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NAVIGATION FOR THE MARS PREMIER NETLANDER DELIVERY

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Abstract

A challenging phase of the MARS PREMIER mission is the release of four Netlanders to the Martian soil. From a navigation point of view, this deployment requires a highly accurate Netlander trajectory entry, which is difficult to obtain with traditional Doppler and ranging radio measurements. This paper presents covariance and propulsive maneuver analyses performed to determine the impact on navigation performance of parameters such as: the addition of ΔDOR measurements, tracking data schedule, and maneuver execution errors. Conclusions are drawn for navigation needs and an assessment is made of the robustness of navigation performance for the Netlander deployment phase.

INTRODUCTION

Initially planned for launches in 2003 and 2005, the Mars Sample Return (MSR) mission will be re-scheduled in the next decade to bring back Martian samples to the Earth. Meanwhile, the risk associated with the most innovative technologies will be lowered through ground tests, flight tests on (or around) the Earth, and flight tests around Mars using real equipment. The 2007 Orbiter mission (MARS PREMIER) will be a major step of this preparation. In addition to the first remote automated rendezvous around Mars, it will deploy a network of four geophysical Martian stations (so-called Netlanders) and relay their data to the Earth. A complementary mission to accommodate science experiments on the orbiter is also being studied.

From a navigation point of view, the Netlander deployment sequence is a critical phase of the mission. As the Netlanders do not have any propulsion capability, each probe is delivered by the Orbiter directly on its entry trajectory. This means that all the Netlander approach maneuvers (the main targeting maneuvers toward the desired aim points and the trim maneuvers to correct the targeting maneuver errors) are performed by the Orbiter before each Netlander release. The navigation challenge of this deployment is driven by the entry accuracy requirement for the Netlanders, which are targeted to sites on the Martian surface within a +/- 3° (3σ) entry corridor and with only about four days of tracking available between each successive Netlander release. Moreover, unlike the Orbiter, whose physical characteristics can be estimated during the cruise phase, the Netlander behavior after release from the Orbiter with respect to solar radiation pressure and non-gravitational accelerations is difficult to estimate and will lead to large uncertainties.

In order to assess the delivery accuracy of the Netlanders and the Orbiter, a covariance analysis of this deployment sequence has been performed using conservative maneuver execution error assumptions. The baseline for this study considers range and Doppler measurements through DSN (Deep Space Network) facilities. The main objectives of this analysis were:

- to check the feasibility of this phase with only Range and Doppler data, and to evaluate the improvement of navigation performance due to additional Delta Differential One-way Range (ΔDOR) measurements,
- to estimate the robustness of navigation performance with respect to error sources.

To meet these objectives, some sensitivity analyses have been done jointly by CNES and JPL concerning the impact of the ΔDOR schedule, the influence of ground station tracking coverage, maneuver execution errors, dynamic stochastic accelerations, and other error sources. Results from JPL and CNES covariance analysis tools have been compared and combined to evaluate the robustness of the Netlander delivery navigation performance.

A propulsive maneuver analysis using orbit determination results and Monte-Carlo simulations to compute statistical maneuvers has also been performed to assess navigation performance corresponding to expected maneuver execution errors assumptions.

Conclusions on the robustness of navigation performance and on navigation needs (ΔDOR, tracking coverage, etc.) with respect to the Netlander entry accuracy have been drawn based on this analysis.

MARS PREMIER MISSION OVERVIEW

A complete overview of MARS PREMIER mission is described in REF[1]. For the present study we will focus on the end of the interplanetary phase concerning the Netlander's deployment. During the cruise phase a set of four Trajectory Correction Maneuvers (TCMs) will adjust the interplanetary trajectory to ensure that the spacecraft reaches the proper velocity and position targets prior to Netlander deployment. TCM4 targets the first Netlander entry point and is followed by a set of maneuvers (MTM : Main Targeting Maneuvers and TTM : Trim Targeting Maneuvers) in order to target the orbiter on the proper trajectory before separating each Netlander probe. When the last Netlander is separated, the spacecraft begins a sequence of three maneuvers (1 main maneuver and 2 trim maneuvers) to target the MOI aim-point. Due to Planetary protection constraints and considering a realistic Orbiter failure probability during the approach phase, the TCM4 maneuver has been scheduled not to happen before MOI -38 days. After this TCM4 maneuver, the Orbiter is assumed to be on a Mars entry trajectory. In other words, the TCM4 maneuver has been merged with the first Netlander main maneuver targeting the first Netlander entry point. The two following figures present the Netlander delivery sequence as well as the approach phase sequence considering the earliest and latest planned dates for Netlander release.

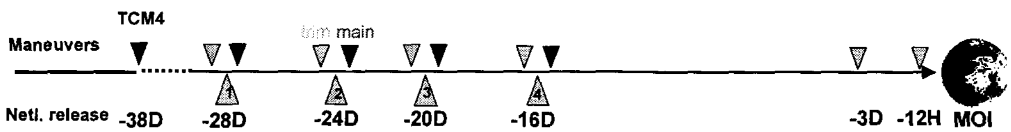

Figure 1 **Nominal delivery sequence (earliest dates)**

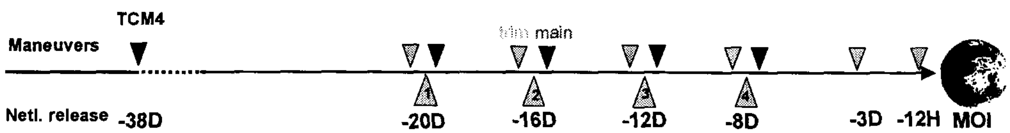

Figure 2 **Backup delivery sequence (latest dates)**

As each Netlander is targeted to a different site on the Martian surface, each requires a different entry point and entry date. Before each Netlander release, main and trim maneuvers are performed in order to target the Netlander's entry point. The main maneuver is performed 2 hours after the release of the previous Netlander. Almost 4 days are dedicated to full-time orbit determination, maneuver computation, and data upload to the Orbiter. The trim maneuver is necessary in order to clean up the errors in the trajectory due mainly to the previous main maneuver execution error. Once the last Netlander has been released (between MOI-16 days and MOI-8 days), the Orbiter has to target the insertion orbit periapsis and inclination. This targeting is performed by a main maneuver just after the release of the last Netlander, then by a trim maneuver (performed if necessary, depending on orbit determination solution) at MOI - 4 or 3 days and at MOI - 24 or 12 hours.

The Netlanders are released from the Orbiter with a relative velocity of 0.4 m/s and a spin rate of about 6.5 RPM for stability during the free-flying coast phase. The release direction is to be such that the Angle of Attack at atmosphere entry is 0. This coast phase (free-flying phase) duration ranges from 8 to 28 days. At the end of the coast phase, the Netlanders enter the Martian atmosphere at given Entry Interface Points (EIP) corresponding to landing sites. Targeted relative Entry Flight Path Angles (FPA) at atmosphere interface radius (3522.2km) are to be in a [-18°, -16°] range with an accuracy of +/- 3° at 3σ.

Once the Netlanders enter Mars' atmosphere, they follow a ballistic trajectory down to the opening of a pilot chute at about Mach 1.5. They then open a main parachute before landing on Mars' surface using airbags.

		Open period	Close period	
Maneuvers	**Dates**	**Delta V (m/s)**	**Delta V (m/s)**	release (m/s)
TCM4 (99%)	MOI-38D	1	0.8	
TTM1(99%)	MOI -28D -2H	statistical	statistical	
release Net1	MOI -28D			0.4
MTM2	MOI -28D +2H	5.9	5.6	
TTM2 (99%)	MOI -24D -2H	statistical	statistical	
release Net2	MOI -24D			0.4
MTM3	MOI -24D +2H	8.9	9.9	
TTM3 (99%)	MOI -20D -2H	statistical	statistical	
release Net3	MOI -20D			0.4
MTM4	MOI -20D +2H	1.2	1.4	
TTM4 (99%)	MOI -16D -2H	statistical	statistical	
release Net4	MOI -16D			0.4
Total Netlander main maneuvers		17	17.7	

MTM: Main Targeting Maneuver

TTM: Trim Targeting Maneuver

Table 1 Netlander deployment maneuvers (nominal sequence)

Just after the last Netlander release, a maneuver is performed to target the orbiter to the insertion trajectory. This insertion trajectory will be a hyperbola whose fly-by periapsis is 600 km and whose inclination may vary depending on arrival date. Two trim maneuvers planned at MOI -3 days and MOI-12h00 will be executed if needed to correct the trajectory. Each maneuver's size and direction will be based on the orbit determination (OD) solution computed about 12h00 earlier.

NAVIGATION CHALLENGE

The first aim of the Mars approach phase is to release the 4 Netlanders. Netlander delivery requires accurate orbit determination, mainly because of the stringent maneuver sequence which allows only 4 days for full-time orbit determination, maneuver computation and data upload to the Orbiter.

The first difficulty comes from the OD process itself. With range and range rate observables only, there is a well known lack of observability in the plane of sky (perpendicular to the line of sight). Consequently, the OD covariance matrix components corresponding to these directions remain quite big after each targeting maneuver performed by the orbiter during the approach phase, even after 3 days of continuous tracking. This leads to delivery ellipses in the B-plane (see Figure 3) with large Semi-Major-Axes (SMAA), the SMAA orientation corresponding roughly to the directions that are difficult to be observed by range and range rate measurements (particularly the out of plane component). Moreover, the FPA (γ) is directly linked to the B-Vector magnitude (see Figure 4), so that a large uncertainty on the B vector implies a large error on FPA. Consequently there are areas in the B-plane that will provide better accuracy in the FPA than others. These regions are those where the B-vector is roughly along the Semi-Minor Axis (SMIA) of the delivery ellipses.

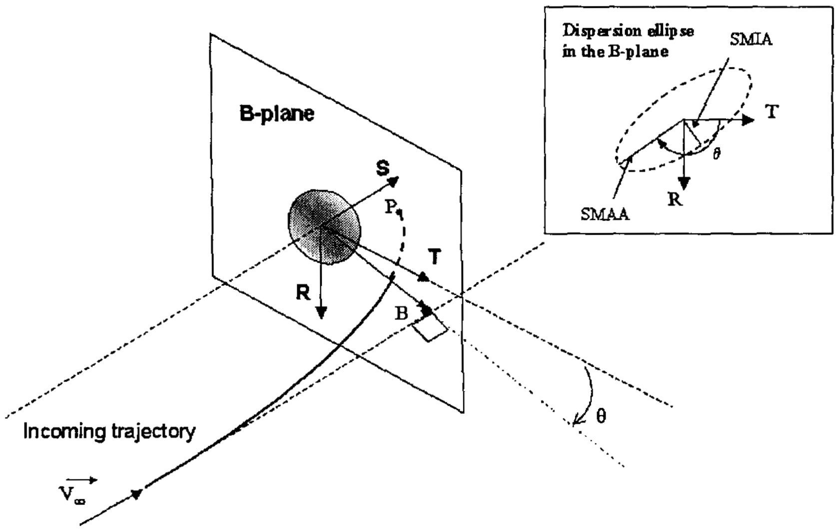

Figure 3 The B-plane coordinate system

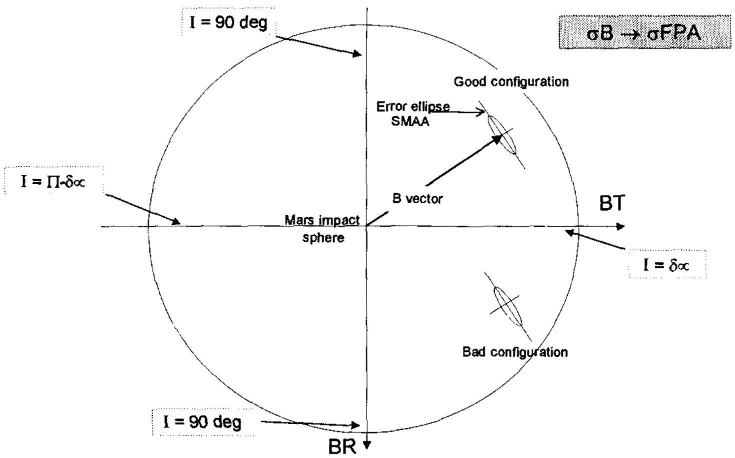

Figure 4 Impact of delivery ellipses on B-vector magnitude

Moreover, if the size of ellipses is supposed to be reduced due to additional measurement types such as ΔDOR, spacecraft-to-spacecraft, or even optical data, there is still a minimal size that can not be absorbed by the OD process and which is due to the propagation of some kinds of errors from the release time to the entry in Martian atmosphere. In the case of Netlanders, this minimal uncertainty has three main causes :

- For each Netlander, the data cutoff is set one day before the release in order to compute and upload the trim maneuver. Therefore, the trim maneuver execution error and the error due to the separation mechanism which occur after this data cutoff are directly propagated into the B-plane and give a minimal error which does not depend on the OD process.

- During the cruise phase, the thermal surface properties of the cruise stage, and thus of the orbiter, can be well estimated, which is not the case for the Netlanders. The way the Netlanders are stored on the cruise stage (see Figure 5) does not allow determination of their properties. Moreover, each Netlander is not similarly exposed to solar radiation and thus does not suffer the same ageing of its materials. This uncertainty on the thermal properties leads to a big error in the solar radiation pressure (SRP) during the coast phase. The main difficulty here is to estimate an order of magnitude of this error.

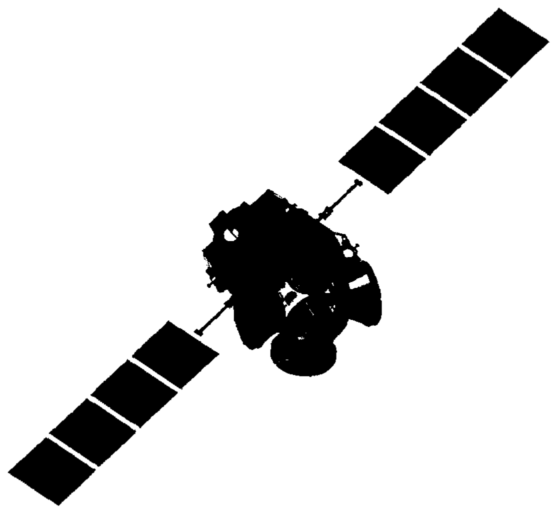

Figure 5 Netlander's location on the cruise stage

- Similarly to the thermal properties, the cruise phase does not allow estimation of the unmodelled forces acting on the Netlanders, which could also have a great impact during the coast phase. However, as the Netlanders can not have gas leaks, which are the main contributor to non gravitational accelerations, these forces are expected to be unimportant.

The impact of these errors are even more important for the Netlanders compared to a classical lander because of the length of the coast phase, which could be 28 days long. For example, a spherical maneuver execution error of 10 mm/s per axis (for 2% errors on a 0.5m/s maneuver) at MOI -8days gives roughly a 7 km circle in the B-plane, while the same error at MOI -28 days gives a 24 km uncertainty.

COVARIANCE ANALYSIS

A covariance analysis has been performed in order to assess the sensitivity of the navigation performance during the Netlander deployment phase to tracking schedule, error sources, and deployment sequence. The baseline trajectory used for these studies is the launch window closing date reference trajectory (see REF[1]) and analyses have been performed on both nominal and backup deployment scenarios.

Error assumptions

The following table details the baseline set of error assumptions considered for this study. As this analysis is dedicated to the Netlander deployment phase, the epoch state has been considered to be MOI-38days (that is to say TCM4) and a huge initial error has been applied. This assumption is not restrictive because this initial error is well absorbed by the filter, and this does not disturb the sensitivity study. Concerning solar radiation pressure uncertainty, a conservative value of 50% error has been considered for the Netlanders. As this value is quite large and washes over every other error source along the line of sight, a smaller figure of 5% has also been used in the computations. It should also be noticed that the maneuvers have been modeled as impulsive burns (rather than finite ones).

Error sources	E=Estimated, C=Considered, S=Stochastic	1 Sigma a priori uncertainties	Comments
Measurements types			
Doppler		0.075 mm/s	data every 5 minutes;
Range		3 m	data every 10 minutes
ΔDOR		0.12 nsec	equivalent to 4.5 nrad
Epoch State		M-38 days	
Position	E	1000 km	
Velocity	E	1 km/s	
Range bias	E	2 m	estimated per pass
Doppler bias	E	0.005 mm/s	estimated per pass
Quasar locations	C	4.85 nrad	considered
Earth Ephemerides	C	DE405+	
Earth GM	C	0.05 km^3/s^2	
Moon GM	C	0.001215 km^3/s^2	
Mars GM	C	0.0512 km^3/s^2	
Station location	C	3 cm	spherical error
Ionosphere - night / day	S	1cm / 4cm (X band), 15cm / 55cm (S band)	update time = 6 hours / correlation time = 0
Troposphere - wet / dry	S	1 cm / 1 cm	
Polar motion	S	10 cm	
UT1	S	10 cm / 0.256 ms	
Solar Pressure (area)	E	5% (Orbiter)	30 m^2 equivalent area
	C	50% (Netlander)	Keep area/mass = const (approx 1/80)
Non gravitational accelerations	S	2.0×10^{-12} km/s^2 (Orbiter)	update time = 1 day / correlation time = 0,
	C	2.0×10^{-12} km/s^2 (Netlander)	Constant assumed for runout
Desats	E	2 mm/s	Spherical covariance Every 5 days from MOI-38d to Net1 release , simultaneous with trim maneuvers from Net1 release to MOI
Maneuvers execution errors	E	ΔV > 1 m/s 0.333 % (prop. magnitude) 0.2 ° (prop. pointing) ΔV < 1 m/s 3.333 mm/s (fixed magnitude) 0.2 ° (prop. pointing)	Conservative values. Assume NetLander statistical trim maneuvers are 0.5 m/s with 2% error per axis (3 sigma).
Netlander separation errors	E	3.333 mm/s	per axis

Table 2 Baseline error assumptions

Tracking Schedule

Ten days of continuous tracking by the Deep Space Network (Goldstone, Canberra, Madrid) have been assumed with a 20° minimum elevation angle. In the case of the backup scenario (latest dates) a complementary tracking schedule of 3x8 hour passes per week from MOI -38 days to MOI -30 days has been considered. This schedule concerns Range and Doppler data (whose noise and frequency are given in Table 2) only. In order to assess the improvement due to additional data types, cases with ΔDOR have also been performed. Two points per week from MOI-38days to Netlander 1 release (that is to say MOI-28days for the nominal scenario and MOI-20days for the backup one), and then one point every other day between each Netlander release have been assumed, alternating North/South and East/West baselines. Moreover, in order to take into account the operational processing of ΔDOR (i.e. one-way transmit mode), range and Doppler data (i.e. two ways tracking data) have been suppressed 2 hours around each ΔDOR point.

CNES/JPL comparison study

The first step of this joint study was to compare CNES and JPL covariance analysis results through test cases to ensure that differences in the independent techniques would not effect further study. The software used by CNES (EPERON_IP) is exclusively dedicated to pure covariance analysis, whereas the JPL software (ODP) is a complete covariance analysis and operational orbit determination tool. Differences are essentially in the models used to characterize the sensitivity to error sources. In the framework of a pure covariance analysis, it is not necessary to have detailed and complete models because there is no need to fit a trajectory using real data. The aim is just to have a rough estimation of the sensitivity of these data to the main error sources. The main purpose of this comparison study was to check that both software packages considered consistent models and that these models produced consistent results.

The following tables detail the comparison study for Netlander 1, with and without ΔDOR. These results are based on the backup scenario (latest dates) and on the launch window closing date trajectory. The first conclusion that can be drawn from these results is the consistency between CNES and JPL results. Most differences are insignificant and those with larger differences can be explained by the model input assumptions. For example, in Table 4, the slight discrepancy in the quasar uncertainty impact comes from the fact that JPL considers the exact quasar right ascension and declination errors whereas CNES uses a single angular error in the plane formed by the baseline and the probe. Moreover, the CNES covariance analysis tool does not yet take into account GM errors that are included in the JPL software, but the corresponding uncertainties have been shown to be negligible. These results have been considered to be close enough according to the purpose of this study. Moreover, this comparison campaign has been completed for the remaining Netlanders (that is to say Netlanders 2 to 4), also giving satisfactory results.

Another important objective of this first step was to identify the main error sources acting during this phase of the mission. Some of these error sources and their impacts on OD accuracy were well known, however some specifics of the Netlander mission lead to unexpected behavior. The main peculiarity of this phase is the bad characterization of the properties of each Netlander, leading to big uncertainties on the impact of solar radiation pressure and other unmodelled forces.

This detailed analysis also allows identification of the main contributors:

- A 50% error on the SRP coefficient induces a big increase of the error ellipse. However, even a 5% error has a non negligible impact on the SMIA of the error ellipse. This can be explained by the relative geometry between the Earth, Sun, probe and Mars. The SMIA corresponds roughly to the line of sight, that is to say the Earth-probe direction, and is the best-observed direction for range and Doppler data. Moreover during this phase, the Earth and Mars are not far from solar conjunction, meaning that the Sun-Mars line is not far from the Earth-Mars line. As the probe is close to Mars, this implies a line of sight close to the Sun-probe line that is the main direction for solar radiation pressure. Thus, in this case an error on the solar radiation force impacts mainly the SMIA of the error ellipse. Moreover, the solar pressure effect in effect during a Netlander's coast arc is independent from the OD process. This explains also why in the case with ΔDOR and 50% SRP error, we can observe a rotation of the ellipse. The SMAA is strongly reduced, but the SMIA remains quite constant, thus becoming bigger than the SMAA.
- A similar effect can be observed concerning stochastic (non-gravitational) accelerations. In this case, the a priori error is spherical and thus applies in all directions (that is to say on the SMAA and SMIA), and its effects are lower than in the 50% SRP case. As these unmodelled forces apply during the coast arc, they are not absorbed by the OD process and so induce a constant error even in the case with additional ΔDOR data.
- The main contributors with respect to the SMIA (except the 50% SRP error) are the maneuver execution errors, which include the trim execution error and the uncertainty due to the separation mechanism. In this case, a spherical 1-sigma uncertainty of 4.7 mm/s is propagated over 20 days, which gives roughly 8 km in the B-plane.

These three error sources are the most important in our study because they can not be reduced by the addition of ΔDOR data, which is the case for all other error sources. Some sensitivity studies have been performed to assess the robustness of the four Netlanders' navigation performance to these main error sources, as well as to other parameters such as the tracking schedule, the deployment scenario and the trajectory. Some cases have been performed on the nominal sequence and others on the backup, to assess the impact of the separation beginning date.

Doppler, Range (no DDOR)	SMAA (km)		SMIA (km)		theta (deg)		sigLTF (s)	
	JPL	CNES	JPL	CNES	JPL	CNES	JPL	CNES
Epoch State	10.53	10.06	0.0048	0.0049	59.23	59.33	3.25	3.17
+ solar radiation pressure -- 5%	16.06	14.94	1.582	1.360	59.98	60.00	5.52	5.19
+ solar radiation pressure -- 50%	17.12	15.54	14.719	13.000	216.11	214.24	5.64	5.28
+ AMDS (desats)	15.49	15.26	0.018	0.020	59.18	59.28	4.70	4.68
+ maneuvers	13.33	12.99	8.310	8.230	58.97	58.94	4.32	4.26
+ Planetary ephemeris	11.17	10.07	0.160	0.110	59.19	59.32	3.33	3.17
+ Station location	10.76	10.46	0.005	0.058	59.22	59.32	3.33	3.30
+ Earth, Moon, Mars GM values	10.66		0.017		59.24		3.29	
+ Range Bias	18.39	18.44	0.0079	0.0091	59.20	59.31	5.56	5.60
+ Doppler Bias	14.08	13.61	0.0054	0.0059	59.23	59.45	4.22	4.13
+ Range and Doppler Biases	23.00	23.63	0.0110	0.0120	59.21	59.31	6.88	7.12
+ Polar Motion	12.14	11.75	0.0050	0.0055	59.23	59.33	3.71	3.65
+ UT1	14.42	13.83	0.0050	0.0061	59.23	59.33	4.31	4.19
+ Polar motion and UT1	15.26	14.70	0.0056	0.0064	59.23	59.33	4.55	4.45
+ Troposphere	10.58	10.11	0.0049	0.0049	59.23	59.33	3.27	3.19
+ Ionosphere	10.60	10.15	0.0049	0.0050	59.23	59.33	3.28	3.20
+ Troposphere and Ionosphere	10.65	10.20	0.0049	0.0050	59.23	59.33	3.30	3.22
+ Stochastic accelerations	17.41	16.68	3.170	3.110	59.97	60.10	6.30	6.13
+ all errors (except stoch. Acc. and GMs) -- SRP 5%	38.76	41.50	8.530	8.430	59.48	59.54	12.85	13.71
+ all errors (except GMs) -- SRP 5%	44.99	46.16	9.148	9.008	59.54	59.59	14.85	15.32
+ all errors (except GMs) -- SRP 50%	45.07	46.22	18.051	16.158	58.23	58.67	14.89	15.36

Table 3 Netlander 1 comparison study - range and Doppler only

Doppler, Range, DDOR	SMAA (km)		SMIA (km)		theta (deg)		sigLTF (s)	
	JPL	CNES	JPL	CNES	JPL	CNES	JPL	CNES
Epoch State	3.58	3.52	0.0039	0.0044	59.22	59.33	1.17	1.15
+ solar radiation pressure -- 5%	3.67	3.60	1.58	1.36	57.93	58.51	1.44	1.42
+ solar radiation pressure -- 50%	15.88	13.70	3.61	3.548	159.14	159.67	1.84	1.72
+ AMDS (desats)	4.91	4.99	0.018	0.002	59.18	59.28	1.53	1.55
+ maneuvers	8.92	8.93	8.31	8.23	56.62	56.08	3.07	3.07
+ Planetary ephemeris	4.37	3.55	0.16	0.11	59.16	59.26	1.42	1.16
+ Station location	3.61	0.55	0.0040	0.0045	59.22	59.33	1.19	1.18
+ Quasar Positions	6.05	3.55	0.0041	0.0057	59.22	59.33	1.81	1.46
+ Earth, Moon, Mars GM values	3.58		0.016		59.23		1.17	
+ Range Bias	3.73	3.68	0.0064	0.0070	59.20	59.31	1.23	1.21
+ Doppler Bias	3.67	3.61	0.0044	0.0049	59.23	59.33	1.21	1.19
+ Range and Doppler Biases	3.76	3.70	0.0096	0.0100	59.21	59.31	1.24	1.22
+ Polar Motion	3.67	3.57	0.0042	0.0047	59.22	59.33	1.21	1.18
+ UT1	3.67	3.61	0.0044	0.0050	59.23	59.33	1.21	1.19
+ Polar motion and UT1	3.73	3.63	0.0045	0.0051	59.23	59.33	1.23	1.20
+ Troposphere	3.58	3.51	0.0039	0.0044	59.22	59.33	1.17	1.15
+ Ionosphere	3.86	3.52	0.0040	0.0045	59.22	59.33	1.26	1.16
+ troposphere and Ionosphere	3.86	3.52	0.0040	0.0045	59.22	59.33	1.26	1.16
+ Stochastic accelerations	4.89	4.83	3.14	3.08	57.17	57.14	2.42	2.41
+ all errors (except stoch. Acc. and GMs) -- SRP 5%	11.76	9.71	8.50	8.39	56.57	55.61	4.49	4.30
+ all errors (except GMs) -- SRP 5%	12.36	10.40	9.09	8.93	55.49	53.62	4.84	4.66
+ all errors (except stoch. Acc. and GMs) -- SRP 50%	18.36	16.35	12.16	10.29	163.38	161.61	4.97	4.76

Table 4 Netlander 1 comparison study - range, Doppler and ΔDOR

Sensitivity study for the nominal scenario

Table 6 and Table 7 show the results obtained for the nominal scenario in some sensitivity cases:

- The baseline case corresponds to the nominal scenario (earliest dates, close launch trajectory), with the baseline error assumptions detailed in Table 2 and Doppler and range data only. The main conclusion in this case is that with a 50% SRP error, the +/-3° (3-sigma) uncertainty requirement on entry FPA is not fulfilled for Netlander 1. However, this is a worst case and the performance is not so bad considering the conservative assumptions used. The second important point to be drawn from this case is the fact that Netlander 1 appears to be the worst case for navigation performance. This is mainly due to the long coast arc (28 days), but this means also that the main maneuvers applied for the following Netlanders (see Table 1) are quite well estimated during the following 3 days of OD.
- The ΔDOR case differs from the baseline by the addition of ΔDOR data as described previously. These additional measurements have a great impact on the SMAA for all Netlanders, however as explained previously the SMIA error values are mostly due to the propagation of errors occurring after the data cutoff and thus can not be reduced by additional data types.
- The 5-day sequence case considers the following Netlander deployment sequence (see Figure 6) where 5 days of OD are scheduled between each successive Netlander release. This alternative sequence of

course impacts only Netlanders 2 to 4, while Netlander 1 performance remains unchanged. The addition of 1 day of DSN tracking allows a slight reduction in the SMAA of the error ellipses. The decrease of the SMIA is mainly due to the decrease of the coast arc length.

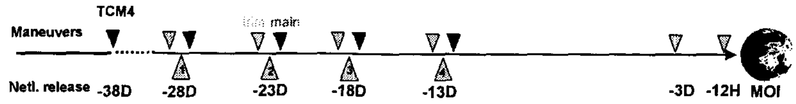

Figure 6 Nominal 5-day deployment sequence

- A case has been performed considering the open launch trajectory in order to compare the influence of the trajectory on navigation performance. The results show an important decrease of the SMAA (especially for Netlander 1) and a slight increase of the SMIA, the orientation of the ellipses remaining quite constant. This can be explained by the comparison of geometry of the two trajectories. Figure 7 shows the evolution of the declination of both trajectories with respect to Earth's equator during the Netlander deployment phases. It can then be noticed that the declination is lower for the close launch trajectory, inducing a degradation of the navigation performance due to the well-known zero declination singularity for range and Doppler data. In order to validate this point, a test case has also been performed using a fictitious trajectory with a near zero declination at TCM4 giving thus a SMAA of roughly 115km for Netlander 1. The slight increase of the SMIA is probably due to the change in the Earth/probe/Mars (or Earth/probe/B-plane) geometry. Indeed as deduced from Figure 7 for the close launch trajectory, the projection of the line-of-sight (that is to say the well observable Earth-probe line) into the B-plane is less disturbed by errors coming from other less observable directions and is so quite directly changed into the SMIA of the error ellipse. For the open launch trajectory, the SMIA instead contains more contribution from less observable directions due to this projection.

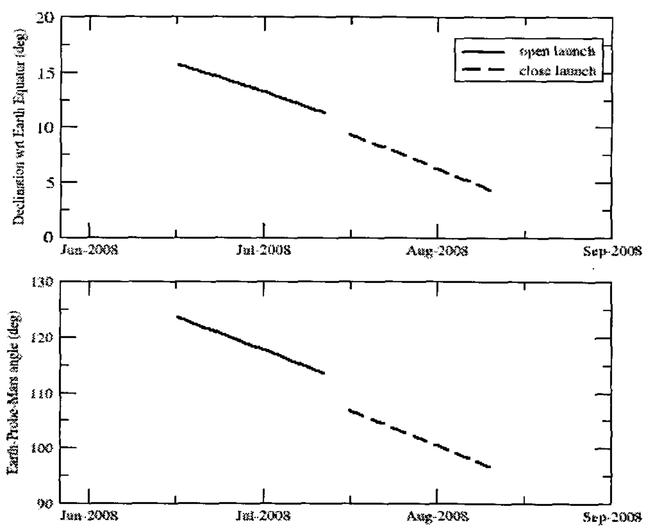

Figure 7 Comparison of open launch and close launch trajectories

- A sensitivity to the maneuver execution errors has also been computed. In this case, the considered uncertainties were those expected to be obtained by the Orbiter instead of the conservative ones, and the trim maneuvers have been computed statistically (see Table 14). As expected, this has no change on Netlander 1 results and reduces significantly the Netlander 2 to 4 uncertainties. This is mostly due to the decrease of the trim execution errors propagated during the coast arc.

ΔV > 1 m/s 0.2 % (prop. magnitude) 0.1 ° (prop. pointing)
ΔV < 1 m/s 2 mm/s (fixed magnitude) 0.1 ° (prop. pointing)

Table 5 Expected maneuver execution errors (1σ)

		SMAA (km)	SMIA (km)	theta (deg)	sigLTF (s)	FPA(deg)
Netlander 1	Baseline	84.790	13.730	59.320	25.890	0.865
	DDOR	17.610	13.627	55.297	7.561	0.414
	5 days sequence	84.790	13.730	59.320	25.890	0.865
	Open launch trajectory	51.564	15.915	61.416	17.168	0.586
	Expected maneuver execution errors	84.465	11.274	59.329	25.763	0.835
Netlander 2	Baseline	56.589	11.375	59.055	17.362	0.553
	DDOR	36.113	11.345	58.492	11.512	0.414
	5 days sequence	49.402	10.737	59.132	15.475	0.494
	Open launch trajectory	43.721	11.975	61.132	14.008	0.485
	Expected maneuver execution errors	49.994	9.014	59.107	15.547	0.475
Netlander 3	Baseline	59.140	9.105	59.115	17.775	0.812
	DDOR	49.022	9.096	59.098	14.984	0.686
	5 days sequence	51.946	8.021	59.179	15.820	0.711
	Open launch trajectory	48.565	10.766	60.597	15.359	0.642
	Expected maneuver execution errors	41.481	7.147	59.029	12.928	0.577
Netlander 4	Baseline	39.657	7.009	59.178	12.337	0.331
	DDOR	14.954	7.004	58.575	5.791	0.223
	5 days sequence	30.675	5.576	59.238	9.958	0.257
	Open launch trajectory	29.565	8.254	60.685	9.714	0.282
	Expected maneuver execution errors	29.662	5.223	59.195	9.608	0.247

Table 6 Sensitivity for the nominal scenario - 5% SRP error

		SMAA (km)	SMIA (km)	theta (deg)	sigLTF (s)	FPA(deg)
Netlander 1	Baseline	84.890	30.010	58.380	25.950	1.158
	DDOR	30.356	17.419	-20.044	7.746	0.874
	5 days sequence	84.890	30.010	58.380	25.950	1.158
	Open launch trajectory	51.613	31.828	63.193	17.180	0.919
	Expected maneuver execution errors	84.564	28.975	58.391	25.818	1.136
Netlander 2	Baseline	56.691	22.600	57.773	17.413	0.734
	DDOR	36.344	22.470	53.836	11.589	0.636
	5 days sequence	49.505	20.893	57.618	15.525	0.664
	Open launch trajectory	43.736	23.618	62.006	14.013	0.696
	Expected maneuver execution errors	50.113	21.501	57.372	15.604	0.677
Netlander 3	Baseline	59.191	16.323	58.543	17.802	0.898
	DDOR	49.085	16.312	58.233	15.017	0.786
	5 days sequence	51.986	13.587	58.682	15.842	0.776
	Open launch trajectory	48.566	17.844	60.755	15.360	0.729
	Expected maneuver execution errors	41.559	15.301	57.790	12.966	0.693
Netlander 4	Baseline	39.693	11.140	58.619	12.355	0.418
	DDOR	15.123	11.033	58.306	11.692	0.340
	5 days sequence	30.697	7.985	58.815	9.969	0.308
	Open launch trajectory	29.565	12.351	60.797	9.714	0.373
	Expected maneuver execution errors	29.711	10.106	58.158	9.632	0.356

Table 7 Sensitivity for the nominal scenario - 50%SRP error

Sensitivity for the backup scenario

Table 8 to Table 12 show the results obtained for the backup scenario in some sensitivity cases:

- The baseline case corresponds to the backup scenario (latest dates, close launch trajectory), with the baseline error assumptions detailed in Table 2 and Doppler and range data only. The major difference wrt the nominal scenario is the size of the main maneuvers, that are bigger (MTM2=7.7m/s, MTM3=14.9m/s and MTM4=2.2m/s, to be compared to Table 1), which induces larger errors in the B-plane. However, compared to the nominal scenario, it can be noted that the performance is significantly improved. This is first due to the longer tracking schedule for Netlander 1 because of the delayed separation date. The second reason for this improvement comes from the decrease of the coast arc duration (8 days shorter), which allows the reduction of the effects of trim maneuver execution errors, SRP errors and unmodelled forces.

Backup scenario - Baseline case		SMAA	SMIA	theta (deg)	sigLTF (s)	sigFPA (deg)
Netlander 1	5% SRP error	44.99	9.11	59.54	14.85	0.47
	50% SPR error	45.07	18.05	58.23	14.89	0.62
Netlander 2	5% SRP error	41.82	7.18	59.80	13.62	0.39
	50% SPR error	41.85	12.77	59.15	13.64	0.46
Netlander 3	5% SRP error	48.07	5.23	58.96	14.33	0.64
	50% SPR error	48.09	8.61	58.72	14.93	0.67
Netlander 4	5% SRP error	28.26	3.41	59.35	10.17	0.21
	50% SPR error	28.27	4.63	59.21	10.18	0.23

Table 8 Backup scenario - Baseline case

- Due to the increasing number of Mars missions planned within the next decade, a limitation of the use of DSN tracking stations has to be investigated in order to assess the robustness of this phase of the mission towards a degradation of the tracking schedule. Thus, some cases have been performed assuming the loss of one or more tracking stations (see Table 9). It appears that the loss of any DSN station has mostly the same impact for the Doppler- and range-only tracking schedule (each station brings essentially the same amount of information). However in the ΔDOR case, Goldstone is of course the most important DSS because it belongs to both baselines. Moreover, the relative impact of Canberra or Madrid removal seems to depend on the considered Netlander (Canberra is most important for Netlanders 1 and 4, Madrid for Netlander 3). This is due to the combination of two effects. First, it appears that geometrically the Goldstone-Canberra baseline is supposed to be the most adapted one because it has a larger projection in the plane of sky (even in the out-of-plane direction) than Goldstone-Madrid, which is well suited to complete the line-of-sight observability provided by range and Doppler data and thus to reduce significantly the SMAA. However, the Goldstone-Madrid baseline has a bigger projection into the orbital plane, which is more useful in estimating maneuver impulse. For a spherical maneuver execution error, the impact will be more important in the orbital plane than in the orthogonal direction. Thus, a ΔDOR baseline giving information in the orbital plane will be more efficient in reducing the impact due to maneuver execution error than an orthogonal baseline. This explains why for Netlanders 1 and 4, which have small maneuver magnitudes (see Table 1) and thus small maneuver execution errors, performance is more sensitive to Canberra loss, whereas for Netlander 3, which has a bigger maneuver, Madrid appears to be more efficient. For Netlander 2, due to a medium maneuver magnitude, the combination of both effects seems to self compensate. In order to check this point, a test case has been performed suppressing MTM3 for the computation of Netlander 3 performance, and as expected in this case the Canberra-Goldstone baseline appears again to be more efficient than Goldstone-Madrid (see Table 10).

Doppler, Range:

		SMAA (km)	SMIA (km)	theta (deg)	sigLTF (s)	FPA(deg)
Netlander 1	All stations Active	44.983	9.113	59.546	14.846	0.474
	Goldstone removed	60.443	9.121	59.425	19.227	0.599
	Canberra removed	63.243	9.121	59.388	19.832	0.623
	Madrid removed	63.016	9.121	59.320	19.861	0.623
	Goldstone and Madrid removed	108.575	9.133	59.207	33.335	1.022
	Goldstone and Canberra removed	94.570	9.135	59.322	28.721	0.894
	Madrid and Canberra removed	98.472	9.142	59.276	30.104	0.930
Netlander 2	All stations Active	41.819	7.182	59.798	13.623	0.389
	Goldstone removed	48.496	7.197	59.747	15.498	0.437
	Canberra removed	47.220	7.184	59.818	15.418	0.429
	Madrid removed	48.400	7.187	59.767	15.576	0.437
	Goldstone and Madrid removed	76.347	7.205	59.734	23.844	0.651
	Goldstone and Canberra removed	62.993	7.201	59.755	20.017	0.547
	Madrid and Canberra removed	67.658	7.244	59.707	21.222	0.583
Netlander 3	All stations Active	52.480	5.231	59.004	16.166	0.693
	Goldstone removed	57.496	5.236	58.986	17.608	0.757
	Canberra removed	55.275	5.232	59.009	17.363	0.728
	Madrid removed	56.131	5.233	58.995	17.325	0.739
	Goldstone and Madrid removed	69.569	5.239	58.975	21.913	0.912
	Goldstone and Canberra removed	64.116	5.238	58.983	20.188	0.842
	Madrid and Canberra removed	64.873	5.267	58.963	20.448	0.852
Netlander 4	All stations Active	29.547	3.411	59.358	10.493	0.216
	Goldstone removed	35.152	3.415	59.309	12.061	0.251
	Canberra removed	33.823	3.412	59.353	12.287	0.242
	Madrid removed	33.877	3.413	59.326	11.777	0.243
	Goldstone and Madrid removed	49.160	3.416	59.289	16.999	0.338
	Goldstone and Canberra removed	42.983	3.416	59.297	15.335	0.299
	Madrid and Canberra removed	44.901	3.425	59.272	15.807	0.312

Doppler, Range, DDOR:

		SMAA (km)	SMIA (km)	theta (deg)	sigLTF (s)	FPA(deg)
Netlander 1	All stations Active	12.337	9.059	55.516	4.835	0.274
	Goldstone removed	60.876	9.121	59.425	19.382	0.603
	Canberra removed	24.944	9.104	60.663	10.959	0.326
	Madrid removed	12.277	9.098	54.875	5.387	0.276
Netlander 2	All stations Active	33.151	7.150	59.678	10.460	0.326
	Goldstone removed	48.659	7.197	59.750	15.560	0.439
	Canberra removed	34.550	7.183	59.949	12.418	0.339
	Madrid removed	35.667	7.180	59.413	10.866	0.341
Netlander 3	All stations Active	43.193	5.220	59.066	13.362	0.574
	Goldstone removed	57.569	5.236	58.987	17.636	0.758
	Canberra removed	44.389	5.232	59.051	14.601	0.589
	Madrid removed	51.285	5.230	58.939	15.067	0.679
Netlander 4	All stations Active	10.408	3.406	59.085	3.837	0.118
	Goldstone removed	35.217	3.415	59.310	12.081	0.251
	Canberra removed	18.003	3.411	59.589	8.952	0.151
	Madrid removed	11.326	3.410	58.842	4.245	0.122

Table 9 Backup scenario - Impact of the tracking schedule - 5% SRP error

Doppler, Range, DDOR - MTM3 removed

		SMAA (km)	SMIA (km)	theta (deg)	sigLTF (s)	FPA(deg)
Netlander 3	Canberra removed	19.345	5.107	59.512	7.959	0.284
	Madrid removed	13.755	5.108	58.844	4.733	0.225

Table 10 Backup scenario - Impact of the tracking schedule - 5% SRP error - MTM3 removed

- In order to assess the maximum acceptable magnitude of impulsive main maneuvers and thus to determine the robustness of navigation with respect to a network on Mars' surface inducing big changes of target, some cases have been performed increasing individually each main maneuver up to 25m/s and 40m/s. The maneuver execution errors have been kept as the conservative ones, and only one MTM impulsive magnitude has been increased at a time. The impact on the following Netlander delivery uncertainties is detailed in Table 11 and Table 12. It appears that the ΔV increase has very little impact on the SMIA, which is due to the fact that the main contributors are linked to the coast arc and hide the effects coming from other estimated error sources. The SMAA is very sensitive to this increase because it represents the non-observable part of this error. The most sensitive Netlander appears to be the second one. This sensitivity is due first to the longer propagation arc (that induces a bigger error in the B-plane), but also to the difference in the nominal burn (that induces a bigger increase with respect to the nominal case). An important result is that the following Netlanders do not seem to be very affected by an increase of the previous MTM. This means the considered Network is quite robust to big maneuvers: the only case which does not satisfy the requirement (i.e. Netlander 3, with a 40m/s MTM3) remains still marginal.

All errors, SRP 5%						
	Doppler, Range:					
		SMAA (km)	SMIA (km)	theta (deg)	sigLTF (s)	FPA(deg)
	Impulsive nominal burns	41.8195	7.18184	59.7976	13.6230	0.388855
Netlander 2	MTM2 = 25 m/s burn	90.5668	7.18539	59.7634	26.4781	0.763911
	MTM2 = 40 m/s burn	118.973	7.18563	59.7605	34.3013	0.991158
	Impulsive nominal burns	52.5239	5.23102	59.0058	16.1837	0.693363
	MTM2 = 25 m/s burn	57.2178	5.23107	59.0141	17.4331	0.752924
Netlander 3	MTM2 = 40 m/s burn	58.4153	5.23108	59.0160	17.7538	0.768147
	MTM3 = 25 m/s burn	73.8935	5.23131	59.0052	21.8557	0.966370
	MTM3 = 40 m/s burn	97.1628	5.23141	59.0051	28.2058	1.26549
	Impulsive nominal burns	29.5622	3.41143	59.3589	10.4979	0.216374
	MTM2 = 25 m/s burn	29.5767	3.41145	59.3596	10.5052	0.216452
	MTM2 = 40 m/s burn	29.5792	3.41146	59.3597	10.5065	0.216465
Netlander 4	MTM3 = 25 m/s burn	33.5328	3.41145	59.3504	11.4432	0.240114
	MTM3 = 40 m/s burn	35.7698	3.41146	59.3469	11.9909	0.253694
	MTM4 = 25 m/s burn	56.8932	3.41305	59.2989	17.2814	0.386618
	MTM4 = 40 m/s burn	73.9685	3.41308	59.2913	21.8391	0.496485

	Doppler, Range, DDOR:					
		SMAA (km)	SMIA (km)	theta (deg)	sigLTF (s)	FPA(deg)
	Impulsive nominal burns	33.1522	7.14975	59.6770	10.4598	0.326316
Netlander 2	MTM2 = 25 m/s burn	69.0384	7.15630	59.9824	21.2496	0.599838
	MTM2 = 40 m/s burn	79.1250	7.15675	60.0041	24.3096	0.680482
	Impulsive nominal burns	43.2264	5.21960	59.0689	13.3795	0.574352
	MTM2 = 25 m/s burn	43.2441	5.21964	59.0690	13.3865	0.574571
Netlander 3	MTM2 = 40 m/s burn	43.2453	5.21964	59.0690	13.3870	0.574586
	MTM3 = 25 m/s burn	57.5078	5.22013	59.1094	17.6531	0.753980
	MTM3 = 40 m/s burn	67.2522	5.22031	59.1236	20.5843	0.877559
	Impulsive nominal burns	10.4049	3.40638	59.0866	3.83797	0.117936
	MTM2 = 25 m/s burn	10.4565	3.40639	59.0904	3.84936	0.118130
	MTM2 = 40 m/s burn	10.4602	3.40639	59.0907	3.85018	0.118144
Netlander 4	MTM3 = 25 m/s burn	10.4755	3.40642	59.0967	3.86296	0.118189
	MTM3 = 40 m/s burn	10.5006	3.40643	59.1002	3.87186	0.118280
	MTM4 = 25 m/s burn	42.3832	3.40840	59.3694	13.1967	0.293538
	MTM4 = 40 m/s burn	49.3579	3.40842	59.3749	15.3174	0.336945

Table 11 Backup scenario - Increase of MTM ΔV - 5% SRP error

[illegible]						
	Doppler, Range:					
		SMAA (km)	SMIA (km)	theta (deg)	sigLTF (s)	FPA(deg)
Netlander 2	Impulsive nominal burns	41.8577	12.6769	59.1470	13.6449	0.463623
	MTM2 = 25 m/s burn	90.5836	12.6845	59.6342	26.4894	0.804549
	MTM2 = 40 m/s burn	118.986	12.6853	59.6862	34.3100	1.02281
Netlander 3	Impulsive nominal burns	52.5417	8.61196	58.8079	16.1938	0.719697
	MTM2 = 25 m/s burn	57.2341	8.61245	58.8482	17.4424	0.777242
	MTM2 = 40 m/s burn	58.4312	8.61255	58.8569	17.7630	0.791998
	MTM3 = 25 m/s burn	73.9060	8.61306	58.9066	21.8631	0.985435
	MTM3 = 40 m/s burn	97.1723	8.61351	58.9484	28.2116	1.280110
Netlander 4	Impulsive nominal burns	29.5692	4.62872	59.2244	10.5015	0.235050
	MTM2 = 25 m/s burn	29.5837	4.62874	59.2252	10.5088	0.235122
	MTM2 = 40 m/s burn	29.5862	4.62874	59.2254	10.5101	0.235134
	MTM3 = 25 m/s burn	33.5390	4.62878	59.2464	11.4465	0.257071
	MTM3 = 40 m/s burn	35.7756	4.62881	59.2556	11.9940	0.269798
	MTM4 = 25 m/s burn	56.8968	4.62983	59.2631	17.2835	0.397371
	MTM4 = 40 m/s burn	73.9713	4.62985	59.2701	21.8409	0.504904
	Doppler, Range, DDOR:					
		SMAA (km)	SMIA (km)	theta (deg)	sigLTF (s)	FPA(deg)
Netlander 2	Impulsive nominal burns	33.2037	12.6498	58.5649	10.4884	0.412578
	MTM2 = 25 m/s burn	69.0597	12.6724	59.7621	21.2637	0.650803
	MTM2 = 40 m/s burn	79.1434	12.6739	59.8381	24.3219	0.725806
Netlander 3	Impulsive nominal burns	43.2480	8.60532	58.7745	13.3916	0.605881
	MTM2 = 25 m/s burn	43.2656	8.60535	58.7749	13.3987	0.606089
	MTM2 = 40 m/s burn	43.2668	8.60535	58.7749	13.3991	0.606103
	MTM3 = 25 m/s burn	57.5237	8.60763	58.9465	17.6623	0.778266
	MTM3 = 40 m/s burn	67.2657	8.60843	59.0054	20.5922	0.898511
Netlander 4	Impulsive nominal burns	10.4278	4.61825	57.7446	3.84777	0.149464
	MTM2 = 25 m/s burn	10.4792	4.61834	57.7652	3.85913	0.149617
	MTM2 = 40 m/s burn	10.4829	4.61834	57.7666	3.85995	0.149628
	MTM3 = 25 m/s burn	10.4981	4.61844	57.7780	3.87270	0.149664
	MTM3 = 40 m/s burn	10.5231	4.61851	57.7897	3.88158	0.149736
	MTM4 = 25 m/s burn	42.3881	4.62683	59.3049	13.1995	0.307564
	MTM4 = 40 m/s burn	49.3620	4.62695	59.3275	15.3198	0.349231

Table 12 Backup scenario - Increase of MTM ΔV - 50% SRP error

Conclusion about the sensitivity study

It should be noted that the purpose of this covariance analysis was rather to get an order of magnitude of the impact of the different parameters influencing the navigation performance than to prove the feasibility of this phase and to assess the exact reachable uncertainty. Some assumptions are still to be refined (such as the error on SRP coefficient, or maneuver execution errors). However this study allows us to identify the main error sources and the way they act on the final B-plane uncertainties. The influence of errors active during the coast arc such as solar radiation pressure, trim maneuvers and separation, and unmodelled forces has been emphasized (see Figure 8). Concerning the tracking schedule (see Figure 9) it has been shown that the addition of a few ΔDOR points significantly improves the performance, and that the loss of one DSN station could eventually be supported by the mission (according to the considered assumptions and requirements). This study also illustrates the effect of a low declination with respect to the Earth's equator for Doppler and range data : due to a higher declination the open launch trajectory gives better performance than the close one. Concerning the deployment scenario, it has been shown that later release dates (to decrease the length of the coast arc) and longer durations between two successive separations (to get more tracking data) are key points in improving the delivery uncertainty (see Figure 10). Finally, the sensitivity to main maneuver sizes (see Figure 11) showed that the considered Network is quite robust to 25m/s (and even 40 m/s maneuvers with ΔDOR).

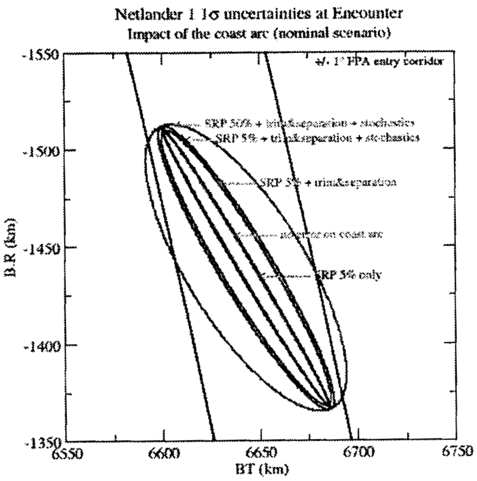

Figure 8 Impact of the coast arc

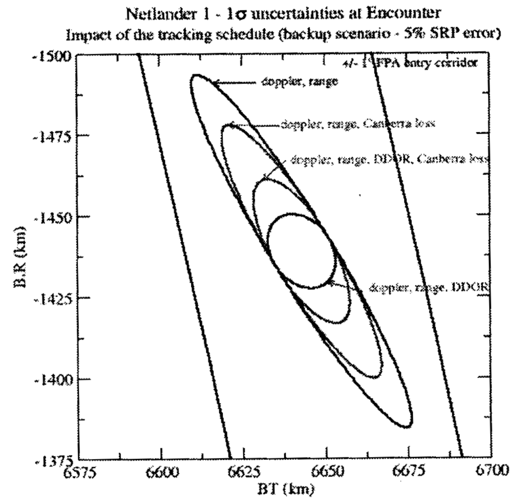

Figure 9 Impact of tracking schedule

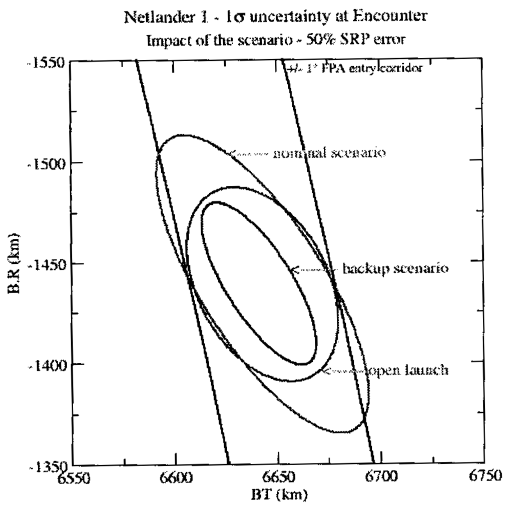

Figure 10 Impact of the scenario

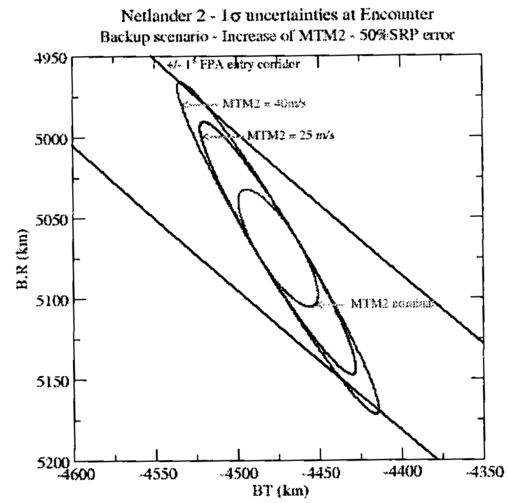

Figure 11 Impact of MTMs

PROPULSIVE MANEUVER ANALYSIS

All these sensitivity studies have been performed considering a conservative value for trim maneuvers of 0.5 m/s. In order to assess that this figure was effectively a worst case, a propulsive maneuver analysis on the orbiter has been done using Monte-Carlo simulations to determine the statistical trim ΔV necessary to correct the uncertainty on the Netlander target in the B-plane. This study was done using the nominal sequence and the baseline error assumptions, except for the maneuver execution errors for which the expected errors described in Table 5 have been considered.

Each drawing of the Monte-Carlo simulates a possible trajectory path by sampling initial conditions, orbiter orbit determination errors (orbiter state knowledge at data-cutoff before the trim maneuver) and maneuver execution errors in a closed loop. Each maneuver is computed by taking into account the previous dispersed aim-point in order to target the desired aim-point. In order to be able to perform a large number of drawings, linear propagations are used between the state vector at the maneuver epoch and the B-plane through a K-matrix (derivative of the B-plane parameters with respect to the Cartesian state vector at the considered epoch). This is possible since the considered dispersions are small enough with respect to the linearity assumption. Statistical results processing is then used to compute mean standard deviations and covariances of pertinent elements such that delivery points in the B-plane or maneuver magnitude. The algorithm of the Monte-Carlo can be then described as follows:

- perturb the nominal B-vector (Netlander 1 aim-point) at initial conditions considering initial B-plane covariance (real B-vector).
- before each Netlander release :
  - perturb the real B-vector by the orbiter OD error distribution in the B-plane before the trim maneuver. The result gives the observed B-vector to compute the maneuver.
  - compute the B-vector shift (trim maneuver) to correct the previous delivery error and propagate it back to the maneuver epoch to compute the needed Cartesian maneuver.
  - perturb the maneuver magnitude and direction by the maneuver execution error distribution and propagate it to the B-plane.
  - apply the maneuver to the real B-vector.
  - compute the B-vector shift (main maneuver) to target the next Netlander aim point and propagate it back to the maneuver epoch to compute the needed Cartesian maneuver.
  - perturb the maneuver magnitude and direction by the maneuver execution errors distribution and propagate it to the B-plane.
  - apply the maneuver to the real B-vector.
- repeat this process for each maneuver (100000 drawings have been performed in order to converge on dispersion ellipses of the delivery B-plane points).

The successive delivery uncertainties of the orbiter after each maneuver are given in Table 13. The main differences from the corresponding Netlander's delivery uncertainties given in Table 6 (expected maneuver execution errors) are due to the errors assumptions in effect during the coast arc:

- For the Orbiter, the initial 5% SRP error is reduced through the OD process and thus the corresponding effect on the SMIA is much lower than for the Netlanders.
- The Netlander delivery uncertainties after the trim maneuvers takes into account the separation mechanism error which effect on the Orbiter is negligible.

Event	Date	SMAA (km)	SMIA (km)	theta (deg)	sigLTF (s)
OD1 (orbiter)	MOI-29D	83.847	2.872	59.252	25.475
TTM1 (full)	MOI-28D -2hours	83.924	3.750	59.241	25.478
MTM2 (full)	MOI-28D +2hours	87.008	27.256	59.130	26.734
OD2 (orbiter)	MOI-25D	49.251	2.713	59.128	15.242
TTM2 (full)	MOI-24D -2hours	49.284	3.113	59.168	15.288
MTM3 (full)	MOI-24D +2hours	60.733	38.100	58.576	20.446
OD3 (orbiter)	MOI-21D	40.907	1.978	59.083	12.697
TTM3 (full)	MOI-20D -2hours	41.045	2.548	59.067	12.683
MTM4 (full)	MOI-20D +2hours	41.106	4.851	59.079	12.775
OD4 (orbiter)	MOI-17D	29.168	1.158	59.215	9.422
TTM4 (full)	MOI-16D -2hours	29.243	1.277	59.215	9.429
MTM5 (critical)	MOI-16D +2hours	36.138	20.106	55.551	11.511

Table 13 Orbiter OD and delivery

The results presented in Table 14 show that the baseline assumption concerning 0.5m/s trim deltaV is a worst case, the maximal statistical trim being 0.16 m/s (at 99%). This implies that the errors observed on the SMIA for the previous studies are very conservative.

Event	Date	Mean (m/s)	Std Dev 1-σ (m/s)	ΔV 99% (m/s)
TTM1	**MOI-28D -2hours**	**0.060**	**0.028**	***0.143***
MTM2	MOI-28D +2hours	5.463	0.011	5.488
TTM2	**MOI-24D -2hours**	**0.055**	**0.035**	***0.160***
MTM3	MOI-24D +2hours	9.792	0.020	9.838
TTM3	**MOI-20D -2hours**	**0.05466**	**0.0283**	***0.1414***
MTM4	MOI-20D +2hours	1.3402	0.00269	1.3465
TTM4	**MOI-16D -2hours**	**0.0403**	**0.0276**	***0.1252***

Table 14 Statistical maneuvers

IMPACT ON THE MISSION DESIGN

The only stringent constraint on navigation performance for Netlanders is with respect to the FPA entry corridor width, i.e. +/-3° (3σ). Outside this corridor, Netlanders would be submitted during the atmospheric path to thermal fluxes or thermal loads not compatible with the design. On the other hand, there is no formal specification to deal with concerning the size of dispersion ellipses for landing sites on Mars. The best effort to have uncertainty ellipses as small as possible has to be performed.

Impact on mission design and landing sites network design

The later the main maneuver execution dates and the smaller their magnitudes, the smaller the navigation errors and thus the landing sites' uncertainty ellipses. As the main part of MTMs is due to a shift of the arrival date (longitude shift from one landing site to the next one), a maximum shift of 2h40 on the arrival date between the different Netlanders has been taken into account for the design of the landing sites network.

From the previously presented results, it can be pointed out that the current landing site network and the Netlander deployment phase is compatible with the navigation accuracy using only Range and Doppler measurements and with the +/-3° at 3σ FPA uncertainty angle. Backup or nominal deployment schedules and use of ΔDOR should also reduce the B-plane uncertainty ellipse. On the other hand, for a given uncertainty ellipse, it would be possible to have larger maneuvers and then to be able to relax the arrival date constraints and thus to have more flexibility in the choice of landing sites.

Uncertainties on landing sites

The inaccuracy of a given landing site is directly correlated to the size and direction of the B-plane uncertainty ellipse. Using atmospheric reentry simulation software and without taking into account the atmospheric dispersion or dispersion on the Linearized Time of Flight (LTF), it is possible to compute directly the footprint on Mars of the 3 sigma B-plane ellipse and to calculate the dimension of the resulting ellipses.

As it can be seen in Figure 12 and Figure 13 for 2 different landing sites, the effect of ΔDOR can be significantly different, even changing the orientation of the landing ellipse, but in any case reducing the size of the error ellipse. In most cases, the orientation of the landing ellipse is not given by the main axis of the B-plane ellipse, but depends mainly of the B-plane targeted point.

In any case, the backup deployment reduces the errors on landing ellipses, especially for the first Netlander. It is more marginal for the following ones: for Landing site 1 the SMAA of the landing ellipse with a SRP error of 5% goes from 990 km for the nominal schedule to 470 km at 3 sigma, and for Landing

Orbiter position and velocity. This study also proved that CNES and JPL tools produce very similar results (with respect to the considered models) and is thus a major step for future studies planned in the framework of a CNES-JPL collaboration on navigation issues in order to refine these results.

ACRONYMS

ΔDOR	Delta Differential One-way Range
DSN	Deep Space Network
DSS	Deep Space Station
FPA	Flight Path Angle
GM	Planetary gravitational constant
LTF	Linearized Time of Flight
MTM	Main Targeting Maneuver
OD	Orbit Determination
SMAA	Semi Major Axis
SMIA	Semi Minor Axis
SRP	Solar Radiation Pressure
TCM	Trajectory Correction Maneuver
TTM	Trim Targeting Maneuver

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