of Use of a Reai Time Tone Tracker to Obtain Same Beam interferometry Data

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The radio metric tracking technique known as Same-Beam Interferometry (SBI) has been shown to improve orbit determination accuracy for the Magellan and Pioneer 12 orbiter. Previous efforts to explore the technique were carried out by making open loop recordings of the carrier signals from the two spacecraft and extracting their phases through post processing. This paper reports on the use of a closed loop receiver to simultaneously measure the carrier signals from two spacecraft in order to produce SBI data in near real time. The Experimental Tone Tracker is a digital closed loop receiver installed in two of NASA's Deep Space Network stations which can simultaneously extract the phase of up to eight tones. The receivers were used in late September and October of 1992 to collect Doppler and SBI data from Pioneer 12 and Magellan. The demise of the Pioneer 12 on October 8th during the start-up phase of our tests precluded the collection of an extensive set of SBI data, however two passes of SBI and several arcs of single spacecraft Doppler data were recorded, The SBI data were analyzed and determined to have statistical errors consistent with error models and similar to open loop data.

INTRODUCTION

Generally, orbit determination for planetary orbiters is performed by observing the time series of the Doppler shift of a radio signal from the spacecraft to earth. The Doppler data have a signature from the motion of the spacecraft about the planet which can be used to infer the state of the spacecraft relative to the planet. When two spacecraft are approaching or are in orbit about the same planet, information about their relative plane-of-sky position can be obtained by simultaneously tracking the carrier phase of both spacecraft at two earth stations, The carrier phase measurements differenced first between stations and then between spacecraft form an observable called Same-Beam Interferometry (SBI). These data, when combined with Doppler data, can result in more accurate position solutions than those produced using only Doppler tracking data. Greater accuracy in absolute and relative positions of nearby spacecraft ma y be a useful capability in future multi-spacecraft missions to Mars. In addition, simultaneous reception of telemetry and radio metric data from several spacecraft may lead to more efficient use of ground tracking resources.

To make SBI measurements two spacecraft must be close enough together angularly, as seen from earth, that their signals can be aquired in the same beamwidth of an earth-based antenna. In addition, two widely spaced antennae must be able to view the spacecraft

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simultaneously. The SBI observable is formed by differencing the carrier phase measured at each station for each spacecraft and then differencing the station-differenced measurement between the two spacecraft. The differencing results in cancellation of media and platform errors producing a high precision data type.

The first demonstrations of orbit determination with SBI data were for the Pioneer 12 and Magellan Venus orbiters in 1991.1 [2,3] Because the present Doppler receiver in each of NASA's Deep Space Network (DSN) tracking stations can only record one carrier signal per band at a time, the data were collected by making open loop recordings of the S-band (2.3 GHz) carrier signals of both spacecraft on the Narrow Channel Bandwidth (NCB) VLBI system.[4] The signal phases were extracted by post processing using the VLB1 correlator. The data processing was time consuming. In addition, a good *a priori* model for the signal phase was required. As a result, data squired while Pioneer 12 was broadcasting in one-way mode were discarded because it was not possible to model the behavior of the spacecraft onboard oscillator well enough to extract the phase.

In August and September of 1992, the Experimental Tone Tracker (ETT) was installed at DSN stations in California and Australia for temporary use. The ETT can simultaneously track and record the phase of up to eight carrier signals. In addition, *a priori* frequency models, required for signal acquisition, can be loaded remotely and data can be retrieved remotely via phone. As a result, data processing is much simpler and turnaround is faster.

SAME-BEAM INTERFEROMETRY

For a short period (2-24 hr) planetary orbiter, the orientation of the orbit plane is the trajectory component least well determined by line-of-sight Doppler measurements. Doppler data acquired simultaneously at two widely spaced DSN stations, and then difference, provide sensitivity to the orientation of the orbit plane.[5] Differenced-Doppler have been used operationally during the orbit phase of the Magellan mission to help meet stringent navigation requirements.[6,7] For the case when two spacecraft are in orbit about the same planet, an SBI observable formed from Doppler measurements, difference between stations and difference between spacecraft, provides further improvements to navigation. A demonstration of this technique using the Magel Ian and Pioneer 12 orbiters at Venus took place in February and April of 1991.

At the time that data were obtained, Pioneer 12, also known as Pioneer Venus Orbiter (PVO), launched in 1978, was in a highly eccentric orbit about Venus with a period of about 24 hours. The Magellan spacecraft joined PVO in orbit around Venus on August 10, 1990. During 1991, Magellan was in a less eccentric orbit with a period of about 3.26 hours. Orbit determination solutions from these data sets have been obtained using various combinations of Doppler, differenced-Doppler, and SBI data. SBI data were taken at S-band for the orbit determination demonstration since PVO was transmitting at S-band and Magellan was transmitting low-rate data at S-band in addition to the primary X-band (8.4 GHz) signal. Using the S-band doubly-diffe.rented data with a 5 minute averaging time, the separation of the two spacecraft in the plane of the sky can be inferred with an angular accuracy of 180 prad for a baseline length of WOO km.† At a distance of 1.5 AU the S131 data accuracy corresponds to a spacecraft-separation measurement accuracy of 40 m.

The quality of orbit solutions using different combinations of Doppler, differcnce.d-

† 8000 km is an average length of the separation vector between antennas from different DSN complexes projected onto the plane normal to the I%tih-spacecraft direction.

Table 1
Data set for February and April SBI demonstration

	PVO Doppler Data (hrs)	Magellan Doppler Data (hrs)	Magellan Difference Doppler(hrs)	SBI data (hrs)
February 14-22 total	52.9	102.0	22,2	6.8
February average (48 hour arc)	13.2	25.5	5.5	1.7
April 6-16 total	96.9	121.8	33.6	11.7
April average (48 hour arc)	19.4	24,3	6.7	2.3

Doppler, and SBI data were assessed by performing orbit solutions for 48 hour non-overlapping arcs of data. 'l'he 48 hour time period for the solutions was chosen to assure that there was at least 1 hour of SBI data available for use in each solution. Each solution arc included 13 Magellan orbits and 2 PVO orbits. 'l'here was Magellan Doppler data during each orbit, and Differenced-Doppler every few orbits. There was PVO Doppler data for about 6 hours per orbit near periapsis. The February and April 1991 data sets are summarized in Table 1.

The solutions for each spacecraft were propagated forward for one orbit period and compared with the solution obtained using the adjacent arc of data. With the February and April 1991 data sets a total of seven comparisons were possible. In addition to comparing successive orbit solutions to measure orbit determ inat ion accuracy, the solut ion-to-solut ion differences were compared to a nominal orbit covariance. This orbit covariance was formed using *a priori* uncertainties for important sources of systematic error, including mismodelling of gravity field, solar pressure, attitude. control maneuvers and station frequency reference biases, Figure 1 shows the difference between each set of two adjacent orbit solutions and the expected value of the difference based on the covariance for different combinations of data for Magellan. The expected error in the position solution varies strongly with the time past periapsis. The results averaged over an orbit period for each spacecraft are shown in '1'able 2. The results given in Table 2 show that orbit solutions generated with Doppler and SBI data improve accuracy by a factor of four compared to solutions using Doppler and Differenced-Doppler, as predicted by covariance studies.

Table 2
Results of February and April SBi experiment

Data Used	RSS position difference for Magellan (km)	RSS position difference for PVO (km)
Doppler Only	4.35	0.32
Doppler plus Differenced-Doppler	0.97	
Doppler plus SBI	0.24	0.23

DESCRIPTION OF EXPERIMENTAL TONE TRACKER

The ETT consists of a modified TurboRogue Global Positioning System (GPS) receiver[8,9,10] which can track up to eight GPS satellites. In the unmodified receiver, L-band (1.5 GHz) GPS satellite signals are downconverted to baseband frequencies,

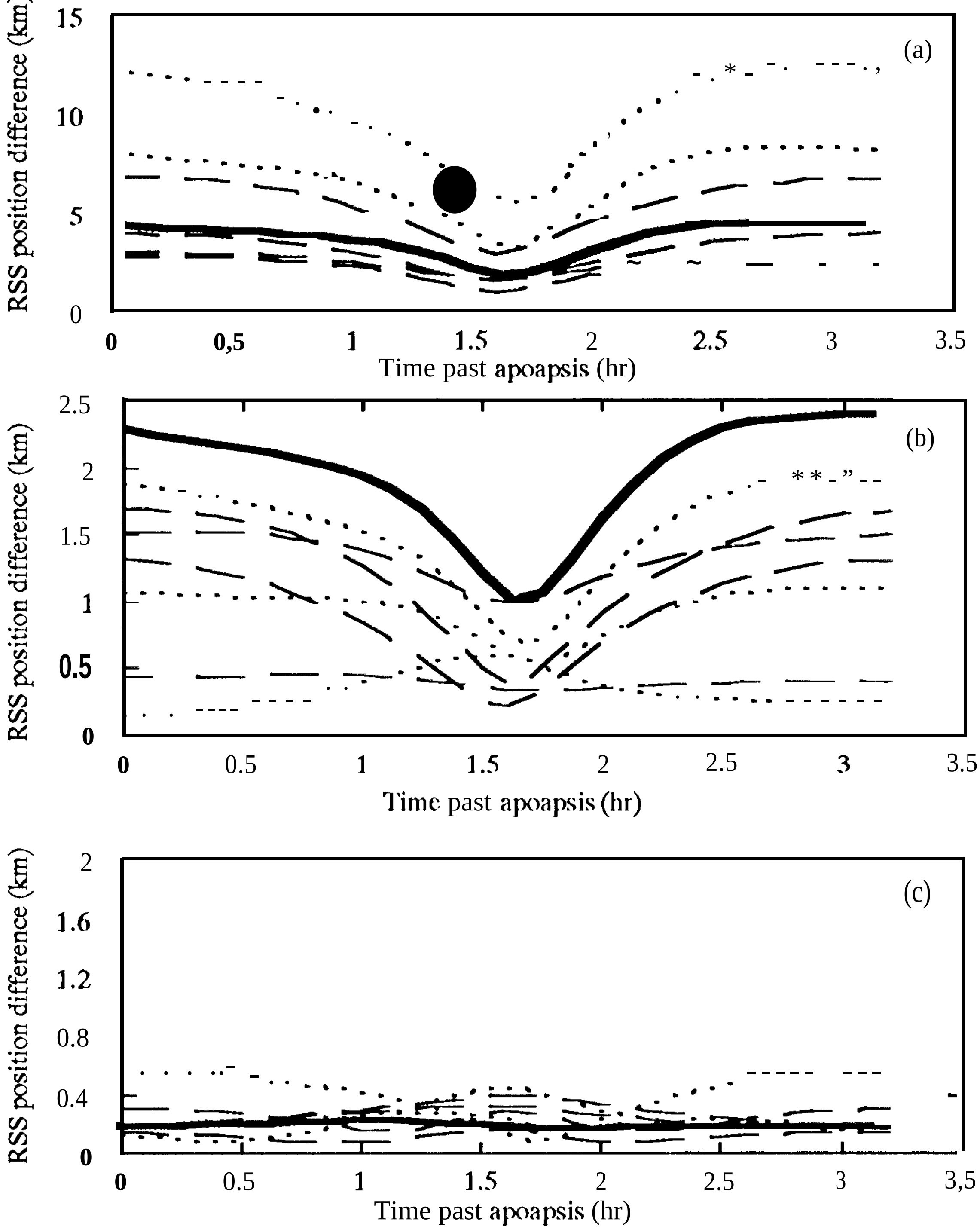

Figure 1. **Magellan** solution-to-solution trajectory differences using three different data schemes, Part (a) uses onl y Doppler data; part (b) uses Doppler and **Differenced-Doppler** data; part (c) uses Doppler and S}31 data. The dashed curves are for solutions in February 1991, The dotted curves are for solutions in April 1991, The dark solid curves show the expected trajectory difference based on the covariance analysis for each case.

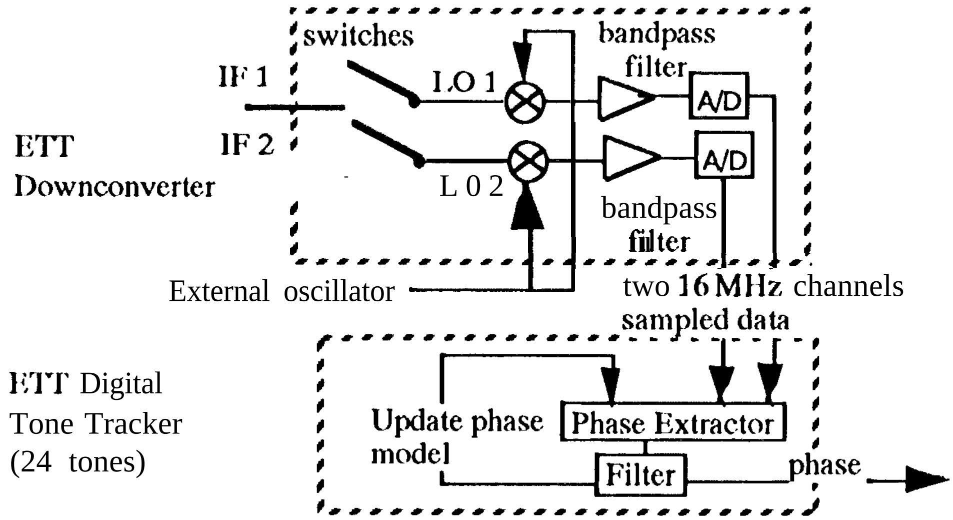

Figure 2. The Experimental Tone Tracker consists of two IF (200-400 MHz) to baseband (± 8MHz) downconverters and a digital tone tracker.

digitized and tracked with a digital phase locked loop. For each satellite, three tone rotators arc provided in order to track the PI, P2 and CA signals broadcast by each satellite. At the DSN stations, spacecraft signals at two deep space frequency bands, near 8.4 GHz (X-band) and near 2.3 GHz (S-band) are mixed down to an IF frequency near 300 MHz for input into the NCB VLBI system. In order to install the ETT with little modification to the DSN stations, a new downconverter was built which takes a signal in the same IF frequency range as for the NCB System.

Figure 2 shows a schematic diagram of the ETT. Two IF signals may be input. In the. DSN stations, these two inputs are the downconverted S-band and X-band signals from an antenna. There are two sets of mixers, filters and digitizers that each output a sampled 16 MHz baseband for input into the digital tone tracker. A switch is provided with each set so that it may use either IF as an input. The two local oscillators can be independently set in the range 200 to 400 MHz in steps of 100 kHz. The two are derived from the same external 5 MHz input and are coherent,

In the baseband tone tracker, the phase and signal to noise ratio of a tone is extracted every 5 msec. These samples are compressed by a quadratic fit to a selected output rate in the range 1 to 60 seconds. An external 1 pulse per second input is used as a reference for the data time stamps.

Signals are acquired with a search algorithm employing Fast Fourier Transforms and an *a priori* frequency model. Once a signal above a defined threshold is detected, the measured frequency and frequency rate are used to initialize the closed loop tracking. The user may specify the frequency range which is to be searched in order to reduce the likelihood of squiring a spurious tone. Dynamic signals such as those from Pioneer 12 and Magellan have been squired within a few minutes using *a priori* frequency models which were within a few kHz of the correct frequency. In addition, the ETT has successfully acquired and tracked the Pioneer 12 carrier in one-way mode during which the signal frequency jumps between two values about 5 Hz apart every few seconds.

RESULTS

Data quality

Carrier signal phase data for Pioneer 12 and Magellan were collected between September 21, 1992 and October 7, 1992 during times that both spacecraft were broadcasting and both were visible at the California and Australia DSN stations. Scheduling constraints and the changing orbit of Pioneer 12 during its final mission phase limited the amount of SBI data that could be squired during that period. The Pioneer 12 mission ended when gravitational perturbations caused the spacecraft to descend into the atmosphere of Venus on October 8, 1992. The two arcs of SBI data that were recorded are from September 22nd and October 6th.

The phases of both spacecraft carrier signals were measured simultaneously and recorded on disk at each of the two DSN stations, The two spacecraft signals were close enough, 4 MHz apart, to appear in the same 16 MHz baseband channel of the ETT. Due to the small data volume recorded from the closed loop tracking, the data for each pass could be retrieved in near real-time. Two hours of carrier phase data recorded once per second for a single tone comprises 300 Kbytes of data.

The carrier phase data from each station were difference between stations and then between spacecraft to form an SBI observable. The data from September 22, 1992 are shown in fig 3. The expected one sigma data noise is 0.13 cycles at S-band for one. second averaged measurements.[2] A data accuracy of 0.13 cycles at S-band for one second averages corresponds to an angular accuracy of 2 nrad for an 8000 km baseline. The r.m.s. scatter of the data from September 22nd are somewhat smaller than predicted, as was the case in the earlier SBI experiments. It is expected that for time scales between a second and an hour, the largest source of error in SBI data is from solar plasma fluctuations. System noise dominates the error for time scales below a second. Errors from fluctuations in earth media and platform errors tend to cancel well when the carrier phase data on each of the four lines of sight are differenced to form SBI data. The power spectrum of phase fluctuations of the SBI data are shown along with the expected contribution from solar plasma and system noise in fig. 4 for the September 22nd data. It should be noted that the uncertainty in the power spectrum obtained from the data increases at lower frequencies.

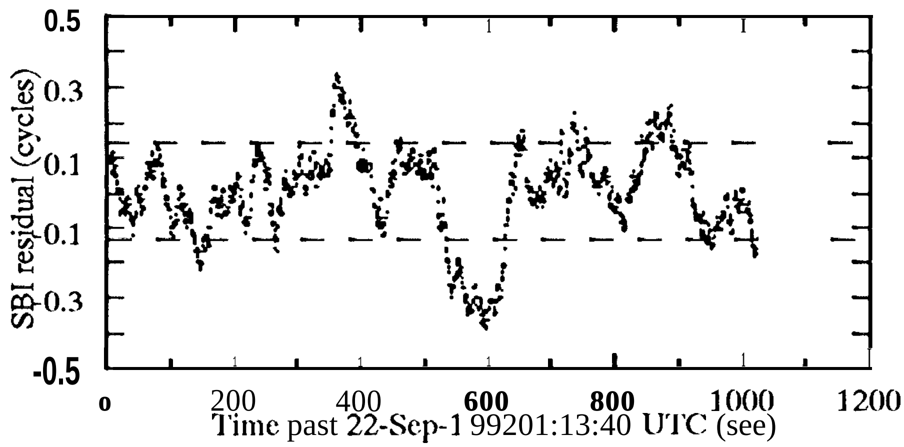

Figure 3. Residuals of Same-Beam Interferometry data from a dynamic model for PVO and Magellan with an additional line remove.d to show the level of data noise. Dashed lima indicate the 1-sigma level of expected data noise at 0.13 cycles.

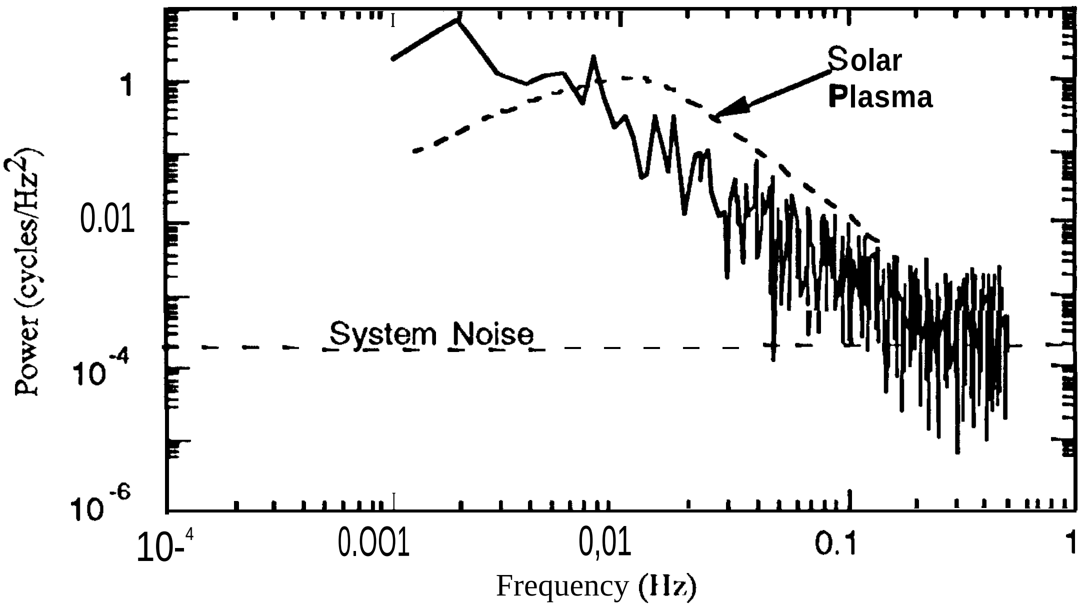

Figure 4. A power spectrum of the fluctuations in the. Same-Bea m Interferometry dat a on September 22, 1992. The dashed lines indicate the expected contributions from solar plasma and ground receiver misc.

One-Way Data

Currently, two-way data are primarily used for determining orbits of interplanetary spacecraft. Two-way data are generated by uplinking a stable reference signal from a ground station, which is coherently transponder by a spacecraft and then received at the same tracking station, 'l'he method of operation in which a ground station receives a signal a spacecraft transmits using its onboard oscillator as a frequency reference is known as one-way tracking.

A new capability that has been demonstrated is the ability to obtain SBI data while one or both spacecraft are transmitting in one-way mode. The NCB VI .BI system, which was used for the earlier experiments, has 250 kHz channels and records data over a wider bandwidth by multiplexing between channels. Because the Magellan and PVO carrier signals are about 4 MHz apart, the NCB receiver recorded Magellan data during part of a second and PVO data during the rest. In order to extract the phase of the carrier during post processing, an adequate model is required. In order to use power efficiently, the PVO spacecraft switched the power to its oscillator between battery power and solar power each spin period of the spacecraft, "l'his resulted in a change in frequency of the oscillator of about S Hz halfway through each 20 sec spin period. This behavior made it impractical to produce a good enough model to extract the signal phase of the spacecraft from the open loop data when PVO was broadcasting in a one-way mode,

In contrast, the ETT uses a model only for initial signal acquisition. The. predicted frequency must be within a few kHz and the error in the predicted frequency rate must typically be less than 0.1 Hz/second. The tone tracker has been used with loop bandwidths between 0.01 Hz and 20 Hz. This flexibility allows its use in a wide set of conditions. In this experiment, the ETT was able to continuously track the carrier signal of PVO in one-way mode for 30 minutes on October 6, 1992. A five minute segment of PVO data from this pass is shown in fig. 5. A short segment is shown in order to show the high frequency change in frequency exhibited by the carrier signal. The PVO carrier signal was tracked by both ETT receivers. The difference between the phase measured at each station is shown in fig.6. The error due to the oscillator behavior is eliminated in the station-differenced data. The SBI data derived from measurements of one-way signal transmissions from Pioneer 12 and Magellan on October 6, 1992 exhibit scatter comparable to SBI data derived from two-way transmissions.

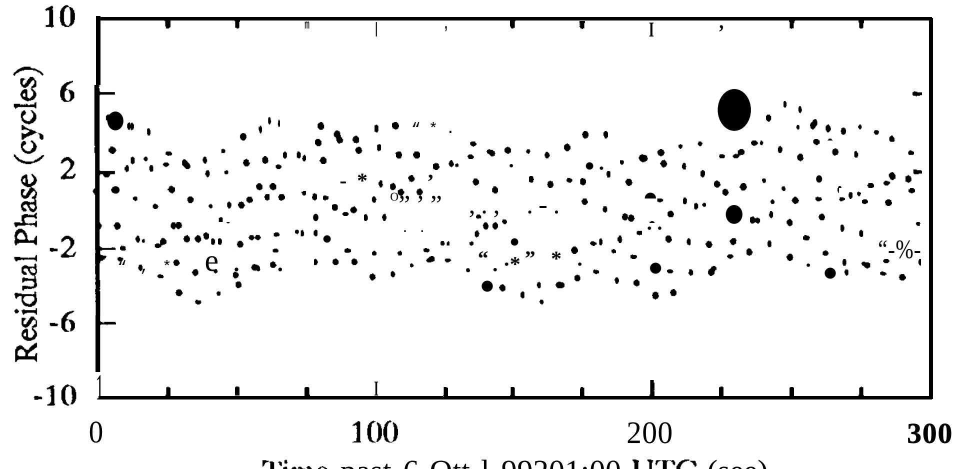

Figure 5. Phase of the PVO carrier signal as **received** al the. California DSN station's **70 m** antenna during a **period of** one-way broadcasting with a dynamic **model** subtracted. **The** spacecraft oscillator changes **frequency** by S Hz every **spacecraft** spin period.

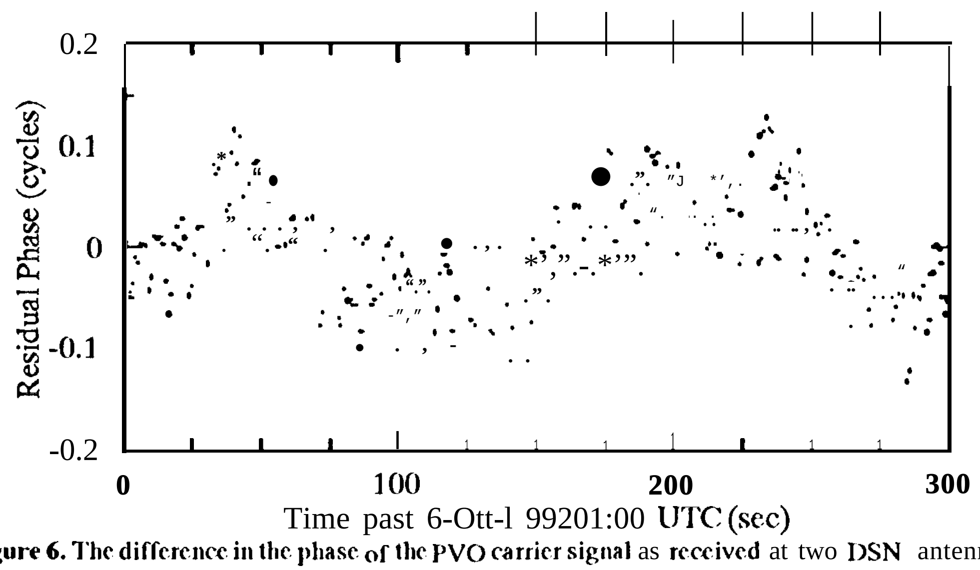

Figure 6. The difference in the phase of the PVO carrier signal as **received** at two DSN antennas, **one in California** and **one in** Aust **ral** ia.

DISCUSSION

A prototype closed loop tone tracker has been demonstrated in the DSN for acquisition of Same-Beam Interferometry data from the Pioneer 12 and Magellan orbiters at Venus. The precision of the radio metric observables generated from these data agrees with expectation. Earlier demonstrations of SBI data acquisition, using the DSN's open loop VI .BI receiver, have shown the strength of these data for improving the accuracy of the orbits of Pioneer 12 and Magellan relative to orbit solutions which used only Doppler data. Data processing has been greatly simplified by the use of closed loop receivers in place. of open loop receivers, and the demonstration with the Experimental Tone '1'racker has shown the feasibility of operational usc of the SBI technique in the DSN.

Development of an operational SBI capability by the DSN may lead to tremendous advantages in efficiency of network tracking support, For example, a single station might be used for acquisition of telemetry and radio metric data from two or more spacecraft in orbit about or landed on Mars, with a second station used only during the baseline overlap periods. 'l'his mode of operation calls for replacing some or all of the two-way Doppler which is typically used today for orbit determination with one-way Doppler so that multiple. uplinks are not required, and it calls for simultaneous reception of telemetry from two or more spacecraft at one station. Fut ure developments arc expected to a llow the DSN to fully real ize the increased efficiency which SBI makes possible. Improvements to the stability of flight oscillators may enable orbit determination accuracy requirements to be met using a combination of one-way Doppler and SBI data in place of two-way Doppler data.11 The implementation of the Block V receiver in the DSN will enable simultaneous reception of Doppler and telemetry from at least two spacecraft at a single station.[12]

In a scenario with multiple spacecraft operating at Mars, the relative positions of landers, rovers, and orbiters could be determined with great accuracy through joint orbit solutions using a combination of Doppler data and SBI. While direct communication between spacecraft and other in situ techniques may enable local navigation, earth-based radio metric tracking will be required as a simple and reliable method for determining spacecraft posit ions.

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