EO-1 Technology Validation Report

Enhanced Flying Formation Algorithm (JPL)

August 8, 2001

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

NASA/GSFC

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

1. INTRODUCTION

A key technology to be flight validated on the New Millennium Program's Earth Orbiter 1 (EO-1) Mission is autonomous navigation. Autonomous, in this context, 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. Figure 1 shows the flight software architecture. An executive called "AUTOCON" hosts the various autonomous navigation flight software. 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 simulation results presented here.

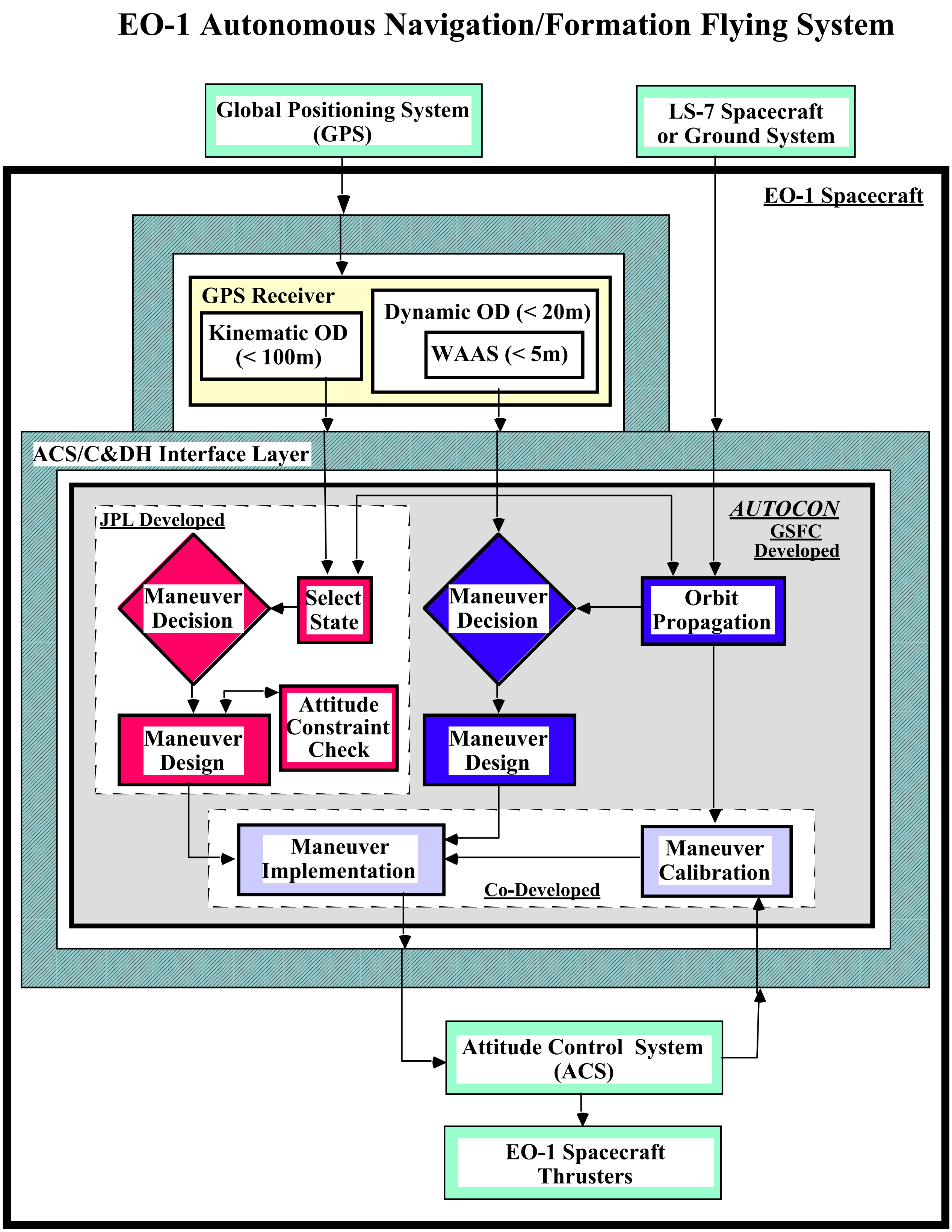

Fig. 1. EO-1 Flight Software Architecture

3. TECHNOLOGY VALIDATION

3.1 GROUND TEST VERIFICATION

The simulation architecture for the JPL approach is shown in Figure 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. The filtered onboard solutions from "GEODE"[13] are expected to be accurate to about 5m (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. 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 full closed-loop flight validation is 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 and LS-7 Table 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 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 and LS-7 Spacecraft Parameters

	EO-1	**LS-7**
Drag Area (m2)	7.7	19.0
Mass (kg)	529	2041
Ballistic Coefficient (A/M)	0.0146	0.0093

Truth data are obtained from the noise free integrated orbits that include the full gravitational and atmospheric drag 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 ±50km (equivalent to about ±3km equatorial longitude ground track offset).

As the semimajor axes of both orbits decrease due to drag, Figure 5, the first control boundary encountered is the LS-7 east ground track constraint, see Figure 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 Figure 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 Figure 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 is run out to accommodate another LS-7 maneuver at 34 days and an EO-1 only formation maintenance maneuver at 55 days.

Simulation of EO-1 Autonomous Navigation/Formation Flying System

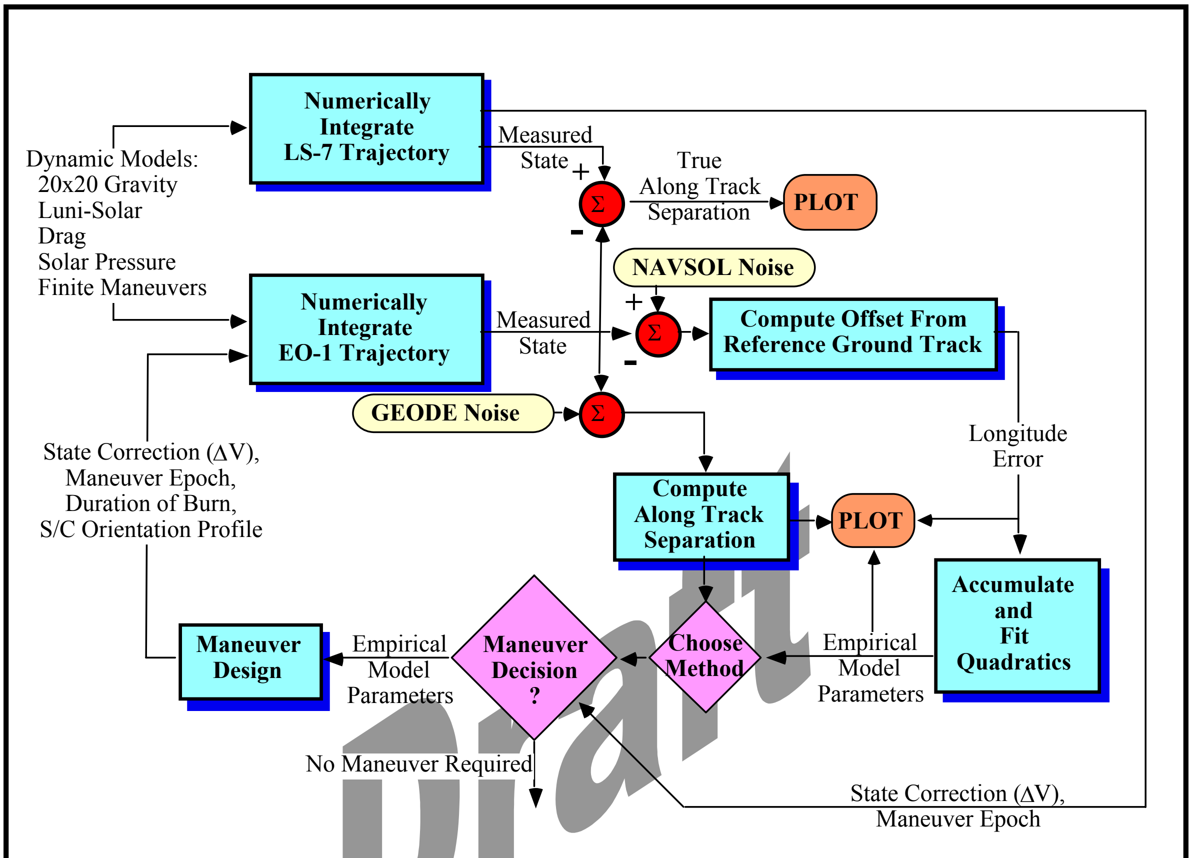

Fig. 2. EO-1 Simulation Architecture

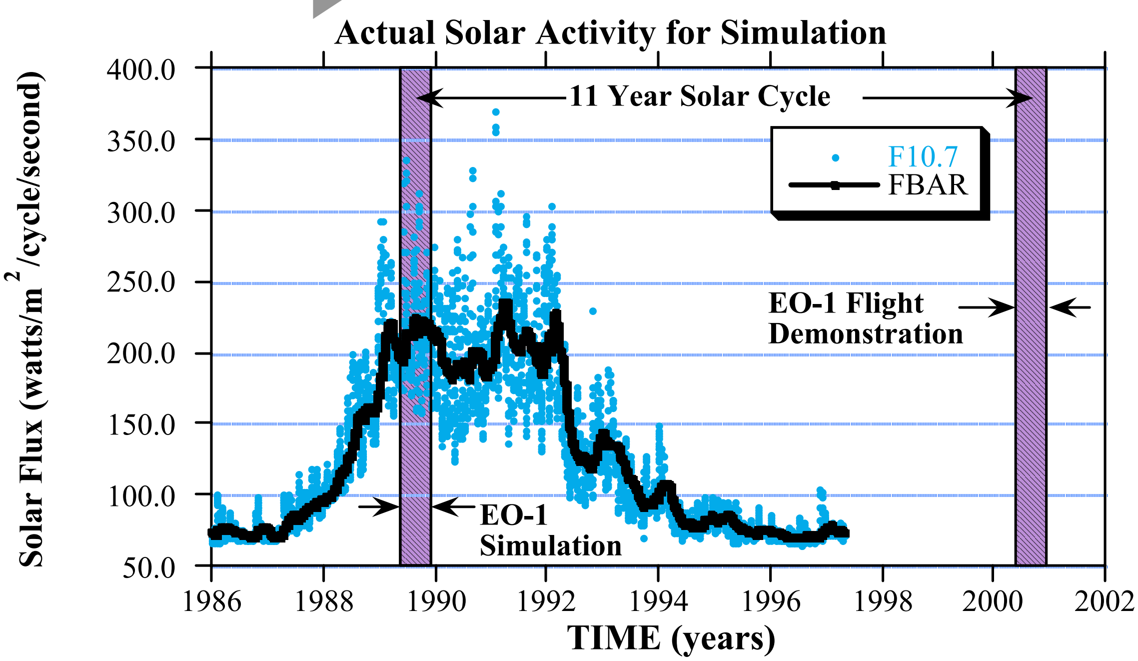

Fig. 3 - Solar Flux History

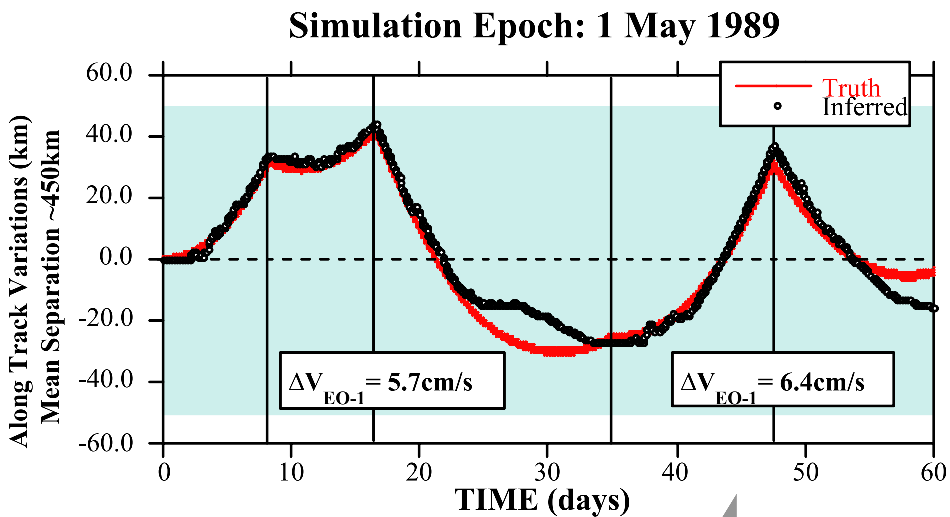

Fig. 4 - Mean Along Track Variations

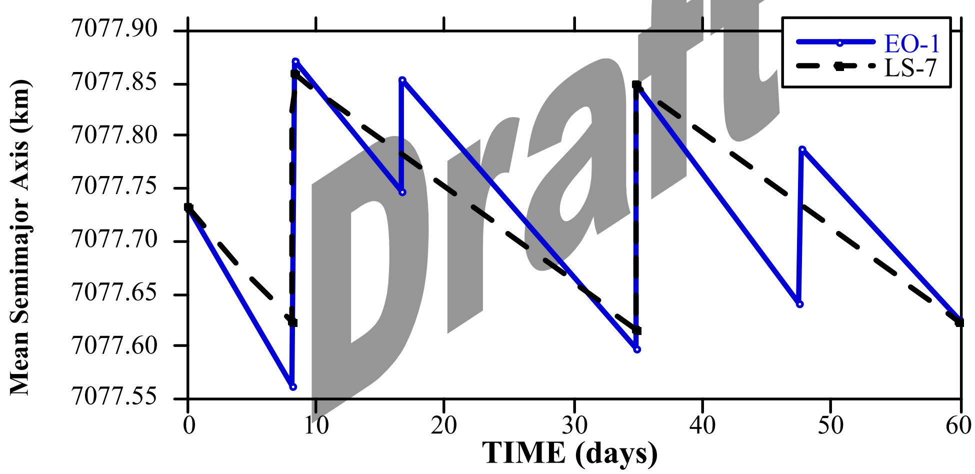

Fig. 5 - Semimajor Axis Variations

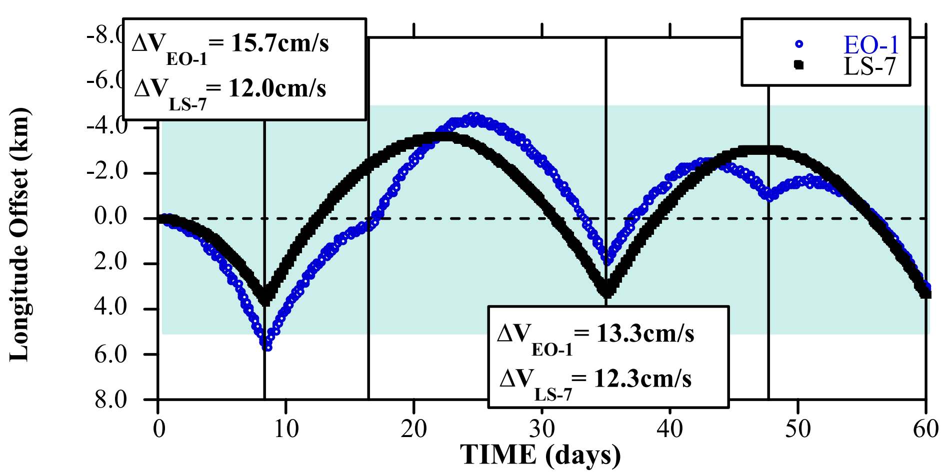

Fig. 6 - Ground Track Variations

3.2 ON-ORBIT TEST VERIFICATION

On-orbit tests began on July 18, 2001.

3.3 ON-ORBIT USAGE EXPERIENCE

Very preliminary at this time.

4. NEW APPLICATIONS POSSIBILITIES

This new technology can be used for single satellite autonomous navigation for 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.

6. LESSONS LEARNED

In progress.

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 is shown to be feasible by simulation. This approach is ready for flight validation.

9. CONCLUSIONS

Once validated, this algorithm can be incorporated in any GPS flight receiver/processor that produces "navigation" or "point" solutions. Only user and partner spacecraft initial conditions are required to initiate ground track and/or formation maintenance maneuver decision and design functions. Ground intervention is minimized to require uplinks only when the partner spacecraft performs a maneuver. The frequency of LS-7 maneuvers is currently about once per month.

10. TECHNICAL REFERENCES

[1] Guinn, J.R., and others, “Autonomous Spacecraft Navigation for Earth Ground Track Repeat Orbits Using GPS,” presented at the AAS/AIAA Space Flight Mechanics Meeting, Austin, TX., 12-15 February 1996
[2] Wertz, J.R., “Implementing Autonomous Orbit Control,” presented at the 19th Annual AAS Guidance and Control Conference, Breckenridge, CO., 7-11 February 1996.
[3] Collins, J., and R. Conger, “MANS: Autonomous Navigation and Orbit Control for Communications Satellites,” AIAA 94-1127-CP, presented at the AIAA International Communication Satellite Systems Conference, San Diego, CA., 15 February 1994.
[4] Ketchum, E., “Autonomous Spacecraft Orbit Determination Using Magnetic Field and Attitude Information,” presented at the 19th Annual AAS Guidance and Control Conference, Breckenridge, CO., 7-11 February 1996.
[5] Anthony, J. and P. Pepperi, “US Air Force Phillips Laboratory Autonomous Space Navigation Experiment,” presented at the AIAA/Utah State University Conference on Small Satellites, September 1992.
[6] Gramling, C.J., and others, “Flight Qualification of the TDRSS Onboard Navigation System (TONS),” presented at the AAS/AIAA Astrodynamics Specialists Conference, Victoria, B.C., Canada, 16-19 August 1993.
[7] Clohessy, W. and R. Wiltshire, “Terminal Guidance System for Satellite Rendezvous,” Journal of the Aerospace Sciences, Vol. 27, No. 9, pp. 653-658, Sept., 1960.
[8] Vassar,R. and R. Sherwood, “Formationkeeping for a Pair of Satellites in a Circular Orbit,” Journal of Guidance, Control, and Dynamics, Vol. 8, No. 2, pp. 235-242, Mar-Apr, 1985.
[9] Middour, J.W., “Along Track Formationkeeping for Satellites with Low Eccentricity,” Journal of the Astronautical Sciences, Vol. 41, No. 1, pp. 19-33, Jan-Mar, 1993.
[10] Folta, D. and others “Foundations of formation flying for Mission to Planet Earth and New Millennium,” presented at the AIAA/AAS Astrodynamics Specialists Conference, July 29-31, 1997.
[11] Guinn, J.R. and R.J. Boain, “Spacecraft Autonomous Navigation for Formation Flying Earth Orbiters Using GPS,” presented at the AIAA/AAS Astrodynamics Specialists Conference, July 29-31, 1997.
[12] GPS Tensor™ Brochure, Space Systems/Loral.
[13] van Grass, F. and M. Braasch, “Selective Availability,” Global Positioning System: Theory and Applications, Vol. 1, pp 3-28, Progress in Astronautics and Aeronautics, Vol. 163, 1996.