ISTS 2006-d-49

# A GLOBAL APPROACH TO DELTA DIFFERENTIAL ONE-WAY RANGE

James S. Border
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California

**Abstract**

Radio interferometric techniques for measuring spacecraft angular position play a role of increasing importance in today's missions of interplanetary exploration. Several national and international space agencies have or are developing operational systems to support spacecraft navigation using interferometric measurements. NASA's Deep Space Network has provided Delta Differential One-way Range (ΔDOR) data for this purpose since 1980. Steady improvements in system performance and operability have taken place with accuracy today approaching the 1-nrad level. In this paper the current performance of NASA's ΔDOR system is presented. Recent data from the Mars Reconnaissance Orbiter cruise from Earth to Mars are used to illustrate system performance at 8.4 and 32 GHz. Technical feasibility and requirements for combining tracking stations from different agencies to support ΔDOR observations are discussed. The advantages of having additional stations to form baselines for measurements are presented. Results of a covariance study for encounter targeting are given for a candidate mission that may need ΔDOR data from additional baselines.

## 1. Introduction

Direct measurements of the plane-of-sky position of a spacecraft play a role of increasing importance in today's missions of interplanetary exploration. These measurements, based on the technique of radio interferometry, provide additional accuracy, efficiency, and robustness for navigation when added to conventional line-of-sight Doppler and range measurements. NASA's Deep Space Network (DSN) has developed a technique known as Delta Differential One-way Range (ΔDOR) to provide angular observables [1]. In ΔDOR measurements, two tracking stations receive signals from a spacecraft and the delay in signal arrival time at one station with respect to the second station is measured. This delay, referred to as 'differential one-way range', gives the technique its name. A similar, nearly simultaneous, delay measurement is made using signals from an angularly nearby quasar that has a well known catalog position, to calibrate the instrumentation. The difference or 'delta' between the spacecraft and quasar delay measurements provides an accurate determination of the spacecraft angular position in the radio reference frame. A single pair of stations or 'baseline' determines one component of angular position. Two baselines are needed to measure both components.

The DSN began development of the ΔDOR technique to support the Voyager 1 encounter with Saturn in 1980 and most recently provided ΔDOR measurements to support orbit insertion for Mars Reconnaissance Orbiter (MRO) in 2006. There has been steady improvements in both the performance and operability of this technique, with accuracy today approaching the 1-nrad level. Initially the DSN developed a unique near-realtime VLBI system to enable rapid data transfer and processing to support spacecraft navigation. Today's system is built around common digital signal processing components that are also used for radio science and telemetry arraying in the DSN. Similar developments in digital signal processing capability are seen around the world in radio astronomy and spacecraft tracking applications.

The ΔDOR system has been widely used by recent missions to Mars including Mars'01 Odyssey [2], Nozomi [3], Mars Exploration Rovers (MER) [4], Mars Express [5], and MRO. The 8.4 GHz radio band (X-band) has been used by these missions. Performance of the ΔDOR system at X-band is characterized in Section 2. Data from MRO are used to verify estimates of system performance. In addition, the first ΔDOR measurements in the 32 GHz radio band (Ka-band) were recently acquired from MRO. First results of system performance at Ka-band are presented.

A number of steps are involved in the end-to-end planning and data generation process for ΔDOR including: station scheduling, spacecraft and ground station event sequencing, receiver and recorder setup for data acquisition, and correlation processing to extract time delay observables. Operational interfaces for equipment setup and observable delivery have been implemented in the DSN. International standards for supporting ΔDOR measurements were first discussed in a meeting of the Consultative Committee for Space Data Systems in 1993 [6].

There is international interest and activity to develop capability for applying VLBI to spacecraft navigation [7,8,9,10,11]. Space agencies of several nations have missions in flight or in planning stages that require radio interferometry measurements for navigation. These agencies also operate tracking stations that are strategically spread around the globe. NASA's Deep Space Network provides two baselines for ΔDOR: Goldstone-Madrid and Goldstone-Canberra. While these baselines span two dimensions, the availability of additional stations at other locations would offer advantages in a number of areas. Scheduling conflicts would be reduced if more stations were available. The robustness of the technique would improve if a single complex such as Goldstone was not essential for every measurement. More independent measurements and more timely measurements would provide improved navigation accuracy. The availability of baselines with a variety of orientations (for example north-south or east-west) would allow efficient scheduling of stations to meet a navigation requirement in a critical dimension.

The ESA stations at New Norcia and Cebreros and the JAXA station at Usuda are at excellent locations to complement the NASA sites. The New Norcia-Cebreros baseline is an orthogonal complement to the Goldstone-Canberra baseline. The Usuda-Canberra baseline is an orthogonal complement to the Goldstone-Madrid baseline. If multiple Space Agencies provide cross-support for ΔDOR data acquisition, then the missions of each agency will benefit from improved navigation. In Section 3, cross-support requirements are discussed. Section 4 presents the results of a covariance analysis, using data from several baseline combinations, to support orbit insertion at Mars for a mission in the 2012 launch opportunity.

## 2. ΔDOR Performance

The performance of the ΔDOR system depends on a number of factors including: the spacecraft downlink signal spectrum, ground station receivers, observation geometry, and calibrations for earth orientation and atmospheric path delay. An error budget, published in 1993, gave a formulation for the expected measurement accuracy as a function of the characteristics and a priori knowledge of input parameters [6]. Using assumptions that were valid at that time, predicted delay measurement accuracy was 0.23 nsec. This corresponds to an angular accuracy of about 9 nrad assuming a baseline length of 8000 km. While the formulation used in [6] to predict accuracy is still valid, the system characteristics have substantially improved. First, more data samples are recorded and transferred to the correlator facility, improving precision. Second, the ground receiver passbands have improved phase linearity, reducing instrumental biases. Third, earth orientation and atmospheric path delays are much better determined by calibration techniques employing GPS satellite observations. Finally, more radio sources are available in the astrometric catalog, allowing selection of reference sources closer to the spacecraft trajectory in an angular sense.

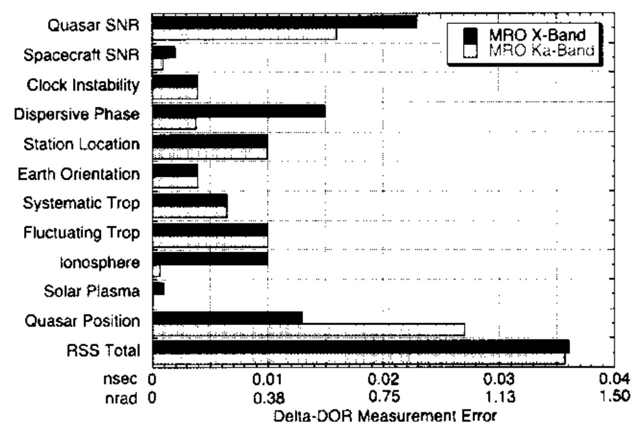


Fig. 1. ΔDOR error budget (1-sigma) for MRO measurements in 2005-2006.

Starting with Odyssey support in 2001, measurement accuracy has been at the 5 nrad level and improving, for spacecraft with spectral components in the downlink signal spanning at least 38 MHz. Performance degrades roughly linearly as spanned bandwidth decreases. Refinements in measurement technique have yielded improved performance from Odyssey to MER to MRO. Current DSN system performance is approaching the 1-nrad level. An error budget is shown in Fig. 1 for recent MRO measurements at both X-band and Ka-band. The expected delay accuracy at X-band is 0.036 nsec, 1-sigma.

Good performance is expected for MRO since the spacecraft is moving through the ecliptic plane with positive declination, viewing geometry is favorable from both DSN baselines, and a large number of reference radio sources is available. In general, the

DSN commits to providing ΔDOR data accuracy of 0.060 nsec.

During MRO cruise phase, X-band data were acquired during 64 ΔDOR sessions in support of navigation. Nine radio source observations in three sequences of quasar1-spacecraft-quasar2 were made during each 1-hour session, generating three separate spacecraft minus quasar delta delay points. The measurement residuals to the final cruise trajectory are shown in Fig. 2. The root-mean-square of residuals is 0.031 nsec, in good agreement with expected system performance. This could be a slight underestimate of true error since the spacecraft trajectory was fit to the data.

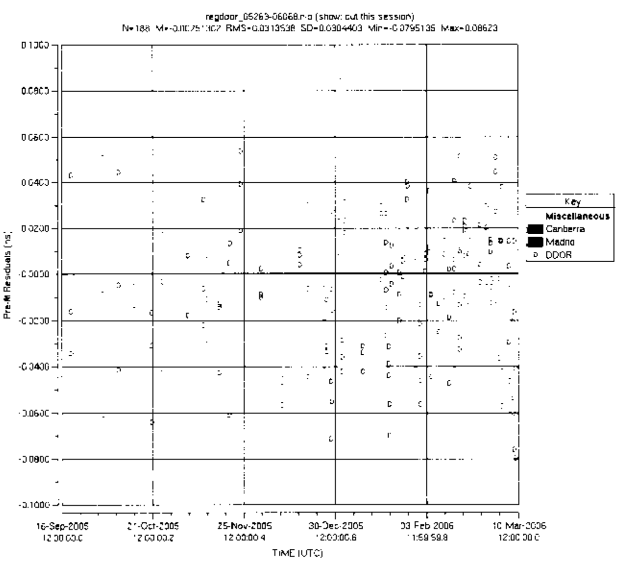


Fig. 2. MRO ΔDOR residuals to final cruise trajectory.

The wider spectrum allocation at Ka-band will eventually enable improved performance for ΔDOR. The MRO spacecraft has a Ka-band transmitter that emits tones spanning four times the spanned bandwidth at X-band. Data were acquired at Ka-band during seven of the MRO ΔDOR observing sessions. The expected accuracy for MRO at Ka-band, shown in Fig. 1, is comparable to the accuracy at X-band. The wider spanned bandwidth and the higher radio frequency reduce some error components, but reduced antenna sensitivity at Ka-band, general roll-off of quasar flux at higher frequencies, and lack of a large Ka-band radio source astrometric data base to properly define the reference source positions cause other error components to grow. For the MRO cruise measurements, the Ka-band data are in general agreement with the X-band data. The precision of the Ka-band quasar delay measurements is less than expected for some observations, likely due to errors in ground station antenna pointing that exceed the very tight 0.004 mdeg requirement.

To take advantage of the reduction in the error components at Ka-band frequencies, other work will be needed to realize a significant improvement in end-to-end system performance. A higher data sampling rate and wider spacecraft signal spanned bandwidth are needed to improve precision. An improvement in troposphere calibration will be needed. This could be achieved by making use of high performance water vapor radiometers at each tracking station. Finally, improvements in the global reference frame, including station coordinates and quasar coordinates, are required. This will require a measurement and analysis campaign, over several years, using radio source data at X-band and Ka-band. If development work is completed in these areas, then end-to-end system performance at Ka-band could improve to better than the 1-nrad level.

To better characterize the system performance, additional time was allocated during one of the ΔDOR observing sessions. A total of 40 observations of the spacecraft and four radio sources were made during the session on Jan. 20, 2006. The sky position of the spacecraft and radio sources is shown in Fig. 3. (Note that the spacecraft is identified as SC 74.) Quasars were observed in all directions from the spacecraft with the closest quasar being about 5 deg away.

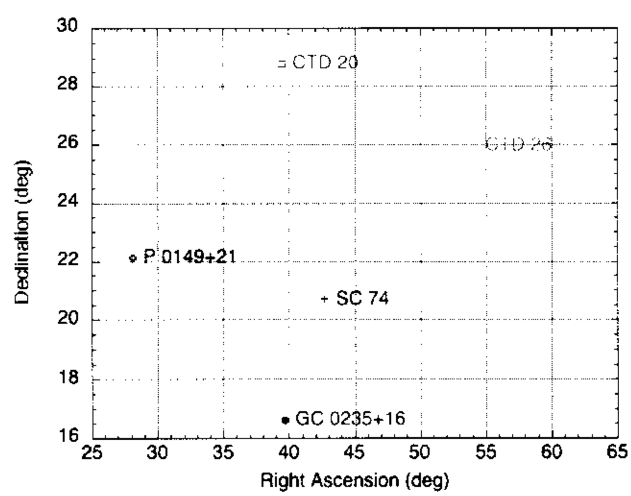


Fig. 3. Plane-of-sky positions of the spacecraft and radio sources during the data session on Jan. 20, 2006.

For this session, a residual was calculated for each individual delay measurement after removal of models including clock offset and drift. During navigation data processing, best values are used for geometric and media model parameters. Even so, data errors remain. These errors in the single source observations are further reduced by differencing between spacecraft and quasar. Normally, a quasar is observed just before and just after each spacecraft observation. After removal of best models, the quasar residuals are linearly interpolated to the time of the spacecraft measurement and subtracted from the spacecraft residual. This procedure removes all temporal errors to first order. Quasars are selected within about 10 deg of the spacecraft. If possible, a quasar is observed on either side of the spacecraft so that the interpolation of residuals also reduces spatial errors. With six radio source observations per session it is even possible to vary the number of observations of each source to effectively weight the data to further reduce spatial errors.

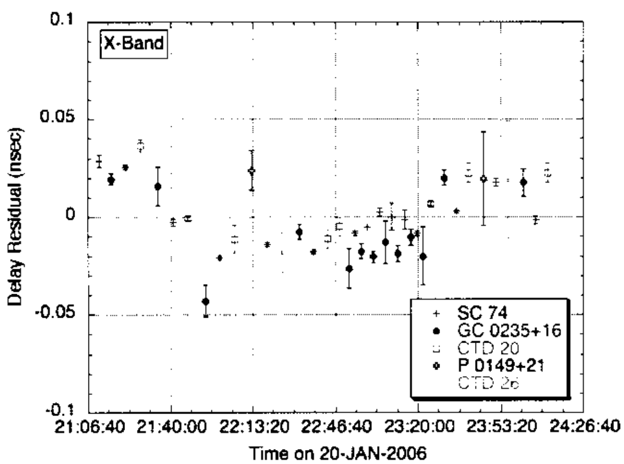


Fig. 4. Delay residuals at X-band for the data session on Jan. 20, 2006.

The residuals for the X-band measurements are shown in Fig. 4. Also shown are error bars due to system noise for each delay measurement. The error in the spacecraft-quasar delay difference is clearly less than 0.03 nsec for measurements throughout the session, when the closer quasar GC 0235+16 is used. Residual differences are larger for the more angularly distant quasars, but a ΔDOR point formed by observing a quasar on either side of the spacecraft would still be accurate to 0.03 nsec.

The availability of Ka-band data for this session allows some insight into the relative magnitude of troposphere and ionosphere errors. If the ionosphere is dominant, residual differences will be reduced at Ka-band. The residuals for the Ka-band measurements are shown in Fig. 5. The precision is too poor for some individual measurements to assess data quality at the level of 0.03 nsec. A higher sampling rate, wider spanned bandwidth, and improved ground station antenna pointing would improve this. However, for many of the measurements, the precision is better than 0.03 nsec. The residual pattern for these more precise measurements is similar at X-band and Ka-band, suggesting that the troposphere is probably the dominant remaining error source.

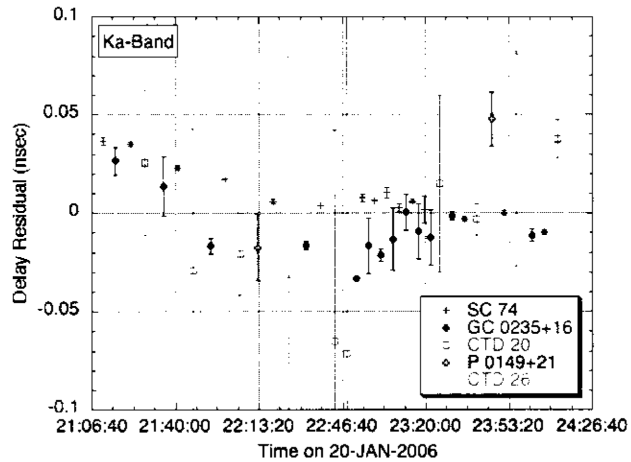


Fig. 5. Delay residuals at Ka-band for the data session on Jan. 20, 2006.

In general, media calibrations provided by observations of GPS satellites do an excellent job of removing errors across the field of observation. For the session on Jan. 20, uncalibrated media effects are apparently quite small. Even so, the differencing between nearby spacecraft and quasar observations is often required to reduce spatial errors to the 0.03-nsec level.

### 3. Requirements for Cross-Support

ΔDOR measurements require the use of stations separated by thousands of kilometers. Combining assets of multiple agencies is a practical approach to obtaining a global network of stations to provide a variety of baseline orientations. The availability of digital receivers and network data transfer makes it feasible to define standards for interoperability that would enable high performance ΔDOR measurements for support of spacecraft navigation from such a global network.

As more nations launch spacecraft for interplanetary exploration, the navigation challenges and potential applications for ΔDOR measurements will continue to increase. At the same time, as more tracking facilities are built, there are more assets that are potentially available for providing ΔDOR measurements. Standards for cross-support of telecommunications services including ΔDOR are currently being developed by the Consultative Committee for Space Data Systems. These standards are intended to provide methods for cooperating agencies to acquire or offer services.

Acquisition of data for a ΔDOR measurement requires high rate recordings of incoming radio signals in frequency channels centered on tones transmitted by a spacecraft. Instrumental delays and phase shifts of the recorded signal must be nearly identical for either narrowband spacecraft tones or broadband emissions from natural radio sources. While it is not necessary or practical to record the entire passband, digital signal processing makes it possible to record slices of the passband that preserve the characteristics of the radio frequency signal important for ΔDOR. These data samples must be transmitted to a common processing site for correlation. Ideally the same recording format would be used at each site, but re-sampling of the data prior to correlation is also an option for data recorded in different native formats.

There will also certainly be numerous logistical problems that will need to be solved including: the scheduling of antennas for routine observations, providing observation schedules in the correct format, and ensuring that all observing stations have been provided with the correct spacecraft signal parameters and correct receiver configuration information.

### 4. Advantages of Additional Baselines

The two DSN baselines have large orthogonal components and good visibility for sources in the northern sky. The Mars missions in the 2003 and 2005 launch opportunities had encounters at positive declination and navigation including ΔDOR was excellent [4]. Additional baselines are needed to support high accuracy navigation at low declinations. Additional baselines would also allow more independent measurements or more timely measurements to be made to support the most demanding navigation challenges.

From a baseline geometry point of view, ideal locations for new assets to supplement the existing DSN stations would be Japan, the western coast of Australia, South Africa, and Chile. Fortunately, high performance spacecraft tracking stations already exist in two of these locations: the JAXA station at Usuda and the ESA station at New Norcia, Australia. ESA also has a tracking station at Cebreros, Spain.

A Mars mission in the 2012 launch opportunity will have an encounter at about –23 deg declination. At this low declination, ΔDOR observations on the Goldstone-Madrid baseline are severely degraded due to low antenna elevation viewing angles. Since navigation solutions make use of Doppler and range measurements in addition to ΔDOR, even one baseline for ΔDOR may provide acceptable results for most missions. The most challenging missions, however, may require target accuracy near the 1-km level. Using only earth-based radiometric data, this performance will be difficult to achieve without the availability of two baselines for ΔDOR measurements.

The Usuda-Canberra baseline, with its north-south orientation, has good visibility for sources throughout the ecliptic. The same is true of the canted Goldstone-Canberra and New Norcia-Cebreros baselines. The latter two baselines are at nearly right angles to each other.

A covariance study was conducted for Mars approach of a candidate mission during the 2012 launch opportunity. Several cases were run assuming ΔDOR data for different combinations of the Goldstone-Canberra (GLD-CNB), Usuda-Canberra (USU-CNB), and New Norcia-Cebreros (NNO-CEB) baselines. The same schedule of Doppler and range measurements was used in each case. Results are 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.

Fig. 6 shows error ellipses for 5 covariance runs: 3 runs use a single baseline and 2 runs use a pair of baselines. Formal 1-sigma errors are 4-5 km for the runs that use a single baseline. Since the orientation of the semi-major axis depends on the baseline, one might expect combinations of baselines to reduce the error magnitude. This is indeed the case. With two baselines the formal error is reduced to 1-2 km. The availability of multiple baselines for ΔDOR combined with range and Doppler data enable high accuracy approach navigation for this solar system geometry.

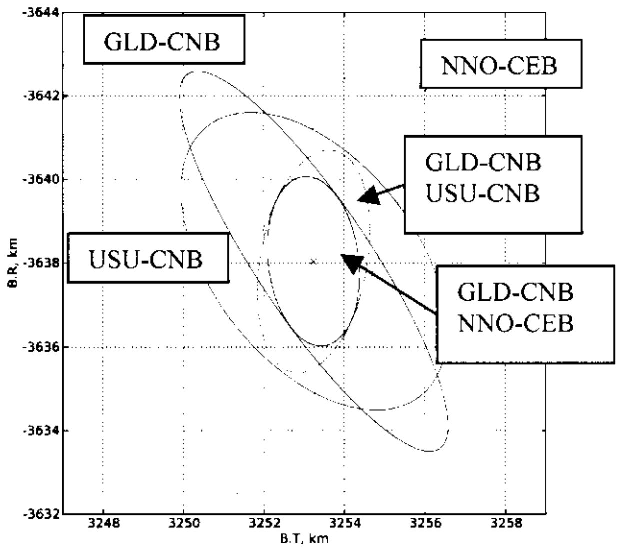


Fig. 6. B-Plane error ellipses for several ΔDOR baseline combinations for a Mars mission in the 2012 launch opportunity.

## 5. Conclusions

A significant improvement in ΔDOR measurement accuracy has been realized over the last decade. The same advances in digital signal processing that have led to these improvements also make it technically feasible for assets of different space agencies to provide cross-support. If more stations are available to form baselines for ΔDOR data acquisition, navigation accuracy and robustness will improve. Existing assets at locations in the western United States, Japan, eastern Australia, western Australia, and Spain form baselines that provide uniformly good geometric coverage for missions throughout the ecliptic plane. The missions of all space agencies will benefit from improved navigation if they combine their assets for this purpose.

To realize these improvements, the space agencies of the participating countries must begin to lay the groundwork that will allow them to combine their spacecraft navigational assets.

## Acknowledgments

I would like to thank Eric Graat for providing ΔDOR residuals to the MRO trajectory and Don Han for providing covariance analysis results for Mars orbit insertion. Valuable review comments on this manuscript were received from Peter Kroger and Tomas Martin-Mur.

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

## References

[1] C. L. Thornton and J. S. Border, Radiometric Tracking Techniques for Deep-Space Navigation, 2003, John Wiley & Sons, Inc.

[2] P. G. Antreasian et al., "2001 Mars Odyssey Orbit Determination During Interplanetary Cruise," *Journal of Spacecraft and Rockets*, vol. 42, no. 3, pp. 394-405, May-June 2005.

[3] M. S. Ryne and S. Nandi, "Nozomi Earth Swingby Orbit Determination," AAS 04-131, *Advances in the Astronautical Sciences, vol. 119, part I*, Proceedings of the 14th AAS/AIAA Space Flight Mechanics Meeting, Maui, Hawaii, Feb. 8-12, 2004.

[4] T. P. McElrath et al, "Mars Exploration Rovers Orbit Determination Filter Strategy," AIAA-2004-4982, 2004 AIAA/AAS Astrodynamics Specialist Conference, Providence, Rhode Island, August 16-19, 2004.

[5] D. Han et al., "Mars Express Interplanetary Navigation from Launch to Mars Orbit Insertion: The JPL Experience," 18th International Symposium on Space Flight Dynamics, Munich, Germany, October 11-15, 2004.

[6] J. S. Border and J. A. Koukos, "Technical Characteristics and Accuracy Capabilities of Delta Differential One-Way Ranging (ΔDOR) as a Spacecraft Navigation Tool," Report of the Proceedings of the Consultative Committee for Space Data Systems on RF and Modulation Standards Approval, Tien M. Nguyen, Editor, CCSDS B20.0-Y-1, February 1994.

[7] R. Ichikawa et al., "An Evaluation of VLBI Observations for the Deep Space Tracking of the Interplanetary Spacecrafts," International VLBI Service for Geodesy and Astrometry (IVS) 2004 General Meeting Proceedings (Nancy R. Vandenberg and Karen D. Baver, editors), Ottawa, Canada, February 9-11, 2004.

[8] I. E. Molotov, "Experiments on the Differential VLBI Measurements with the Former Russian Deep Space Network," 18th International Symposium on Space Flight Dynamics, Munich, Germany, October 11-15, 2004.

[9] G. E. Lanyi et al., "Determination of Angular Separation Between Spacecraft and Quasars with the Very Long Baseline Array," The Interplanetary Network Progress Report, vol. 42-162, Jet Propulsion Laboratory, Pasadena, California, August 15, 2005.

[10] L. Iess et al., "The European Delta-DOR correlator", to be presented at the 57th International Astronautical Congress (2006).

[11] N. James et al., "The implementation of an ESA Delta-DOR capability", to be presented at the 57th International Astronautical Congress (2006).

ISTS 2006-d-49

# A GLOBAL APPROACH TO DELTA DIFFERENTIAL ONE-WAY RANGE

James S. Border
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California

**Abstract**

Radio interferometric techniques for measuring spacecraft angular position play a role of increasing importance in today's missions of interplanetary exploration. Several national and international space agencies have or are developing operational systems to support spacecraft navigation using interferometric measurements. NASA's Deep Space Network has provided Delta Differential One-way Range (ΔDOR) data for this purpose since 1980. Steady improvements in system performance and operability have taken place with accuracy today approaching the 1-nrad level. In this paper the current performance of NASA's ΔDOR system is presented. Recent data from the Mars Reconnaissance Orbiter cruise from Earth to Mars are used to illustrate system performance at 8.4 and 32 GHz. Technical feasibility and requirements for combining tracking stations from different agencies to support ΔDOR observations are discussed. The advantages of having additional stations to form baselines for measurements are presented. Results of a covariance study for encounter targeting are given for a candidate mission that may need ΔDOR data from additional baselines.

## 1. Introduction

Direct measurements of the plane-of-sky position of a spacecraft play a role of increasing importance in today's missions of interplanetary exploration. These measurements, based on the technique of radio interferometry, provide additional accuracy, efficiency, and robustness for navigation when added to conventional line-of-sight Doppler and range measurements. NASA's Deep Space Network (DSN) has developed a technique known as Delta Differential One-way Range (ΔDOR) to provide angular observables [1]. In ΔDOR measurements, two tracking stations receive signals from a spacecraft and the delay in signal arrival time at one station with respect to the second station is measured. This delay, referred to as 'differential one-way range', gives the technique its name. A similar, nearly simultaneous, delay measurement is made using signals from an angularly nearby quasar that has a well known catalog position, to calibrate the instrumentation. The difference or 'delta' between the spacecraft and quasar delay measurements provides an accurate determination of the spacecraft angular position in the radio reference frame. A single pair of stations or 'baseline' determines one component of angular position. Two baselines are needed to measure both components.

The DSN began development of the ΔDOR technique to support the Voyager 1 encounter with Saturn in 1980 and most recently provided ΔDOR measurements to support orbit insertion for Mars Reconnaissance Orbiter (MRO) in 2006. There has been steady improvements in both the performance and operability of this technique, with accuracy today approaching the 1-nrad level. Initially the DSN developed a unique near-realtime VLBI system to enable rapid data transfer and processing to support spacecraft navigation. Today's system is built around common digital signal processing components that are also used for radio science and telemetry arraying in the DSN. Similar developments in digital signal processing capability are seen around the world in radio astronomy and spacecraft tracking applications.

The ΔDOR system has been widely used by recent missions to Mars including Mars'01 Odyssey [2], Nozomi [3], Mars Exploration Rovers (MER) [4], Mars Express [5], and MRO. The 8.4 GHz radio band (X-band) has been used by these missions. Performance of the ΔDOR system at X-band is characterized in Section 2. Data from MRO are used to verify estimates of system performance. In addition, the first ΔDOR measurements in the 32 GHz radio band (Ka-band) were recently acquired from MRO. First results of system performance at Ka-band are presented.

A number of steps are involved in the end-to-end planning and data generation process for ΔDOR including: station scheduling, spacecraft and ground station event sequencing, receiver and recorder setup for data acquisition, and correlation processing to extract time delay observables. Operational interfaces for equipment setup and observable delivery have been implemented in the DSN. International standards for supporting ΔDOR measurements were first discussed in a meeting of the Consultative Committee for Space Data Systems in 1993 [6].

There is international interest and activity to develop capability for applying VLBI to spacecraft navigation [7,8,9,10,11]. Space agencies of several nations have missions in flight or in planning stages that require radio interferometry measurements for navigation. These agencies also operate tracking stations that are strategically spread around the globe. NASA's Deep Space Network provides two baselines for ΔDOR: Goldstone-Madrid and Goldstone-Canberra. While these baselines span two dimensions, the availability of additional stations at other locations would offer advantages in a number of areas. Scheduling conflicts would be reduced if more stations were available. The robustness of the technique would improve if a single complex such as Goldstone was not essential for every measurement. More independent measurements and more timely measurements would provide improved navigation accuracy. The availability of baselines with a variety of orientations (for example north-south or east-west) would allow efficient scheduling of stations to meet a navigation requirement in a critical dimension.

The ESA stations at New Norcia and Cebreros and the JAXA station at Usuda are at excellent locations to complement the NASA sites. The New Norcia-Cebreros baseline is an orthogonal complement to the Goldstone-Canberra baseline. The Usuda-Canberra baseline is an orthogonal complement to the Goldstone-Madrid baseline. If multiple Space Agencies provide cross-support for ΔDOR data acquisition, then the missions of each agency will benefit from improved navigation. In Section 3, cross-support requirements are discussed. Section 4 presents the results of a covariance analysis, using data from several baseline combinations, to support orbit insertion at Mars for a mission in the 2012 launch opportunity.

## 2. ΔDOR Performance

The performance of the ΔDOR system depends on a number of factors including: the spacecraft downlink signal spectrum, ground station receivers, observation geometry, and calibrations for earth orientation and atmospheric path delay. An error budget, published in 1993, gave a formulation for the expected measurement accuracy as a function of the characteristics and a priori knowledge of input parameters [6]. Using assumptions that were valid at that time, predicted delay measurement accuracy was 0.23 nsec. This corresponds to an angular accuracy of about 9 nrad assuming a baseline length of 8000 km. While the formulation used in [6] to predict accuracy is still valid, the system characteristics have substantially improved. First, more data samples are recorded and transferred to the correlator facility, improving precision. Second, the ground receiver passbands have improved phase linearity, reducing instrumental biases. Third, earth orientation and atmospheric path delays are much better determined by calibration techniques employing GPS satellite observations. Finally, more radio sources are available in the astrometric catalog, allowing selection of reference sources closer to the spacecraft trajectory in an angular sense.

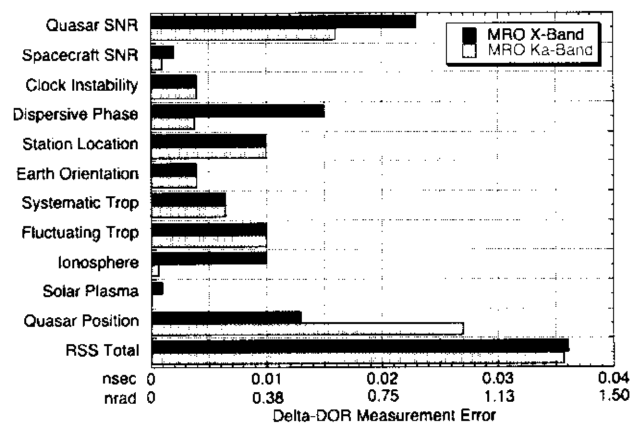


Fig. 1. ΔDOR error budget (1-sigma) for MRO measurements in 2005-2006.

Starting with Odyssey support in 2001, measurement accuracy has been at the 5 nrad level and improving, for spacecraft with spectral components in the downlink signal spanning at least 38 MHz. Performance degrades roughly linearly as spanned bandwidth decreases. Refinements in measurement technique have yielded improved performance from Odyssey to MER to MRO. Current DSN system performance is approaching the 1-nrad level. An error budget is shown in Fig. 1 for recent MRO measurements at both X-band and Ka-band. The expected delay accuracy at X-band is 0.036 nsec, 1-sigma.

Good performance is expected for MRO since the spacecraft is moving through the ecliptic plane with positive declination, viewing geometry is favorable from both DSN baselines, and a large number of reference radio sources is available. In general, the

DSN commits to providing ΔDOR data accuracy of 0.060 nsec.

During MRO cruise phase, X-band data were acquired during 64 ΔDOR sessions in support of navigation. Nine radio source observations in three sequences of quasar1-spacecraft-quasar2 were made during each 1-hour session, generating three separate spacecraft minus quasar delta delay points. The measurement residuals to the final cruise trajectory are shown in Fig. 2. The root-mean-square of residuals is 0.031 nsec, in good agreement with expected system performance. This could be a slight underestimate of true error since the spacecraft trajectory was fit to the data.

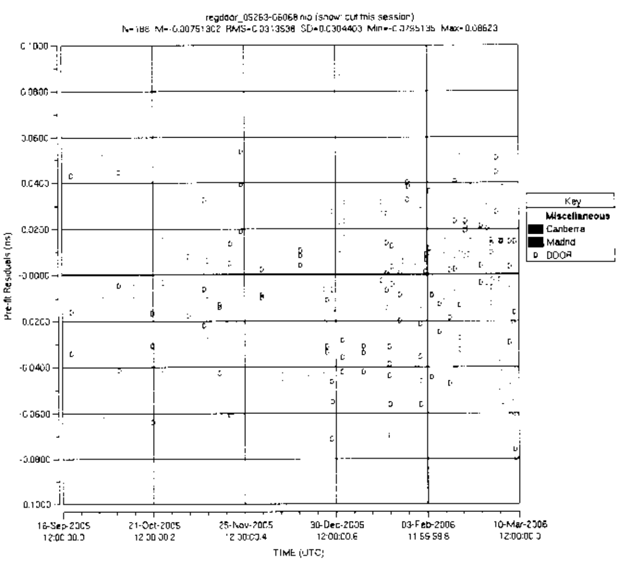


Fig. 2. MRO ΔDOR residuals to final cruise trajectory.

The wider spectrum allocation at Ka-band will eventually enable improved performance for ΔDOR. The MRO spacecraft has a Ka-band transmitter that emits tones spanning four times the spanned bandwidth at X-band. Data were acquired at Ka-band during seven of the MRO ΔDOR observing sessions. The expected accuracy for MRO at Ka-band, shown in Fig. 1, is comparable to the accuracy at X-band. The wider spanned bandwidth and the higher radio frequency reduce some error components, but reduced antenna sensitivity at Ka-band, general roll-off of quasar flux at higher frequencies, and lack of a large Ka-band radio source astrometric data base to properly define the reference source positions cause other error components to grow. For the MRO cruise measurements, the Ka-band data are in general agreement with the X-band data. The precision of the Ka-band quasar delay measurements is less than expected for some observations, likely due to errors in ground station antenna pointing that exceed the very tight 0.004 mdeg requirement.

To take advantage of the reduction in the error components at Ka-band frequencies, other work will be needed to realize a significant improvement in end-to-end system performance. A higher data sampling rate and wider spacecraft signal spanned bandwidth are needed to improve precision. An improvement in troposphere calibration will be needed. This could be achieved by making use of high performance water vapor radiometers at each tracking station. Finally, improvements in the global reference frame, including station coordinates and quasar coordinates, are required. This will require a measurement and analysis campaign, over several years, using radio source data at X-band and Ka-band. If development work is completed in these areas, then end-to-end system performance at Ka-band could improve to better than the 1-nrad level.

To better characterize the system performance, additional time was allocated during one of the ΔDOR observing sessions. A total of 40 observations of the spacecraft and four radio sources were made during the session on Jan. 20, 2006. The sky position of the spacecraft and radio sources is shown in Fig. 3. (Note that the spacecraft is identified as SC 74.) Quasars were observed in all directions from the spacecraft with the closest quasar being about 5 deg away.

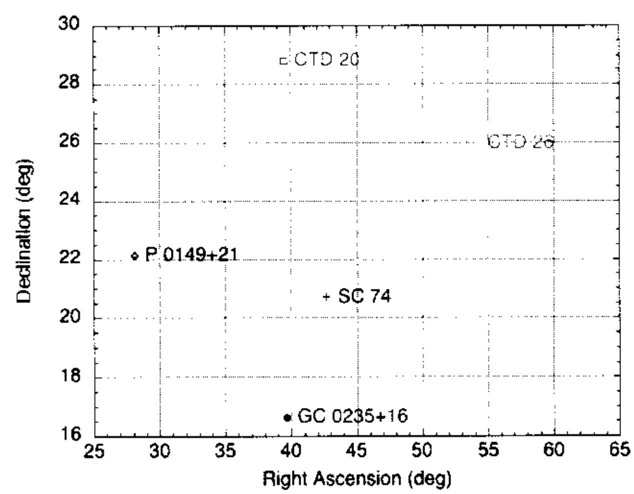


Fig. 3. Plane-of-sky positions of the spacecraft and radio sources during the data session on Jan. 20, 2006.

For this session, a residual was calculated for each individual delay measurement after removal of models including clock offset and drift. During navigation data processing, best values are used for geometric and media model parameters. Even so, data errors remain. These errors in the single source observations are further reduced by differencing between spacecraft and quasar. Normally, a quasar is observed just before and just after each spacecraft observation. After removal of best models, the quasar residuals are linearly interpolated to the time of the spacecraft measurement and subtracted from the spacecraft residual. This procedure removes all temporal errors to first order. Quasars are selected within about 10 deg of the spacecraft. If possible, a quasar is observed on either side of the spacecraft so that the interpolation of residuals also reduces spatial errors. With six radio source observations per session it is even possible to vary the number of observations of each source to effectively weight the data to further reduce spatial errors.

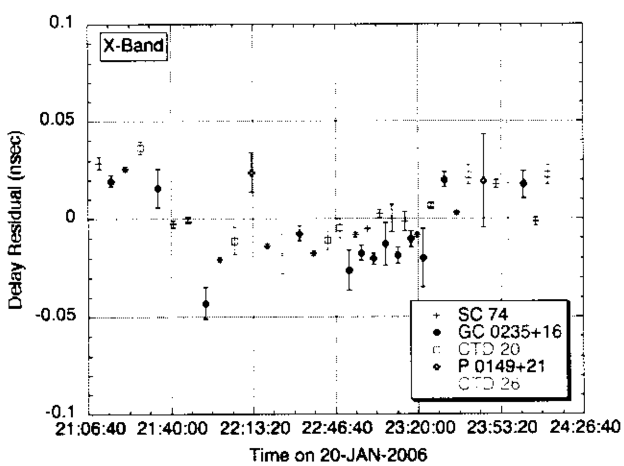


Fig. 4. Delay residuals at X-band for the data session on Jan. 20, 2006.

The residuals for the X-band measurements are shown in Fig. 4. Also shown are error bars due to system noise for each delay measurement. The error in the spacecraft-quasar delay difference is clearly less than 0.03 nsec for measurements throughout the session, when the closer quasar GC 0235+16 is used. Residual differences are larger for the more angularly distant quasars, but a ΔDOR point formed by observing a quasar on either side of the spacecraft would still be accurate to 0.03 nsec.

The availability of Ka-band data for this session allows some insight into the relative magnitude of troposphere and ionosphere errors. If the ionosphere is dominant, residual differences will be reduced at Ka-band. The residuals for the Ka-band measurements are shown in Fig. 5. The precision is too poor for some individual measurements to assess data quality at the level of 0.03 nsec. A higher sampling rate, wider spanned bandwidth, and improved ground station antenna pointing would improve this. However, for many of the measurements, the precision is better than 0.03 nsec. The residual pattern for these more precise measurements is similar at X-band and Ka-band, suggesting that the troposphere is probably the dominant remaining error source.

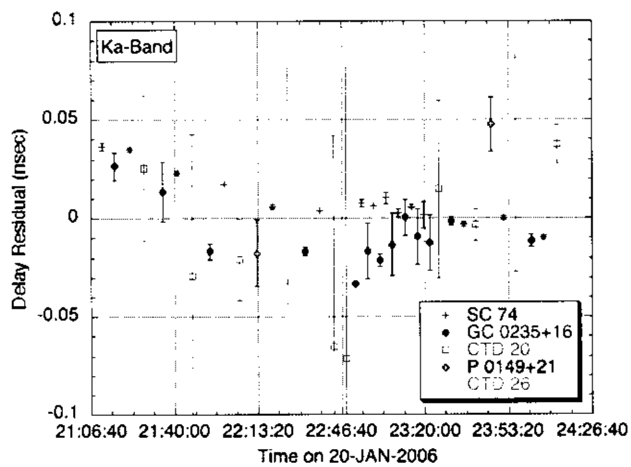


Fig. 5. Delay residuals at Ka-band for the data session on Jan. 20, 2006.

In general, media calibrations provided by observations of GPS satellites do an excellent job of removing errors across the field of observation. For the session on Jan. 20, uncalibrated media effects are apparently quite small. Even so, the differencing between nearby spacecraft and quasar observations is often required to reduce spatial errors to the 0.03-nsec level.

## 3. Requirements for Cross-Support

ΔDOR measurements require the use of stations separated by thousands of kilometers. Combining assets of multiple agencies is a practical approach to obtaining a global network of stations to provide a variety of baseline orientations. The availability of digital receivers and network data transfer makes it feasible to define standards for interoperability that would enable high performance ΔDOR measurements for support of spacecraft navigation from such a global network.

As more nations launch spacecraft for interplanetary exploration, the navigation challenges and potential applications for ΔDOR measurements will continue to increase. At the same time, as more tracking facilities are built, there are more assets that are potentially available for providing ΔDOR measurements. Standards for cross-support of telecommunications services including ΔDOR are currently being developed by the Consultative Committee for Space Data Systems. These standards are intended to provide methods for cooperating agencies to acquire or offer services.

Acquisition of data for a ΔDOR measurement requires high rate recordings of incoming radio signals in frequency channels centered on tones transmitted by a spacecraft. Instrumental delays and phase shifts of the recorded signal must be nearly identical for either narrowband spacecraft tones or broadband emissions from natural radio sources. While it is not necessary or practical to record the entire passband, digital signal processing makes it possible to record slices of the passband that preserve the characteristics of the radio frequency signal important for ΔDOR. These data samples must be transmitted to a common processing site for correlation. Ideally the same recording format would be used at each site, but re-sampling of the data prior to correlation is also an option for data recorded in different native formats.

There will also certainly be numerous logistical problems that will need to be solved including: the scheduling of antennas for routine observations, providing observation schedules in the correct format, and ensuring that all observing stations have been provided with the correct spacecraft signal parameters and correct receiver configuration information.

## 4. Advantages of Additional Baselines

The two DSN baselines have large orthogonal components and good visibility for sources in the northern sky. The Mars missions in the 2003 and 2005 launch opportunities had encounters at positive declination and navigation including ΔDOR was excellent [4]. Additional baselines are needed to support high accuracy navigation at low declinations. Additional baselines would also allow more independent measurements or more timely measurements to be made to support the most demanding navigation challenges.

From a baseline geometry point of view, ideal locations for new assets to supplement the existing DSN stations would be Japan, the western coast of Australia, South Africa, and Chile. Fortunately, high performance spacecraft tracking stations already exist in two of these locations: the JAXA station at Usuda and the ESA station at New Norcia, Australia. ESA also has a tracking station at Cebreros, Spain.

A Mars mission in the 2012 launch opportunity will have an encounter at about –23 deg declination. At this low declination, ΔDOR observations on the Goldstone-Madrid baseline are severely degraded due to low antenna elevation viewing angles. Since navigation solutions make use of Doppler and range measurements in addition to ΔDOR, even one baseline for ΔDOR may provide acceptable results for most missions. The most challenging missions, however, may require target accuracy near the 1-km level. Using only earth-based radiometric data, this performance will be difficult to achieve without the availability of two baselines for ΔDOR measurements.

The Usuda-Canberra baseline, with its north-south orientation, has good visibility for sources throughout the ecliptic. The same is true of the canted Goldstone-Canberra and New Norcia-Cebreros baselines. The latter two baselines are at nearly right angles to each other.

A covariance study was conducted for Mars approach of a candidate mission during the 2012 launch opportunity. Several cases were run assuming ΔDOR data for different combinations of the Goldstone-Canberra (GLD-CNB), Usuda-Canberra (USU-CNB), and New Norcia-Cebreros (NNO-CEB) baselines. The same schedule of Doppler and range measurements was used in each case. Results are 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.

Fig. 6 shows error ellipses for 5 covariance runs: 3 runs use a single baseline and 2 runs use a pair of baselines. Formal 1-sigma errors are 4-5 km for the runs that use a single baseline. Since the orientation of the semi-major axis depends on the baseline, one might expect combinations of baselines to reduce the error magnitude. This is indeed the case. With two baselines the formal error is reduced to 1-2 km. The availability of multiple baselines for ΔDOR combined with range and Doppler data enable high accuracy approach navigation for this solar system geometry.

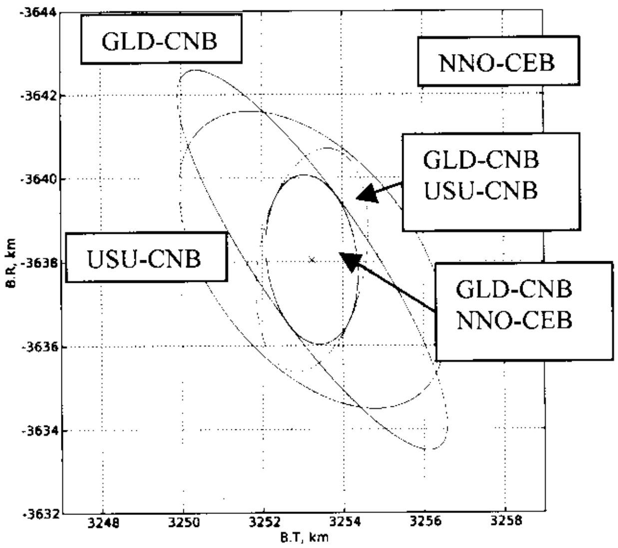


Fig. 6. B-Plane error ellipses for several ΔDOR baseline combinations for a Mars mission in the 2012 launch opportunity.

### 5. Conclusions

A significant improvement in ΔDOR measurement accuracy has been realized over the last decade. The same advances in digital signal processing that have led to these improvements also make it technically feasible for assets of different space agencies to provide cross-support. If more stations are available to form baselines for ΔDOR data acquisition, navigation accuracy and robustness will improve. Existing assets at locations in the western United States, Japan, eastern Australia, western Australia, and Spain form baselines that provide uniformly good geometric coverage for missions throughout the ecliptic plane. The missions of all space agencies will benefit from improved navigation if they combine their assets for this purpose.

To realize these improvements, the space agencies of the participating countries must begin to lay the groundwork that will allow them to combine their spacecraft navigational assets.

### Acknowledgments

I would like to thank Eric Graat for providing ΔDOR residuals to the MRO trajectory and Don Han for providing covariance analysis results for Mars orbit insertion. Valuable review comments on this manuscript were received from Peter Kroger and Tomas Martin-Mur.

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.



### References

[1] C. L. Thornton and J. S. Border, Radiometric Tracking Techniques for Deep-Space Navigation, 2003, John Wiley & Sons, Inc.

[2] P. G. Antreasian et al., "2001 Mars Odyssey Orbit Determination During Interplanetary Cruise," *Journal of Spacecraft and Rockets*, vol. 42, no. 3, pp. 394-405, May-June 2005.

[3] M. S. Ryne and S. Nandi, "Nozomi Earth Swingby Orbit Determination," AAS 04-131, *Advances in the Astronautical Sciences, vol. 119, part I*, Proceedings of the 14th AAS/AIAA Space Flight Mechanics Meeting, Maui, Hawaii, Feb. 8-12, 2004.

[4] T. P. McElrath et al, "Mars Exploration Rovers Orbit Determination Filter Strategy," AIAA-2004-4982, 2004 AIAA/AAS Astrodynamics Specialist Conference, Providence, Rhode Island, August 16-19, 2004.

[5] D. Han et al., "Mars Express Interplanetary Navigation from Launch to Mars Orbit Insertion: The JPL Experience," 18th International Symposium on Space Flight Dynamics, Munich, Germany, October 11-15, 2004.

[6] J. S. Border and J. A. Koukos, "Technical Characteristics and Accuracy Capabilities of Delta Differential One-Way Ranging (ΔDOR) as a Spacecraft Navigation Tool," Report of the Proceedings of the Consultative Committee for Space Data Systems on RF and Modulation Standards Approval, Tien M. Nguyen, Editor, CCSDS B20.0-Y-1, February 1994.

[7] R. Ichikawa et al., "An Evaluation of VLBI Observations for the Deep Space Tracking of the Interplanetary Spacecrafts," International VLBI Service for Geodesy and Astrometry (IVS) 2004 General Meeting Proceedings (Nancy R. Vandenberg and Karen D. Baver, editors), Ottawa, Canada, February 9-11, 2004.

[8] I. E. Molotov, "Experiments on the Differential VLBI Measurements with the Former Russian Deep Space Network," 18th International Symposium on Space Flight Dynamics, Munich, Germany, October 11-15, 2004.

[9] G. E. Lanyi et al., "Determination of Angular Separation Between Spacecraft and Quasars with the Very Long Baseline Array," The Interplanetary Network Progress Report, vol. 42-162, Jet Propulsion Laboratory, Pasadena, California, August 15, 2005.

[10] L. Iess et al., "The European Delta-DOR correlator", to be presented at the 57th International Astronautical Congress (2006).

[11] N. James et al., "The implementation of an ESA Delta-DOR capability", to be presented at the 57th International Astronautical Congress (2006).