Paper AAS 01 - 450
545140

American Astronautical Society

FOLLOW THAT SATELLITE: EO-1 MANEUVERS INTO CLOSE FORMATION WITH LANDSAT-7

Robert L. DeFazio. Senior Aerospace Engineer,
NASA/Goddard Space Flight Center, Greenbelt, MD 20771

Skip Owens, Systems Engineer,
a.i. solutions, Inc., Lanham, MD 20706

Susan Good, Systems Engineer,
a.i. solutions, Inc., Lanham, MD 20706

AAS/AIAA Astrodynamics Specialists Conference

Quebec City, Quebec, Canada July 30-August 2, 2001

AAS Publications Office, P.O. Box 28130, San Diego, CA 92198

ABSTRACT

FOLLOW THAT SATELLITE: EO-1 MANEUVERS INTO CLOSE FORMATION WITH LANDSAT-7

As the Landsat-7 (LS-7) spacecraft continued NASA's historic program of earth imaging begun over three decades ago, NASA launched the Earth Observing -1 (EO-1) spacecraft carrying examples of the next generation of LS instruments. The validation method for these instruments was to have EO-1 fly in a close formation behind LS-7 on the same World Reference System (WRS) path. From that formation hundreds of near-coincident images would be taken by each spacecraft and compared to evaluate improvements in the EO-1 instruments.

This paper will address the mission analysis required to launch and maneuver EO-1 into the formation with LS-7 where instrument validation was to occur plus a summary of completing the formation acquisition. EO-1 is required to operate one minute + / - 6 seconds behind LS-7 during the period of co-fly imaging with a cross track separation of within + / - 3 kilometers. This separation time can also be stated as a one minute + / - 6 seconds time difference in the Mean Local Time (MLT) at the descending nodes. Achieving the required MLT is heavily dependent on the time of launch. The EO-1 launch window, which had to accommodate the dual payloads of EO-1 and SAC-C, was very limited ranging from 0 to 22 seconds over the 16-day LS-7 WRS repeat cycle during which EO-1 was launched. Each EO-1 launch opportunity that occurred on a different day of a LS-7 16-day repeat cycle required a separate and distinct maneuver profile. These profiles varied significantly in duration and amount of onboard propellant required to achieve them. EO-1 launched on a day judged to have "medium" resource requirements for achieving the formation with LS-7.

To phase EO-1 one minute behind LS-7 in the along track direction, a series of altitude adjusts separated by specific drift intervals was executed. Additional maneuvers slightly changed the EO-1 inclination to maintain the MLT requirements. Orbit maneuvers were planned and executed within errors of less than 1.5 percent and propellant usage was near nominal, i.e. consuming 3.4 kilograms out of a launch and early-orbit 3-sigma propellant budget of 11 kilograms. While the pre-launch 3-sigma propellant budget allowed for 1+ years of EO-1 mission life, the success of EO-1 launch and early orbit operations provided sufficient propellant for nearly 4 years of on-orbit operations. Special action taken during the EO-1 maneuver period involved some maneuver re-planning to reduce concerns about a potential close approach between EO-1 and LS-7. The result of this re-planning was a safer close approach and improvement in future formation acquisition planning.

FOLLOW THAT SATELLITE: EO-1 MANEUVERS INTO CLOSE FORMATION WITH LANDSAT-7

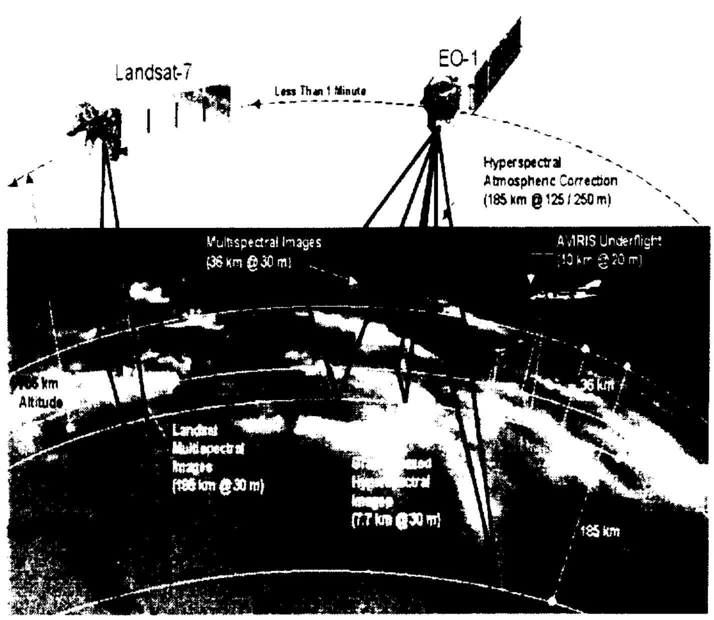
INTRODUCTION

When NASA developed its New Millennium Program in the mid 1990's, an early candidate was the Earth Observing-1 spacecraft (EO-1). EO-1 was to be designated as a moderately budgeted technology mission with three categories of future technologies. While most of the technologies involved smaller contributions to spacecraft hardware, the premier technologies involved a new generation of earth imaging instrument and the expanded onboard data storage to make it feasible. The Advanced Land Imager (ALI), developed by MIT's Lincoln Labs was the foremost technology and a candidate to become the next NASA Landsat imaging instrument. To validate its improvement over the current LS-7 Thematic Mapper, EO-1 will take several hundred co-images for comparison with LS-7 to measure improvements in the many spectral bands important to earth imaging. The best spatial relationship to accommodate the co-imaging test has both spacecraft on the same WRS path, one minute +/- 6.0 seconds apart. Thus, both will fly and image through roughly the same column of air before its composition changes significantly. LS-7 has been in orbit since mid-April 1998.

As part of a dual payload launch, EO-1 was co-manifested with the Argentine SAC-C spacecraft for launch aboard a Delta-II 7920 Expendable Launch Vehicle (ELV) on November 21, 2000. EO-1 separated first after a powered flight of 3600 seconds with SAC-C release following 1840 seconds later. The orbit maneuver sequence to place EO-1 in the required formation with LS-7 began 3 days after launch.

Following a 3.5week sequence of orbit and attitude maneuvers, EO-1 arrived in its formation with LS-7. Then the co-imaging began in earnest. Two other EO-1 earth imaging instruments, NASA's Atmospheric Corrector and TRW's Hyperion instrument were added to the co-imaging comparison. The relative locations of the ground swaths of the LS-7 Thematic Mapper and the three EO-1 instruments are shown in Figure 1.

Figure 1 EO-1 Instruments Ground Swath Widths

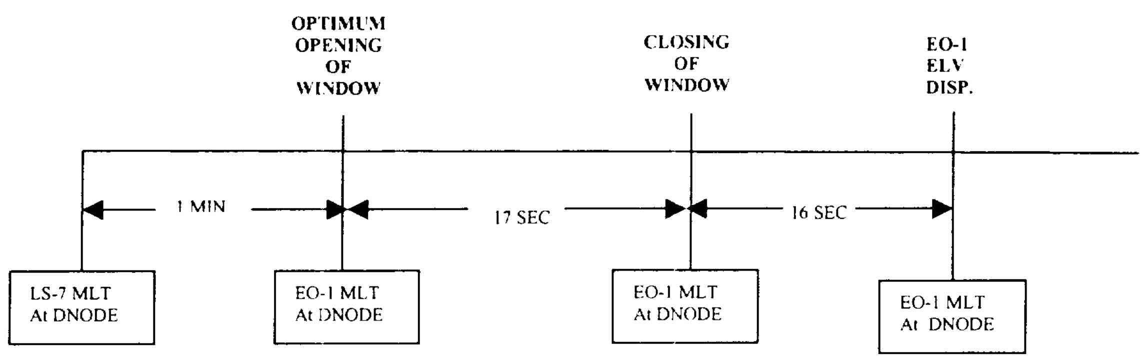


A LAUNCH WINDOW FOR EO-1

The EO-1 launch window was determined after an evaluation of requirements and constraints related to both the formation flying configuration of LS-7 and EO-1 and the co-manifesting of EO-1 and SAC-C on the same ELV. LS-7 and EO-1 were to have a Mean Local Time (MLT) difference at the descending node of 1 min. +/- 6.0 seconds. The most economical way to initially meet this requirement is by timing the launch of EO-1. This involves accurately knowing what LS-7's MLT at the descending node will be on EO- 1's launch day. This was predicted with help from the LS-7 Project. The LS-7 MLT prediction was complicated by a LS-7 inclination maneuver that altered the evolution of MLT at the descending node. With excellent cooperation from the LS-7 Project a prediction of LS-7's MLT was possible following the inclination maneuver. One month before EO-1 was launched, LS-7 performed their annual inclination adjust maneuver. This gave EO-1 a reasonably well-understood prediction of LS-7's MLT at the descending node throughout EO-1's potential launch period. (From this point on, when MLT is mentioned, unless otherwise noted, it refers to the MLT at the descending node.)

With a nominal, optimum liftoff for EO-1 based on the prediction of LS-7's MLT, the next facet of EO-1's launch window computations involves ELV MLT dispersions and the relationship between EO-1's and SAC-C's MLT requirement. EO-1 could have experienced a MLT dispersion from the ELV of +/- 16 seconds. Each second of MLT error requires 0.165 kg. of hydrazine to correct. When this dispersion is coupled with the Project's desire to have no greater than a 30 second difference between the achieved MLT and an optimum value with respect to LS-7, the situation shown in Figure 2 results.

Figure 2 Relation of EO-1 and LS-7 MLTs as a Function of Launch Window



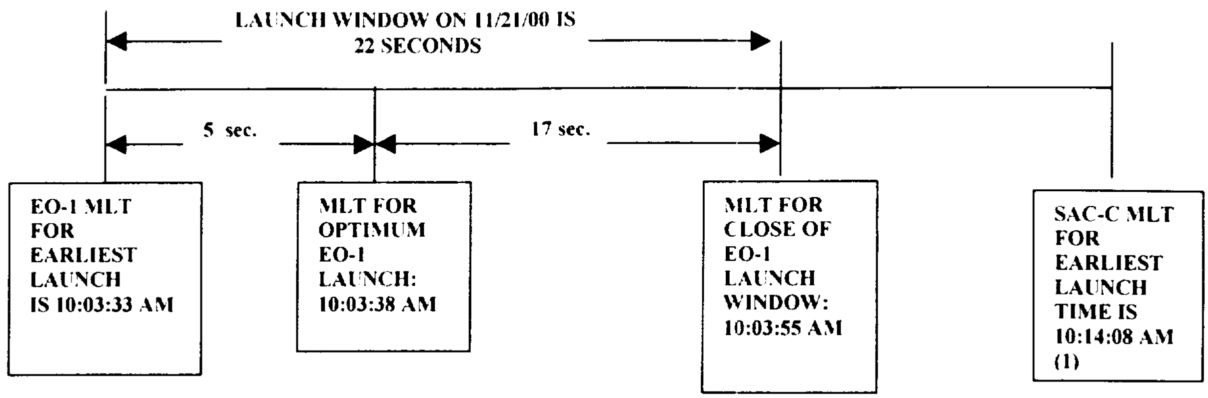
In Figure 2, there is at least a 17-second launch window with a 33-second maximum MLT difference if a +3-sigma dispersion in MLT is realized for the closing of the window launch. An extra 3 seconds of ELV MLT dispersion was added just before launch. The hydrazine budgeted to restore the EO-1 MLT to a value 1 minute behind LS-7 is 5.5 kg.

The last component of the EO-1 launch window computation involves SAC-C. To demonstrate the effect of SAC-C's launch window requirement, a specific launch date will be used as an example. Assume that EO-1 is launching on November 16, 2000. On that date an accurate prediction of LS-7's MLT is 10:02:38. This would yield an optimum MLT for EO-1 of 10:03:38.

To place SAC-C at its earliest allowable MLT of 10:14:08 (the ELV performs a nodal rotation for SAC-C after EO-1 is separated), the EO-1 MLT can be no earlier than 10:03:33 for a launch window opening.

EO-1 could and did incorporate this additional 5 seconds into an already sparse launch window, thereby providing a 22-second window for November 16th. An agreement was reached with the ELV managers to try and launch EO-1 at the optimum time (keeping MLT one minute behind LS-7). However, if Collision Avoidance (COLA) concerns threatened a launch opportunity and the extra 5 second offered relief, this additional time could also be used for the launch. See Figure 3.

Figure 3 EO-1 Launch Window Concepts



(1) The earliest MLT that SAC-C would accept from a launch of EO-1/SAC-C. Achieved when launch places EO-1 MLT at 10:03:33 AM or later

The LS-7 MLT during the months of November and December, 2000 changed by about an average of 0.5 seconds per week. As the LS-7 MLT evolved later in time, EO-1 gained about 5 seconds in the close of its launch window over this time span. With the EO-1 MLT at window opening staying at 10:03:33, the launch window grew from 22 to 27 seconds. The actual launch of EO-1/SAC-C occurred on November 21, 2000.

There is yet another facet to the EO-1 launch window saga. When computing the maneuver sequences to place EO-1 into the same orbit and World Reference System path as LS-7, the day of launch had significant bearing on the launch window. At issue is LS-7's location on the WRS during its 16 day repeat cycle. This will be discussed in the section describing the EO-1 orbit maneuvers needed to achieve the formation with LS-7.

EO-1 FLIGHT DYNAMICS SOFTWARE TOOLS

The EO-1 mission utilized two different flight dynamics software tools during the course of the mission: ***FreeFlyer®*** for pre-launch analysis, launch, and early orbit phases; and AutoCon™ during the normal operations and autonomous formation-flying phase. Each of these software tools has unique abilities that were required for each of the mission phases.

The pre-launch analysis, launch and early orbit tool ***FreeFlyer*** is a commercial-off-the-shelf product developed by *a.i. solutions Inc.* ***FreeFlyer*** is an orbital mechanics and trajectory design tool, which includes capabilities critical to the EO-1 mission seen below in Figure 4.

The aforementioned capabilities, as well as ***FreeFlyer's*** ability to model multiple spacecraft and the flexibility of its natural scripting language, made it the tool of choice for EO-1.

Figure 4 *FreeFlyer* Features Critical to EO-1

Gravitational Modeling	Maneuver Modeling/Design
Sun Earth (With Full Geopotential) Moon	Finite Maneuver Modeling Impulsive Maneuver Modeling Fuel Depletion Via Tank Blow- Down Down Curves Maneuver Targeting Via A Differential Targeter
Force Modeling	**Planning Flexibility**
Solar Radiation Pressure Atmospheric Drag	Natural Scripting Language For Adding Custom Features and Products Without Compiling

Multiple spacecraft modeling allowed for simultaneous propagation and maneuver targeting of both the EO-1 and LS-7 spacecraft, as well as modeling the entire NASA constellation of morning observing spacecraft to avoid and monitor any close approaches during the insertion into the constellation. The scripting capability allowed for the flexibility in the number of maneuvers, the types of maneuvers and the sequence of the maneuvers in the ascent profile. This maneuver flexibility was crucial due to the possible 16 different ascent profiles caused by LS-7's 16-day repeat cycle. Scripting flexibility also helped in re-planning the ascent after launch due to launch vehicle dispersions, drag changes, LS-7 maneuvers and close approach minimization.

The normal operations and formation flying software tool is AutoCon. AutoCon is also developed by *a.i. solutions Inc* and is the heritage of ***FreeFlyer***. Both software tools share the same mathematical engine, but ***FreeFlyer*** has additions such as 3D views and 3D-orbit visualization, satellite constellation and formation tools, visualization, and an advanced user interface. Because of AutoCon's object orientated design, it had the scalability to be stripped of all the unnecessary objects and programming to meet the on-board memory limitations and run smoothly on EO-1's Mongoose-5 processor. Through this process, two versions of AutoCon were derived for the EO-1 mission. AutoCon-G™ (AutoCon-Ground™) was used in the control center to plan ground track control maneuvers and produce the required products for mission analysts and scientists. AutoCon-F™ (AutoCon-Flight™) was integrated on-board EO-1, and was also used to calculate the GTC ground track control maneuvers, but designed to do so autonomously. Both versions of AutoCon had the Folta-Quinn[3] algorithm built into them to calculate the formation flying station-keeping maneuvers.

SOFTWARE / SCRIPT PREPARATION

There were 3 different categories of software scripts for the EO-1 mission: the LS-7 prediction scripts, the EO-1 ascent script, and the EO-1 ground track control (GTC) and product generation scripts. The LS-7 prediction scripts and the EO-1 ascent script are run using ***FreeFlyer*** while the EO-1 GTC and product generation scripts are run using AutoCon-G.

Before the EO-1 mission, LS-7 was using ***FreeFlyer*** to plan their GTC maneuvers one or two weeks into the future. However, EO-1 formation flying required knowledge of LS-7 maneuvers 30 days in advance and science and imaging required LS-7 and EO-1 maneuver plans 6 weeks in advance. The solution to this was to provide LS-7 with another ***FreeFlyer*** script similar to their current operational script except that it plans maneuvers for the next 6 weeks. The EO-1-LS-7 Interface Control Document[2] (ICD) between EO-1 and LS-7 outlines the specific products and formats for the deliverables of the new LS-7 planning script. The ICD specifies weekly deliveries of LS-7 predicted maneuver plans and 6-week ephemeris files, while also constraining LS-7 maneuvers to Tuesdays so EO-1 could maneuver two days later on Thursdays. The ICD was crucial to set the stage for open lines of communication and cooperation between the LS-7 and EO-1 control centers.

The EO-1 ascent script was also developed and run using ***FreeFlyer***. The full force modeling for the ascent maneuver planning was gravitational modeling of the Sun, Earth and Moon. The Earth geopotential modeling was a 21x21 JGM2 and the solar flux model used was Jacchia-Roberts, with daily prediction files from NOAA. The propagator used was a Runge-Kutta 8(9) with 60-second step size. Since the purpose of the ascent script was to help in the planning of initializing the formation with LS-7, the main driver for the design of the ascent script was flexibility. Factors such as launch day, launch time and launch vehicle dispersions could potentially change the size, type and number of maneuvers required to get into formation with LS-7. In order to minimize the impact from these potentially time consuming changes, the EO-1 script was designed into many independent sections. Each of these sections contained one type of maneuver (i.e. inclination, semi-major axis, eccentricity control, etc...) and the targeting logic involved with each of these maneuvers. One of these sections contained the RESTOR[4] utility developed at Goddard Space Flight Center. The RESTOR utility calculates a two-burn solution to achieve a user-input argument of perigee and eccentricity for a frozen and/or Sun-synchronous orbit. These individual sections were then accessed and controlled by the main logic section of the script. The user-input section of the script prompts the user to input the LS-7 ephemeris file (which included modeled LS-7 GTC maneuvers) and the EO-1 injection or orbit determination (OD) state. The user then decides what types of burns are needed for the ascent, the number of burns and the order the burns are implemented. The time spacing between each maneuver was also adjustable by setting the number of orbits between each of the maneuvers. All of these inputs are collected in an array and that array is analyzed by the main logic section of the script. The logic section of the script is composed of a complex set of conditional statements that sets flags and variables to allow different sections of the script to be accessed and maneuver goals to be achieved by ***FreeFlyer's*** differential targeter. The result was a maneuver-planning tool flexible enough to turn an extremely complex problem such as formation initialization into a very manageable problem. In addition to planning the ascent sequence, the ascent script also produced all the necessary operational products, such as pre-maneuver and post maneuver states, an EO-1 ephemeris file, mean-local time reports, fuel use reports, finite and impulsive maneuver reports and of course data plots.

Once EO-1 is in formation with Lansdsat-7, the normal operations phase of the mission begins and the ***FreeFlyer*** ascent-planning tool is no longer needed. Drag make-up maneuvers or ground track control (GTC) maneuvers are required to counteract the drag forces and maintain formation flying with LS-7. One of the technologies being tested on the EO-1 mission is autonomous maneuver planning and the algorithm behind this is the Folta-Quinn algorithm. This algorithm takes a LS-7 state and an EO-1 state along with user inputs and constraints, and calculates a two-burn solution to maintain the formation. As mentioned in a previous section, the Folta-Quinn algorithm is integrated into AutoCon-G in the operations center and in AutoCon-F on-board EO-1. There are two maneuver-planning scripts that utilize the Folta-Quinn algorithm. One script plans maneuvers for the next 30 days and produces planning products and the other script does the same thing for an 8-day time period. These two scripts use the LS-7 ephemeris file generated from the ***FreeFlyer*** LS-7 maneuver planning script and plans formation station-keeping maneuvers. Other AutoCon scripts used in the phase of the mission include Improved Interrange Vector (IIRV) and Extended Precision Vector (EPV) generation scripts and maneuver reconstruction and calibration scripts. The maneuver command file generation script in AutoCon was used in all phases of the mission since this special format file actually commanded the spacecraft to maneuver. An inclination burn planning script was also required so EO-1 can match LS-7's annual inclination burns that control the mean local time. All of these scripts are run using AutoCon-G, while a derivative of the maneuver planning script is run on-board EO-1 in AutoCon-F.

ACHIEVING FORMATION WITH LS-7

The EO-1 ELV trajectory provided by Boeing Aerospace enabled us to compute an EO-1 separation state vector for any launch date. After EO-1 was separated from its launch vehicle, a plan developed by the EO-1 Flight Dynamics team was generated to place it into its initial formation with LS-7. Because EO-1 had to achieve the same WRS path as LS-7, the required maneuvers, and even the order in which they needed to be executed, changed from one launch day to another. This was due to the World Reference System (WRS) path difference between LS-7 and EO-1 at the time EO-1 was released into its post-injection orbit. Table 1 is a section of a table created by Terry Arvidson of the Landsat-7 Flight Operations Team, which shows the role played by the WRS path difference. Throughout any given operational day, the specific WRS path that LS-7 was on in a given revolution is shown. Knowing the ELV powered flight trajectory, EO-1 always injected into WRS path 58, following spacecraft separation. Overlaying LS-7's 16-day repeat cycle with possible EO-1 launch dates, it is clear what initial conditions exist for designing a maneuver profile to achieve the EO-1 formation with LS-7. Besides the correct initial conditions for LS-7, a prediction of the orbit over the following 5 weeks was required to accurately plan the EO-1 formation acquisition sequence. The prediction had to include a best estimate of any ground track maintenance maneuvers occurring while EO-1 was being maneuvered into formation. A script was prepared for the *FreeFlyer* software to generate the necessary LS-7 predicted orbit ephemeris.

Table 1 LS-7 Paths Flown on Calendar Dates

CYCLE																	
DAY	REV	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	2000
1	LS-7	102	118	134	150	166	182	198	214	230	13	29	45	61	77		NOV 21
2	LS-7	93	109	125	141	157	173	189	205	221	4	20	36	52	68	84	NOV 22
3	LS-7	100	116	132	148	164	180	196	212	228	11	27	43	59	75		NOV 23
4	LS-7	91	107	123	139	155	171	187	203	219	2	18	34	50	66	82	NOV 24
5	LS-7	98	114	130	146	162	178	194	210	226	9	25	41	57	73	89	NOV 25
6	LS-7	105	121	137	153	169	185	201	217	233	16	32	48	64	80		NOV 26
7	LS-7	96	112	128	144	160	176	192	208	224	7	23	39	55	71	87	NOV 27
8	LS-7	103	119	135	151	167	183	199	215	231	14	30	46	62	78		NOV 28
9	LS-7	94	110	126	142	158	174	190	206	222	5	21	37	53	69	85	NOV 29
10	LS-7	101	117	133	149	165	181	197	213	229	12	28	44	60	76		NOV 30
11	LS-7	92	108	124	140	156	172	188	204	220	3	19	35	51	67	83	DEC 1
12	LS-7	99	115	131	147	163	179	195	211	227	10	26	42	58	74		DEC 2
13	LS-7	90	106	122	138	154	170	186	202	218	1	17	33	49	65	81	DEC 3
14	LS-7	97	113	129	145	161	177	193	209	225	8	24	40	56	72	88	DEC 4
15	LS-7	104	120	136	152	168	184	200	216	232	15	31	47	63	79		DEC 5
16	LS-7	95	111	127	143	159	175	191	207	223	6	22	38	54	70	86	DEC 6

EO-1 was launched on November 21, 2000 on the first day of a 16 day LS-7 repeat cycle on the WRS. Table 1 shows the LS-7 - EO-1 WRS path difference if the EO-1 launch date were to progress through an LS-7 16-day repeat cycle.

Table 2 Formation Acquisition Propellant vs. Launch Date

EO-1 Launch Date	LS-7 - EO-1 WRS Path Number Difference	Window Length (sec) (Based On ≤ 33 Sec. 3-Sigma MLT from Optimum Launch Time)	Nominal Propellant (kg) to Formation from Optimum Launch Time	3-Sigma Propellant (kg) to Formation from Closing of Window	Window Length (sec) (Based on Maximum Of 9.2 kg of Propellant to Achieve Formation)
2000					
11/21	-3	22	3.70	10.75	10
11/22	+6	22	4.13	11.18	7
11/23	-1	23	1.78	8.93	22
11/24	+8	23	6.61	13.66	NONE
11/25	+1	23	1.75	8.80	23
11/26	-6	23	7.00	14.05	NONE
11/27	+3	23	1.75	8.80	23
11/28	-4	23	5.00	12.05	NONE
11/29	+5	23	1.92	8.97	22
11/30	-2	24	1.55	8.60	24
12/01	+7	24	5.35	12.40	NONE
12/02	0	24	1.82	8.87	23
12/03	-7	24	6.90	13.95	NONE
12/04	+2	24	1.72	8.77	24
12/05	-5	24	4.95	12.00	NONE
12/06	+4	24	1.90	8.95	23

In addition, Table 2 shows how the formation acquisition propellant varied with the launch date and the initial WRS path difference. Using data from the EO-1 propellant budget in Table 3, the launch window had to be reduced or eliminated for certain launch dates during the 16-day LS-7 repeat cycle. The adjusted launch window durations permitted acquisition of the required formation with LS-7 and execution of all the other required spacecraft operations during a 1-year lifetime.

Table 3 EO-1 Propellant Budget

Launch Vehicle Injection Error	
Altitude	1.0 kg
Inclination	1.1 kg
MLT at Descending Node	5.5 kg
Phasing to LS-7 Orbit	1.6 – 4.2 kg
1 Year of Station Keeping	2.0 kg
Reentry Propellant	8.5 kg
Total Propellant Budget Required	**19.7 - 22.3 kg**
Total Propellant Loaded	**22.3 kg**

As the initial WRS path difference varied, the complexity and propellant costs of the formation acquisition sequence also varied. In a January, 2000 paper[1], the relationship of initial WRS path difference to EO-1 delta-V for drift rate adjustment was provided. This plot is shown in Figure 5. The delta-V in Figure 5 is that value to initiate the drift of EO-1 on the WRS toward the same path that LS-7 occupies. At EO-1 separation following launch, the mean semi-major axis of EO-1 was approximately 4.5 km less than that of LS-7. Based on the WRS path difference, the direction of the delta-V in Figure 2 indicated whether EO-1 would be maneuvered above LS-7, or below LS-7 in order to achieve the desired formation on the WRS within the specified time. Having EO-1 move above LS-7 slowed the drift of EO-1 and allowed LS-7 to drift faster with respect to EO-1 and close the gap if coming from behind. If EO-1 was lagging LS-7, an altitude decrease would allow EO-1 to gain on LS-7. In either case, the delta-V to initiate proper drift needed to be reversed to remove the drift when nearing the formation. The maneuver magnitudes and directions to initiate drift were tailored to permit the EO-1 to attain the formation in about 3-4 weeks. For the actual EO-1 launch on November 21, 2000, the formation acquisition sequence was designed as shown in Figures 6A through 6G.

Having the semi-major axis at EO-1 injection about 4.5 kilometers below that of LS-7 and coupled with a WRS path difference of −3, indicates in Figure 5 that a positive delta-V is required to raise the EO-1 orbit above that of LS-7. Using this start to the formation acquisition profile allowed LS-7 to move toward and past EO-1 to achieve the required spacing on the WRS.

Before the drift maneuvers are performed, two other issues must be addressed. A small engineering maneuver in the same direction as the upcoming drift maneuvers is recommended. A 60-second maneuver occurring 3 days after launch will serve this purpose. See Figure 6A.

Another matter that required attention before the drift maneuvers were executed was an inclination adjustment. This helped prevent the MLT difference at the descending node from violating the requirement of one minute +/- 6 seconds while the semi-major axis was offset to permit proper drift to the desired formation. A positive inclination change from 98.21 degrees to the vicinity of 98.22 degrees helped keep the MLT within the required range. See Figures 6C and 6D.

For a November 21, 2000 launch of EO-1, the initial drift maneuvers raised the semi-major axis to a maximum value to 7085 km. The exact size of the individual drift maneuvers and the spacing between was based on maneuver size limitations set by Attitude Control System personnel and approved by the Project for the formation acquisition period. The 3-day interval before maneuver 1 was a Project requirement to permit initial checkout of spacecraft systems. Starting with a 60-second calibration burn, the Flight Dynamics Team began a series of seven orbit maneuvers spread out over the next 25 days. See Figure 6A.

The engineering burn raised the semi-major axis about 400 meters. The second maneuver adjusted the inclination from its separation value of 98.21 degrees to a biased value of 98.22 degrees to control the evolution of MLT during the formation acquisition sequence. The next two maneuvers, called drift burns 1 and 2, continue to increase the semi-major axis to 7085 km. (The maximum maneuver size was limited to less than 1200 seconds.) Following drift burn 2, an interval of 10 days was adopted to allow LS-7 to approach and move in front of EO-1 and achieve the same WRS path. See Figure 6E to observe the reduction of path difference as EO-1 drifts between maneuvers. About 18 days after launch, EO-1 and LS-7 were on the same WRS path. The fifth and sixths burns (drift burns 3 and 4), were executed to slow and stop the drift rate between the two spacecraft. These two burns also shaped the final, frozen orbit. Drift burn 3 began to lower EO-1's semi-major axis to reduce the relative motion between the two spacecraft. LS-7 had been approaching EO-1 from behind with respect to WRS paths. Therefore, LS-7 had to pass EO-1 and move in front. The proximity of the two spacecraft when they passed was an important side issue that is to be discussed later. Drift burn 4 was the final altitude adjust maneuver placing EO-1 into its required frozen orbit in formation with LS-7.

A small inclination adjust in maneuver 7 sets the EO-1 inclination to match that of LS-7; thus the MLT evolution of both spacecraft will be approximately the same. See Figures 6C and 6D. As drift maneuvers were planned and executed to phase EO-1 and LS-7 into the same WRS path, a residual effect was to drive the mean argument of perigee and mean eccentricity toward values required to achieve a frozen orbit. See Figure 6B to follow the evolution of mean argument of perigee throughout the formation acquisition sequence. The required frozen orbit value of mean eccentricity for EO-1 was approximately 0.00116.

In Table 4, the nominal post-launch orbit maneuver plan is presented. Timing of the maneuvers and the estimated propellant usage is shown.

Figure 5 Delta-V for EO-1 Drift Maneuvers

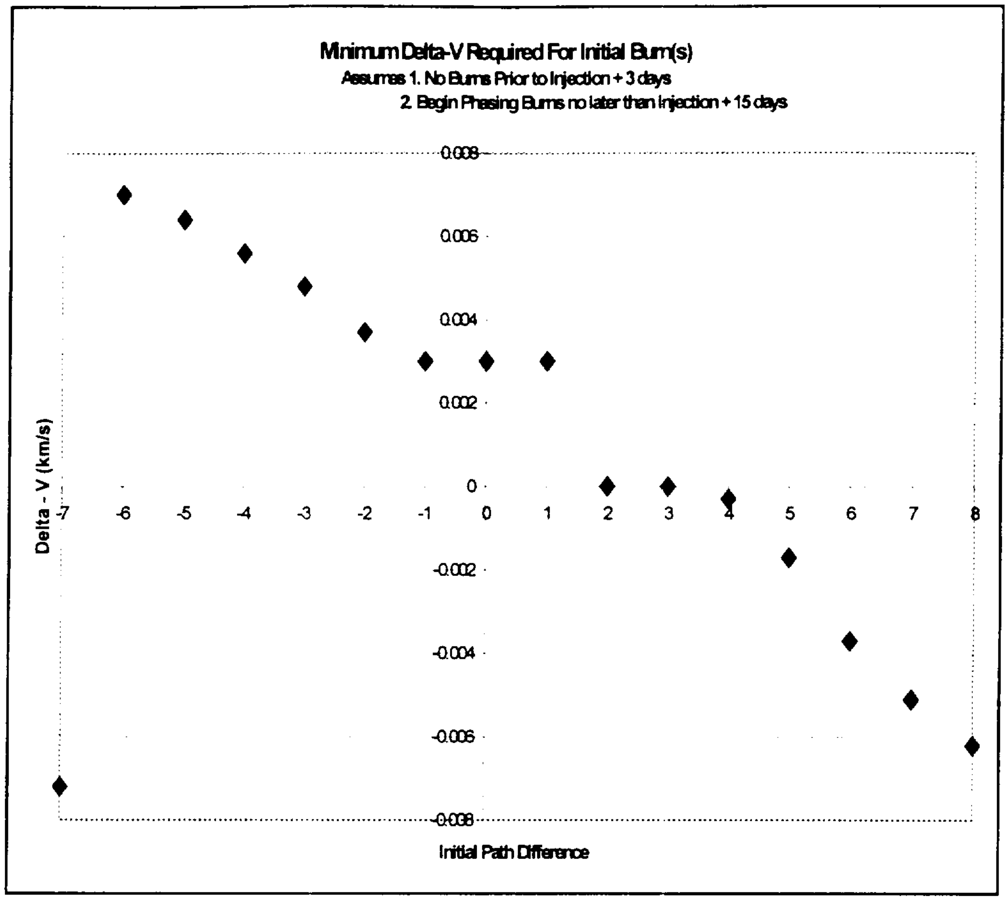


Figure 6A Semi-Major Axis Profile during Formation Acquisition

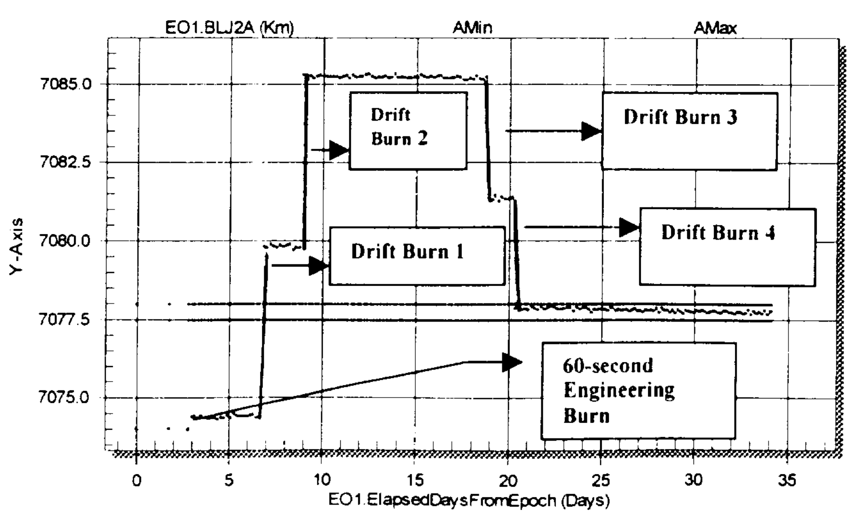


Figure 6B Argument of Perigee Profile during Formation Acquisition

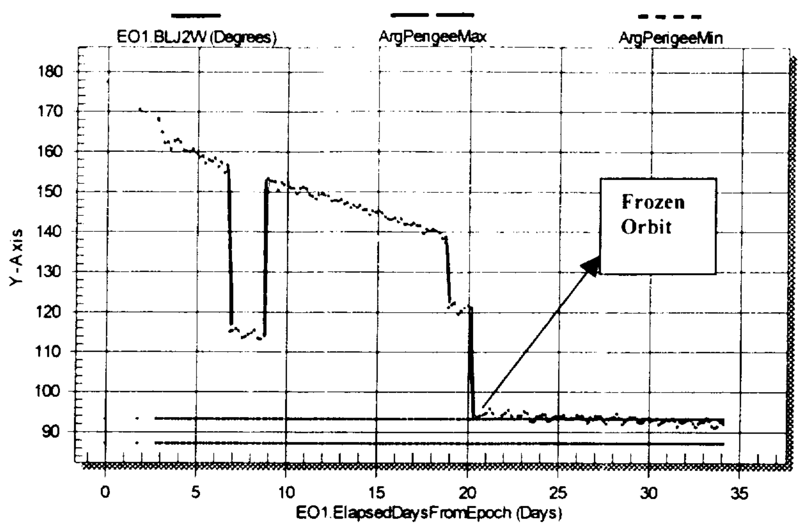


Figure 6C Inclination Profile during Formation Acquisition

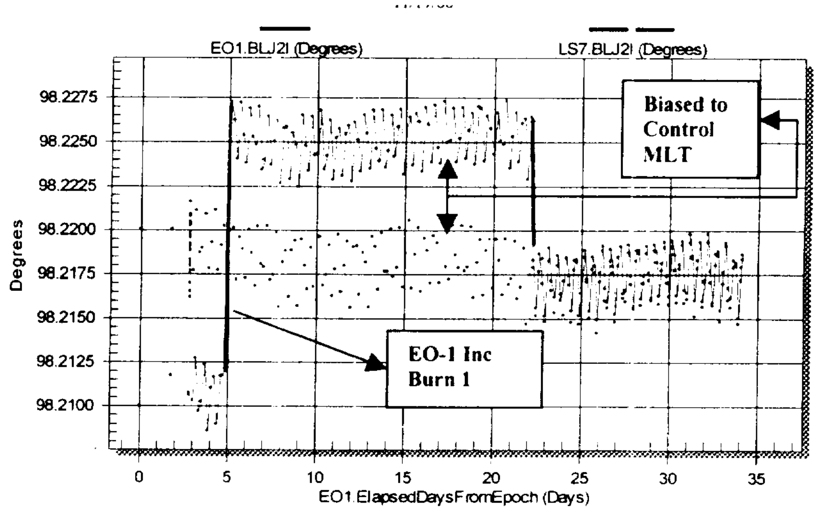


Figure 6D Difference in Right Ascension of Ascending Node Profile between EO-1 and LS-7 during Formation Acquisition

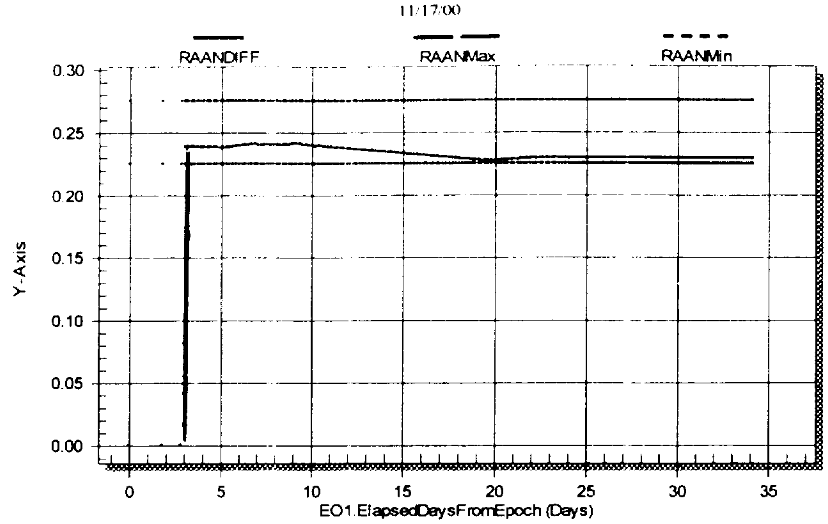


Figure 6E Path Difference between EO-1 And LS-7 during Formation Acquisition

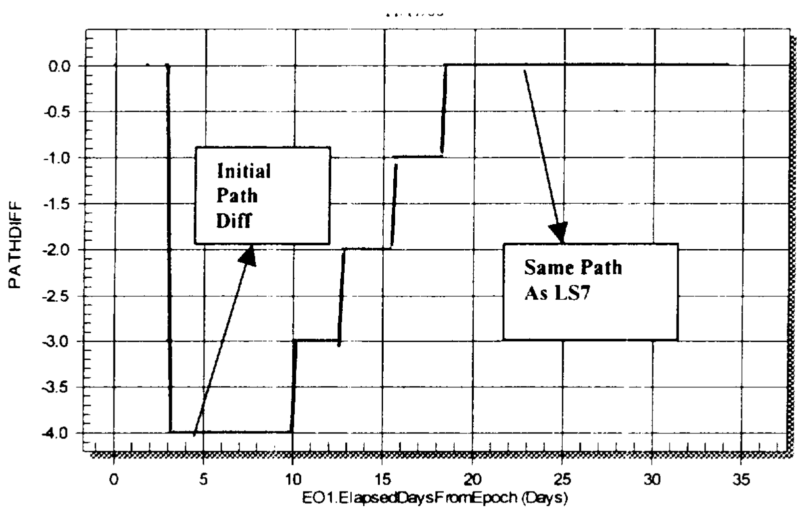


Figure 6F Relative Positions of EO-1 and LS-7 in Ground Control Boxes following Formation Acquisition

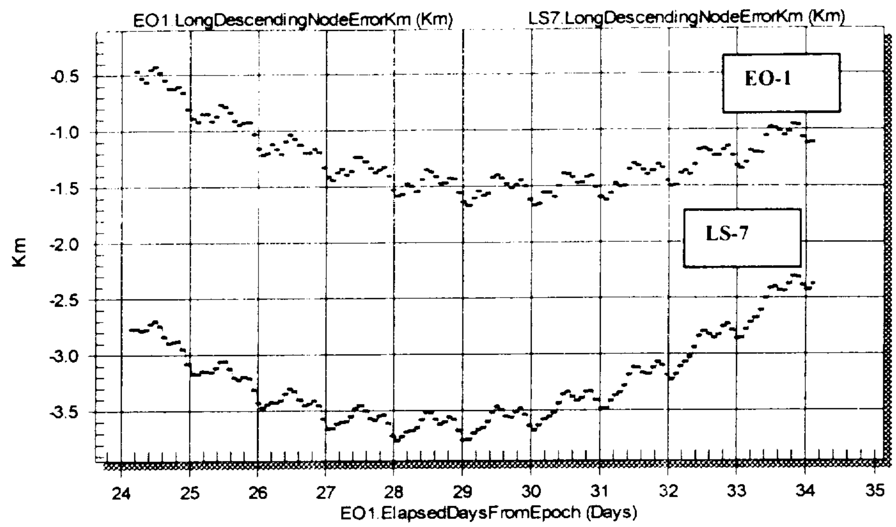


Figure 6G Along Track Separation Difference between EO-1 and LS-7 following Formation Acquisition

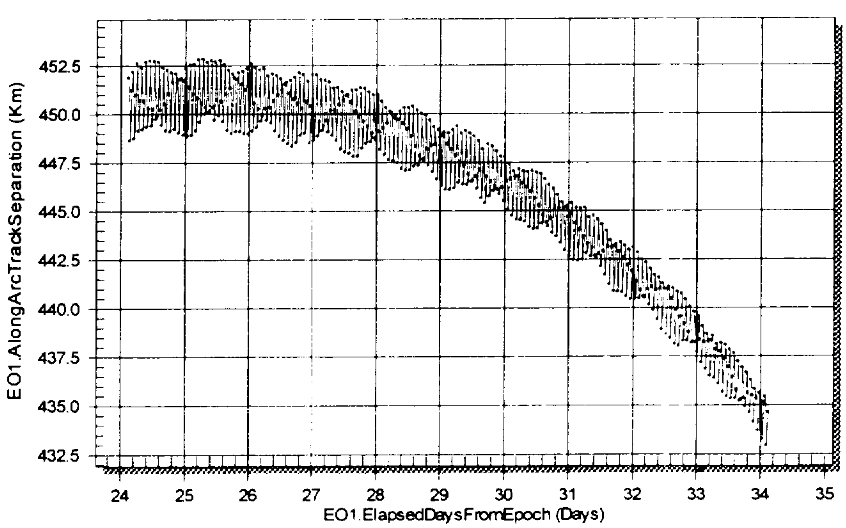


Table 4 Nominal Post-Launch Formation Acquisition Profile

Burn	Start Time	End Time	Duration(sec)	Fuel (kg)
1	Nov 24 2000 15:15:26.502	Nov 24 2000 15:16:26.502	60.000	0.056
2	Nov 26 2000 14:35:37.391	Nov 26 2000 14:46:36.403	659.012	0.589
3	Nov 28 2000 14:38:17.505	Nov 28 2000 14:54:40.777	983.272	0.817
4	Nov 30 2000 13:36:58.168	Nov 30 2000 13:55:00.611	1082.443	0.833
5	Dec 10 2000 14:17:14.587	Dec 10 2000 14:30:36.796	802.209	0.580
6	Dec 12 2000 01:08:21.726	Dec 12 2000 01:21:15.364	773.638	0.534
7	Dec 13 2000 22:20:40.574	Dec 13 2000 22:27:48.585	428.011	0.286
			Total	3.695

ASCENT RE-PLANNING FOR CLOSE APPROACH

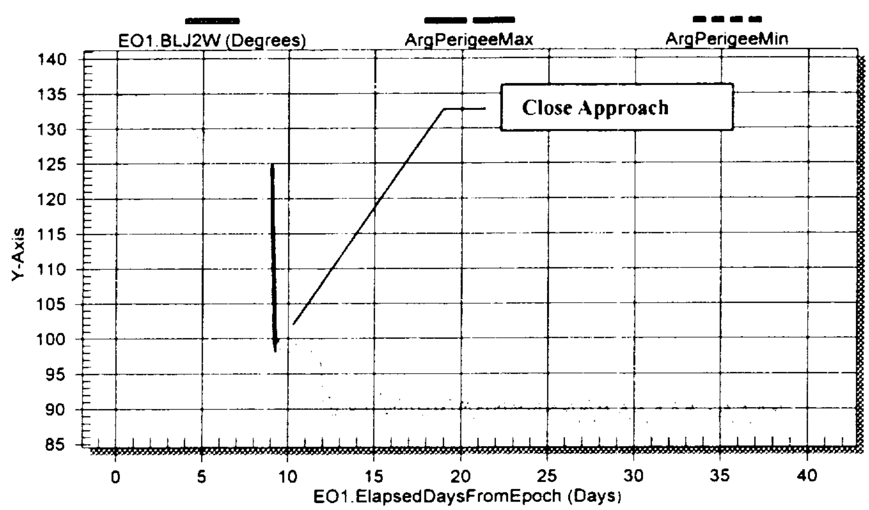
During the EO-1 ascent there were two types of close approaches that were of concern: a close approach between EO-1 and LS-7 as the formation was initialized and any close approach involving SAC-C. Since SAC-C was not prepared to begin maneuvering until about a month after launch, any close approaches between SAC-C and another spacecraft would need to be avoided by maneuvering the other spacecraft. The EO-1 maneuver planning team monitored the close approaches by periodically taking OD solutions from SAC-C, EO-1, LS-7 and Terra and checking for any close approaches in the near future. If any close approaches were discovered, the operations teams of the satellites involved would be notified and appropriate actions would be taken.

After EO-1's second semi-major axis-raising burn was complete, EO-1 had a period of 9 days to drift without any maneuvers. This drifting time was used for looking at the close approach and formation initialization problem in more detail. The analysis during the 9 days of drift showed that the original close approach predicted before launch had changed, and this was expected since EO-1 had performed four maneuvers and LS-7 had performed one. These maneuvers, along with changes in atmospheric drag, changed the close approach between LS-7 and EO-1 to within 11 kilometers. The upcoming semi-major axis maneuver (the one planned for just before the close approach) was re-planned in an effort to increase the close approach distance. The initial strategy used was to decrease the size of the next maneuver so as to not lower EO-1's semi-major axis as much as originally planned. The hope was to keep EO-1 several kilometers higher when LS-7 passed in front of EO-1. The results of re-planning that maneuver were surprising because the relative semi-major axis distance between EO-1 and LS-7 at the time of the close approach was increased, but the close approach itself decreased. Without re-planning the next maneuver the close approach would have been 11 km, but after re-planning the next maneuver to keep EO-1 even higher than LS-7 the close approach was reduced to 500 meters. It was obvious from the results of the re-planned maneuver that the semi-major axis of EO-1 with respect to LS-7 was not the reason for the close approach.

While formation flying, EO-1 and LS-7 are in a Sun-synchronous frozen orbit, which means they have a frozen line of apsides with an argument of perigee at approximately 90 degrees. At the time of the close approach, EO-1 was not in a frozen orbit but did have an argument of perigee of about 95 degrees. The cause of the close approach was due to two things: the along-track crossing of the two spacecraft and nearly identical perigee heights. Almost all of the semi-major axis difference at the time of the along track crossing was in apogee. Therefore, as EO-1 and LS-7 approached their perigees over the North Pole, they were at nearly the same height above the earth. The re-planned maneuver did keep EO-1's semi-major axis higher, but it only changed the apogee height so EO-1 and LS-7 still had very similar perigee heights. The re-planned maneuver also changed EO-1's period enough to move the zero along track crossing to over the North Pole, which is why the predicted close approach dropped to 500 meters.

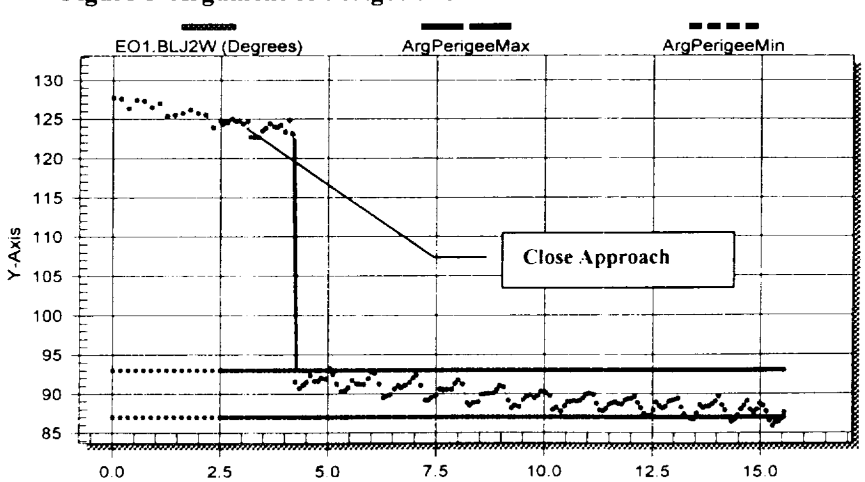
The final re-plan of the next EO-1 maneuver was changed to maximize the close approach distance in two ways. The first increased the height difference as EO-1 and LS-7 went over the poles. This was accomplished in two ways: the maneuver size was decreased and the maneuver was located in the orbit such that the argument of perigee was not rotated. Figure 7 shows the original change in argument of perigee on day 9 of the plot and Figure 8 shows the argument of perigee change as a result of the re-planned maneuver on day 2.5 of the plot (note there is no visible change in argument of perigee). The second feature of the re-designed maneuver was the resulting period of EO-1. The maneuver duration was planned such that the resulting EO-1 period would modify the along-track crossing location to a point over the equator where the additional cross track separation would increase the safety of the close approach. The orbit maneuver summary section of this paper includes more details about how this maneuver and all the following maneuvers in the ascent sequence were re-designed.

Figure 7 Argument of Perigee Profile of Original Maneuver Plan



Close Approach Range = 11.0 km
Along Track = 9.0 km / Cross Track = 3.1 km / Radial = 5.4 km

Figure 8 Argument of Perigee Profile of Final Maneuver Plan



EO-1-LS-7 Along Track Crossing Latitude = 0 degrees (Equator)
Close Approach Range = 30.3 km
Along Track = 0 km / Cross Track = 28.5 km / Radial = 10.2 km

EO-1 and SAC-C also had a close approach during the ascent period, but the close approach was much different than the EO-1-LS7 close approach. SAC-C was still in a state of free-drift after its release from the 3rd stage of the launch vehicle and had a semi-major axis much lower than that of EO-1 and Landsat-7. Also, since SAC-C had not started maneuvering, its line of apsides was not yet frozen. SAC-C's apside rotation would rotate a full 360-degrees approximately every 60 days. As SAC-C's line of apsides rotated it would intersect its perigee with that of EO-1, LS7 and Terra, but since SAC-C's semi-major axis was so much lower there was still a significant distance between them. The SAC-C close approaches were not caused because of co-located perigees, but because of co-located apogees and perigees. SAC-C's apogee was at approximately the same height as EO-1 and LS7's perigees, so as SAC-C's apogee rotated through EO-1 and LS7's perigees there were close approaches. The first close approach was between SAC-C and EO-1 and a few orbits later SAC-C had a close approach with LS7. These close appraoches took place several days after the EO-1-LS7 close approach. The EO-1 and LS7 Flight Operations Teams monitored SAC-C during these close approaches, but since the close approaches were greater than 20 kilometers evasive maneuvering was not necceassary.

EO1 was NASA's first sun-synchronus formation flying mission, and there were many lessons learned. The frozen sun-synchronus orbit is a dangerous orbit to insert into if it is part of a constellation of spacecraft. Since maintaining the sun-synchronus orbit requires tight control of the orbit eccentricity, inclination, and semi-major axis, all spacraft in the constellation cross the north and south poles at approximately the same altitude. Phasing another satellite into the constellation, such as EO1, requires an ascent to the operational orbit altitude. Until the ascent is complete, the orbital periods between the entering spacecraft and those of the constellation are different, which leaves open the possibility of the entering satellite crossing other satellites in the along track direction. Phasing into a sun-synchronus constellation must be planned very carefully as to avoid having an along track crossing near the poles with similar arguments of perigee. The best ways to avoid this dangerous situation is to plan the ascent in such a way that you do not cross another satellite in the along track direction. If this is unavoidable such as in EO1's case, then the entering satellite must keep its argument of perigee rotated as far away from 90-degrees as possible until there are no more along track crossings with any other satellites in the constellation. Once the phasing part of the ascent is complete it is safe to rotate the argument of perigee to the desired 90-degrees and achieve the frozen orbit.

ATTITUDE CONTROL AND SPACECRAFT ORIENTATION

The EO-1 spacecraft uses two methods for attitude control: reaction wheels and thrusters via a closed loop control system. During a delta-V maneuver, EO-1 uses canted thrusters and off-pulses them to maintain attitude during the maneuver. EO-1's thrusters are canted in such a way that if all 4 thrusters are on for the same amount of time the effects of the canting are cancelled out. However, due to using the thruster for attitude control during the maneuver and because of EO-1's off-centered center of mass 2 of the thrusters are on about 50% of the time while the other 2 are on almost all of the time. This difference in on time between the thrusters produces a thrust vector that is off from the planned nominal thrust vector. In addition to these errors in the thrust direction with respect to the spacecraft body, the closed loop Attitude Control System (ACS) takes a finite amount of time to correct for the initial jolt produced by turning the thrusters on. This lag time produces what is called a hang-off error, or a constant attitude error due to the ACS not being able to totally compensate for that initial error due to thruster ignition. This hang-off error would also vary on the type of maneuver (i.e. orientation of the spacecraft) and the length of the burn. In an attempt to compensate for all of these factors, an additional ***FreeFlyer*** script was created. This script would take each of the four duty cycles and thrust scale factors for the thrusters, the burn duration, ideal orientation for the thrust vector and the estimated hang-off errors and calculate the orientation (as Euler angles and as a quaternion) EO-1 should be in during the burn to cancel out all of these errors. This method was not necessary during the normal operations phase of the mission because the station-keeping maneuvers were small enough that the error had no effect on the results of the maneuver. Also, since the station-keeping maneuvers were so short the ACS never reached steady state, so the hang-off errors were difficult to predict. The ascent and formation initialization, however, was sensitive to these errors. Since the ascent maneuvers were so long in duration and because any small burn accuracy errors would be