Enhanced Formation Flying Validation Report

(JPL Algorithm)

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Joseph R. Guinn
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California 91109

NASA/GSFC

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1. INTRODUCTION

A key technology that was flight validated on NASA's New Millennium Program Earth Observing-1 (EO-1) mission was autonomous navigation. In the context of this report, autonomous navigation is defined as determining and controlling the orbit of a spacecraft. Autonomous, as used in this report, refers 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. Autonomous formation flying is a type of autonomous navigation that, for EO-1 and Landsat 7 (LS-7), involved having EO-1 maintain a one-minute (~450-km) along track separation behind Landsat 7 to within six seconds. 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[1,2,3,4] 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 spacecraft control and maintain their dynamic states with respect to one another according to some pre-specified requirement, usually expressed as a nominal separation distance and a control band on that separation. The characteristics of this pre-specified 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.

The operational purpose of the EO-1 formation flying is to accommodate the acquisition of 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 would be maintained and controlled with respect to one another according to the mission requirement for "simultaneity" of measurements. The required control band is approximately ±6.5 seconds (~50km), which was derived from the mission requirement that the EO-1 ground track be no more than ±3 km 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 would be 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[7,8,9] and techniques from this report can be extended to support such missions.

2. TECHNOLOGY DESCRIPTION

Since EO-1 is a technology validation mission, two autonomous navigation approaches were selected for flight validation. Figure 1 shows the flight software architecture. An executive called "AutoCon™," developed by a.i. solutions Inc. under contract to NASA Goddard Space Flight Center (GSFC), hosts the two autonomous navigation flight software sets[10]. GSFC developed an autonomous formation-flying algorithm that accommodates a general set of orbits for multiple spacecraft. The Jet Propulsion Laboratory (JPL) developed a second approach based on a more simple control algorithm that focused on missions flying ground track repeat orbits. Further, the JPL approach requires only GPS kinematic "navigation solutions" for orbit knowledge inputs. The software is completely generalized to function around any planet, moon, or small body. However, orbit knowledge information around central bodies other than Earth, where no GPS is available, would require periodic orbit ephemeris updates from Earth. Thus, on-board orbit control is the primary function of the JPL algorithm. A complete description of the algorithm was published[11] that provides the mathematical formulation.

EO-1 Autonomous Navigation/Enhanced Formation Flying System

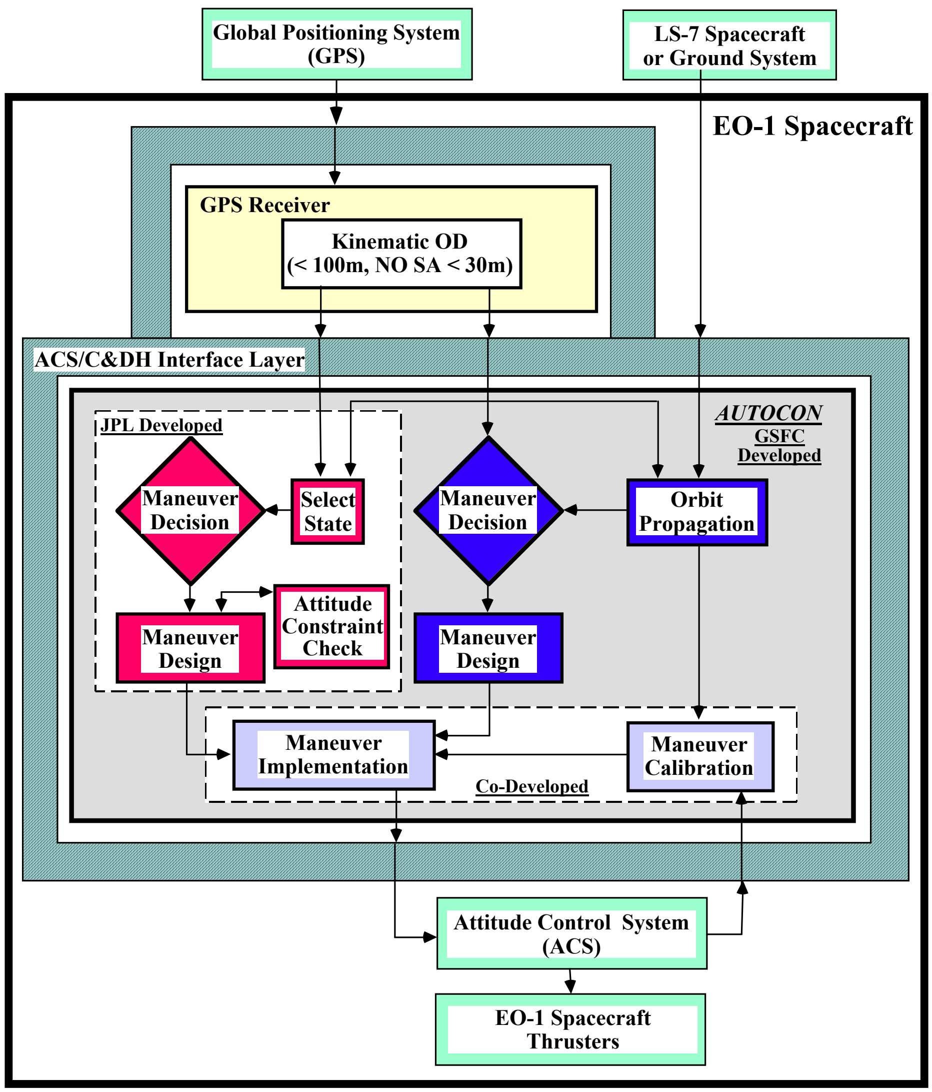

Figure 1. EO-1 Flight Software Architecture (JPL Approach)

3. TECHNOLOGY VALIDATION

Ground based simulations were performed to prepare for the flight demonstration. The ground tests also served 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 Figure 2. Simulated trajectories with gravitational and drag dynamics were required. In addition, noise was 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)[12,13] was applied. Onboard solutions without the effects of Selective Availability (SA) were expected to be accurate to about 30m (3σ).

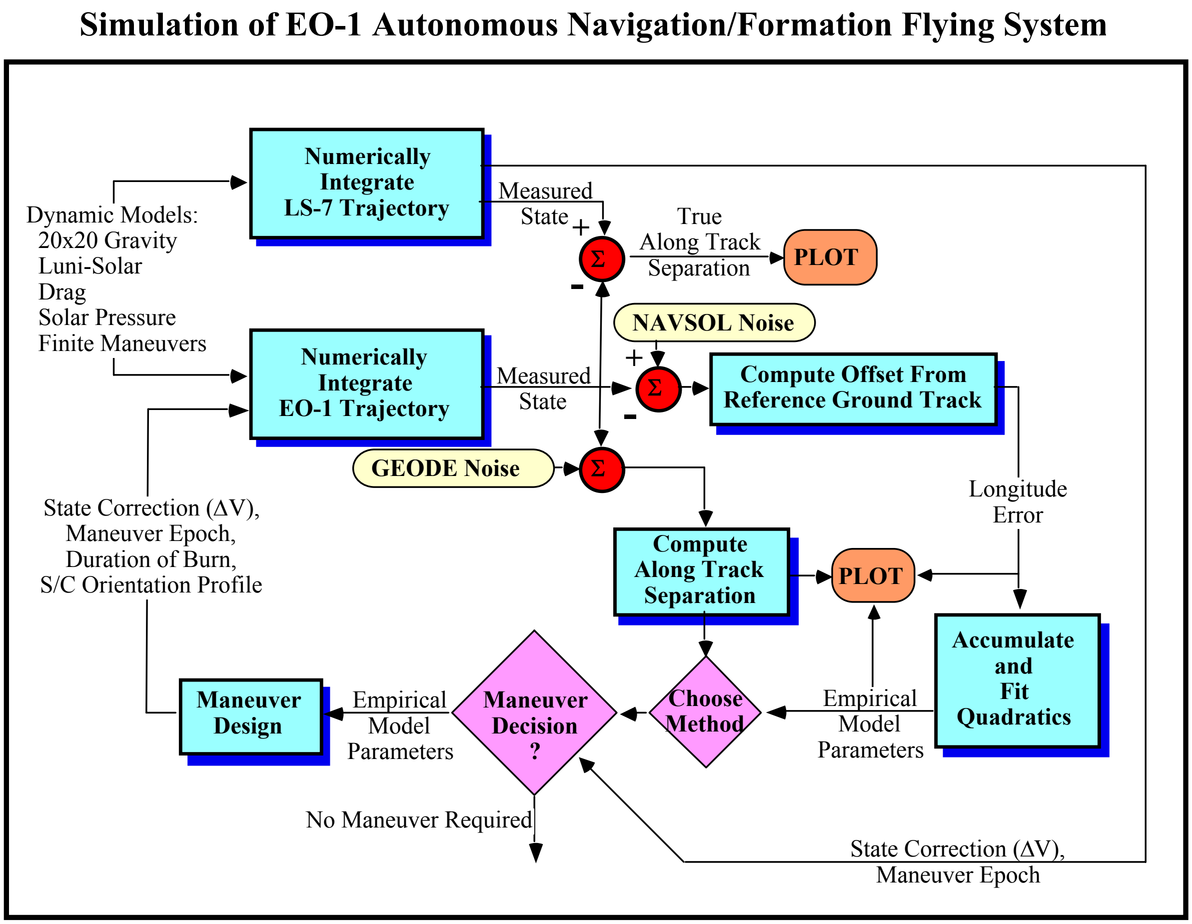

Figure 2. EO-1 Simulation Architecture

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. Figure 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.

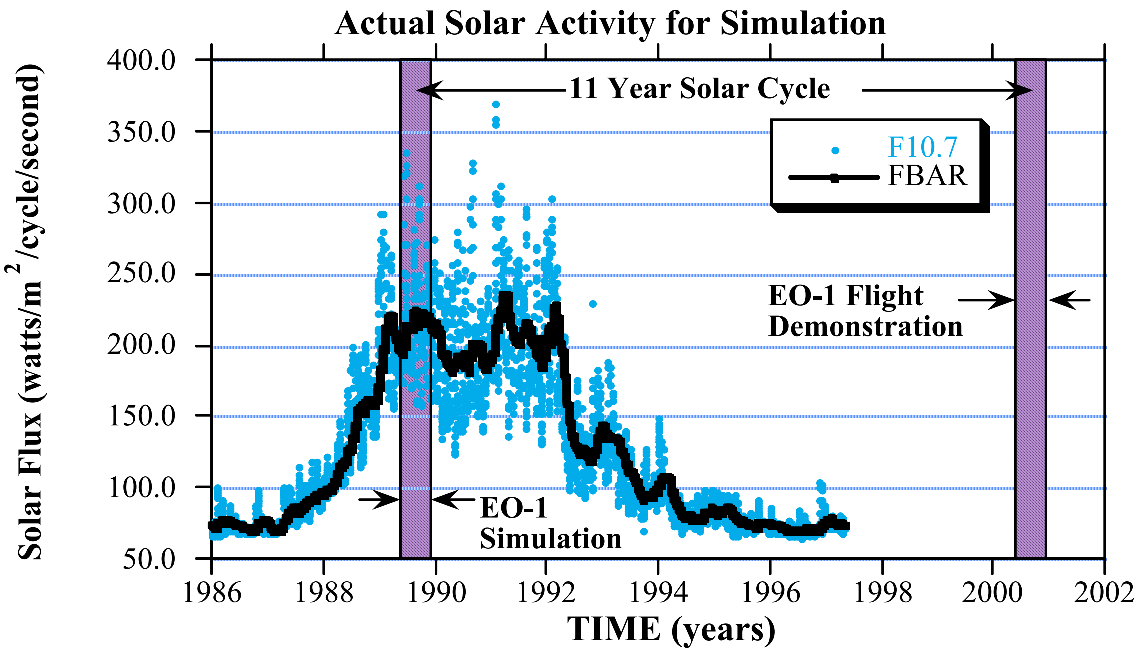

Figure 3. Solar Flux History

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

Table 1. EO-1 and LS-7 Orbit Parameters

	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 were 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 and LS-7 Spacecraft Parameters – Simulation

	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 was obtained from the noise-free integrated orbits that included the high-fidelity gravitational (20x20, EGM96 field) and atmospheric drag (DTM) dynamics. Figure 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 ±50 km (equivalent to about ±3 km equatorial longitude ground track offset).

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

In Figure 6, the longitude offsets relative to the desired ground track are presented for EO-1 and LS-7. The EO-1 data was derived from the simulated GPS states with 450-m (3σ) noise. The LS-7 data was noise free and represented "truth" values. A separation of 3 km developed around 16 days and was equivalent to the 50-km along track separation discussed earlier (see Figure 4). Thus, a single EO-1 maneuver was performed that raised the EO-1 semimajor axis and brought 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.

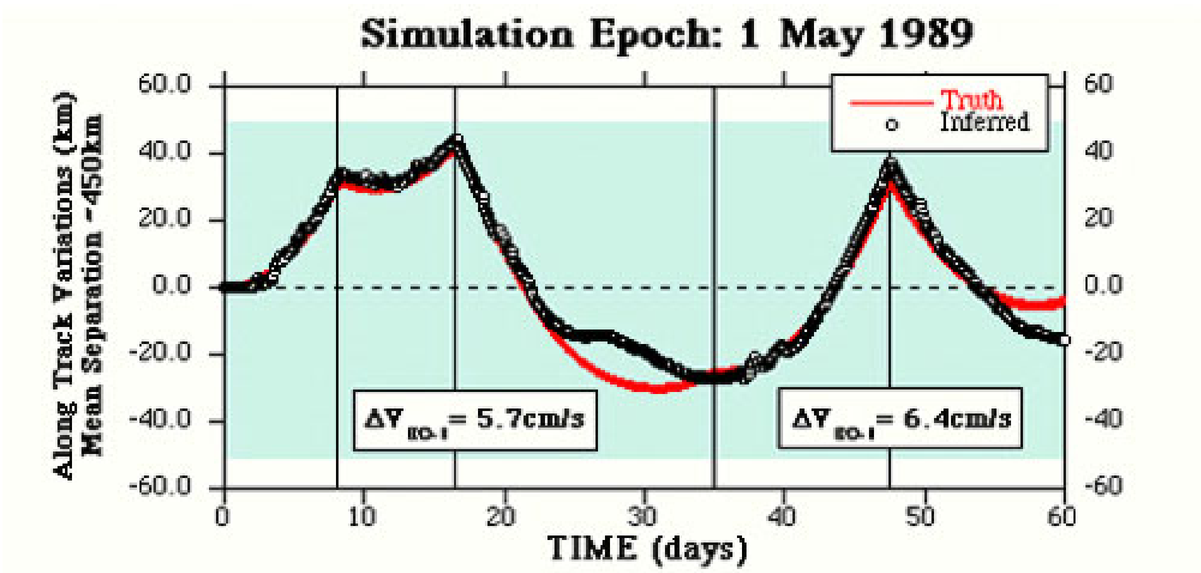

Figure 4. Mean Along Track Variations

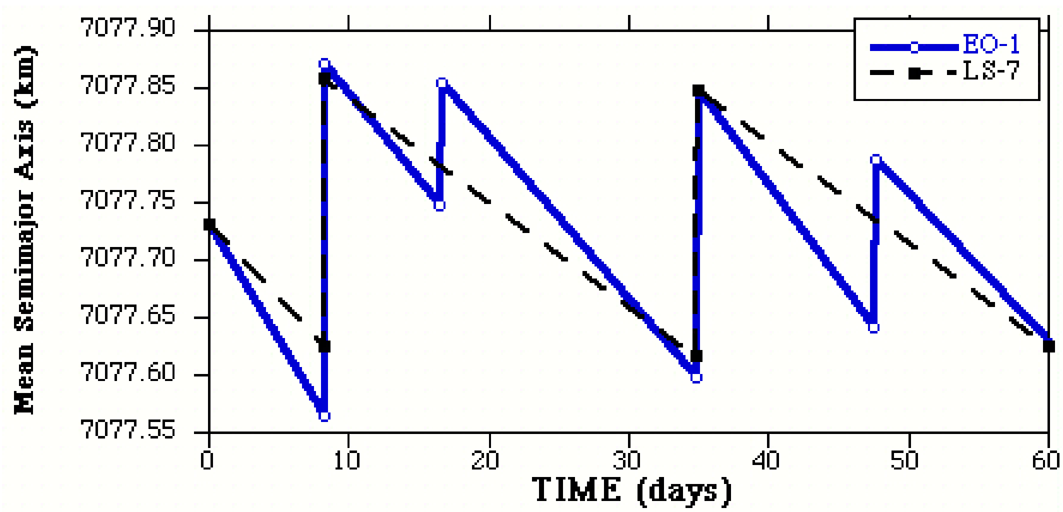

Figure 5. Semimajor Axis Variations

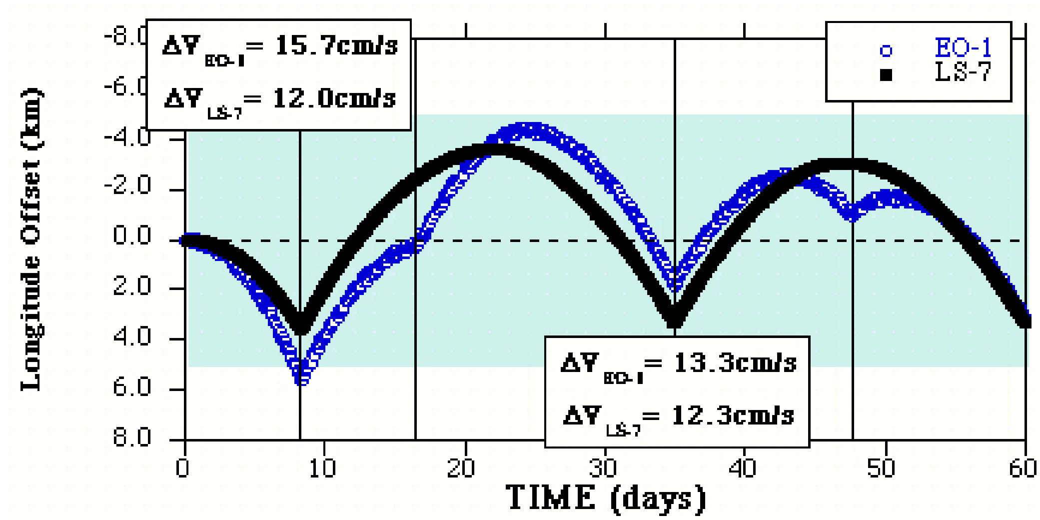

Figure 6. Ground Track Variations

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 60-m (3σ) 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 Figure 7. Ground solutions were obtained by comparing the Landsat-7 and EO-1 project teams reconstructed orbit ephemeredes. The LS-7 solutions were based on Tracking and Data Relay Satellite (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 JPL Autonomous Navigation (JAN) onboard algorithm and the ground determined values.

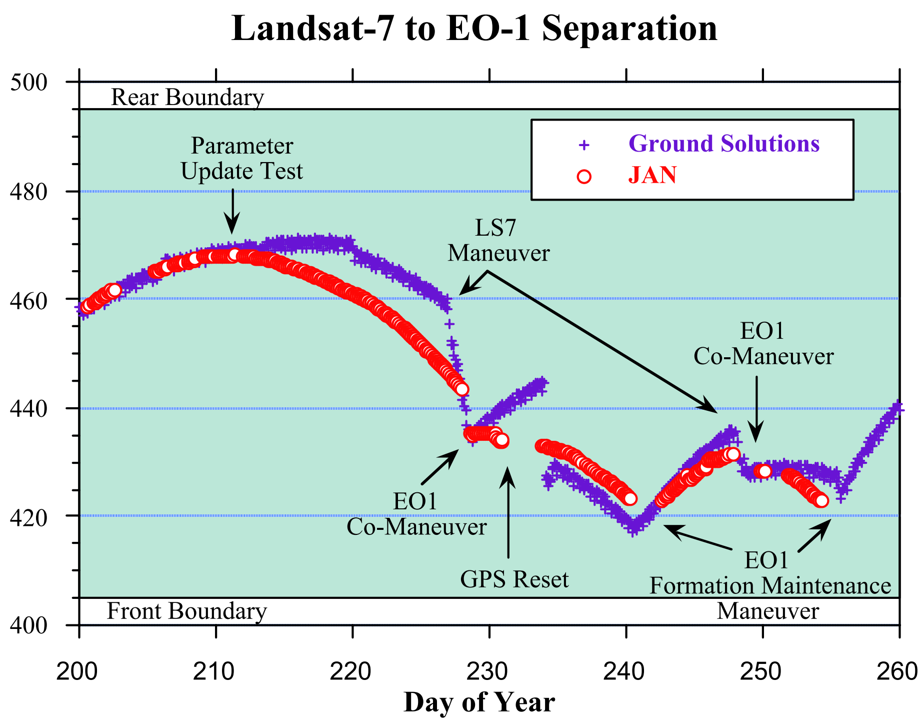

Figure 7. On-Orbit Performance

Table 4. Onboard vs. 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 2 sec / ~3 mm/s	Manual Mode 2 maneuver ground plan used
Formation Maintenance 28 Aug 2001	9 sec / 23.8 mm/s	9 sec / ~24 mm/s	Semi-Autonomous 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 Manually patched to complete successfully
Formation Maintenance 12 Sep 2001	10 sec / 26.6 mm/s	10 sec / ~27 mm/s	Fully Autonomous Ops procedure error: terminated prematurely
Co-maneuver 19 Sep 2001	27 sec / 72.1 mm/s	27 sec /~72 mm/s	Fully Autonomous Completed successfully

4. NEW APPLICATIONS POSSIBILITIES

This new technology could also be used for single satellite autonomous navigation of ground track repeat missions. No software modifications would be required, only inputs (table uploads) would 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 could 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 are 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 LS-7 maneuvers as possible to reduce along track runoff.

7. CONTACT INFORMATION

Joseph R. Guinn
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive, Mail Stop 301-125
Pasadena, California 91109
e-mail: joe.guinn@jpl.nasa.gov
Phone: 1+818-354-0425 FAX: 1+818-393-6388

8. SUMMARY

The resulting performance of using GPS "navigation solutions" for autonomous orbit determination and a simple empirical algorithm for autonomous orbit control was 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 (three co-maneuvers, two 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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