2003 Mars Exploration Rover Orbit Determination Using ΔVLBI Data

Brian M. Portock, Robert Haw, Louis A. D'Amario
Jet Propulsion Laboratory, California Institute of Technology,
Pasadena, CA 91109-8099

Abstract

The Mars Exploration Rover mission plans to launch two spacecraft, each containing one rover, and to deliver them to the surface of Mars allowing the rovers to collect science data on the surface. The mission has baselined an intensive campaign of ΔVLBI measurements which make it possible to meet stringent atmospheric entry delivery accuracy requirements. The entry flight path angle (FPA) uncertainty requirements range from 0.17° to 0.25° (3σ), depending on the landing site. The improvement in the FPA uncertainty due to ΔDOR ranges from 0.03° to 0.10° (3σ) depending upon the landing site. This reduction in entry FPA uncertainty corresponds to a reduction in the downtrack component of the landing ellipse ranging from 11 km to 40 km. The addition of ΔDOR also reduces the delivery accuracy sensitivity due to variations in the amount of Doppler and range data.

Introduction

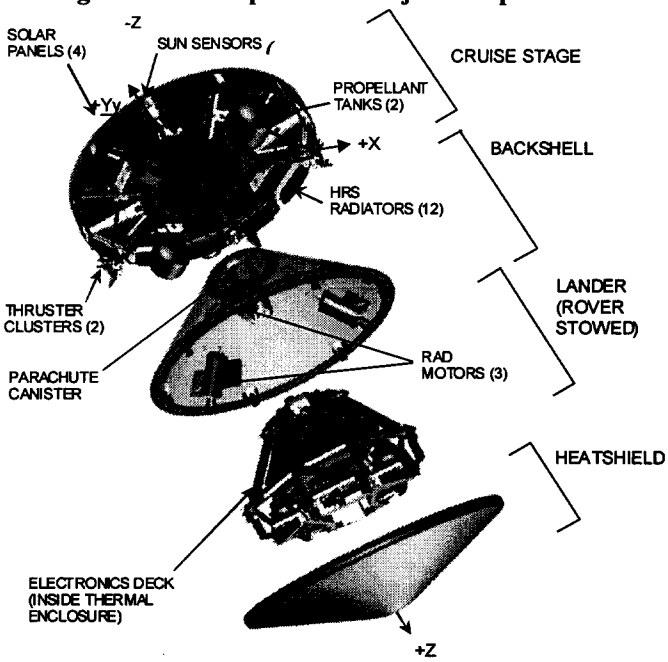
The Mars Exploration Rover (MER) mission plans to launch two spacecraft, each containing one rover, and to deliver them to the surface of Mars allowing the rovers to explore the surface and collect science data. Each spacecraft must be delivered to enter the Mars atmosphere accurately in order to meet the physical requirements of the entry, descent, and landing system, meet the requirement of surface safety (i.e. safe surface terrain) and to allow scientifically interesting landing sites to be selected. In the past, interplanetary missions have used two-way Doppler and ranging data along with small amounts of various other data types for interplanetary navigation, but the resurgence of the ΔVLBI system, for navigation use, has given the Mars Exploration Rover mission another option. The MER mission has baselined an intensive campaign of ΔVLBI measurements which make it possible to meet stringent delivery accuracy requirements. The ΔVLBI data enables a higher accuracy Mars delivery than that of Doppler and range only. This allows smaller landing ellipses for science and a more robust entry, descent, and landing system. This paper will show the improvements to the atmospheric entry delivery accuracy due to the addition of ΔVLBI data to the standard Doppler and range tracking.

Spacecraft Configuration

The MER spacecraft in cruise configuration is shown in Figure 1. The design of the MER flight system is an adaptation of the Mars Pathfinder spacecraft design. As such, during flight, MER is a spin-stabilized spacecraft with a nominal spin rate of 2 rpm. The MER flight system consists of four major components: cruise stage, backshell, Lander structure (containing the Rover), and the heatshield. The mass allocation for the entire flight system (including propellant load) is 1063 kg.

The cruise stage includes solar panels, the propulsion system, which includes two propellant tanks and two thruster clusters, the Attitude Control System, which includes a star scanner, IMU, and Sun sensors, and a LGA and a MGA for X-band communications with Earth. Both antennas are oriented in the spacecraft – Z direction. The cruise stage is separated from the backshell/heatshield assembly approximately 15 min prior to Entry.

Figure 1. MER Spacecraft Major Components



During the interplanetary transfer to Mars, the Lander structure (containing the Rover) is enclosed by the backshell/heatshield assembly, which is also referred to as the aeroshell. The aeroshell protects the Lander

and Rover from extreme heat loads experienced during atmospheric entry. The heatshield thermal protection system dissipates energy as the spacecraft enters the Martian atmosphere. The backshell includes the parachute canister and Rocket Assisted Deceleration (RAD) motors, both of which are used to slow the Lander prior to touchdown on the surface. The backshell also includes an aft-mounted LGA for X-band communications during EDL.

Propulsion

The MER propulsion system includes the hardware needed to perform spin control, attitude control and trajectory correction maneuvers (TCMs) during Cruise and Approach. The propulsion system hardware, located on the cruise stage, is a monopropellant hydrazine system.

The propellant system consists of two hydrazine tanks, line feeds and filters, two latch valves, and eight thrusters in two clusters of four thrusters each. The eight thrusters are used for spin-rate maintenance, attitude control, and TCMs.

The thruster cluster assemblies are diametrically opposed, and each contains four thrusters. On one side of the spacecraft thrusters 1 through 4 are aligned 40 deg off the –X axis; that is, starting from a –X orientation, the thrusters are pointed 40 deg toward the +Z direction and 40 deg toward the –Z direction in the X-Z plane, and 40 deg toward the +Y direction and 40 deg toward the –Y direction in the X-Y plane. Thrusters 5 through 8 are aligned 40 deg off the +X axis in a similar fashion on the opposite side of the spacecraft.

Spacecraft attitude maneuvers (turns) and spin-rate control are accomplished by pulse-mode firing of coupled thruster pairs. There are two sets of thruster pairs that can be used for these maneuvers.

Telecomunications

The MER telecommunications subsystem uses X-band for direct-to-Earth (DTE) communications during all mission phases and a UHF system used both during a portion of EDL and also on the surface of Mars for relay communications through the Mars Odyssey and MGS orbiters.

The X-band telecommunications system design is single-string coherent X-Band Uplink/X-Band Downlink with electronics located in the Rover. The same X-band electronics are used from launch through end of mission, but four different sets of X-band antennas are required:

- An MGA-LGA pair on the cruise stage for communications during interplanetary flight.
- A backshell-mounted LGA to support communications during EDL.
- One small patch LGA on the Lander base petal to support communications after landing and prior to Rover deployment.
- An HGA-LGA pair on the Rover for surface operations.

The heart of the X-Band telecommunications system is the Small Deep Space Transponder (SDST), which supports phase coherent turn-around Doppler and ranging, command signal demodulation and detection, telemetry coding and modulation, and differential one-range (DOR) tone generation (at ± 19 MHz). The DOR tones are used in the ΔVLBI measurement.

The two communications antennas (LGA and MGA) and the solar panels on the MER spacecraft cruise stage are oriented along the spacecraft –Z axis. The attitude strategy during early cruise, when the Sun-Spacecraft-Earth (SPE) angle is large (up to 100 deg), is to maintain the –Z axis pointed between the direction to the Earth and direction to the Sun. This strategy allows a telecom link to Earth using the LGA, while providing sufficient power for spacecraft operations. Once the SPE angle becomes small enough, the attitude strategy changes to one which maintains the –Z axis pointed to within ±8 deg of Earth, in preparation for switching the telecom link to the MGA which occurs somewhat later. The solar panels still provide sufficient power, because the SPE angle is not as large.

Attitude Maintenance

Since the MER spacecraft is spin-stabilized, its attitude remains inertially fixed as long as there are no thruster firings. The ACS will command the thrusters to fire to perform attitude maneuvers to accomplish the attitude strategy described above. The total number of attitude maneuvers in the current strategy (including a practice turn prior to TCM-1, but not counting the turns required for ACS/NAV characterization or the final turn to the Entry attitude) is 13 for MER-A and MER-B. However, this should be considered the minimum number of attitude maneuvers required, because, additional turns will almost certainly be necessary during flight operations to optimize uplink and downlink and for activities

other than those required for telecom and power considerations. The average time between attitude maneuvers is 16-18 days, depending on the exact launch date and MER-A vs. MER-B.

During attitude maneuvers, the thrusters are fired as couples, so that there is no net ΔV imparted to the spacecraft inherent in the design. However, because of thruster misalignments and plume impingement effects, there generally will be a residual ΔV. It is important to model the ΔVs resulting from these "ACS events" in the orbit determination process in order to satisfy the delivery accuracy requirements for atmospheric entry. The Flight System is required to limit the residual ΔV resulting from ACS events for accurate modeling of the trajectory. The Flight System requirement limits the residual ΔV from attitude maneuvers to 3 mm/s (3σ) along each spacecraft axis for attitude maneuvers less than 15 deg and 6 mm/s (3σ) along each spacecraft axis for attitude maneuvers greater than 15 deg.

Spacecraft Targeting

The combined effect of orbit determination errors and maneuver execution errors mapped to the atmospheric entry interface point is referred to in this document as the delivery accuracy. TCMs 4, 5, and 6 during the Approach phase are the key maneuvers used to target to the desired atmospheric entry interface conditions and therefore the delivery accuracy from these maneuvers is very important. The entry interface conditions consist of inertial entry flight path angle (FPA), B-plane angle, and time at the entry interface point, defined as Mars radius equal to 3522.2 km (see Figure 1). These conditions can also be met by targeting a B-plane aimpoint (B•T, B•R) along with a time of flight.

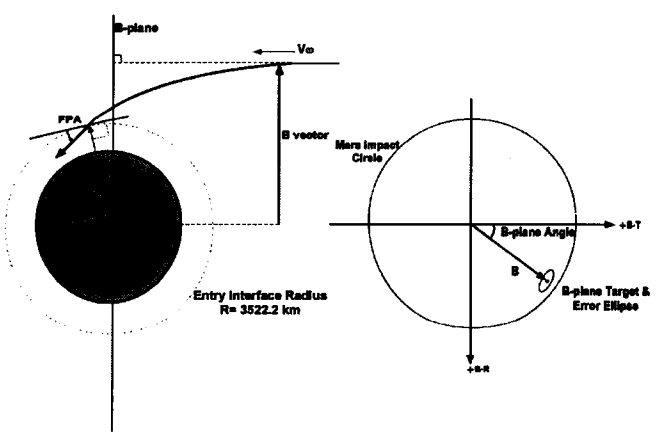


Figure 2: B-plane Targeting

The entry interface conditions are derived from the desired landing target based on the trajectory of the spacecraft during the entry, descent and landing (EDL) phase. Targeting a specific B-plane angle and entry time corresponds to targeting latitude and longitude on the surface. The entry FPA is a parameter that affects the ballistic trajectory of the EDL system through the atmosphere. The atmospheric trajectory, and the entry FPA, are constrained by the limits of the flight system. The flight system is designed for an entry FPA of -11.5 deg ±0.55 deg (3σ). There is a tighter requirement on the FPA uncertainty due to landing ellipse size. The FPA uncertainty is the error source that drives the size of the downtrack component of the landing ellipse. The landing ellipse sizes range in semi-major axis from 80 km to 340 km (3σ) corresponding to FPA uncertainty requirements ranging from 0.17 deg to 0.25 de (3σ), depending on the latitude of the landing site.

Data Type Comparison

ΔVLBI data measures components of the spacecraft's position that are orthogonal to the components measured by Doppler and range data, therefore adding valuable information to the estimation process. Doppler and range measure the line-of-sight component of position and velocity. The ΔVLBI data, for MER, is known as Delta Differenced One-way Range (ΔDOR). This data type employs two Deep Space Network (DSN) stations at different complexes to simultaneously receive tones (known as DOR tones) from the spacecraft followed by simultaneous observations of a quasar as a reference radio source. These observations are used to measure the angular difference between the spacecraft and the quasar in the plane-of-sky along the line between the two DSN complexes. This direction is orthogonal to the line-of-sight to the spacecraft.

The way in which line-of-sight measurements relate to information about the trajectory depends on where the spacecraft is in its trajectory, but generally for Mars missions Doppler and range data supplies information in the spacecraft's trajectory plane. The manner in which the ΔDOR data relates to the trajectory depends on the trajectory and the DSN complexes, or baselines, used in the measurement. Since ΔDOR measures the plane-of-sky position of the spacecraft along the baseline, the way in which that baseline relates to the trajectory differs. The

usual DSN complex pairs used as baselines are Goldstone-Madrid and Goldstone-Canberra. The Goldstone-Madrid baseline (oriented East-West) primarily measures the right ascension component of the spacecraft corresponding to an in-plane component of the trajectory. By similar reasoning, the Goldstone-Canberra baseline (oriented North-South) primarily measures the declination component of the spacecraft corresponding to the out-of-plane component of the trajectory (for most Mars missions). The third possible baseline, Madrid-Canberra, represents the longest baseline for the DSN, but is rarely scheduled because of very brief overlapping view periods.

ΔDOR data is independent of spacecraft dynamics. It is not necessary to rely on dynamic models to infer position as is the case for Doppler and range. The ΔDOR observable is a phase delay time expressed in units of nanoseconds (ns) that is equivalent to an angular separation between the spacecraft and the quasar. For the DSN, a delay of 1 ns corresponds to about 37.5 nanoradians (nrad) of angular displacement. Knowing the quasar's angular position determines a component of the spacecraft's position in plane-of-the-sky. By taking another measurement with an almost perpendicular baseline determines a second component.

Orbit Determination Performance Analysis Process and Assumptions

Orbit determination performance (OD) processing is accomplished by a covariance study using a multiple batch consider-parameter filter, incorporating a baseline set of simulated data. The simulated data consists of two-way coherent Doppler, two-way coherent ranging data, and ΔDOR measurements. All significant error sources are accounted for in the filter with a priori uncertainty assumptions. Each error source is either estimated as a part of the process or considered. Estimating the parameter allows the filter to use the tracking data to solve for the model parameter to better than the a priori uncertainty. Considering a parameter accounts for error due to that parameter without using the data to gain knowledge about the parameter.

All trajectory correction maneuvers (TCMs) contained within the data arc are estimated. Future TCMs (i.e., with respect to a given data cutoff time) are treated in one of two ways. For generating entry uncertainties from a specific TCM, the TCM directly after the data cutoff time is considered in the filter at the a priori uncertainty, while any other future TCMs are ignored.

Spacecraft attitude control system (ACS) ΔV events (e.g., spacecraft turns for attitude maintenance) are estimated in the OD filter when these events fall within the data arc, and they are considered at all times when the ACS event schedule places them in the future (i.e., between the end of the data arc and Entry). Each ΔV from an ACS event is modeled with a three-component impulse.

The solar pressure model consists of four components. For navigation analyses, however, only a single component (the solar array component) is estimated in the filter. This strategy is believed prudent, because the alternate choice of increasing the filter's complexity by estimating all four solar pressure components does not elicit any greater insight or accuracy.

Stochastically estimated parameters include Earth orientation parameters, media effects, and Doppler and range data biases. The data biases are estimated during each tracking pass. Moreover, dynamic model margin has been incorporated to account for non-gravitational acceleration mis-modeling. A single, three-component stochastic acceleration is estimated along the trajectory for this purpose.

The considered parameters consist of quasar locations, station locations (a correlated 9x9 error covariance), and the Earth and Mars ephemerides. Considering these parameters (especially the quasar locations) is conservative, but is judged prudent in the absence of real data.

Table 1 presents a summary of the OD filter assumptions and error sources for the orbit determination results presented in the sections that follow. The tracking data collection assumptions are shown in Table 2 for ΔDOR and Table 3 for Doppler and range.

Error Source	Estimated?	A Priori Uncertainty (1σ)	Correlation Time	Update Time	Comments/References
2-way Doppler (mm/s)	–	0.075	–	–	~4.5 mHz
Range (m)	–	4	–	–	29 range units
²DOR (nrad)	–	4.5	–	–	0.12 ns
²DOR Schedule	Level 2⁻				Level 2 (DSN request) with last point of final baseline pair no later than 2 days before data cutoff.
Epoch State					
Position (km)	√	1000	–	–	
Velocity (km/s)	√	1	–	–	
Range Bias (m)	√	2	0	Per pass	Estimated per pass.
Doppler Bias (mm/s)	√	0.005	0	Per pass	Estimated per pass.
Mars & Earth Ephemerides		DE405+	–	–	
Station Locations (cm)		3	–	–	
Pole X, Y (cm)	√	2 → 10	0	6 hrs	*Use lower value up to 7 days before data cutoff; then ramp up to higher value at data cutoff. (For UT1, 0.256 ms ⇒ ~10 cm.)
UT1 (cm)	√	2 → 10	0	6 hrs	
Quasar Locations (nrad)		2	–	–	
Ionosphere – day (cm)	√	55	0	6 hrs	S-band values.
Ionosphere – night (cm)	√	15	0	6 hrs	
Troposphere – wet (cm)	√	1	0	6 hrs	
Troposphere – dry (cm)	√	1	0	6 hrs	
Solar Pressure					Sunlit area of spacecraft.
Area (%)	√	5	–	–	
ACS Event ²V (mm/s)	Every 8 days				
Line-of-Sight Comp.	√	3	–	–	
Lateral Comp.	√	3	–	–	
Normal Comp.	√	3	–	–	
TCMs					Spherical uncertainty (mm/s).
TCM-1	√	422, 440	–	–	MER-A Open Melas (VM53A), MER-B Open Hematite (TM20B)
TCM-2	√	17, 15	–	–	
TCM-3	√	3, 5	–	–	TCM-4 at E - 8 days TCM-5 at E - 2 days TCM-6 at E - 6 hrs (no TCM-5)
TCM-4	√	3, 3	–	–	
TCM-5	√	3, 3	–	–	5% (3σ) proportional error (per axis) 6 mm/s (3σ) fixed error (per axis)
TCM-6	√	7, 7	–	–	
Non-gravitational Accelerations (km/s²)	√	2.0×10^{-12}	10 days	1 day	Spherical covariance. Estimated daily (1 day batches).

Table 1 Baseline Orbit Determination Error Assumptions

Relative Time (days)		Frequency of ²DORs			
Start	End	DSN Request	Level 1	Level 2 (Baseline)	Level 3
L + 14	E - 45	1/week	1 every other week	1/week	1/week
E - 45	E - 28	2/week	1/week	2/week	2/week
E - 28	E - 8	1 every other day	2/week*	1 every other day*	1 every day*
E - 8	Entry	1/day	2/week*	1 every other day*	1 every day*

*Last ²DOR point of final baseline pair no later than 2 days before data cutoff.

Table 2: ΔDOR Frequency Levels

MER-A Open: Doppler and Range Coverage			
Launch Date = 5/30/03, Arrival Date = 1/4/04			
Relative Time (days)		Doppler and Range Coverage	
Start	End	DSN Request	Baseline Navigation Analysis
Launch	L + 30	Continuous	Continuous to L + 15 days; 2 tracks/day thereafter
L + 30	E - 45	3 tracks/week	3 tracks/week
E - 45	E - 21	~2.5 tracks/day	2 tracks/day
E - 21	Entry	Continuous	2 tracks/day
Notes:	1. Approach data arc starts at E - 60 days.		
	2. Approach phase starts at E - 45 days.		

Table 3: Baseline Doppler and Range Tracking Coverage

Results

The results in Tables 4 and 5 are based on the process and assumptions described in the previous section. The process was applied to both missions which are labeled MER-A (1st launch) and MER-B (2nd launch). The MER-A trajectory was targeted to a representative site named Melas Chasma at 282.1° east longitude and 8.7 ° south latitude (IAU 2000 reference frame) assuming a launch at the open of the launch period. The MER-B trajectory was targeted to a representative site named Hematite at 353.8° east longitude and 2.0° south latitude (IAU 2000 reference frame) also assuming a launch at the open of the launch period. These results address two main topics. The first set of results in Table 4 show the improvement in the overall delivery accuracy due to the addition of ΔDOR data to the Doppler and range data. Table 5 shows the corresponding improvement in the downtrack component of the landing ellipse due to a decrease in the entry FPA uncertainty. Table 6 shows the effect on the delivery accuracy from different levels or frequency of ΔDOR points. Table 7 shows the effect of varying the amount of Doppler and range tracking when a given amount of ΔDOR data is assumed.

The addition of ΔDOR to the Doppler and range data provides a significant improvement to delivery accuracy from each maneuver. This improvement in delivery accuracy adds robustness to the design of the EDL system as well as allows for smaller landing ellipses on the surface as seen in Table 5.

	MER-A Open Melas Chasma		MER-B Open Hematite	
	ΔDOR Frequency		ΔDOR Frequency	
	Baseline Level 2	Doppler & Range Only	Baseline Level 2	Doppler & Range Only
TCM-4 Delivery (3σ) @ E – 8 days:				
Semi-major Axis (km)	16.8	46.2	17.8	27.1
Semi-minor Axis (km)	10.1	12.4	11.2	12.1
Ellipse Orientation Angle (deg)	112.0	91.5	109.3	98.8
Entry Time (s)	8.8	10.1	9.0	11.6
B Magnitude (km)	10.4	14.6	11.9	12.4
TCM-5 Delivery (3σ) @ E – 2 days:				
Semi-major Axis (km)	10.7	21.4	10.5	15.4
Semi-minor Axis (km)	3.6	6.1	3.4	4.4
Ellipse Orientation Angle (deg)	113.0	95.4	107.2	101.3
Entry Time (s)	3.2	3.9	3.6	5.3
B Magnitude (km)	4.1	6.5	4.2	5.0
TCM-6 Delivery (3σ) @ E – 6 hrs:				
Semi-major Axis (km)	9.5	11.1	7.3	8.8
Semi-minor Axis (km)	1.4	1.5	1.9	1.9
Ellipse Orientation Angle (deg)	118.0	118.0	115.4	115.4
Entry Time (s)	2.4	2.8	2.5	2.6
B Magnitude (km)	3.0	3.5	3.4	3.9

Table 4: TCMs 4, 5, and 6 Delivery Accuracy(3σ), Doppler and Range Only vs. Baseline with ΔDOR

	MER-A Open Melas Chasma		MER-B Open Hematite	
	ΔDOR Frequency		ΔDOR Frequency	
	Baseline Level 2	Doppler & Range Only	Baseline Level 2	Doppler & Range Only
TCM-4 Delivery (3σ) @ E – 8 days:				
TCM-5 Delivery (3σ) @ E – 2 days:				
TCM-6 Delivery (3σ) @ E – 6 hrs:				

Table 5: TCMs 4, 5, and 6 Landing Ellipse Downtrack Error(3σ), Doppler and Range Only vs. Baseline with ΔDOR

The greater the number of ΔDOR points acquired, the greater is the improvement as compared to the solution assuming Doppler and range data only. However, once a threshold is reached with the frequency of ΔDOR measurements, there is little additional improvement as can be seen in Table 6. One reason for this is the method used for simulating ΔDOR data. The data schedule is generated by first determining the time that is 48 hours before the data cut-off time for a given maneuver. Then working backwards in time, two consecutive ΔDOR points are scheduled (1 East/West baseline and 1 North /South baseline). From that point back to the beginning of the data arc, the appropriate ΔDOR schedule is followed for any given ΔDOR "level" as shown in Table 2. Therefore, before each maneuver, for any level of ΔDOR, there are always two points (one from each baseline) approximately 48 hours before the data cut-off. This attribute tends to lessen the impact of a reduced frequency of ΔDOR points. The overall improvement from a higher frequency of ΔDOR points (beyond the level at which delivery accuracy shows substantial improvement) is in the robustness of the navigation design to measurement failures. The 48 hour ΔDOR latency accounts for the measurement processing time as well as measurement failures in the last day before the data cut-off.

The sensitivity to DSN coverage during the Approach phase is shown in Table 7. In the presence of ΔDOR data, delivery accuracy is less sensitive to variations in Doppler and range coverage. Table 7 shows that decreasing the Doppler and range tracking by 50% has an appreciable negative impact on delivery errors. An increase to continuous coverage, on the other hand, produces little improvement. This shows that some coverage may be reduced to help alleviate the burden on the DSN complexes, but by reducing the coverage to only one track per day does have a negative impact on the accuracy.

	MER-A Open Melas Chasma				MER-B Open Hematite			
	ΔDOR Frequency				ΔDOR Frequency			
	Level 3	Baseline Level 2	Level 1	Doppler & Range Only	Level 3	Baseline Level 2	Level 1	Doppler & Range Only
TCM-4 Delivery (3σ) @ E – 8 days:								
TCM-5 Delivery (3σ) @ E – 2 days:								
TCM-6 Delivery (3σ) @ E – 6 hrs:								

Table 6: TCMs 4,5,and 6 Entry FPA Delivery Accuracy (3 σ) vs. Varying Levels of ΔDOR

	MER-A Open Melas Chasma			MER-B Open Hematite		
	Doppler and Range Coverage			Doppler and Range Coverage		
	150% 3 trks/day	Baseline 2 trks/day	50% 1 trk/day	150% 3 trks/day	Baseline 2 trks/day	50% 1 trk/day
TCM-4 Delivery (3σ) @ E – 8 days:						
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
TCM-5 Delivery (3σ) @ E – 2 days:						
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
TCM-6 Delivery (3σ) @ E – 6 hrs:						
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Table 7: TCMs 4,5,and 6 Entry FPA Delivery Accuracy (3 σ) vs. Varying Doppler and Range Tracking Schedules

Conclusions

In order to meet the stringent Mars atmospheric entry requirements, MER navigation has baselined the use of ΔDOR measurements in addition to Doppler and range data. The overall improvement in the FPA uncertainty due to ΔDOR ranges from 0.17° to 0.25° (3σ), depending upon the landing site. This improvement in entry FPA accuracy causes a reduction in the downtrack component of the landing ellipse ranging from 11 km to 40 km. This improvement in landing ellipse size has been significant in the ongoing landing site selection process enabling sites that would previously have been unsafe or questionable. The addition of ΔDOR also reduces the delivery accuracy sensitivity due to variations in the amount Doppler and range data. Therefore ΔDOR data through its accuracy and orthogonal nature relative to Doppler and ranging has made a significant improvement to MER approach navigation.

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