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VENUS ATMOSPHERIC PROBE AND FLYBY RELAY SPACECRAFT CROSS-LINK TRACKING IMPACT ON RELATIVE POINTING ACCURACY

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Scientific exploration of Venus using an atmospheric probe requires relaying telemetry to Earth as the probe descends through the atmosphere to the surface of Venus. Using the flyby spacecraft to relay the probe telemetry to Earth will require precise carrier-to-probe pointing accuracy of the relay spacecraft's antenna. NASA's Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging (DAVINCI) mission uses this carrier-to-probe relay technique. Although DAVINCI includes a coherent cross-link for science, this is not baselined for navigation tracking. This paper explores the potential effectiveness of cross-link tracking for reducing trajectory uncertainty and improving spacecraft-to-probe pointing.

INTRODUCTION

Scientific exploration of Venus by means of a deep atmospheric probe requires an optimal approach for relaying telemetry back to Earth as the probe descends from atmospheric entry interface (EI) to the surface of Venus. One means of accomplishing this is for the flyby spacecraft, which released the probe, to serve as a telecommunications relay link to Earth. This eliminates the need for the descent probe to have a relatively high-power communication capability, with operational success depending on the relative pointing accuracy of the relay spacecraft's antenna. NASA's Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging (DAVINCI) mission (Ref. 1, 2, 3), selected as part of NASA's Discovery Program for launch in 2029, will use this carrier-to-probe communication relay technique. NASA selected DAVINCI in June 2021 for further formulation after an initial concept study to support a June 2029 launch date. DAVINCI's concept for determining sufficiently precise spacecraft-to-probe pointing is based on trajectory uncertainty analysis using radio metric tracking data before and after probe separation from the relay spacecraft collected by NASA's Deep Space Network (DSN). Covariance analyses of the resulting spacecraft and probe predicted trajectories include realistic perturbations from propulsive targeting maneuver execution errors, probe deployment and other dynamic and geometric uncertainties. These analyses yield relative position uncertainties at EI that together provide the pointing accuracy available to support the probe telemetry link using DSN data alone. Because this performance was found to be within requirements, DAVINCI does not baseline the use of any cross-link tracking capability between the relay spacecraft and the probe after separation in order

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to optimize relative pointing, despite using a coherent cross-link Doppler link for science data collection.

This paper explores the potential effectiveness of cross-link tracking data for reducing the trajectory uncertainty and thereby improving the relative pointing between a Venus probe and flyby relay spacecraft. It uses the DAVINCI mission's Venus approach and flyby timeline of events as an example along with the trajectory for the proposed probe EI crossing on April 10, 2028. A future study will focus on the current mission's trajectory, which has a probe EI crossing on June 21, 2031. In this study the EI is defined as the point where the probe trajectory crosses an altitude of 145 km above the surface of Venus. This is considered to be above the sensible atmosphere for drag perturbations. The covariance study of the proposed trajectory includes a parametric sweep of various precisions for spacecraft-to-probe ranging and Doppler tracking data types, used both individually and combined in an orbit determination (OD) filter. In all cases, the time between probe deployment or separation (SEP) from the relay spacecraft and EI is 48 hours, and the divert maneuver for the relay spacecraft is 2 hours after SEP at EI-46h, as currently planned for DAVINCI. The mission event times for the proposed trajectory are shown in Table 1.

Table 1. Venus Probe Mission Event Timeline

Mission Event:	**Case 1: Entry April 10, 2028 (times in ET)**
Launch of S/C-Probe	May 25, 2026 23:45:36.0
Start of Venus Approach Arc	February 12, 2028 10:00:00
S/C Probe Separation (SEP)	April 8, 2028 10:18:14.5
S/C Divert	April 8, 2028 12:18:20.3
Atmospheric Entry Interface (EI)	April 10, 2028 10:18:14.5

ANALYSIS ON APPROACH TO VENUS

The covariance analysis in this paper is divided into two parts and OD filter runs. The first part uses a DSN tracking data arc that starts approximately two months before the Venus atmospheric EI and continues up to the S/C Probe Separation (SEP). The second part studies the trajectory uncertainties of the S/C and Probe separately in a combined OD filter setup that uses the state and fully correlated covariance from the first result as *a priori* for the OD filter in the subsequent portion of the study. This OD filter can not only produce individual trajectory uncertainties for the S/C and Probe relative to Venus, but also compute the relative trajectory uncertainty between the S/C and Probe. The analysis first computes the mapped state covariance of the joined S/C-Probe at a time just before the S/C separates from the Probe for each trajectory. Then the covariance matrices are used as the *a priori* uncertainty for the subsequent OD filter for each study case that includes not only the DSN tracking of the S/C but also simulated cross-link tracking between the S/C and Probe. As noted in the Introduction, the Probe cannot be directly tracked by the DSN.

The OD filter setup for the approach phase before SEP is based on realistic DSN tracking used in the DAVINCI proposal and Concept Study Report. The nominal force models used in propagating the DAVINCI trajectory in the navigation software and the uncertainties applied to each of these models and to the simulated OD tracking data are summarized in Table 2.

Table 2: DAVINCI S/C-Probe Approach covariance analysis uncertainties.

	Error Source	*a priori* Uncertainty (1- σ)	Correlation Time	Update Time
Dynamic	Position	100 km	-	-
	Velocity	0.1 m/s	-	-
Stochastic	3-Axis Accelerations	3x10-12 km/s^2	0 hours (white)	6 hours
	Solar Pressure Scale	5%	3 days (exp. correlated)	1 day
	Per-pass range biases	28 Range Units	0 hours (white)	every pass
Constant Bias	Solar Pressure Scale	20%	-	-
	Venus GM	0.1 km^3/s^2	-	-
	Impulsive TCMs	From Monte Carlo	-	-
Consider	Earth Ephemeris	DE423[4] scaled x2	-	-
	Venus Ephemeris	DE423[4] scaled x2	-	-
	DSN Station Locations	Ref. 5	-	-
	UT1	2.5 cm	-	-
	Earth Pole X,Y	0.2 cm, 0.2 cm	-	-
	Troposphere (dry, wet)	1 cm, 1 cm	-	-
	Ionosphere (day, night)	5.5 cm, 1.5cm	-	-

COVARIANCE RESULTS

Selected results from a preliminary study (performed in 2020) for the DAVINCI probe arrival at Venus in 2028 are analyzed. This covariance analysis includes realistic constraints on both DSN tracking of the relay S/C and on the S/C-probe cross-link tracking. Every filter case includes a common *a priori* covariance at SEP that came from a simulation of tracking and targeting maneuvers for the combined S/C-with-probe on approach to Venus. A conservative Doppler-only cross-link tracking uncertainty of 7.5 mm/s (1-σ) gives a slightly improved result over not having any cross-link tracking. Greater improvement is expected while using more precise Doppler cross-link tracking and by adding a ranging data type on the cross-link. The cross-link tracking for the preliminary study cases is assumed to occur only at the three pre-planned 20-minute communication checks before probe entry, so increasing the quantity of tracking by extending the arc length or tracking continuously should also improve the result. This may not be possible for DAVINCI due to other constraints, but this study is only using DAVINCI as an example for the test cases.

The details of the covariance analysis filter setup, the resulting effect of cross-link Doppler on the separate Venus-relative state estimate errors for the S/C and probe individually, and the effect of cross-link Doppler on the relative state estimates for probe position uncertainty relative to S/C are shown in the sub-sections below. Most covariance cases studied here assumed a ground-in-the-loop concept of operations so the nominal data cut-off (DCO) at EI-18hr allowed time to acquire cross-link tracking, downlink it, process it on the ground, and uplink the improved pointing information. To see how an on board, autonomous system for pointing improvement would compare to this, a later section looks at real-time state filter results with DCOs at EI-12hr, EI-6hr, EI-2hr, and EI-1hr. The filter setup for all the following test cases for improvement use the following assumptions:

<u>Filter setup: S/C DSN tracking and S/C-to-probe Doppler tracking, from SEP to EI.</u>

Basic Study Assumptions:

- Uses the originally proposed DAVINCI 2026 Launch Trajectory with initial carrier-with-probe wet mass of 2011 kg and EI on 10-APR-2028 10:18:14.5
- Consider the Earth-Venus ephemeris covariance for DE423 scaled up by 2 (for conservatism)
- Estimate stochastic S/C accel & solar radiation pressure (SRP) scale coefficient
  S/C, probe 3-D stochastic acceleration at 3x10-12 km/s^2 (1-σ), 6 h batch, tau=0. (white)
  S/C, probe SRP scale coefficient stochastic scale at 5%, 1 day batch, tau = 3 days (exponentially correlated)
- Estimate divert maneuver with 1-σ uncertainty of RA, Dec, magnitude (0.2 deg, 0.2 deg, 2.3 cm/s)
- DSN Doppler, ranging tracking of S/C (weighted at 0.1 mm/s, 200 m).
- S/C-to-probe Doppler weighted at 0.1 mm/s to 7.5 mm/s for 60 s count times (weight varies for the parametric studies).
- Final DCO at EI – 18 hr (to allow for downlink of cross-link data, ground processing, and uplink of improved pointing).
- S/C-Probe Doppler tracking in three 20-minute arcs starting at EI-1.5d, EI-1.0d, EI-17.6h; weight at 7.5 mm/s.
- Fix S/C filter epoch by re-integrating it starting at SEP (to match epochs with the Probe integration).

Filter results: Venus-relative position uncertainties for S/C and Probe separately and Probe uncertainties relative to the S/C from SEP to EI <u>without</u> cross-link tracking.

As mentioned above, a filter run called the 'baseline' case was made without any S/C-to-probe cross-link Doppler or ranging to show the effect of only the *a priori* uncertainties at SEP on the Probe uncertainty relative to the S/C. Note this mapping of Probe position and velocity uncertainty also accounts for the S/C position and velocity uncertainty. For insight into the effect of the DSN tracking (and in the next section the cross-link tracking), the individual uncertainties in the S/C and Probe relative to Venus are also shown over the SEP to EI study arc. The uncertainty in the S/C position and velocity relative to Venus due to *a priori* uncertainties and DSN tracking of the S/C only over the study arc are shown in Figure 1. The uncertainty in the probe position and velocity relative to Venus due to only *a priori* uncertainties over the study arc are shown in Figure 2.

The uncertainties are shown in coordinates either centered at Venus for the S/C and Probe individually or centered at the S/C for the Probe errors relative to the S/C. The coordinate axes for the individual S/C and Probe uncertainties shown in Figure 1 and Figure 2 for the S/C and Probe, respectively, have the 'R' direction from Venus to S/C or probe, 'H' is the direction of angular momentum of the relative velocity of the S/C or probe about Venus, and 'HxR' completes the right-handed Cartesian coordinate system triad (R, HxR, H).

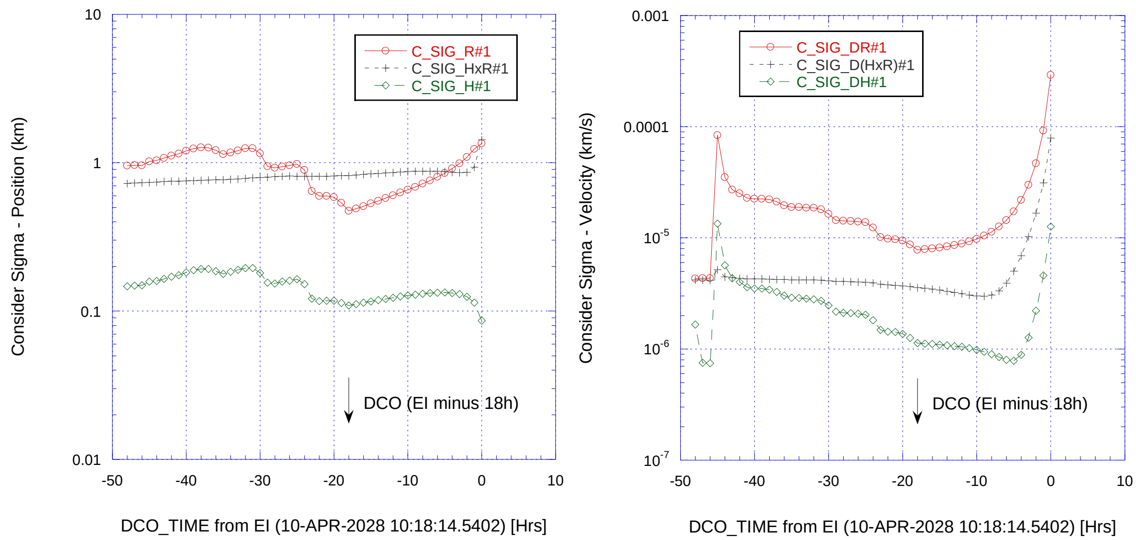

Figure 1. Baseline Case: Position and velocity uncertainty (1-σ) of S/C from Probe Separation (EI-48h) to EI *with DSN tracking only*. Venus-centered [R,HxR,H] coordinates.

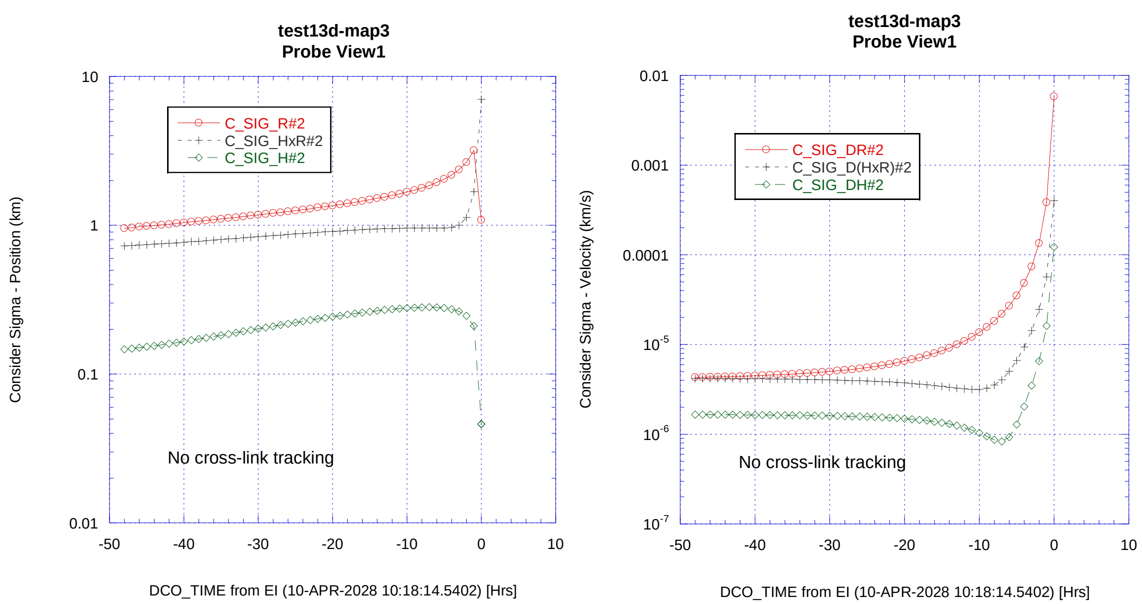

Figure 2. Baseline Case: Position and velocity uncertainty (1-σ) of Probe from Probe Separation (EI-48h) to EI *with no tracking*. Venus-centered [R,HxR,H] coordinates.

The probe position and velocity uncertainties relative to the S/C are shown in Figure 3. The coordinate axes for the relative uncertainties shown in Figure 3 have the 'R' direction from S/C to probe, 'H' is the direction of angular momentum of the relative position and velocity of the probe about the S/C, and 'HxR' completes the right-handed Cartesian coordinate system triad (R, HxR, H). The important uncertainty directions for S/C-to-probe pointing are the two directions, HxR and H, that are orthogonal to the line-of-sight, or R vector. Note further that the coordinate's direction definition depends on the center, Venus or S/C, that is specified for Figure 1, Figure 2 and Figure 3. Hence, the 'R' and 'H' directions for the S/C and the probe are not the same as they are on slightly different trajectories after separation, and greatly different trajectories after the S/C divert maneuver.

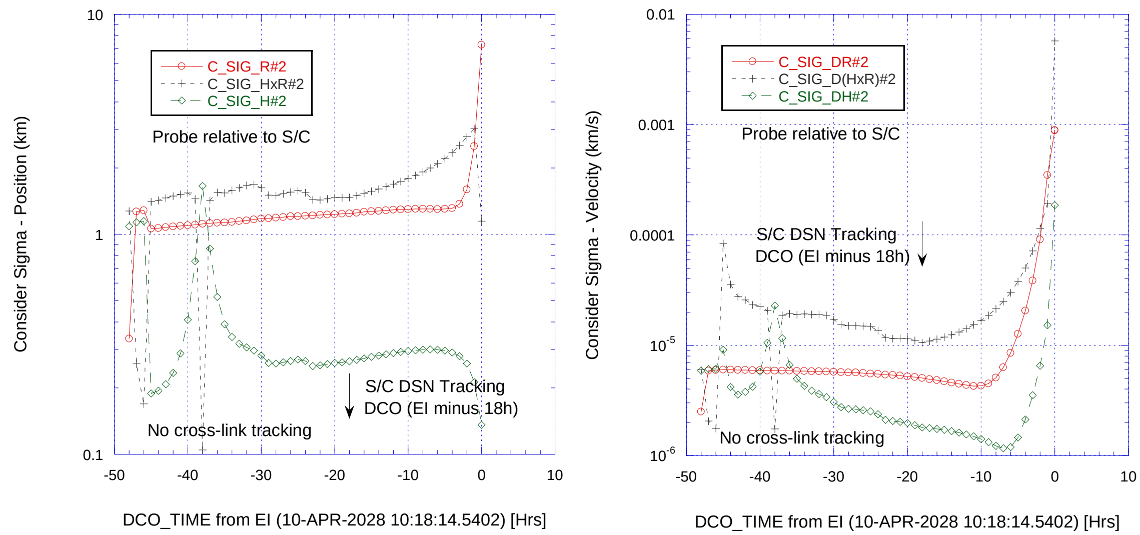

Figure 3. Baseline Case: Relative position and velocity uncertainty (1-σ) of Probe relative to the S/C from probe separation (EI-48h) to EI *with no cross-link tracking, but S/C DSN tracking is included*. S/C-centered [R,HxR,H] coordinates for the Probe.

Figures 1-3 show the evolution of the relative position error as the S/C and probe separate at EI-48h and the S/C divert burn is executed at EI-46h. The divert burn effect on the relative velocity error is evident in the abrupt growth in HxR velocity uncertainty (black '+'s) at EI-46h. There is an exchange of the HxR and H coordinates due to the relative motion at EI-38h and also somewhere between EI-1h and EI as seen by the crossing of the 'R' and 'HxR' plots from EI-1h to EI.

Filter results: Venus-relative position uncertainties for S/C and Probe separately and Probe uncertainties relative to the S/C from SEP to EI <u>with</u> cross-link tracking.

The first study of the effectiveness of cross-link tracking uses minimal cross-link tracking (in order to conserve Probe battery power) and an assumption of weighting Doppler tracking data at a conservative 7.5 mm/s. The tracking schedule includes three 20-minute cross-link data arcs spaced over the SEP to EI timeframe, with a DCO at EI-18hr. The plotted results are nearly identical to the results shown in the previous subsection, so the differences are shown in tabular form for the S/C and Probe separately with and without the cross-link tracking in Table 3. The (R, HxR, H) coordinate axes for the individual S/C and Probe uncertainties are the same as those used in the previous section.

The improvement in relative error for this test case is computed using the baseline case of no cross-link tracking discussed in the previous section and as shown in Figure 3. The differences and computed percentages of improvement over the baseline when including the cross-link Doppler tracking (weighted at 7.5 mm/s) are shown in Table 3. Note that in Table 3 the cross-link tracking has primarily improved the S/C position uncertainty and has relatively little effect on the probe position uncertainties. It appears the cross-link tracking of the probe at EI (145km altitude), which is deeper in the Venus gravity well than the S/C, has helped tie the S/C to Venus and thus improved the S/C position uncertainty.

Table 3. Position uncertainty of S/C and probe relative to Venus at EI, 145km altitude for the initial test of cross-link Doppler weighted at 7.5 mm/s and DCO at EI minus 18 hr.

S/C (With DSN Tracking up to DCO) Position Uncertainty at Entry Interface (EI)				
S/C-to-Probe Doppler tracking	R (1-σ, km)	HxR (1-σ, km)	H (1-σ, km)	Position RSS (1-σ, km)
Without (baseline)	1.347	1.429	0.086	1.966
With	0.940	1.180	0.078	1.510
Improvement	0.407 (30.3%)	0.250 (17.5%)	0.008 (9.8%)	0.456
PROBE				
S/C-to-Probe Doppler tracking	R (1-σ, km)	HxR (1-σ, km)	H (1-σ, km)	Position RSS (1-σ, km)
Without (baseline)	1.087	7.011	0.0461	7.095
With	1.060	6.997	0.0457	7.077
Improvement	0.027 (2.5%)	0.034 (0.2%)	0.0004 (0.9%)	0.018

The position uncertainty of the Probe relative to the S/C at the EI is what drives the initial S/C to Probe pointing uncertainty before encountering the Venus atmosphere, so the corresponding relative uncertainties are shown in Table 4. Note that including the cross-link Doppler tracking improves the lateral components (HxR and H) of uncertainty by about 111 m and 7 m, respectively. This is a 9.7% improvement in HxR uncertainty and a 5.2% improvement in H uncertainty over the baseline case.

Note that for the assumptions given, and mostly due to the large cross-link Doppler uncertainty, the relative error is improved only slightly while including the S/C-to-probe Doppler tracking weighted at 7.5 mm/s. Since the covariance results without cross-link tracking were used to verify the S/C to Probe link design in the proposal, the modest improvement shown here was not sufficient to baseline the cross-link tracking for improving the relative pointing. This result motivated further study to see what improvements could be quantified by increasing the amount of cross-link tracking, by including ranging, or by increasing precision of the measurements. The following sections quantify the improvements associated with each of these modifications to assumptions used in the first study.

Table 4. Relative position uncertainty of probe to S/C at EI, 145km altitude for the initial test of cross-link Doppler weighted at 7.5 mm/s and DCO at EI minus 18 hr.

Probe-to-S/C Doppler tracking	R (1-σ, km)	HxR (1-σ, km)	H (1-σ, km)	Position RSS (1-σ, km)
Without (baseline)	7.271	1.148	0.136	7.362
With	7.188	1.037	0.129	7.263
Improvement	0.083 (1.1%)	0.111 (9.7%)	0.007 (5.2%)	0.099

Parametric Filter Results: Probe uncertainties relative to the Spacecraft with different cross-link tracking data scenarios.

The first parametric study kept the cross-link tracking schedule as used in the 2020 preliminary study, but varied the tracking weight and added ranging to the Doppler tracking. The results are summarized in Table 5 where the percentage improvement in each component of uncertainty as compared to the baseline case is shown in parentheses below each component's uncertainty. Note that all the cases in Table 5 use the basic assumption of a tracking schedule that includes three 20-minute cross-link data arcs spaced over the SEP to EI arc, with DCO at EI-18hr.

Table 5. Relative position uncertainty of probe to S/C at entry interface (EI), 145km altitude for various Doppler and ranging weights all with DCO at EI minus 18 hr.

Probe-S/C Relative Position Uncertainty at Entry Interface (EI)				
S/C-to-Probe Doppler weight	R (1-σ, km)	HxR (1-σ, km)	H (1-σ, km)	Position RSS (1-σ, km)
Baseline	7.271	1.148	0.136	7.362
7.5 mm/s	7.188 (1.1%)	1.037 (9.7%)	0.129 (5.2%)	7.263
1.0 mm/s	7.186 (1.2%)	1.017 (11.4%)	0.127 (6.4%)	7.259
0.1 mm/s	7.184 (1.2%)	0.820 (28.6%)	0.116 (15.0%)	7.232
Addition of Ranging				
S/C-to-Probe Doppler, ranging weight	R (1-σ, km)	HxR (1-σ, km)	H (1-σ, km)	Position RSS (1-σ, km)
0.1 mm/s, 1.0 m	7.123 (2.0%)	0.712 (38.0%)	0.109 (20.1%)	7.159
Ranging only 1.0 m	7.188 (1.1%)	0.799 (30.4%)	0.118 (13.0%)	7.233

Note the best performing case for improvement in the important HxR and H component directions are for combined Doppler and ranging weighted at 0.1 mm/s and 1.0 m, respectively. The time history of Probe relative position uncertainty to the S/C is shown in Figure 4. Comparing this plot to Figure 3 note that the final values of uncertainty in HxR and H components are improved by 38.0% and 20.1%, respectively, as shown also in Table 5.

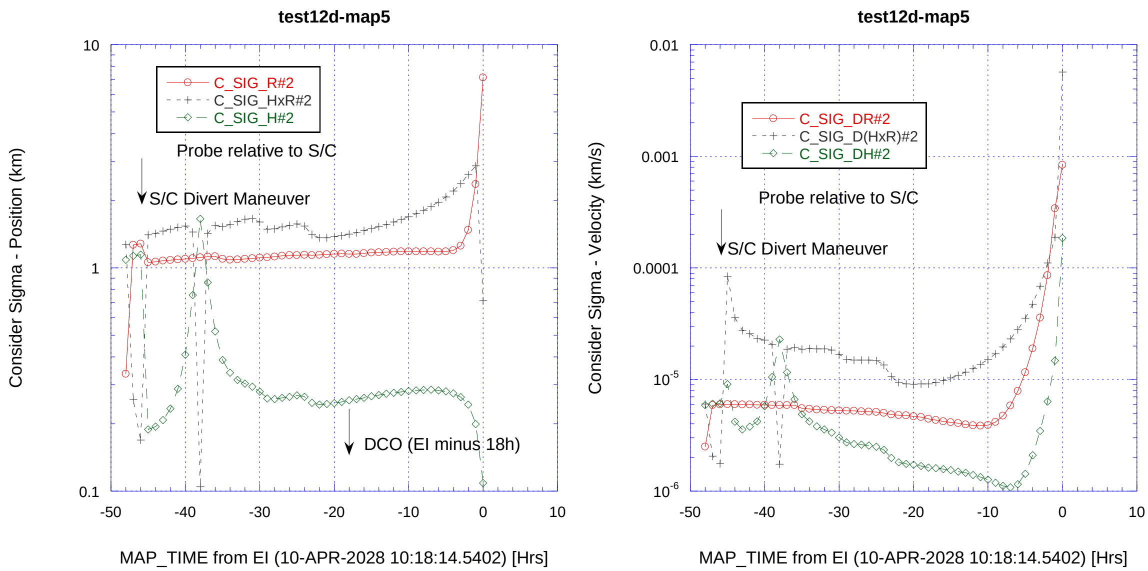

Figure 4. Relative position and velocity uncertainty (1-σ) of Probe relative to the S/C from probe separation (EI-48h) to EI with cross-link Doppler and ranging tracking and S/C DSN tracking. S/C-centered [R,HxR,H] coordinates for the Probe.

A change to the cross-link tracking schedule by making the arc continuous results in a best possible result for a given OD filter setup and DCO. Using the best case from Table 5 with ranging and Doppler weighted at 1.0 m and 0.1 mm/s, respectively, the OD filter was repeated with continuous cross-link tracking for the nominal DCO at EI-18 hr. This run was repeated with a DCO at EI-12 hr to test sensitivity of the results to including more tracking closer to Venus. The results are shown in Table 6. As a reminder, this case is mostly provided as a theoretical peak performance comparison as the Probe battery is unlikely to be able to support this much radio communication.

Table 6. Relative position uncertainty of probe to S/C at EI for continuous cross-link ranging and Doppler (weighted at 1.0 m and 0.1 mm/s, respectively) with nominal and extended DCO.

Probe Relative Position Uncertainty to S/C at Entry Interface (EI)				
DCO	R (1-σ, km)	HxR (1-σ, km)	H (1-σ, km)	Position RSS (1-σ, km)
EI – 18 hr	5.659 (22.2%)	0.367 (68.0%)	0.068 (50.2%)	5.672
EI – 12 hr	5.611 (22.8%)	0.360 (68.6%)	0.068 (50.3%)	5.623

On Board Filter results: Probe uncertainties relative to the S/C with cross-link tracking DCO close to EI.

Examining the time history of uncertainties over the cross-link arc in Figure 1 and Figure 2, it is apparent that the position errors of both S/C and Probe begin to grow after the early DCO at EI-18 hr. This early DCO was required to allow time for downlink, ground processing, and uplink of the improved pointing information for the assumed ground-in-the-loop concept of operations. However, if it were possible to process the cross-link information on board and autonomously compute the pointing improvements, then pointing performance could be improved over the gains shown above because prediction of uncertainty past the DCO is reduced. The following OD filter cases were run to test the theoretical peak improvement possible by extending the data arc closer to EI.

The cases for DCO close to EI start with the continuous tracking, ranging and Doppler, best weighing OD results from Table 6. The data arc for this case is then extended to result in four tests with OD filter DCOs at EI-6 hr, EI-4 hr, EI-2 hr, and EI-1 hr. The study shows sensitivity of the results as the DCO is pushed closer to EI (and to Venus). The results again represent a theoretical peak performance on board and are tabulated in Table 7. The percent uncertainty improvements are relative to the baseline case. Notice that even at 2 hours before EI, the

Table 7. Relative position uncertainty of probe to S/C at EI for continuous cross-link ranging and Doppler (weighted at 1.0 m and 0.1 mm/s, respectively) with later DCO times.

Probe-S/C Relative Position Uncertainty to at Entry Interface (EI)				
DCO	R (1-σ, km)	HxR (1-σ, km)	H (1-σ, km)	Position RSS (1-σ, km)
EI – 6 hr	1.141 (84.3%)	0.596 (48.1%)	0.0494 (63.7%)	1.289
EI – 4 hr	0.786 (89.2%)	0.344 (70.1%)	0.0458 (66.4%)	0.859
EI – 2 hr	0.101 (98.6%)	0.0302 (97.4%)	0.0395 (71.0%)	0.113
EI – 1 hr	0.0129 (99.8%)	0.0132 (98.9%)	0.0386 (71.7%)	0.043

Another case that uses only cross-link Doppler weighted at 7.5 mm/s, based on the first case shown in Table 4, shows the gains in relative position uncertainty possible when using real-time, on board processing. This is a more realistically achievable scenario for DAVINCI since it conserves probe battery power over the continuous tracking scenarios of the theoretical peak performance cases shown in Table 7. The tracking schedule for this new case includes three 20-minute cross-link data arcs spaced over the SEP to EI timeframe like the first case except the third 20-minute cross-link pass has a DCO at EI-1hr. The results shown in Table 8, while not as good as the continuous cross-link ranging and Doppler in Table 7 (with DCO EI-1h), does indicate a notable improvement over the ground-in-the-loop results shown in Table 4. The ground-based use of three 20-minute arcs of cross-link Doppler weighted at 7.5 mm/s with DCO at EI-18h results in a HxR relative position uncertainty of 1.037 km, 1-σ (Table 4) while the on board equivalent with DCO at EI-1h results in 395 m, 1-σ (Table 8). The HxR position component uncertainty is the largest contributor to the pointing uncertainty in both cases. A further reduction of the Doppler weighting to 1.0 mm/s was also tested for this case scenario, and the results are shown in Table 8, last row. This further reduces the HxR position component uncertainty from 395 m to 257 m, 1-σ.

The on board case relative position uncertainty results with Doppler weighted 1.0 mm/s are shown in Figure 5. Comparing Figure 5 to Figure 4 shows the improvement in relative position uncertainty available on board and with a modest improvement in Doppler precision (from 7.5 mm/s to 1.0 mm/s, 1-σ). The improvement in relative velocity uncertainty is especially evident in Figure 5 in the radial component where a reduction occurs during each of the three 20-minute passes of cross-link Doppler. The effect of moving the third 20-minute cross-link arc DCO to EI-1hr shows an overall reduction in relative position uncertainty in Figure 5 relative to Figure 4 as the probe nears the EI.

Table 8. Relative position uncertainty of probe to S/C at EI, 145km altitude for the on board test of cross-link Doppler weighted at 7.5 mm/s and 1.0 mm/s and DCO at EI minus 1hr.

Probe-to-S/C Doppler tracking	R (1-σ, km)	HxR (1-σ, km)	H (1-σ, km)	Position RSS (1-σ, km)
Without (baseline)	7.271	1.148	0.136	7.362
7.5 mm/s weight DCO EI – 1 hr	0.686 (90.6%)	0.395 (65.6%)	0.066 (52.1%)	0.794
1.0 mm/s weight DCO EI – 1 hr	0.505 (93.0%)	0.257 (77.6%)	0.062 (54.3%)	0.571

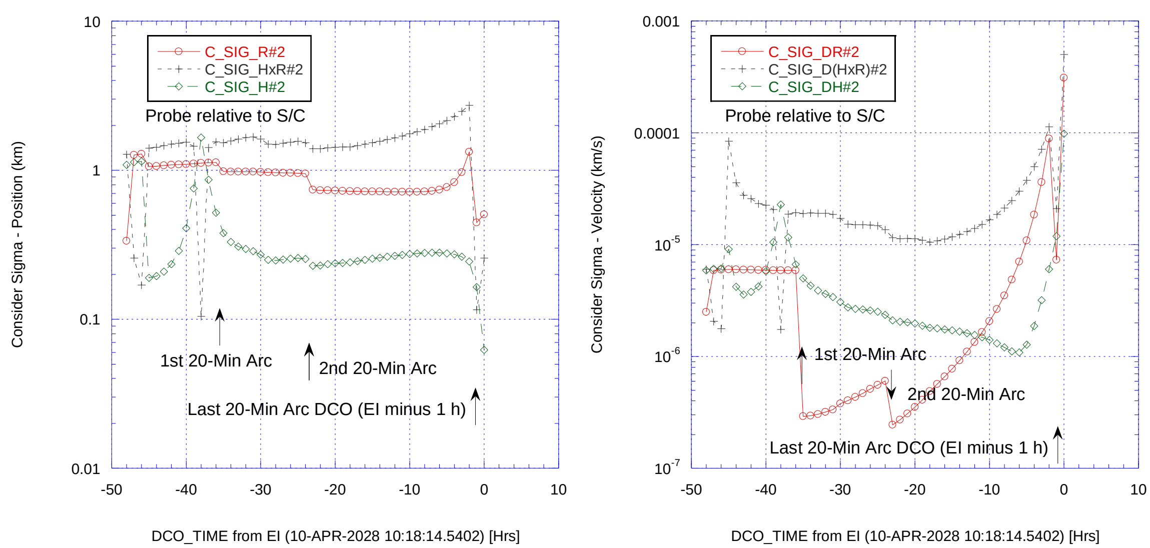

Figure 5. Relative position and velocity uncertainty (1-σ) of Probe relative to the S/C from probe separation (EI-48 hr) to EI with cross-link Doppler weighted at 1.0 mm/s and S/C DSN tracking. S/C-centered [R,HxR,H] coordinates for the Probe.

SUMMARY

Preliminary results performed during the DAVINCI concept study report motivated a parametric study not only for improvements in the Doppler cross-link tracking precision but also for the addition of cross-link ranging at various precisions. It was demonstrated that improved tracking precision will result in more significant improvements in the relative position estimates for relay spacecraft and probe and this would produce improved pointing uncertainties from EI to the surface of Venus. This would increase the maximum transmission of scientific data from the instrument-rich DAVINCI probe mission descent trajectory which includes the potential for hundreds of descent NIR Images (Ref. 2).

One feature of the S/C-Probe relay pointing analysis thus far has been that it assumes ground processing of the cross-link tracking. This means the tracking and uplink timeline must accommodate not only expected navigation processing time on the ground, but also one-way light times for the downlink of tracking data and the uplink of new pointing information. The covariance analysis "current state" results are obtained from the existing analyses by requesting additional output from the orbit determination filter. Results above show that for three 20-minute cross-link Doppler arcs weighted at 7.5 mm/s the relative position 1-σ uncertainty at EI may be reduced from about 1 km to about 400 m in the HxR component by including the last 20-minute arc at EI-1h in the onboard OD filter.

An onboard, autonomous, current-state navigation solution for relay spacecraft and probe relative position should have more precise estimates and would result in more precise pointing than the ground pointing solution because it would not need to include time-forward trajectory prediction due to relay and processing time delays. This would be particularly beneficial for the probe during its descent through the atmosphere where position uncertainties are larger. In addition, autonomy of pointing to maximize the radio gain could be aided and made more robust to local maxima due to locking up on a side lobe by including information from an onboard OD filter solution and associated uncertainties of the estimated pointing direction of the S/C to probe. The cross-link tracking could thus provide independent verification of an autonomous attitude correction based strictly on searching for a maximum antenna gain.

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