Landsat Data Continuity Mission (LDCM) Safe Operations Ascent Design

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For the past 40-years, Landsat Satellites have collected Earth's continental data and enabled scientists to assess change in the Earth's landscape. The Landsat Data Continuity Mission (LDCM) is the next generation satellite supporting the Landsat science program. LDCM will fly a 16-day ground repeat cycle, Sun-synchronous, frozen orbit with a mean local time of the descending node ranging between 10:10 am and 10:15 am. LDCM is scheduled to launch in January 2013 on an Atlas 5 launch vehicle. This paper will focus on the safety and Afternoon constellation coordination considerations included in the ascent trajectory design. The ascent design presented in this paper is shown to meet all the mission requirements and to be robust to maneuver dispersions and several contingencies.

I. Introduction

For the past 40-years, Landsat Satellites have collected Earth's continental data and enabled scientists to assess change in the Earth's landscape. The Landsat Data Continuity Mission (LDCM) is the next generation satellite supporting the Landsat science program. LDCM will fly a 16-day ground repeat cycle, Sun-synchronous, frozen orbit with a mean local time of the descending node ranging between 10:10 am and 10:15 am. LDCM is scheduled to launch no earlier than January 2013 on an Atlas V launch vehicle.

The LDCM spacecraft is similar to the other spacecraft in the Landsat series. The spacecraft is equipped with two instruments: (1) the Operational Land Imager (OLI) and (2) the Thermal InfraRed Sensor (TIRS). It has a three axis stabilized attitude with the capability to image both nadir and off-nadir. The propulsion system is composed of 8 5-lbf (22 N) hydrazine thrusters operated in blowdown mode. The baseline lifetime is 5 years with enough fuel on-board for a 10-year mission assuming the current launch date.

At the end of the commissioning period, LDCM is required to be phased about half a period ahead of Landsat 7. There are different ascent trajectories dependent on the relative Landsat-7 to LDCM orbit geometry, which varies with each launch day and launch time within the 16-day repeat cycle. The ascent design has several constraints. First, it must ensure an underfly with the Landsat 7 satellite on day 40 of the commissioning period for cross-calibration of the TIRS and OLI instruments. Second, it must avoid close approaches with Afternoon and Morning constellation members that fly in this same 705-km altitude orbit. Finally, the ascent must achieve the LDCM operational orbit target which is phased with Landsat 7 such that LDCM can image the same scene that Landsat 7 imaged 8 days ago. This geometry effectively doubles the frequency of the image data available for a given geographic location. Its operational ground control box with respect to the World Reference System (WRS-2) grid is ± 2-km.

This paper will present a revised ascent trajectory design which takes into considerations additional Afternoon and Morning constellation safety guidelines as well as various contingency scenarios and corresponding mitigations.[1]

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First, the baseline design is presented with additional details on two challenges of the LDCM ascent: “705-km neighborhood” constellation safety and the 70-minute launch window. Then a selected set of dispersions and contingencies are discussed as well as any necessary mitigation strategies.

II. Nominal Ascent

The launch services are provided by the NASA Kennedy Space Center (KSC). The launch vehicle is an Atlas-V 401 rocket with a Centaur upper stage that is managed by KSC and procured from United Launch Alliance. LDCM will be launched on the Atlas-V 401 rocket Vanderberg Air Force Base into an orbit which is nominally 25-km below its operational altitude to account for 3-sigma launch vehicle dispersions. At present, a launch window of 70 minutes is allocated for any launch date. The launch vehicle will provide right ascension of the ascending node steering so that the mean local time at the descending node target is not affected by the large launch window. The launch vehicle will target mean local time of 10:11 am ± 1min. Such a large launch time window is not typical for ascending into a repeat cycle orbit and presents additional challenges which are addressed later in this section. At the end of the ascent, LDCM is inserted into a 16-day repeat cycle (233 orbits) frozen and Sun-synchronous orbit with an 8 WRS-2 path offset from Landsat 7. The LDCM mean local time of the Descending node at the end of the ascent is required to be between 10:10 am and 10:15 am.

An engineering burn of about 10 seconds is scheduled no earlier than 8 days after launch. A period of 3 days is allocated for orbit determination, burn calibration and re-planning between maneuvers. The current design has a baseline of two maneuver pairs to raise the orbit and one inclination maneuver to correct for inclination dispersions (if any). These maneuvers are designed in pairs to achieve the frozen orbit condition as quickly as possible. The first pair is used to achieve the underfly condition with Landsat 7 on Day 40. No maneuvers are allowed during the underfly period which is defined from Launch+35 days to Launch+42 days. The second pair is used to insert into the final orbit after the underfly is complete. The inclination maneuver, if needed, is scheduled as soon as possible with a lower priority with respect to the phasing maneuvers. In addition, the design will attempt to place maneuvers during the day shift whenever possible and avoid retrograde maneuvers. Finally, the entire ascent and commissioning phase is required to be completed within 90 days after launch.

The next two sections discuss in more detail two challenges of the LDCM ascent design: (1) ensuring constellation safety and (2) planning an ascent with a large launch time window.

A. **Constellation Safety Considerations**

The LDCM orbit will be screened daily by the conjunction assessment risk analysis (CARA) team from NASA GSFC Robotics Systems Protection Program (RSPP) for collision risk with any spacecraft or orbital debris. The CARA team will advise the LDCM mission as to whether an avoidance maneuver is needed which will then be planned and executed as needed throughout the LDCM mission lifetime. However, the LDCM ascent and orbit design also includes some mitigation to collision risks with the Afternoon constellation members (composed of Aqua, CALIPSO, and Cloudsat, Aura and PARASOL) and Morning constellation members (composed of Terra, LandSat 7, SAC-C and EO-1). The goal is to increase response time for the constellation members in the event of a contingency which prevents LDCM from maneuvering out of a collision. Both members of the Afternoon and Morning constellations fly an orbit with very similar period and shape. This is currently referred to as the “705-km neighborhood” as the constellation members have an equatorial height of about 705 km. Due to their similar orbit period and shape, the “705-km neighborhood” spacecraft have very small radial separation at their respective orbital planes crossing point. Consequently, collision risks between the member spacecraft are mitigated by enforcing an along-track separation at the plane crossing points. Said differently, the spacecraft do not reach their respective plane crossing point at the same epoch. The Afternoon constellation defines an Equator time crossing control for each one of its members. As long as the member spacecraft remains within this control, no collision risk exists within the constellation. Any control box violation is notified to the constellation members which then monitor and coordinate any maneuver avoidance activities. Since LDCM is a member of the Morning constellation, the collision risks with the Afternoon constellation members are mitigated by setting the lower bound of its mean local time control to 10:10 am. This ensures that LDCM will arrive at the plane crossing point with the proper time separation buffer after Aura passed the same point. In the event where LDCM cannot perform its required orbit maintenance maneuvers, there is a period of at least 14 days for the Afternoon constellation members to plan and execute an avoidance maneuver. Two collision volumes are defined about all the spacecraft in the "705-km neighborhood": (1) a monitor volume which is defined in the local radial, along-track and cross-track frame of the spacecraft as (±5 km, ±25 km, ±25 km) and (2) an action volume which is defined as (±0.5 km, ±5 km, ±5 km). When a spacecraft enters the monitor volume of another spacecraft, close coordination between the two parties involved starts and the avoidance maneuver planning is initiated as well as monitoring of the two spacecraft predicted separations. If the spacecraft is predicted to violate the action volume, immediate maneuver planning starts with the intent to execute a maneuver prior to the identified violation time. For this reason, the current "705-km neighborhood" guidelines is to design both the ascent trajectory and the routine orbit such that there is a minimum of 14 days between a contingency and a violation of any spacecraft monitor volume. This time period allows for proper monitoring, planning and coordination with the least impact to science.

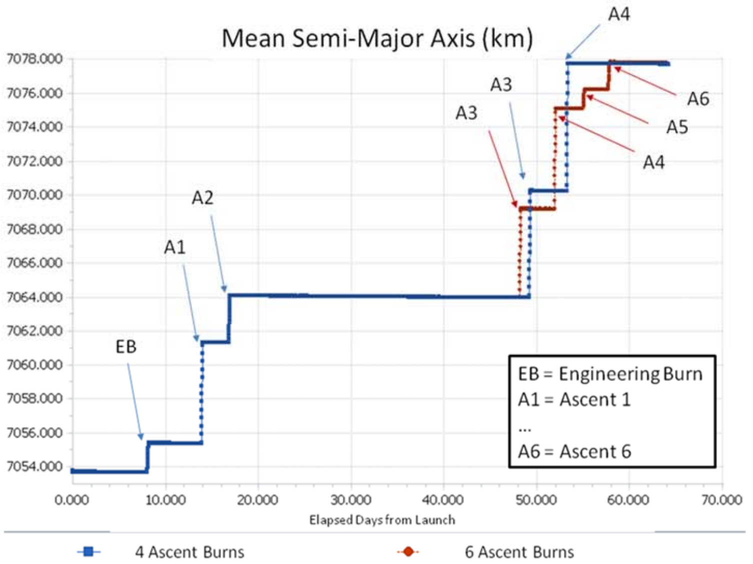

Figure 1. Mean Semi-Major Axis Evolution for a 6 ascent burns versus a 4 ascent burns scenario.

Another guideline is that the spacecraft ascending into "705-km neighborhood" does not enter the constellation fleet envelope until its last maneuver. This design ensures that most of the ascent radius is below any constellation members' radius and that only last maneuver contingencies pose a potential threat to the "705-km neighborhood" members. However, to meet the underfly constraint with Landsat 7 on Day 40, LDCM will have most of its ascent radius partially within the constellation envelope. This should not be an issue since LDCM will not be frozen until the last maneuver and therefore will have a large radial separation at the plane crossing points with the "705-km neighborhood" members throughout most of the ascent. An attempt was made to minimize the amount of incursion in the fleet envelope after the first two ascent maneuvers while waiting for the underfly activities. To do so, LDCM reduced the first two ascent maneuvers size from the initial 70% of the total DV required for the ascent to about 40% whenever possible.

A trade space between the number of burns was also performed to investigate whether 6 ascent burns was a better option than 4 ascent burns (Note that the inclination burn is not included in the total burn number. Figure 1 represents the time history of the mean semi-major axis for 4 burns ascent versus a 6 burns ascent for a nominal injection. Each burn is

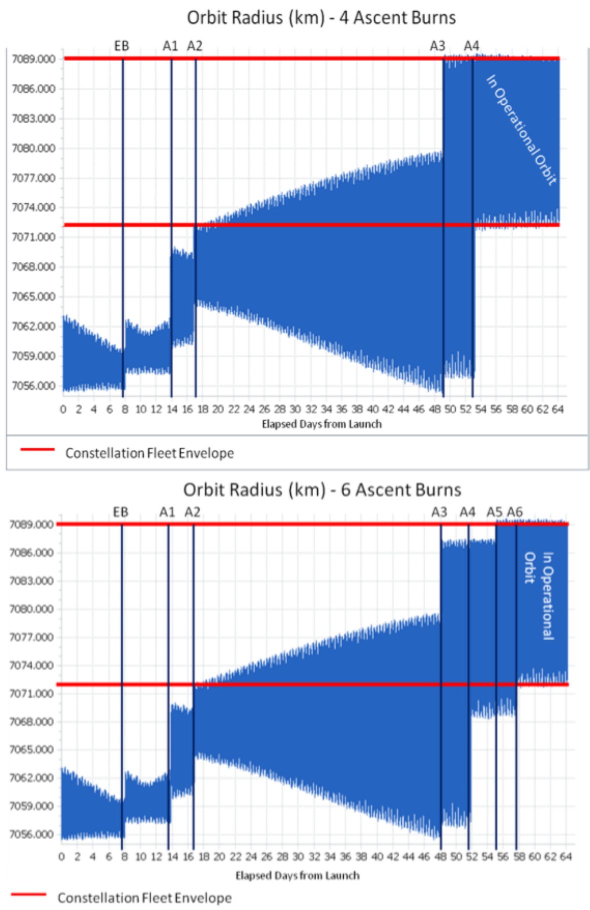

Figure 2. LDCM Orbit Radius History for a 4-burn ascent (Top) and a 6-burn ascent (Bottom) with respect to the constellation fleet envelope (shown in red).

indicated by an arrow where EB stands for Engineering Burn and A1 for Ascent burn 1, A2 for Ascent burn 2, etc. The two ascent scenarios are identical up until A3 burn since they both use A1 and A2 to achieve the underfly constraint on Day 40. The main difference is that the 4-burn scenario uses two large burns to achieve the final phasing whereas the 6-burn scenario has two large and two small burns. As expected, because of the desired 3 days in between maneuver, the 6-burn scenario lengthens the ascent phase duration as compared to the 4-burn scenario. Another important safety consideration is how much of the LDCM orbital radius is within the constellation fleet envelope. Figure shows the LDCM radius history as a function of the elapsed time from launch for the 4-burn (top figure) versus the 6-burn (bottom figure) scenario. As seen in Figure , the 4-burn scenario spends a smaller amount of time in the constellation fleet envelope (after A3) prior to reaching the final operational orbit. Other factors which drive the overall ascent safety are the mean argument of perigee and mean eccentricity evolution, and when LDCM is near a frozen orbit condition. Figure 3 shows the mean argument of perigee and mean eccentricity evolution for both scenarios. The 4-burn and 6-burn cases are represented in blue and red respectively. The green box represents the targeted frozen condition. In case of maneuver contingency, the further LDCM is from the targeted frozen conditions, the larger is the radial separation at the plane crossing point with the "705-km neighborhood" constellation members. As observed in Figure 3, the last two burns of the 6-burn ascent are very close to the frozen conditions. Consequently, if A5 or A6 are missed, LDCM would have a small radial separation at the plane crossing points. Overall, the 4-burn ascent seems nominally preferable, as it reduces the number of burns and the ascent duration. It provides the least amount of time incursion in the constellation fleet envelope while providing larger radial separations at the plane crossing points. Finally, in case the last burn fails, the length of time to perform a once around and to rephase with the final insertion target is significantly shorter which minimizes the likelihood to have to perform a retrograde maneuver to meet the maximum ascent duration of 90 days.

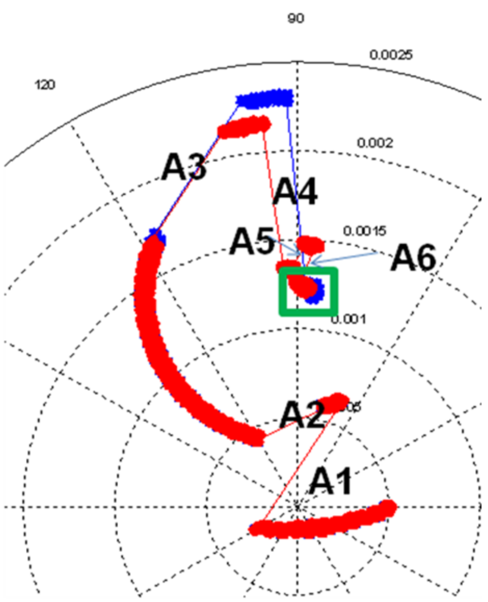

Figure 3. Mean Argument of Perigee and Mean Eccentricity Evolution for a 4-burn ascent (blue) versus a 6-burn ascent (red). The green box indicates the targeted frozen condition

Table 1 below summarizes the catch-up rates and corresponding synodic periods for a nominal 4-burn and 6-burn ascent scenario. In the 4-burn scenario, if the last burn is not performed, LDCM would wait 44 days to rephase with the LDCM target point. If this wait time is deemed too long, a small retrograde maneuver could be performed. In the 6-burn scenario, if the last burn is not performed, LDCM would have to quickly perform an orbit raising maneuver to place LDCM above its targeted semi-major axis so that it drifts back towards its insertion point. Then, it would perform a retrograde maneuver to insert into its final orbit. If LDCM could not perform an orbit raise in time (while behind Aura at the crossing point), it would have to perform a large orbit lowering maneuver to increase its catch-up rate significantly. This option is not preferred since it requires LDCM to respond within one or two weeks to the anomaly depending on the size of the last ascent burns, and has a bigger impact on the "705-km neighborhood" members and fuel consumption.

Table 1 Typical Catch-Up Rate and Synodic Period for LDCM Nominal Ascent (6-burn vs. 4-burn ascent)

	6-Burn Ascent		4-Burn Ascent	
	Catch-Up Rate (deg/day)	Synodic Period (Days)	Catch-Up Rate (deg/day)	Synodic Period (Days)
Post Separation	26.3	13.7	26.3	13.7
Post Engineering Burn	24.9	14.5	24.9	14.5
Post Burn 1	18.3	19.7	18.2	19.8
Post Burn 2	15.1	23.7	15	23.9
Post Burn 3	9.4	38.2	8.1	44

Post Burn 4	2.9	122.4	n/a	n/a
Post Burn 5	1.6	222.8	n/a	n/a

B. **Launch Time Window**

As mentioned earlier, LDCM has a uniquely large launch time window of 70 minutes. Typically, missions are inserted into orbit with a launch time window of a few minutes or less. If LDCM was similar to these missions, for each launch day in the 16-day cycle, there would be a unique relative geometry with respect to Landsat 7. Consequently, LDCM would only have 16 unique nominal ascent scenarios. Figure 4 illustrates the LDCM-Landsat 7 relative phasing at separation for the beginning of the launch time window for each day in the 16-day cycle. Landsat 7 argument of latitude will increase for each launch day in steps of 9/16 of an orbit (i.e., 202.5°) relative to the LDCM separation point. Figure 5 shows the Landsat 7- LDCM relative phasing at separation for Day 1 of the cycle for the entire launch time window. Note that Landsat 7 argument of latitude increases for each minute of launch time delay by about 3.7 deg. Consequently, LDCM will have a large number of ascent scenarios which essentially spans the full 360 degree of relative phasing at separation. Note that it is expected that each day in the cycle will share many scenarios with previous days as they have a large amount of relative phasing angle overlap. Figure 6 summarizes the different ascent solutions for a January 15, 2013 launch with launch time ranging from 0 min to 70 min of launch delay in steps of 5 min. Each ascent burn is coded by a unique color and name. The inclination burn is labeled as well as a place holder in the event of inclination dispersions from the launch vehicle.

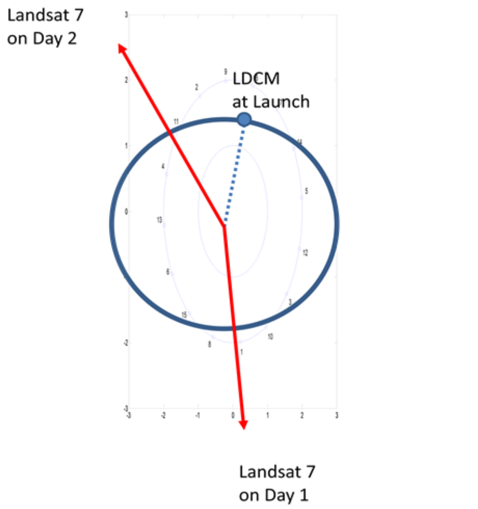

Figure 4. LDCM-Landsat 7 relative phasing for each day of the 16-day cycle at the beginning of the launch time window.

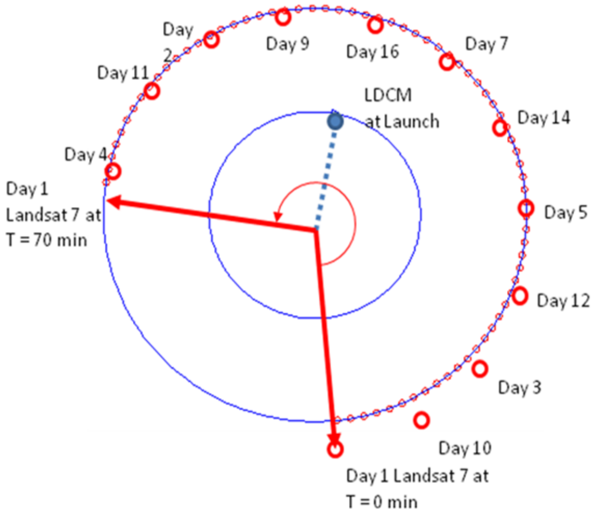

Figure 5. LDCM-Landsat 7 relative phasing for Day 1 for the entire launch time window

III. Ascent Dispersions and Contingencies

This section walks through a selected set of LDCM dispersions and contingency scenarios. First, the effects of last maneuvers dispersions on the final phasing conditions are analyzed. Note that the launch vehicle dispersions and first maneuver dispersions were discussed in a previous publication.[1] Then, various ascent contingencies will be presented as well as their impact on meeting constraints, overall safety with respect to the "705-km neighborhood" constellation, and fuel consumption.

A. Dispersions Scenarios

The current estimated burn dispersion values are 10% (3-sigma) for the burn magnitude and 10° (3-sigma) for the burn direction. However, it is expected that by the time the last maneuver is executed, maneuver calibration activities would have reduced these values significantly. For this paper, a 2% (3-sigma) and 5° (3-sigma) for the burn magnitude and direction are assumed for the last maneuver execution error. In the event of last maneuver dispersions, LDCM may perform a trim maneuver to either raise or lower the semi-major axis to remain within its operational ground-track error control box of ± 2-km. Note that the actual required control box is ± 5-km. This analysis will determine how soon LDCM will violate the operational and required control box under maneuver dispersions and whether there is sufficient time to plan and execute a trim maneuver. Figure 7 represents the historical ground track error at the descending node following the last ascent maneuvers for five different scenarios: (1) no maneuver dispersions, (2) -2% magnitude error and -5° yaw error, (3) -2% magnitude error and +5° yaw error, (4) +2% magnitude error and -5° yaw error, and (5)) +2% magnitude error and +5° yaw error. As seen in Figure 7, LDCM reaches the boundary of the ±2 km box in 1 to 2 days from the last ascent maneuver. The minimum time to plan a trim maneuver is two orbits, so LDCM should be able to correct for the post-calibration, 3-sigma dispersions and remain within the required control box.

	Launch Time Window (min from the center of the window)														
L+Days	-35	-30	-25	-20	-15	-10	-5	0	5	10	15	20	25	30	35
8	EB	EB	EB	EB	EB	EB	EB	EB	EB	EB	EB	EB	EB	EB	EB
9															
10															
11			A1		INC	A1	A1	INC	INC	INC	INC	INC	INC	INC	INC
12	A1			A1											
13								A1							
14		A1	A2			A2	A2								
15	A2			A2	A1										
16		A2						A2							
17			INC			INC	INC		A1						
18	INC			INC	A2										
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Figure 6. Ascent Scenarios for a launch on January 15, 2013 for a launch time ranging from 0 to 70 minutes in steps of 5 minutes.

B. Contingency Scenarios

The main contingencies considered in this paper are delays in the ascent and missed maneuvers due commissioning schedule changes, conjunction mitigations or spacecraft contingencies. Currently, the engineering burn is scheduled to occur no earlier than 8 days after launch. However, there could be delays in the spacecraft commissioning which would require the engineering burn to occur later. For this analysis, a week delay is assumed for the engineering burn. However, the underfly is still scheduled to occur on Day 40 after launch. The ascent was re-designed to accommodate the ascent delay and met all the required constraints. Figure 8 shows the mean semi-major axis history for the nominal case (engineering burn on day 8, shown in blue) versus the delayed ascent case (engineering burn on day 15, in red). The re-designed ascent has a larger Ascent 1 (A1) and Ascent 2 (A2) burn to account for the engineering burn delay and still meet the LandSat-7 underfly constraint. However, the overall ascent duration has only increased by 3 days. This is due to the smaller catch-up rate post-underfly (since A1 and A2 were larger). In addition, the incursion in the constellation fleet envelope occurs slightly sooner with the delayed ascent. However, the amount of additional incursion is fairly small.

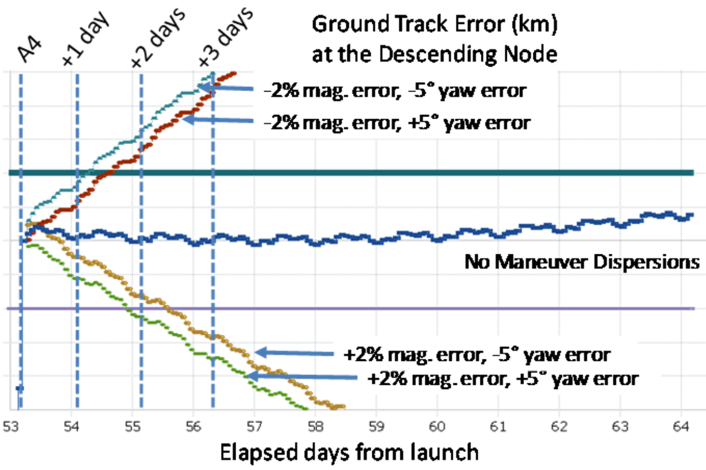

Figure 7. Ground Track Error (km) History for Different Maneuver Execution Errors for Ascent 4 Burn.

Another contingency presented in this paper is missed maneuvers. This can be thought of as a delayed maneuver from the original plan. In this paper, it is assumed that another maneuver can occur as early as 3 days after the missed maneuver time. Only the first ascent maneuver and last ascent maneuver contingencies are discussed here. If the first ascent maneuver is missed, the ascent needs to be re-planned such that the underfly constraint is met on Day 40. This case is identical to the delayed engineering burn case presented above. The new ascent will have larger A1 and A2 burns to slow the spacecraft catch-up rate to the underfly target point. The longer the delay between the missed maneuver time and the next maneuver, the larger the maneuvers will need to be.

In the case of a missed final burn, two different ascent alternatives are available. LDCM can wait a full synodic period to attempt again its final insertion or if this option violates the maximum 90 days commissioning duration, a retrograde maneuver can be performed to decrease the synodic period, followed by another orbit raising maneuver to insert into its final orbit.

Figure 8. Mean Semi-Major Axis Evolution: Engineering Burn on Day 8 vs. Engineering Burn on Day 15.

Figure 9 shows the evolution of the synodic period as LDCM semi-major axis increase towards its operational value. Based on this figure, the proper retrograde maneuver magnitude is chosen so that one synodic period later, LDCM is phased with its insertion target again so it can perform its final insertion burn. The typical ascent duration ranges from 48 days to 56 days. Consequently, a synodic period ranging from 34 days to 42 days would ensure that the 90 days maximum ascent duration constraint is met. For example, if the synodic period before the last maneuver is 44 days and the last maneuver is not executed on day 53 of the ascent as originally scheduled, a retrograde maneuver needs to be performed to lower the semi-major axis by about 2 km. Note that as explained earlier in this paper, there should be no safety concern with the "705-km neighborhood" constellation when waiting the additional month to finalize LDCM's insertion into its operational orbit.

Figure 9. Synodic period (days) as a function of the mean semi-major axis difference from the final operational orbit (km).

IV. Conclusions

In this paper, a revised LDCM ascent trajectory design was presented which satisfies the mission requirements while mitigating collision with the "705-km neighborhood" constellation members. The design is also flexible such as to accommodate the large launch time window. All nominal ascent scenarios use about 18 kg of fuel or 13 m/s of Delta-V. Finally, it was shown that in the presence of maneuver dispersions and for the selected contingency scenarios, the LDCM ascent can be quickly re-planned to meet its original objectives. In case of large inclination dispersions, an inclination maneuver will be executed as soon as possible with a lower priority with respect to the ascent burns.

References

[1]Mann, L.M., Nicholson A.M., Good S.M. and Woodard M.A., "Landsat Data Continuity Mission (LDCM) Ascent and Operational Orbit Design", *22nd AAS/AIAA Space Flight Mechanics Meeting*, Charleston, South Carolina, January 29, 2012-February 2nd, 2012, AAS12-254.