Enhanced Formation Flying (GSFC Algorithm) Summary

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NASA's first-ever autonomous formation flying mission has been successfully demonstrated. The Earth Observing-1 (EO-1) satellite was launched in November 2000 as a technology mission designed to fly in formation with Landsat 7, another NASA satellite. Both satellites carry instruments that enable scientists to study high-resolution images and climatic trends in the Earth's environment.

The EO-1 satellite flew only 1 minute (450 kilometers) behind Landsat 7 in the same ground track and maintained the separation within 2 seconds, guaranteeing that EO-1 met the requirement that its ground track in the cross-track direction remain within +/- 3 kilometers of Landsat 7's at the equator. This close separation enabled EO-1 to observe the same ground location through the same atmospheric region so that paired scene comparisons between the two satellites could be made.

The advanced technology demonstrated by the EO-1 mission is called Enhanced Formation Flying (EFF), which was developed by NASA's Goddard Space Flight Center (GSFC). Using this technology, satellites can react to each other and maintain their proximity without human intervention. EFF allows satellites to autonomously react to each other's orbit changes quickly and more efficiently. It also permits scientists to obtain unique measurements by combining data from several satellites rather than by flying the full complement of instruments on one costly satellite. The EO-1 EFF validation successfully accomplished ten formation-flying maneuvers that included reactionary maneuvers, formation maneuvers, and an inclination maneuver.

Formation flying, as seen in Figures 1 and 2, is exactly that: satellites flying in a predetermined relative position and maintaining their respective positions by using onboard control. EO-1 starts a formation located at a distance of approximately 450 kilometers behind Landsat 7 and above by approximately 50 meters. Due to the difference in the accelerations from atmospheric drag and spacecraft design, the EO-1 satellite orbit decays faster than that of Landsat 7. While above Landsat 7, EO-1 drifts away from Landsat 7. After several days of atmospheric drag, EO-1 is below Landsat 7 and is drifting toward it. When EO-1 is outside the required separation distance, or if the Landsat 7 satellite has maneuvered away, EO-1 autonomously computes and performs a maneuver to reposition it to an initial condition to repeat the relative motion and meet science data collection requirements.

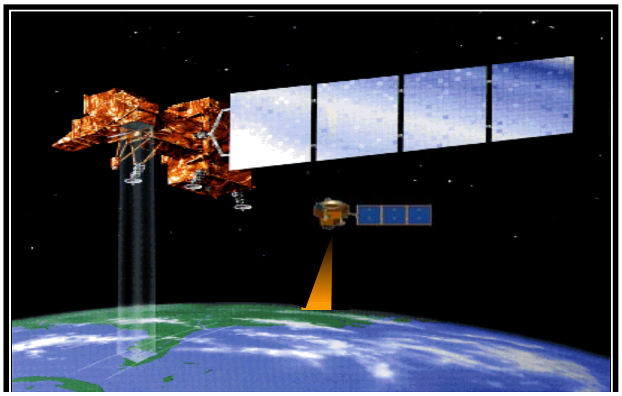

Figure 1. NASA's EO-1 in Formation with Landsat 7

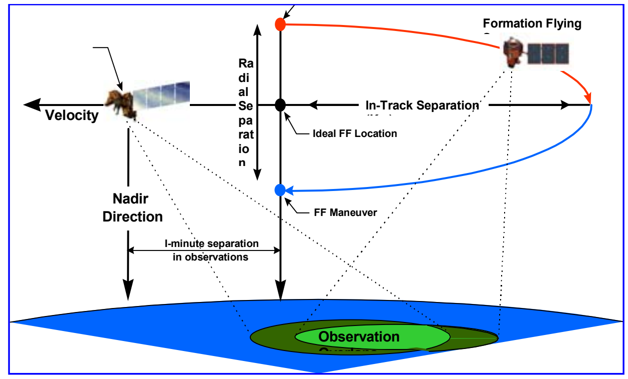

Figure 2. EO-1 and Landsat 7 Formation Geometry

The idea and algorithm for an autonomous maneuver control system for this NASA first was conceived and developed by Dave Folta, John Bristow, and Dave Quinn, aerospace engineers at GSFC. This maneuver-control algorithm, called the Folta-Quinn (FQ) formation-flying algorithm, was designed as a universal 3-dimensional method for controlling the relative motion of multiple satellites in any orbit. The algorithm was combined with a new ground software package that was then converted to a flight software version and interfaced with the EO-1 command and data handling (C&DH) component. This combined flight software package utilized an onboard flight code called AutoCon™, developed by a.i. solutions Inc. under contract to GSFC, that incorporated artificial intelligence (AI) technologies such as fuzzy logic and natural language scripting to resolve multiple conflicting constraints and provide automated maneuver planning. The software package also provided for the ingest and smoothing of real-time navigation data from any orbit determination system (the onboard Global Positioning System (GPS) in the case of EO-1), the transfer of data from the maneuver algorithm for maneuver commands, the computation of onboard predictions of where the satellites will be in the future, the generation of necessary attitude pointing information, and the actual commanding of thruster firings. This total software system constitutes the EFF system.

The term "enhanced" in the EFF context refers to the improvements over basic formation flying computations. The basic computation is a simple maneuver used to alter the semi-major axis (SMA) or to allow orbit period changes as a derived means of relative orbit maintenance. The enhancements included in EFF for the New Millennium Program EO-1 are:

- Natural language script (ASCII) to control the system without flight software modifications.
- A universal 3-dimensional targeting algorithm that allows maneuvers in any direction to maintain the formation from direct measurements. This also allows formation maintenance maneuvers and inclination maneuvers.
- A GPS smoother that ensures consistent and accurate GPS input.
- Autonomous calibration of maneuvers that allows the maneuver performance to be measured and used in the planning of the next burn.
- Interface to telemetry and spacecraft attitude and propulsion data through a common C&DH path.
- Interface to the command system through both the C&DH (received) and the stored command processor (issued).
- A fuzzy logic control system that allows multiple constraint evaluations in script form.
- Additional tasks, such as propagation of Tracking and Data Relay Satellite (TDRS) states for antenna pointing or, as in the EO-1 case, propagation of Landsat 7 state for target computations.

- The computation of the attitude quaternion to orient the spacecraft in the correct direction based on thruster location and pointing.

All of these enhancements were fully tested during integration and test and during comprehensive spacecraft performance tests. These enhancements were also used onboard during the formation flying experiment. Figure 3 shows a functional diagram of EFF and the AutoCon™ system.

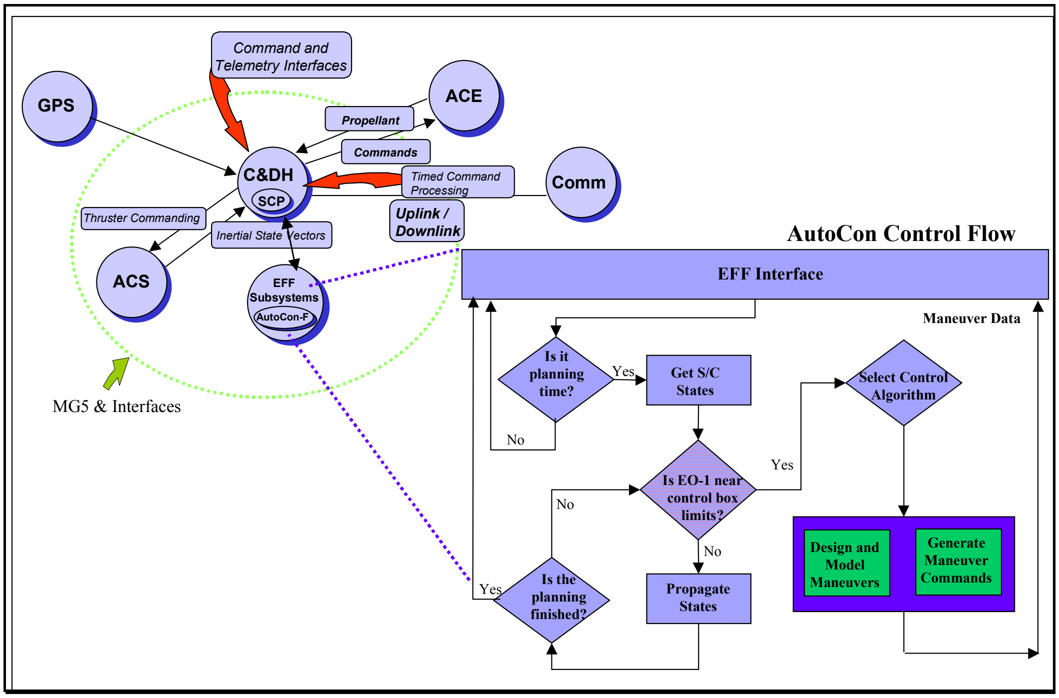

Figure 3. EO-1 EFF Functional Diagram (GSFC Approach)

The EO-1 software validation activity certified that all software requirements had been properly implemented and that the EFF software met all operational objectives. The core AutoCon™ flight control software was qualified by executing a series of test plans, test data, and test scenarios. The results of each stage of validation were checked and documented. These activities had inputs from both the developers of AutoCon™ and the EO-1 attitude control system (ACS) software engineers. Quality assurance was integrated into each stage.

The ground testing results were that AutoCon™ returned a maneuver-required flag and related information for the planning of the maneuver. There were no interface errors. The AutoCon™ software ran within the tolerance specified for the memory and timing requirements of the onboard computer. This verified the AutoCon™ interface to the ACS. An analysis of the downlinked telemetry showed that the data provided through memory to the AutoCon™ system and that the execution of the high level AutoCon™ system in terms of fuzzy logic, system control limits and flags were as expected. An indication by AutoCon™, that the data for the maneuver algorithms had been generated and control passed to the correct maneuver process was as expected. The results were that the data within the telemetry data packets matched the ground-generated data.

The onboard validation planning process originally assumed that the Landsat 7 maneuvers occurred every two to three weeks. The reality was that Landsat 7 performed maneuvers every three to four weeks and then for a short period more frequently at one-week intervals. The requirement to maintain a one-minute separation between EO-1 and Landsat 7 was always met, but frequently EO-1 maneuvered before a complete “revolution” of the EO-1 formation cycle. The onboard validation testing centered on interfaces, the FQ algorithm, performance of the propagation, and overall system loading and safety.

The EFF experiment was executed over a several-month period, from January 2001 through July 2001 and then again in November 2001. The executions generated more than 600 maneuver test plans and ten successful maneuver commands to control the formation. The validation tests were divided into two areas, functional tests and autonomous maneuver execution tests.

Functional validation was evaluated by comparing onboard and ground results in terms of the absolute difference in the computed ΔV (cm/s) and the related percentage error for several maneuver scenarios. A total of 12 scenarios consisting of three maneuver sets (two maneuvers per set) for a total of 36 combined maneuvers were verified. The locations and epochs of these maneuvers were chosen randomly at approximately one per day over a three-week span. The resulting data show that there was excellent agreement between the onboard system and ground validation system. In addition, a comparison between the original FQ algorithm code and the onboard system was performed. This comparison was done for only the first FQ targeted maneuver of each maneuver scenario. These results also showed excellent comparisons.

A total of 10 maneuvers were planned and validated in the manual, semi-autonomous, and fully autonomous mode with seven reported on. All were used to plan a formation flying maintenance maneuver with the semi-autonomous and autonomous mode generating commands onboard that were used onboard as well. The commands generated onboard in the fully autonomous mode were placed in the absolute time sequence with other spacecraft commands at approximately 12 hours before the maneuver execution The results showed that there was excellent agreement between the onboard system and the ground validation system.

Although EFF is an extremely powerful tool, which contains some very complex concepts and capabilities, it was designed for ease of learning and use. EFF is critical to NASA’s ability to successfully support the tight requirements of formation flying. It is the enabling technology that provides quick and accurate response, of a “following” formation-flying satellite, to orbit variations and maneuvers of an independently controlled “target” satellite. This capability does not exist in any other maneuver-planning software system. EFF is very robust in that it supports autonomous operations for relative separation control, demanding three-axis control for inclination and non-Keplerian transfers, and in that it can be applied to any orbit about any celestial body.