MARS APPROACH NAVIGATION USING THE VLBA

Tomas J. Martin-Mur [(1)], Dolan E. Highsmith [(2)]

[(1)] *Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena California 91109, USA, +1-818-393-6276, Tomas.J.Martin-Mur@jpl.nasa.gov*
[(2)] *Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr, Pasadena California 91109, USA, +1-818-393-7855, Dolan.E.Highsmith@jpl.nasa.gov*

ABSTRACT

The Very Large Baseline Array (VLBA) is a set of ten radio telescopes that operate jointly as one of the largest astronomical instruments in the world. The VLBA can be used to track spacecraft signals, and a number of spacecraft experiments and tracking campaigns have been performed in the last five years to evaluate the technique, demonstrate its capabilities, and also to improve the Saturn ephemeris. The latest of these experiments was performed during the approach of the Phoenix spacecraft to Mars. At that time the VLBA tracked not only Phoenix and a number of quasars, but also the Odyssey and MRO spacecraft as they were orbiting Mars. That allowed direct reference of the Phoenix observations to Mars, therefore removing the errors that could be introduced by the tie between the quasar and the Mars ephemeris. In the last couple of days before entry, the VLBA could track Phoenix and the orbiters within the same beam, eliminating temporal and reducing spatial interpolation errors. This paper will explain the advantages of VLBA and same-beam multi-spacecraft tracking, will describe the results of the Phoenix VLBA experiment, and will show the improvement in Mars approach orbit determination accuracy that could be obtained supplementing the DSN with an operational VLBA system for future Mars transfer opportunities.

1. INTRODUCTION

Mars missions have stringent orbit insertion or entry delivery requirements. These requirements are fulfilled by performing approach navigation using the best available models with intensive tracking of the spacecraft. The traditional line-of-sight tracking measurements, two-way radiometric Doppler and ranging, are used by most deep space missions in most mission phases and, for accurate delivery to a Mars-relative target, interferometric delta differenced one-way range (ΔDOR) is used to complement the line-of-sight measurements and to provide a tie to the quasar-based celestial reference frame. ΔDOR is based on the quasi-simultaneous observation of wideband tones from a spacecraft and the wideband signal at the same frequency range from a quasar. Two ground antennas at different stations track simultaneously one source, and then the other, and the measurement at one antenna is correlated with the measurement of the same source at the other antenna in order to derive the difference in the arrival time of the signal. This cancels certain delays that are transmitter dependent. The measurements to at least one of the sources are repeated in order to be able to interpolate at the measurement time of the other source. Then the differenced measurements to each source are differenced once more to cancel certain receiver dependent delays. What this produces is a measurement of the separation in the plane of sky between the spacecraft and the natural source, as seen from the baseline of the two stations. The quasar position is tied to other celestial sources using VLBI surveys and combinations, so we obtain a tie to the celestial reference frame. Performing measurements with baselines at different orientation, like East-West and North-South, can give us an estimate of the two-dimensional location of the spacecraft in the celestial reference frame. If we need to target to a planet, we also need to tie the position of that planet to the celestial reference frame, and this can be done by determining the planetary ephemerides using a combination of radiometric, astrometric and interferometric observations, that for Mars includes the interferometric observation of spacecraft orbiting Mars. So once we have our ΔDOR measurements, with their assessed measurement noise, we also have to consider the error of the position of the natural source, and the error in the prediction of the location of our planetary target, to be able to tie the current plane-of-sky position of our spacecraft to the expected location of the desired target. The prediction error will also be driven by how well we can model and predict the dynamics of our spacecraft, especially the effect of non-conservative forces such as attitude control system (ACS) thruster firings and solar radiation pressure forces. Usually there are two types of requirements levied on approach navigation, one is the requirement to be able to deliver within a set of constraints, like flight path angle, or location above Mars surface, and the other is to have an appropriate knowledge of where we are going to be. If we can predict that our delivery is not going to fulfill the constraints, we can execute trajectory correction maneuvers that can correct our path and deliver the spacecraft to the right target. Knowledge is required as the starting point of any trajectory prediction, but may also be needed to either reconstruct the actual trajectory of the spacecraft, or to provide the spacecraft with an up-to-date estimate of its location, in order to time a sequence of events or to initialize a guidance algorithm.

The Very Long Baseline Array [1] (VLBA) is a set of ten radio telescopes operated by the National Radio Astronomy Observatory (NRAO), the world's largest dedicated full-time astronomical instrument using the technique of very long baseline interferometry (VLBI). Each VLBA station has a 25 meter antenna, and the ten sites are widely dispersed, with one antenna in Hawaii and one in the US Virgin Islands, and eight other antennas in the contiguous United States. The array is remotely controlled from the Array Operations Center in Socorro, New Mexico, and it operates by simultaneous tracking of one or more celestial sources by all or most of the antennas in the array. The distances between the antennas go incrementally from 52 to 10,328 kilometers, resulting in a mix of baseline lengths that allow for the resolution of phase ambiguities and the derivation of detailed flux density maps of celestial sources. The array can also be used to track spacecraft signals. In this case, because the source is moving in the celestial frame, the correlation needs to use an a priori spacecraft trajectory in order to predict spacecraft signal delay for each baseline. This technique was previously used to track the Opportunity (MER-B) spacecraft as it approached Mars [2], by performing scans of the spacecraft signal and the signal of quasars in the same portion of the sky. The VLBA can track any kind of signal and does not require the spacecraft wideband tones that ΔDOR requires to be able to produce the best possible results, so it can track at any time when the spacecraft is transmitting, and does not conflict with simultaneous Doppler or range tracking, or with command uplink and telemetry downlink.

2. SPACECRAFT-TO-SPACECRAFT AND SAME-BEAM INTERFEROMETRY

When traditional VLBI measurements are used to deliver spacecraft to a planetary interface they are limited mostly by three factors: the measurement error budget for the ΔDOR correlation, the quasar position error, and the error in the position of the planetary target (neglecting for now the modeling of the spacecraft dynamics). One possible way to reduce these errors is by, instead of tracking a natural source, tracking a spacecraft that is orbiting the planet that is our target [3]. The location of the spacecraft relative to a reference frame centered at the target planet can be known much better than the position of the planet relative to the celestial reference frame, so that error is removed, makes the error in the location of the natural source not relevant, and reduces other error sources as the spacecraft approaches the planet, because spatial interpolation errors between the two sources, such as media, become smaller. Finally, when the spacecraft is close enough to the planet, it is possible to track the two spacecraft simultaneously within the same beam, and temporal interpolation errors are eliminated. There is one major difficulty with implementing spacecraft-to-spacecraft differencing: it is necessary to record data at the frequency channels used by the two spacecraft, and the fact that the average frequency is different can make the measurement susceptible to inter-frequency biases in the tracking equipment.

One advantage of using the VLBA, over other deep space antennas for same-beam interferometry (SBI), is that the VLBA antennas, at 25 meters, are smaller than deep space tracking antennas, which have diameters in the range between 34 and 70 meters. Beamwidth is inversely proportional to antenna diameter, so it is possible to start using same beam interferometry earlier with a smaller antenna. At the deep space X-band downlink frequency (8.425 GHz) a 25 meter antenna has a -3dB beamwidth of about 0.100 degrees, while for a 34 meter antenna it would be 0.073 degrees. For Phoenix the spacecraft was moving at about 0.032 degrees per day with respect to Mars, so it could be tracked for the last three days using SBI with a 25 meter antenna, but only less than 54 hours with a 34 meter antenna and a little more than one day with a 70 meter antenna.

Another advantage of doing dual spacecraft differencing is that spacecraft signals are usually much stronger (within a narrow bandwidth) than quasar signals, consequently the required recording times and bandwidth are smaller, and the raw data can be transmitted faster from the collecting antennas to the processing center; the data can be available to the navigation team earlier than if spacecraft to quasar differencing was used. Some quasar data is still needed for inter-frequency bias calibration, but it does not need to be recorded for the whole duration of the experiment.

The spacecraft-to-spacecraft differencing requires knowledge of the position of the reference spacecraft, but usually that position is better known than the location of a radio source. Radio source catalog location accuracies are currently in the range from 0.5 to 0.7 nrad [4], equivalent to about 110 to 160m at 1.5 AU. If the tracking data from the orbiting spacecraft are also processed while the VLBA data is being transmitted and correlated, it would be possible to obtain reference trajectories at the 10m level, and that is with respect to our target, so we are also not affected by planetary ephemeris errors that can also be in the 100m level.

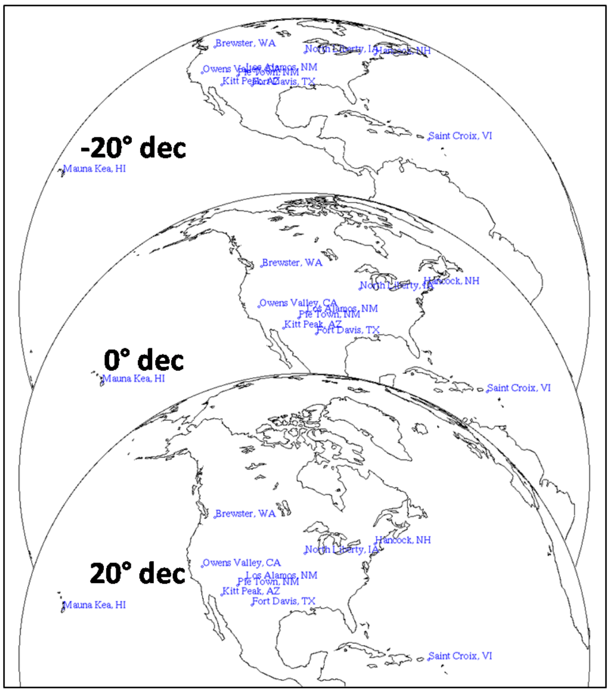

Fig. 1: VLBA visibility from different declinations

Fig. 1 shows the visibility of the VLBA network from different source declinations. Typical Mars arrival opportunities have declinations between -26 and 26 degrees, but lower declinations may be possible for the trajectory of the spacecraft earlier in cruise. The VLBA has successfully tracked sources down to a declination of -45 degrees, but the duration of the observing session at lower declinations is reduced.

3. THE PHOENIX APPROACH VLBA EXPERIMENT

The VLBA has been used to track spacecraft a number of times. It was tested during the Opportunity approach to Mars in January of 2004, and it has been used routinely to track the Cassini spacecraft in order to improve the Saturn ephemeris. In those cases it was used to perform spacecraft-quasar differencing, in the case of Cassini for the obvious reason that there is no other spacecraft in the proximity of Saturn. When it was proposed to perform another test during the 2008 Phoenix approach to Mars, it was decided to try to track simultaneously or quasi-simultaneously the approaching spacecraft and the two NASA spacecraft orbiting Mars, Mars Odyssey and the Mars Reconnaissance Orbiter (MRO). A total of eight VLBA tracking sessions were performed: the first on March 1 2008 to verify that all the spacecraft could be tracked, and then seven more sessions between May 14 and May 25, 2008, tracking the spacecraft down to Phoenix cruise stage separation. The last seven sessions had a typical duration of one to two hours, with measurements created every two or three minutes.

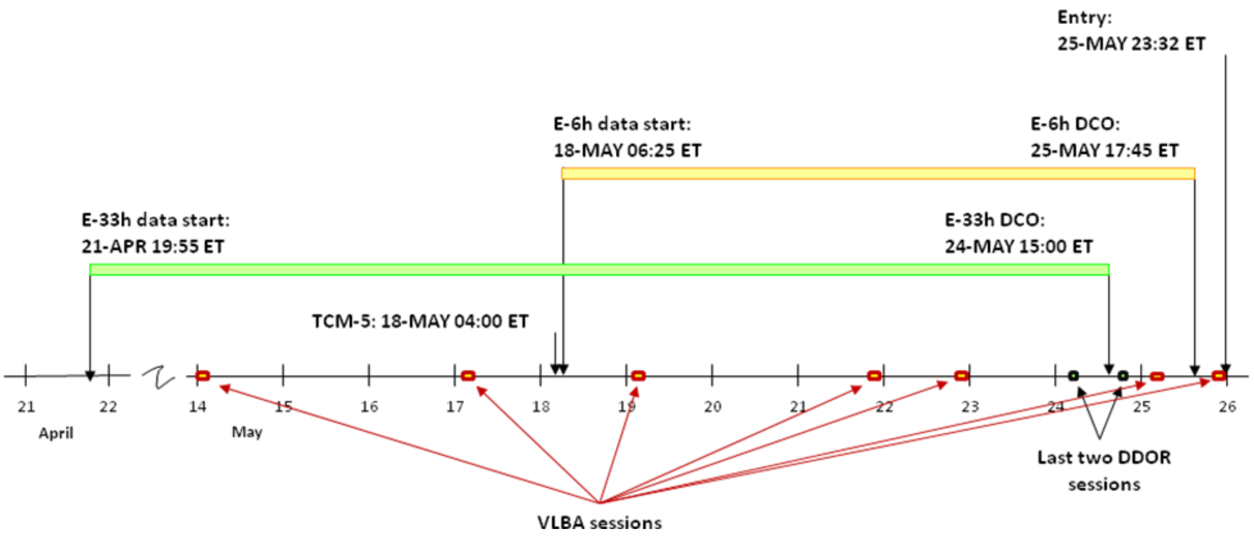

Fig. 2: Timeline of the Phoenix approach VLBA experiment

The VLBA data were delivered after Phoenix landed, and we used the best reconstructed trajectories for MRO and Odyssey spacecraft to process the VLBA data, with an orbit accuracy relative to the center of Mars estimated to be about 10m (1σ) [5].

The setup that was used to process the data was the same as the one used during the Phoenix approach operations [6] [7]. Three data arcs were used, one starting on April 21, 2008 and with a data cut off (DCO) at 33 hours before entry, and two starting on May 18, 2008 with data cut offs at 6 hours before entry and at entry, that happened on May 25 2008 23:32 ET. The X-band transponder was located on the cruise stage and stopped operating when the cruise stage was jettisoned right before entry. All the VLBA baseline combinations were used, and the Phoenix measurements were differenced with those from MRO and Odyssey. A measurement weight of 15 picoseconds was used for the VLBA delta-differenced observables, to represent the expected measurement, instrumental, and uncompensated path-delay errors. Because VLBA data were not recorded each day, the DSN ΔDOR were also included in the solutions, together with DSN two-way Doppler and ranging observations. Continuous DSN Doppler and range tracking was performed starting sixty days before entry, and two daily session of DSN ΔDOR were performed starting eighteen days before entry.

Initial processing of the data at JPL showed large residuals for some VLBA passes. These data problems were traced to procedural errors in some data reductions at NRAO. Problems were corrected and data were re-delivered, resulting in usable data for all passes. The fit of the DSN and VLBA data produced post-fit residuals for the DSN data similar to those produced fitting DSN data only, and produced the residuals shown in Table 1 for the VLBA dual-spacecraft differenced data. The last two observing sessions on 5/25 were done using same-beam interferometry, as were the measurements of Odyssey and MRO. Pre-fit residuals were calculated using the best available trajectories for the three spacecraft. For the post-fit residuals the same orbits were used for the orbiting spacecraft, held fixed, and the trajectory of Phoenix, as well as other dynamic and measurement parameters, were estimated. In order to model the errors in the orbiter trajectory, offsets in the radial, transversal and normal positions were estimated as stochastic parameters with a priori knowledge of 1, 10 and 100 meters, a time constant of six hours and updates every hour.

Table 1: Pre-fit and post-fit RMS of VLBA sc/sc residuals (picoseconds)

type	DCO	target	reference	3/1	5/14	5/17	5/19	5/22	5/23	5/25	5/25
pre-fit	Entry	Odyssey	MRO	3.64	3.43	6.44		2.87	2.22	0.86	2.73
pre-fit	Entry	Phoenix	MRO	11.46	9.36	9.47	12.52	7.65	6.00	3.81	3.55
pre-fit	Entry	Phoenix	Odyssey	13.08	10.25	10.11		7.01	7.13	3.98	2.46
post-fit	Entry – 33h	Phoenix	Odyssey & MRO		3.93	3.84	4.15	5.64	3.54		
post-fit	Entry – 6h	Phoenix	Odyssey & MRO				4.16	5.51	3.58	1.94	
post-fit	Entry	Phoenix	Odyssey & MRO				4.16	5.57	3.60	1.95	2.07

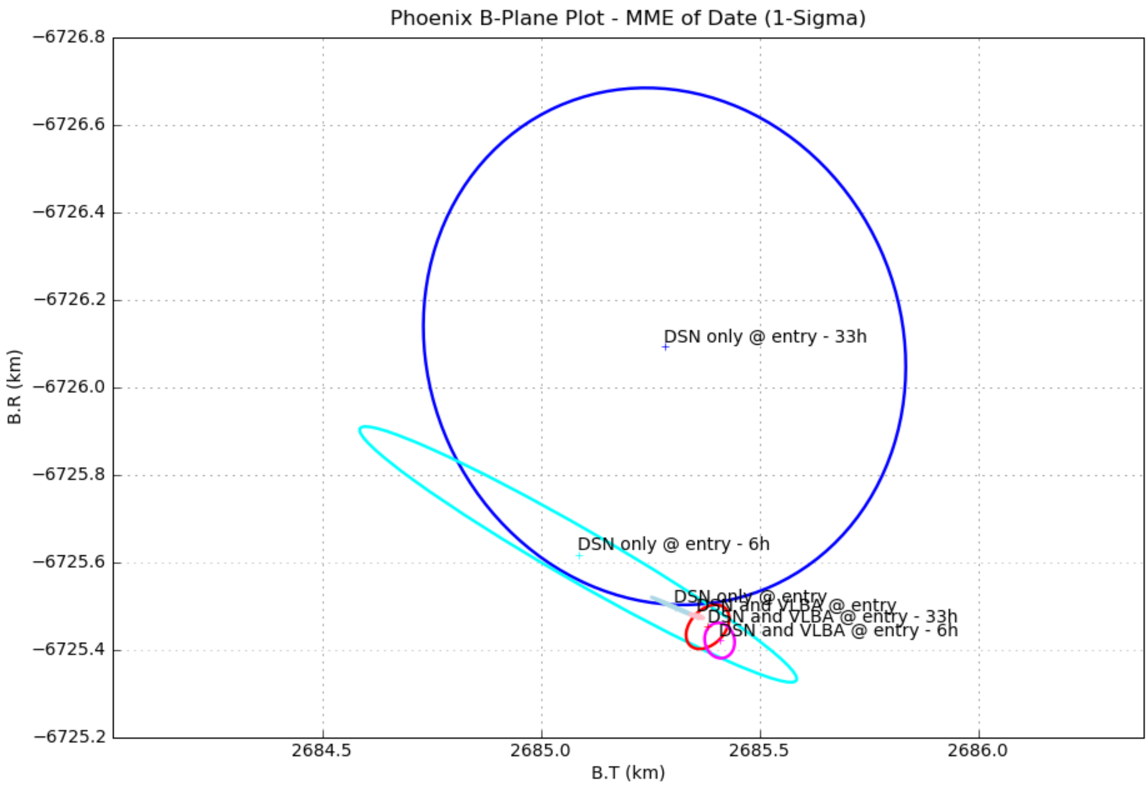

Fig. 3: Phoenix navigation solutions plotted to the B-plane

Fig. 3 shows the DSN-only and DSN-plus-VLBA solutions plotted on the B-plane. Phoenix needed to be delivered to an entry flight path angle corridor of -13 degrees ± 0.2 degrees (3-sigma) [6], corresponding to a B vector magnitude of ±5.84 km (3-sigma). During approach, and because of the uncertainty on the execution error of the TCM-5 maneuver and the fact that Phoenix was a three-axis stabilized spacecraft with no reaction wheels, the DSN solution did not center on the final estimate until hours before entry, when Doppler data that could sense the gravity field of Mars was included in the solution. The DSN-plus-VLBA solutions converged to close to the final solution much earlier, and had B-plane errors significantly smaller than the DSN-only solutions.

These results confirm the usefulness of using the VLBA to perform spacecraft-to-spacecraft tracking for a Mars approaching spacecraft, as well as the correctness of the approach used to process the data. Work still needs to be performed to arrive at a better VLBA weighting approach that uses the baseline length and source separation of each measurement, and that properly takes into account the correlations between simultaneous measurements with a common station and measurements at different times from the same baseline.

4. MSL ANALYSIS RESULTS

We have also performed simulations for the 2011 Mars Science Laboratory (MSL) mission, using the same setup that is currently used to assess the accuracy of its navigation performance using DSN data [8], and adding VLBA dual spacecraft data. The data added simulates differencing with MRO and Odyssey, and assumes sessions of one and a half hours of duration, starting two weeks before arrival, with measurements every two and a half minutes, and the same measurement weight, 15 ps, as that used for the Phoenix experiment. The current mission plan is for MSL to perform the last two nominal trajectory control maneuvers, TCM-4 and TCM-5, at entry minus 8 days and entry minus 2 days, in order to target to the required entry flight path angle with an accuracy of ±0.2 degrees. It will also be important, since the descent will be guided, to know accurately the Mars relative position and velocity of the spacecraft at entry, in order to initialize the guidance algorithm and to be able to land with a landing dispersion much smaller than those achieved by the MER rovers. Mars and the spacecraft will be at a declination of about -10 degrees when the spacecraft approaches Mars.

For MSL TCM-4 delivery errors are mostly dominated by TCM-4 maneuver execution errors and the use of VLBA data does not significantly change the TCM-4 delivery performance. TCM-5 delivery and knowledge errors are dramatically decreased when VLBA data are added, even when the most significant VLBA station, Mauna Kea, is excluded from the solution, or when the VLBA tracking sessions are reduced to just 30 minutes. Fig. 4 shows the B-plane results for the no-margin case for a launch on November 14, 2011, and arrival on August 31, 2012 for a landing at the Holden Crater. The TCM-5 DCO is at entry minus 2.5 days and the knowledge DCO is at entry minus 6 hours. Five delivery and knowledge cases are shown: the current DSN no-margin performance, four cases showing the effect of adding VLBA data, three with 90 minute sessions and all ten VLBA stations, with only the seven westernmost VLBA stations (i.e. excluding Saint Croix, Hancock and North Liberty), or with only the nine easternmost VLBA stations (i.e. excluding Mauna Kea), and one more case with the ten VLBA stations and 30 minute observing sessions. The cases with a limited set of stations were analyzed in order to assess what would be the effect of missing stations in the VLBA network.

The advantage of using VLBA for MSL would not be to fulfill delivery and knowledge requirements, since they are comfortably fulfilled using the planned DSN data, but to be able to fulfill those requirements earlier before entry, and so provide more confidence in the navigation solutions. The improved knowledge performance could be used to further reduce the landing dispersion, but the planned landing sites have been selected already using the required dispersion, so VLBA data could just be used to improve margins for the entry descent and landing (EDL) subsystem.

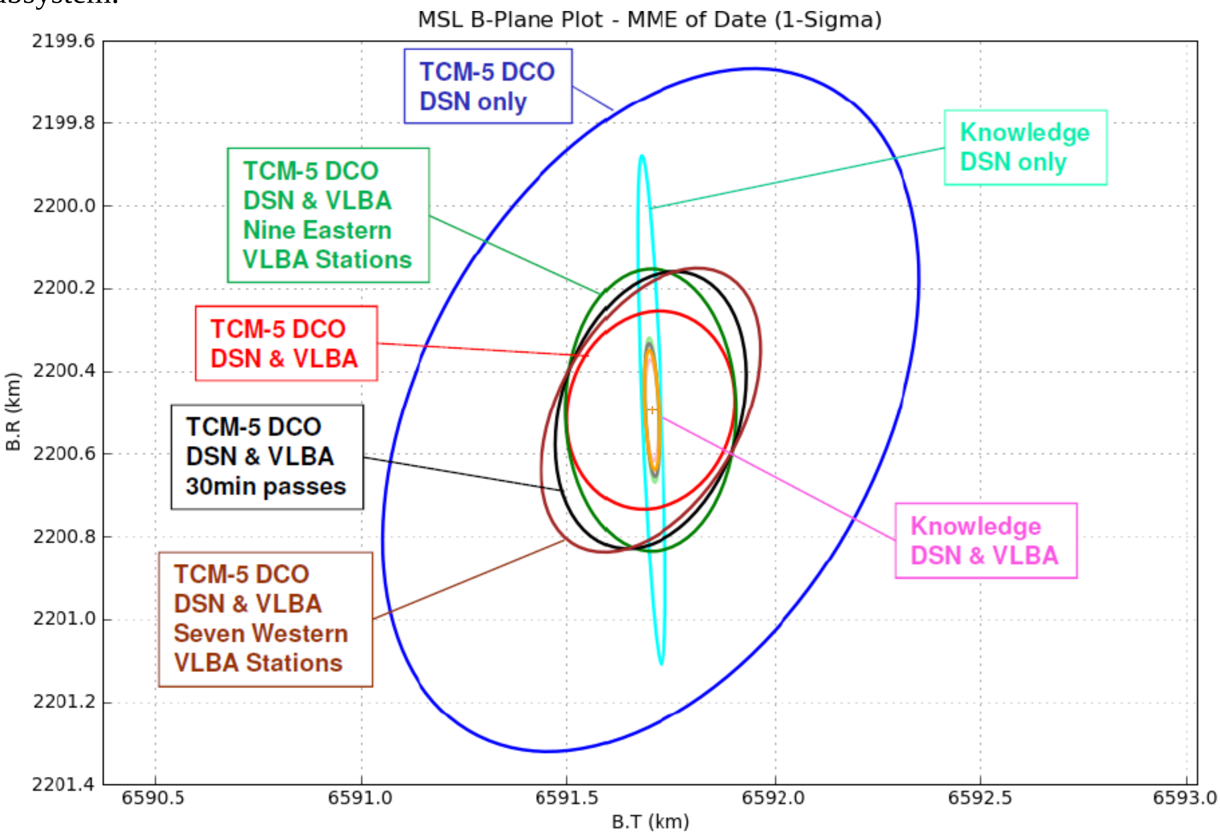

Fig. 4: MSL B-plane plot

5. MAVEN ANALYSIS RESULTS

It is also informative to evaluate the benefits of using VLBA for the approach navigation of a Mars orbiter. As an example, we evaluated the performance of the Mars Atmosphere and Volatile EvolutioN (MAVEN) mission. MAVEN will be the next NASA Mars orbiter, with launch planned in November 2013, and arrival in September 2014. The Mars orbit insertion (MOI) maneuver has a B-plane target of nearly 600 km altitude with a delivery requirement of ±50 km (3σ). The final trajectory correction maneuver (TCM-4) is planned at seven days out, with a full week allowed for design and test, putting the TCM-4 DCO at MOI-14 days. The baseline tracking coverage includes only three DSN tracks per week for Doppler and range, complemented by only two ΔDOR sessions per week. This is in contrast to the MSL tracking, which is expected to be continuous during approach (three DSN tracks per day for Doppler and range and two ΔDOR sessions per day). In addition, during the last month of approach to Mars, the MAVEN declination will move southward from -17 degrees to -22 degrees at arrival, increasing the noise on the Goldstone-Madrid ΔDOR baseline by more than a factor of three.

Even with the reduced tracking and de-weighted ΔDOR, the MAVEN navigation analysis using baseline performance assumptions meets the TCM-4 delivery requirement with margin. Therefore, given the less stringent delivery requirement for MAVEN compared to MSL, the results of the MAVEN analysis are evaluated based on the position knowledge improvement afforded by VLBA in the context of improved margins for MAVEN and other benefits for future orbiters. Four cases are evaluated based on various tracking data combinations: 1) the baseline DSN tracking listed above, 2) continuous DSN, 3) the baseline DSN tracking plus two VLBA measurements per week, and 4) continuous DSN plus daily VLBA measurements. The dual-spacecraft VLBA measurements use the same setup as with the MSL analysis, but they begin 30 days prior to Mars arrival.

Fig. 5 shows the evolution of the norm of the position covariance mapped to Mars arrival or, in other words, the OD knowledge at MOI. The left plot begins at MOI-30 days, with the same data plotted on the right but zoomed in to MOI-10 days. Lines for each of the four cases are shown, along with vertical lines indicating the location of TCM-4, the last targeted maneuver for MAVEN, and TCM-5, a contingency maneuver opportunity for orbiter safety. The plot clearly shows the knowledge improvement in the VLBA cases, with the Baseline DSN + 2/Week VLBA case performance nearly matching that of the Continuous DSN + Daily VLBA case. This is a key result in that it demonstrates that significantly better OD knowledge can be obtained with modest amounts of VLBA rather than by tracking around the clock with only the DSN. Future proposals could possibly reduce their cost by including concentrated VLBA campaigns in place of continuous DSN coverage.

The plots also indicate potential operational advantages of adding VLBA measurements. First, increased OD knowledge would result in smaller statistical ΔVs for late TCMs, which, in turn, would result in smaller delivery uncertainties. Second, VLBA provides a direct tie to Mars much sooner than the Doppler, providing an opportunity to move the contingency maneuver TCM-5 earlier. For example, Fig. 5 shows that the Continuous DSN case does not reach a position knowledge of 2 km until within the last day, versus more than four days out with VLBA. Additional advantages would include quicker reconstruction of maneuvers or anomalous ΔVs (from a safe mode, for instance), safely targeting MOI closer to the planet to save propellant, reducing the reliance on the DSN, or simply to increase margin.

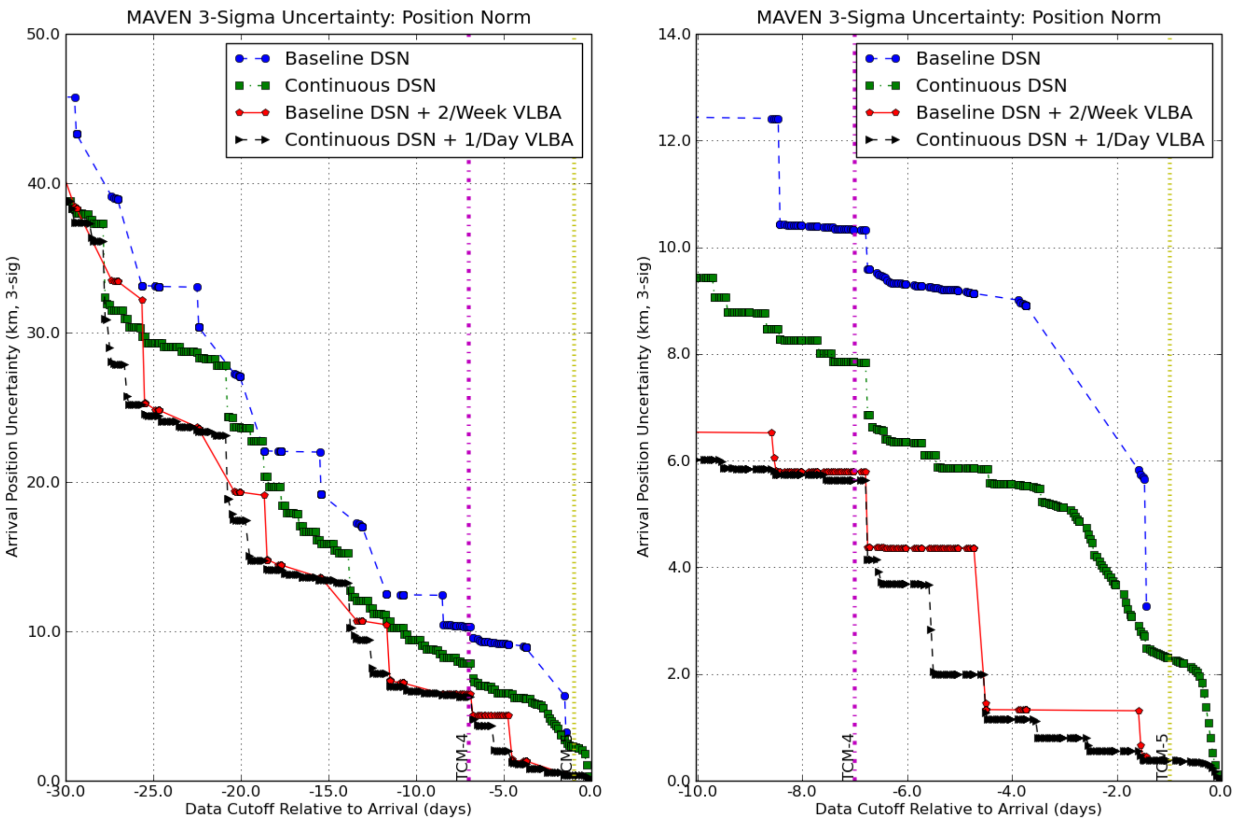

Fig. 5: MAVEN position knowledge uncertainty with various tracking data combinations, mapped to Mars arrival

6. OTHER FUTURE MARS APPROACH OPPORTUNITIES

The 2016 Mars transfer Type II opportunities will result in a Mars declination at arrival that could be as low as -25.8 degrees, but it should be possible to use the VLBA with short observing sessions. The 2018, 2020 and 2022 opportunities can result in positive Mars declinations at the arrival time, and these opportunities are also more favorable for landed missions, due to the potentially lower arrival speed. VLBA could be used for these opportunities to reduce the entry knowledge error and facilitate a more precise guided landing.

7. CONCLUSION

Using the VLBA in combination with the DSN to support the approach navigation of Mars missions can improve the accuracy of the navigation solutions when compared with just using Doppler, range and ΔDOR from the DSN. The greatest benefit is in the improvement of the trajectory prediction, as it can help improve the knowledge of the spacecraft state at entry in order to better initialize the EDL sequence. This benefit is also greater when the spacecraft dynamics are less predictable, as is the case for 3-axis stabilized spacecraft without reaction wheels, or when a fast turnaround solution is required to recover the knowledge of the trajectory, such as right after a contingency maneuver or an unexpected spacecraft event. Use of VLBA could also significantly reduce the need for DSN tracking passes, freeing the DSN antenna time so it can be used to support other missions.

8. ACKNOWLEDGMENTS

We would like to express our appreciation to the advocacy of the use of VLBA for navigation tracking, and for the continuous encouragement and support, from Barry Geldzahler (NASA) and Jim Ulvestad (NRAO). We acknowledge our colleagues at NRAO for the excellent work supporting the VLBA spacecraft experiments, especially Jon Romney and Ed Fomalont, as well as our JPL colleagues Jim Border, Chuck Naudet and Bill Folkner for their help understanding and processing the VLBA data.

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

9. REFERENCES

[1] Napier, P.J., "The Very Long Baseline Array", Proc. IEEE, 82, 658.

[2] Martín-Mur, T., et al, "Use of Very Long Baseline Array Interferometric Data for Spacecraft Navigation", *Proceedings of the 25th International Symposium on Space Technology and Science*, Kanazawa, Japan, May 4-11, 2006

[3] Edwards, C.D. et al, "Spacecraft-Spacecraft Very Long Baseline Interferometry for Planetary Approach Navigation", AAS 91-181

[4] Fey, A.L. et al, "The Second Extension of the International Celestial Reference Frame: ICRF-Ext-1", 2004, AJ, 116, 3587

[5] Highsmith, D., et al, "Mars Reconnaissance Orbiter Navigation During the Primary Science Phase", AIAA 2008-6422

[6] Portock, B.M., et al, "Navigation Challenges of the Mars Phoenix Lander Mission", AIAA 2008-7214

[7] Ryne, M., et al, “Orbit Determination for the 2007 Mars Phoenix Lander”, AIAA 2008-7215

[8] D’Amario, L.A., “Mission and Navigation Design for the 2009 Mars Science Laboratory Mission”, IAC-08-A3.3.A1