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LANDSAT DATA CONTINUITY MISSION (LDCM) ASCENT AND OPERATIONAL ORBIT 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. This paper presents the preliminary ascent trajectory design from the injection orbit to its final operational orbit. The initial four burn ascent design is shown to satisfy all the LDCM mission goals and requirement and to allow for adequate flexibility in re-planning the ascent.

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.

This paper will present the preliminary ascent trajectory design from the injection orbit to its final operational orbit. There are 16 different ascent trajectories dependent on the relative Landsat-7 to LDCM orbit geometry, one for each launch day 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. 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.

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This paper will discuss the overall method used to design the different ascent trajectories and will provide a preliminary discussion on the effect of launch injection dispersions and possible maneuver contingencies.

LDCM MISSION OVERVIEW

The Landsat Data Continuity Mission (LDCM) is a collaboration between NASA and the U.S. Geological Survey (USGS). It will provide measurements of the Earth's terrestrial and polar regions and add on to the 38-year long Landsat land imaging data set.[1]

NASA’s LDCM responsibilities include development of the instruments, spacecraft, launch vehicle, implementation of the USGS-funded Mission Operations Element, and mission on-orbit verification. NASA is acquiring most elements of the LDCM space segment from industry with Goddard Space Flight Center (GSFC) acting as the mission integrator and leading mission systems engineering. USGS is providing the ground data processing systems. Upon completion of on-orbit verification, USGS will lead post-launch calibration activities, satellite operations, data product generation and data archiving.

The LDCM Ground System includes all of the ground-based assets needed to operate the LDCM observatory. The primary components of the Ground System are the Mission Operations Element (MOE), Collection Activity Planning Element (CAPE), Ground Network Element (GNE), and the Data Processing and Archive System (DPAS).

The MOE is being provided by the Hammers Corporation. The MOE provides capability for command and control, mission planning and scheduling, long-term trending and analysis, and flight dynamics analysis. The overall activity planning for the mission is divided between the MOE and CAPE. The GNE is comprised of two nodes located at Fairbanks, Alaska and Sioux Falls, SD. Each node in the GNE includes a ground station that is capable of receiving LDCM X-band data. Additionally, each station provides complete S-band uplink and downlink capabilities. The DPAS includes those functions related to ingesting, archiving, calibration, processing, and distribution of LDCM data and data products. It also includes the portal to the user community. The Ground System, other than the MOE, is developed by USGS.

LDCM ASCENT OVERVIEW

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 and is managed by KSC and procured from United Launch Alliance. LDCM will be launched on the Atlas-V 401 rocket into an orbit which is nominally 25-km below its operational altitude. At present, a launch window of 50 minutes is allocated for any launch date. The start (t= 0 min), middle (t= 25 min) and end (t= 50 min) of the launch window is referred to as ‘Open’, ‘Middle’ and ‘Close’ in this paper. 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. At the end of the ascent campaign, the LDCM spacecraft needs to be in its mission orbit with the requirements summarized in Table 1.

Table 1. LDCM Mission Orbit Requirements.

Parameter	Value
Equatorial Altitude	705 +/- 1 km altitude
Inclination	98.2 +/- 0.15 degree
Eccentricity	Less than or equal to 0.00125
Mean Local Time – Descending Node (DN)	10:00 am +/- 15 minutes
Ground Trace Error	+/- 5 km cross track at DN, WRS2 grid
Repeat Cycle	16 days (233 orbits)

An engineering orbit adjust maneuver is scheduled to occur on Day 8. A minimum of 3 days between maneuvers is desired to allow for orbit determination, maneuver reconstruction, calibration and re-planning activities. Consequently, the first ascent orbital adjust maneuver cannot occur any earlier than Day 11. In addition, the design will attempt to place maneuvers during the day shift whenever possible.

The preliminary nominal ascent design includes two pairs of maneuvers. These maneuvers are designed in pairs such as to achieve the frozen orbit condition as quickly as possible. The first maneuver is used to achieve the desired under fly geometry with Landsat 7. No maneuver shall occur from 38 to 42 days from launch where the underfly occurs. The second maneuver is designed to reach the final operational target phasing. When possible, the third and fourth maneuvers are nominally 3 days and 6 days respectively from the second maneuver to minimize the ascent duration. The first maneuver pair represents about 70% of the DV required to raise LDCM to its final orbit altitude. This ensures a slower catch-up rate at the end of the ascent which then increases the team's response time in case of a maneuver contingency. This is important when coordinating avoidance maneuvers with the members of the Morning (composed of Terra, Landsat 7, SAC-C and EO-1) and Afternoon (composed of Aqua, CALIPSO, Cloudsat and Aura) constellations. The final maneuver magnitudes are slightly modified to provide the desired ground track error evolution.

An injection mean local time of the descending node value of 10:11 a.m. is selected to ensure that LDCM will stay within the allotted range in spite of the launch vehicle dispersions. A minimum value of 10:10 a.m. provides for adequate buffer time between LDCM and the Afternoon constellation members at the Northern and Southern orbit crossing points.

NOMINAL ASCENT

This section discusses the 16 different nominal ascent sequences if LDCM were to launch at the opening of its launch window. Table 2 lists the injection state for a launch date of January 25th, 2013 at the middle of the launch window. This launch date is referred to as Day 1 of the 16-Day cycle.

Table 2. LDCM Mission Injection State (Launch Window Open) in MJ2000 Earth Equator Cartesian.

Epoch	X (km)	Y(km)	Z(km)	VX (km/s)	VY (km/s)	VZ (km/s)
Jan 25 2013 19:23:44.334	812.416	1439.89	6859.92	1.1768	-7.2855	1.3922

Since the overall concept is similar for different launch times, this paper only includes the open window nominal ascent profiles. For each launch day in the 16-day cycle, Landsat 7 and LDCM have different relative angle geometries as illustrated in Figure 1. At separation for the open launch window, LDCM has an argument of latitude of about 79°. 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 LDCM separation. Figure 1 shows the position of Landsat 7 (in the outer circle) for each day in the 16-day cycle where Day 1 is chosen to be January 25th, 2013. LDCM separation position (labeled in the inner circle) has an initial catch-up rate of about 26° per day. Since LDCM cannot perform any maneuver until Day 8 and its first ascent until Day 11, in most ascent cases, it will have caught up and passed Landsat 7 once before any ascent burn are performed. In addition, LDCM needs to underfly Landsat 7 starting on Day 40 of the ascent. These two constraints on the ascent operations enforces in most cases two underfly of Landsat 7 and lengthen the ascent duration.

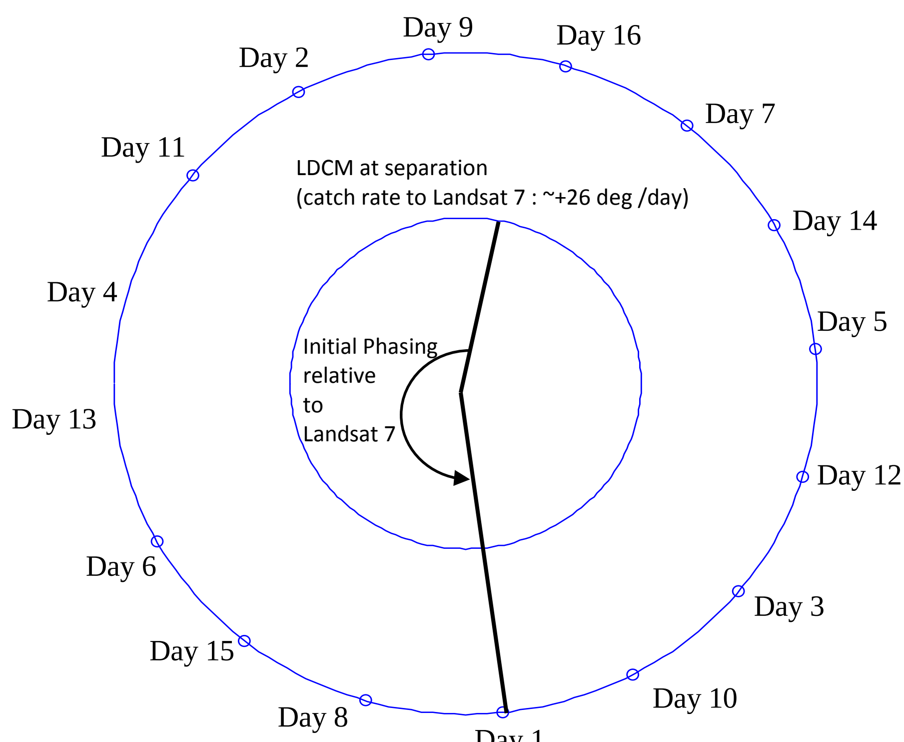

Figure 1. Relative Phasing between LDCM (at Separation) and Landsat 7 for the 16 days in the cycle.

Table 3 below summarizes the catch-up rates and corresponding synodic periods for a typical four burn nominal ascent where the first two burns magnitude represent about 70% of the entire ascent required delta-V. At the end of the ascent sequence, the catch-up rate is slow. In the event of an anomaly during the last burn which would have LDCM go past its desired phasing location, it would take LDCM about 250 days (not including drag effects) to re-phase without any lowering maneuvers.

Table 3. Typical Catch-Up Rate and Synodic Period for LDCM Nominal Ascent

	Catch-Up Rate (deg/day)	Synodic Period (Days)
Post Separation	26.31	13.68
Post Engineering Burn	25.87	13.94
Post Burn 1	13.87	25.94
Post Burn 2	10.97	32.80
Post Burn 3	1.44	249.12

The ascent profiles were simulated in the FreeFlyer® software, a commercial off-the-shelf (COTS) spacecraft Mission Design tool developed by a.i. solutions, Inc. Both the trajectory propagation and maneuver were modeled using the parameters listed in Table 4. The propulsion system is composed of 8 5-lbf (22 N) hydrazine thrusters operated in blowdown mode. Individual thruster body locations and thruster performance data were configured in FreeFlyer.

Table 4. LDCM Orbit Propagation and Maneuver Modeling Parameters

Parameters	**Value**
Propagator	Runge-Kutta 8(9)
Propagator Stepsize	60 seconds
Central Body	JGM-2 30x30
Non-central Bodies	Sun, Moon
Drag Area	21.83 m^2
Drag Model	Jacchia-Roberts (Schatten Predictions, May 2011, +2-sigma)
SRP Area	34.71 m^2
C_D	2.2
C_R	1.5
Dry Mass	2631.4 kg
Propellant Mass	453.6 kg
Initial Pressure	350 psia
Initial Temperature	20.9 deg C

Table 5 summarizes the 16 different nominal ascent sequences starting on January 25th, 2013. The nominal ascent campaign lasts about 60 days. The first ascent orbit adjust maneuver location varies from Day 11 to Day 37 to achieve the underfly geometry for different phasing angle with Landsat 7 at injection. However, orbit adjust maneuvers 2, 3 and 4 have fairly consistent elapsed mission times from launch. Indeed, all 16 ascents trajectories must be phased with Landsat 7 at Day 38 for the underfly with comparable catch-up rates and elapsed time between burns. Consequently, after the underfly, it is expected that, overall, the ascent profiles should be very similar.

Table 5. Nominal Ascent for the 16 Days of the Cycle starting on January 25th, 2013 (Day 1) Launch Date (Open Window)

Day in the Cycle	Launch Date	Engineering Burn (Days fr. Launch)	Ascent Burn 1 (Days fr. Launch)	Ascent Burn 2 (Days fr. Launch)	Ascent Burn 3 (Days fr. Launch)	Ascent Burn 4 (Days fr. Launch)
1	January 25, 2013	8	28	49	52	60
2	January 26, 2013	8	16	50	53	56
3	January 27, 2013	8	31	50	53	56
4	January 28, 2013	8	20	50	53	56
5	January 29, 2013	8	35	49	52	56
6	January 30, 2013	8	23	51	54	59
7	January 31, 2013	8	13	53	56	59
8	February 01, 2013	8	27	50	53	56
9	February 02, 2013	8	14	50	53	56
10	February 03, 2013	8	30	50	53	56
11	February 04, 2013	8	18	51	53	57
12	February 05, 2013	8	33	49	52	56
13	February 06, 2013	8	22	51	53	56
14	February 07, 2013	8	37	47	50	57
15	February 08, 2013	8	25	50	53	56
16	February 09, 2013	8	11	50	53	56

Figure 2 shows the mean semi-major axis evolution for a nominal ascent (Day1, open window). Ascent maneuvers 1 and 2 are sufficiently ahead of the underfly period, which is desired so as to not interrupt science activities during that time.

Figure 3 shows the history of the mean argument of perigee (AOP) as a function of the mean eccentricity (ECC). At the end of the ascent the AOP and ECC are within the frozen point specified for the mission (indicated by the orange box).

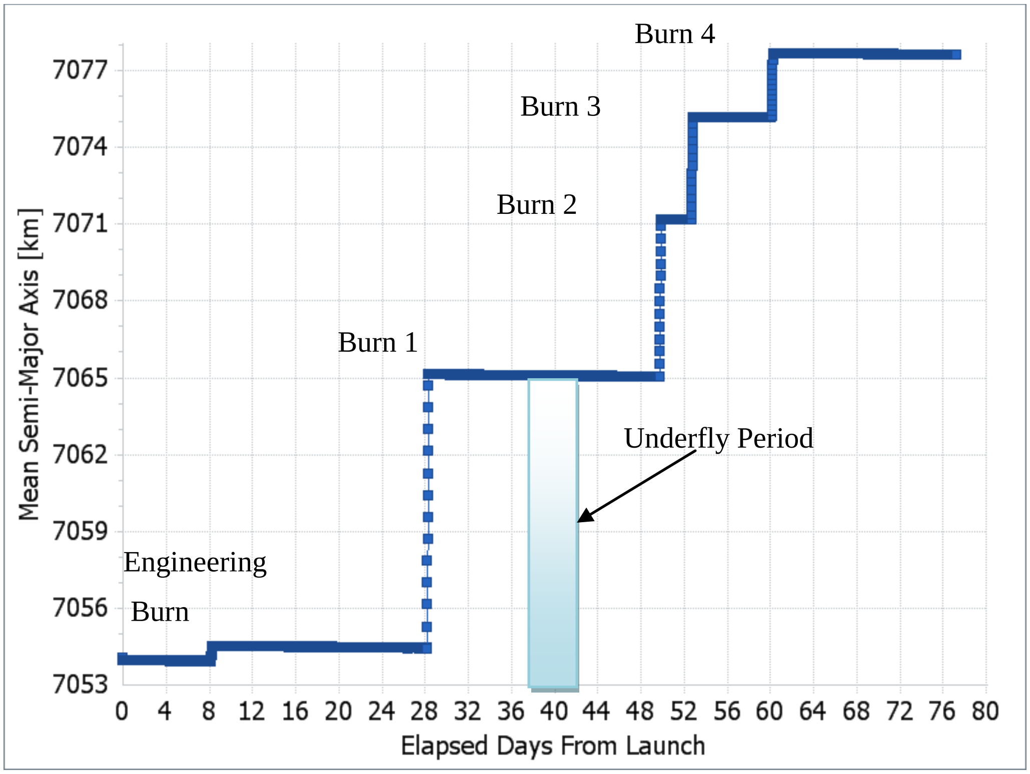

Figure 2. Mean Semi-Major Axis History for Day 1, Open Window, Nominal.

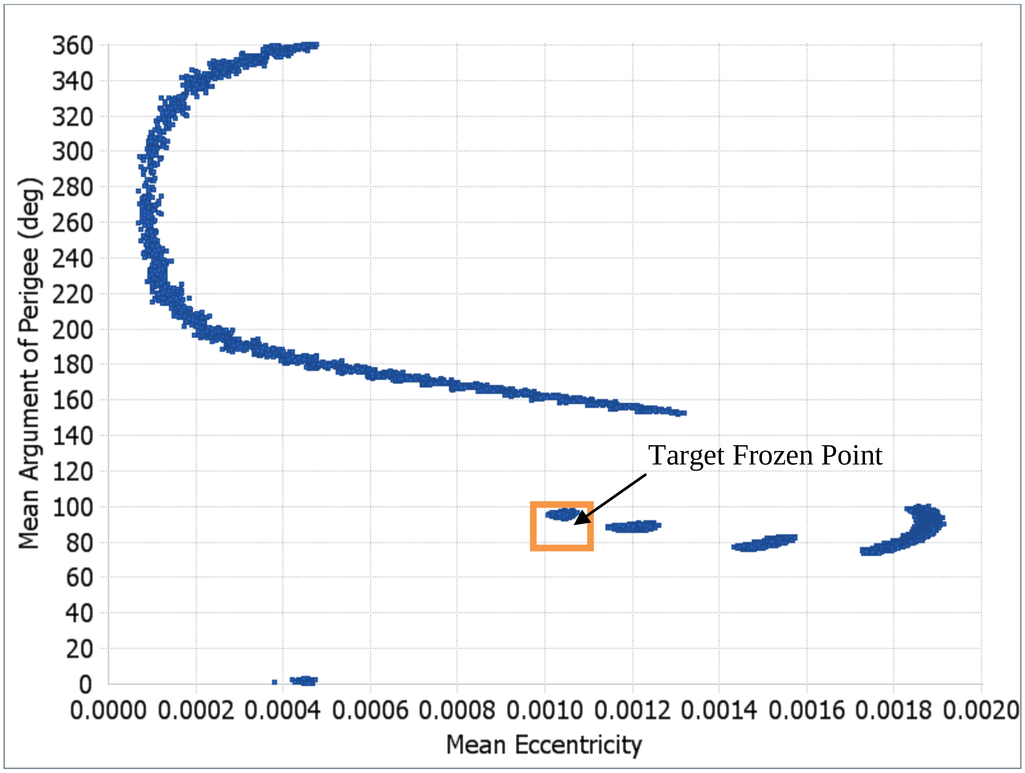

Figure 3. Mean Argument of Perigee vs. Mean Eccentricity History for Day 1, Open Window, Nominal.

Figure 4 represents the evolution of the mean local time at the descending node. The LDCM mean local time must be between 10:10 and 10:15 am. The lower bound is set to ensure appropriate reaction time for other 705-km neighborhood constellations such as the afternoon constellation in case of an anomaly preventing LDCM from performing any maneuvers. Indeed, because the Afternoon and Morning constellations operate at essentially the same orbit period and orbit eccentricity/argument of perigee, their orbit intersects at about the same on-orbit position with nearly no radial separation.[2] The upper bound of the mean local time is a science requirement. It is desired that LDCM mean local time is as close as possible to Landsat 7's, which is predicted to be about 10:06 am around LDCM launch time. Consequently, LDCM will maintain a mean local time control box near 10:10 am with an inclination maneuver once a year.

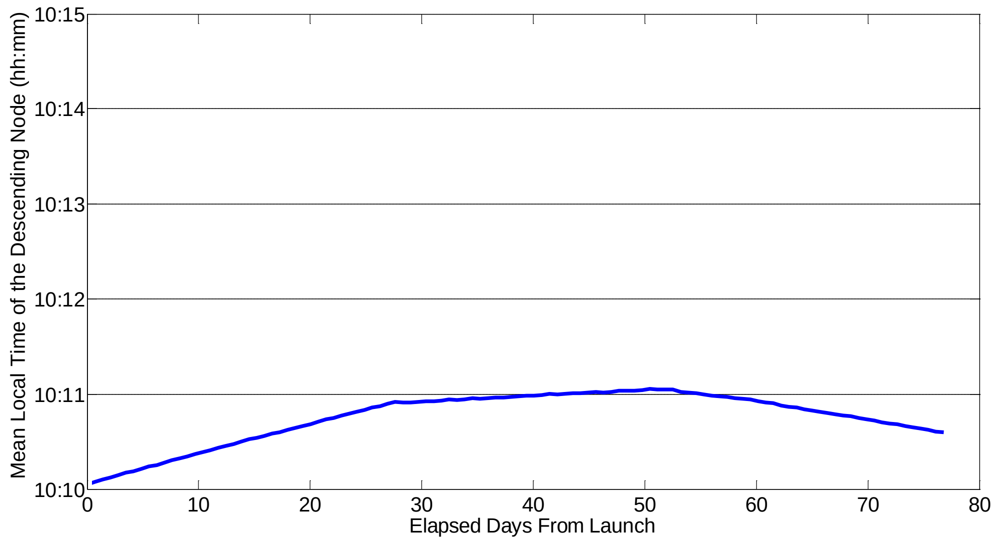

Figure 4. Mean Local Time of the Descending Node History for Day 1, Open Window, Nominal.

Figure 5 represents the history of the error in longitude at the descending node with respect to the WRS-2 grid. This is also referred to as ground-track error (GTE) and is given in unit of kilometers. When in its operational orbit, LDCM is required to stay within ±5 km of the WRS-2 grid for its mission lifetime. An operational GTE box of ±2 km (shown as the red and blue lines in Figure 5) is chosen such as to never violate the required box. LDCM will perform routine drag-make up maneuvers (i.e., semi-major increase) to maintain the specified operational GTE box.

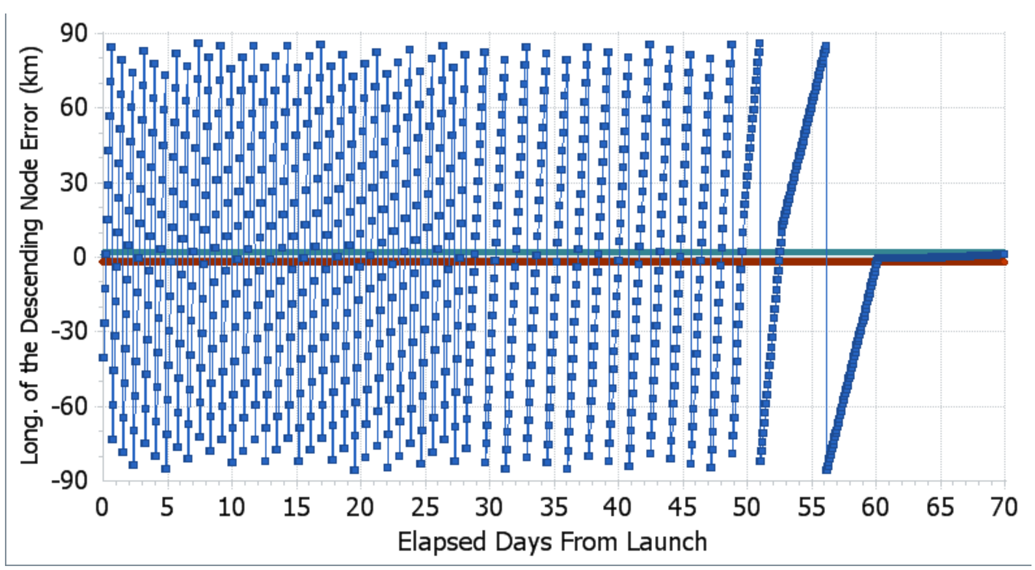

Figure 5. Longitude of the Descending Node Error History (with respect to the WRS-2 grid).

Another important parameter for the LDCM ascent design is where in its 50-min launch window it is injected. Indeed, Landsat 7 has an orbital period of about 98 min so in 50 min it will be about 180 deg away in argument of latitude from where it was at the opening of the window. Said differently, Landsat 7 moves about 3.7 deg per minute of launch window delay. The large difference in initial phasing angle throughout the launch window means a different ascent profile for a given day across the launch window. Table 6 gives an example of the expected variability of the ascent profile for a given launch day and shows the different ascent profiles for the open, middle and close window. Table 6 also lists the amount of delta-V, propellant mass consumed and duration of each ascent burn. Note that the launch vehicle will provide right ascension of the ascending node (RAAN) steering which is important to ensure that LDCM's mean local time at injection is not affected by the large launch time variations. As seen in Table 6, the ascent profiles are drastically different for a given launch day. If LDCM is inserted at the close of its window, the first ascent burn occurs early on Day 14 and the burn magnitudes were modified to ensure the underfly on Day 38. If inserted in the middle of its window, the first ascent burn occurs on Day 36. Overall, the total duration and propellant mass consumed are comparable. Note that this table only shows examples of feasible ascent plans but that many other options exist by varying the burns magnitude and time.

Table 6. Nominal Ascent for January 25th, 2013 (Day 1) Launch Date for different time in the Launch Window (Open, Middle and Close).

Launch Window		**Open**	**Middle**	**Close**
Ascent Burn 1	Days	28	36	14
	Dt (sec)	63.8	54.7	66.8
	DV (m/s)	5.7	4.9	5.9
	Dm (kg)	8	7	8.5
Ascent Burn 2	Days	49	49	50
	Dt (sec)	37.5	46.1	19.6
	DV (m/s)	3.3	4.0	1.7
	Dm (kg)	4.7	5.7	2.4
Ascent Burn 3	Days	52	52	53
	Dt (sec)	24.8	20.1	47
	DV (m/s)	2.1	1.7	4.0
	Dm (kg)	3	2.4	5.8
Ascent Burn 4	Days	60	55	56
	Dt (sec)	15.7	19.9	8.1
	DV (m/s)	1.3	1.7	0.7
	Dm (kg)	1.9	2.4	0.9

DISPERSED ASCENT

In this section, the effect of dispersions on the ascent plans, both launch vehicle injection and maneuver execution, are presented.

Launch Vehicle Injection Dispersions

LDCM will be launched on an Atlas V 401 with the expected following performances listed in Table 7.

Table 7. Expected Launch Vehicle Dispersions (at first descending node)

	Nominal Value	Expected Errors
Semi-Major Axis (km)	7063.14	±3.88 (3-sigma)
Eccentricity	0	+ 0.000188 (3-sigma)
Inclination (°)	98.22	± 0.0543 (3-sigma)
Mean Local Time (Descending Node)	10:11 AM	± 1min

A set of four dispersed scenarios were extracted from ULA's preliminary launch vehicle performance assessment. These scenarios are selected to provide combinations of 3-sigma levels dispersions in both semi-major axis and inclination.

Table 8. Dispersed Scenarios Studied (at first descending node)

Scenario #	Semi-Major Axis (km)		Eccentricity		Inclination (°)	
	Value	Offset from Nominal	Value	Offset from Nominal	Value	Offset from Nominal
Nominal	7063.14	0	0	0	98.22	0
1	7066.02	2.88	0.000152	0.000152	98.154	-0.066
2	7058.45	-4.69	0.000223	0.000223	98.219	-0.001
3	7059.49	-3.65	0.000258	0.000258	98.265	0.045
4	7065.60	+2.47	0.000149	0.000149	98.283	0.063

Table 9 summarizes the four ascent burns for the nominal case as well as the four dispersion cases studied. The first orbital adjustment moves to day 13-15 for a +3-sigma error in semi-major axis and day 23-26 for a -3-sigma error respectively. As expected, if LDCM is injected with a higher initial semi-major axis, its corresponding catch-up rate will be slower potentially resulting in slightly longer ascent duration (between 57-65 days). Depending on the semi-major axis dispersions, LDCM required ascent propellant mass will vary from the nominal ascent between -1.9 to +3.89 kg for the scenario considered.

Table 9. Dispersed Ascent Scenarios for January 25th, 2013 (Day 1) Launch Date for Middle Launch Window.

Dispersion Case		Nominal	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Ascent Burn 1	Days	36	15	23	26	13
	Dt (sec)	54.7	59.16	81.11	78.02	57.6
	DV (m/s)	4.9	5.29	7.24	6.97	5.15
	Dm (kg)	7	7.59	10.35	9.96	7.39
Ascent Burn 2	Days	49	52	48	48	51
	Dt (sec)	46.1	15.90	37.51	38.81	14.12
	DV (m/s)	4.0	1.41	3.27	3.38	1.25
	Dm (kg)	5.7	2.00	4.65	4.82	1.78
Ascent Burn 3	Days	52	54	51	51	54
	Dt (sec)	20.1	41.40	37.33	31.55	47.56
	DV (m/s)	1.7	3.65	3.2	2.71	4.14
	Dm (kg)	2.4	5.14	4.55	3.85	5.91
Ascent Burn 4	Days	55	65	54	56	57
	Dt (sec)	19.9	6.65	15.28	16.78	7.53
	DV (m/s)	1.7	0.57	1.3	1.43	0.65
	Dm (kg)	2.4	0.81	1.84	2.02	0.92
Total	DV (m/s)	12.30	10.92	15.01	14.49	11.19
	Dm(kg)	17.50	15.54	21.39	20.65	16.00

For each dispersed case presented in Table 9, no propellant was expended to correct for the inclination dispersions. Figure 6 shows the mean local time of the descending node history for the nominal ascent and the four dispersed scenarios studied. Among the selected scenarios, only Scenario 1 requires an early inclination maneuver so as to not violate the lower bound of the mean local time requirement. The inclination maneuver can be performed on Day 11 since the first ascent burn is not scheduled until Day 15. A maneuver of about 6 m/s is needed to correct the inclination dispersion which corresponds to approximately 10 kg of propellant.

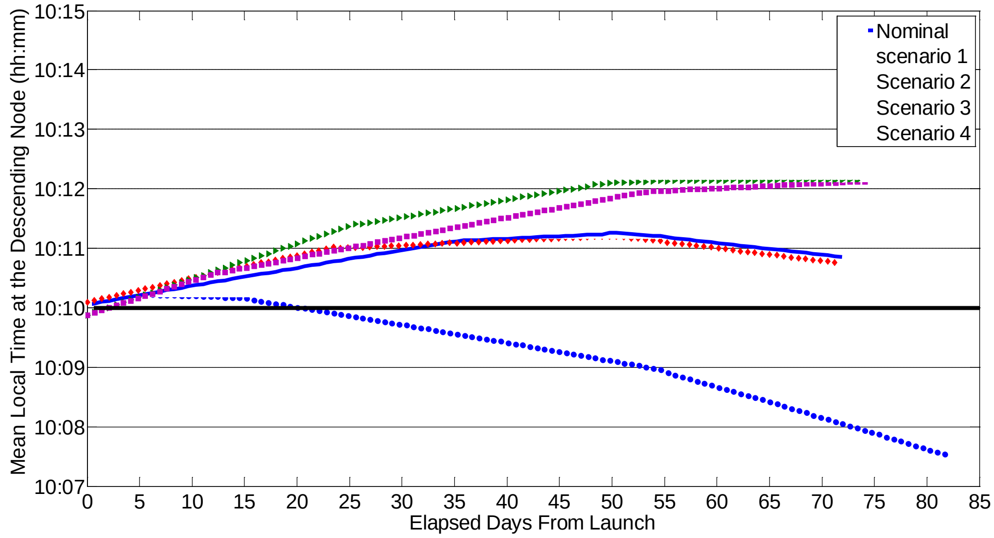

Figure 6. Mean Local Time of the Descending Node (hh:mm) for the different Launch Vehicle Dispersion States Studied.

Ascent Burn 1 Maneuver dispersions

The main focus of this subsection is to evaluate how much the first maneuver dispersions affect the underfly geometry and whether a trim maneuver is needed prior to the underfly. This is of a concern since the first maneuver is fairly large and does not benefit from previous calibration information. If the first burn is close to the underfly period, the maneuver execution error will not have a significant effect on the underfly geometry. Consequently, Day 16 is selected for this analysis as a worst case scenario since its first burn occurs on Day 11 (the earliest possible time). The drift rate error due to the maneuver execution dispersion will build up over a total of 27 days which is the maximum possible for the LDCM ascent. Figure 7 shows the WRS-2 path difference between LDCM and Landsat 7 during the underfly period (from Launch + 38 days to Launch + 42 days) for different Ascent Burn 1 maneuver execution error levels. For the nominal case, the underfly (i.e. path difference of zero) occurs between day 39 and day 41. When applying ± 1% error on the first ascent burn, the underfly time is shifted 4-5 orbits earlier or later depending on the direction of the error. An error level ± 5% will shift the underfly time between day 38 and day 40 for a cold burn performance and between day 40 and 42 for a hot burn performance respectively.

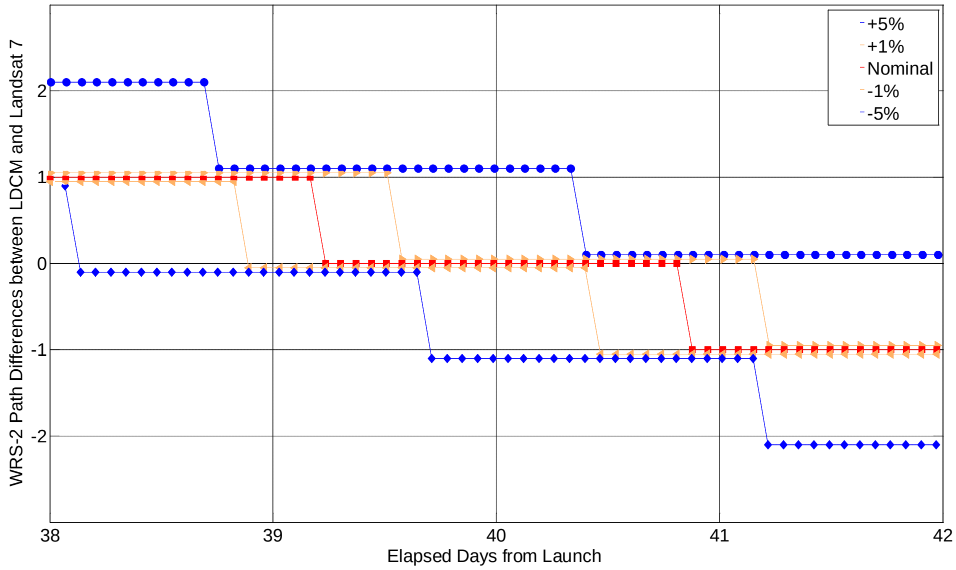

Figure 7. WRS-2 Path Differences between LDCM and Landsat 7 during the Underfly Period for Various Burn 1 Maneuver Dispersion Level.

CONCLUSION

This paper presented a preliminary ascent trajectory design from the injection orbit to its final operational orbit for the LDCM mission. The initial four burn ascent design was shown to satisfy all the LDCM mission goals and requirement and allow for adequate flexibility in re-planning the ascent. However, large initial maneuver dispersions could offset the underfly geometry such that the underfly is no longer centered on Day 40 of the ascent. In addition, it was shown that an inclination maneuver may be needed early on to correct for large inclination dispersion from the launch vehicle. Consequently, future ascent design will investigate a 6-burn ascent with an early inclination maneuver as a place-holder. These additional burns allow for smaller initial burn less sensitive to maneuver dispersions as well as the ability to correct for early maneuver dispersion and achieve the proper underfly geometry at the desired time.

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[2] Strategy for Mitigating Collisions Between Landsat5 and the Afternoon Constellation, J. Levi, E. Palmer 2011 AAS / AIAA Astrodynamics Specialist Conference, Girdwood, AK, 31 JUL – 4 AUG 2011