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USE OF VERY LONG BASELINE ARRAY INTERFEROMETRIC DATA FOR SPACECRAFT NAVIGATION

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Abstract

Very Long Baseline Interferometric (VLBI) techniques have been used to support numerous interplanetary missions since the late 1970s. These techniques involve the simultaneous tracking of two or more sources, at least one of them a spacecraft, by widely separated ground antennas. The recordings from the sources are correlated and differenced to obtain very precise estimates of the angular separation between the sources. The main VLBI technique that is used at JPL is known as the Delta Differential One-way Ranging (ΔDOR). Two DSN antennas simultaneously track a source, and alternate between sources. The signals recorded at the antennas from each source are correlated to obtain the delay in arrival to the two antennas, and the delays are differenced to remove common-source errors. An alternative technique is to use carrier phase differences between antennas. This is routinely done by the Very Large Baseline Array (VLBA) as part of source imaging. The VLBA capabilities are used for scientific research, but also have the potential to be used for navigation. Two main experiments were performed with the VLBA and JPL spacecraft. This paper describes and analyzes these experiments and discusses the possible uses of VLBA tracking for spacecraft navigation.

Introduction

The use of VLBI for deep-space spacecraft tracking dates back to the late 1970s, and this tracking technique has been used to support a number of interplanetary missions since then.Antennas from the NASA Deep Space Network have been used for this purpose to support many missions, starting with experiments with the Viking Landers, closely followed by the first operational use with Voyager. After that the system has been used to support many other missions, and it is currently especially important for achieving precise planetary insertions.

VLBI Techniques

The use of Very Long Baseline Interferometry for deep space spacecraft tracking dates back to the late 1970s when the first differential phase delay measurements were made of planetary orbiters - Viking at Mars and Pioneer 12 at Venus [1]. During 1979-1989, telemetry sub-carrier harmonics were used for Δ-DOR of the Voyager 1 and 2 spacecraft during cruise [2]. During this period the technique was further developed and refined at JPL, providing an additional navigation tracking measurement - an angular position relative to a quasar that was then at the 100 nrad accuracy level, improving the plane of sky position determination by an order of magnitude. During the 1980s and early 1990s the Δ-DOR technique was further refined by the JPL Deep Space Network (DSN) Technology Program, and used to support several interplanetary missions at the 30-nrad accuracy level. In the early 1990s the technique was used for the first time to track a planetary orbiter - the Magellan spacecraft at Venus - and the data helped to improve the tie of the planetary ephemerides to the celestial reference frame to the 5-nrad level.

The MCO failure in 1999 made painfully clear how important Δ-DOR is for interplanetary navigation. That low-cost mission did not use the VLBI capabilities and suffered from plane-of-sky modeling errors that contributed to its demise. Right after the failure the DSN embarked on an urgent operational implementation of Δ-DOR tracking, in order to reliably support future users with demanding navigation requirements. The new system was used to support the 2001 Mars Odyssey mission with great success, at a 5-nrad accuracy level, and recent measurements for MER and MRO have been at the 2-nrad level.

The VLBI techniques involve the simultaneous tracking of two or more sources, at least one of them a spacecraft, by widely separated ground antennas. The recordings from the sources are correlated and differenced to obtain very precise estimates of the angular separation between the sources. VLBI can determine very precise plane-of-sky locations and is therefore complementary to the classical line-of-sight range and Doppler measurements.

The main VLBI technique that is used at JPL is known as the Delta Differential One-way Ranging. Two DSN antennas simultaneously track a source (a quasar or a spacecraft), and alternate between sources. The signals recorded at the antennas from each source are correlated

to obtain the delay in arrival to the two antennas, and the delays are differenced to remove common-source antennas errors. This produces a very precise measurement of the angular separation between the spacecraft and the radio source. It is known as ranging because what is measured is the difference in group delay using tones, referred to as DOR tones, that are modulated on the spacecraft downlink carrier signal. It is also possible to perform delta differential Doppler, but that is less accurate than ranging for determining plane-of-sky position.

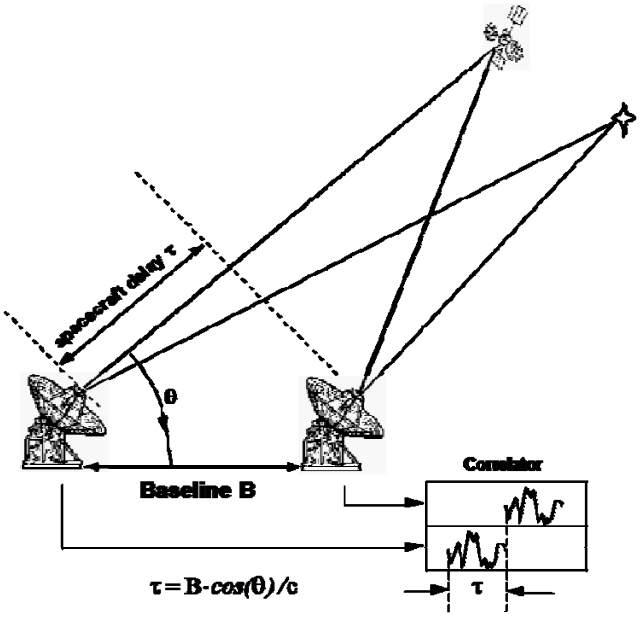

Figure 1 The Delta-DOR Concept

An alternative technique is to use carrier phase differences between antennas. This cannot be done with the bandwidths allocated to spacecraft tracking and with the intercontinental baselines of the DSN, but is routinely done by the Very Large Baseline Array (VLBA) as part of natural source imaging. The VLBA [3] is a scientific network of 25-meter radio-telescope antennas operated by the National Radio Astronomy Observatory (NRAO). The network consists of ten antennas, eight of them in the continental USA and one each at Mauna Kea and St. Croix. The antennas form baselines of various lengths and orientations, with the resultant geometry aiding in the resolution of the carrier phase delays ambiguities between the different antennas. For a given baseline length, carrier phase differences are potentially more accurate than group delay differences.

Both VLBI techniques require the recording and transfer of considerable amounts of data between the remote antenna locations and the processing center. For DSN processing this means that the recordings need to be optimized to provide the highest possible accuracy within a limited data volume, in order to be able to transfer the spacecraft and quasar recordings over the existing data lines in a few hours. The demands are more lax for VLBA, because its scientific users do not have the timeliness requirements that navigation users have, and can wait for tapes to be transported using commercial shipping services.

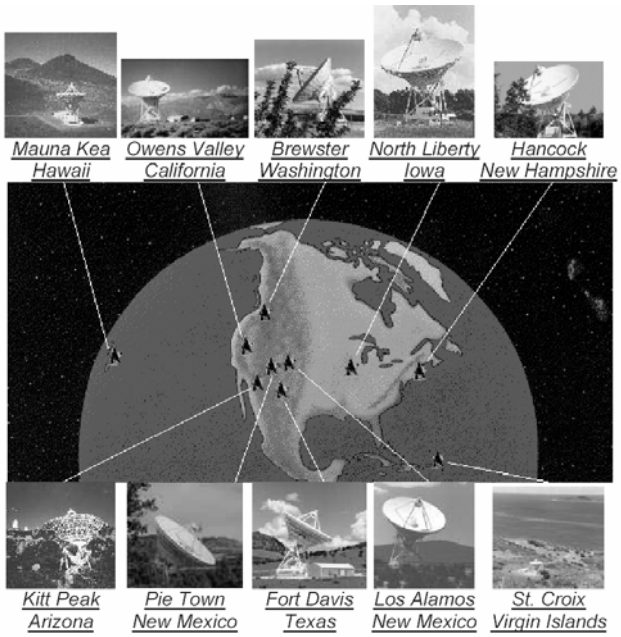

Figure 2.The VLBA Network

One significant difference between the DSN Δ-DOR and the VLBA system is that the DSN Δ-DOR works best when the spacecraft transmits DOR tones and, although it can also work with certain telemetry set ups, it usually disrupts telemetry. VLBA recordings can be done with any spacecraft signal and do not disrupt telemetry transmission or require special equipment at the spacecraft. The VLBA can also use weaker, and therefore more and closer, quasars than those required by DSN Δ-DOR, reducing the errors introduced by the difference in line-of-sight between the spacecraft recording and the quasar recording.

The VLBA Spacecraft Tracking Experiments

The VLBA capabilities are routinely used for scientific research, but also have the potential to be used for spacecraft navigation. The VLBA uses phase referencing to determine the position of the spacecraft relative to one or more quasars. This technique is sometimes called imaging because it makes use of algorithms that can be used to obtain interferometric images of astronomical sources. The main challenge is that the signal must be modeled to the level of accuracy required to reliably enable phase connection. The combination of different baseline lengths in the VLBA, and the precise a priori knowledge of the spacecraft locations, has enabled the successful application of phase referencing for spacecraft tracking for these experiments.

VLBA data turn-around time is typically one month, so experiments using the current system can demonstrate the accuracy that the VLBA can provide, but more efficient

transport methods would have to be used to provide the kind of timeliness needed to support navigation operations.

Two main experiments were performed with the VLBA and JPL spacecraft. The first was to track MER-B as it was approaching Mars in January of 2004, the other to track Cassini after it was inserted into its Saturn orbit. The MER-B experiment was very useful to demonstrate the kind of accuracy that could be achieved with the new technique, because the spacecraft was being intensively tracked at the same time by the DSN, both with high precision range and Doppler and with Δ-DOR. The Cassini experiment demonstrated how VLBA could support, in a non-interference basis, missions that do not routinely perform Δ-DOR.

VLBA usually provides plane-of-sky angular offsets with respect to the a priori location, but for these experiments the VLBA data was post-processed [4] to obtain differential time-of-arrival measurements between the spacecraft and a reference quasar. This removed any possible modeling discrepancies between the VLBA imaging software and JPL's Orbit Determination Program (ODP), and produced a measurement that could easily be processed by the ODP.

The MER-B Experiment

MER-B was observed by the VLBA during the final days of its approach to Mars. There were three data takes on the evenings of January 19, 21 and 23, 2006, and MER-B landed on Mars on the evening of the 25. The recordings were correlated by NRAO and the results sent to the JPL tracking section, were they were analyzed and converted into a formulation and format that could be used by JPL navigation [5,6]. Time of arrival measurements were converted into differential one-way range values and the observables were output in to a format that could be processed by the JPL navigation software. Each data take produced about 800 delta difference observables, or about 24 per each of the possible baselines, with two separate 90 minute sessions for each take. JPL Navigation transformed station coordinates for the VLBA stations to the same epoch and reference frame as those used for the DSN sites.

The tracking data were processed using the same assumptions that were used for the operational MER-B orbit determination [7], and different combinations of tracking data types were tried in turn in order to compare solutions and understand the contribution from each data type (Range, Doppler, DSN Δ-DOR, and VLBA). A five-day data arc without maneuvers was selected for the orbit fit, from 12:00 UTC of January 19 to 12:00 UTC of January 24, 2006.

One issue that needed to be resolved was how to weight the VLBA data relative to the weights that were used for DSN data. Since we were using the Δ-DOR formulation to process the VLBA data, we had about 2400 data points, including every one of the possible 45 baselines. These measurements were correlated, temporally and also because some of the possible VLBA baselines are linear combinations of the others, so the weight needed to be adjusted to account for this. We decided to use all the data and adjust the weight, instead of using only a few baselines and times, because using all that data made the solution more robust and less sensitive to measurement errors and outliers. For the solution we used a weight of 80 picoseconds for the VLBA delay data, which corresponds to about 10 picoseconds - a typical measurement noise - times square root of 60 (forty-five possible baselines divided by nine independent baselines and multiplied by twelve points per session).

A number of cases using different data combinations were fitted and for each of them the MER-B trajectory and its associated covariance were mapped to the Mars B-Plane. The B-Plane is a plane that contains the Mars center of mass and is perpendicular to the incoming hyperbolic asymptote of the spacecraft trajectory, with the B.R axis oriented towards the South Pole. The B-Plane is used to analyze and monitor the evolution of hyperbolic trajectories during the approach to the target body. For the covariance study, and in order to highlight the effects of the different data combinations, the Mars ephemeris and GM covariance were not considered.

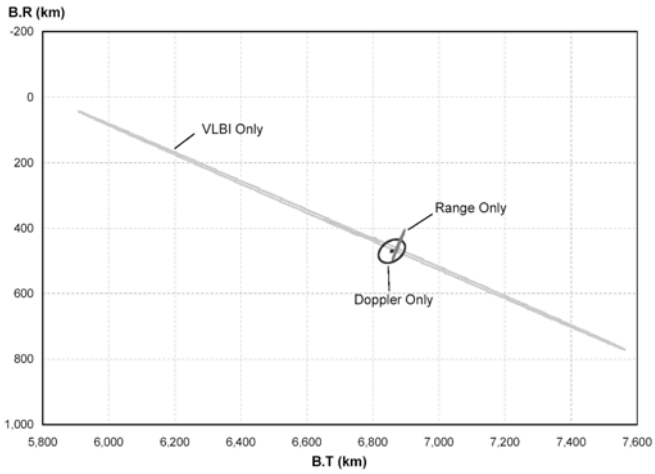

Figure 3. 3-Sigma Error Ellipses for MER-B when using single data types

Figures 3 and 4 show what the 3-sigma error ellipses looked like when only VLBI data, only Doppler data, only range data, and the three in combination were used. As it was mentioned before, the VLBI data is complementary of the line-of-sight data. In this case the line-of-sight direction was almost perpendicular to the velocity, so the range data could determine very well the B.T component, critical in this case to determine the appropriate flight-path angle, but the VLBI data could not resolve it to the required accuracy because the B.T direction was almost perpendicular to the plane of sky.

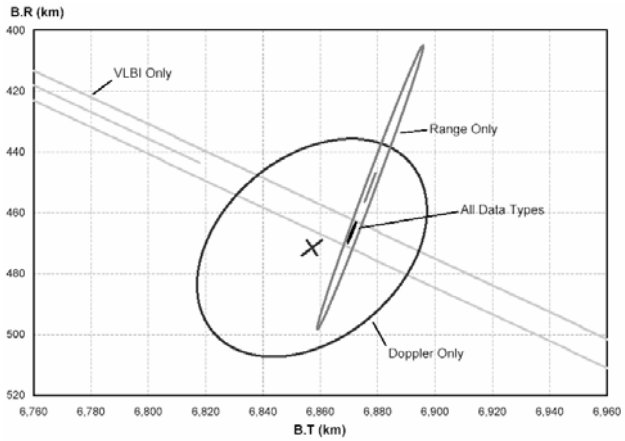

Figure 4. 3-Sigma Error Ellipses for MER-B when using different data types

When the VLBA data were processed together with the DSN data, the pre-fit residuals of the VLBA data were consistent with the expected accuracy of the converged DSN solution, and using the VLBA data in the fit produced solution shifts that were consistent with the expected accuracy of the DSN solution. Figure 5 shows the comparison between the original DSN solution and a solution that used the VLBA data in addition to the DSN range, Doppler and Δ-DOR. A solution with just the DSN range and Doppler and the VLBA data had an error ellipse that was slightly larger than that with all the data combined.

We also tried different weighing and data selection schema to validate our VLBA weighting assumptions. Among others we tried solutions that only used data from independent baselines, and where the VLBA data was down sampled, adjusting the weight of the individual measurements to a factor of the measurement noise. The error ellipses and solutions in all cases were consistent with our baseline assumptions.

In summary, the VLBA data obtained for MER-B were consistent with the DSN Δ-DOR data, and could have replaced the Δ-DOR data in the navigation solution if it could have been processed within the stringent navigation deadlines. As should be expected, the phase referenced data from the VLBA baselines (of up to ~4,000 Km) were slightly more accurate than the group delay data from the DSN baselines (of about 10,000 Km). In any case, and for this particular application, the actual performance of the planetary insertion would had been dominated by quasar location and Mars ephemeris uncertainties - hundreds of meters - and the actual landing by atmospheric uncertainty - tens of kilometers.

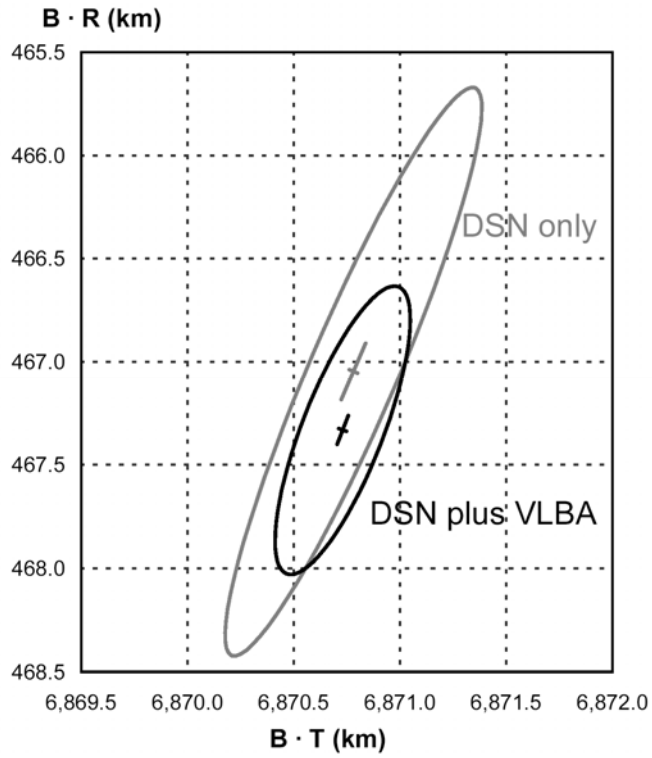

Figure 5. 3-Sigma Error Ellipses for MER-B

The Cassini Experiment

In preparation for the Huygens probe mission, the Cassini Navigation team discovered that the uncertainty of the mass of Saturn's third largest moon, Iapetus, had a significant effect on its targeting dispersion at entry into Titan's atmosphere on Jan 14, 2005. The orbit determination (OD) process for the Cassini mission requires the OD filter to include the estimation of the masses and ephemerides of the major moons of Saturn and of Saturn, as well as the spacecraft state, using 2-way X-band radio-metric data and optical navigation images of the satellites[8]. Shortly after Cassini's orbit insertion at Saturn on Jun 30, 2006 - six months before the Huygens entry - and owing to the complex and interconnected nature of the Saturnian system, the navigation team's estimate for the Iapetus mass unexpectedly shifted over four times its formal sigma, putting into question the formal uncertainty values. The reassessed level of uncertainty to Iapetus' gravity perturbation on the probe could have jeopardized the probe mission since six days after its release on Dec 25, 2004 the probe was to fly relatively slowly past Iapetus at a range of 64,000 km. The flyby distance was later increased to 126,000 km in order to lessen the effect of the uncertainty of the Iapetus mass.

It has been known that Iapetus plays a significant role in the shift of the Saturnian system barycenter from the center of Saturn. Cassini OD covariance studies showed that the Iapetus mass estimate could be improved through either direct measurements using radio-metric data before

and after a close flyby of Iapetus or by indirect measurements inferred through improvements in the Saturn barycenter position determination using radio-metric data before and after the first and second Titan flybys & Saturn periapses (Titan-A, Oct 26, 2004 and Titan-B, Dec 13, 2004). Prior to Cassini's arrival at Saturn on June 30, 2004, knowledge of Iapetus mass (GM) had been primarily determined using the radio-metric and optical data through distant Pioneer and Voyager 1 & 2 flybys.

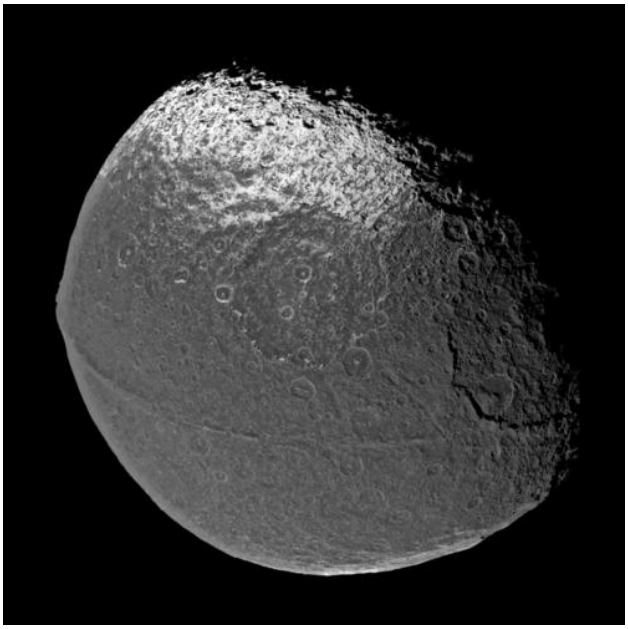

Figure 6. Composite view of Iapetus created with images taken during the December 24, 2004 flyby.

The covariance analysis showed that a closest yet flyby to Iapetus of 1.1Mkm on Oct 18, 2004 would help determine its mass significantly, especially after the radio-metric data measured its barycentric position following the Titan-A flyby. In addition, the covariance studies indicated that the Iapetus mass uncertainty would be further reduced following the Titan-B flyby. To further confirm the estimates from the Oct 2004 flyby, several VLBA measurements of Cassini were performed in order to improve the plane-of-sky knowledge of the spacecraft, and of Saturn, and therefore decorrelate ephemeris errors from other error sources.

Five data takes were scheduled in Oct of 2004 (14, 16, 17, 19 20). Previous experimental data takes of Cassini on June 30, 2004 and September 8, 2004 were also processed and evaluated. All the data takes were successful and the VLBA observables were used by the navigation team and the Solar System Dynamics team to improve the trajectory of Cassini before the Huygens delivery, and to improve the ephemerides of Saturn [9]. The preprocessing and data weighting that was used were similar to those described for the MER data. From September 2004 through October 2004, the S/C (at Saturn) was approximately 1.4 billion km from Earth, thus with accuracies of 10 – 100 ps, the spacecraft plane-of-sky position could be determined down to the 0.5 – 5 km level.

The VLBA data had a significant effect on the orbit and the GM of Saturn, but essentially it had no influence on the satellite orbits and other dynamical parameters. At the time of the VLBA experiment, the Cassini spacecraft 1-sigma position uncertainty relative to Saturn's barycenter ranged from 4 – 10 km. Because of the accuracy of Cassini's relative position to Saturn, the VLBA data reduced the down-track and normal components of Saturn's barycenter to 2 km and the Iapetus' GM estimates were consistent with the optical navigation/radio-metric-only solutions used in operations. When data from other spacecraft flying by Saturn - Pioneer, Voyager - was added, there was no degradation to the optical and radio-metric tracking data residuals, confirming that the VLBA data helped to improve the orbit of Saturn. The biggest effect was observed in the out-of-plane direction, where the shift was about 6 times the 8 Km formal uncertainty associated with the original ephemerides. VLBA data had a similar effect on the estimation of Saturn's GM, with a reduction of more than 1 sigma from the original value occurs as a consequence of including the VLBA data. The reduction was almost entirely in the contribution of the planet GM to the system GM as the satellite GMs changed very little.

Conclusion

The VLBA can provide plane-of-sky spacecraft tracking accuracy comparable with the DSN Δ-DOR, and is limited by the same reference frame and catalog errors that limit Δ-DOR. It complements line-of-sight data in the same way as Δ-DOR does. The advantages of using VLBA are that it does not require special DOR tones or telemetry settings at the spacecraft, and it can work with any spacecraft signal, without interfering with other spacecraft activities. Because of the VLBA network size, it has inherent redundancy, and it can stand a few sites not being available without a noticeable degradation of performance. The VLBA system is very automated and it has a very short set-up time, and the phase reference technique allows it to use weaker, closer, multiple quasar sources.

The VLBA is currently being used primarily for scientific applications, and it has a prioritization, scheduling, and data delivery processes that may not fit the demanding operational needs of spacecraft navigators. The best use of VLBA for spacecraft navigation could perhaps be to improve the quasar catalog, especially in higher frequency bands where the sources are more compact, and to perform periodic measurements of planetary orbiting spacecraft in order to improve the planetary ephemerides and the tie of the ephemerides to the celestial reference frame.

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