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RELATIVE NAVIGATION FOR SPACECRAFT FORMATION FLYING

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The Goddard Space Flight Center Guidance, Navigation, and Control Center (GNCC) is currently developing and implementing advanced satellite systems to provide autonomous control of formation flyers. The initial formation maintenance capability will be flight-demonstrated on the Earth-Orbiter-1 (EO-1) satellite, which is planned under the National Aeronautics and Space Administration New Millennium Program to be a coflight with the Landsat-7 (L-7) satellite. Formation flying imposes relative navigation accuracy requirements in addition to the orbit accuracy requirements for the individual satellites. In the case of EO-1 and L-7, the two satellites are in nearly coplanar orbits, with a small difference in the longitude of the ascending node to compensate for the Earth's rotation. The GNCC has performed trajectory error analysis for the relative navigation of the EO-1/L-7 formation, as well as for a more advanced tracking configuration using cross-link satellite communications. This paper discusses the orbit determination and prediction accuracy achievable for EO-1 and L-7 under various tracking and orbit determination scenarios and discusses the expected relative separation errors in their formation flying configuration.

INTRODUCTION

National Aeronautics and Space Administration (NASA) Enterprises are recognizing the advantages of flying multiple satellites in coordinated virtual platforms and constellations to accomplish science objectives. Formation flying techniques and space vehicle autonomy will revolutionize space and Earth science missions and enable many small, inexpensive satellites to fly in formation and gather concurrent science data.

The Guidance, Navigation, and Control Center (GNCC) at the Goddard Space Flight Center (GSFC) maintains a cutting-edge technology program that enhances satellite performance, streamlines processes, and ultimately enables cheaper science. Technology focus areas within the

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GNCC encompass control system architectures, sensor and actuator components, propulsion, electronic systems, design and development of algorithms, embedded systems, and space vehicle autonomy. Through collaboration with government, universities, non-profit organizations, and industry, the GNCC incrementally develops key technologies that conquer NASA's challenges.

The GNCC is currently providing innovative technology solutions on two NASA missions associated with formation flying and coordinated virtual platforms. The New Millennium Program (NMP) Earth Orbiter (EO)-1 mission, scheduled for launch in 1999, will demonstrate key aspects of formation flying, and the Earth Observing System (EOS)-AM1, scheduled for launch in 1998, will perform coordinated science observations with Landsat-7 (L-7). The essential formation control requirement on EO-1 is to maintain a 1-minute separation from L-7 to within a tolerance of 6 seconds. In addition, L-7 will fly over the EOS-AM1 groundtrack 15 minutes later to provide coordinated observations between the two satellites. Demonstrations of constellation control of L-7 and EOS-AM1, autonomous navigation of EO-1 using a spaceborne Global Positioning System (GPS) receiver, and aspects of autonomous formation flying on EO-1 are key initial steps toward enabling fully autonomous control of a group of small, single-instrument satellites that can collect scientific data as if all of the instruments were on a single, large platform. This "virtual platform" approach lowers the total risk, increases science data collection, and adds considerable flexibility to future NASA Earth and space science missions.

To support the EO-1/L-7 formation flying experiment, GNCC has performed trajectory error analysis for the relative navigation of EO-1 with respect to L-7. In addition, central to the achievement of the strategic goal of virtual platforms are cross-link satellite communications and autonomous relative navigation. Although neither of these technologies will be demonstrated on the NMP EO-1 flight, the GNCC has investigated an advanced approach for autonomous relative navigation using cross-link satellite measurements. This approach extends the Onboard Navigation System (ONS), developed by GSFC to support single satellite autonomous navigation, to process tracking measurements derived from a cross-link satellite signal. This paper discusses the orbit determination and prediction accuracy achievable for EO-1 and L-7 under various tracking and orbit determination scenarios and discusses the expected relative separation errors in their formation flying configuration.

RELATIVE NAVIGATION ACCURACY REQUIREMENTS FOR THE EO-1 AND L-7 FORMATION

Formation flying refers to the coordinated control of a group of satellites such that the satellite positions relative to a reference position (e.g., one of the satellites) are maintained according to some predetermined constraints dictated by the overall mission goals, usually a separation distance and formation tolerance. The separation distance and formation tolerance for coordinated Earth sensing missions are typically on the order of hundreds and tens of kilometers, respectively, but may reduce to the order of meters in the future.

Formation flying requires both "formation sensing" and "formation control". Formation sensing provides a measure of the satellite relative positions as input to the formation control algorithms, which compute the maneuvers required to maintain the formation. The most straight-forward relative navigation approach computes the satellite relative positions by differencing the absolute position vectors of each satellite. In such a case, the target or command satellite would have to obtain accurate position vectors for not only itself, but also for the chase satellites in the formation either via ground uplink or a satellite-to-satellite communications cross-link. While each satellite may have its own onboard ephemeris knowledge or onboard navigation system, a

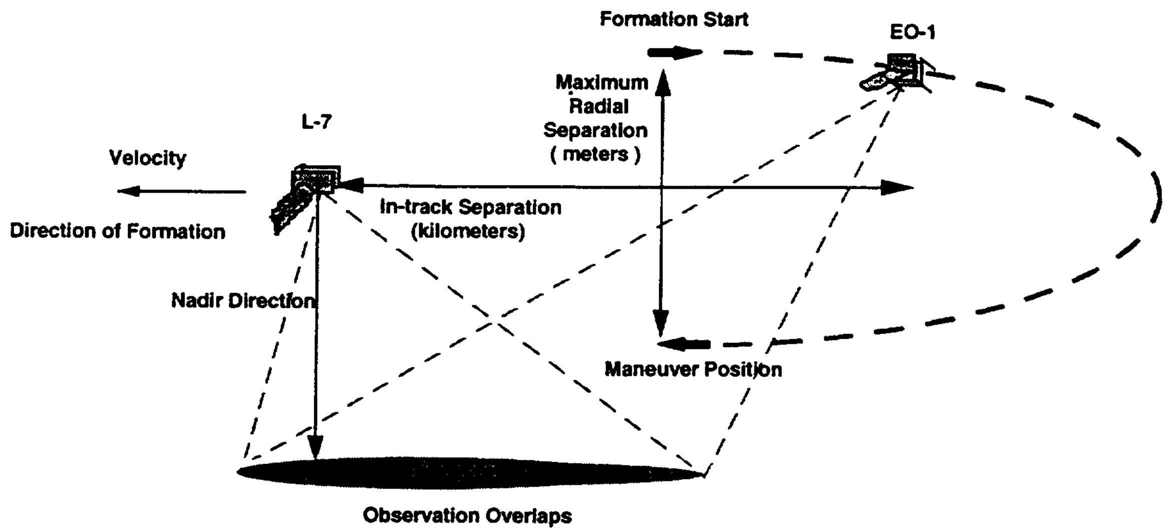

Figure 1 Example of Relative Separation Evolution For the EO-1/L-7 Formation

means to communicate the knowledge from one satellite to another is required to determine the relative separations.

Formation flying EO-1 with L-7 will enable coordinated, coregistered observations of the reference geographic sites for scientific comparison of the imaging sensors onboard the satellite. The two satellites will be placed in nearly coplanar orbits, with a 0.25 degree difference in the right ascension of the ascending node to compensate for the Earth's rotation. The separation between the satellites is nominally 450 kilometers (≅1 minute). The formation tolerance is approximately ±40 kilometers (≅6 seconds).

Figure 1 illustrates one proposed formation control strategy for the EO-1/L-7 formation.[1] The initial EO-1 position is behind L-7 at the minimum acceptable in-track separation (≅410 kilometers) and the initial altitude is about 25 meters above that of L-7 (nominally at a 705-kilometer altitude). Initially, the relative in-track separation increases because of the longer period of the higher EO-1 satellite. However, due to its larger area-to-mass ratio, the EO-1 orbit decays faster than L-7, which reduces the initial altitude separation and decreases the relative orbital velocities. The proposed strategy is to select the initial altitude separation such that the maximum acceptable separation (≅490 kilometers) is not reached before the radial separation reaches zero. When the EO-1 orbit decays below the L-7 altitude, the in-track separation will decrease. When the minimum acceptable separation is reached, a maneuver is executed to restore EO-1 to the initial formation configuration. To reduce the frequency of the formation control maneuvers to approximately weekly, the semimajor axis difference, or equivalently the radial separation, between the two satellite must be maintained within approximately ±25 meters. To maintain a radial separation of ±25 meters, the relative radial separation must be known to about 5 meters. The change in velocity that is needed to maintain a ±25-meter radial separation is approximately 2.7 centimeters per second in the in-track direction. Therefore, to accurately plan and perform this maneuver, the relative in-track velocity must be known to about 0.5 centimeters per second.

To monitor the state of this formation, the navigation software must compute the relative separations of one satellite with respect to the other. In the planned EO-1/L-7 formation-flying configuration, the L-7 position is periodically determined on the ground using NASA's Tracking and Data Relay Satellite System (TDRSS). A predicted L-7 state vector is uplinked to EO-1. L-7 executes its nominal mission independent of EO-1, including its ground-track control maneuvers.

EO-1 will use a Global Positioning System (GPS) receiver to compute its real-time position and velocity. NASA's Ground Network (GN) will provide a backup tracking capability for EO-1. The EO-1 satellite will host autonomous formation flying software to adjust its orbit to maintain the desired formation with respect to L-7.

Table 1 lists the relative navigation accuracy requirements for the EO-1/L-7 formation.

Table 1
RELATIVE NAVIGATION ACCURACY REQUIREMENTS FOR EO-1/L-7 FORMATION FLYING

Description	Requirement (3-sigma)
In-track relative separation	1 minute (≈ 450 kilometers)
Radial separation	± 25 meters
Mean radial separation tolerance	± 5 meters
In-track separation tolerance	± 6 seconds (≈ 40 kilometers)
Ground-track separation tolerance	± 3 kilometers (in cross-track direction)

RELATIVE NAVIGATION ACCURACY FOR THE EO-1 AND L-7 FORMATION

In this section, accuracy estimates are provided for computation of the relative separation of EO-1 with respect to L-7 in the radial (R), in-track (I), and cross-track (C) directions. It is straightforward to estimate the individual satellite orbit determination and prediction errors. Orbit determination and error analysis programs, such as the Goddard Trajectory Determination System (GTDS) and the Orbit Determination Error Analysis System (ODEAS), are based on the concept of processing one user satellite at a time. To assess the relative positioning errors, these independently-derived errors must be combined. To properly combine independently-estimated orbital errors to get relative errors, a breakdown of the total errors into its component errors is needed. These component errors are contributed by various error sources.

In the case of EO-1 and L-7, the tracking measurement errors for the two satellites are statistically uncorrelated, since they will be tracked using different tracking systems with different tracking schedules. Therefore, the individual satellite errors arising from measurement noise and uncertainties in measurement biases and tropospheric and ionospheric refraction delay are uncorrelated. Such errors can be combined using the root-sum-square (RSS) method.

On the other hand, the satellite orbital errors arising from satellite force model errors can be considered fully correlated since the two satellites are following each other closely in essentially the same orbit, thereby always experiencing the influence of essentially the same dynamic environment. Examples of such errors are those due to uncertainties in geopotential, atmospheric drag, and solar radiation pressure models. When computing the relative errors, the orbital error terms for the two satellites arising from correlated dynamic error sources are algebraically subtracted before combining with those arising from the measurement-related error sources.

This procedure can be symbolically expressed as follows:

$$\text{Relative Error} = \left(\sum_{\text{meas error}} \left[(EO-1)^2 + (L-7)^2 \right] + \sum_{\text{dyn error}} \left[(EO-1) - (L-7) \right]^2 \right)^{\frac{1}{2}} \quad (1)$$

Relative Separation Errors Based on Previous Studies

This section presents an estimate of the relative separation errors for the EO-1/L-7 formation based on previous studies of orbit determination (OD) accuracies for the Landsat-4 (L-4) and L-7 missions. These studies assumed TDRSS tracking or GN tracking and used either orbit error covariance analysis or analysis of the orbit determination solutions obtained using real tracking data. The definitive OD accuracy results are presented in Table 2.

Table 2
DEFINITIVE ORBIT DETERMINATION POSITION ERRORS FOR L-4 AND L-7

Description	Tracking Schedule	Radial (meters)	In-Track (meters)	Cross-Track (meters)	RSS (meters)
Covariance Analysis Results (Maximum 3σ)					
Arc Length (Hours)					
30	35 TDRSS passes	13	14	6	16
34	12 TDRSS passes	7	33	15	37
34	7 GN passes	10	55	3	56
48	9 GN passes	3.5	30	8	32
Definitive OD Results (Maximum Differences)					
Arc Length (Hours)					
34 (*)	21 TDRSS passes	1.4	x	x	7
34 (+)	11 TDRSS passes	11	50	25	54
34 ($)	11 TDRSS passes	3	31	8	31

*: 34-hour high-quality reference solutions ; results shown represent maximum definitive position overlap

+: Maximum position comparison between reference solutions and solutions obtained using nominal TDRS orbit solutions

$: Maximum position comparison between reference solutions and solutions obtained using high-quality TDRS orbit solutions

x: Data not available

The covariance analysis results listed in Table 2 were based on GSFC Flight Dynamics Division internal memoranda. These covariance results provide maximum 3-sigma error estimates. Radial errors vary from 3.5 to 13 meters and in-track errors vary from 14 to 55 meters. The first of three definitive OD results presented in Table 2 is taken from a study performed using an unusually dense TDRSS tracking of L-4.[2] These solutions were obtained using 21 tracking contacts over the 34-hour OD arc, approximately twice the nominal tracking. These results are the maximum position differences between two consecutive definitive OD arcs in the 10-hour overlapping region. Such overlap comparisons are often used as a measure of definitive OD consistency. These solutions produced maximum radial overlap of 1.4 meters and maximum total overlap of 7 meters. Nominal L-4 definitive OD accuracies would be 5- to 10-times larger than these results. In addition, these solutions were obtained by simultaneously estimating the user and two TDRS spacecraft that were used as relays. To improve the overall OD accuracy for the user and TDRSs, high-density Bilateration Ranging Transponder System (BRTS) tracking was also included in the solution. In normal operational OD scenarios, TDRS OD solutions are performed first without any user tracking data, and then the user OD is performed using the TDRS OD solutions.

The other two OD accuracy results listed in Table 2 are based on a study in which two sets of L-4 OD solutions (obtained using more nominal OD scenarios) were compared with the solutions obtained using the high-density TDRSS tracking discussed above.[3] The first of the two solutions were obtained using TDRS solutions with nominal accuracy, the second using high-quality TDRS solutions. The radial and in-track position errors associated with these solutions are seen to vary from 3 to 11 meters, and 31 to 50-meters, respectively. These errors are comparable to those obtained using the covariance analysis.

The quality of the orbit determination solutions improves when the number of tracking contacts in a given orbit determination arc increases. In the case of TDRSS tracking, the solutions improve further when better quality TDRS state vectors are used. Except for the special case of high-density tracking of L-4, the number of tracking contacts assumed or used in the studies is approximately 10, and the orbit determination arc lengths chosen were 34 or 48 hours. TDRSS tracking and GN tracking produced solutions with comparable quality. Table 2 shows that the OD accuracies for Landsat spacecraft achievable using nominal TDRSS or GN tracking will be in the range of 3 to 13-meters in the radial direction and 30 to 55-meters in the in-track direction.

Table 3 lists the worst case maximum 3σ or position difference errors (in meters) from Table 2. In addition, Table 3 lists the EO-1 orbit determination accuracy expected based on processing GPS Standard Positioning Service (SPS) measurements using a sophisticated Kalman filter based on the ONS algorithms, with GPS Selective Availability (SA) at typical levels. The GPS accuracy estimates are based on GSFC Flight Dynamics Analysis Branch's evaluation of the GPS Enhanced Orbit Determination Experiment (GEODE) capability for the TOPEX/Poseidon and Explorer Platform/Extreme Ultraviolet Explorer satellites.[4] Typically unfiltered GPS receiver satellite solution errors are about ten times larger.

Table 3.
DEFINITIVE POSITION ACCURACY USING DIFFERENT ORBIT DETERMINATION OPTIONS

Orbit Determination Option	Maximum 3σ Definitive Position Accuracy (meters)			
	Radial	Cross-track	In-track	RSS
Filtered GPS (for EO-1)	11	10	35	35
GN (for EO-1)	10	8	55	56
TDRSS (L-7)	11	25	50	54

A worst case estimate for the relative separation errors associated with the use of these orbit determination options for EO-1 and L-7 can be approximated by forming the root sum square (RSS) of the error for each spacecraft. Comparing the resulting relative position accuracies to the relative separation tolerances listed in Table 1 indicates that even when the worst case position errors given in Table 3 are assumed, the in-track and ground-track separation tolerances can be easily met. However, the requirement on the mean radial separation will not be satisfied easily.

In addition, if the orbit determination solutions are computed on the ground and predicted navigation data are uplinked to the satellite, the prediction accuracy is degraded depending upon the method by which the uplink is prepared. Thus, an additional error margin is needed when the OD solutions are generated on the ground. Reference 5 provides estimates of prediction accuracies for these satellites based on orbit determination experience.

Covariance Analysis to Estimate Relative Separation Errors

To evaluate the impact of the correlation of the dynamic errors on the relative navigation accuracy, additional covariance analysis was performed using ODEAS. The objective of this new study was to correctly estimate the relative separation errors of EO-1 with respect to L-7 using Equation (1) and to identify the major error sources for the relative separation errors using standard tracking methods. At the time of this analysis, there was an interest in examining the backup to GPS receiver navigation for EO-1, which consists of GN tracking using a maximum of four contacts per day from three ground stations (Wallops, Poker Flat, and Spitzbergen). Tracking for L-7 consisted of eight TDRSS 10-minute contacts per day via two TDRSs. Table 4 lists the uncertainties used for the major error sources included in this analysis.

Table 4
3-SIGMA ERROR UNCERTAINTIES

Error Source	Uncertainties (3-sigma)	
	EO-1	L-7
Range-rate noise (meters per second)	0.001	0.0028
Radial/in-track/cross-track TDRS position (meters)		10/100/40
Ground antenna position per axis (meters)	3.0	3.0
Ground-to-satellite ionospheric delay (percent)	100	100
TDRS-to-satellite ionopsheric delay (percent)		100
Ground-to-satellite tropospheric delay (percent)	45	45
Earth's gravitational constant (parts per million)	0.03	0.03
70x70 Joint Goddard Model 2 (JGM2) for Earth's nonspherical gravity (unitless))	3*(JGM2 clone –JGM2)	3*(JGM2 clone –JGM2)
Daily solar flux for mean solar flux of 200 Janskys		
Days 1, 2, 3 of definitive arc (percent)	5	5
Days 1, 2, 3 of prediction (percent)	14, 22, 32	14, 22, 32
81-day solar flux for mean solar flux of 200 Janskys		
Days 1, 2, 3 of definitive arc (percent)	9.1, 9.4, 9.6	9.1, 9.4, 9.6
Days 1, 2, 3 of prediction (percent)	9.8, 10.1, 10.3	9.8, 10.1, 10.3

Orbital elements for the two satellites were chosen such that the two trajectories have a nominal in-track separation of 1 minute and the L-7 ground-track retraces that of EO-1. The EO-1 orbit is initially higher than the L-7 orbit with a mean radial difference of 25 meters. The area-to-mass ratio used for EO-1 (0.0146 meters^2/kilogram) was about twice that of L-7 (0.0067 meters^2/ kilogram), so the EO-1 orbit decays faster (due to the stronger drag) than the L-7 orbit. Note that the most recent EO-1 satellite design yields an area-to-mass ratio of only 0.008 meters^2/ kilogram.

Over a 6-day period, 3-day-definitive and 3-day-predictive ephemeris errors for both L-7 and EO-1 were computed using the batch covariance analysis capability of ODEAS. These results are summarized in Table 5. This table consists of three sections: the top section lists the definitive and predictive errors for EO-1, the middle section lists the errors for L-7, and the bottom section the relative separation errors that were computed using Equation (1).

Table 5
MAXIMUM 3-SIGMA POSITION AND VELOCITY ERRORS

Description	Definitive Ephemeris		Predictive Ephemeris					
			1 day		2 days		3 days	
	Position (m)	Velocity (cm/sec)	Position (m)	Velocity (cm/sec)	Position (m)	Velocity (cm/sec)	Position (m)	Velocity (cm/sec)
EO-1 Error (Maximum 3σ)								
Radial	6.8	2.2	7.0	21.0	11.6	101.4	21.0	286.3
In-track	27.1	0.7	197.5	0.7	965.6	1.1	2701.9	1.9
Cross-track	13.5	1.4	11.3	1.2	11.3	1.2	11.3	1.2
L-7 Error (Maximum 3σ)								
Radial	6.7	4.0	7.3	10.7	8.9	49.0	11.8	134.9
In-track	43.1	0.7	101.7	0.7	467.5	0.8	1272.8	0.9
Cross-track	46.3	4.9	48.5	5.1	51.5	5.4	54.4	5.7
Relative Separation Error (Maximum 3σ)								
Radial	8.4	4.4	7.4	11.9	9.1	56.1	12.6	155.6
In-track	48.8	0.9	112.1	0.7	534.9	0.8	1468.1	1.1
Cross-track	47.1	4.9	49.3	5.2	52.3	5.5	55.3	5.8

Examination of these results indicates that the definitive EO-1 cross-track and in-track position errors are smaller than those of L-7. This may be explained by observing that the L-7 OD includes TDRSS-related error sources, such as satellite-to-satellite ionospheric refraction errors and TDRS ephemeris errors, which are absent in EO-1 tracking. These TDRSS-related error sources are the major error contributors in the definitive period for L-7. Using the height-of-ray-path (HORP) editing technique may reduce the contributions due to the satellite-to-satellite ionospheric refraction effects. Because HORP editing was not used for these solutions, the L-7 errors may be somewhat pessimistic. In addition, the predictive EO-1 in-track position errors are approximately twice as large as those of L-7. This is due to the fact that at the relatively high solar flux level of 200 Janskys most of the predictive error arises from atmospheric drag modeling errors due to solar flux uncertainty. Because the area-to-mass ratio assumed for EO-1 is about twice that of L-7, the impact of atmospheric drag modeling errors on EO-1 is twice as large as for L-7.

The relative separation errors between EO-1 and L-7, shown in the bottom section of Table 5, were computed by combining the EO-1 and L-7 error budgets such that the errors due to the correlated dynamic errors (such as Earth gravity and solar flux uncertainties) were algebraically subtracted and errors due to the statistically uncorrelated measurement related errors (such as measurement noise and atmospheric refraction effects) were combined using the RSS method.

The maximum radial separation errors for the definitive and 1-day predictive periods are 8.4 meters and 7.4 meters (3-sigma), respectively. Although the first-day predictive error is smaller than the error for the definitive period in this particular simulation, it may not be a feature that can be expected in general for other simulations. These results show that the predictive radial separation errors increase slowly reaching 12.6 meters for the 3-day prediction, considerably smaller than the individual EO-1 radial position error. Similarly, the predictive cross-track separation errors increase slowly with the length of the prediction period. However, the in-track position separation errors steadily increase outside the definitive period, but remain considerably smaller than the individual EO-1 in-track position errors. This behavior indicates that there is considerable cancellation of correlated dynamic errors in the computation of the relative separation errors.

Because the atmospheric drag coefficient is estimated over the definitive OD arc, the solar flux uncertainties do not contribute significantly to the definitive ephemeris errors. However, beyond the definitive arc, the in-track position errors for low-Earth satellites grow rapidly due to the solar flux uncertainties. The increase in the relative radial and in-track position errors during the prediction period is primarily due to the solar flux uncertainties. On the other hand, the cross-track errors are relatively insensitive to the solar flux uncertainties. Because the actual area-to-mass ratios for EO-1 (0.008) and L-7 (0.0067) will be much closer than the area-to-mass ratios used in this covariance analysis, the cancellation of the individual satellite radial and in-track prediction errors should be more complete and the growth of relative radial and in-track position errors in the 3-day prediction periods should be substantially smaller than those presented in Table 5.

Relative Navigation Scenarios

Covariance results were used to compute relative navigation accuracies for the following two candidate scenarios for providing relative navigation of EO-1 with respect to L-7:

- Scenario A: The relative separation is computed onboard EO-1 using predicted EO-1 and predicted L-7 navigation data that is computed on the ground and uplinked daily to the satellite.
- Scenario B: The relative separation is computed onboard EO-1 using real-time EO-1 navigation data computed onboard and predicted L-7 navigation data that is computed on the ground and uplinked daily to the satellite.

Table 6 summarizes the resulting relative separation error estimates based on the use of 1-day predicted L-7 ephemerides.

Table 6
MAXIMUM 3-SIGMA NAVIGATION ERRORS FOR CANDIDATE SCENARIOS

Error Component	Scenario A Errors			Scenario B Errors		
	EO-1 Predictive	L-7 Predictive	Relative	EO-1 Definitive	L-7 Predictive	Relative
Position (meters)						
Radial	7.0	7.3	7.4	6.8	6.4	6.4
In-Track	197.5	101.7	112.1	27.1	96.7	98.6
Cross-Track	11.3	48.5	49.3	13.5	26.7	28.0
Velocity (centimeters per second)						
Radial	21.0	10.7	11.9	2.2	10.1	10.2
In-Track	0.7	0.7	0.7	0.7	0.7	0.7
Cross-Track	1.2	5.1	5.2	1.4	2.8	2.9

The relative radial errors are similar for both scenarios. In both cases, the relative errors are smaller than the RSS of the individual errors due to the partial cancellation of the dynamic contributions from atmospheric drag modeling errors. These results indicate that a radial separation accuracy of 10 meters is achievable using the nominal tracking configuration for the EO-1/L-7 formation. The relative in-track error for scenario A is much smaller than the RSS of the individual satellite contributions due to the significant cancellation of the contribution from atmospheric drag modeling errors. The relative in-track error for scenario B is nearly equal to the RSS of the individual satellite contributions because the EO-1 in-track dynamic errors are small and therefore provide little cancellation of the L-7 dynamic errors. As a result, the relative in-track separation errors are only slightly larger for scenario A than for scenario B. In both scenarios, the relative cross-track errors are nearly equal to the RSS of the individual satellite contributions because the major cross-track error contributors are uncorrelated measurement-related errors.

The change in velocity that is needed to maintain a ±25-meter radial separation is approximately 2.7 centimeters per second in the in-track direction. Therefore, to accurately plan and perform this maneuver, the relative in-track velocity must be known to about 0.5 centimeters per second. The relative in-track errors for both scenarios are about 0.7 centimeters per second (3-sigma), very close to the accuracy needed to control the formation.

AUTONOMOUS RELATIVE NAVIGATION USING CROSS-LINK SATELLITE MEASUREMENTS

The Flight Dynamics Analysis Branch of GSFC's GNCC has developed an Onboard Navigation System (ONS) for autonomous navigation using TDRSS or GN communications signals.[6,7] The ONS extracts high-fidelity tracking measurements onboard from the forward-link communications signal and processes these measurements to estimate the satellite's current state and to maintain an estimate of the satellite time. By making full use of the communication, time, and computing subsystems already available on many NASA satellites, the ONS is convenient to implement, requiring no additional flight hardware. This section presents a concept for relative navigation using the ONS and projects the navigation accuracy achievable onboard to support formation flying requirements.

The ONS concepts have been extended to support real-time relative navigation to meet formation sensing requirements. Figure 2 illustrates one possible ONS tracking configuration for the coordinated control of a target and one or more chase satellites. In this configuration, the target satellite performs relative navigation of the chase satellites based on Doppler and possibly pseudorange measurements derived from a cross-link communications carrier signal transmitted from the chase to the target satellite. The target satellite hosts the relative ONS algorithms to determine the chase satellite's relative positions with respect to the target. The target state is determined independently using another onboard navigation system (possibly Global Positioning System (GPS) or GN ONS). These orbital state estimates are used in the onboard autonomous maneuver control software hosted on the target satellite to plan the formation maintenance maneuvers for the entire fleet. The target satellite executes the maneuvers required for absolute formation control and the chase satellites execute the maneuvers required to maintain their positions relative to that of the target. In this relative ONS configuration, the ground system's role is reduced to periodic verification of the system performance, providing a significant decrease in operations costs for multiple mission sets.

The GSFC Flight Dynamics Analysis Branch has evaluated the accuracy achievable using a relative ONS for L-7 position determination in support of the EO-1/L-7 formation flying

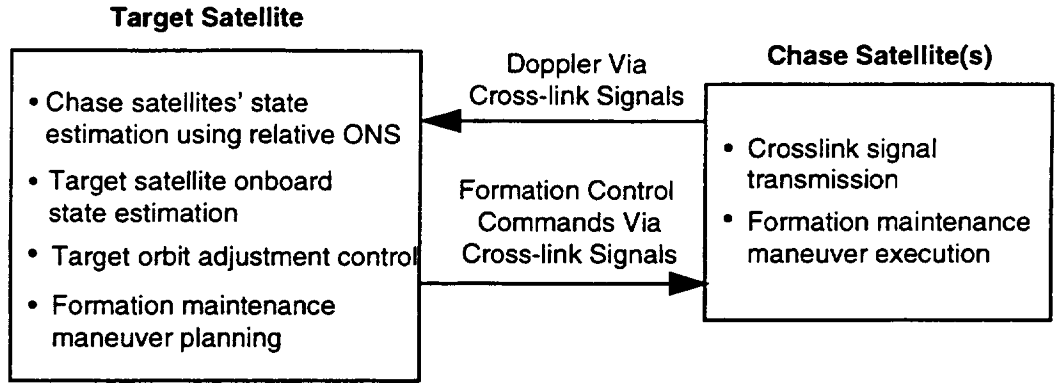

Figure 2 Relative ONS Tracking Configuration Example

application. Reference 8 discusses this analysis in detail. In the proposed EO-1/L-7 configuration, L-7 periodically transmits an S-band communications carrier signal that is received by an S-band receiver on EO-1. The receiver on EO-1 accurately measures the relative Doppler and optionally pseudorange on the cross-link signal. The ONS flight software, resident on EO-1, processes the cross-link measurements to compute the L-7 navigation data.

For this evaluation, the reference orbits and cross-link measurements were simulated using nearly identical orbital parameters for the two satellites that produced a 1 minute in-track separation, a 25-meter mean radial separation, and right ascension of the ascending node differences (ΔRAAN) of 0.0, 0.25, 0.5, 1 and 4 degrees. The relative range-rate between the two satellites results from gravitational acceleration differences due to the satellite relative positions and changing velocity in noncircular orbits and atmospheric drag acceleration differences due to the different area-to-mass ratios of the satellites. The area-to-mass ratio used for EO-1 was approximately twice that of L-7, which augments the relative velocity contribution due to the nonconstant velocity of two noncircular orbits. The drift between the two satellites changes the relative satellite separations inducing a change in the range-rate between the satellites. With these satellites flying relatively close together in identical coplanar orbits, the Doppler profile has low dynamic signature, varying between ± 9 hertz. Without pseudorange measurements, the relative position of L-7 as the chase vehicle is not directly observable, but must be deduced based on the weak dependence of the relative range-rate on the relative separation.

The performance of the relative ONS was studied as a function of tracking measurement quality, tracking frequency, and relative orbital geometry using simulated tracking measurements. Simulated cases included processing only one-way Doppler and one-way Doppler and pseudorange measurements using prototype relative ONS flight algorithms to estimate the L-7 position and velocity and optionally the atmospheric drag coefficient and measurement biases. The relative ONS algorithms used to process the cross-link data are an extension of the ONS algorithms used with TDRSS and GN carrier signals and GPS navigation signals, modified to process cross-link tracking measurements for estimation of the transmitting (chase) satellite. Two tracking scenarios were studied: 1) two 2-minute cross-link contacts per orbit and 2) three 5-minute cross-link contacts per orbit. Doppler measurements were simulated using three levels of measurement noise: 1 hertz (consistent with nominal temperature compensated crystal oscillator (TCXO) performance), 0.1 hertz (consistent with high quality TCXO performance), and 0.001 hertz (consistent with ultrastable oscillator (USO) performance). Pseudorange measurements were simulated with measurement noise of 5 meters.

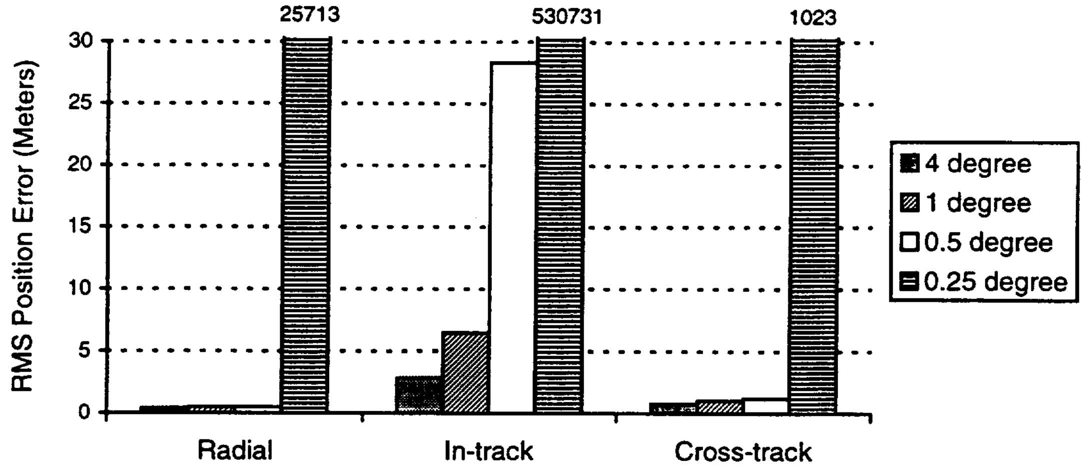

Figure 3 Comparison of Solutions Obtained Using USO-Quality Doppler Measurements With Plane Separations of 0.25, 0.5, 1 and 4 Degrees

In the case of coplanar satellites, TCXO-quality Doppler-only simulations using a tracking schedule of two 2-minute contacts per orbit did not provide sufficient observability to achieve filter convergence. When the Doppler measurements were augmented with pseudorange, the radial position could be determined to within 5 meters; however, the in-track position errors showed inconsistent trends and the cross-track position was not observable. In addition, the pseudorange bias and the atmospheric drag coefficient were not observable.

The non-coplanar satellite configurations provided considerably better performance. Solutions were obtained by processing Doppler measurements for these configurations to estimate the position and velocity of the chase satellite and the Doppler measurement bias. Figure 3 compares the root-mean-square (RMS) of the position error components for each solution. The Doppler-only solution for the case of 0.25 degree plane separation diverged. Solutions for the other three cases appear to be stable with errors progressively increasing with decreasing plane separations, well within the separation tolerances listed in Table 1. The cross-track position was observable for the three higher plane separations. The radial and cross-track position errors were relatively insensitive to the plane separations, with RMS errors of about 0.5 meters and 1 meter, respectively. The in-track error variation was larger. The estimated Doppler biases associated with these solutions were seen to be stable as well.

For the case with 0.25 degree plane separation (which is the nominal EO-1/L-7 configuration), stable position, velocity and Doppler bias estimates were achieved when both pseudorange and Doppler measurements were processed. However, when estimation of a pseudorange bias was also attempted, it was not observable. It was also found that stable and accurate position and velocity estimates are achievable if the Doppler bias is not estimated. For all plane separations, position errors were reduced when pseudorange measurements were included in the solutions.

The formation plane separation is not an arbitrary design parameter but is usually selected to achieve groundtrack cross-track coincidence for a specified satellite in-track separation. The above analysis indicates that 0.5 degree is close to the minimal plane separation that permits accurate onboard, real-time estimation of the position, velocity, and Doppler bias of the chase satellite using only Doppler measurements. The relative radial, in-track, and cross-track (RIC) position errors for the 0.5 degree RAAN separation case are presented in Figure 4. This solution

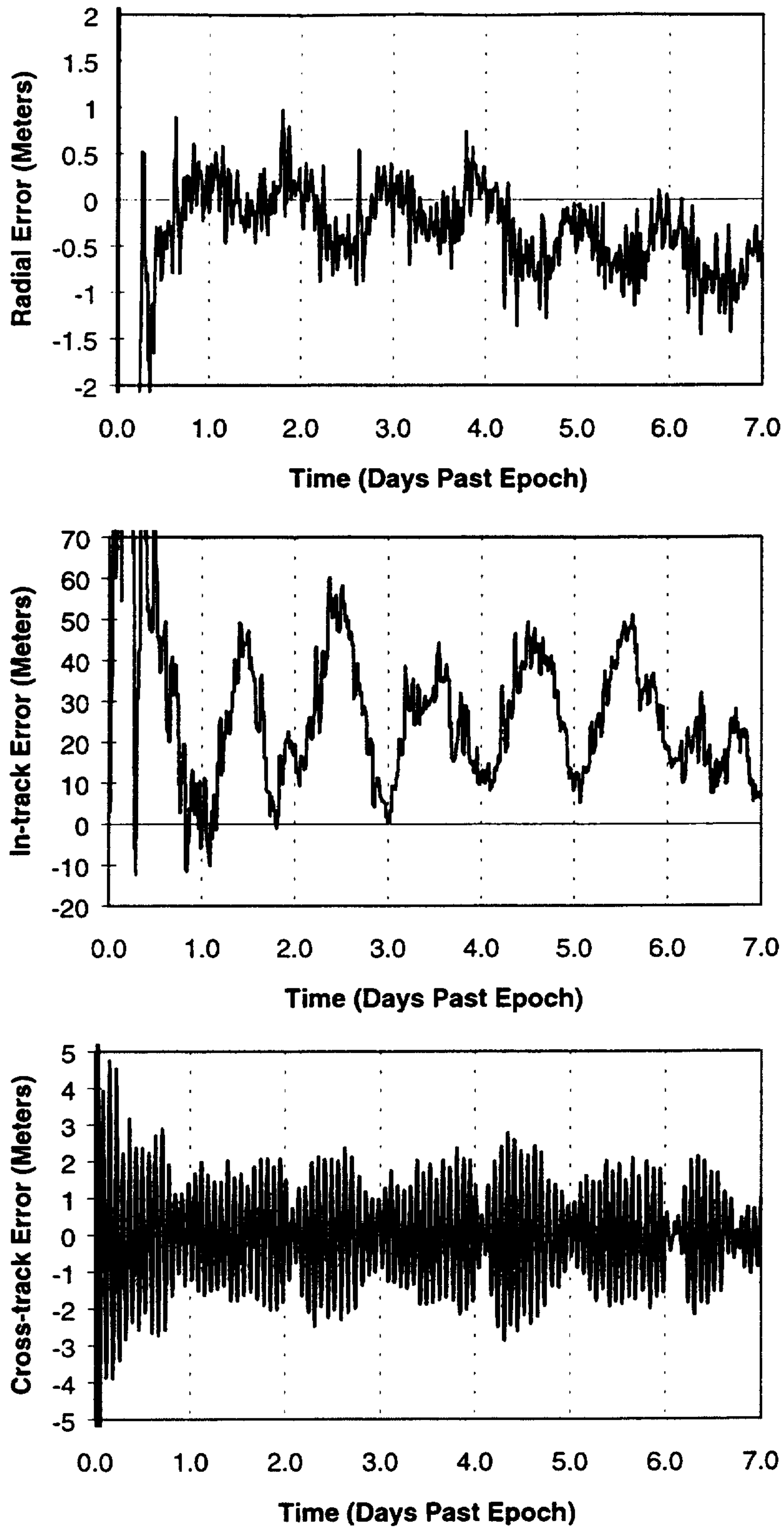

Figure 4 Relative RIC Position Errors Using USO-Quality Doppler Measurements With 0.5 Degree Plane Separation

was obtained solving for the position, velocity and Doppler bias using USO-quality Doppler measurements. For the same satellite configuration, a solution obtained by processing moderate-quality Doppler measurements (simulated using a Doppler noise of 0.1 hertz), indicated that, with three 5-minute contacts per orbit, the relative radial position can be estimated to better than 3 meters. In similar simulations with a reduced tracking schedule of two 2-minute contacts per orbit providing either the USO-quality or moderate-quality Doppler measurements, the time for the relative ONS filter to converge to an accurate steady state increased, but the accuracy of the solution was not significantly improved.

CONCLUSIONS

This paper presents a summary of orbit determination and prediction accuracies achievable for EO-1 and L-7 under various tracking and OD scenarios and discusses expected relative navigation errors in their formation-flying configuration.

A survey of orbit determination and prediction accuracy studies previously performed for EO-1 and L-7 indicates that, regardless of tracking measurement type, the expected definitive 3-sigma position errors are approximately 10, 25, and 55 meters in radial, cross-track and in-track directions, respectively. Computation of the relative satellite positions by differencing the independent OD solutions should satisfy all of the formation separation tolerances, regardless of the plane separation, except for the radial separation tolerance of approximately 5 meters. These studies also suggest that the independent OD accuracies can be improved using special tracking and OD scenarios. In the case of TDRSS or GN tracking, this involves using high density tracking (for example, approximately one pass per orbit). In the case of using GPS for EO-1 navigation, it may be necessary to remove the measurement corruption caused by selective availability (for example, using corrections provided by the Federal Aviation Agency's Wide Area Augmentation System (WAAS), use of differential GPS techniques, or the use of dual frequency P-code measurements).

Covariance analysis was performed to investigate the impact of correlated dynamic errors on the relative separation accuracy. These results indicate that the relative separation errors obtained using definitive solutions are 8.5-, 50-, and 47-meters, respectively, in radial, in-track and cross-track directions. Those derived from 1-day-predicted ephemerides are 7.4, 49, and 112 meters, respectively. The results derived from 1-day-predicted ephemerides are applicable to the case where both EO-1 and L-7 ephemeris data are prepared on ground and uplinked to the satellite. The correlation of the dynamic errors due to solar flux uncertainties provides considerable cancellation when the individual satellite position prediction errors are combined to compute the separation errors. When the correlation between satellite dynamic errors is taken into account, the results indicate that a radial separation accuracy of 7.5 meters (3-sigma) and a relative in-track velocity of 7 centimeters per second (3-sigma) are achievable using the nominal tracking configuration for the EO-1/L-7 formation. Because the actual area-to-mass ratios for EO-1 (0.008) and L-7 (0.0067) will be much closer than the area-to-mass ratios used in the covariance analysis, the cancellation of the individual satellite radial and in-track prediction errors will be more complete and the growth of relative radial and in-track position errors in the 3-day prediction periods will be smaller than these estimates.

In addition, the performance of a relative ONS using cross-link measurements was characterized for the relative navigation of a two-satellite formation similar to EO-1 and L-7, with RAAN differences of 0.0, 0.25, 0.5, 1.0 and 4.0 degrees. Because of the limited degree of observability present in the cross-link measurements for coplanar satellites, the associated navigation performance is very sensitive to measurement quality, measurement quantity, and a priori state knowledge. Increasing the orbit plane separation to 0.5 degree greatly improves the potency of the Doppler measurements by increasing the variation in the relative satellite dynamics from ±9 hertz in the coplanar case to a variation of ±42 hertz. It was found that position, velocity, and a Doppler bias could be accurately estimated in the real-time relative ONS algorithms using only one-way Doppler cross-link measurements of moderate quality. Increasing the tracking frequency and duration reduced the time for the filter to converge to an accurate steady state, but did not significantly improve the accuracy of the solution. For satellite formations with a plane separation of 0.5 degree or greater, a radial separation accuracy of 2 meters (3-sigma) is achievable using the relative ONS capability with USO-quality Doppler measurements.

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