INNOVATIONS IN DELTA DIFFERENTIAL ONE-WAY RANGE: FROM VIKING TO MARS SCIENCE LABORATORY

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ABSTRACT

The Deep Space Network has provided the capability for very-long-baseline interferometry measurements in support of spacecraft navigation since the late 1970s. Both system implementation and the importance of such measurements to flight projects have evolved significantly over the past three decades. Innovations introduced through research and development programs have led to continuous improvements in performance. This paper provides an overview of the development and use of interferometric tracking techniques in the DSN starting with the Viking era and continuing with a description of the current system and its planned use to support navigation of the Mars Science Laboratory spacecraft.

1. INTRODUCTION

The Deep Space Network (DSN), consisting of radio antennas near Goldstone, California; Madrid, Spain; and Canberra, Australia, provides radio links to interplanetary spacecraft to support radiometric tracking, telemetry, and commanding. Radio signal travel time and frequency shift are measured to obtain estimates of line-of-sight range and range-rate between a tracking station and a spacecraft. Navigation for the earliest interplanetary spacecraft was based on these measurements, known as range and Doppler. The rotation of the earth imposes a diurnal signature on the received Doppler that depends on the angular coordinates of the spacecraft [1,2], allowing the trajectory of a distant spacecraft to be estimated from a series of range and Doppler measurements. This technique provided reliable navigation for the missions to Mars and the other inner planets in the 1960s and early 1970s.

As space missions became more ambitious the requirements for accurate navigation became more stringent. For example there is a narrower entry corridor to be captured into orbit about a planet rather than to fly by the planet. Researchers began looking at methods to augment range and Doppler with additional data and also to improve geometric model accuracy. The use of radiometric data acquired simultaneously or nearly simultaneously at two widely separated tracking stations, and then differenced, was studied. This concept, based on the technique of very-long-baseline interferometry (VLBI) used by radio astronomers [3], offered to help solve two outstanding problems [4]. First, differenced ranges from northern and southern hemisphere stations would not lose sensitivity to spacecraft declination when the spacecraft was near earth's equatorial plane, as is the case for Doppler tracking. Second, differenced data have less sensitivity to unmodeled spacecraft accelerations and hence reduce aliasing of state parameters. The original idea was to form differenced data from range and Doppler measurements, but it was noted that data accuracy must be very high before differenced data could contribute to trajectory estimation.

Prior to orbit estimation, models for the position and motion of the tracking stations and the spacecraft in a common inertial reference frame must be developed. Radio signal propagation equations are solved to produce predicted values for range and range-rate observables. Spacecraft state parameters are then adjusted to fit the trajectory to the data. Sensitivity analysis, which reveals how errors in model parameters relate to errors in spacecraft trajectory estimates, showed that key model parameters are the coordinates of the tracking stations, the orientation of the earth in inertial space, and, if approaching a target, the location of the target body in the inertial reference frame. Astronomical models had been largely based on optical observations until the advent of VLBI. Research was begun to determine the suitability of the DSN for performing VLBI and to what level VLBI could aid in direct spacecraft tracking and in the determination of additional data including polar motion, UT1, and station locations that are needed for orbit determination [5]. Other researchers also noted that the developing field of differential interferometry could have applications to spacecraft tracking [6].

An earlier development in the DSN deserves mention. While centuries of optical observations had determined angular coordinates of the inner planets to a reasonable accuracy of about 0.1 second of arc (500 nrad), the scale of the solar system was only poorly known. The uncertainty in the Astronomical Unit (AU) was as large as 6 parts in 10^4. One of the goals of NASA's first interplanetary mission, Mariner 2 with a launch date of August 27, 1962, was to determine a better value for the AU based on miss distance from Venus at the time of flyby. But just before this, on March 10, 1961, Richard M. Goldstein of JPL detected the first successful radar bounce off Venus [40]. The development of planetary radar at the Goldstone site improved the value for the AU by two orders of magnitude and allowed a trajectory design correction of 33,000 km for Mariner 2. Only because of this correction, onboard spacecraft instruments were pointed toward Venus, and scientifically useful data about Venus were obtained during the Mariner 2 flyby. Further, the development of sensitive open loop receivers in the DSN for planetary radar applications helped pave the way for VLBI.

The DSN began a program of VLBI measurements to improve geophysical models in 1971 [7] and then expanded the program to also define a more stable inertial reference frame in 1974 [8]. Observatories and institutions around the world contributed to this effort. A catalog of precise coordinates of distant radio sources, mostly quasars, was built to define a nearly inertial celestial reference frame. This work eventually resulted in an IAU resolution to establish the radio frame as the fundamental celestial reference frame [9]. Plate tectonics, crustal deformation, and wobbles of the earth about its spin axis were studied by VLBI. This work greatly improved knowledge of tracking station locations and tied together the terrestrial and celestial reference frames. But there remained the work to improve direct spacecraft tracking and to improve the location of target bodies in the radio reference frame. An accuracy requirement of 50 nrad for spacecraft VLBI was established to support the planned close flyby of Mars by the Galileo spacecraft.

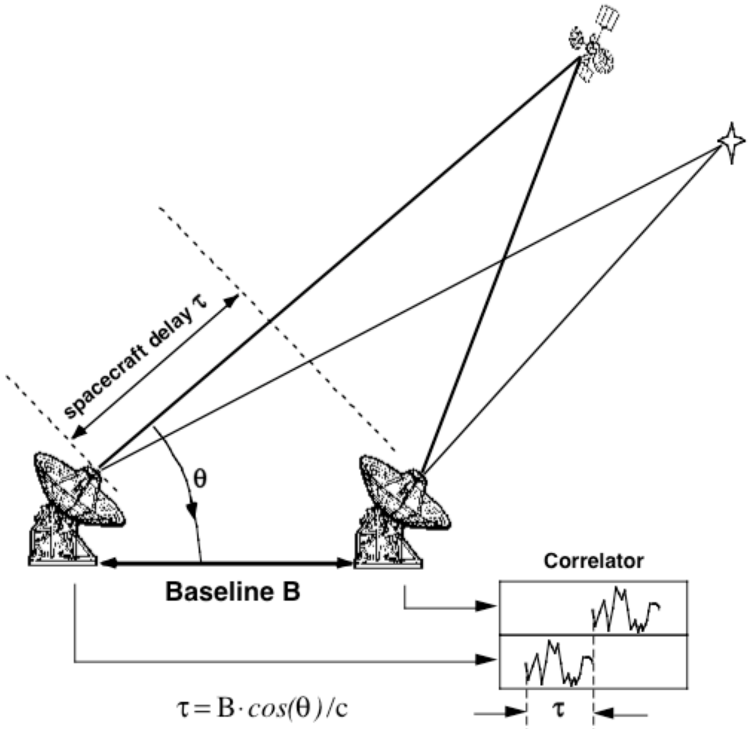

Fig. 1. Delta-VLBI Observation Geometry

Just as range and Doppler measurements determine the line-of-sight components of spacecraft state, interferometric measurements determine the plane-of-sky components of spacecraft state. Fig. 1 shows the geometry for differential VLBI observations. Measurements of time delay, as shown in the figure, provide a direct geometric determination of angular position. VLBI measurements are a natural complement to range and Doppler for spacecraft tracking.

Several approaches for VLBI-like spacecraft tracking were investigated. Measurements of conventional range and Doppler, differenced between stations, would build on DSN and spacecraft radio system design and on DSN operational expertise. But as measurement system errors were better understood, it became clear that media calibrations and instrumental synchronization between stations were insufficient to provide once-differenced data with high enough accuracy to significantly improve orbit determination. Differential measurements, that is alternate spacecraft VLBI and quasar VLBI, would be necessary to generate high quality data. Differential VLBI not only has the geometric strength of range or range-rate differenced between stations, it also benefits from cancellation of common-mode errors that arise from uncertainty in media delays, clock offsets, instrumental delays, and station locations.

Experiments were planned to investigate the technique, and systems were implemented to meet mission requirements, while ongoing research contributed to performance improvements. This paper presents an overview of the development of VLBI spacecraft tracking in the DSN. To begin, phase delay rate and time delay measurements are compared. Next, the origin of the technique known as Delta Differential One-way Range (ΔDOR) is discussed and the changing use of ΔDOR by a number of missions is presented. The measurement systems used over the years to meet increasing accuracy requirements for ΔDOR are described. Improvements in the technique are discussed and current system performance is presented. Finally, the importance of ΔDOR measurements of orbiting spacecraft to tie the planetary ephemeris to the radio frame is noted.

2. NARROWBAND AND WIDEBAND TECHNIQUES

Differential VLBI, or Delta-VLBI as it is known in the DSN, can be done by measuring either phase delay rate over a relatively long (several hour) time interval, or time delay over a shorter interval. Initial studies predicted the 50 nrad accuracy goal could be met with either Delta-VLBI phase delay rate or Delta-VLBI time delay, provided that spacecraft emit appropriate signals and receiving systems are properly designed. The former option is the VLBI analogue to Doppler while the latter option is the VLBI analogue to range. The information content of phase delay rate measurements arises from the diurnal signature imposed by earth rotation, just as for Doppler. Over a pass, phase is alternately measured for the spacecraft and the quasar. A precise history of signal phase for each source, including connection of integer cycles of phase across gaps, must be developed. The time interval must be nearly the full view period overlap when both sources are visible from both stations in order to extract angular coordinates from the diurnal signature in the data. One drawback of this technique is loss of sensitivity to spacecraft declination for sources near the earth's equatorial plane, just as for Doppler.

The information content of a time delay measurement is the angle between the baseline vector joining the two antennas and the direction to the radio source. The time delay technique requires observations of at least two sources, and as will be explained later, normally three or more time delay measurements are made. The information content for Delta-VLBI time delay measurements between a spacecraft and a quasar is the angle between the two sources. A measurement on a single baseline provides one angular component, but two baselines must be used to determine both components of angular position.

The phase delay rate technique has the advantage that it requires only a 'narrowband' signal, that is a spacecraft carrier signal or other signal of limited bandwidth. On the other hand, the time delay technique requires a 'wideband' signal that will enable a group delay measurement. Until the late 1970s, no spacecraft with wideband signals were available, and VLBI ground systems had only limited capability to record wide bandwidth signals. For these reasons, the first demonstrations used only the Delta-VLBI phase delay rate technique.

The earliest measurements, begun in 1972 with the Mariner 9 spacecraft in orbit at Mars, proved difficult. These measurements had the dual purpose of developing the VLBI technique in the DSN while also measuring the position of Mars in the radio reference frame [10]. But problems were encountered with station instrumentation, specifically with frequency stability in the signal downconversion chain needed to capture the spacecraft signal in the video (baseband) channel of the VLBI recorder. Also, media effects were large at the frequency of the S-band downlink and new algorithms had to be developed for processing spacecraft signals since their spectral characteristics differed from those of natural radio sources. Ultimately, it would take years before high quality results were obtained. Over this time, DSN instrumentation was improved to meet the demands of the new VLBI program as well as to better serve other users.

In 1979 a demonstration of Delta-VLBI phase delay rate was carried out using S-band or X-band downlinks[1] from the two Voyager spacecraft near the times of their Jupiter flybys [11,12]. Of 25 scheduled opportunities, data suitable for analysis were acquired on 22 passes. The goal was to demonstrate angular accuracy of 50 nrad, but results showed scatter that was ten times larger. A leading cause of the larger error magnitude was that it had not been possible to schedule the spacecraft and the stations for the full duration of the view period; pass durations were typically 2.5 hr rather than 4.5 hr. It was known that shorter passes provided less accuracy. Further, instrumental effects and uncalibrated media delays were larger than expected. The relatively large angular separation of 10 deg from the Voyagers to a source in the radio catalog contributed to the phase errors. While the measurement of phase of the radio frequency signal can be very precise, any unmodeled effects at even the few cm level can seriously degrade the interpretation of a time series of phase. The DSN system could not yet perform overall to the 1 cm level.

Meanwhile, conventional tracking with range and Doppler was becoming more accurate in the radio frame newly defined by VLBI observations. It remained a priority for support of future missions to tie the planetary ephemeris to the radio frame. Efforts continued to make Delta-VLBI phase delay rate observations of the Viking orbiters at Mars and the Pioneer 12 orbiter at Venus. Between 1980 and 1983, eight successful passes were made with Viking and three successful passes were made with Pioneer 12, all with dual band S/X downlinks. All these data were combined to estimate a rotational offset between the radio frame and the frame of the inner planets [13]. An accuracy of about 100 nrad was achieved for both right ascension and declination components with the limiting error source being knowledge of the spacecraft orbits relative to the planet centers.

A more natural use for VLBI phase delay rate is to provide an instantaneous measurement of spacecraft velocity in the plane-of-sky. This data type was considered a necessary complement to Doppler to accurately determine the orientation of the orbit plane for navigation of a low circular planetary orbiter, such as in the Venus Orbiting Imaging Radar (VOIR) mission proposed for 1983 [41]. However, VOIR was cancelled, and by the time this type of data was needed by the Magellan mission in 1990, external calibrations of station clock rates and media delays had improved to the point where quasar-based calibrations for delay rate were not necessary. Doppler data acquired simultaneously at two stations and then differenced met the Magellan navigation requirement during its radar mapping phase in Venus orbit.

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[1] Four measurements were made at both S- and X-band.

3. ORIGINS OF ΔDOR

The radio astronomy community was continuing to develop techniques for differential time delay measurements. In 1970 a method for synthesizing VLBI group delays from recordings of several separated frequency channels was published [14]. Since group delay precision depends on bandwidth, this offered a way to improve precision without the need to record a very large slice of the spectrum. VLBI recording systems were developed that could sample widely separated sections of the frequency spectrum. But the most accurate measurements of differential time delay are made using phase delays for which the integer cycle ambiguity in the absolute phase delay is resolved. Data acquired at the DSN Goldstone site and at Haystack radio observatory in 1971-1974 were used to estimate the relative positions of 3C 345 and NRAO 512 to about 2 nrad [15]. The close angular separation of these sources permitted the integer cycle ambiguity at RF to be resolved. Group delays over a bandwidth of 25 MHz were also available for the later passes in this series of measurements, but their accuracy was noted to be 80 times worse than the phase delays.

Generally, the DSN cannot expect to resolve the integer cycle ambiguity at the RF wavelength for a spacecraft-quasar differential measurement. DSN baselines are too long, spacecraft-quasar angular separations are too large, and available observation intervals are too short to develop an estimate of delay to better than 1/2 RF cycle. Given restrictions on the spectrum allocation for deep space research at X-band, time delay observables based on group delays over a bandwidth of about 50 MHz would need to be used. Interest in the DSN was shifting toward development of just such a capability, since the promise of short passes of VLBI time delay was now more appealing than the problematic longer passes of phase delay rate.

Quasars emit broadband noise signals across a wide segment of the RF spectrum and VLBI systems record filtered channels of the signal voltage plus background noise. Quasar VLBI fringe phase is obtained from cross-correlation of channels of data from two stations. The individual channel bandwidths must be of order 1 MHz to provide adequate signal-to-noise ratio for correlation of the weak extra-galactic radio signals. The bandwidth synthesis technique [14] is used to generate group delays from multiple channels of phase data. Spacecraft signals of the 1970s looked very different. Telemetry sidebands might extend a few hundred kHz about a carrier and several discrete components might appear in the downlink spectrum. It did not appear feasible to use cross-correlation for spacecraft VLBI signal processing. How could the DSN make a spacecraft delay measurement that would correspond to a quasar delay measurement?

The DSN had developed a system for ranging that made use of discrete tones. A sequence of sine waves, modulated on the carrier signal, was transmitted to the spacecraft and received back at the station. The range tone phase was measured at the station essentially in the same manner that the carrier signal was measured to obtain Doppler. Multiple tones allowed for resolution of cycle ambiguities and an accurate measurement of range was obtained from the group delay derived from the ranging tone phase. David W. Curkendall of JPL is credited with the realization that the equivalent of VLBI delay observables could be obtained by differencing spacecraft range measurements received simultaneously at two stations [16]. The key insight is that differential range and VLBI have nearly the same sensitivity to errors in station locations, earth orientation, transmission media delays, and station clock offsets. An advantage of differential range is that the spacecraft signal phase is extracted separately at each station, avoiding the loss that occurs in cross-correlation when two voltage streams containing weak signals are multiplied. This new measurement technique was named Delta Differential One-way Range. The challenges now were to demonstrate the ΔDOR technique on existing spacecraft and to convince future projects to build their spacecraft to transmit discrete spectral components separated by ~50 MHz. Range tones could provide a ~1 MHz bandwidth, but this would not be enough to meet the proposed accuracy requirement for ΔDOR. The spectral components needed for this type of measurement became known as DOR tones.

The name of the technique suggests that measurements are done using signals that originate onboard the spacecraft. The term "one-way" refers to a signal that travels from spacecraft to ground station. But in fact the signal source could be a transmitting ground station and then the spacecraft measurement type is differential round-trip range. Round-trip signals are necessary for precise range and range-rate, so that only the ground station clock but not the spacecraft clock is involved in the measurement. For differential range, the offset and instability in the spacecraft clock cancel, so that one-way measurements are as accurate as round-trip measurements. Most ΔDOR measurements are done in the one-way mode.

4. EARLY ΔDOR EXPERIENCE WITH VOYAGER AND VIKING: 1979-1989

The twin Voyager spacecraft had encounters with Saturn in 1980 and 1981 occurring near zero degrees geocentric declination. Since Doppler are not sensitive to declinations near zero, the project had decided to use conventional range, differenced between stations[2], to supplement Doppler for targeting. Since this would be the first (and only) use of differenced range in operational tracking, a ΔDOR experiment was planned to help validate the use of differenced range. These spacecraft did not have DOR tones, but measurements over a restricted bandwidth could be made using harmonics of the spacecraft's 360 kHz telemetry subcarrier signal. Measurements began in 1979. At this time, the DSN stations were equipped with Mk II VLBI systems [17]. All use of the Mk II system was considered to be a "research and development" activity and not operational support. Data from two time-multiplexed frequency channels, each with a bandwidth of 2 MHz, were recorded on magnetic tape. Telemetry subcarrier harmonics ranging from the +/- 5th to +/- 9th were observed, providing a spanned bandwidth in the range of 3.6 to 6.48 MHz. It was believed that accuracy as good as 100 nrad might be possible.

Signals were detected in the early measurements, but the time delay observables did not appear to be correct. David S. Brown of JPL is credited with the realization that instrumental phase shifts on the baseband spacecraft and quasar signals were not cancelling, due to the use of both upper and lower sideband channels in the Mk II VLBI system. This was the last piece of the puzzle necessary to perform ΔDOR. The Mk II frequency downconversion system was modified to use two channels of the same sideband, each centered on the received frequency of a spacecraft tone. Subsequently, data were acquired from both Voyager spacecraft beginning in January 1980 with angular position accuracies approaching 100 nrad [18], allowing ΔDOR to contribute to the successful Voyager flybys of Saturn [19].

At this same time, ΔDOR measurements were attempted with the Viking Lander 1, with the simultaneous goals of demonstrating the ΔDOR technique and tying Mars to the radio reference frame [20]. Since the lander position on the surface was known, this would be an ideal frame tie. Because the spacecraft telemetry spectrum did not span enough bandwidth, range tones were transmitted from a ground station, and transponded at the spacecraft, to provide the necessary wide bandwidth signals for ΔDOR. Unfortunately, only a few measurements could be attempted and time ran out before the technique was made to work with Viking.

The long tour of Voyager 2 through the outer solar system provided the opportunity to develop the ΔDOR technique. A new VLBI system was being implemented in the DSN to provide operational support for measurements of inter-station clock synchronization, UT1, polar motion, and ΔDOR. The implementation was done in phases. In the first phase, completed in January 1981, the Mk II

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[2] Round-trip range measurements were alternately made at two stations separated in time by the round-trip light time.

analog baseband signals were sent to an open loop recorder, used for radio science, known as the Occultation Data Assembly (ODA). The ODA digitized, filtered the channels to a bandwidth of 250 kHz, and recorded the data on a computer tape [21]. Recorded data could be transmitted within hours from the stations to a computer disk at JPL, over links that had been established for communications. Data were correlated first in software on a mainframe computer on the Caltech campus and, by mid 1981, on a dedicated mini-computer at JPL that interfaced with a custom digital signal processor board. Having the data on a random access disk, instead of a serial access tape, greatly facilitated the extraction of spacecraft tone phase. Delta-DOR observables could now be delivered to a navigation team within 24 hours whereas previously it had taken weeks to ship magnetic tapes from the DSN stations and process the data on a hardware correlator.

Validation of data correctness was a goal just as important as meeting an accuracy requirement. Side-by-side comparisons of data output were made as new system implementations were completed. Recording systems, correlators, and data processing software were checked against each other. Absolute accuracy was more difficult to assess, although basic consistency was established by showing that spacecraft trajectory solutions with and without ΔDOR agreed within statistical uncertainties.

After the successful Saturn encounters, and with ΔDOR on its way to becoming an operational DSN capability, the Voyager project dropped its requirement for differenced range and used ΔDOR for its Uranus encounter in 1986 and its Neptune encounter in 1989. Final targeting for these encounters relied on the spacecraft camera to image the planet's moons and develop direct knowledge of spacecraft position relative to the planet. Delta-DOR was employed during cruise to maintain the radiometric solution and approach trajectory within an acceptable level of accuracy so only small maneuvers would be necessary once camera images located the spacecraft position relative to the planet.

A demonstration of improved accuracy for Delta-DOR measurements was begun in 1982 to help validate the technique for planned use by Galileo. Observation frequencies were switched from S-band to X-band, where the stronger signal allowed detection of higher order telemetry subcarrier harmonics spanning 14 MHz, and further, reducing the effects of charged particles. A greater number of passes was scheduled to investigate internal data consistency and measurement errors. Internal consistency at the 25 nrad level was obtained [22], but biases and drifts over a few month period were larger by an order of magnitude. Eventually it was understood that these offsets were due to inconsistencies in the tie between the radio catalog and the outer planet ephemeris that, at the time, was based solely on optical data.

The final phase of the Narrow Channel Bandwidth (NCB) VLBI system was completed in 1985 [23]. The analog portion of the Mk II VLBI system was replaced with hybrid analog and digital components. The name for this system derived from its modest sampling rate as compared to systems built for astronomy research. The 500 kilobits/sec sample rate allowed for near realtime data transfer, necessary for navigation support, but also limited system sensitivity. A key design feature was the time multiplexing of signals at intermediate frequency, enabling all baseband (video) signals to pass through the same analog-to-digital converter and digital low pass filter. This was necessary to reduce instrumental phase differences between spacecraft and quasar signals and to allow group delays over a bandwidth of 40 MHz to meet the 50 nrad accuracy requirement.

Almost all measurements during this time were made using a standard sequence of a 9 min spacecraft observation followed by a 9 min quasar observation. Experimental variations were avoided so as to minimize the impact on the project. The ΔDOR development effort and the Voyager project benefitted from each other during this decade, but it should be acknowledged that

ΔDOR was not a critical data type for Voyager or any other project during this time period. As a result, ΔDOR was vulnerable to the inevitable cycles of budget cuts in the DSN.

5. MAGELLAN, GALILEO, MARS OBSERVER: 1989-1997

Though the Galileo launch was delayed, and there would be no close flyby of Mars, ΔDOR had become a requirement for the Magellan cruise phase to Venus, the Galileo flybys of Earth followed by its cruise to Jupiter, and the Mars Observer cruise phase. Use of ΔDOR allowed reductions in the amount of tracking time needed to collect coherent Doppler for navigation, provided an independent cross-check on trajectory solutions, and maintained accurate targeting so as to reduce fuel usage for corrective maneuvers. An important lesson learned from the Voyager demonstration was to record *more* than the minimum amount of data necessary to generate a time delay observable. At least three observations, either in sequence spacecraft-quasar-spacecraft or quasar-spacecraft-quasar, were recorded to estimate station clock offsets and drifts and to help identify any temporal variations such as a jump in the station clock. Also, at least three frequency channels were recorded in order to identify any dispersive instrumental error such as multipath at one frequency. These additional data allowed for internal validation of the measurement prior to delivery to the navigation team.

Encouraging results from the Voyager demonstration, good instrumental design of the new NCB VLBI system, and ongoing improvements in related calibration systems led to expectations that performance would be better than the original 50 nrad accuracy requirement.

The Magellan mission was designed to make high resolution radar maps of the Venus surface. Though the transponder did not have DOR tones, the high rate telemetry system needed to send the radar data back to Earth had sidebands spanning 30 MHz at X-band, providing a good signal for ΔDOR observations. But most of the cruise passes were scheduled on DSN 34m antennas as opposed to early Voyager ΔDOR passes that mostly used 70m antennas. While the wide signal bandwidth drove some error sources down, the smaller ground apertures forced selection of stronger radio sources at greater angular separations from the spacecraft. Magellan was observed during cruise from July 1989 to August 1990 with typical data accuracy of 30 nrad. The targeting for orbit insertion was so accurate that no orbit trim maneuvers were needed for the scientific mission to begin [24]. Magellan was observed in orbit at Venus from September 1990 to August 1994, with a typical data accuracy of 20 nrad, to establish a better radio-planetary frame tie.

The Galileo mission began with several flybys of inner planets for gravitational assists, and visited two asteroids before heading to Jupiter. The spacecraft communicated through its low gain antenna at S-band while in the inner solar system, providing a bandwidth of 7.65 MHz for ΔDOR. Measurements were acquired from January 1990 to December 1993 with an accuracy of 50 nrad. The restricted bandwidth and the larger effects of charged particles at the S-band frequency prevented higher accuracy. The mission was re-planned during flight, when the spacecraft high gain antenna failed to deploy, and the requirement for ΔDOR on approach to Jupiter was dropped. But ΔDOR was obtained during the orbital phase from July 1996 to September 1997 for the purpose of tying the position of Jupiter to the inner planets [25].

Mars Observer was the first spacecraft to transmit DOR tones with the full spanned bandwidth of 38.25 MHz at X-band. By this time operational procedures had been streamlined and ΔDOR was becoming a routine DSN capability. The spacecraft was observed throughout cruise from October 1992 to August 1993, with a data accuracy of 23 nrad. However, only 3 days prior to the planned arrival at Mars, communication with the spacecraft was lost. By all accounts, Mars Observer had been on course for an accurate insertion into orbit about Mars [26].

While, as for Voyager, ΔDOR was beneficial for these missions, it could not be said that it was essential for mission success. Even though ΔDOR had performed well as a navigation tool during this decade, missions planned for the late 1990s did not identify a critical need for this capability and dropped requirements for ΔDOR as part of cost cutting moves.

6. MARS PROGRAM: 2001-2012

Following the failures of two Mars missions in 1999, NASA reinvigorated its Mars program with renewed emphasis on robustness and reliability. Delta-DOR and onboard optical imaging were alternately considered as methods to ensure navigation success and ΔDOR was quickly adopted. Collateral developments made it possible to put together a new system for ΔDOR observations, much improved over previous implementations, in time for the launch of Mars Odyssey in April 2001. The procedural and component designs that made this possible are discussed in the next two sections of this paper. The role of ΔDOR in the Mars program is discussed in this section.

Delta-DOR served its purpose for the Odyssey spacecraft by providing a cross-check on navigation solutions and ensuring successful targeting for Mars orbit insertion. Excellent results were obtained for cruise navigation [27] with the new ΔDOR system delivering accurate data, within 12-24 hrs, with high reliability. This in-flight success drew the attention of the Mars Exploration Rover (MER) development team. The MER project evaluated the possibility of using ΔDOR to reduce the size of its landing error ellipse. Significantly, new science opportunities emerged when the decision was made to use ΔDOR in this way, as improved targeting enabled more landing site options [28]. Delta-DOR was now serving its intended purpose as a critical part of mission operations. The ΔDOR system again performed well and navigation delivery accuracy was excellent for both rovers in 2003-2004 [29].

By default, ΔDOR is now considered a useful data type for any mission needing to navigate precisely through the solar system. Delta-DOR was used by Mars Reconnaissance Orbiter (MRO) in 2005 for insertion into orbit [30] and by Phoenix in 2007-2008 to land on the Martian surface [31], both with excellent results. Mars Science Laboratory (MSL), planned for launch in 2011, requires ΔDOR to support targeting accuracy similar to what was needed for Phoenix, but also requires a late knowledge update to initiate onboard guidance systems for controlled descent through the atmosphere. The DSN ΔDOR service now meets expectations in terms of relevance, accuracy, reliability, and ease of use.

7. OPERATIONAL CONSIDERATIONS

Delta-DOR began as an experiment conducted outside the normal scope of DSN operations. It had been necessary to adapt and make use of research equipment and techniques due to long lead times for spacecraft and DSN implementations. Since ΔDOR passes were infrequent compared to the normal tracking passes performed by the DSN, the manual steps necessary for data acquisition were problematic. Even worse, missions had an awkward time placing the sequence steps for a ΔDOR observation into their timelines. By the 1990s ΔDOR had become unpopular due to its perceived lack of reliability and its difficult interfaces with the missions. Table 1 shows the number of scheduled observations and the success rate for several missions over the past three decades.

The ΔDOR technique could be made to work well, but failures still occurred for various reasons. The success rate achieved in the 1980s and 1990s did not match the 99% success rate expected of conventional DSN tracking activities. Most failures could be broadly grouped into two categories: (i) error in manual procedure and (ii) equipment failure. When there was an opportunity to re-implement the ΔDOR system to support the Mars program beginning in 2000, new emphasis was placed on operational considerations. Modernization tasks in the DSN in the 1990s plus development of a new system for telemetry arraying[3] made it possible to fully integrate ΔDOR data acquisition into DSN operations. Further, the flight projects were coached to develop scheduling and sequencing tools to support ΔDOR. A flexible interface was developed to select quasars to be observed as well as the number and duration of alternate spacecraft and quasar observations. At the preliminary design review for ΔDOR development for Mars Odyssey in 2000, it was stated that system reliability should be no worse than that expected for two DSN stations to perform conventional tracking activities at the same time, that is 0.99^2. A success rate close to this value has been obtained for over 1000 observations spread across 16 missions since 2000.

Table 1. Number of scheduled ΔDOR observations and success rate over three decades.

Spacecraft	**VLBI System**	**Period**	**Number of Scheduled Observations**	**Success Rate**
Voyager	Mk II + ODA	1981 – 1984	144	67%
VEGA	NCB	1985 – 1986	62	97%
Voyager	NCB	1986 – 1987	90	62%
Phobos	NCB	1988	21	81%
Magellan (cruise)	NCB	1989 – 1990	56	86%
Galileo	NCB	1990 – 1992	48	88%
Mars Observer	NCB	1992 – 1993	66	86%
Mars Odyssey	RSR	2001	48	98%
MER	VSR	2003 – 2004	131	98%
MRO	VSR	2005 – 2006	65	98%
Phoenix	WVSR	2007 – 2008	105	100%

8. ERROR BUDGET DEVELOPMENT AND SYSTEM INNOVATIONS

Estimating the uncertainty in a ΔDOR measurement has always been an important aspect of the technique, both as an aid to system development and to allow valid assessment of accuracy for navigation targeting. The earliest writings on ΔDOR [32] contained a breakout of the components that contribute to measurement error, including assumptions about geometry, recording sequence, calibration, and a calculation of error magnitude. A total error was calculated as the root-sum-square (rss) of the components. This breakout became known as the ΔDOR error budget. A new error budget was developed for each mission, based on spacecraft characteristics, trajectory geometry, and current DSN capabilities. While conditions would vary from one pass to another, the error budget was meant to represent the performance that the mission could count on. The larger error sources were studied by DSN technology development tasks and recommendations were made for improving system performance. Since most components of the error budget affected range and Doppler as well as ΔDOR, system upgrades would provide synergistic improvements to all radiometric tracking techniques. But implementation in the DSN is driven by new mission requirements, available technology, and trade-offs between cost and performance, so program level justification was required for system upgrades.

The error budget published for Voyager in 1980 [18] shows an rss error of 135 nrad. The dominant component is dispersive instrumental phase due to the restricted bandwidth (3-6 MHz) of the spacecraft signal. Performance improvement had to wait for spacecraft with wider bandwidth signals. To investigate the error budget for the Galileo mission, experiments were planned to observe pairs of natural radio sources using a 38 MHz spanned bandwidth [33]. The ΔVLBI time delay error was investigated as a function of source separations, source elevations, source strengths,

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[3] The telemetry arraying system was based on a design for a VLBI upgrade that had been proposed for the DSN but not funded in 1992. Array system components provided all the functionality needed for VLBI.

solar plasma, and ionosphere. It was found that the 50 nrad requirement could be met for source separations as large as 25 deg.

When spacecraft signals with wider bandwidths were observed starting in 1989, the errors due to dispersive instrumental phase and thermal noise came down, and the rss error fell to the 20-30 nrad level. But now all error components were roughly of the same magnitude, implying that significant development would be needed to further improve system performance.

Data from all missions have been analyzed to verify and improve upon ΔDOR error budget estimates. It is especially instructive to examine measurement residuals to a reconstructed trajectory for which navigators can establish an independent estimate of trajectory accuracy that can serve as a "truth model". The error budgets presented in this paper have all been verified by analyses of this type.

8.1 System Improvements: 1993-2000

The last operational use of ΔDOR to support spacecraft navigation, prior to Mars Odyssey in 2001, was for the Mars Observer mission in 1992-1993. During this hiatus, a number of system improvements occurred that would benefit new users. The most important of these are discussed below.

DSN Operations: Three upgrades in the DSN led to improved overall reliability and operability. First, anticipating the challenges of spacecraft communications at 32 GHz, antenna-pointing models were improved. Blind pointing, that is pointing to a predicted angular coordinate without realtime feedback, became more reliable. Second, new microwave controllers allowed setting and monitoring of the downlink signal polarization from the operator's console. Third, distribution of intermediate frequency signals within the station was automated. Though these upgrades were not driven by ΔDOR, they ensured the correct downlink signal would be routed to the VLBI system.

VLBI System: A new VLBI system for downconverting and recording signals was developed to replace the NCB system. The new system was based on the Full Spectrum Recorder [34] that had been developed to support Galileo telemetry arraying. The first version of the new system to support the wide bandwidth recordings needed for quasar observations was the Radio Science Receiver (RSR). As the name suggests, this system was primarily developed to support Radio Science applications, but was initially shared between Radio Science and VLBI. In 2003 another version of this system, known as the VLBI Science Receiver (VSR), was implemented to provide dedicated support for VLBI applications. The system front end bandwidth was increased in 2005 and named Wideband VSR (WVSR) [35]. The RSR, VSR, and WVSR had several major advantages over the NCB system. The control interface was robust and allowed realtime monitoring of signal acquisition. The digital finite impulse response filters used for narrowing the input bandwidth had purely linear phase response, eliminating a major source of instrumental error. The system was capable of recording rates as high as 80 megabits/sec, in contrast to the 0.5 megabits/sec capacity of the NCB system. This higher record rate, coupled with increased communications bandwidth to provide playback of the greater data volume, allowed a corresponding increase in precision. In addition, the data correlation algorithm was improved to generate time delay observables with sub-cm model accuracy to realize the full precision available from the data.

GPS Calibration System: The DSN's GPS calibration system had become operational for providing parameters used to model signal delay through the troposphere and ionosphere, and to model the orientation of the Earth in inertial space. These calibrations provided a significant improvement in accuracy, with reduced latency, compared to the calibrations available before GPS data were used.

Model Consistency: The consistency of models used for development of the radio reference frame and for spacecraft navigation should also be mentioned. Model inconsistencies could prevent the full accuracy of ΔDOR measurements from being utilized in spacecraft navigation. In the early 1990's, a working group was formed at JPL to examine reference frame issues. As a result, models were added to the JPL navigation software to allow accurate transformations between the recommended terrestrial and celestial systems. The International Celestial Reference Frame (ICRF) [9] defined by the positions of radio sources was adopted as the fundamental celestial frame.

8.2 System Improvements: 2001-2003

The actual performance of the ΔDOR measurement system improved further by 2003 due to several other factors.

Improved Station Locations: The station locations used for the first look at data from Mars orbit, and to support the Odyssey mission, were based on a 1993 solution. Continental drift was not accurately modeled over the following 10 years, and the newer DSN 34m stations were not accurately surveyed. Modeling improved when a new joint solution for DSN station locations was completed in 2003, and referenced to epoch 2003.

Improved Quasar Catalog: The first look at data from Mars orbit, and the Odyssey cruise measurements, used the published ICRF Extension 1 catalog [36]. This catalog, while defining a reference system, was not optimal for supporting differential astrometry using specific sources. A new solution was generated at JPL using more long baseline DSN data. This solution added a substantial number of new measurements and reduced systematic errors, especially for southern hemisphere sources, relative to ICRF-Ext-1. For the first time, good positions were obtained for certain sources that had relatively few observations in the data set used for ICRF-Ext-1.

Global Ionosphere Maps (GIM): The ionosphere calibrations used for the first look at data from Mars orbit and for Odyssey cruise supports were based on single shell, single GPS receiver data sets. A substantial improvement occurred when a new calibration system that incorporated multiple receivers near each site and multiple shell models was implemented in 2003.

Observation Technique: A higher sampling rate was used for quasar recording that allowed more precise time delays or use of weaker sources that were closer in an angular sense to the spacecraft trajectory. Multiple quasars were observed, with one on either side of the spacecraft when possible, to provide improved cancellation of spatial errors. Further, observations were scheduled to avoid the lowest elevation angles.

8.3 Evolution of System Performance

The performance of the ΔDOR system over its three decades of existence is shown in Fig. 2. Missions which provided drivers for system improvements are used to illustrate performance over different eras and the key system upgrades and innovations are identified. Delta-DOR was also used to support numerous other missions during the times shown with similar levels of performance. The current ΔDOR error budget is shown in Fig. 3 [37]. Performance for X-band measurements is now approaching fundamental limits. A further significant advance in the ΔDOR technique will likely require spacecraft downlinks at 32 GHz, where a wider spanned bandwidth is allowed for DOR tones and quasar cores are more compact.

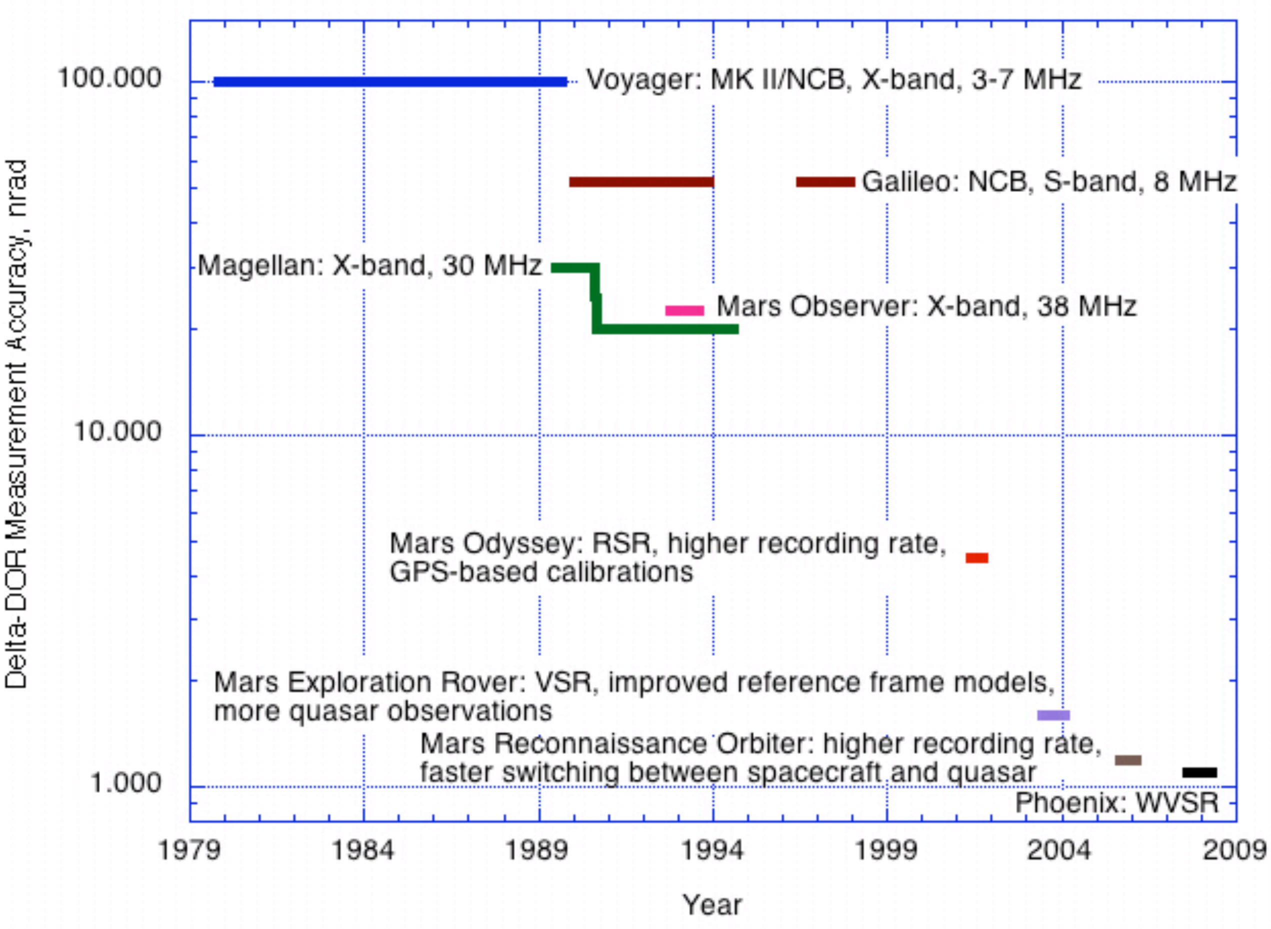

Fig. 2. Evolution of ΔDOR System Performance

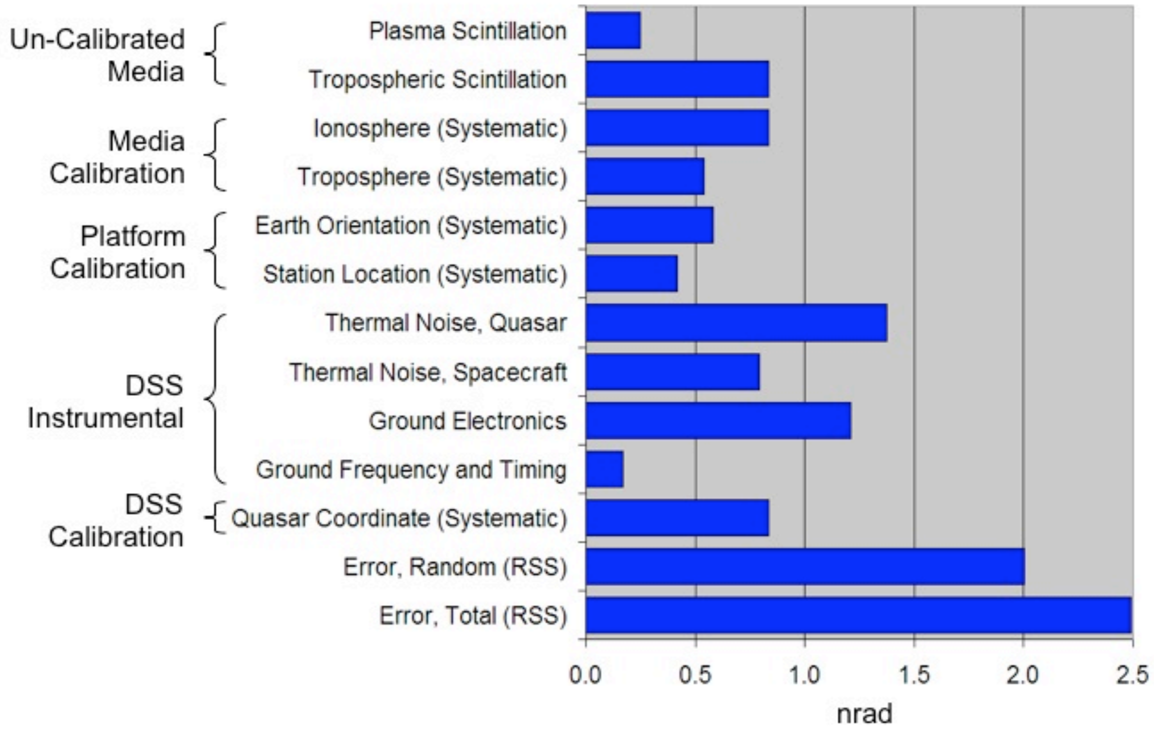

Fig. 3. Delta-DOR Error Budget for 2009.

Note that the single measurement angular accuracy of 1 nrad, at the typical Earth-Mars distance of 1 AU for encounter geometry, corresponds to 150 m in plane-of-sky position. This accuracy meets or exceeds the navigation needs for targeting a descent module to the top of the Martian atmosphere. A functional description of the current system can be found in [38].

9. FRAME TIE

The first significant advance to tie the radio frame to the planetary frame, since the 100 nrad tie using VLBI measurements of planetary orbiters in the early 1980s, came in 1993 through joint analysis of lunar laser ranging data and VLBI data [39]. Though indirect, this method provided knowledge of the positions of the inner planets in the radio frame with 15 nrad accuracy. Delta-DOR measurements of Magellan at Venus in 1990-1994 confirmed this tie and improved the accuracy to 5 nrad. However, even better accuracy was desired to support missions sending a lander direct from Earth to the surface of Mars.

The Mars missions themselves provided the infrastructure to improve the frame tie. Further, ΔDOR measurements of spacecraft at Mars provided the best means to establish the absolute accuracy of the ΔDOR technique. Nothing was left to chance. A few ΔDOR measurements of Mars Global Surveyor (MGS) were obtained in early 2001 using the newly developed RSR-based ΔDOR system. Since the MGS orbit was known relative to the Mars center to about 20 m, the ΔDOR residual, that is the observed value minus the best model value, provided a direct measure of the Mars position error and/or the ΔDOR measurement error. The residuals from both DSN baselines were at the 5 nrad level providing confidence both in the planetary ephemeris and in the new ΔDOR system for support of Odyssey.

After Odyssey orbit insertion, enough ΔDOR measurements were obtained from MGS and Odyssey to fully determine the orientation of the planetary ephemeris in the radio frame with 2 nrad accuracy. The fit of the data over a synodic period of Mars ruled out any bias in the ΔDOR system and verified the absolute accuracy of the data. This provided the verification necessary for the planned use of ΔDOR to support the MER landings. Since MRO orbit insertion, ΔDOR data are being acquired at the rate of one per month from Odyssey and MRO to improve accuracy of the Mars ephemeris to the 1 nrad level for MSL.

10. SUMMARY

From the earliest missions to the inner planets, two-way range and Doppler were the workhorse data used by the navigation system and these were developed and refined to their maximum inherent accuracies. As the inner planets were visited, the planetary ephemerides were also improved by these encounters and the opportunities they afforded to tie in the ephemerides to that same range-Doppler tracking system. During the development of the navigation system for Voyager it was recognized that the one weakness in the refined range-Doppler system was its poor performance at zero declination. Accordingly, the explicit differencing of two-way ranging data using intercontinental baselines was brought to the forefront to cure that weakness. And to improve the monitoring of polar motion, universal time variations, and station clock synchronization, the VLBI system was introduced as an allied, but independent system. Slowly the understanding and appreciation of the benefits of tying these systems together developed during Voyager operations and Viking Lander monitoring. Abandoning the explicit differencing of ranging data and instead moving to what is now called the Delta-DOR system, by broadcasting suitable waveforms directly from the spacecraft, paved the way for the merging of these systems enabling the achievement of inherent accuracies fully two orders of magnitude better than was possible when the systems were operating individually. The fundamental coordinate system is now referred to the nearly invariant quasar-based frame and spacecraft are navigated via measurements that couple to and precisely relate themselves to this frame. These developments, as this paper has shown, came neither easily nor quickly, but the current systems now routinely deliver reliable operation at the 98% goal and with accuracies approaching 1 nanoradian.

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