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PRECISION X-BAND DOPPLER AND RANGING NAVIGATION FOR CURRENT AND FUTURE MARS EXPLORATION MISSIONS

Jeffrey A. Estefan,* Vincent M. Pollmeier,* and Sam W. Thurman**

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

This paper describes a navigation error covariance analysis of two scenarios derived from the *Mars Observer* mission and the planned *Mars Environmental SURvey* (*MESUR*) Pathfinder mission, respectively. 1 he analysis was performed to establish the potential navigational performance of the X-band tracking system in NASA's Deep Space Network, and to evaluate the sensitivity of the predicted performance to variations in the quantity of data acquired, the ground system error modeling assumptions, and data reduction schemes. The simulated data arcs used in the analysis are representative of the actual data arcs that will be used to predict the aim point for the Mars orbit insertion maneuver, in the case of Mars Observer, and the interplanetary trajectory aim point corresponding to the target Mars landing site in the case of *MESUR* Pathfinder. The results indicate that with a suitable sequential data reduction scheme and accurate calibrations of instrumentation, transmission media, and platform model parameters, navigation accuracies of 5 to 15 km (1 σ) can be achieved, equivalent to 15 to 40 nrad in geocentric angle uncertainty.

INTRODUCTION

As current and future Mars exploration missions evolve in an environment of tighter fiscal constraints, there is strong interest in utilizing new and/or enhanced radio navigation techniques to simultaneously improve performance and reduce navigation-related requirements on spacecraft and their associated mission operations systems. in response to these challenges, a great deal of progress has been made recently to improve the capability of conventional Doppler and ranging data types, Doppler and ranging have received widespread use in nearly all interplanetary missions supported by NASA's Deep Space Network (DSN), as they are collected as an integral part of routine tracking, telemetry, and command operations. Two-way ranging, for example, has been an operational data type

* Members Technical Staff, Navigation Systems Section; Members AAS
** Technical Manager, Navigation Systems Section; Member MS

for many years; however, early mission experience suggested that ranging data could not be utilized at their inherent accuracy due to the presence of small, unmodeled nongravitational forces that act on virtually all spacecraft, which are caused by attitude control thruster firings and other spacecraft activity. In addition, inconsistent and unreliable ranging system/station delay calibrations often precluded the effective use of precise ranging. Recent experiments utilizing two-way ranging data acquired from the *Galileo* and *Ulysses* spacecraft have met with remarkable success in yielding improved navigation performance;[1-3] in these experiments, simultaneous modeling of nongravitational acceleration parameters and range bias parameters for each station pass was shown to largely remove the effects of nongravitational forces and ranging data calibration errors from the orbit solutions.

In this paper, it will be shown that for the Mars *Observer* and *Mars Environmental SURvey* (*MESUR*) Pathfinder missions, remarkable navigation accuracies can potentially be achieved with X-band Doppler and ranging, through use of more sophisticated data reduction techniques and improved calibrations of transmission media effects and Earth platform parameters (station locations and Earth pole orientation). These developments make it possible to utilize Doppler and ranging data at or near their inherent accuracies, and enable these data types to deliver accuracies comparable with more sophisticated data types that involve relatively greater complexity and costs for mission operations,

MISSION SCENARIOS

in this section, a brief description of the two mission scenarios used for this analysis is provided. Several studies have been performed in recent years investigating the potential navigation performance of Earth-based and in situ radio tracking techniques for missions to Mars; a survey of results obtained in several of these studies has been conducted by Thurman, *et al.*[4] Since this survey was completed, however, some significant advances in new or alternative data reduction and calibration methods have been made, which are the focus of these mission scenarios and the analysis developed from them.

Mars Observer Interplanetary Cruise

The *Mars Observer* spacecraft was launched successfully on September 25th, 1992. The spacecraft carries an X-band (7.2 GHz uplink/8.4 GHz downlink) transponder and is the first interplanetary spacecraft to rely solely on a single-frequency X-band telecommunication system.[5] The inter-planetary cruise phase of the mission extends from injection to initiation of the Mars Orbit Insertion (MOI) burn, a duration of about eleven months. This period has been segmented for mission planning purposes into five subphases, each ending prior to a planned trajectory correction maneuver. The trajectory segment selected for this analysis was the fourth subphase, a 182-day time period extending from February 1993 to early August 1993, which represents the longest leg of the interplanetary cruise, and has the most stringent navigation accuracy requirements in order to support the final maneuver prior to MOI. Over the time span of the data arc, which extends from Encounter minus 194 (E- 194) days to E- 12 days, the Earth-to-spacecraft range varies from about 80×10^6 to 330×10^6 km, while the geocentric declination of the spacecraft ranges from 22 deg to about 1 deg. The Sun-Earth-Probe (SEP) angle over this period varies from 125 deg to 45 deg. This mission scenario poses an interesting problem as the declination of *Mars Observer* at encounter is within one degree of zero, a geometry which is thought to be very difficult for Doppler tracking, due to Doppler data's relative insensitivity to some components of the spacecraft state in this regime.

MESUR Pathfinder Interplanetary Cruise

The *MESUR* Pathfinder mission is the first of a series of low-cost, rapid turnaround science missions, and will serve as a precursor to the larger scale *MESUR* Network mission.[6] *MES UR* Pathfinder also plans to employ X-band tracking exclusively, however, unlike *Mm-s Observer,* it will utilize a direct atmospheric entry and descent trajectory to achieve a landing.[7] For this analysis, the launch epoch was assumed to be December 3, 1996 with the interplanetary cruise phase lasting eleven months; Mars encounter occurs on November 10, 1997. Over the time span of the data arc, whit}] extends from U-162 days to E- 15 days, the Earth-to-spacecraft range varies from about 115 x 10^6 to 285 x 10^6 km, while the geocentric declination of the spacecraft ranges from **4** deg to **-24** deg. The SEP angle over this period varies from 105 deg to 50 deg. As seen from these trajectory characteristics, the Earth-to-Mars cruise of *MESUR* Pathfinder represents the opposite extreme from the *Mars Observer* scenario: the declination of the spacecraft at encounter is nearly -25 deg, the maximum possible declination magnitude for a Mars encounter.

DATA ACQUISITION SCHEDULES

In each mission scenario, there were two data acquisition schedules that were considered; a baseline schedule representing fairl y dense DSN coverage (from three passes per week to one or two passes per clay), and a reduced schedule containing no more than one or t wo passes per week. * The baseline data schedules are representative of the level of coverage in recent interplanetary missions such as *Magellan, Galileo,* and of course, *Mars Observer,* in which telemetry data acquisition for spacecraft monitoring and other engineering "housekeeping" funct ions is often the driver for coverage requirements, As , discussed earlier, future interplanetary missions may utilize less coverage than is traditional, in order to reduce operations costs. The reduced coverage cases are therefore representative of the level of coverage anticipated for telemetry acquisition in future missions such as *MESUR* Pathfinder and *Cassini.*

The *Mm-s Observer* baseline data schedule consists of one simulated horizon-to-horizon tracking pass of two-way Doppler and ranging data from Madrid on a daily basis from E-194 days to E-90 days. Two daily tracking passes were acquired from Madrid and Canberra from E-90 days to E-30 days, and from E-30 days to E-12 days (data cutoff), data were acquired continuously from all three DSN sites. The reduced data schedule consisted of a reduction of the single *daily* tracking pass from Ii-194 days to E-90 days to a *weekly* pass, a reduction of the two daily passes from E-90 days to E-30 days to two weekly passes, and a reduction of continuous tracking from E-30 days to E-12 days to a single pass per day. For *MESUR* Pathfinder's baseline data schedule, three horizon-to-

• In all cases, the data were assumed to be acquired from the DSN's 34-m High Efficiency (HEF) Deep Space Stations (DSSs) located near Goldstone, California (DSS 15), Canberra, Australia (DSS 45), and Madrid, Spain (DSS 65).

horizon tracking passes were simulated cm a weekly basis from E-162 days to E-40 days using alternating DSN sites, followed by continuous coverage from E-40 days to E-15 days (data cutoff) utilizing all three sites. The reduced data schedule simply consisted of a single tracking pass acquired weekly throughout the entire data arc (Ij-162 days to E-1S days), alternating between all three DSN sites.

To account for data noise, an assumed one-sigma random measurement uncertainty of 0.0126 mm/s was chosen for two-way Doppler, and for two-way ranging, the one-sigma random measurement uncertainty was assumed to be 1 m; these noise variances were used in all cases. 1(should be noted that the data weights quoted here are for the round-trip range-rate and range, respectively. Both data types were collected at a rate of onc point every 10 min, and the noise variances were adjusted by an elevation-dependent function for all stations, to reduce the weight of the low-elevation data; furthermore, no data were acquired at elevations of less than 10 deg.

ORBIT DETERMINATION STRATEGIES

The orbit determination error model and filter strategies employed in this analysis are summarized in Tables 1 and 2. The filter (estimated) and consider* parameters were grouped into three categories: spacecraft epoch state, spacecraft nongravitational force model, and ground system error model. Effects of uncertaint y in the ephemeris and mass of Mars were neglected, as they arc believed to be relativel y smal 1 in these scenarios.[8] Different modeling assumptions were made depending on the filter strategy employed. In this analysis, two different filter strategies were utilized; a "standard" filter, in which station location, Earth orientation, and transmission media (ionosphere, troposphere) calibration errors were treated as consider parameters, and an "enhanced" filter, in which station location, Earth orientation, and troposphere calibration errors were represented as filter parameters, and on] y ionosphere calibration errors were treated as consider parameters (ionospheric effects at X-band arc generally small relative to other ground system error sources). The motivation behind the enhanced filter is not so much to improve upon the *a priori* ground system calibrations, but to incorporate a more accurate model of the physical world into the filter. A batch-sequential *U-D* factorized estimation scheme was employed in both cases;[9] a batch size of onc day was used with the standard filter, while a batch size often minutes was used with the enhanced filter, in order to track short-term fluctuations in the troposphere.

Both the standard and enhanced filtering strategies contain filter parameters representing spacecraft nongravitat ional forces such as solar radiation pressure and small anomalous forces due to gas leaks from valves and pressurized tanks, attitude control thruster misalignments, etc. The nongravitational force model used herein was based on past experience and the modeling of current spacecraft such as *Mars Observer*. For the processing of two-way ranging data, both the standard and enhanced filter models included a stochastic bias parameter associated with each ranging pass from each station, in order to approximate the slowly-varying, nongeometric delays in ranging measurements that are caused principal y by station delay cali bration errors and uncalibrated solar plasma effects.

* A *consider* parameter is treated by the filter as an unmodeled systematic error which is not estimated, but is allowed to affect the error statistics of the estimated parameter set.

Table 1

"STANDARD" ORBIT DETERMINATION FILTER WITH CURRENT AND IMPROVED GROUND SYSTEM ERROR MODELS

Estimated Parameter Set	*Uncertainty (1σ)* Current	Improved	remarks
Spacecraft Epoch State	*a priori,*		
position components	105 km	--	constant
velocity components	1 km/s		parameters
Nongravitational Force Model			
solar radiation pressure:	*a priori,*		
radial (G_r)	10% (≈0.13)	—	constant
transverse (G_x/G_y)	10% (≈0.01)		parameters
anomalous accelerations:	steady-state,		Markov parameters,
radial (a_r)	10-12 km/s^2	- -	10 day time Constant
transverse (a_x/a_y)	10^{-12} km/s^2		10 day time constant
Ground System Error Model			
range biases: (one per station per pass, ranging data only)	*a priori,* 4m	*a priori,* l m	uncorrelated from pass to pass
-Consider Parameter Set			
DSN station locations:			
spin radius (r_s)	0.18 m	0.09 m	relative uncertainty
z-height (z_s)	0,23 m	0.10 m	between stations is
longitude (λ)	3.6 x 10^{-8} rad	1.8 x 10-8 rad	lto2cm
transmission media:			
zenith troposphere (each station)	*5 cm*	1 cm	wet plus dry components
zenith ionosphere (each station)	3 cm	1.5 cm	X-band values

The use of stochastic range delay parameters to process ranging data has become known as the "precision ranging" data filtering technique, which has made it possible to successfully utilize ranging data at accuracies of a few meters in the recent radio navigation demonstration s cited earlier.

When the current and improved ground system error models were used with the standard filter (see Table 1), the DSN station location error covariances incorporated Earth orientation uncertainty, and Earth pole modeling uncertainty that is due to limitations in the current orbit determination software system; therefore, no explicit Earth orientation parameters were included in the consider parameter set, When the current and improved

Table **2**

"ENHANCED" ORBIT DETERMINATION FILTER WITH CURRENT AND IMPROVED GROUND SYSTEM ERROR MODELS

	Uncertainty (1σ)		
Estimated Parameter Set	*Current*	*Improved*	*Remarks*
Spacecraft Epoch State	*a priori,*		
position components	105 km	---	constant
velocity components	1 km/s		parameters
Nongravitational Force Model			
solar radiation pressure:	*a priori,*		
radial (GJ	10% (=0.13)	---	constant
transverse (G_x/G_y)	10% (≈0.01)		parameters
anomalous accelerations:	steady-state,		Markov parameters,
radial (a_r)	10-12 km/s^2	---	10 day time constant
transverse (a_x/a_y)	10-12 km/s^2		10 day time constant
range biases *(one per* station per pass, ranging data only)	*a priori,* 4 m	*a priori,* 1 m	uncorrelated from pass to pass
Ground System Error Model			
DSN station locations:	*a priori,*	*a priori,*	constant parameters,
spin radius (r_s)	*0.18* m	*0.09* m	relative uncertainty
z-height (z_s)	0.23 m	0.10 m	between stations is
longitude (λ)	3.6 x 10-B rad	1.8 x 10^{-8} rad	1 to 2 cm
Earth orientation:	steady-state,	steady-stale,	Markov parameters
pole orientation	1.5 x 10-8 rad	5.0x 10^{-9} rad	1 day time constant
rotation period	0.2 rns	0.1 ms	12 hr time constant
transmission media:	*a priori,*	*a priori,*	random walk,
zenith troposphere	5 cm	1 cm	N = 1 cm^2/hr (current)
(each station)			N= 3.3 mm^2/hr (improved)
Consider Parameter Set			
zenith ionosphere (each station)	3 cm	1.5 cm	X-band values

error models are used with the enhanced filter, described in Table 2, the DSN station location error covariance which was used in the standard filter cases was utilized; however, the enhanced filter model also includes three exponentially correlated process noise parameters to account for the *dynamical* uncertainties in the Earth's pole location and rotation period.

The station location covariance used in the current ground system error model represents the uncertainty in the station location and pole model solutions developed by Finger and Folkner;10'11 this covariance matrix and its associated station location set arc being used operationally by the *Mars Observer* Navigation Team. In the improved error model, the same covariance matrix was utilized, but was scaled down by a factor of two in sigma. The tropospheric calibration uncertainty in the improved ground system model represents the predicted performance of a Global Positioning System (GPS)-based troposphere calibration system, and the ionospheric calibration uncertainty represents the predicted performance of an improved version of the current GPS ionosphere calibration system.[12] Also, the improved ground system error model presumes a significant improvement in ranging system calibration accuracy, and a tacit assumption of relatively large (>45-60 deg) SEP angles for ranging data acquisition, leading to small (<1 m) solar plasma delays.

PERFORMANCE ASSESSMENT

Using the baseline data schedule, orbit determination error statistics were computed for DSN Doppler-only and Doppler-plus-ranging data sets using the standard and enhanced filter strategies, and for the current and improved ground system calibration error models as well, Using the reduced data schedule, error statistics were computed for a subset of the baseline cases. The orbit determination error statistics were propagated to the time of Mars encounter and expressed as dispersions in a Mars-centered aiming plane, or B-plane, coordinate system (see Appendix); specifically, the magnitude of the semi-major axis and semi-minor axis of the one-sigma B-plane dispersion ellipse, and the one-sigma uncertainty in the linearized time-of-flight, expressed as a positional uncertainty in the time-of-flight (downtrack) direction,

Mars Observer Interplanetary Cruise Scenario

in this scenario, a long (six month) data arc was employed, based on the operations plan of the *Mars Observer* Navigation Team. The results are summarized in Tables 3 and 4. "Table 3 gives the dimensions of the aim point dispersions around the nominal MOI aim point for the baseline data schedule cases, and Table 4 gives the dimensions of the MOI aim point dispersions for the reduced data schedule cases,

The results in this scenario indicate that the standard filter is extremely sensitive to station location/Earth orientation and tropospheric calibration error consider parameters; it should be emphasized that no attempt was made to "optimize" the performance of the standard filter in either the *Mars Observer* or *MESUR* Pathfinder mission scenarios. Subsequent efforts (not shown herein) found that through such time-honored practices as artificially "deweighting" (reducing the assumed accuracy) of the Doppler data to about 1 mm/s, accuracies of about 80 km can be achieved for Doppler-only cases, and accuracies of about 30 km for Doppler-plus-ranging cases.[13] With the enhanced filter, the Doppler data were only able to determine the Earth-spacecraft range at encounter to just under 50 km; this direction is closely aligned with the semi-major axis of the B-plane dispersion ellipse. When ranging data were used with the enhanced filter, accuracies on the order of 10 km resulted, except in the case in which the improved ground system error model is u scd, in

Table 3

MARS OBSERVER AIM POINT DISPERSIONS*
FOR BASELINE OAT-A SCHEDULE CASES

Filter Model	Ground System Error Model	Radio Metric Data Types	Aim Point Dispersions (1σ,km)	B-Plane Ellipse Orientation (deg)
standard	current	Doppler	583 × 176 × 236	*147*
standard	current	Doppler/ranging	183x3x234	65
standard	improved	Doppler	199x68x96	*146*
standard	improved	Doppler/ranging	59x1x82	*65*
enhanced	current	Doppler	47x12x13	*157*
enhanced	current	Doppler/ranging	11 × 0.4 X11	*64*
enhanced	improved	Doppler	44x8x9	*.155*
enhanced	improved	Doppler/ranging	36x 0.3 x 37	*64*

Table 4

MARS OBSERVER AIM POINT DISPERSIONS
FOR REDUCED DATA SCHEDULE CASES

Filter Model	Ground System Error Model	Radio Metric Data Types	Aim Point Dispersions (1σ,km)	B-Plane Ellipse Orientation (deg)
standard	current	Doppler/ranging	140X1 X144	*64*
standard	improved	Doppler/ranging	46X *0.5* x *48*	*64*
enhanced	current	Doppler	*51X15X17*	159
enhanced	current	Doppler/ranging	*14 X0.4 x* 14	*64*

which dispersions of roughly 30 km were obtained; a more detailed examination of this case found that the ionospheric calibration error consider parameters were dominating the aim point dispersions, indicating that the ionospheric calibration errors must also be modeled in the filter in order to obtain good (10 km or better) performance. The B-plane dispersion ellipses in the Doppler-plus-ranging cases were consistently oriented with the semi-major axis roughly normal to the Earth-Mars line, while the orientations of the dispersion ellipses in the Doppler-only cases were consistently parallel to this line. As indicated earlier, this occurs because of Doppler data's poor ability (relative to ranging data)

* Aim point **dispersions are expressed as *B* piano semi-major axis x *B* piano semi-minor axis x position uncertainty in time-of-flight (downtrack) direction,**

to determine the Earth-spacecraft range at encounter. Expressed as a geocentric angle uncertainty, the accuracy achievable with the enhanced filter (10 to 15 km) was found to be 30 to 40 nrad.

One interesting result obtained in this scenario was that the use of a reduced data schedule and the standard filter led to substantial reductions in the orbit determination dispersions over the corresponding cases with the baseline data schedule. This indicates that "thinning" out the data arc greatly reduced the sensitivity of the dispersions to unmodeled station location/Earth orientation and tropospheric calibration errors. To check the performance of the enhanced filter with a reduced data schedule, additional cases were computed with the current ground system error model, and, as seen in Tables 3 and 4, no noticeable change occurred over the statistics obtained with the baseline data schedule in both Doppler-only and Doppler-plus-ranging cases.

MESUR Pathfinder Interplanetary Cruise Scenario

The results of this scenario are summarized in Tables 5 and 6. Table 5 gives the dimensions of the aim point dispersions around the nominal aim point in the B-plane for the baseline data schedules. Table 6 gives the dispersions for the reduced data schedule cases. Note that the actual *MESUR* navigation requirements are not specified in terms of aim point dispersions but rather by landing dispersion requirements. For purposes of comparison to the *Mars Observer* analysis, however, aiming plane uncertainties are quoted here.

In this scenario, the performance obtained from Doppler and ranging data with the standard filter was much better than in the *Mars Observer* scenario; even with the current ground system error model, dispersions of 23 km or less were obtained, even though the Earth-spacecraft range over the data arc was not significantly different from *Mars Observer's*. Even with the large encounter declination, the Doppler-only cases with the standard filter indicate significant sensitivity to station location/Earth orientation and tropospheric calibration error consider parameters. As in the *Mars Observer* scenario, some cases with deweighted Doppler data were computed; the results indicated that Doppler-only accuracies of 50 to 60 km could be obtained with the Doppler data weighted at 1 mm/s, a factor of 25 poorer than the inherent accuracy of about 0.04 mm/s. The addition of ranging data reduced these sensitivities substantially.

This scenario in particular indicated that the improved ground system error model yielded significantly better performance (factors of two to three) over the current ground system error model, even in some of the cases in which the enhanced filter was used. As in the *Mars Observer* scenario, the orientations of the *B*-plane dispersion ellipses in the Doppler-only cases were consistently about 90 deg away from the orientations of the ellipses in the Doppler-plus-ranging cases, again, due to Doppler's weak ability to determine range, relative to that of ranging data. The *MESUR* Pathfinder results with a reduced data schedule also indicate that very little degradation in performance is incurred over the results obtained with the baseline data schedule.

Table 5

MESUR PATHFINDER AIM POINT DISPERSIONS FOR BASELINE DATA SCHEDULE CASES

Filter Model	Ground System Error Model	Radio Metric Data Types	Aim Point Dispersions (1σ,km)	B-Plane Ellipse Orientation (deg)
standard	current	Doppler	826x24x109	179
standard	current	Doppler/ranging	23x1x14	85
standard	improved	Doppler	409X11X54	179
standard	improved	Doppler/ranging	9X1X5	85
enhanced	current	Doppler	18x6x4	178
enhanced	current	Doppler/ranging	5x0.6x3	89
enhanced	improved	Doppler	13x3x2	181
enhanced	improved	Doppler/ranging	3x0.3x2	8 9

Table 6

MESUR PATHFINDER AIM POINT DISPERSIONS FOR REDUCED DATA SCHEDULE CASES

Filter Model	Ground System Error Model	Radio Metric Data Types	Aim Point Dispersions (1σ,km)	B-Plane Ellipse orientation (deg)
standard	current	Doppler/ranging	24x1x7	88
standard	improved	Doppler/ranging	11X1X4	88
enhanced	current	Doppler	22x9x5	170
enhanced	current	Doppler/ranging	9X0.7X4	89

DISCUSSION

Although this analysis focused on establishing the inherent capability of conventional Doppler and ranging data, it is important to note briefly some recent developments in improving the performance of Doppler data by redefining the Doppler measurement, Presently, the "raw" Doppler data generated by the DSN Doppler system are not direct frequency shift measurements, but counts of the number of cycles of the transmitted carrier signal phase relative to the received carrier signal phase that have accumulated since the beginning of a pass, These cycle counts are differenced to form measurements of the average Doppler shift over short time periods, typically 1 to 10 rein; it is these *differenced-range Doppler* measurements that were anal yzed in this paper.[14] The alternative phase

Doppler formulation, known as *counted Doppler*, *uses the* original Doppler count as the Doppler observable, since the precision of these data is very high (a few millimeters at X-band frequencies), and differencing the counts to form differenced-range Doppler data effectively increases the data noise level.

Figure 1 illustrates the aim point dispersion ellipse (1 σ) for the *Mars Observer* case from 'Table 3 in which the conventional differenced-range Doppler formulation was used, and, in addition, the dispersion ellipse obtained for the same case with the alternative counted Doppler formulation, which was computed in another study.[15] In both cases, the data were reduced with the enhanced filter strategy and the current ground system error model. As is evident from Fig. 1, the Earth-to-spacecraft range component of the MOI aim

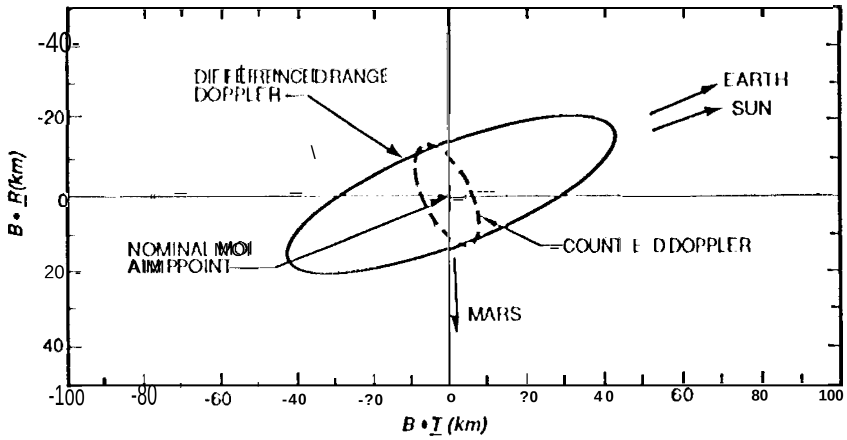

Fig. 1 *Mars Observer* Aiming Plane Dispersions

point was determined much more accurately with only a change in the data formulation. Though not shown, the counted Doppler formulation did not yield any improvement in accuracy in the time-of-flight direction; however, the important observation is that with counted Doppler, an accuracy of 15 km or better (50 nrad in geocentric angle) appears achievable in all three components of the aim point.

SUMMARY AND CONCLUSIONS

"This paper described the results of a navigation error covariance analysis designed to characterize the accuracy obtainable with precision Doppler and ranging data in current and future missions to Mars. Navigation performance was evaluated as a function of: 1) data acquisition schedule, 2) orbit determination (data reduction) strategy, and 3) accuracies with which ground system parameters are calibrated. The assumed Doppler and ranging data accuracies were chosen to reflect the actual performance of the DSN's X-band tracking system, as observed in recent interplanetary missions such as *Magellan*, *Galileo*, and *Ulysses*. *The* results indicate that the navigation performance predicted in both the *Mars Observer* and *MESUR* Pathfinder mission scenarios was determined principally by the choice of data reduction strategy, and to a lesser extent by the assumptions made for ground system parameter calibration accuracies. It was found that the navigation performance obtained with data schedules of one to two passes per week is generally not degraded relative to cases in which onc to two passes were acquired per day.

The results obtained with the current data reduction strategy, in which ground system error sources are not modeled, often leads to very poor performance and unpredictable behavior, due to the effects of the unmodeled error sources, In the cases in which this "standard" filtering strategy was used, the dominant sources of navigation uncertainty were consistently found to be unmodeled station location/Earth orientation and tropospheric calibration errors, In the standard filter cases in which only Doppler data were used, the navigation dispersions exhibited much greater sensitivity to ground system calibration errors than in cases in which ranging data were included, The use of an "enhanced" filter that dots contain models for ground system error sources yielded much better performance and greater consistency between the results obtained in the two scenarios. in addition, the navigation dispersions obtained with the enhanced filter were observed to be less sensitive. to the assured ground system calibration accuracies than those obtained with the standard filter. It must be noted, however, that this ncw filtering strategy is still in the experimental stages of development. Overall, the results predict that navigation accuracies (1σ) of 5 to 15 km, or about 15 to 40 nrad in geocentric angle uncertainty, may be achieved in the mission scenarios investigated.

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APPENDIX

Planetary approach trajectories are typically described in aiming plane coordinates, often referred to as "B-plane" coordinates (see Fig. A-1). The coordinate system is defined by three orthogonal unit vectors, **S**, **T**, and **R** with the system origin taken to be the center of the target planet, The **S** vector is parallel to the spacecraft velocity vector (V_∞) relative to the target planet, while **T** is normally specified to lie in the ecliptic plane (the mean plane of the Earth's orbit), however, in this analysis, **T** was defined to lie in the Martian equatorial plane. Finally, **R** completes an orthogonal triad with **S** and **T**.

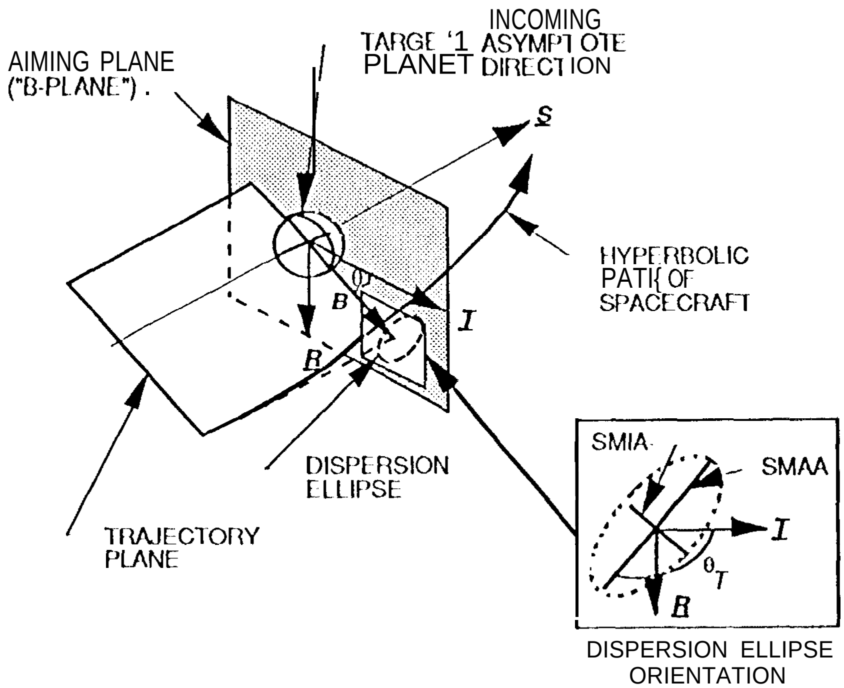

Fig. A-1 Aiming Plane Coordinate System Definition

The aim point for a planetary encounter is defined by the miss vector, *B*, which lies in the **T**-**R** plane, and specifics where the point of closest approach would be if the target planet had no mass and did not deflect the flight path. The time from encounter (point of closest approach) is defined by the *linearized rime-of-flight* (LTOF), which specifics what the time of flight to encounter would be if the magnitude of the miss vector were zero. Orbit determination errors are characterized by a one-sigma or three-sigtna B-plane dispersion ellipse, also shown in Fig. A-1, and the one-sigma or three-sigrna uncertainty in 1 .TOF. *In* Fig. A-1, SMIA and SMAA denote the semi-minor and semi-major axes of the dispersion ellipse, respectively.