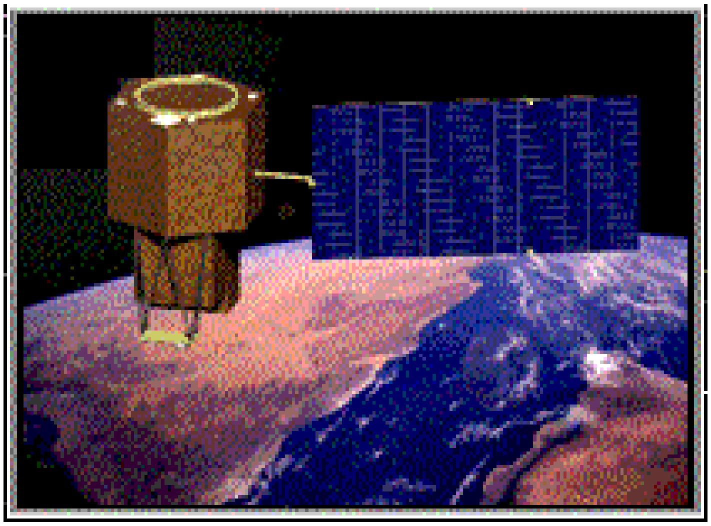


NMP / E0-1 VALIDATION PLAN

ENHANCED FORMATION FLYING

by
Flight Dynamics Analysis Branch/Code 572
Guidance Navigation & Control Branch
Goddard Space Flight Center

4/04/01

Preface

This document is under the configuration management of the Flight Dynamics Division (FDD) Earth Observing -1 (EO-1) Enhanced Formation Flying (EFF) Team. Change requests to this document shall be submitted to the EO-1 EFF team, and changes shall be implemented following concurrence of the EFF team. The current document were maintained in an on-line library.

Questions concerning this document and proposed changes shall be addressed to:

David Folta (david.folta@gsfc.nasa.gov) or
Code 572, Flight Dynamics Analysis Branch
Goddard Space Flight Center
Greenbelt, MD 20771
(301)286-6082

Change Pages:

4/04/01: Updated to reflect reorganization of GSFC codes 712 and 550 into one code…572.

4/04/01: Updated to reflect prime mission goals for autonomous formation flying control.

4/04/01: Updated Timeline as the launch occurred Nov. 2000

4/04/01: Preliminary Results

1.0 Technology Name:

Autonomous Navigation and Control of Formation Flying Spacecraft

2.0 Sponsorship:

ADT Lead:Robert Connerton/GSFC

2.1 Sponsoring IPDT:

Autonomy

2.2 Team Members

NASA-GSFC
JPL
a.i.-solutions, Inc.

Technology candidate contact:

Frank Bauer/GSFC/570
Neil Dennehy/GSFC/570
Dave Folta/GSFC/572
John Bristow/GSFC/583

3.0 Overview

This plan focuses on the validation of the core AutoCon flight control architecture required to support Enhanced Formation Flying (EFF) during the extended EO-1 mission. The Autocon flight code resides in the EO-1 onboard computer and interface through the ACS. AutoCon was developed and unit tested by GSFC 572. This effort was accomplished in several AutoCon builds which were integrated into the EO-1 ACS build-3. AutoCon was unit and system tested based on simulations using a ground system version of AutoCon prior to integration with the ACS. The validation of the software was performed in multiple phases with each phase meeting a specific objective as described in section 6.0 below. The Prelaunch verification of these algorithms was performed in the software test facility and required interfaces to the ACS for command and telemetry and to the GPS hardware for state vector data. The validation of the AutoCon flight code was completed in coordination with the ACS testing and its integration into the spacecraft.

3.1 EO-1 Formation Flying Requirements

The formation flying requirement of EO-1 is to maintain a 1-minute separation between EO-1 and Landsat-7 with EO-1 following the Landsat-7 ground track to a tolerance of +/- 3 km tolerance, approximately 6 seconds. This translates into an along-track distance of approximately 450 km with tolerance of ~50 km. The mapping of this requirement into a formation flying requirement is to place a constraint on the initial separation between the two spacecraft, and maintaining that separation. Using the formation flying algorithms developed by GSFC and JPL, simulations show that formation flying requirements can be easily met by a wide margin. By performing this spacecraft separation maintenance, pair scene comparisons between Landsat-7 and E0-1 can be made.

4.0 Introduction

The primary objective of enhanced formation flying is to demonstrate onboard autonomous formation flying control of the EO-1 spacecraft with respect to the Landsat-7 spacecraft. A secondary goal is to enable the collection of correlated science measurements and to demonstrate significantly improved space science data return through near-simultaneous observations. The AutoCon flight control architecture is modular and accommodates the Goddard Space Flight Center and the Jet Propulsion Laboratory formation flying algorithms under a single architecture. Algorithms from several industry partners may be tested during an extended mission. All algorithms must conform to AutoCon specifications in order to allow uploading. Individual algorithms are invoked through ground commanding of an AutoCon control mode switch. The enhanced formation flying technology demonstration were fully validated during the prime EO-1 mission.

The core AutoCon flight control architecture required to support all enhanced formation flying (EFF) algorithms during the EO-1 mission was developed, integrated with the ACS, and placed onboard the spacecraft prior to the EO-1 launch in November 2000. Validation of the core AutoCon architecture occurs during the first year of EO-1 operations. The core AutoCon flight control software must be integrated with the ACS and the spacecraft prior to launch to reduce the risk and the amount of software being uploaded later in the mission. The GSFC Formation flying control algorithm was uploaded and executed under the AutoCon flight control software during the prime mission immediately after launch.

5.0 Technology Description

Spacecraft with multiple scientific payloads often present competing/conflicting requirements on spacecraft design and operation. Separating scientific payloads onto several single-string spacecraft can accomplish the same complex missions without the added design and operational overhead, while risking only one payload at a time. The proposed approach for onboard formation flying control enables a large number of spacecraft to be managed autonomously and with a minimum of ground support. The technology will enable group of spacecraft to detect errors and cooperatively agree on the appropriate maneuver to maintain the desired positions and orientations.

The sensitivity of scientific instruments can often be increased by expanding the effective observation baselines, which can be achieved by distributing the scientific payloads on many separate spacecraft. However, data collection will impose quite stringent requirements on the Real-Time cooperation between these spacecraft to react to disturbances such as environmental forces. The technologies proposed herein for formation flying spacecraft will eventually make these missions routine and cost effective. Formation flying will also play a key role in the development of future orbiting very long baseline interferometers (Origins program), and allow the establishment of multiple spacecraft arrays for the coincident collection/calibration of instrument data required for future Earth science.

This joint technology features flight software that is capable of autonomously planning, executing, and calibrating routine spacecraft orbital maneuvers. A ground-based prototype using fuzzy logic was previously developed by GSFC (Code 572) for the TRMM and SAIL/UFO missions to demonstrate the viability of automated orbit control. The autonomous formation flying control software in this proposal built on this existing capability for the maneuver planning, calibration, and evaluation tasks. The fuzzy control engine was ideal for this function because it can easily handle conflicting constraints between spacecraft subsystems.

The AutoCon flight control system needs data from additional sensors and spacecraft subsystems such as propulsion data, ground track data, and navigation and attitude data. It is then possible to autonomously generate, analyze, and execute the maneuvers required to initialize and maintain the vehicle formation. Because these calculations and decisions can be performed onboard the spacecraft, the lengthy period of ground-based planning, currently required prior to maneuver execution, were eliminated. The proposed system now in flight is modular so that it can be easily extended to future missions. Furthermore, the AutoCon flight control system is designed to be compatible with various onboard navigation systems (*i.e.* GPS, TONS, or an uploaded ground-based ephemeris). The existing automated maneuver planning tool (AutoCon) was modified for onboard autonomous formation flying control to demonstrate that improved science data return can be achieved by correlating nearly simultaneous data. This was accomplished by having the flight control system plan a maneuver that places EO-1 within 1 minute of separation from Landsat-7 and then maintains that separation to a tight tolerance of 6 seconds for an extended period of time.

6.0 Technical Validation Objectives

The EO-1 software test validation certifies that all software requirements have been properly implemented and that Phase-1 of the Enhanced Formation Flying (EFF) software meets all operational objectives.. This section summarizes the approach used to accomplish these goals.

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 have inputs from both the developers of AutoCon and the EO-1 ACS software engineers. Quality assurance were integrated into each stage.

The qualification of the processes that was used to monitor validation are by; analysis, inspection, test, and demonstration. The requirements by which the test show qualification are by ACS external interfaces, functional, sizing, timing, and tractability.

The validation of each of these tests was performed at the following levels. Please note that Level 1-4 are the verification process required to support Level-5 validation of AutoCon.

- Level-1: AutoCon, using a PC or workstation environment to develop, test, provide high fidelity simulations, and proof of concept fuzzy logic rules.

- Level-2: Virtual Simulation, using a virtual simulation of the ACS with an embedded AutoCon core architecture flight code design to test the interfaces, telemetry, and commands with the ACS.
- Level-3: Software Test Facility, using a full spacecraft simulation of the ACS and GPS data to test AutoCon. Test all interfaces to the ACS and C&DH for telemetry and commanding. Performed on a Mongoose breadboard with supporting hardware.
- Level-4: Flatsat, testing of the AutoCon flight code on flight hardware and ACS system software.
- Level-5: Operational testing/validation of the core AutoCon flight code. These tests are expected to require a minimum amount testing to verify proper execution of the AutoCon flight control system.

To date, Levels 1-4 have been successfully completed. Level 5 is underway.

To minimize associated test costs associated with these tests, the following approach is recommended.

- For each functional requirement develop scenarios that were executed for the mission.
- Develop system test for each scenario
- Develop system unit, integration tests for EO-1 AutoCon to develop a system checkout matrix
- Perform system tests for the mission scenarios and catalog results in matrix

The EO-1 maneuvers were computed onboard under a single system architecture called AutoCon which employs separate maneuver decision/design modules or algorithms. AutoCon will control execution of the modules through an onboard mode switch, and perform constraint evaluation via fuzzy logic control. The AutoCon specifications were levied on the industry partners in order to facilitate uploading algorithms during the extended mission. Data and processing requirements from industry partners were assessed during this initial phase of the technology.

6.1 AutoCon Test Plan Matrix

The following test plan matrix, Table 1, indicates the level and focus of the acceptance test. Following subsections provide more detail on each test.

Table-1 AutoCon-F Test Plan Matrix

Test =>	**AutoCon Executive**	**Maneuver Decision**	**Maneuver Planning GSFC Algorithm**
Scenarios	*Test AutoCon-F and EFF Exec*	*Test Maneuve Decisionr Logic*	*Test Maneuver Algorithm, Cmd, and Calibration*
1	Normal Mode I/F Run to Completion	Normal Mode I/F Run to Completion	Target to Intercept Run to Completion
2	Normal Mode 2- Day Propagation	Normal Formation Limit & Propagation	Target to both Positive / Negative Radial Separation
3	Normal Mode 2- Day Prop with Various Cmd Tables / Modes	Normal Formation Limit & Propagation, No-Fuzzy input	Target to Along-track and +/- Radial Separation
4	Normal Mode Prop & Fuzzy Table Upload	Formation Limit via Table Update & Normal Propagation	Target to Along-track, Cross-track, Radial Separation
5	Normal EFF Mode Disable L-7	Normal Formation Limit but Commanded Maneuver Time.	Input L-7 Gnd-track Maneuver Data and Target to Along-track and Radial Separation
6	Normal EFF Mode Disable GPS I/F		Input L-7 Inclination Maneuver Data and Target to Along-track and Radial Separation
7	Check Tlm Output		Perform Maneuver Calibration
8	Check Cmd Ouput		Perform EO-1 Gnd-Track Maneuver only
9	Cmd Upload New Targets		
10	Upload Cmds i.e. Override		

6.1 AutoCon Executive and Fuzzy Logic Validation

Validation of the Build-1 of core AutoCon architecture executive was performed during the first year of the EO-1 mission. This build is the system level control of all of the enhanced formation flying algorithms. The objective is to test the fuzzy logic control and the development of the fuzzy logic engines. The test ensure that the input, output, CPU memory, storage, processing speed requirements and the interface to the ACS provided data performs as expected and that control were invoke at the proper time for maneuver algorithms.

6.1.1 Required data/necessary measurements:

The data required to validate AutoCon in Phase-1 are listed below from reference 1 (the AutoCon / ACS ICD). Fuzzy logic and fuzzy rule sets are the primary data requirements. Secondary data requirements are real data sets of EO-1 position state vectors from the EO-1 GPS orbit determination solutions and the Landsat-7 state vectors from the uplink of these vectors. The ACS provides data in memory locations for input to the fuzzy logic control. Output files for placement into the interface with the ACS for telemetry were exercised.

CCSDS Header	EO-1 Mass	CCSDS Packet Header (include s/c Id ?)
EFF UTC Time (MET of current EFF Cycle + UTCF)	EO-1 Coefficient of Drag	ACS UTC Time (MET of current ACE 8 Hz Pkt Hdr + UTCF)
Heartbeat Cycle Count	EO-1 Coefficient of reflectivity	EO-1 ACS X-Position Vector
Autocon Cycle Count	EO-1 Drag Area	EO-1 ACS Y-Position Vector
WARM Restart Cnt	EO-1 SRP Area	EO-1 ACS Z-Position Vector
EFF Burns Planned		EO-1 ACS X-Velocity Vector
EFF Planned Burns Implemented	LS-7 Mass	EO-1 ACS Y-Velocity Vector
EFF Planned Burns Loaded	LS-7 Coefficient of Drag	EO-1 ACS Z-Velocity Vector
EFF Planned Burns Executed	LS-7 Coefficient of reflectivity	Valid EO-1 ACS
EFF Planned Burns Aborted	LS-7 Drag Area	EO-1 ACS State Source Status -- sometjing ???
ACS TLM Pkt Received Cnt	LS-7 SRP Area	EO-1 GPS SPS State Epoch
GPS TLM Pkt Received Cnt		EO-1 GPS SPS X-Position Vector
RCS TLM Pkt Received Cnt	F10.7	EO-1 GPS SPS Y-Position Vector
	KP	EO-1 GPS SPS Z-Position Vector
SCRIPTS - Free Flowinf Text		EO-1 GPS SPS X-Velocity Vector
Along Track Tolerance Fuzzy Set		EO-1 GPS SPS Y-Velocity Vector
Radial Tolerance Fuzzy Set		EO-1 GPS SPS Z-Velocity Vector
Fuzzy Set		Valid EO-1 GPS SPS

					EO-1 GPS GEODE State Epoch
LS-7 State Epoch					EO-1 GPS GEODE Y-Position Vector
LS-7 State X-Position Vector					EO-1 GPS GEODE Z-Position Vector
LS-7 State Y-Position Vector					EO-1 GPS GEODE X-Velocity Vector
LS-7 State Z-Position Vector					EO-1 GPS GEODE Y-Velocity Vector
LS-7 State X-Velocity Vector					EO-1 GPS GEODE Z-Velocity Vector
LS-7 State Y-Velocity Vector					Valid EO-1 GPS GEODE
LS-7 State Z-Velocity Vector					EO-1 GPS WAAS State Epoch

6.1.2 Approach

The validation approach is to execute AutoCon onboard with these input data values listed and allow AutoCon to process the data using the control algorithms. These algorithms both notify the ACS and ground through telemetry of a maneuver and in phase-2 invoke the maneuver planning algorithms within AutoCon. The validation shows that the fuzzy logic properly resolves conflicting constraints; that AutoCon can ingest the data from the ACS correctly for internal use; and that the interfaces with the ACS for all telemetry and command is working correctly. The final result of the phase-1 validation is that the telemetry output confirms the maneuver decision has selected a proper time for a maneuver. Also, the validation proves the interface to AutoCon via ACS uplinked tables functions properly and confirm the required memory sizing of the onboard computer

6.1.3 Anticipated Results

The anticipated results are that AutoCon returns a maneuver required flag and related information for the planning of the maneuver. There should not be any interface errors. The AutoCon software should run within the tolerance specified for the memory requirements and timing requirements of the onboard computer. The validation verifies the AutoCon interface to the ACS. An analysis of the downlinked telemetry shows the data provided though memory to the AutoCon system and the execution of the high level AutoCon system in terms of fuzzy logic, system control limits and flags was as expected. An indication by AutoCon that the data for the maneuver algorithms has been generated and control passed to the correct maneuver process is expected. The results anticipated are the data within the telemetry data packets match the ground generated data. The differences between the ground and onboard AutoCon are expected to meet the values due only to difference in the software (constrained software run times or precision) and hardware (PC based versus Flight hardware). Scenarios for the validation address each difference.

6.1.4 Supporting I&T Data

Supporting I&T data of propulsion data, health and safety data, and other constraint data uplinked for AutoCon control were required. The input data includes preloaded fuzzy rule set and constraint checking limits. The validation requires that these data be commandable for a complete checkout of this algorithm. The validation requires software and hardware used for independent checking of orbital data, the use of the ground operational version of AutoCon for the validation of the fuzzy logic and rules, and the use of the Hammers Co.'s VirtualSat and the Flight Software Testbed for checking of all interfaces and the associated timing requirements.

Table 6-2 Supporting I&T Hardware and Software

Data Validated	Software	Hardware
Orbital Data	Freeflyer	PC/Windows-NT
Interface Checkout	VirtualSAT	PC/Windows-NT
AutoCon-Ground	AutoCon	PC/Windows-NT
Table Loads, Algorithms, etc.	Flight S/W TestBed	PC/Workstations
Telemetry Data	Telemetry Processor	EO-1 Control Center H/W

6.1.5 Rationale

The reasoning for this validation is to test the control methodology of the AutoCon executive through the processing of the fuzzy logic rules and the fuzzy logic engines. The difference expected are discussed above are to be minimal and only due to implementation in the spacecraft specified hardware software.

7.0 Scientific Validation Objectives

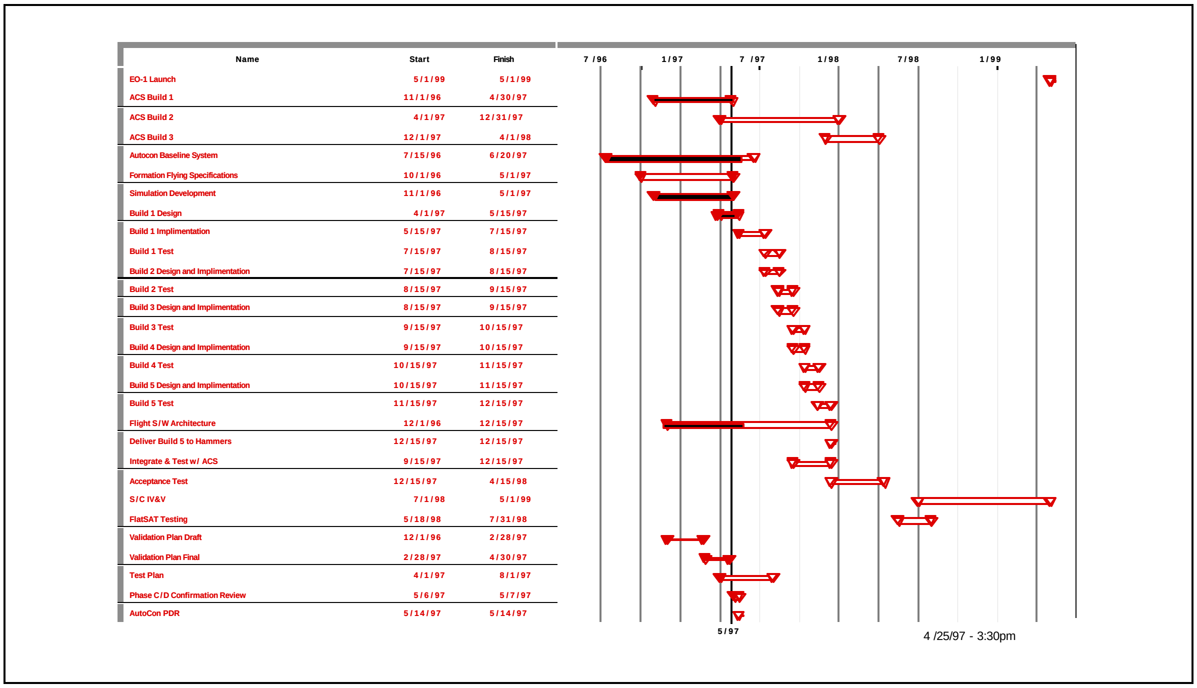
The enhanced formation flying demonstrates the capability of EO-1 to fly over the same ground track as Landsat-7 within 3km at the equator. This requirement allows images to be taken for the project's paired scene comparison science requirements. The validation proves the correctness of the onboard algorithms for autonomous control.

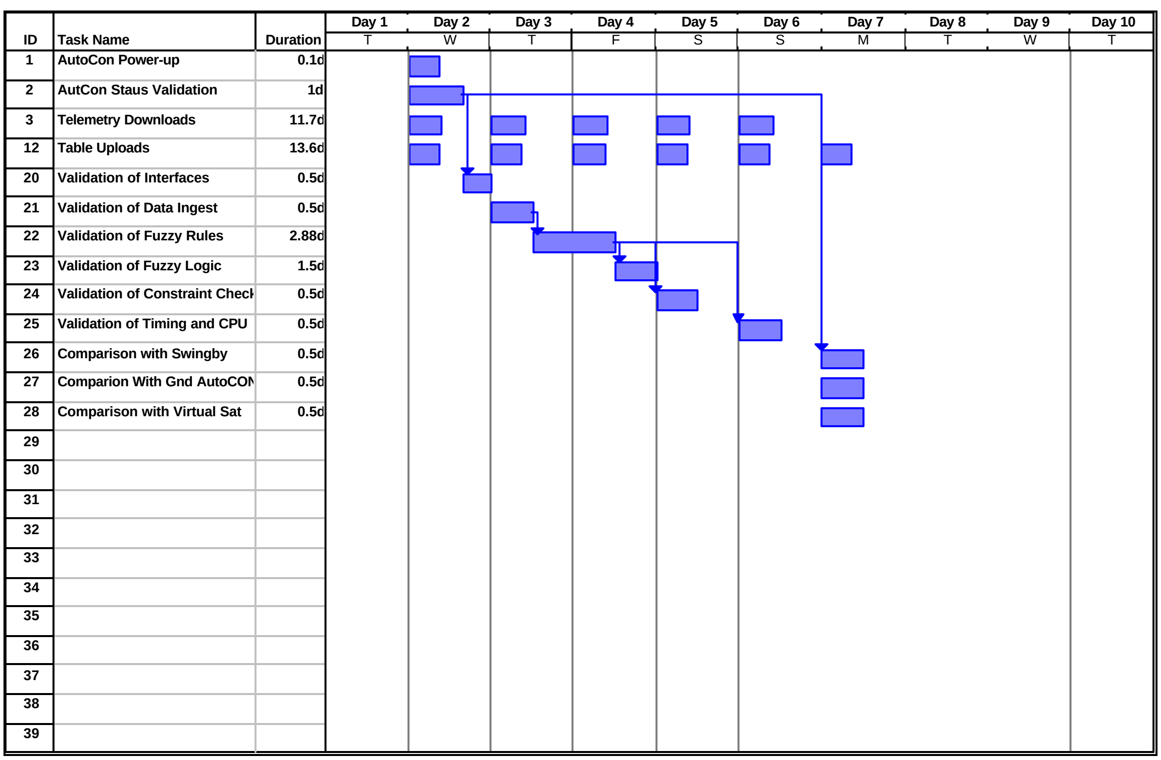
8.0 Schedules

Two schedules are listed below. One for the overall development and support of the validation of AutoCon, and the other which shows the schedule of activities for the validation.

The overall AutoCon schedule includes the development, integration, pre-launch testing, and on-orbit validation of the core architecture (Table 1). It should be noted that all the software was unit and system tested at the Flight Dynamics Facility before the integration into the ACS build-3.

Table -1 Master Schedule





9.0 Required Facilities

The EFF software requires both an independent set and a common set of test tools, equipment, and facilities which are also being developed for the EO-1 ACS testing, and GPS testing. The facility is the Virtual Sat facility of the Hammers Co. It were required to validate the AutoCon onboard algorithms as they interface with the onboard ACS flight code. A ground-based version of the AutoCon system within VituralSat allows full integration and test of the complete system of all fuzzy logic algorithms as they are developed. It is anticipated that the flight code validation tests yields the same results are the ground tests.

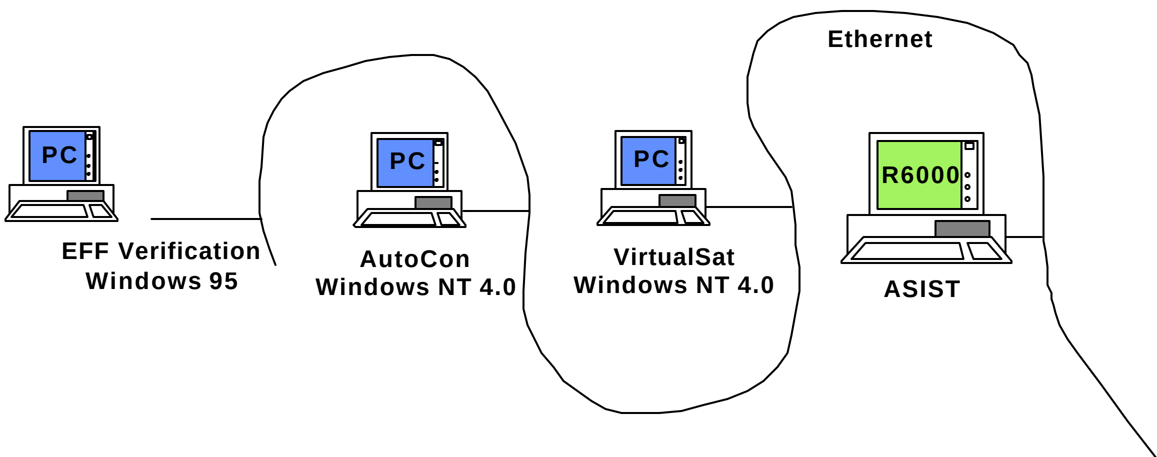


Figure 1. Virtual Sat Facility

The EO-1 **Flight Software TestBed** will also be used for validation as it reflects only ground software that duplicates the onboard processes. This facility were used for testing of the scripts before upload.

10. Preliminary Results: EO-1 Enhanced Formation Flying (EFF) Validation Test #1 (EFFV1)

EFF Functional Tests Purpose : Simulate Autocon-F Planning Maneuvers RK45,8x8 is used to perform 48 hour plan ahead if no burn is planned

The functional test for EO-1 EFF are being performed and compared for 36 different maneuver computed by the GSFC Algorithm. These tests incorporate the following data;

- Landsat-7 State
- EO-1 State
- Drag Coefficient
- Targeting goals
- AutoCon Scripts
- EO-1 and L-7 Propagator
- EO-1 and L-7 Force Models
- EO-1 and L-7 Atmospheric Model
- SLP file
- EO-1 and L-7 Spacecraft Parameters, Cd, Mass, etc.
- EO-1 Thruster and Tank data

Twelve tests were completed with three maneuvers executed for each pair of EO-1 / L-7 state inputs. This yields 36 individual maneuvers tested.

The epochs (dates) of the onboard test data are: January 12, at 0 hours, through February 9th 2001.

// Products: eo1mcf.Report - maneuver command file
EO1 Forcemodel file
EO1 Propagator file
EO1 State file
EO1 Tank file
EO1 Thruster file
LS7 Forcemodel file
LS7 Propagator file
LS7 State file

// Outputs: EFF Maneuvers.Report - contains detailed maneuver plan
GSFCAlgorithm1.Telm - simulated telemetry
GSFCAlgorithm2.Telm - simulated telemetry
GSFCBurnPlan.Telem - simulated telemetry
Burn1.maneuver
Burn2.maneuver
Burn1.Report - burn report

Burn2.Report - burn report
EO1.ForceModel;
EO1.Propagator;
EO1_Initial.state;
LS7.ForceModel;
LS7.Propagator;
LS7_Initial.state;

The onboard Telemetry data used matched the test data epochs.

EO-1 State from GPS onboard
L-7 State Uploaded
EO-1 Telemetry packet 1 and 2

Results as of 4/4/01:

Pending further analysis as of 4/4/01. Continuous testing nearing completion, Manual Test of real maneuvers underway.

Sample validation of the comparison of continuous test procedures, onboard versus ground is shown below.