Orbit Determination Issues for Libration Point Orbits

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LIBRATION POINT ORBITS AND APPLICATIONS

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ABSTRACT. Libration point mission designers require knowledge of orbital accuracy for a variety of analyses including station keeping control strategies, transfer trajectory design, and formation and constellation control. Past publications have detailed orbit determination (OD) results from individual libration point missions. This paper collects both published and unpublished results from four previous libration point missions (ISEE 3, SOHO, ACE and MAP) supported by Goddard Space Flight Center's Guidance, Navigation & Control Center. The results of those missions are presented along with OD issues specific to each mission. All past missions have been limited to ground based tracking through NASA ground sites using standard range and Doppler measurement types. Advanced technology is enabling other OD options including onboard navigation using onboard attitude sensors and the use of the Very Long Baseline Interferometry (VLBI) measurement Delta Differenced One-Way Range (DDOR). Both options potentially enable missions to reduce coherent dedicated tracking passes while maintaining orbital accuracy. With the increased projected loading of the DSN, missions must find alternatives to the standard OD scenario.

INTRODUCTION

Orbit determination for libration point orbits (LPOs) is quite unique. The regime is far from the Low Earth Orbits (LEO) typically supported by the Goddard Space Flight Center (GSFC) and far from the interplanetary orbits supported by the Jet Propulsion Laboratory (JPL). The regime offers very little dynamics thus requiring extensive amount of time and tracking data in order to attain a solution.

NASA's GSFC has designed and supported every libration point mission except the recent Genesis mission out of JPL. This paper presents a summary of the analyses and orbit determination results of four previous libration point missions supported by GSFC's Guidance, Navigation & Control Center (GNCC). ISEE-3 was the first libration point mission in 1978. ISEE-3 stayed in a halo orbit for only three years before departing on the next phase of its mission. It was 17 years later before a second mission, SOHO, was flown to a libration point. SOHO was the first mission designed to remain in the vicinity of a libration for the mission duration. SOHO was quickly followed by ACE, the first mission to follow the quasi-periodic Lissajous orbit pattern. The latest mission, MAP, the first mission to the Earth-Sun L2 point, is also presented here with as yet unpublished results.

The majority of these missions have used the Deep Space Network (DSN) assets to support tracking services. However, with the projected loading on the DSN in future years, this option is becoming far less feasible. Alternatives include commercial tracking assets such as the Universal Space Network (USN), which is scheduled to support the future Triana mission, and the use of advanced technology to reduce the required tracking services from the DSN.

One such technology is the use of Celestial Navigator (CelNav). CelNav is a onboard Kalman filter that processes one-way forward Doppler measurements and onboard attitude sensor data. CelNav analysis results are presented here.

Another alternative is the use of the Very Long Baseline Interferometry (VLBI) measurement called Delta Differenced One-Way Range (DDOR). DDOR is actually an angular measurement from a nearby quasar to the spacecraft. DDOR is being implemented at some of the DSN sites and its applicability to LPOs is presented here.

PAST MISSIONS

International Sun-Earth Explorer-3 (ISEE-3)

The first libration point mission was ISEE-3 (Figure 1). Launched as part of an international cooperative agreement between ESA and NASA on August 12, 1978, ISEE-3 entered a large halo orbit about the Earth-Sun L1 point on November 20, 1978. The spacecraft remained in the halo orbit for 3 ½ years before departing on June 10, 1982 for the second phase of its mission.
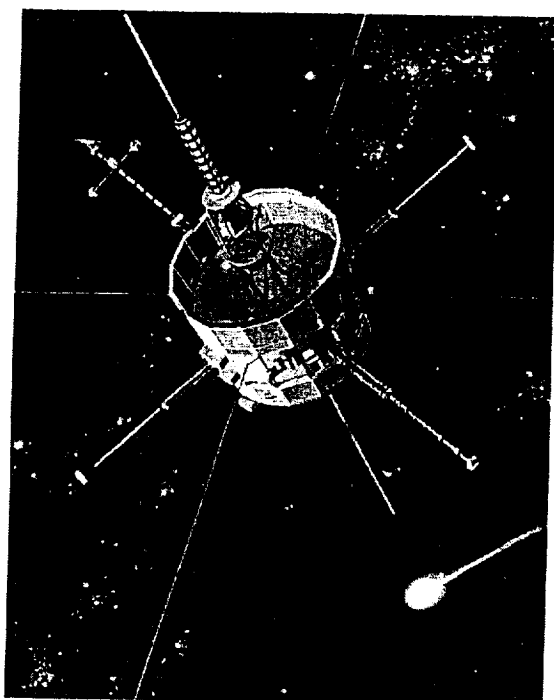

Figure 1: ISEE-3 Spacecraft

ISEE-3 flew in a large halo orbit about L1 of approximately 600,000 km in Y-amplitude (in ecliptic plane perpendicular to Earth-Sun line). The dynamics in the vicinity of the libration point are not significantly different for different size halo or Lissajous orbits. All have an approximate period of 6 months. The class, phase and Z-amplitude (out of the ecliptic) of the halo or Lissajous orbit all have an effect on the orbital accuracy. However, these effects are small and, given the number of variables affecting orbital accuracy, it is usually measured only to order-of-magnitude.

ISEE-3 was ground tracked by NASA S-band Tracking Data Network (STDN) sites during the halo orbit phase. The tracking schedule was irregular but generally consisted of multiple short passes (5 minutes) at acquisition-of-signal (AOS), maximum elevation, and near loss-of-signal (LOS) from each station [Joyce 84]. Covariance analysis was performed pre-mission to assess the expected orbital uncertainties. Covariance analysis indicated an optimum batch tracking arc length of 21 days. Station-keeping maneuvers were performed every 45 days enabling two completely independent orbital solutions between each maneuver. OD was performed every other week giving a 7-day overlap period. The covariance analysis was comparable to comparisons between consecutive definitive solutions obtained during the actual mission. The definitive overlap comparisons are obtained by differencing the trajectories obtained by the two overlapping solutions. Table 1 details the covariance analysis and definitive overlap comparisons.

Table 1: ISEE-3 Comparisons of Overlap Differences and Covariance Analysis [Joyce 84]

Period	Overlap Compare (km)	Covariance Analysis (km)
A	8.1	6.0
B	9.0	5.5
C	3.6	5.4

Corresponding velocity uncertainties were 0.3 to 2.0 cm/sec from the definitive overlap differences.

Definitive overlap comparisons are not a direct measure of absolute orbital accuracy. However, without an independent tracking source, they are the best available measure.

Solar & Heliospheric Observatory (SOHO)

SOHO was launched on December 2, 1995 as a joint ESA and NASA mission. SOHO performed a direct insertion into a large Earth-Sun L1 halo orbit with a Y-amplitude of approximately 670,000 km (see Figure 2).

SOHO tracking is performed by the DSN, primarily the 26-m antennas, but some 34-m and 70-m MARK IVA antennas are also used. The MARK IVA SRA ranging system is generally slightly more accurate. The nominal tracking schedule for SOHO is 5 hours per day from alternating DSN sites. This schedule is extremely inconsistent for SOHO however.
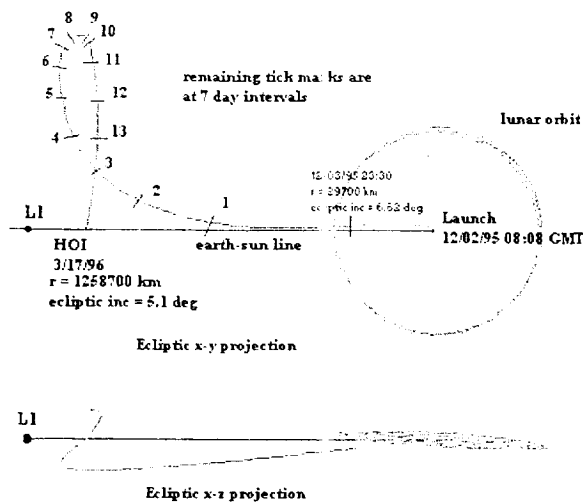
3

remaining tick marks are at 7 day intervals

lunar orbit

12/03/95 23:30
r = 39700 km
ecptic inc = 6.62 deg

Launch
12/02/95 08:08 CMT

L1

HOI
3/17/96
r = 1258700 km
ecliptic inc = 5.1 deg

earth-sun line

Ecliptic x-y projection

L1

Ecliptic x-z projection

Figure 2: SOHO Trajectory in Solar Rotating Coordinates

Covariance analysis was performed pre-mission in order to assess orbital accuracy and to determine the batch arc length. The covariance analysis used a conservative tracking schedule of only 1 hour per day. This analysis indicated that an optimum arc length of 21 days would give orbital accuracy to less than 9 km. Table 2 details these results.

Table 2: SOHO Covariance Analysis Results [Jordan 93]

Data Span (d)	Axis	Maximum Total Error			
		Def Period		60d Pred	
		Pos (km)	Vel (cm/s)	Pos (km)	Vel (cm/s)
14	Y	10.1	0.42	17.4	0.79
21	Y	8.6	0.19	8.4	0.34
14	Z	6.6	0.39	20.1	1.05
21	Z	5.7	0.26	11.3	0.06

SOHO performs station-keeping maneuvers every 8 to 12 weeks. Additionally, attitude maneuvers are performed much more frequently with the use of spacecraft thrusters. While the attitude maneuvers are designed for zero delta-V, thruster performance and misalignments contribute about a 5% error. The batch definitive arcs are broken at all maneuver points instead of attempting to model these maneuvers. Modeling would add an additional error source into the solution and would require a detailed engine model in the OD software. Data arcs were generally kept at the standard 21 days when possible, but were often shorter. As part of the

solution process, the solar radiation pressure coefficient (C_r) was estimated along with range biases for each pass from the MARK IVA antennas (averaging about 6 per solution).

SOHO's definitive overlap requirements were 50 km and 3 cm/sec. During long periods free of spacecraft perturbations, overlap comparisons were obtained. Actual definitive overlap comparisons average about 7 km. That uncertainty is primarily in the cross-track direction (plane-of-the-sky perpendicular to the projection of the velocity vector into that plane). Radial uncertainty are generally less than 1 km. Table 3 details the position and velocity definitive overlap comparisons.

Table 3: SOHO Definitive Overlap Comparisons

	RSS	Radial	Along-track	Cross-track
Pos (km)	7	1	2	7
Vel (mm/s)	0.4	0.1	0.2	0.3

These overlap compares were obtained during long periods without spacecraft perturbations. The routine OD for SOHO was not typically this accurate due to the use of much shorter data arcs.

The predicted orbital uncertainty requirement after a 44-day propagation is 100 km and 10 cm/sec. Definitive solutions were compared to predicted solutions after 44 days of propagation to obtain a predictive overlap comparison. The SOHO predictive overlaps were generally around 14 km. Table 4 details the predictive overlap comparisons. Note that the radial component is no longer constrained by the measurement data and grows significantly.

Table 4: SOHO Predictive Overlap Comparisons

	RSS	Radial	Along-track	Cross-track
Pos (km)	14	9	2	11
Vel (mm/s)	0.7	0.2	0.3	0.6

An additional study was performed for the MAP mission using real SOHO tracking data. This analysis was performed to show the effects of reducing the 5 hours per day of SOHO tracking data to only 37 minutes per day for MAP. The

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SOHO definitive ephemeris using all available tracking data was used as the truth ephemeris. Table 5 shows the comparisons for the reduced tracking data solutions. The results are somewhat erratic but generally show a degradation of accuracy of less than 2 km.

Table 5: SOHO Reduced Tracking Data Results [Nicholson 99]

Epoch	Editting	C	Pos RSS (km)	Vel RSS (cm/sec)
980111	None	1.309	NA	NA
980111	37 min/day	1.304	8.31	0.236
980111	37 min twice/day	1.306	0.71	0.081
980321	None	1.384	NA	NA
980321	37 min/day	1.278	19.6	3.82
980405	None	1.371	NA	NA
980405	37 min/day	1.360	0.65	0.142
980417	None	1.389	NA	NA
980417	37 min/day	1.392	1.21	0.411

Advanced Composition Explored (ACE)

ACE was launched on August 25, 1997 as a NASA Explorer program mission. ACE performed a direct insertion into an Earth-Sun L1 small Lissajous orbit with a Y-amplitude of about 150,000 km (see Figure 3). ACE was the first spacecraft to fly in the quasi-periodic Lissajous pattern. The periodic halo orbits do not exist at the smaller amplitudes.
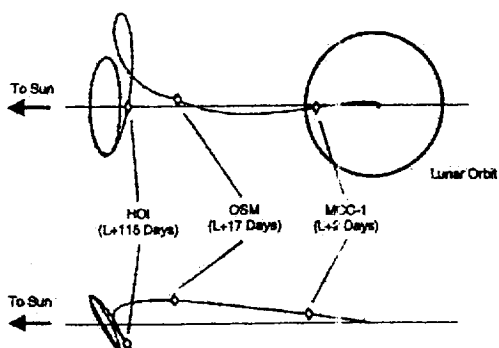

Figure 4: ACE Trajectory in Solar Rotating Coordinates

The ACE spacecraft is spin-stabilized at 5 rpm with the spin axis of the spacecraft required to point within 20 degrees of the Sun at all times. In addition, the High Gain Antenna (HGA) is required to point Earth-ward within 4.5 degrees. These two constraints require ACE to perform

reorientation maneuvers as frequently as every 5 days. These maneuvers are performed with thrusters and therefore force the analysts to break the arc around these maneuvers to obtain clean data arcs free of spacecraft perturbations. Thus, ACE uses data arcs of 4 to 14 days, which are clearly not optimal for OD accuracy [Colombe 02]. For the longer data arcs, C_r and pass dependent range biases from 70-m sites are estimated.

ACE gets approximately one 3.5-hour pass per day from the DSN with an additional 2 or 3 one-hour passes per week. The DSN data is primarily from the 26-m and 34-m sites.

Because ACE extends the batch data arc as long as possible between attitude maneuvers, there are no definitive overlap comparisons available. Single point overlaps are obtained by differencing consecutive definitive solutions at the time of the attitude maneuvers. Those overlaps indicate a mean position difference of 10 km and a velocity difference of 1.2 cm/sec. Table 6 details the ACE overlap comparisons.

Table 6: ACE Overlap Comparisons

	RSS	Radial	Along-track	Cross-track
Definitive Point Overlap				
Pos (km)	10	4	5	8
Vel (mm/s)	1.2	0.9	0.1	0.9
2-Week Predictive Overlap				
Pos (km)	23	8	6	21
Vel (mm/s)	1.2	0.9	0.1	0.9

ACE never attempted to model the spacecraft maneuvers in order to obtain longer tracking arcs. Analysis was done for this particular scenario for a future libration point mission, Constellation-X. At the time, the current Constellation-X design called for momentum unloads using spacecraft thrusters every other day. Since a two-day arc was clearly not sufficient for OD, modeling of the maneuvers would be required.

Covariance analysis was performed for a scenario with 4 mm/sec delta-Vs applied every other day with a thruster performance uncertainty of either 3% or 5%. The delta-Vs were applied toward the Sun in hopes absorbing

some of the error in the estimated C_r. The tracking schedule used was 10 minutes of range and Doppler tracking data every day from a single station with a 21-day tracking data arc. Estimating the spacecraft maneuvers was not possible due to the sheer number.

The definitive OD position and velocity errors for the 3% and 5% delta-V error cases as shown in Table 7.

Table 7: Constellation-X Covariance Analysis Assuming Multiple Spacecraft Maneuvers [Marr 98]

Delta-V Error	Pos Error (km)	Vel Error (cm/sec)
3%	12-47	3.5-4.0
5%	16-78	5.8-6.5

Note that the errors seen in the Constellation-X analysis are considerably highly than that seen for ACE using shorter data arcs. In addition, the larger velocity errors would require much more frequent station-keeping maneuvers, and a higher station-keeping delta-V budget, in order to maintain the Lissajous orbit.

Microware Anisotropy Probe (MAP)

MAP is the latest libration point mission. MAP was launched on June 30, 2001 and used a lunar swingby to insert into a small Lissajous orbit about the Earth-Sun L2 point (see Figure 5). MAP is the first mission to remain in the vicinity of the L2 point for an extended period of time.
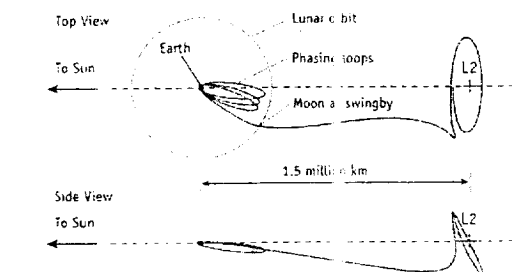

Figure 5: MAP Trajectory in Solar Rotating Coordinates

Tracking services for MAP are provided by the DSN. MAP receives a minimum of one 45-minute pass per day from the DSN 34-m or 70-m sites. Because MAP receives exclusively MARK IVA tracking data, MAP has the highest quality measurement data set of any previous mission.

However, MAP does not possess an equivalent quantity of measurement data than earlier missions.

The MAP spacecraft is spin stabilized about an axis that precesses once per hour about a 22.5-degree half-angle cone about the Sun-MAP line. Because of the unique attitude requirements for MAP, the cross-sectional area for solar radiation pressure forces is nearly constant. This greatly reduces attitude dependent errors on solar radiation force modeling which is typically a large error source. Most missions estimate the C_r but current GSFC software limits the solar radiation force calculation to a fixed cross-sectional area and a single constant estimated C_r over the entire data arc. Thus, the estimated C_r normally soaks up changing forces due to attitude changes and solar events. For MAP, this estimated C_r is extremely consistent ($\pm$ 0.005) and varies only in response to solar events [Fink 02]. This improves overall OD accuracy for MAP.

Because of the C_r consistency, MAP is able to use longer data arcs than other missions. MAP uses a minimum of 14-day arcs after maneuvers up to a current maximum of 72 days of spacecraft unperturbed motion.

In addition, because MAP receives a large amount of 70-m tracking data, they have been able to calibrate the range biases from various stations and are able to apply these biases to future solutions. This eliminates numerous parameters from the estimated state vector [Fink 02].

Since OD data arcs are extended to much longer lengths for MAP, overlap differences do not exist. However, post-processed solutions using two consecutive 5-week arcs do give adequate comparisons. Over the short prediction span of 5 weeks, the overlap differences were 2.0 km and 0.83 mm/s. The overlaps increase when the prediction span is increased to 9 weeks: 6.7 km and 3.9 mm/s. Table 8 details the MAP results.

Table 8: MAP Overlap Comparisons [Fink 02]

	RSS	Radial	Along-track	Cross-track
5-Week Predictive Overlap				
Pos (km)	2.0	0.3	1.4	2.0
Vel (mm/s)	0.83	0.36	0.40	0.79
9-Week Predictive Overlap				
Pos (km)	6.7	6.2	2.3	1.8
Vel (mm/s)	3.9	3.8	0.4	0.6

These MAP results are fairly optimistic as they are taken during a period of relative solar inactivity and continuous science mode operation. Results are significantly worse with irregularly high solar winds or when the science mode attitude is changed.

ADVANCED TECHNOLOGY

Celestial Navigator (CelNav)

CelNav is a part of the Goddard Enhanced Onboard Navigation System (GEONS) software package developed by GSFC's GNCC. CelNav uses standard spacecraft attitude sensors and communication components to provide autonomous navigation. Analysis to date indicates that real-time autonomous navigation accuracies to 10 km RMS for LPO missions are achievable using high-accuracy attitude sensors and one-way Doppler measurements [Folta 99].

CelNav uses directional measurements from standard attitude sensors (e.g. Earth and Sun sensors) and one-way forward-link Doppler measurements from a ground station communications receiver augmented with a Doppler extraction capability (see Figure 6 for a schematic). The one-way forward Doppler is obtained from the spacecraft communication link, thus eliminating the need for dedicated tracking services. The directional measurements are the angles of the line-of-sight unit vector from the sensor to the celestial object, measured with respect to the sensor frame of reference.
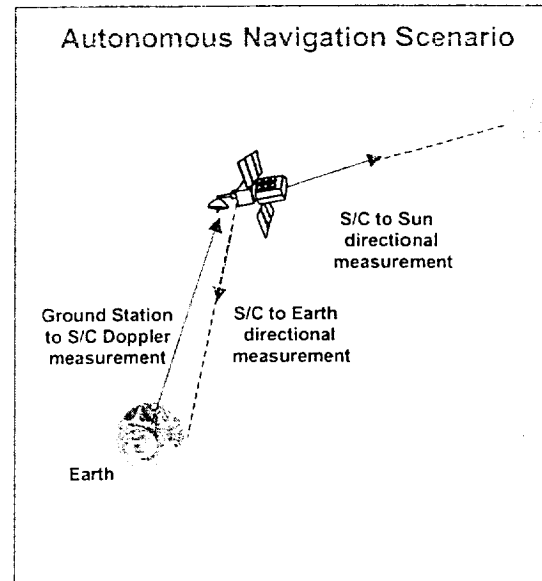

Figure 6: CelNav Measurement Sources

Simulated analyses using realistic and optimistic levels for the measurement noise and biases and the Doppler tracking frequency have been performed. Directional measurement noise standard deviations were selected to be consistent with the current digital sun sensor technology of 1 arc-minute and an onboard attitude determination accuracy of 1 arc-minute (achievable using star trackers). The one-way Doppler measurement accuracy is primarily dependent on the noise and stability characteristics of the onboard oscillator that provides the frequency reference used in the Doppler extraction process. The optimistic reference frequency quality was modeled based on expected performance of a typical ultra-stable oscillator (USO) [Folta 99].

For the optimistic case using unbiased Earth and Sun directional measurements with noise consistent with current digital sun sensor technology and Doppler measurements referenced to an USO, orbital error was 7 km and 2 mm/sec. Various tracking scenarios are shown in Table 9. When Doppler tracking was eliminated, orbital errors increased significantly. The addition of more realistic parameters including a noise USO (10 times the noise sigma), reduced Doppler tracking data, directional measurement biases and the elimination of Earth directional measurements all degraded solution accuracy a range of 14 to 22 km.

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Table 9: CelNav Solution Accuracy [Folta 99]

Tracking Scenario	Pos Error (km)	Vel Error (mm/sec)
Nominal	7	2
Eliminated Doppler tracking	62	30
Increased Doppler measurement noise from 0.001 Hz to 0.01 Hz	22	3
Reduced Doppler tracking from 2 to 1 4-hr pass per day	17	NA
Added directional measurement bias of 0.1 arc-minute	22	4
Eliminated Earth directional measurements	14	NA

Steady-state accuracy was not found to be very sensitive to elimination of Sun directional measurements or a 4-fold increase in the directional measurement noise to 6 arc minutes (consistent with existing Earth sensor technology and 0.1 degree accurate attitude determination).

Figures 7 and 8 compare the steady-state position and velocity performance for the optimistic case with a realistic case starting at the least favorable tracking geometry and including 0.1 arc-minute directional measurement biases and Doppler measurements from a noisy USO with Doppler tracking reduced to one 2-hour contact every other day (Realistic with Sun, Earth, and Doppler) and a realistic case identical to above but without Doppler tracking (Realistic with Sun and Earth).
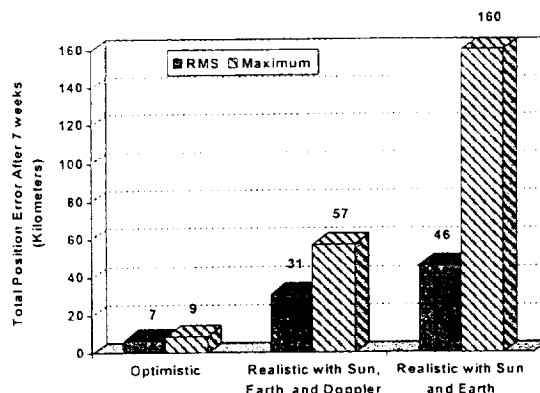

Figure 7: CelNav Position Errors Based on Various Sensor Accuracies
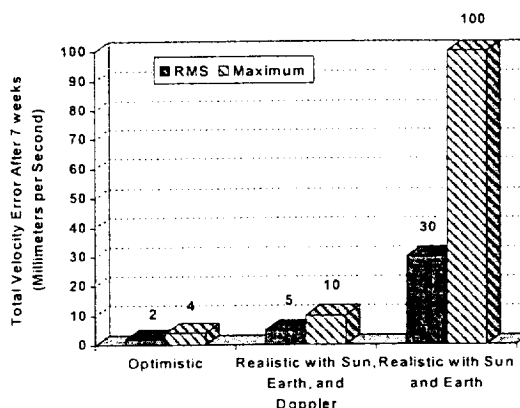

Figure 8: CelNav Velocity Errors Based on Various Sensor Accuracies

As a comparison, analysis using the realistic sensor parameters gave rather good results for a highly elliptical (1.8 by 9 Re) orbit. Attitude sensors alone gave a position RMS of 15 km, while the addition of Doppler data dropped that error to 1.5 km [Long 00].

Delta Differenced One-Way Range (DDOR)

All previous LPO missions have used ground based tracking using range and Doppler measurement types. Both of these measurements give information only along the spacecraft line-of-sight. Information perpendicular to this line is inferred only from time-varying changes in these measurements and the dynamical model used. Thus, the radial component of the orbital uncertainty is considerably more accurate than the plane-of-the-sky components.

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DDOR is a true VLBI measurement type that is being implemented at the DSN 34-m and 70-m (X-band only) sites as a nominal measurement type by May 2003 [Cangahuala 01].

DDOR is obtained by double differencing simultaneous observations of the spacecraft from two widely separated ground sites followed immediately by observations from an angularly nearby quasar (see Figure 9 for a schematic). The differential range to both the spacecraft and the quasar is determined from the observations. These measurements are then algebraically differenced to provide a precise determination of the angular position offset between the two sources as common measurement errors tend to cancel. With multiple baselines, the 2D angular component can be determined. This information provides previously unavailable plane-of-the-sky knowledge. Potentially, the use of this measurement type could reduce plane-of-the-sky orbital uncertainty to the current radial levels.
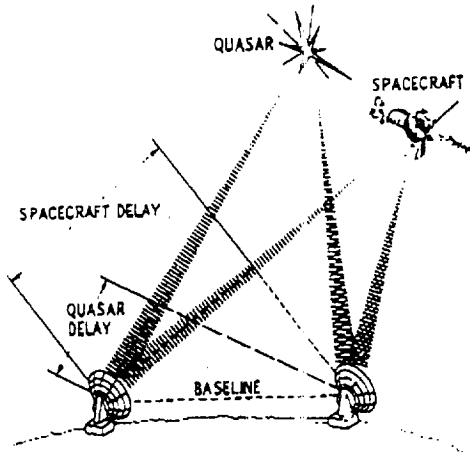

Fig. 1 ADOR geometry.

Figure 9: DDOR Measurement Type

Each tracking station simultaneously views the spacecraft and records radio tones being broadcast. The antennas then simultaneously slew off the spacecraft and record the signals from a reference quasar which is located angularly near the spacecraft The calculation of the angular separation between the spacecraft and the quasar is then,

$$\alpha = \frac{\left(\Delta \tau_{S/C} - \Delta \tau_{Q}\right)c}{B}$$

where α is projection of the angular separation between the spacecraft and quasar onto the baseline between the two stations, $\Delta \tau_{S/C}$ is the time delay between when a radio signal from the spacecraft is received at the first station and when it is received at the second station, $\Delta \tau_{Q}$ is the same for the quasar signal, c is the speed of light, and B is the baseline length [Pollmeier 92]. Intercontinental baselines between DSN stations range from 8,000 to 10,500 km. Accuracies are typically expressed as a distance measurement (numerator of above equation) since the baseline lengths vary.

DDOR has been used operationally before on interplanetary missions such as Voyager, Galileo, and Magellan. It has also been tested on Mars Global Surveyor and Mars Odyssey. Accuracies of 21 to 50 cm were seen for Voyager measurements (30 cm equals 37.5 nrad at 8000 km baseline) [Border 82]. The DDOR requirement for Galileo was 50 nrad [Pollmeier 92]. Current DDOR implementation states accuracies of 7.5 nrad with telemetry subcarriers and 5 nrad with Differenced One-Way Range tones [Cangahuala 01]. Figure 9 shows the DDOR error budget for the current implementation.
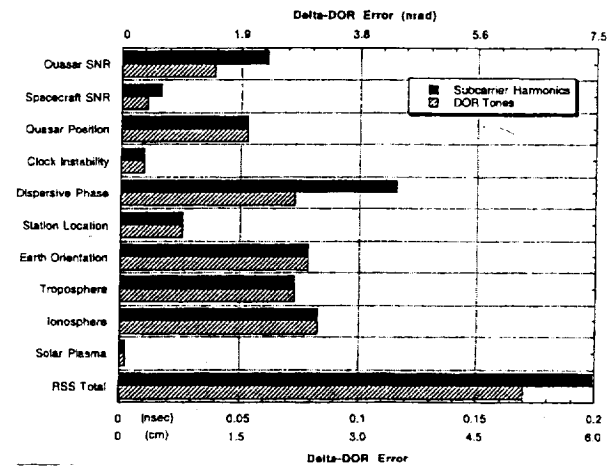

Figure 9: DDOR Error Budget [Cangahuala 01].

Covariance analysis was performed by GNCC at the request of NASA HQ to assess the use of DDOR for LPOs. Analysis indicates improved orbital accuracy can be obtained while reducing tracking times by 80%. Table 10 details some of the analysis for a SOHO orbit using 14 hours per week of DSN tracking. The use of DDOR measurements could reduce that tracking to 2.5

hours per week and improve total position
uncertainty by more than 25%.

Table 10: Covariance Analysis Results Using
DDOR for LPOs

R&D Sch*	DDOR	Baseline	Def Pos Acc (km)	Tot DSN Trk Time (hrs/ wk)
2 hrs/day	None	NA	3.8	14
1 hr/3 days	None	NA	6.5	2.5
1 hr/3 days	Once/day	50% Gds-Mad 12% Can-Mad 38% Gds-Can	2.8	2.5

* Rotating stations each day including both
northern/southern hemisphere

The use of DDOR has many advantages. DDOR
is one-way data type (downlink only). There is
no need to calibrate the spacecraft uplink for
refraction which simplifies ground station
operation. Spacecraft angular position, or plane-
of-the-sky position components, is more
accurately determined by DDOR; five-fold
improvements are possible.

However, there are drawbacks to the use of
DDOR. For each acquisition during Voyager,
10^9 bits were reduced to obtain one
measurement. This extensive post-processing
typically took up to 24 hrs [Border 82]. Thus far,
DDOR has been used as a supplemental
measurement source with independent solutions
obtained from standard measurement types used
as references. An increased reliance on DDOR
and large reductions in standard tracking would
reduce the quality of assurance of DDOR.

CONCLUSIONS

Previous LPO missions have obtained OD
accurate to 2 to 10 km. The best accuracy has
been achieved by MAP and is due in part to the
favorable attitude and consistent C_r estimates.
The worst accuracy has been achieved by ACE
and is due primarily to the shortening of the
batch data arc due to frequent spacecraft
perturbations. The amount of tracking data

received for each mission is not highly correlated
with the OD accuracy achieved. This suggests
that other issues such as spacecraft perturbations,
spacecraft attitude, and use of MARK IVA data
are more important than quantity of tracking
data.

The use of DDOR measurements can increase
the accuracy of a standard range and Doppler
tracking scenario by 25% while reducing the
total amount of tracking time by 80%. DDOR
data greatly improves the plane-of-the-sky
position error components. While DDOR has not
yet been used for any LPO missions, it has been
used operationally on interplanetary missions.

The use of CelNav would eliminate the need for
all coherent dedicated tracking passes. The
performance of CelNav using realistic sensor
performance indicates that autonomous
navigation using directional and Doppler
measurements can meet onboard navigation
requirements on the order of 30 km. Higher
accuracy is achievable by reducing measurement
noise and increasing the Doppler tracking
frequency. Autonomous navigation using only
directional measurements can provide a lower-
cost navigation method for missions with less
stringent onboard navigation requirements, i.e.
greater than 50 km.

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