THE IMPACT OF MANEUVER FAILURES ON THE EOS AFTERNOON CONSTELLATION

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ABSTRACT

The first four satellites, Aqua, CloudSat, Calipso, and Parasol, in NASA's EOS Afternoon constellation will fly in similar orbits within 4 minutes of each other. This study was undertaken to examine the effect of one or more missions failing to perform a scheduled orbit maintenance maneuver. Tools were developed to rapidly calculate the initial orbital elements for the satellites that established the formation. Baseline maneuver strategies were implemented to maintain the desired spacing of the satellites. Maneuver failures were examined and close approach opportunities were identified. It was found that close-approaches between CloudSat and Calipso could occur in less than one day after a missed maneuver if close coordination between the missions is not achieved.

PURPOSE

The first four satellites in the Earth Observing System Afternoon (EOS-PM) Constellation: Aqua, CloudSat, Calipso, and Parasol, will fly in relatively close proximity. Though each satellite can be maintained independently within its desired control box, failure to perform expected maneuvers could impact the other missions. This study was performed to examine and characterize the effect of selected sets of satellites failing to perform scheduled maneuvers. The focus was on understanding the level of coordination and responsiveness needed between missions to avoid close approaches between the spacecraft.

The analysis was broken up into three tasks. First, to determine a set of initial orbital elements for each satellite that establishes the constellation and meets mission requirements. Second, to implement a nominal maneuver strategy for each satellite. These strategies will maintain the satellite's required ground track and orbital spacing. And third, to examine the effect of up to two satellites within the constellation failing to perform a scheduled maneuver.

ESTABLISH CONSTELLATION

The first task performed was to determine the set of orbital elements which would place each satellite in the desired position in the EOS-PM constellation, also called the PM train. Aqua is the lead satellite in the PM train and was placed in an orbit which has a 16 day, 233 orbit repeat cycle corresponding to the World Reference System (WRS-2) grid used by Terra and Landsat-7. In this orbit, a satellite will fly over the same point on the ground every 16 days. Aqua's nominal mean local time at the ascending node is 1:30PM, though it is allowed to drfit between 1:30PM and 1:45PM. Parasol is also on the WRS-2 grid, but will follow behind Aqua by 240 seconds, measured at the ascending node (this lag is referred to as orbit phasing or phase time). CloudSat and Calipso will fly in close formation with each other, Calipso 120 seconds behind Aqua and CloudSat 105 seconds behind Aqua. CloudSat and Calipso both have a 16 day, 233 orbit repeat cycle but their mean local time at the ascending node will be 75 seconds later than Aqua's, resulting in a ground track offset relative to Aqua's and the WRS-2 grid.

A starting epoch of October 10, 2004, a date after all missions will be operational and after Aqua's mid-mission inclination maneuver, was chosen for this analysis. All of the orbits were assumed to have an inclination of 98.144°. An eccentricity(e) of 0.0012 and argument of perigee(ω) of 90° was chosen to maintain each satellite in a frozen orbit which has no secular drift in either eccentricity or argument of perigee.

To determine the semi-major axis(a) and right ascension(Ω) for Aqua, a two-level iterative process was developed. The nonlinear solvers in MatLab [1] were used to drive a $FreeFlyer^{TM}$ script that propagated the orbit and calculated the desired orbital parameters. The inner iterations of the two level scheme would adjust a and Ω until the satellite was placed in a repeating orbit; on the WRS-2 grid. The outer iterations would adjust the initial epoch and repeat the inner iterations until the desired mean local time at the ascending node was achieved. This approach is similar to that used by Lim [2] and Webb [3] to calculate the ICESat repeating ground track.

A similar process was used to place the three trailing satellites in line relative to Aqua. A single level iteration scheme was used in which semi-major axis, longitude of the ascending node, and the initial epoch were varied until the desired phasing, repeat orbit, and mean local time offset were achieved.

	Aqua	**Parasol**
Epoch	Oct 10 2004 01:29:08.181	Oct 10 2004 01:32:51.701
BLJ2 a (km)	7077.675317	7077.674753
BLJ2 e	0.0012	0.0012
BLJ2 i (°)	98.144	98.144
BLJ2 Ω (°)	221.439870	222.442370
BLJ2 ω (°)	90	90
BLJ2 M (°)	1	0
Mean Local Time	1:30:00	1:30:00
	CloudSat	**Calipso**
Epoch	Oct 10 2004 01:30:36.701	Oct 10 2004 01:30:51.701
BLJ2 a (km)	7077.674276	7077.674251
BLJ2 e	0.0012	0.0012
BLJ2 i (°)	98.144	98.144
BLJ2 Ω (°)	221.753372	221.753541
BLJ2 ω (°)	90	90
BLJ2 M (°)	0	0
Mean Local Time	1:31:15	1:31:15

Table 1: Initial Orbital Elements, 4x4 Geopotential

The initial or reference Brouwer-Lyddane(J2) elements for the four satellites are listed in Table 1. Similar results were achieved using higher order gravity fields. It is worth noting that although the behavior of the orbit doesn't change based on the number of geopotential terms modeled, the change in semi-major axis, compared to the 4x4 case shown, is of the same magnitude as the required orbit maintenance maneuvers. This emphasizes the need to match the initial elements to the gravity model when calculating maneuvers.

Figures 1-4 show the ground track error relative to the WRS-2 grid for each satellite. The small(< 150 m) variations are typical and due to the tesseral terms in the gravity field. The important characteristic is the zero average slope, which confirms that the orbit has the desired repeat cycle. It can also be seen that Aqua and Parasol are on the WRS-2 grid while CloudSat and Calipso are offset 13.9 km and 20.85 km westward, respectively. Without atmospheric drag, the three trailing satellites maintain a constant, fixed distance behind Aqua, measured both in phase, Figure 5, and range, Figure 6.

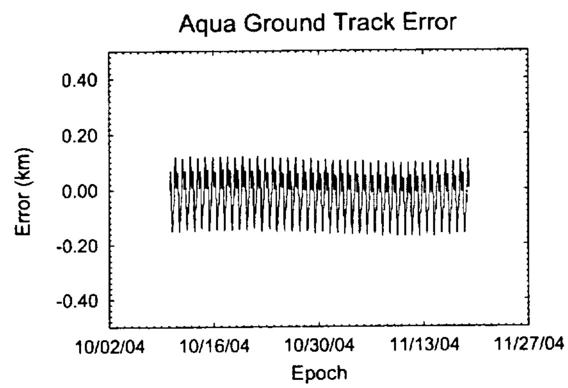

Figure 1: Aqua Ground Track Error, No Drag, 4x4 Geopotential

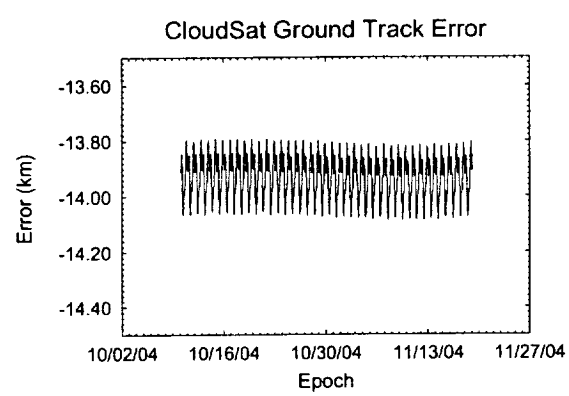

Figure 2: CloudSat Ground Track Error, No Drag, 4x4 Geopotential

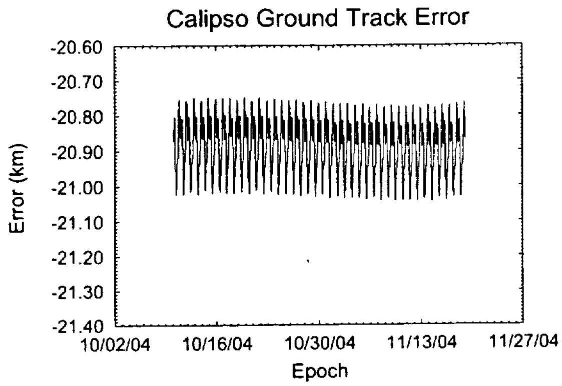

Figure 3: Calipso Ground Track Error, No Drag, 4x4 Geopotential

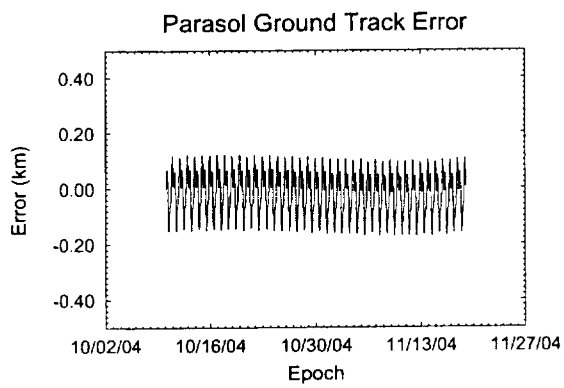

Figure 4: Parasol Ground Track Error, No Drag, 4x4 Geopotential

NOMINAL MANEUVER STRATEGIES

Atmospheric drag is the dominant perturbing force on the satellite orbits and results in the need to perform maneuvers to maintain the satellites in formation. For this analysis the following maneuver strategies were chosen for each satellite.

Aqua maneuvers independently, maintaining its ground track relative to the WRS-2 grid within ± 10 km. This is equivalent to a ± 22 second control box relative to the reference orbit. Parasol is also maintained independently within a ± 10 km ground track control box. Calipso is maintained within ± 10 km a control box relative to its initial -20 km offset ground track. The relative motion of the maneuvered satellites is shown in Figure 7.

CloudSat's maneuvers are tied to Calipso due to

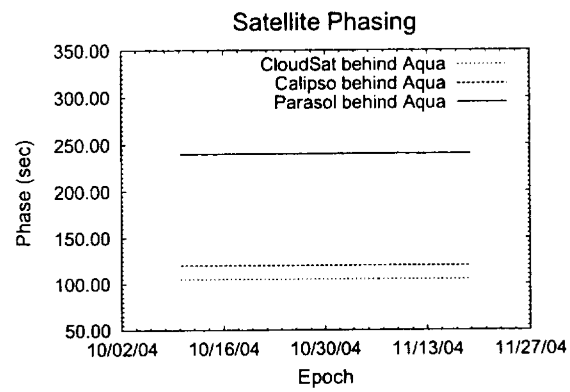

Figure 5: Orbit Phase behind Aqua, No Drag, 4x4 Geopotential

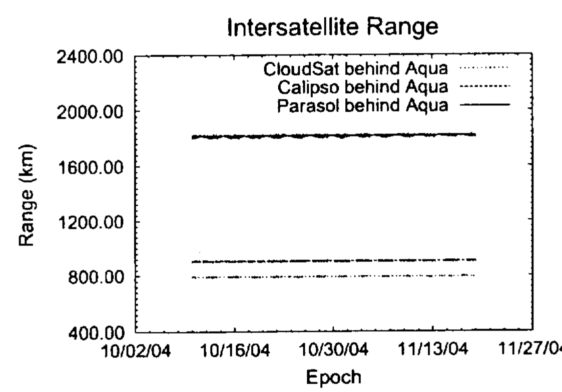

Figure 6: Intersatelite Range from Aqua, No Drag, 4x4 Geopotential

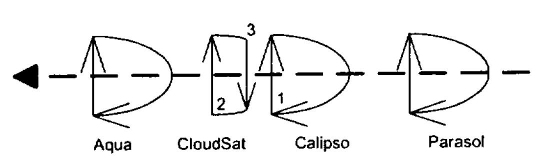

Figure 7: Constellation Relative Motion

	Aqua	Parasol
Dry Mass (kg)	3039	120
Fuel Mass (kg)	200	20
Area (m^2)	47.95	1.0
C_D	2.2	2.7
Thrusters	4	3
Thrust (N)	0.09	1.0
Isp (sec)	200	220
	CloudSat	**Calipso**
Dry Mass (kg)	821	600
Fuel Mass (kg)	76	27.2
Area (m^2)	8.3	9.5
C_D	2.2	2.7
Thrusters	2	2
Thrust (N)	4.45	1.0
Isp (sec)	220	212

Table 2: Spacecraft Properties

their close proximity. The maneuver strategy implemented has CloudSat performing two maneuvers for every one Calipso performs. When Calipso raises its orbit, point 1 in Figure 7, CloudSat also raises its orbit, point 2. Halfway between Calipso maneuvers, point 3, CloudSat performs an orbit lowering maneuver. Both the raising and lowering maneuvers were sized to maintain CloudSat between 75 and 120 km from Calipso. This corresponds to a ±2.5 second control box 15 seconds in front of Calipso.

The maneuver strategies described above were implemented in $FreeFlyer^{TM}$ using the spacecraft parameters and force model listed in Tables 2 and 3. The maneuvers performed for this analysis are listed in Table 4. The resulting ground tracks of each satellite are shown in Figures 8-11. Figure 9 shows that a CloudSat orbit raising maneuver causes the ground track to drift within a ±10 km control box from the eastern edge(-5 km) to the western edge(-25km). A orbit lowering maneuver results in the ground track drifting back to the eastern edge in time for the next maneuver to occur with Calipso's next maneuver. Figures 12 and 13 show the relative phase and range behind Aqua of the maneuvered satellites. Figure 14 shows that CloudSat is maintained 75-120 km from Calipso with this strategy.

MANEUVER FAILURES

The main task in this study was to examine what will occur if up to two satellites fail to perform scheduled maneuvers. Of particular interest is the amount

Geopotential	JGM-2
Order	4
Degree	4
Solar Gravity	No
Lunar Gravity	No
Solar Radiation Pressure	No
Atmospheric Density Model	Harris-Preister

Table 3: Force Model Parameters

Maneuver	Epoch	Duration* (sec)
Cloud 1	Oct 26 2004 07:30:00	-6.42684
Calipso 1	Nov 11 2004 13:27:00	79.34851
Cloud 2	Nov 11 2004 13:27:20	19.36560
Aqua 1	Nov 15 2004 17:57:00	54.86191
Parasol 1	Nov 27 2004 00:18:00	7.595172
Cloud 3	Dec 03 2004 02:07:14	-5.79300
Calipso 2	Dec 24 2004 14:46:00	65.56777
Cloud 4	Dec 24 2004 14:46:30	15.96962
Aqua 2	Jan 04 2005 16:04:00	44.62905
Cloud 5	Jan 18 2005 08:53:25	-5.06473
Parasol 2	Feb 04 2005 15:24:00	6.600084
Calipso 3	Feb 12 2005 03:01:00	65.24259
Cloud 6	Feb 12 2005 03:01:41	15.82117
Cloud 7	Mar 05 2005 22:16:35	-5.73644
Aqua 3	Feb 28 2005 06:16:00	48.54981
Calipso 4	Mar 27 2005 17:31:00	76.15452
Cloud 8	Mar 27 2005 17:31:54	19.51881
* Negative Duration Indicates Orbit Lowering Maneuver		

Table 4: Maneuvers Performed

of time the other missions will have to react before close-approaches, defined to be less than 10 km in range between satellites, will occur. For the purpose of this study, a close approach was deemed likely if one of the spacecraft passes in front of another in the train. Of the maneuvers listed in Table 4, 14 combinations of maneuver failures in the November-December 2004 time frame were chosen for examination as listed in Table 5. The orbits are identical to those in the previous section up to the time of the maneuver failure, where the satellite failing to perform its maneuver takes no further action and continues to decay. The other satellites continue to maneuver as previously shown.

RESULTS

In the first case examined, Aqua fails to perform its orbit raising maneuver on November 15. As the orbit continues to decay, Aqua moves ahead of the

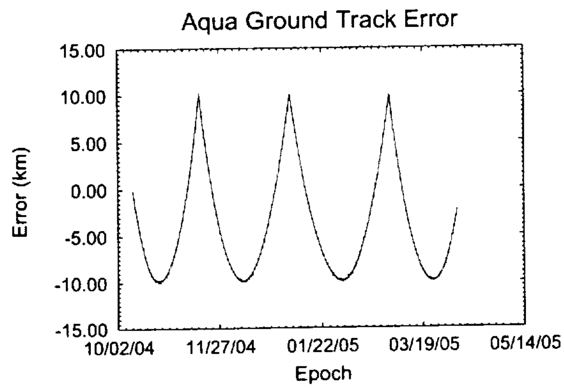

Figure 8: Aqua Ground Track Error, Nominal Maneuvers, 4x4 Geopotential

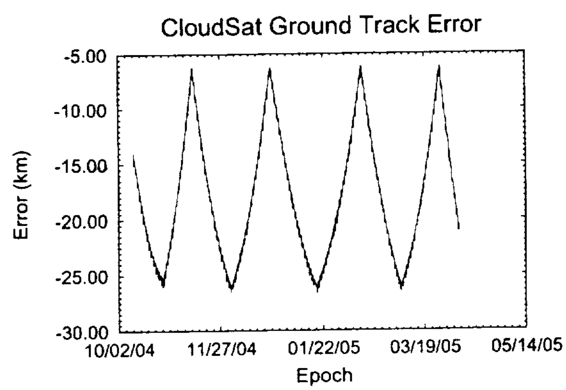

Figure 9: CloudSat Ground Track Error, Nominal Maneuvers, 4x4 Geopotential

formation. This can be seen as the steadily increasing phase of the other satellites in Figure 15.

The second case examined has CloudSat failing to perform an orbit raising maneuver on November 11. As the orbit decays, CloudSat moves away from Calipso and towards Aqua, Figure 16. After two to three weeks CloudSat will have caught up to and passed close to and in front of Aqua, where the phase becomes negative. CloudSat moving away from Calipso after failing to perform its maneuver can also be seen in the figure.

Case 3 looked at the other possible type of CloudSat maneuver, an orbit lowering. If CloudSat fails to perform its orbit lowering maneuver on December 3, it continues to move back towards Calipso. In about 1 week, CloudSat will cross behind Calipso, shown in Figure 17 where the CloudSat and Calipso lines

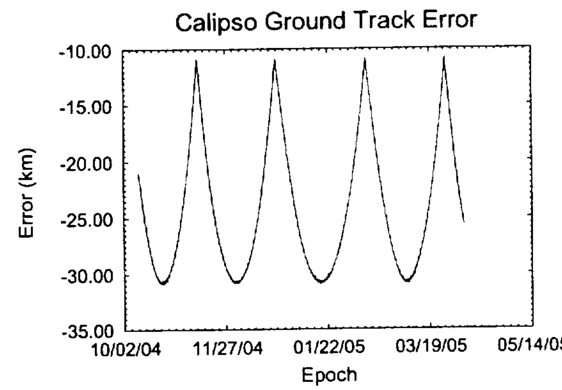

Figure 10: Calipso Ground Track Error, Nominal Maneuvers, 4x4 Geopotential

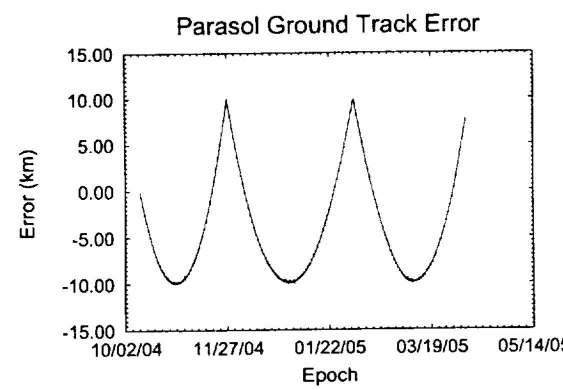

Figure 11: Parasol Ground Track Error, Nominal Maneuvers, 4x4 Geopotential

cross. If no further action is taken, CloudSat will eventually pass back in front of Calipso and then in front of Aqua as drag eventually lowers its semimajor axis.

Case 4 examines Calipso not performing an orbit raising maneuver on November 11. If CloudSat performs its orbit raising maneuver, Calipso quickly approaches CloudSat. The two satellites will pass each other within approximately 1 day. After passing CloudSat, Calipso would eventually catch up with and pass Aqua, Figure 18.

The final single satellite maneuver failure examined involved Parasol not performing its November 27 maneuver. Since Parasol is at the back of the train, it takes several weeks before it passes ahead of the rest of the satellites. This can be seen in Figure 19.

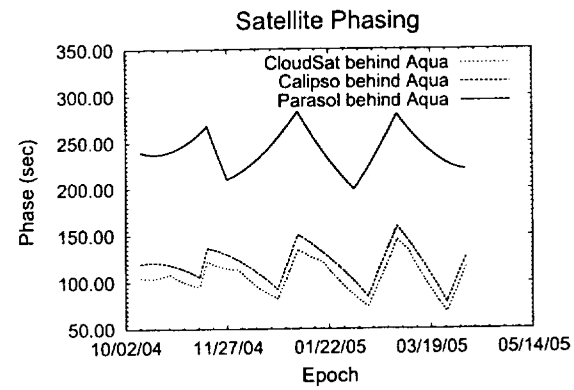

Figure 12: Orbit Phase behind Aqua, Nominal Maneuvers, 4x4 Geopotential

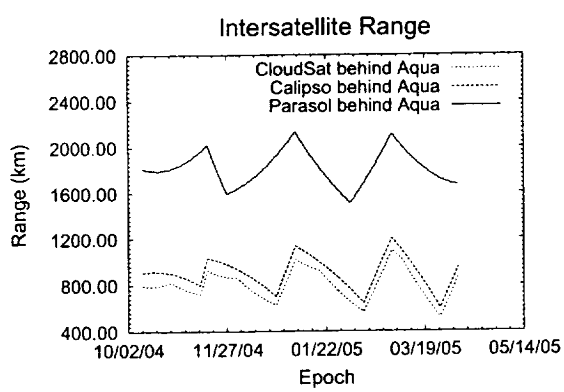

Figure 13: Intersatelite Range from Aqua, Nominal Maneuvers, 4x4 Geopotential

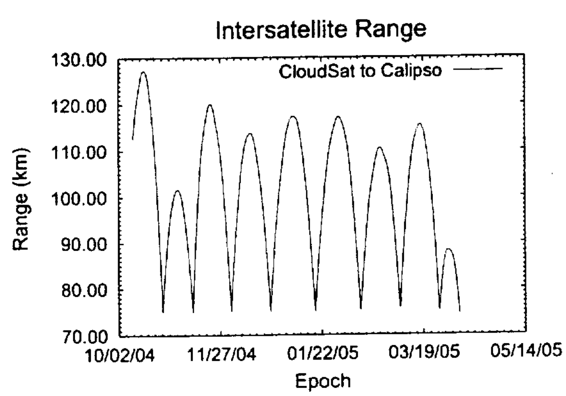

Figure 14: CloudSat to Calipso Range, Nominal Maneuvers, 4x4 Geopotential

Case 1	Aqua 1 (Nov 15 2004)
Case 2	Cloud 2 (raising) (Nov 11 2004)
Case 3	Cloud 3 (lowering) (Dec 03 2004)
Case 4	Calipso 1 (Nov 11 2004)
Case 5	Parasol 1 (Nov 27 2004)
Case 6	Aqua 1 and Cloud 2
Case 7	Aqua 1 and Cloud 3
Case 8	Aqua 1 and Calipso 1
Case 9	Aqua 1 and Parasol 1
Case 10	Cloud 2 and Calipso 1
Case 11	Cloud 3 and Calipso 1
Case 12	Cloud 2 and Parasol 1
Case 13	Cloud 3 and Parasol 1
Case 14	Calipso 1 and Parasol 1

Table 5: Maneuver Failure Combinations

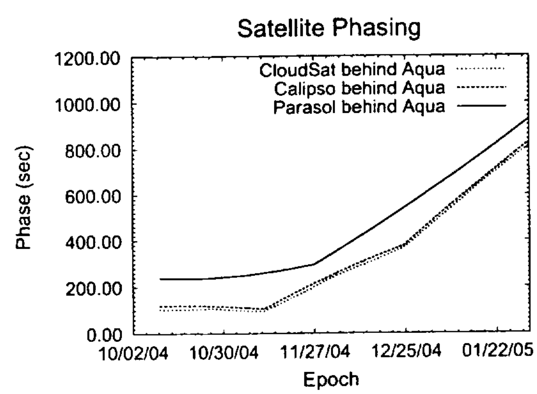

Figure 15: Orbit Phase behind Aqua, Case 1, 4x4 Geopotential

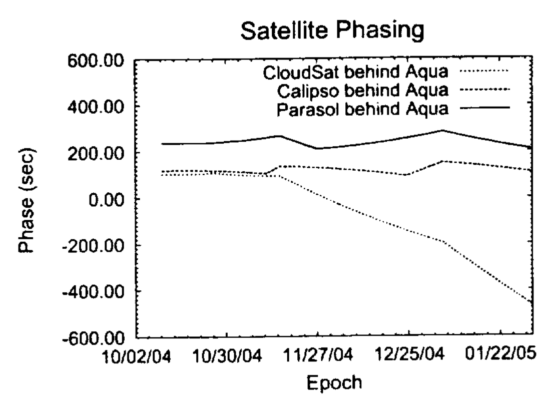

Figure 16: Orbit Phase behind Aqua, Case 2, 4x4 Geopotential

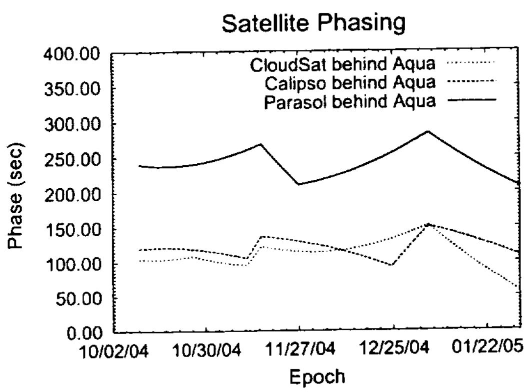

Figure 17: Orbit Phase behind Aqua, Case 3, 4x4 Geopotential

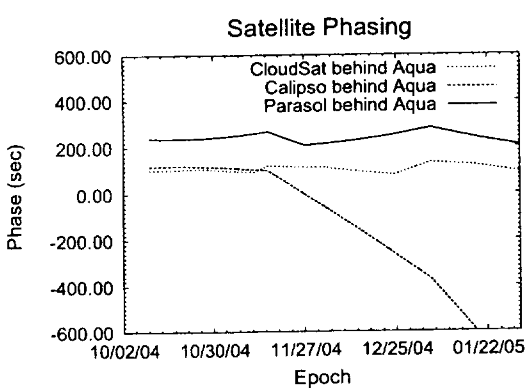

Figure 18: Orbit Phase behind Aqua, Case 4, 4x4 Geopotential

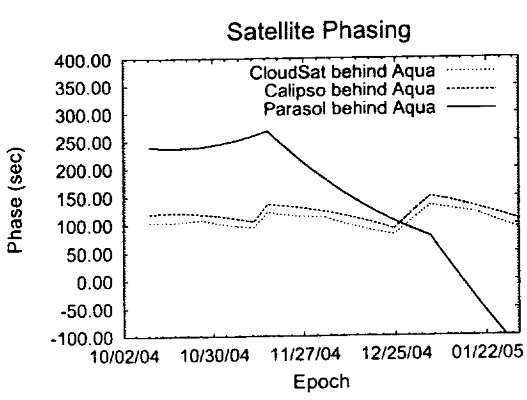

Figure 19: Orbit Phase behind Aqua, Case 5, 4x4 Geopotential

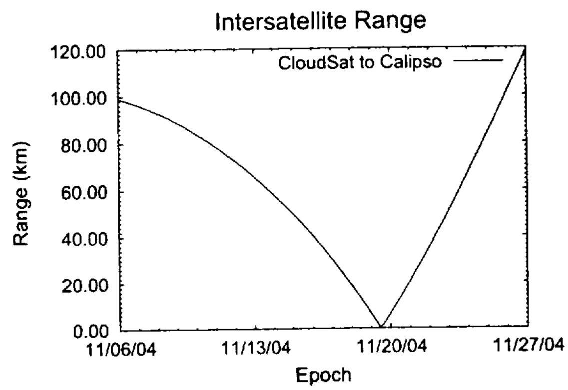

Figure 20: CloudSat to Calipso Range, Case 10, 4x4 Geopotential

The remaining cases examined involved combinations of two satellites failing to perform their scheduled maneuvers. Case 6 combines Aqua failing to perform maneuver 1 and CloudSat failing to perform maneuver 2. Both satellites continue to decay and move ahead of the train but their differing ballistic coefficients cause Aqua to move away faster than CloudSat.

Case 7 is a combination of Cases 1 and 3. Aqua moves safely ahead of the train while CloudSat will cross Calipso in approximately one week.

Case 8 is a combination of Cases 1 and 4. Aqua moves safely ahead of the train while CloudSat and Calipso will cross in approximately one day.

Case 9 combines Cases 1 and 5. Aqua moves ahead of the train while Parasol eventually catches up to the earlier satellites.

The next two cases examined a combination of CloudSat and Calipso maneuver failures. Case 10 shows the effect of both CloudSat and Calipso failing to perform orbit raising maneuvers. Both satellites continue to decay, but their different ballistic coefficients cause Calipso to decay faster and cross ahead of CloudSat within one week, Figure 20. Both satellites would eventually catch up to Aqua.

Case 11 shows the effect of CloudSat failing to perform an orbit lowering maneuver after Calipso has failed to perform an orbit raising maneuver. As in Case 4, since CloudSat performed its orbit raising maneuver, Calipso quickly crossed ahead of CloudSat, Figure 21.

Case 12 is a combination of Cases 2 and 5. It is several weeks before any of the satellites cross in front of each other.

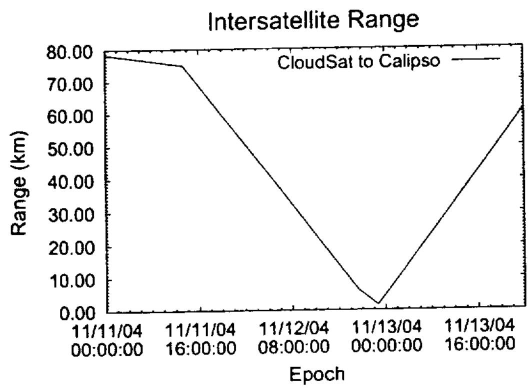

Figure 21: CloudSat to Calipso Range, Case 11, 4x4 Geopotential

Case 13 is a combination of Cases 3 and 5. It is nearly a week before CloudSat crosses with Calipso and several weeks before Parasol passes through the formation.

Case 14 is a combination of Cases 4 and 5. As seen before, CloudSat maneuvering when Calipso does not causes the satellites to cross within one day.

CONCLUSIONS

The purpose of this study was to examine what the effect of up to two satellites in the EOS Afternoon constellation not performing scheduled maneuvers will have on the rest of the constellation. Of particular interest was the amount of time each mission will have to react before close approaches between the satellites occur. To do this, orbital elements establishing the constellation had to be determined and a nominal maneuver strategy for maintaining the constellation had to be implemented. Once that was done, a number of maneuver failure cases were examined.

A summary of the maneuver failure cases examined and the time frame before a close approach would occur is presented in Table 6. Twelve of the fourteen cases examined result in the possibility of close approaches between satellites. Four of those cases require rapid action by one or more missions to prevent a close approach from occurring within one day of the maneuver failure. Although the exact timing of and collision risk during a close approach would depend on a number of factors including the actual atmospheric density, this study does show the need for coordination between the various missions when they are preparing to maneuver. CloudSat and Calipso in particular need to closely coordinate their maneuver planning in order to eliminate the risk of close approach associated with CloudSat raising its orbit when Calipso does not do the same.

Case	Maneuvers	Close Approach	Response Time
1	Aqua 1	No	
2	Cloud 2	Yes	2-3 weeks
3	Cloud 3	Yes	1 week
4	Calipso 1	Yes	**1 day**
5	Parasol 1	Yes	4 weeks
6	Aqua 1, Cloud 2	No	
7	Aqua 1, Cloud 3	Yes	1 week
8	Aqua 1, Calipso 1	Yes	**1 day**
9	Aqua 1, Parasol 1	Yes	5-6 weeks
10	Cloud 2, Calipso 1	Yes	1 week
11	Cloud 3, Calipso 1	Yes	**1 day**
12	Cloud 2, Parasol 1	Yes	2 weeks
13	Cloud 3, Parasol 1	Yes	1 week
14	Calipso 1, Parasol 1	Yes	**1 day**

Table 6: Close Approaches

ACKNOWLEDGEMENTS

This paper was prepared under NASA contract NAS5-01090.

REFERENCES

[1] *Using MatLab.* The MathWorks, Natick, MA, 1998.

[2] Samsung Lim. *Orbit Analysis and Maneuver Design for the Geoscience Laser Altimetry System.* PhD thesis, The University of Texas at Austin, December 1995.

[3] H.J. Rim, B. E. Schutz, C. Webb, and P. Demarest. Repeat orbit characteristics and a maneuver strategy for a synthetic aperature radar satellite. *Journal of Spacecraft and Rockets*, 37(1), January-February 2000.