Enhanced Formation Flying (JPL Algorithm) Summary

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A key technology that was flig$_{ht}$ validated on NASA's New Millennium Program Earth Observing-1 (EO-1) mission was autonomous navigation/Enhanced Formation Flying (EFF). In the context of this report, navigation is defined as determining and controlling the orbit of a spacecraft. 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. 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 LS-7 to within six seconds. 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 spacecraft imaging systems. LS-7 is a non-cooperative partner with EO-1, except to share its mission plan and navigational data at orbit maintenance maneuvers times.

Two autonomous navigation approaches were selected for flight validation on the EO-1 mission. 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. 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 Global Positioning System (GPS) kinematic "navigation solutions" for orbit knowledge inputs. The software was 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 was the primary function of the JPL algorithm. Figure 1 shows the flight software architecture.

EO-1 Autonomous Navigation/Enhanced Formation Flying System

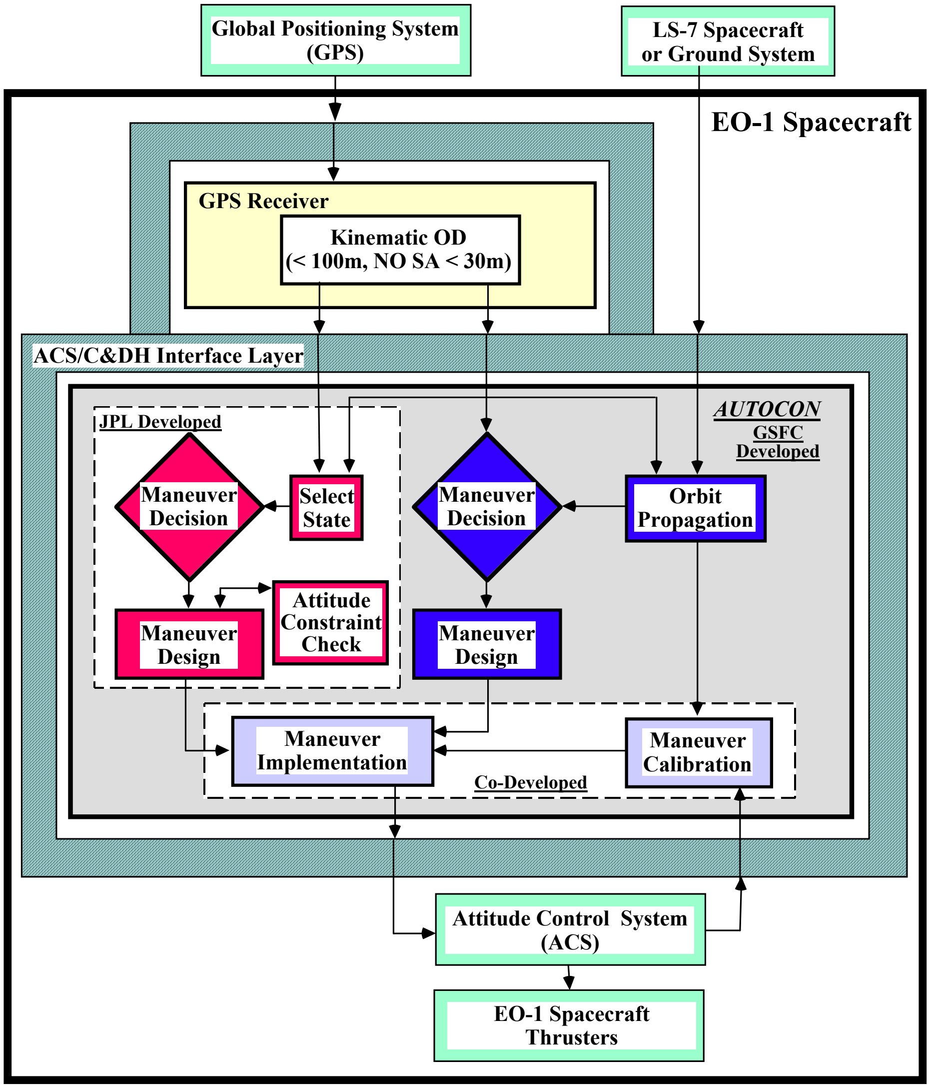

Figure 1. EO-1 EFF Flight Software Architecture (JPL Approach)

Ground-based simulations were performed to prepare for the flight demonstration. 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. As a result, the epoch May 1, 1989, was selected based on the known 11-year solar cycle. Truth data were obtained from the noise-free integrated orbits that included high-fidelity gravitational field and atmospheric drag dynamics. The EO-1 data were derived from the simulated GPS states with 450 m (3σ) noise. The LS-7 data were noise-free and represented "truth" values. The true and inferred along track variations vs. days, with the nominal one-minute (~450 km) separation removed, were determined for the EO-1 and LS-7 for a period of 60 days. The autonomously controlled EO-1 along track variations remained within the prescribed ±50-km band and matched the LS-7 variations very closely. The longitude offsets relative to the desired ground track vs. days were determined for EO-1 and LS-7 also for a period of 60 days. The relative offsets remained within a satisfactory ±5-km band, and the EO-1 offsets closely followed that for LS-7.

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 due largely to the absence of "Selective Availability." The as-flown drag area and mass parameters resulted in the LS-7 drag being about 72% of that for EO-1. As shown in Figure 2, the achieved along track separations for the on-orbit validation period demonstrated that the JPL Autonomous Navigation (JAN) on-board algorithm produced four highly successful maneuvers, two of which were LS-7 co-maneuvers and two of which were formation maintenance maneuvers.

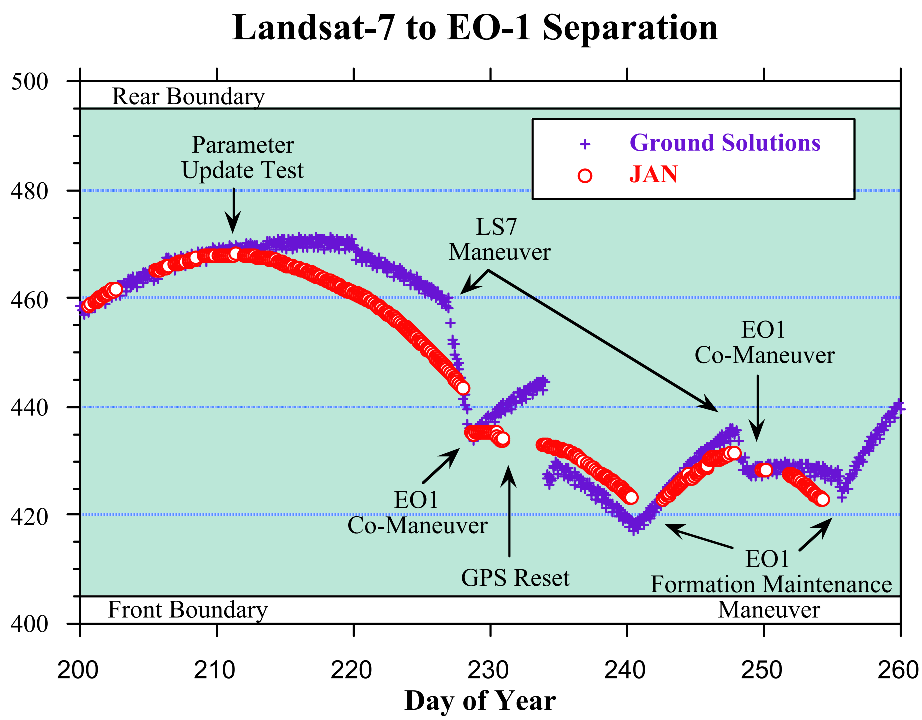

Figure 2. On-Orbit Performance

Benefits of the JPL algorithm are: minimal memory and onboard processor requirements (<100 kB RAM), simplicity - relies on GPS onboard navigation solutions (position only), no numerical integration required, no navigation (Kalman) filtering required, and autonomous - LS-7 maneuvers are the only routine data transmitted to EO-1.

The JAN algorithm, that uses GPS "navigation solutions" for *autonomous orbit determination* and a simple empirical algorithm for *autonomous orbit control*, has been shown to be feasible by simulation and on-orbit testing performance. With some minor augmentations, to improve robustness, this technology is ready for operational use.