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Using Connected-Element Interferometer Phase-Delay Data for Magellan Navigation in Venus Orbit

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The pointing accuracy needed to support Magellan's Synthetic Aperture Radar mapping of Venus places stringent requirements on navigation accuracy. This need is met with a combination of two-way Doppler and narrowband Δ Very Long Baseline Interferometer (ΔVLBI) data, which are capable of determining the spacecraft's orbit to the required level, typically about one-kilometer position uncertainty. Differenced Doppler (two-way Doppler minus three-way Doppler) is also capable of meeting mission navigation requirements, and serves as a backup to narrowband ΔVLBI. The Magellan Project specifies that the turn-around time for processing narrowband ΔVLBI data must be 12 hours or less, a very difficult requirement to meet operationally. In this article, the use of phase-delay data, taken from a Connected-Element Interferometer (CEI) with a 21-km baseline, for Magellan orbit determination was investigated to determine if navigation performance comparable with narrowband ΔVLBI and differenced Doppler could be achieved. CEI possesses an operational advantage over ΔVLBI data in that the observables are constructed in near-real time, thus greatly reducing the turn-around time needed to process the data, relative to the off-line system used to generate ΔVLBI observables. Unfortunately, the results indicate that CEI data are much less powerful than narrowband ΔVLBI and differenced Doppler for orbiter navigation, although there was some marginal improvement over the navigation performance obtained when only two-way Doppler data were used.

I. Introduction

Magellan will arrive at Venus in August 1990, and after a short period of time devoted to orbit trim and systems checkout, the spacecraft will begin its 243-day primary mission phase, the mapping of Venus. Navigation of Magellan will be very challenging due to the high pointing accuracy required by the Synthetic Aperture Radar (SAR) system. The SAR pointing accuracy requirements correspond to a navigation accuracy of about a one-kilometer (1σ) position uncertainty at periapsis. Furthermore, this level of performance must be maintained over most of the primary mission, except for an 18-day period around superior conjunction, during which mapping operations are suspended.[1]

[1] S. Mohan, et al., "Magellan Navigation Plan," JPL D-1480 (internal document), Revision B, Jet Propulsion Laboratory, Pasadena, California, March 23, 1988.

Navigation studies carried out early in Magellan's history[2] discovered that Doppler-based orbit determination, which had been sufficient for previous missions such as Mariner–Mars '71 and Viking, would not meet navigation requirements and that new radio metrics, such as narrowband Δ Very Long Baseline Interferometry (ΔVLBI) and differenced Doppler, would be needed [1]. It is now well known that the orbit determination accuracy obtained with two-way Doppler is dependent on the orbit orientation with respect to the plane of the sky, which is the plane perpendicular to the Earth–spacecraft line of sight [2,3]. Recent studies done in support of Magellan navigation planning[1] [4] show that the combination of either narrowband ΔVLBI or differenced Doppler with two-way Doppler produces improvements of a factor of 2 to 10 in orbit determination uncertainty over Doppler-only navigation.

The major drawback involved with the use of narrowband ΔVLBI data is the time required to process the raw measurement data into observables. The Magellan Project requires a turn-around time of 12 hours for each of the two narrowband ΔVLBI scans scheduled daily during the primary mission. Connected Element Interferometry (CEI), a new technique currently under development, can be used to generate medium accuracy (100–400 nrad for individual measurements) angular observations in near-real time, using relatively close (10–100 km apart) stations [5]. This study investigated the possibility that CEI angular measurements could be used to infer angular rate information, which is directly observed with narrowband ΔVLBI. It was hoped that this approach might be capable of producing orbit determination accuracy comparable with that of ΔVLBI, thus offering an alternative data type for Magellan navigation that would reduce the operational strain imposed on the Deep Space Network (DSN).

II. The Magellan Venus Mapping Orbit

Magellan orbital elements relative to Venus' equator are given in Table 1. Since Venus has a nearly spherical gravity field, the spacecraft's orbit remains nearly fixed in orientation with respect to Venus throughout the primary mission. The mapping orbit's orientation with respect to the plane of the sky does, however, change during the primary mission due to the relative motion of Venus and the Earth. The orbit geometry chosen for analysis in this study represents Magellan's orbit as seen from the Earth on December 4, 1990, 120 days after Venus Orbit Insertion (VOI+120). Table 2 gives the orbital elements in the plane-of-the-sky coordinate system for this date.

III. Tracking Schedule

Nominally, trajectory solutions for Magellan are generated daily, based on 24 hours of continuous two-way Doppler data from Deep Space Stations (DSSs) 14, 42, and 61 and on two 10-minute ΔVLBI scans using the baselines defined by DSS 14 to 42 and DSS 14 to 61, taking place during the same 24-hour period. Doppler data are not taken for a 1-hour period centered about each periapsis, since the spacecraft's antenna is pointed at Venus during that time. Doppler data are also not taken from 10 minutes before to 5 minutes after each apoapsis while a star sighting is being done to update the spacecraft's inertial attitude reference system.[3] Since Magellan's orbit period is 3.15 hours, the data going into each trajectory solution are spread over just under eight revolutions. There are certain time periods within the primary mission in which the declination of the spacecraft is too low for it to be viewed from the DSS 14 to DSS 61 baseline, thus leaving out one of the two daily ΔVLBI scans. The epoch for this investigation, December 4, 1990, was intentionally chosen during one of these periods in which only one ΔVLBI baseline is available, since it is these periods in which the mission navigation requirements can only marginally be met.

Simulated CEI data were generated using the DSS 13 to DSS 15 baseline within the Goldstone DSN complex. This baseline is 21 kilometers in length and is oriented in a near north–south direction. During the 24-hour period used in the study, the spacecraft was in view of DSS 13 to DSS 15 for just under three revolutions, with a total view time of six hours available, subject to the restrictions described above regarding time periods during which the spacecraft could not be tracked. Two different CEI data rates were used in the CEI navigation simulations, either 5 points/hour or 10 points/hour.

One case was studied which included differenced Doppler data (two-way Doppler minus three-way Doppler) in place of narrowband ΔVLBI data. The data schedule for this case contained the Doppler data from the baseline case plus one pass (approximately two hours) of differenced Doppler data using the DSS 14 to DSS 42 baseline. Differenced Doppler data are constructed by differencing the Doppler signal received at a Deep Space Station operating in a coherent (two-way) mode with the Doppler signal received at another, distant station (known as "three-way"

[2] J. Ellis and R. Russell, "Earth-Based Determination of a Near-Circular Orbit About a Distant Planet," JPL Technical Memorandum 391-406 (internal document), Jet Propulsion Laboratory, Pasadena, California, March 9, 1973.

[3] S. Mohan, et al., op. cit.

Doppler). In theory, the information content of differenced Doppler data is equivalent to that of narrowband ΔVLBI data. In practice, the narrowband ΔVLBI data are more accurate due to the cancellation of the effects of several error sources common to both receiving stations through the use of a quasar (extragalactic radio source, or EGRS). Because of this, it is necessary to obtain more differenced Doppler data than narrowband ΔVLBI data to get comparable navigation performance.

IV. Filter Model

A. Type

The filter used was a batch-weighted, least-squares, with the exception that narrowband ΔVLBI and differenced Doppler data were processed sequentially due to the presence of stochastic parameters, as noted below.

B. Estimated Parameters

(1) Spacecraft epoch state vector.

(2) Venus harmonic gravity coefficients up to degree 3, order 3.

(3) Spacecraft drag coefficient.

(4) Stochastic station oscillator frequency error—this parameter is only included for cases with narrowband ΔVLBI data.

(5) Stochastic troposphere error—this parameter is also included only for cases with narrowband ΔVLBI data.

(6) Stochastic Doppler frequency error—this parameter is only included for the cases with differenced Doppler data.

C. Considered Parameters

(1) Venus harmonic gravity coefficients of degree and order 4–5.

(2) Mass of Venus.

(3) Seven mass concentrations *(mascons)*, see Table 3 for a list detailing the name, location, size, and a priori uncertainty of each.

(4) Station coordinates of DSSs 14 (Goldstone), 42 (Canberra), and 61 (Madrid).

(5) Impulsive maneuver representing daily momentum wheel desaturation.

(6) Quasar location uncertainty (right ascension and declination).

D. Data Accuracy

(1) Two-way Doppler: 10.0 mm/sec (60-sec count time).

(2) Narrowband VLBI: 0.13 mm/sec (equivalent to 1 mHz).

(3) Differenced Doppler: 0.39 mm/sec (equivalent to 3 mHz).

(4) CEI phase-delay: 1 mm (50 nrad, 4 mm (200 nrad), or 8 mm (400 nrad).

V. A Priori 1σ Uncertainties

A. Estimated Parameters

(1) Spacecraft epoch state: 10^6 km in position and 1 km/sec in velocity.

(2) Venus 3 × 3 gravity harmonics.[4]

(3) Spacecraft drag coefficient: 0.5 (50-percent uncertainty).

(4) Stochastic station oscillator frequency error: the σ of this parameter is zero except during the 10-min ΔVLBI scan, when the σ = 0.3538 mHz, with a time constant τ = 27.6 sec.

(5) Stochastic troposphere error: this parameter also has a σ of zero except during the ΔVLBI scan, during which the σ = 1.223 mHz, with a time constant τ = 60.7 sec.

(6) Stochastic Doppler frequency error: the σ is zero except during the differenced Doppler pass, during which it has a σ = 0.55 mHz, with a time constant τ = 3604 sec.

B. Considered Parameters

(1) Remaining Venus gravity harmonics up to 5 × 5.[4]

(2) GM of Venus: 1.0 km^3/sec^2.

(3) Mascons: see Table 3.

(4) Station coordinates for DSSs 14, 42, and 61:

Coordinate	14	39	54
Spin rad., m	0.74	0.81	0.79
Z-height, m	8.70	8.70	8.70
Long., deg	1.8×10^{-5}	2.1×10^{-5}	2.2×10^{-5}

(5) Momentum wheel desaturation burn: 8.3×10^{-7} km/sec.

[4] Ibid., Appendix E.

(6) Quasar location uncertainty: 167 nrad in both right ascension and declination.

VI. Results

A total of eight simulation cases was run, all using the Magellan delivery of the Orbit Determination Program on a Sun 3/260 workstation. Table 4 contains a summary of the results, with navigation performance being defined in terms of the 1σ uncertainty in the longitude of the ascending node in the plane of the sky, the dominant orbit-determination error. Figure 1 shows a graphic comparison of the eight cases. This figure shows that, of the five cases run using simulated CEI data, only one yielded results that were appreciably better than the Doppler-only case. Recalling that only one scan of narrowband ΔVLBI data was included in the ΔVLBI case (taken from the DSS 14 to DSS 42 baseline; the spacecraft cannot be viewed from the DSS 14 to DSS 61 baseline at this time), Fig. 1 shows that the performance obtained using two hours of differenced Doppler data was actually better than that obtained with ΔVLBI data. This is not always the case however, when narrowband ΔVLBI scans can be taken using both the DSS 14 to DSS 42 and the DSS 14 to DSS 61 baselines.

A breakdown of the root sum square (RSS) contribution of different error source groups to the total RSS error in longitude of the ascending node is given in Table 5. Figure 2 shows a graphic version of the data in Table 5, the four cases in the figure corresponding to the four cases in the table. Figure 2 shows clearly that the CEI data are much more sensitive to gravity field uncertainty and mascons than the ΔVLBI data. Even excluding all consider error sources, the comparison of the computed (state-only) solution uncertainty shows that narrowband ΔVLBI data are much more powerful than CEI data in this situation. Further, Fig. 1 shows that, even if the CEI data were accurate to 1 millimeter (which is very optimistic), the sensitivity of this data type to the consider errors becomes extreme.

VII. Conclusions

An error analysis was conducted to determine the usefulness of CEI phase-delay data in the navigation of the Magellan mission. The results indicate that CEI data are much less capable than narrowband ΔVLBI and differenced Doppler data in this situation, both in information content, which is reflected in the comparison of computed solution uncertainties, and in sensitivity to consider error sources such as gravity field uncertainty. Based on the results presented in this article, this data type would likely not be capable of meeting Magellan navigation requirements during any portion of the primary Venus mapping mission.

References

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[2] L. Wood, "Orbit Determination Singularities in the Doppler Tracking of a Planetary Orbiter," *Journal of Guidance, Control and Dynamics,* vol. 9, no. 4, pp. 485–494, July–August 1986.

[3] R. Russell and S. Thurman, "An Analytic Development of Orbit Determination for a Distant Planetary Orbiter," Paper AAS-89-402, AAS/AIAA Astrodynamics Conference, Stowe, VT, pp. 7–10, August 1989.

[4] P. Esposito and S. Demcak, "Orbit Determination Study Results for the Venus Radar Mapper Orbiter," Paper AAS-85-414, AAS/AIAA Astrodynamics Conference, Vail, CO, pp. 12–15, August 1985.

[5] C. Edwards, "Angular Navigation on Short Baselines Using Phase Delay Interferometry," *IEEE Transactions on Instrumentation and Measurement,* vol. 38, no. 2, pp. 665–667, April 1989.

Table 1. Magellan orbital elements relative to Venus equator

Epoch: December 4, 1990 18:20:42 UTC		
Semi-major axis:	a	10189.7
Eccentricity:	e	0.38168
Inclination:	i	85.9743°
Argument of periapsis:	ω	170.016°
Longitude of ascending node:	Ω	354.205°
Altitude at periapsis:		249.50 km
Altitude at apoapsis:		8027.0 km
Sun-Earth-probe angle:		9.0°

Table 2. Magellan orbital elements relative to the plane of the sky

Epoch: December 5, 1990 22:42:30 UTC		
Semi-major axis:	a	10189.7 km
Eccentricity:	e	0.38168
Inclination:	i	55.7623°
Argument of periapsis:	ω	84.2673°
Longitude of ascending node:	Ω	10.0999°

Table 3. Mascons considered in Magellan orbit determination[a]

Name	Lat, deg	Long, deg	Radius, km	σ km^3/sec^2
Ovda Regio	−5.4	95.6	900	0.040
Leda	42.5	55.2	600	0.012
Hestia	6.4	64.6	350	0.010
Tellus	34.0	83.2	900	0.020
Bell Regio	28.9	49.0	500	0.010
FN27	7.1	78.0	350	0.010
Maxwell	65.0	10.0	900	0.040

[a] All seven mascons have a radial position of 6000 km; for comparison, Venus has a mean radius of 6052 km.

Table 4. Summary of results for all cases

Case	Quasar–S/C Angle, deg	Node Uncertainty, 1σ
CEI 50 nrad, 10 pt/hr	26	0.25650°
CEI 200 nrad, 10 pt/hr	26	0.10530°
CEI 400 nrad, 10 pt/hr	26	0.10140°
CEI 200 nrad, 5 pt/hr	26	0.09959°
CEI 200 nrad, 10 pt/hr	3	0.08809°
Doppler only	–	0.10450°
Doppler + ΔVLBI	26	0.03679°
Doppler + differenced Doppler	–	0.02963°

Table 5. Root-sum-square error breakdown of node error for selected cases

Error Source	RSS Contribution, deg[a]			
	Case 1	Case 2	Case 3	Case 4
Computed	0.0242	0.0479	0.0500	0.0532
Gravity field	0.0195	0.0650	0.0700	0.0801
Mascons	0.0071	0.0229	0.0246	0.0281
Quasar location	0.0183	0.0265	0.0555	0.0158
Station locations	0.0003	0.0001	0.0001	0.0001
Momentum wheel desat	0.0002	0.0008	0.0009	0.0010
RSS total, deg	0.0368	0.0880	0.1053	0.1014

[a]Case 1: Baseline operational case with Doppler, narrowband ΔVLBI
Case 2: Doppler, 4-mm CEI, data rate 10 pt/hr, quasar–S/C angle 3°
Case 3: Doppler, 4-mm CEI, data rate 10 pt/hr, quasar–S/C angle 26°
Case 4: Doppler, 8-mm CEI, data rate 10 pt/hr, quasar–S/C angle 26°

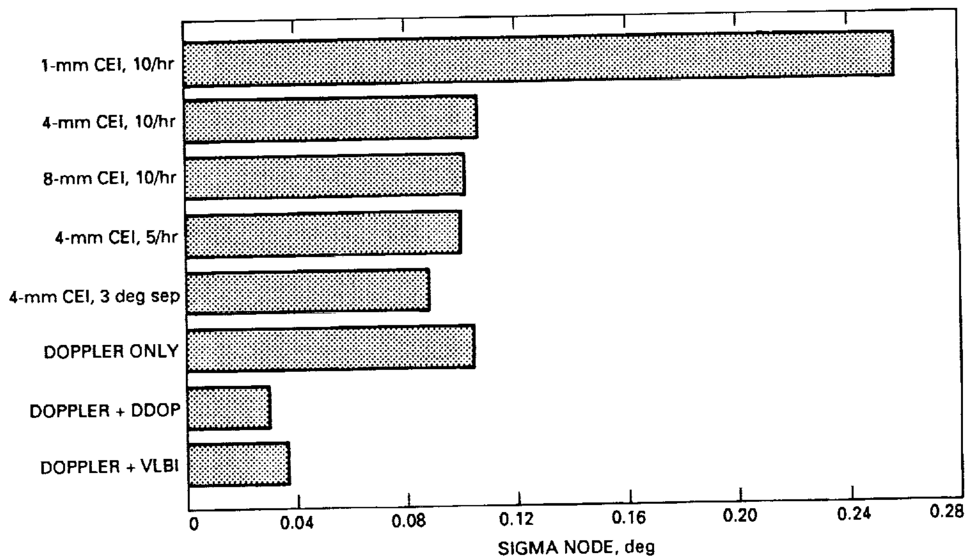

Fig. 1. Navigation performance obtained with different data strategies.

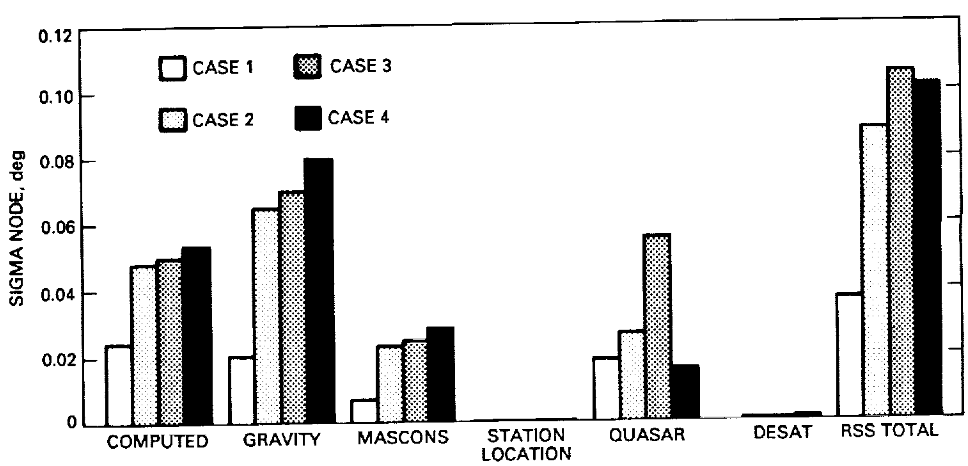

Fig. 2. RSS error breakdown for selected data strategies.