# EO-1 Technology Validation Report

# Enhanced Formation Flying (JPL Algorithm)

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# 1. INTRODUCTION

A key technology flight validated on the New Millennium Program's Earth Orbiter 1 (EO-1) mission is autonomous navigation. In the context of this report it is defined as autonomously determining and controlling the orbit of a spacecraft. Autonomous formation flying is a type of autonomous navigation that for EO-1 and Landsat-7 involved maintaining a one-minute along track separation to within six seconds. A simple algorithm developed at NASA's Jet Propulsion Laboratory (JPL) was flight validated and the results are present here.

Autonomous, as used in this report, relates to a state of self-contained sensing, judging, and decision making to empower actions on the spacecraft without outside advice or intervention. Thus, autonomous navigation is navigation done by a spacecraft based on capabilities resident within that spacecraft and without ground intervention. Since the Global Positioning System (GPS) appears to be a stable, continuous, and reliable service, onboard orbit determination based on GPS is still considered an autonomous function.

Single spacecraft autonomous navigation has been proposed[1-4] and partially validated for various mission scenarios[5-6]. Within autonomous navigation, there are several possible "control objectives" dictated by the navigation requirements and implemented principally within the maneuver decision and design functions of an autonomous navigation system. Two or more spacecraft in Earth orbit actively preserving, within limits; some geometrical alignment is just one possible control objective achievable within the context of autonomous navigation. This would be formation flying. In its simplest form, two spacecrafts control and maintain their dynamic states with respect to one another according to some prespecified requirement, usually expressed as a nominal separation distance and a control band on that separation. The characteristics of this prespecified requirement, as a first order factor, determine the complexity of algorithms and the difficulty of the overall autonomous navigation implementation such that large distances and tight control bands are more difficult and costly.

For the EO-1 mission the problem is to make EO-1 fly in formation one minute (~450km) behind the Landsat-7 (LS-7) satellite. Formation flying here is required to take coordinated, co-registered images of reference geographic sites for a scientific comparison of the two imaging systems. In this mode of operation, the relative positions of EO-1 and LS-7 will be maintained and controlled with respect to one another according to the mission requirement for "simultaneity" of measurements. The separation distance between EO-1 and LS-7 can be as great as 15 minutes (~6750km) and still provide adequate science data collection. The control band of ±7.5 seconds (~50km) is derived from the mission requirement that the EO-1 ground track be no more than ±3km away from the LS-7 ground track.

LS-7 is considered to be a non-cooperative partner with EO-1, except perhaps to share its mission plan and navigational data at Orbit Maintenance Maneuvers. Smaller control bands are possible if some form of cooperative, near real-time data exchange were possible between EO-1 and LS-7, thus providing a more rigorous demonstration of formation flying. Cooperative formation flying using various methods of filtering spacecraft to spacecraft range have been proposed[7-9] and techniques from this paper can be extended to support such missions.

# 2. TECHNOLOGY DESCRIPTION

Since EO-1 is a technology validation mission several autonomous navigation approaches have been selected for flight validation. Fig.1. shows the flight software architecture. An executive called "AUTOCON" hosts two autonomous navigation flight software sets. The Goddard Space Flight Center (GSFC) is responsible for developing AUTOCON with it's set of autonomous navigation algorithms[10]. An empirical approach capable of using only the GPS kinematic "navigation solutions" is provided by the Jet Propulsion Laboratory (JPL)[11]. In this reference, a generic mathematical formulation is presented that provides the basis for the flight validation results presented here.

EO-1 Autonomous Navigation/Enhanced Formation Flying System

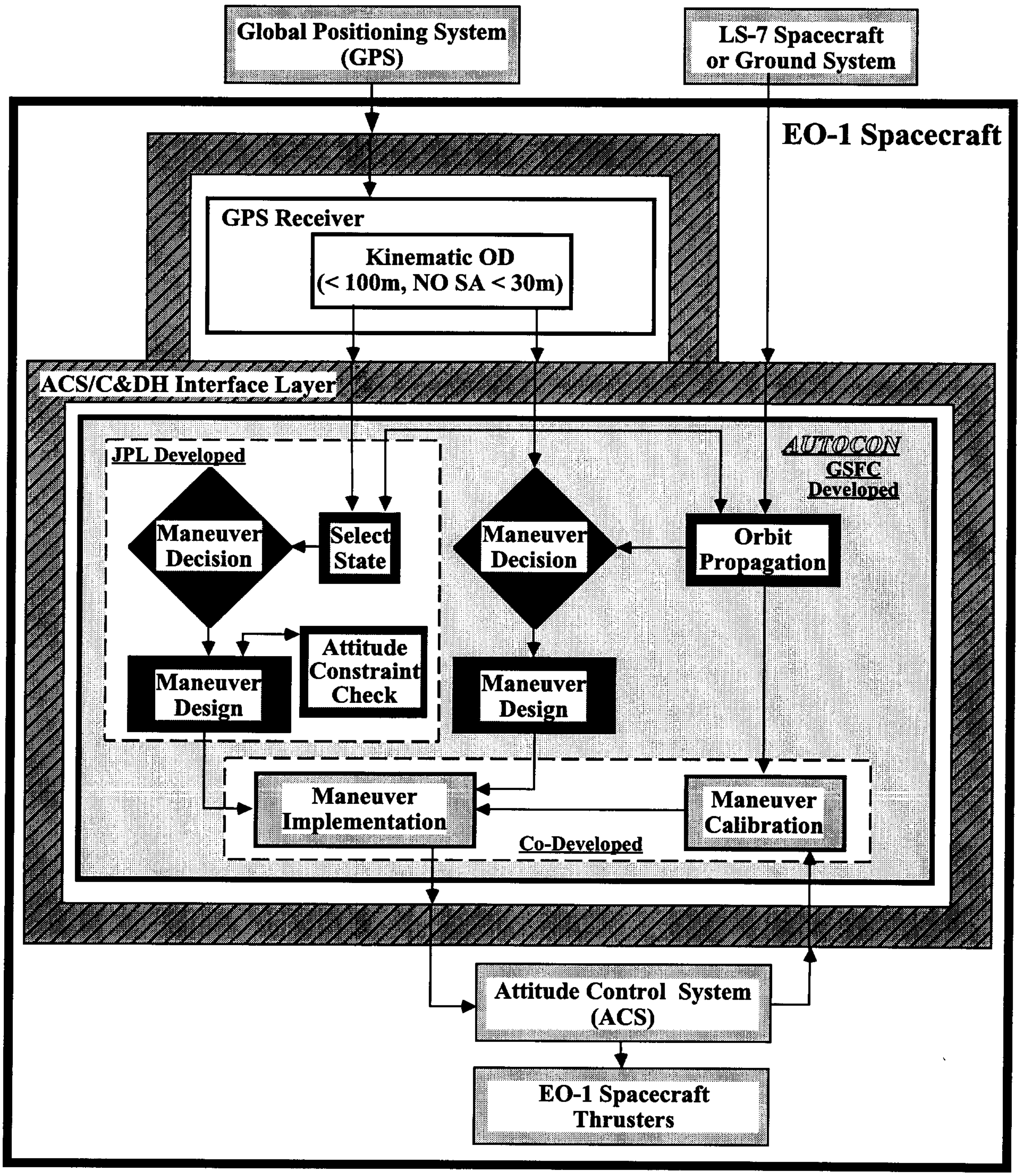


**Figure 1. EO-1 Flight Software Architecture**

# 3. TECHNOLOGY VALIDATION

Ground based simulations were performed to prepare for the flight demo. The ground tests also serve to demonstrate the possibility of automating a ground based navigation system for future missions that do not require onboard navigation.

### 3.1 Ground Test Verification

The simulation architecture for the JPL approach is shown in Fig.2. Simulated trajectories with gravitational and drag dynamics are required. In addition, noise is added to the resulting EO-1 orbits to simulate the expected GPS measurement system performance. For the GPS "navigation solutions", random noise of 450m (3 σ)[12] is applied. Onboard solutions without the effects of Selective Availability (SA) are expected to be accurate to about 30m (3σ).

The choice of epoch was driven by the solar activity cycle since atmospheric drag depends largely on the levels of solar flux and geomagnetic index. Fig.3 shows actual solar flux data from January 1, 1986 to June 1, 1997. Accounting for the known 11 year solar cycle and noting that originally planned full closed-loop flight validation was scheduled for May 1, 2000, the epoch May 1, 1989 was selected.

A 10:00 A.M. descending equatorial crossing is required for the LS-7 orbit. Thus, EO-1's requirement is 10:01 A.M descending crossing. The longitude of ascending node for each spacecraft reflects these requirements and the full set of initial mean orbital elements are given in Table 1.

**Table 1**

| | EO-1 | LS-7 |
|---|---|---|
| Semimajor Axis (km) | 7077.732 | 7077.732 |
| Eccentricity | 0.001175 | 0.001175 |
| Inclination (°) | 98.2102 | 98.2102 |
| Long. of Asc. Node (°) | 188.547 | 188.297 |
| Arg. of Periapsis (°) | 90.0 | 90.0 |
| Mean Anomaly (°) | -3.645 | 0.0 |
| Epoch: May 1, 1989 00:00:00 UTC | | |

A box-wing model was chosen for drag area representation of both spacecraft. The areas and masses selected are based on the best-known dimensions as of summer 1997. Table 2. gives the EO-1 and LS-7 values used in the simulation.

**Table 2**

| | EO-1 | LS-7 |
|---|---|---|
| Drag Area ($m^2$) | 7.7 | 19.0 |
| Mass (kg) | 529 | 2041 |
| Area-to-Mass Ratio ($m^2$/kg) | 0.0146 | 0.0093 |

Truth data were obtained from the noise free integrated orbits that include the high fidelity gravitational (20x20, EGM96 field) and atmospheric drag (DTM) dynamics. Fig.4. shows the true and inferred along track variations with the nominal one-minute (~450km) separation removed. The along track control band was set at ±50km (equivalent to about ±3km equatorial longitude ground track offset).

As the semimajor axes of both orbits decrease due to drag, Fig.5, the first control boundary encountered is the LS-7 east ground track constraint, see Fig.6 at about day eight. At that time both LS-7 and EO-1 perform along track maneuvers to raise their respective semimajor axes. Since the EO-1 orbit decays faster than LS-7 the EO-1 maneuver magnitude is larger to achieve the same post maneuver semimajor axis. An additional component is also added to the EO-1 maneuver to null the along track separation.

In Fig.6 the longitude offsets relative to the desired ground track are presented for EO-1 and LS-7. The EO-1 data are derived from the simulated GPS states with 450m (3σ) noise. The LS-7 data are noise free and represent "truth" values. A separation of 3km develops around 16 days and is equivalent to the 50km along track separation discussed earlier (see Fig.4.). Thus, a single EO-1 maneuver is performed that raises the EO-1 semimajor axis and brings the EO-1 ground track back toward LS-7's.

The simulation was run out to accommodate another LS-7 maneuver at 34 days and an EO-1 only formation maintenance maneuver at 55 days.

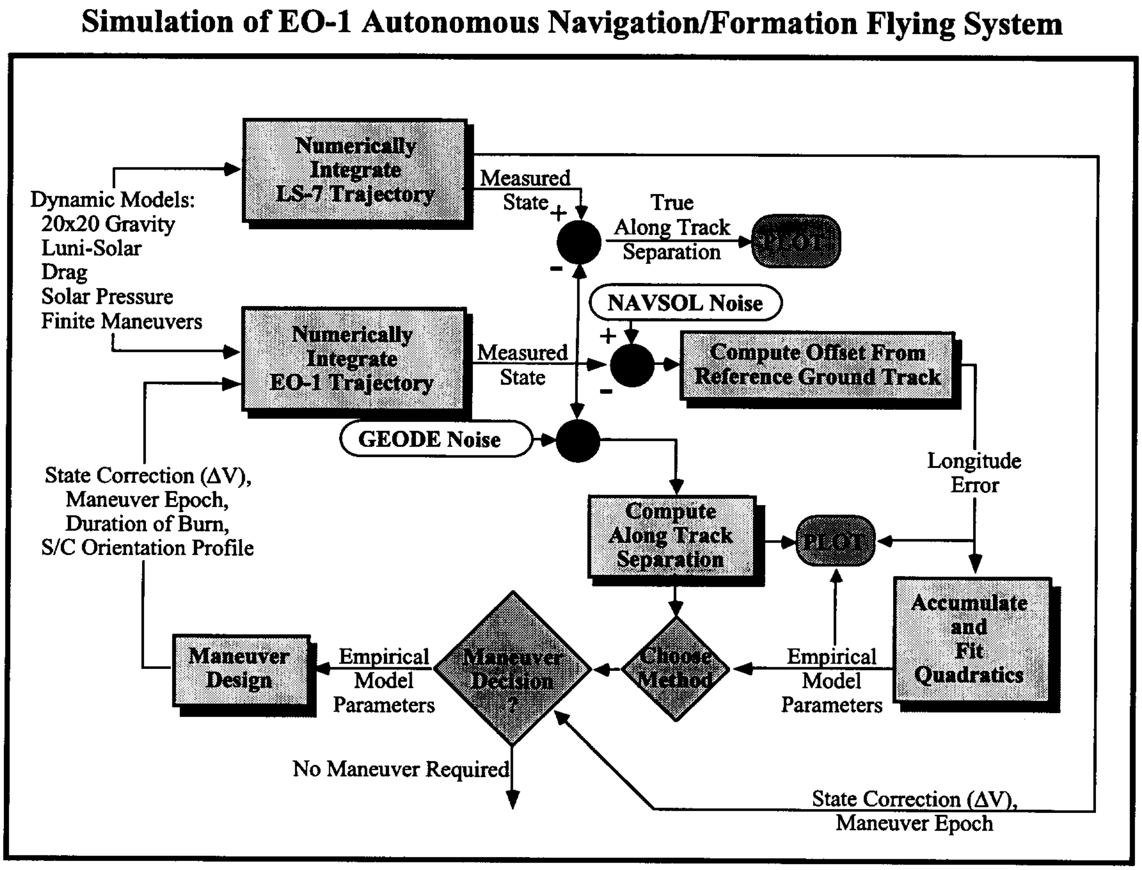


Fig.2. - EO-1 Simulation Architecture

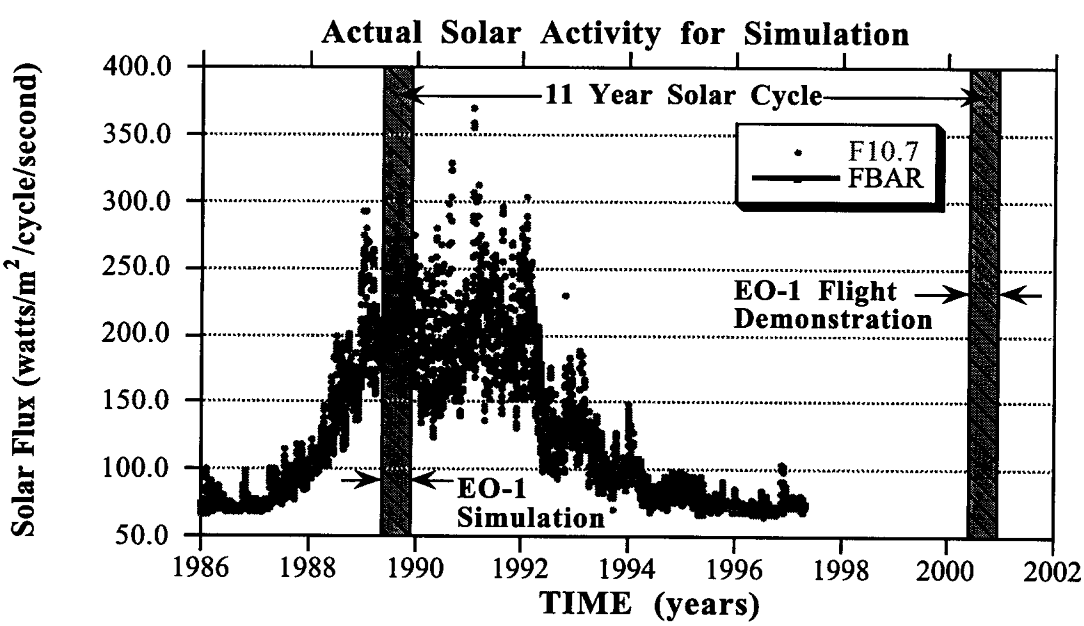


Fig. 3 - Solar Flux History

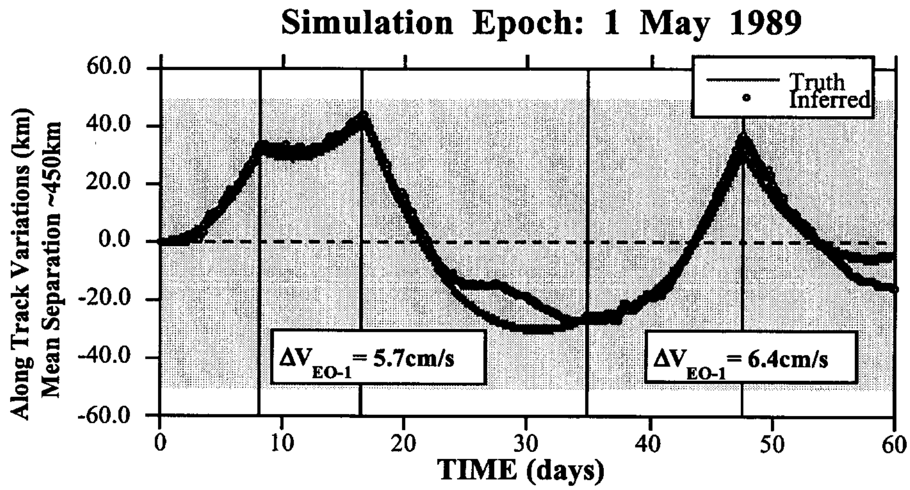


Fig. 4 - Mean Along Track Variations

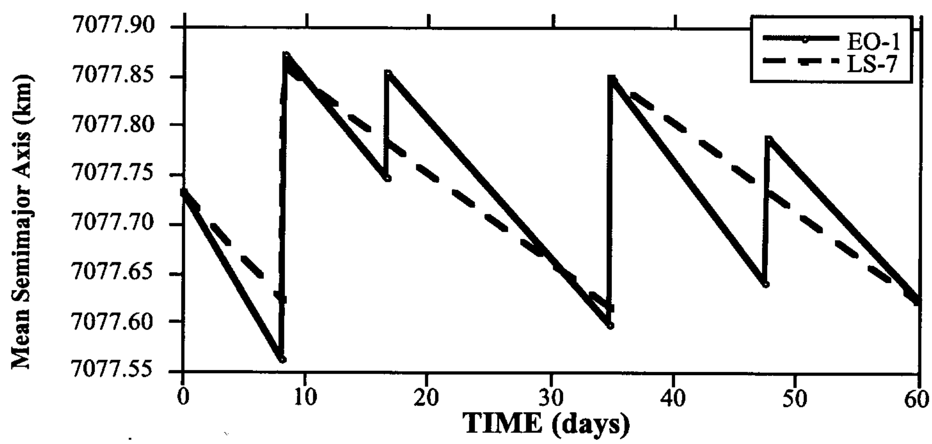


Fig. 5 - Semimajor Axis Variations

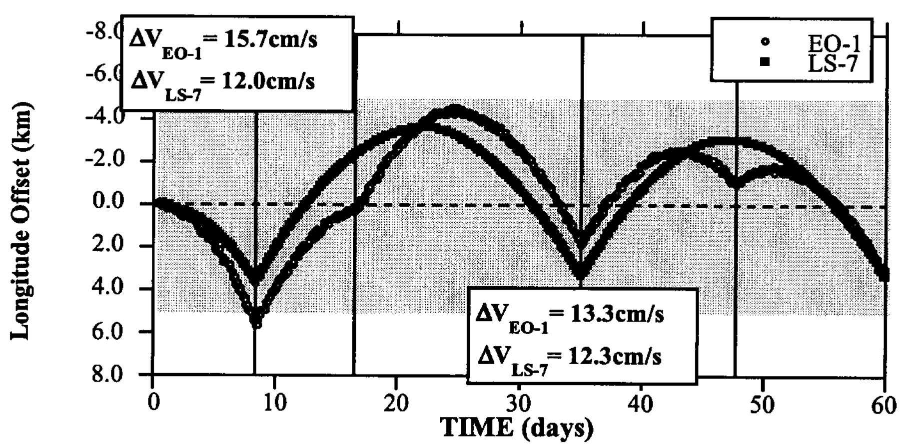


Fig. 6 - Ground Track Variations

### 3.2 On-Orbit Test Verification

Flight validation was conducted between July and September 2001. One of the most significant differences between the simulation and on-orbit tests was the improved quality of GPS "navigation solutions". On-orbit random noise of 60m ($3\sigma$) performance was achieved. The as-flown drag area and mass parameters are given in Table 3. The resulting ballistic coefficient ratio resulted in the LS-7 drag being about 72% of that on EO-1.

**Table 3 – As-Flown Spacecraft Characteristics**

| | EO-1 | LS-7 |
|---|---|---|
| Drag Area ($m^2$) | 6.03 | 15.21 |
| Mass (kg) | 566 | 1958 |
| Area-to-Mass Ratio ($m^2$/kg) | 0.0107 | 0.0078 |

### 3.3 On-Orbit Usage Experience

The achieved along track separation for the on-orbit verification period is shown in Fig. 7. Ground solutions were obtained by differencing the Landsat-7 and Eo-1 project teams reconstructed orbit ephemeredes. The Landsat-7 solutions were based on TDRS S-Band doppler observations while the EO-1 solutions were derived from ground based S-Band doppler measurements. Table 4. compares the five maneuvers produced by the JAN onboard algorithm and the ground determined values.

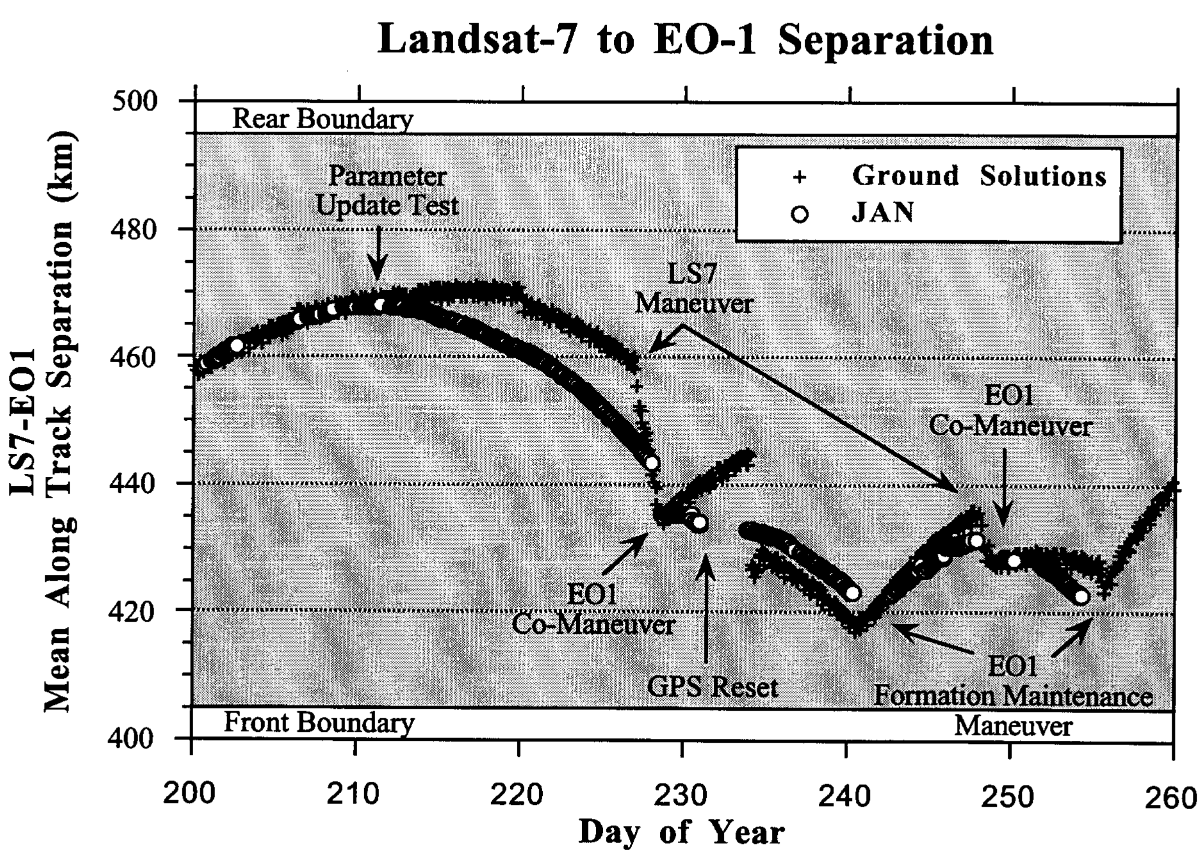


**Fig. 7 – On-Orbit Performance**

**Table 4 – Onboard verses Ground Performance**

| **Maneuver Type & Date** | **Onboard Plan** Burn Duration / Magnitude | **Ground Plan** Burn duration / Magnitude | **Comments** |
|---|---|---|---|
| Co-maneuver **16 Aug 2001** | **23 sec / 61.1 mm/s** | **22sec / ~58 mm/s**<br>**2 sec / ~3 mm/s** | **Manual Mode**<br>2 maneuver ground plan used |
| Formation Maintenance **28 Aug 2001** | **9 sec / 23.8 mm/s** | **9 sec / ~24 mm/s** | **Semi-Autonomous**<br>Success: but bad table parameters required re-initialization after maneuver |
| Co-maneuver **5 Sep 2001** | **16 sec / 43.5 mm/s** | **16 sec /~43 mm/s** | **Semi-Autonomous**<br>Manually patched to complete successfully |
| Formation Maintenance **12 Sep 2001** | **10 sec / 26.6 mm/s** | **10 sec / ~27 mm/s** | **Fully-Autonomous**<br>Ops procedure error: terminated prematurely |
| Co-maneuver **19 Sep 2001** | **27 sec / 72.1 mm/s** | **27 sec /~72 mm/s** | **Fully-Autonomous**<br>Completed successfully |

# 4. NEW APPLICATIONS POSSIBILITIES

This new technology can also be used for single satellite autonomous navigation of ground track repeat missions. No software modifications are required, only inputs (table uploads) need to change to allow the algorithm to monitor and adjust the ground track without regard to formation constraints.

# 5. FUTURE MISSIONS INFUSION OPPORTUNITIES

Several missions are proposed to fly on the World Reference System (WRS) morning and afternoon grids. These so-called AM and PM constellations can use this algorithm to perform autonomous navigation functions. The software is completely generalized to function around other planets, moons or small bodies. Equator crossing information around other central bodies where no GPS is available would require periodic orbit ephemeris updated from Earth.

# 6. LESSONS LEARNED

Several findings became apparent: Two to three days of GPS observations required to converge on an accurate solution; more advanced outlier editing for GPS outage case should be considered; a maneuver magnitude scaling factor to accommodate alternate maneuver strategies should be added; the maneuver implementation interface should have been tested more; EO-1 co-maneuvers should be performed as soon after Landsat-7 maneuvers as possible to reduce along track runoff.

# 7. CONTACT INFORMATION

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# 8. SUMMARY

The resulting performance of using GPS "navigation solutions" for autonomous orbit determination and a simple empirical algorithm for autonomous orbit control is shown to be feasible by simulation and in-flight testing. With some minor augmentations, to improve robustness, this technology is ready for operational use.

# 9. CONCLUSIONS

Flight validations were completed from July 18 - September 19, 2001. Five maneuvers were performed (3 co-maneuvers, 2 formation maintenance maneuvers, see figure 7). All onboard planned burn durations were within one second of ground plans (see table 4).

Benefits of autonomous navigation are: Ground tracking network for navigation not required; Reduces mission operations ground team effort and size; Applicable to many future Earth science missions

Benefits of the JPL algorithm are: Minimal memory and onboard processor requirements (<100kB RAM); Simple, relies on GPS onboard navigation solutions (position only); No numerical integration required; No navigation (Kalman) filtering required; Autonomous, Landsat-7 maneuvers are only routine data transmitted to EO-1.

# 10. ACKNOWLEDGEMENTS

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