AAS 03-250

APPROACH NAVIGATION FOR THE 2009 MARS LARGE LANDER

P. Daniel BURKHART *

The current Mars exploration plan envisions the launch of a large lander in the 2009 launch opportunity with a soft landing on Mars in the fall of 2010. The goal is to achieve a landed surface position within $10km$ of the target landing site. Current entry descent and landing (EDL) analysis shows that the largest contributor to the landed position error is uncertainty of the initial conditions, which are supplied by the ground-based navigation process. The focus of this paper is the performance of the approach navigation process using combinations of Deep Space Network (DSN) Doppler, ranging and delta differential one-way range (ΔDOR) measurements along with optical navigation data collected by the spacecraft. Results for several combinations of data types will be included.

INTRODUCTION

The current plan for the exploration of Mars envisions the launch of a large lander in the 2009 launch opportunity with a soft landing on Mars in the fall of 2010. This lander, currently known as Mars Science Lander (MSL, previously Mars Smart Lander), will be either a rover with a range and lifetime at least twice as great as that planned for the 2003 Mars Exploration Rover (MER) or a large stationary lander. Either plan will most likely include a significantly larger science payload than has been sent to the surface of Mars since Viking. In addition, MSL will be the first use at Mars of a complete closed-loop guidance navigation and control (GN&C) system, including guided entry and targeting capability with a lifting body (via trim tab or center of gravity offset) to greatly reduce targeting errors during the entry descent and landing (EDL) phase. The goal is to achieve a landed surface position within $10km$ of the target landing site. The guided entry capability allows the entry body to remove errors in the trajectory from errors in the final trajectory correction maneuver (TCM) and other sources up to a level defined in the guidance algorithm design. This limit will be used to gauge the impact of the approach navigation errors.

Although the science payload and the desired landing site have not been determined, the project goal is to design an EDL system that can access as much of the Martian surface as possible. The goal is for a system that can be reused for future landers, including a

*Senior Engineer, Navigation and Mission Design Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109.

possible Mars sample return mission in the next decade. The scenario used for this study pushes the limits on the accessible locations by choosing a landing site and conditions that are unfavorable to the landing system. The resulting landing location of $41.45°S$, $286.5°E$, the "EDL Challenge Site," includes in a single scenario a high-altitude landing site, an atmospheric density at the landing site at a seasonal minimum (which reduces parachute performance), and an entry target that has the most challenging geometry relative to entry flight path angle error. These conditions represent the upper limits of the requirements for the EDL system design.

The challenge for approach navigation is clear. Current EDL analysis shows that the largest contributor to the landed position error is uncertainty of the initial conditions, as the hypersonic guidance is able to compensate for most of the error that accumulates once in the atmosphere. The entry vehicle initial states and errors are supplied by the ground-based navigation process, which determines the spacecraft position and velocity along with the error at a defined Mars entry interface point. These data are relayed to the spacecraft before atmospheric entry to initialize the EDL system.

The focus of this paper is the performance of the approach navigation process. Tracking data for orbit determination (OD) are available from several sources. Two-way range and Doppler (range-rate) data are available via the Deep Space network (DSN). Other DSN data includes delta differential one-way range (ΔDOR) measurements collected along two proposed baselines. Along with these data, an optical navigation camera will be included on the spacecraft, with optical navigation data available for the approach navigation process during the last 15 days of cruise. These data are all processed together on the ground to determine the initial position and velocity for initialization of the onboard EDL system.

Approach navigation results for landing at the EDL Challenge Site will be presented for arrival on September 6, 2010 and October 27, 2010. Part of this analysis is the determination from an approach navigation perspective the placement of the final TCM to ensure the landed position uncertainty limit can be met. Approach navigation results for the selection of the final course correction maneuver placement, along with the uncertainties used to initialize the onboard systems, will be shown. Results for several combinations of data types will be included.

APPROACH NAVIGATION DESCRIPTION

The fundamental objective of approach navigation is to ensure the spacecraft will arrive at the correct location at the correct time. Tasks that support this objective include characterization of the spacecraft dynamics for prediction (the determination of the future position of the spacecraft), the determination of the spacecraft state at specified times to facilitate TCM design, and assistance in the resolution of anomalies in the spacecraft flight plan. The impact of the first two of these tasks can be investigated via covariance analysis, specifically by evaluating the influence of selected error sources and assumed error levels on the resulting target uncertainties and performing the above analysis for specific TCM profiles.

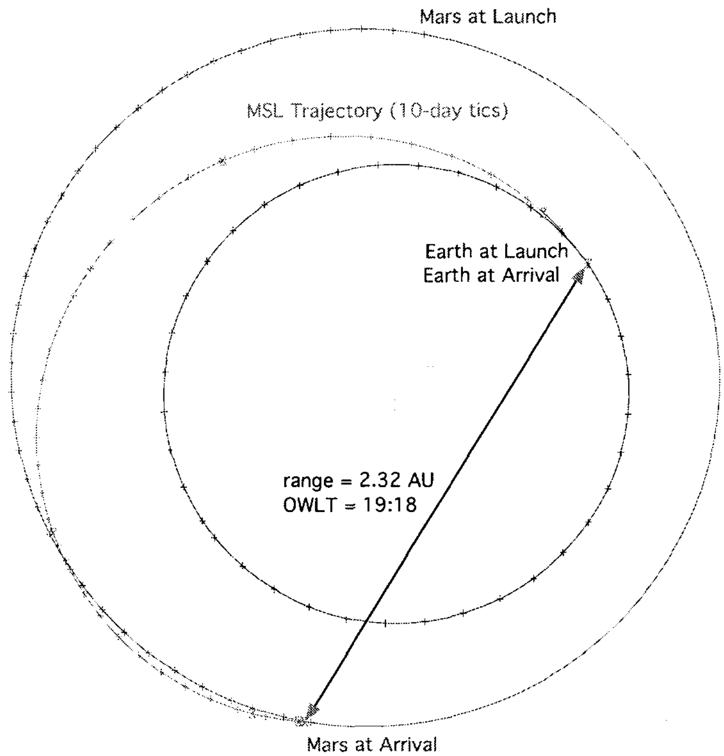

Figure 1 MSL Transfer Trajectory

The desired target for this analysis is located at a radial distance from the center of Mars of $3,522.2\,km$ from the center of Mars (or $125\,km$ above the reference Mars surface, the defined upper limit of the atmosphere for EDL analysis). This target point is chosen to ensure the lander arrives at the specified surface target of $41.45°S$, $286.5°E$, the EDL Challenge Site, for arrival dates of September 6, 2010 and October 27, 2010. Interplanetary trajectories for both of these cases are similar in transfer time and arrival geometry, although the arrival velocity is higher for the October 27, 2010 arrival case. The transfer trajectory for the October 27, 2010 arrival date case is shown in Figure 1, along with the distance and one-way light time (OWLT) from the Earth to the spacecraft on the arrival date. This is an important parameter, since the signal travel time must be factored into the timeline used for the final state upload.

The data that are used for the approach navigation analysis are shown in Table 1, along with the assumed data weights, bias parameters as required and data collection schedule for the last $60d$ of cruise. Two-way Doppler and range data from the DSN have been used for interplanetary navigation since the earliest missions. ΔDOR data requires the simultaneous use of two DSN stations located at different complexes. In addition, one of the complexes must be Goldstone, so there are at most two opportunities to collect this data type per day. This data provides a measure of the position error normal to the line

Table 1 Data Types and Uncertainties

Data Type	1σ Uncertainty	1σ Bias	Data Rate (last 60 days)
Two-way Doppler	$0.075\ \frac{mm}{s}$	$0.005\ \frac{mm}{s}$	Continuous, $10min$ compression
Two-way Range	$3\,m$	$5\,m$	Continuous, $20min$ integration time
ΔDOR	$4.5\,nrad$	-	2 per week, $E-60d$ to $E-28d$ every other day, $E-28d$ to $E-7d$ daily, last 7 days
Optical	$0.3\,pixel$	-	Deimos: $2hr$, $E-15d$ to $E-2d$ Phobos: $30min$, $E-5d$ to $E-36h$ Phobos: $10min$, $E-36h$ to $E-12h$

of sight along the baseline between the two DSN stations, so provides a direct measure of the out-of-plane position error that Doppler and range data cannot provide. ΔDOR data has been used in many deep-space missions until 1992, with the system revived in recent years and baselined for all Mars missions since Mars Odyssey in 2001. Optical data requires the addition of an optical navigation camera to the cruise vehicle. The camera is used to take images that include one of Martian moons along with stars that have a known location. This data provides a two-dimensional position measure normal to the camera boresight of the spacecraft relative to Mars, but the data are only useful within the last $15d$ of cruise. Optical navigation has not been used at Mars since Viking, but may be required to meet the stringent entry knowledge requirements the small landing footprint requires. Data strategies with Doppler and range data, Doppler, range and ΔDOR data, Doppler, range and optical data and optical data only have been investigated.

The frequency of Doppler and range data is consistent with investigation of the feasibility of obtaining an acceptable targeting accuracy with Doppler and range data only. The Doppler and range data sample rates assumed are standard for interplanetary cruise. The schedule used for ΔDOR is consistent with the MER baseline case. Cases with ΔDOR data assume a Doppler and range outage during the ΔDOR data collection times of 2 hours since the spacecraft transmitter is configured in a one-way mode during ΔDOR data collection. The optical data collection frequency is usually determined by the amount of data that can be stored onboard and the downlink data volume allocations. The start and end points of the optical data schedule are bounded by the limits of useable data at the beginning and the ground processing time to meet the state update timing requirement at the end. The collection of optical data does not impact the collection of Doppler and range data, so no data outages are assumed for cases with optical data.

The set of approach navigation error sources that are used for this analysis and the values assigned to them are shown in Table 2. The parameters and values used in developing the filter setup are based on past lander flight experience and the assumed baseline for the MER mission. There are several differences from a more traditional filter setup due to the stringent targeting requirements. Parameters for media and Earth platform are estimated as stochastics instead of being considered, while quasar and station location errors remain consider parameters. In addition, the requirements of optical navigation data processing requires that Earth, Mars, Phobos and Deimos ephemeris errors are moved into the set of estimated parameters, while cases without optical data assume these are consider parameters. The values assumed for the uncertainties of parameters not associated with the spacecraft are defined and agreed to independent of a specific mission and will not change as the spacecraft design evolves. The values for the spacecraft-dependent parameters (solar pressure, stochastic accelerations) are based on the current design, and will change as the spacecraft design evolves.

EDL DESCRIPTION

One of the major tasks for the interplanetary navigation team described earlier is to provide expected entry states and uncertainties at a defined interface point to the flight team. For MSL and most other Mars landers, the interface point is defined as a radial distance from the center of Mars of $3,522.2km$ or a reference altitude of $125km$.

The landed position error is a combination of errors from approach navigation and various sources in the Martian atmosphere. The impact of the approach navigation errors on the landed position error depends on many factors, including the characteristics of the EDL system used. For MSL, analysis has shown that errors in the initial conditions supplied to the EDL system are the largest contributor to the surface position error. Regardless of the EDL system used, there are two main approach navigation results of interest, namely delivery error and knowledge error. Both of these errors are defined at the entry interface point, but are different in the data cutoff assumed.

Delivery error is defined as the level of uncertainty relative to an absolute target. The delivery solution answers the question "How accurately can we target a specified entry point?" The navigation solution used for the delivery analysis has a data cutoff associated with a TCM and is used to design the TCM. The delivery process involves determining where the spacecraft will go without performing a TCM, then designing a TCM to target the desired entry point. The total delivery error includes expected maneuver execution errors (but does not include direct measurement of the maneuver execution, as it assumes a cutoff before the execution). The maneuver error is a significant error source that is greatly reduced with additional data after the maneuver is performed.

Knowledge error is defined as the level of uncertainty associated with the actual entry point. This answers the question "How accurately do we know the actual spacecraft entry point?" The navigation solution used for the knowledge analysis has a data cutoff placed such that as much data as can be collected and processed are used. The limit of the data collection is the time required to process the data and update the onboard state before entry interface. The knowledge uncertainly is significantly smaller than the delivery error since the final maneuver can now be solved for and data deep in the Mars gravity well (within $24hr$ of entry interface) are included in the solution. This solution is used to initialize the onboard

Table 2 Filter Setup for Late Cruise OD Analysis

Filter Parameter	*apriori* uncertainty (1σ)	Process Noise	Correlation Time	Comments
Initial Position and Velocity	$1000\,km$, $1\,\frac{km}{s}$	N/A	N/A	
Solar Pressure	5% of component area	N/A	N/A	Estimate area only
Stochastic Acceleration $(X,Y,Z)_{sc}$	$9\times10^{-12}\frac{km}{s^2}$ $9.6\times10^{-12}\frac{km}{s^2}$ $12.5\times10^{-12}\frac{km}{s^2}$	$9\times10^{-12}\frac{km}{s^2}$ $9.6\times10^{-12}\frac{km}{s^2}$ $12.5\times10^{-12}\frac{km}{s^2}$	N/A	RCS Activity and SRP mismodeling, 1 hour updates
Station Range Bias	$2\,m$ (14 RU)	$2\,m$ (14 RU)	N/A	Pass-dependent bias
Station Doppler Bias	$0.005\,\frac{mm}{s}$	$0.005\,\frac{mm}{s}$	N/A	Pass-dependent bias
Quasar Locations	$4.85\,nrad$	N/A	N/A	Considered
Opnav Centerfinding	3% Phobos 15% Deimos	N/A	N/A	Relative to Diameter
Troposphere	$1\,cm$ (wet) $1\,cm$ (dry)	$1\,cm$ (wet) $1\,cm$ (dry)	0 hours	Stochastic, 6 hour updates
Ionosphere	$3\,cm$ (day) $1\,cm$ (night)	$3\,cm$ (day) $1\,cm$ (night)	0 hours	Stochastic, 6 hour updates
Station Locations	Full covariance	N/A	N/A	Considered
Polar motion	$10\,cm$	$10\,cm$	0 hours	Stochastic, 6 hour updates
Earth rotation	$0.256\,ms$	$0.256\,ms$	0 hours	Stochastic, 6 hour updates
Ephemeris	Full covariance	N/A	N/A	Earth/Mars and Mars Satellites Est w/ optical

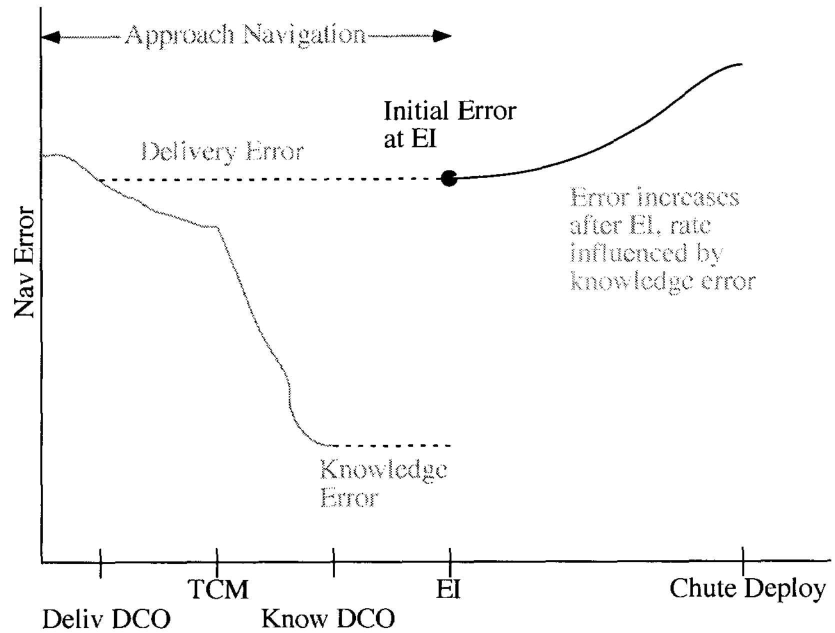

Figure 2 Error at Chute Deploy - Ballistic Case

EDL system.

The impact of the delivery and knowledge errors on the landed position error depends on the EDL system used by the lander. Total error in a relative sense for two different EDL systems are described here and shown in Figures 2 and 3. For both of these cases, the errors associated with approach navigation are the same. Approach navigation results of interest for both cases are provided at the entry interface point, as described earlier, for both delivery and knowledge solutions. The error at entry interface as a function of data cutoff time is represented for the approach navigation portion of each figure, while the error shown after entry interface is a current state error. Most Mars landers have used a ballistic entry system, where the entry body is designed to have no lift (i.e. no aerodynamic forces normal to the velocity vector). This is shown in Figure 2, where the error once the spacecraft enters the atmosphere is limited by the delivery error. The knowledge error has little impact on the overall error, as the spacecraft knowledge of it's location has little impact on the performance of the EDL system. In other words, the driving approach navigation error contribution to the total error is the delivery error. For this reason, the operations challenge for a ballistic lander is to move the final TCM and the data cutoff as close as possible to entry interface to reduce the delivery error as much as possible while maintaining adequate safety margins. The ability to execute a TCM with enough tracking to adequately reconstruct what happened and to allow the capability to perform an emergency maneuver in case of a problem (if desired or required) are the major constraints on the delivery data cutoff.

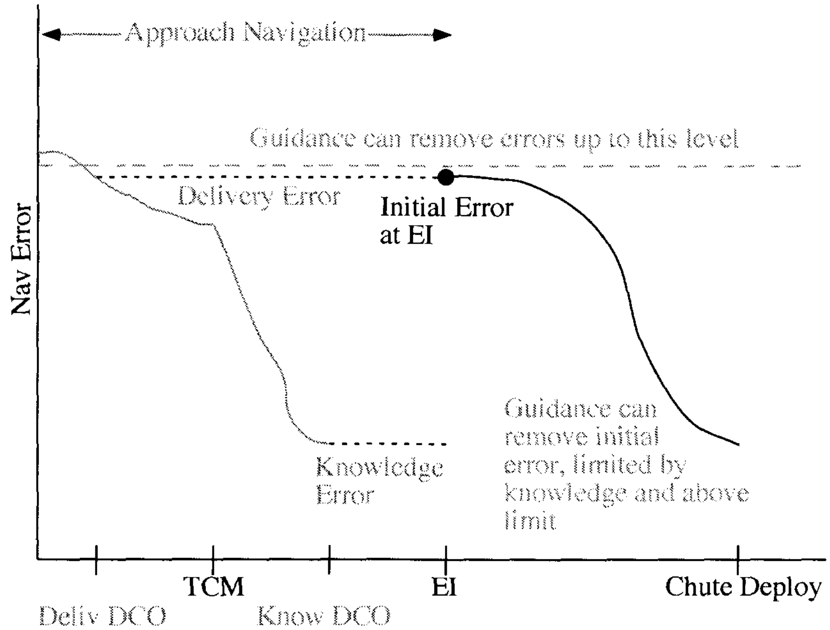

Figure 3 Error at Chute Deploy - Guided Entry Case

The EDL system proposed for MSL includes guided entry with a lifting body. The error history for this setup is shown in Figure 3. In this case, the total error after entry interface is reduced during the atmospheric flight. The closed-loop guidance system has the ability to remove the delivery errors up to a level based on the guidance system design and is a function of the total lift available, a portion of which is available to remove delivery errors once in the atmosphere. Since MSL will not have external measurements available after entry interface until close to the ground, the limit to the overall error removal by guidance is the knowledge error as determined by approach navigation. The knowledge solution includes the best estimate of the error available to the onboard system and guidance can only remove errors that the system is aware of. The situation depicted in Figure 3 is the desired design, where the delivery error is within the limit of error that can be removed by guidance. The plan is to design the guidance and the approach navigation scenario together such that the delivery error is smaller than the error that can be removed by the guidance system. Unlike the ballistic case, the approach navigation contribution to the error, assuming the delivery error is within the guidance limit, is the knowledge error. The final maneuver need only be close enough to entry interface to ensure the delivery error is below the specified level. From an operations perspective, the challenge is to move the data cutoff for the knowledge update as close to entry interface as possible to reduce the knowledge error. In this case, the main constraint is on the knowledge solution and depends on how quickly data can be collected and processed successfully and a state update prepared and transmitted to the spacecraft before entry interface.

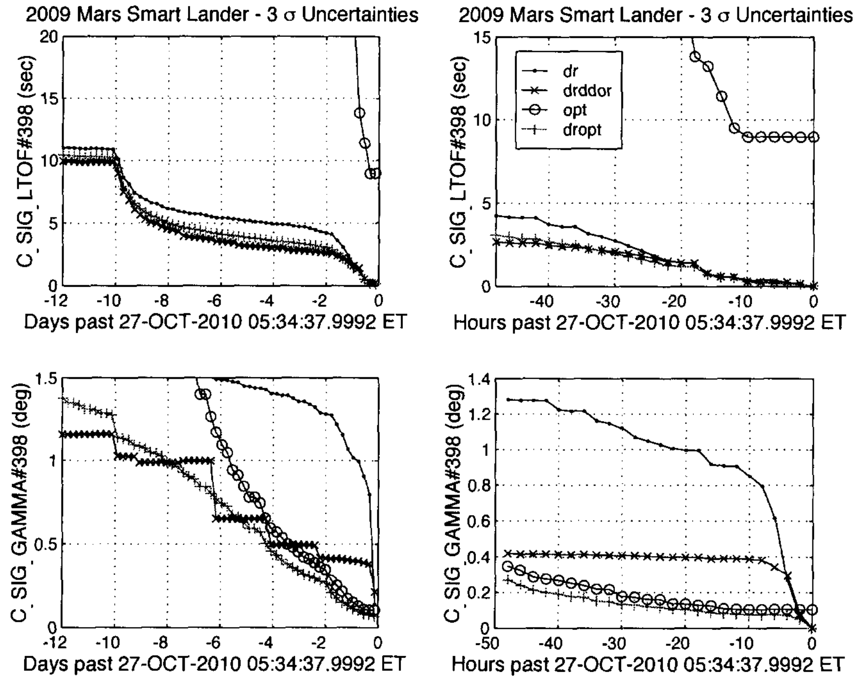

Figure 4 October 27, 2010 History Plots

RESULTS

The first trajectory investigated was the October 27, 2010 arrival case. Analysis for the data combinations described earlier were performed and entry interface errors as a function of data cutoff were generated. These errors are plotted as a function of time for this case in Figure 4. The main parameter used to describe the performance of a particular approach navigation solution is entry flight path angle (EFPA or GAMMA in the plot) error. This is plotted along with linearized time of flight (LTOF) error, which is the error in the time of arrival at the target point. Data for the Doppler and range case (abbreviated "dr"), the Doppler, range and ΔDOR case (drddor), Doppler, range and optical case (dropt) and optical data only (opt) are plotted as a function of time. The main purpose for including the LTOF results is to emphasize the limitation of optical data alone, that is the poor determination of position along the camera boresight or the LTOF. All the other data combinations have Doppler and range data and have similar performance since the Doppler and range data measure the LTOF component well. This explains why an optical-only onboard navigation system designed like this optical system cannot be used for this entry problem.

Recall that for a guided-entry system one of the main parameters of interest is the approach navigation delivery error that can be removed by the guidance system. Based on analysis for this case, the error limit is defined in terms of EFPA as $0.6°\ 3\sigma$. The results show quite clearly that Doppler and range data alone do not determine the EFPA to the delivery limit from guidance until $8hr$ from entry interface. The optical-only and Doppler, range and ΔDOR cases both meet this requirement approximately $4d$ from entry interface, while the Doppler, range and optical data case crosses nearly $5d$ from entry interface.

As the Doppler and range case alone has errors that do not meet the requirements, the cases with the added ΔDOR or optical data are of most interest. The results show the relative merits of both data strategies. Recall that optical data are only available within $15d$ of entry, so the results with and without optical data are the same more than 15d from entry. As optical data are added, the errors decrease steadily through the remainder of approach. The ΔDOR case is different. These data are available throughout cruise, if desired, and reduce the errors earlier in cruise, as is shown by the early histories on the left side of the plots. Note as well that ΔDOR data are available much less frequently, limited to times when the spacecraft is visible by two DSN complexes at the same time. At most, there can be only 2 ΔDOR points collected per day. The improvement in the ΔDOR case is discontinuous with long intervals with small improvement since the ΔDOR data is the limiting data type. Performance between $10d$ and $4d$ from entry interface for both cases are similar. However, once within $4d$ of entry interface, the larger data volume of optical data continues to reduce the errors significantly, while ΔDOR data collection, limited to periods of DSN overlaps, does not reduce as quickly.

For the purposes of EDL analysis, the delivery data cutoff was placed $3d$ from entry interface, assuming a final TCM execution $2d$ from entry interface. This assumes $24h$ after data cutoff to complete the navigation analysis, design the maneuver and transmit the commands to the spacecraft before the TCM is executed. Results from the four cases considered are plotted in the B-plane in Figure 5. The plot includes ellipses for the four cases along with the EFPA corridor defined by guidance shown for reference. Note that as the entry target moves North, the corridor will rotate counterclockwise relative to the entry target, but the error ellipses do not rotate as they move North. Thus, the EFPA error decreases as the target moves North although the error ellipses are essentially the same.

The plots show clearly why the Doppler and range case EFPA errors are so large. The major axis corresponds to the out-of-plane component of the error, which is poorly observed by Doppler and range data, while the minor axis aligns with the Earth line of sight. In cases where the out-of-plane component of the error dominates the error along the radial axis, the EFPA error will be large. This corresponds to cases that are nearer to the North or South pole. For this case, the maximum EFPA error results when the entry interface point is roughly $72°S$, or when the major axis is aligned along the radial direction. As the target moves North, the EFPA error eventually will meet the requirement, but the landing sites available would be limited to a much smaller latitude band than desired. The addition of ΔDOR data reduces the out-of-plane error and the major axis by nearly a factor of three, small enough for the error at this target to meet the EFPA error requirement. The added data does little to improve the minor axis, which is well defined by the Doppler and range data. The error for optical data only in the B-plane is nearly circular, which is consistent with the way the data are defined and collected. This case meets the EFPA limit, but

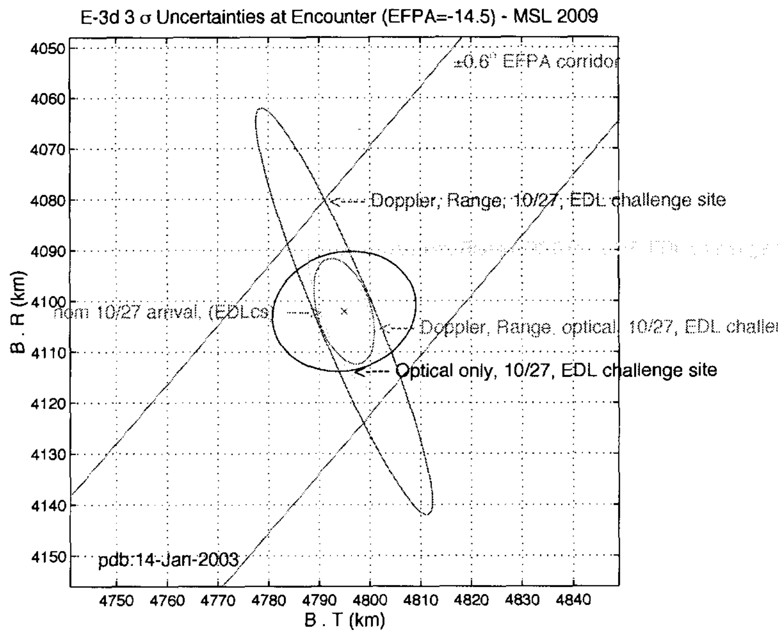

Figure 5 October 27, 2010 Delivery Results

recall the large LTOF error from earlier. Adding Doppler and range data to the optical data reduces the minor axis consistent with the other Doppler and range cases, while the major axis is limited by the opnav data. Note that, based on the defined data collection strategies and delivery cutoff, the addition of ΔDOR or optical data to the Doppler and range data improves the solution approximately the same amount.

To complete the data set needed for the EDL simulations, a knowledge case is required to initialize the spacecraft simulation. The data cutoff for this case was defined to be $18h$ from entry interface, although this cutoff will be scrutinized closely based on it's impact on the landed position error. Results for this data cutoff are shown in Figure 6. The main point to notice is the significant improvement of the Doppler, range and optical case relative to the Doppler, range and ΔDOR case, as shown earlier in the history plots. This is due to the collection of only a few ΔDOR points after the delivery cutoff, while a large volume of optical data are collected.

Results for a second trajectory, arriving on September 6, 2010, were computed as well. The errors at entry interface for the four data strategies used for the previous case as a function of data cutoff were generated and plotted in Figure 7. For this case, the LTOF errors are larger than before, while the EFPA errors are smaller. The EFPA limit of $0.6°$ defined for the previous case will be used as the criteria for defining the delivery cutoff for comparison, but it is important to note that the guidance capability for this trajectory has not been determined. As the guidance capability is a function of arrival velocity due to the use of lift for control, the EFPA error limit will most likely be different for each trajectory and entry

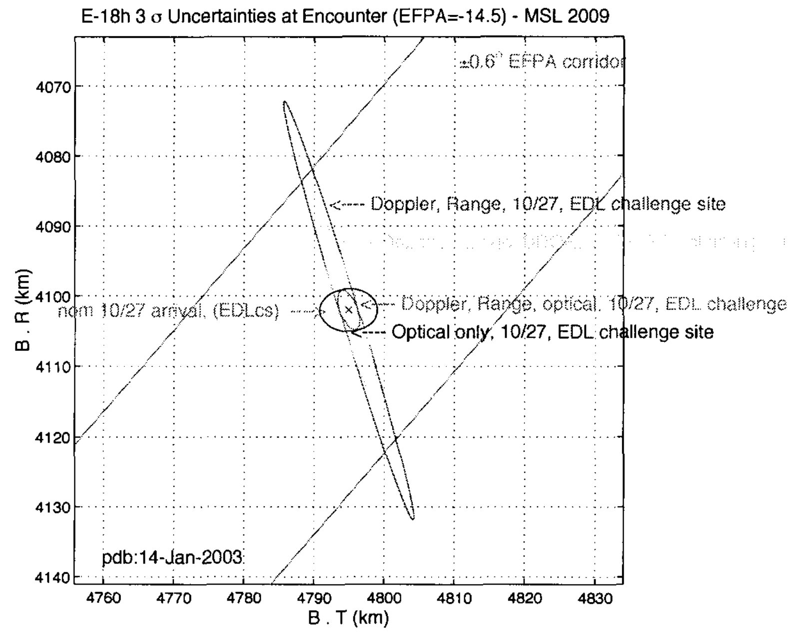

Figure 6 October 27, 2010 Knowledge Results

point studied. Using the cutoffs defined earlier, the requirements are met earlier than for the first trajectory. The Doppler, range and ΔDOR errors drop below $0.6°$ approximately $7d$ from entry interface, while the Doppler, range and optical case reaches that limit about $6d$ from entry interface. Other than these variations, the relative merits of each data type for this case are the same as for the October 27, 2010 arrival case.

The delivery and knowledge cases presented are for the same data cutoffs as before, namely $3d$ from entry interface for delivery and $18h$ from entry interface for knowledge. The delivery results are shown in Figure 8. The main difference is that the difference between adding ΔDOR or optical data to the Doppler and range data is smaller, as is the improvement over the Doppler and range case. This is most likely due to the lower arrival velocity for the September 6 case versus the October 27 case, which decreases the impact of velocity errors on the final position errors, and due to the improvement of the Doppler and range results over the October 27 results. Finally, the error for the optical-only case is smaller than in the October 27 case, consistent with the other results.

The knowledge results for the September 6 case are shown in Figure 9. The Doppler and range results are smaller than the October 27 case, consistent with the delivery case. The relative improvement by adding ΔDOR or optical data to the Doppler and range is similar to the later arrival case. This is expected, as the impact of trajectory differences is reduced as the data cutoff moves closer to the entry interface time.

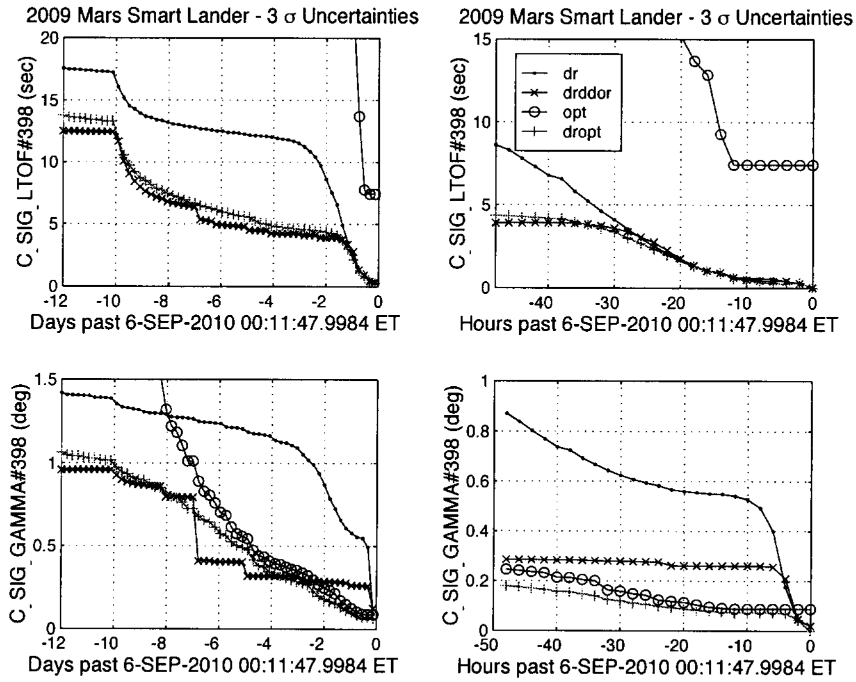

Figure 7 September 6, 2010 History Plots

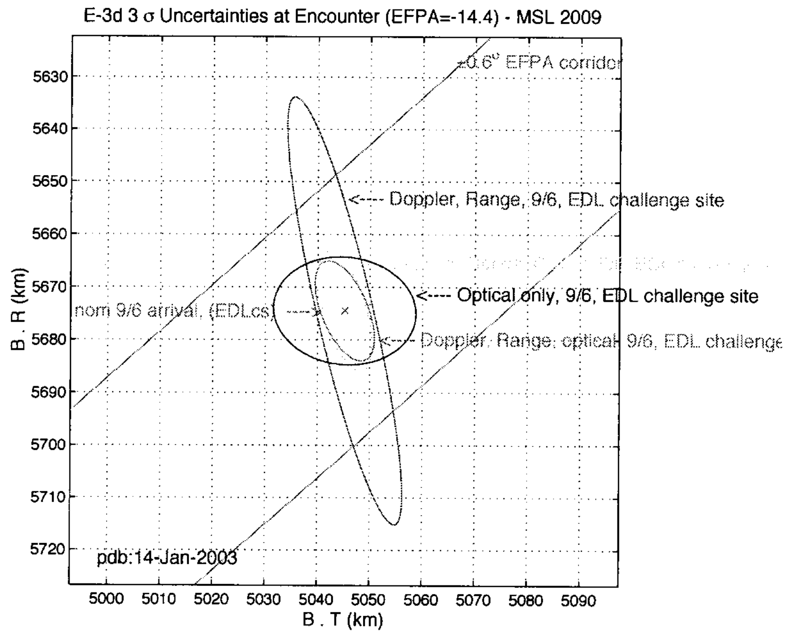

Figure 8 September 6, 2010 Delivery Results

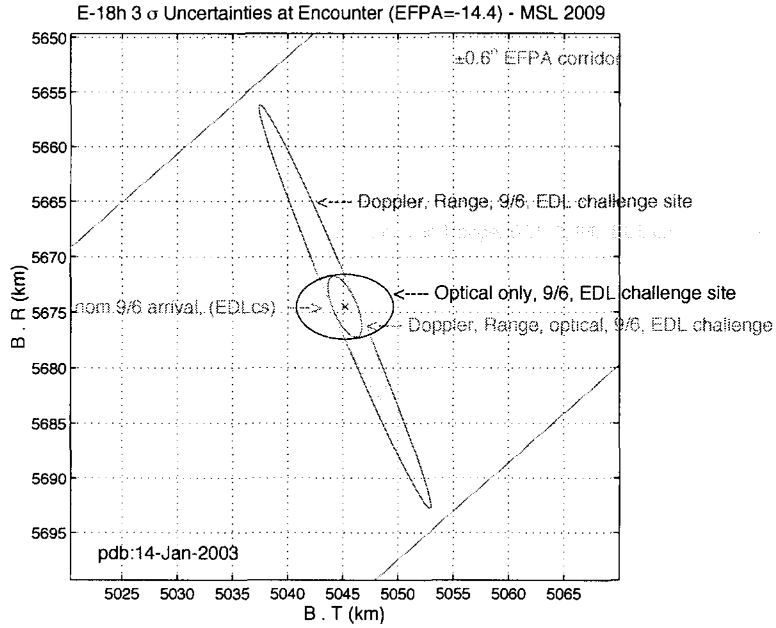

Figure 9 September 6, 2010 Knowledge Results

CONCLUSIONS AND FUTURE WORK

The main goal of this analysis was to assess the errors at entry interface based on a specific set of navigation assumptions and a reasonable TCM profile for late cruise. While these decisions are still not final, analysis has been performed to assess the performance of these assumptions relative to the requirements that are available at this stage. Doppler and range data alone do not meet the guidance limits defined. The addition of ΔDOR and optical data to the standard Doppler and range data significantly improves the errors at entry interface and produces results that can meet the requirements.

Since MSL will be using a guided entry system, the driving errors from approach navigation on the total error are the knowledge errors. Both data strategies generate results that meet the delivery limit, so there are two viable options. The addition of ΔDOR data and optical data improves the delivery errors approximately the same based on data cutoffs between $10d$ and $4d$ from entry interface. It is important to note that the knowledge requirements have not been defined clearly, so it is not clear if the to-be-defined knowledge requirement can be met with the ΔDOR case or the optical case. The extra data available in the short time from delivery cutoff to knowledge cutoff ($54h$ in this case) from the optical system as compared to ΔDOR system results in a much smaller error at knowledge cutoff with the optical data than with the ΔDOR data.

Careful analysis will be required to determine the knowledge data cutoff for operations. Due to the nearly linear improvements even to very late, there will be greater desire to move the knowledge data cutoff in as far as possible for solutions with optical data.

In addition to the above analysis, other future work includes analysis for other landing sites and arrival trajectories, analysis of the maneuver strategy to make sure it meets the requirements of the other spacecraft systems, investigation of changes in the frequency of data collection and careful scrutiny of the navigation assumptions for the spacecraft-depended parameters as the spacecraft design evolves.

ACKNOWLEDGEMENTS

Thanks to Brian Rush of the Optical navigation group for providing the optical navigation simulated data and guidance for the processing of the optical data. Thanks also to Rob Maddock and Bill Strauss for supplying the trajectories for the EDL Challenge Site cases investigated and the MER navigation team for supplying details of their navigation process to use as the basis for the MSL analysis

The work described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

REFERENCES

1. "Mars Exploration Rover (MER) Project Navigation Plan," JPL D-19660, February 20, 2002.

2. Rush, B., Bhaskaran, S., and Synnott, S.P. 2002, "Improving Mars Approach Navigation Using Optical Data," *Advances in the Astronautical Sciences*, Vol. 109, P. 1651. AAS/AIAA Astrodynamics Conference, Jul. 30 to Aug. 2, 2001, Quebec City, Quebec, Canada, 2001, eds. David B. Spencer, Calina C. Seybold, Arun K. Misra, Ronald J. Lisowski

3. Lockwood, M.K et. al., "Entry Configurations and Performance Comparisons for the Mars Smart Lander," AIAA Atmospheric Flight Mechanics Conference and Exhibit, paper AIAA 2002-4407, 5-8 August 2002, Monterey, California.

4. Mendeck, G. F. and Carman, G. L., "Guidance Design for Mars Smart Lander Using the Entry Terminal Point Controller," AIAA Atmospheric Flight Mechanics Conference and Exhibit, paper AIAA 2002-4502, 5-8 August 2002, Monterey, California.