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Continuously Improving Parametric Modeling with Historical Data on the ICESat-2 Mission

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Abstract— **This paper delves into the details of the Joint Confidence Level (JCL) process performed for the Ice, Cloud, and Land Elevation Satellite (ICESat)-2 mission and how past performance was incorporated into subsequent JCL models to enable the project to continuously analyze potential slips to their launch readiness date (LRD). One year prior to the mission Preliminary Review (mPDR), the JCL model development process began. The first model was well received at the mPDR, held on October 10, 2012, and the input received by the Standing Review Board was incorporated into the model for the official data drop for key decision point (KDP)-C.**

The 70% JCL results of the October 2012 mPDR model forecast an LRD of February 2017 and associated cost of $830M. This result in 2012 immediately highlighted potential challenges with the project-planned LRD of July 2016.

The year following the mPDR, the project had sustained a one-year slip in the LRD due to problematic systems engineering requirement issues which impacted all project subsystems. This slip moved the project planned LRD from July 2016 to July 2017, an additional 5 months beyond the 2012 model's 70% JCL result for the LRD of February 2017. As the project was quickly approaching the mission Critical Design Review (mCDR), the need for reliable JCL results increased significantly. The project held discussions on the JCL modeling process and focused on the input uncertainty distributions. Specifically, to identify the uncertainty distributions that the 2012 mPDR model would have needed to produce a 70% LRD result of July 2017. This led the project to compare multiple uncertainty distributions, and ultimately spurred the project to utilize uncertainty distributions that incorporated project past performance and historical data to forecast potential LRD slips.

The revised results, created in 2014 and utilizing the new uncertainty distributions, showed that with 70% confidence, the ICESat-2 mission would launch in August 2018 with a cost of $1,044M. Today, ICESat-2 is scheduled to launch on September 15, 2018 with a project management (PM) agreement value of $1,056M. This illustrates how a JCL model can be continuously improved to produce valuable results for a project, even in cases of LRD delays.

The primary reason for the ICESat-2 LRD delay is due to a laser failure on the primary instrument. Laser failure was one of the highest risk and uncertainty drivers within the JCL model. The project placed the most risk in this area of the model, and the model further identified the laser as the top risk driver and contributor to the LRD result. This further illustrates how a JCL can be used to predict and quantify possible issues on new technology missions.

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1. INTRODUCTION

This paper describes the development of the ICESat-2 JCL between cost and schedule. The first in-house advocate JCL model was developed in October 2012 as was required for KDP=C.

After sustaining a one-year launch slip in 2013, the project (the ICESat-2 project) had a need for an updated model with reliable results. Finalized in February 2014, the new model incorporated historical data derived from the one-year launch slip. The results of the February 2014 model will then be compared to the current schedule, as of July 2018.

The topics will include an overview of the models, the assumptions made, and the rationale for applying various uncertainties and probabilities.

2. BACKGROUND

Providing a brief overview of the mission, ICESat-2 is a follow-on to the first ICESat mission which launched in 2003 and deorbited in 2010.

ICESat-2 is designed and intended to continue the measurements of sea ice and ice sheets, as well as cloud and land measurements. ICESat-2 is a single instrument mission. That instrument is the Advanced Topographic Laser Altimeter System (ATLAS) and includes a new technology laser. ATLAS was designed, built and tested in-house at the Goddard Space Flight Center (GSFC). ATLAS represents a majority of the total mission life cycle development cost as well as a majority of the project's technical and developmental risk.

3. MODEL OVERVIEW & ASSUMPTIONS

The software used to develop the JCL models was Joint Analysis of Cost and Schedule (JACS) which is an add-in to Microsoft (MS) Project. The model includes resources and risks and is identical to the ICESat-2 project Integrated Master Schedule (IMS) in terms of durations and logic.

The project ensured that the cost loading was timely, transparent, traceable, and defendable. The costs were decomposed to time-dependent and time-independent costs. Finally, spending contours were assigned to the costs.

The model contains all risks, threats, and liens. The risks were only placed on the costs to go. The risk probability of occurrence and costs/schedule consequences were identified. For correlation, we evaluated the nominal values used for space projects, modeled accordingly, and determined a value of 0.5 should be used.

The models included launch vehicle costs and all costs to go, including Phase E, in order to have a full life cycle cost (LCC) comparison between our baseline plan and the model results.

The JCL development process was a very collaborative effort, in which contributions from everyone made for a successful JCL. All team members provided input into the JCL, the project worked extensively with the Standing Review Board, and we received much assistance from the NASA Cost Analysis Division.

4. MODEL COST & ANALYSIS SCHEDULE DEVELOPMENT

4.1 Cost Development

The model consists of development costs up through and including launch. Costs to date, funded schedule reserve, on orbit checkout, and Phase E costs are included in the results, but are not affected by risks or uncertainty.

For the 2012 mPDR model, actual costs through June 30, 2012 are added to the final JCL results to calculate the total ICESat-2 JCL cost (including Pre-Phase A costs).

The ICESat-2 JCL allocated available budget of $452M across schedule elements in phases B, C, and D.

Figure 1 shows the trace from the mission LCC to the JCL value.

	Value
Total LCC (incl. Pre-Phase A)	$806M
Less Post Launch (JCL finish date)	$69M
Less Cost-to-Date (6/30/12)	$195M
Total B/C/D Cost	$542M
Less Project UFE (Reserve)	$90M
JCL Input Value	$452M

Figure 1. Trace from Life-Cycle Cost (LCC) to the JCL value

Within the analysis model, hammock tasks (schedule summary tasks used to encompass the duration of all work within an area of interest) were created to support cost loading. Then, spending contour profiles were assigned to all costs for how we predicted the cost spending to occur. The subsystem product development leads (PDLs) were interviewed for their assessment of these spending contours, as well as their input on the uncertainty levels to assign (low, medium or high).

Finally, for each hammock task activity, time-independent and time-dependent costs were identified, which translate into approximately 34 schedule activities which were cost loaded.

The time-dependent costs scaled with activity durations, meaning, as activity durations and finish dates push out, due to risk impacts, the time-dependent cost will vary and most likely increase. Conversely, time-independent costs are associated with a specific activity, but do not scale with duration.

Figure 2 provides a high-level, rolled-up view of the entire model, as well as providing insight into the level in which costs were loaded into the analysis schedule.

	Proj-WBS	UID		Start	Finish	Dur	%	Total Slack	JC Co	JACS TI Task Cost	JAC Thrs % Like	JACS TI Cost Uncertainty	JACS TI pendin Contou	JACS TD Task Cost	JACS TD Cost Uncertainty	JACS TD Spendin Contour	JACS Duration Uncertainty
0		0	ICESat II Master Schedule	3/30/2012	1/15/2016	889d	0%	0d	0	$0.00	0			$0.00			
1	883151	9201	ICESat-2 Total Mission	6/30/2012	1/15/2016	889d	0%	0d	0	$0.00	0			$0.00			
2	883151.01	5496	Management	6/30/2012	1/15/2016	889d	0%	0d	0	$0.00	0			$0.00			
3	883151.01	9080	Management (Hammock)	6/30/2012	1/15/2016	889d	0%	0d	1	$2,234.50	0	Tri*(95,100,105,10,90)	Flat	$19,363.90	Tri*(95,100,105,10,90)	Flat	
28	883151.02	5510	Systems Engineering (GSFC)	6/30/2012	1/15/2016	889d	0%	0d	0	$0.00	0			$0.00			
29	883151.02	9117	Systems Engineering (Hammock)	6/30/2012	1/14/2016	888d	0%	0d	1	$2,100.00	0	Tri*(95,100,105,10,90)	Flat	$7,937.20	Tri*(95,100,105,10,90)	Flat	
40	883151.03	5526	Safety and Mission Assurance	6/30/2012	1/15/2016	889d	0%	0d	0	$0.00	0			$0.00			
41	883151.03	9120	Safety and Mission Assurance (Hammock)	6/30/2012	1/15/2016	889d	0%	0d	1	$0.00	0	Tri*(95,100,105,10,90)	Flat	$7,122.50	Tri*(95,100,105,10,90)	Flat	
57	883151.05	5524	Science Payload (GSFC ATLAS Instrument Development)	6/30/2012	2/13/2015	658d	0%	0d	0	$0.00	0			$0.00			
58	883151.05.01	8794	ATLAS GSFC Instrument Management (Hammock)	6/30/2012	2/13/2015	658d	0%	231d	1	$28.00	0	Tri*(95,100,105,10,90)	Flat	$4,353.80	Tri*(95,100,105,10,90)	Flat	
61	883151.05.02	8795	Instrument Systems Engineering	6/30/2012	2/13/2015	658d	0%	231d	1	$0.00	0	Tri*(95,100,105,10,90)	Flat	$7,023.90	Tri*(95,100,105,10,90)	Flat	
64	883151.05.05	8959	Instrument Development	6/30/2012	2/13/2015	658d	0%	0d	0	$0.00	0			$0.00			
65	883151.05.05.01	8797	Optics (Hammock)	6/30/2012	11/13/2013	345d	0%	544d	1	$3,919.00	0	Tri*(95,105,110,10,90)	Turtle	$10,098.70	Tri*(95,100,110,10,90)	nt Loaded	
69	883151.05.05.02	8798	Mechanisms	6/30/2012	6/26/2013	249d	0%	640d	1	$1,984.00	0	Tri*(95,105,110,10,90)	t Loaded	$1,762.00	Tri*(95,100,105,10,90)	nt Loaded	
73		9330	Primary Structure	6/30/2012	6/13/2013	240d	0%	649d	1	$3,058.00	0	Tri*(95,100,105,10,90)	Turtle	$1,689.00	Tri*(95,100,105,10,90)	nt Loaded	
77	883151.05.05.03	8799	Laser Transmitter Integrated Product (through SN2 & SN3) (Hammock)	6/30/2012	12/18/2013	369d	0%	520d	1	$1,176.00	0	Tri*(95,105,110,10,90)	Front Loaded	$20,047.00	Tri*(95,100,105,10,90)	Front Loaded	
81	883151.05.05.04	8800	Laser Reference System (LRS) (Hammock)	6/30/2012	11/14/2013	346d	0%	543d	1	$1,700.00	0	Tri*(95,100,105,10,90)	t Loaded	$2,400.00	Tri*(95,100,105,10,90)	nt Loaded	
85	883151.05.05.05	8801	Thermal (Hammock)	6/30/2012	8/30/2013	295d	0%	594d	1	$2,415.00	0	Tri*(95,100,105,10,90)	t Loaded	$1,363.00	Tri*(95,100,105,10,90)	Flat	
89	883151.05.05.06	8802	MEB (Hammock)	6/30/2012	10/1/2013	316d	0%	573d	1	$5,267.00	0	Tri*(95,105,110,10,90)	t Loaded	$11,952.90	Tri*(95,100,105,10,90)	nt Loaded	
95	883151.05.05.07	8803	Flight Software (Hammock)	6/30/2012	7/15/2013	261d	0%	628d	1	$245.00	0	Tri*(95,100,105,10,90)	Flat	$2,128.00	Tri*(95,100,105,10,90)	Flat	
99	883151.05.05.08	8804	Detectors (Hammock)	6/30/2012	9/10/2013	301d	0%	588d	1	$4,491.00	0	Tri*(95,105,110,10,90)	t Loaded	$4,359.00	Tri*(95,100,105,10,90)	nt Loaded	
103	883151.05.05.10	8806	BCE (Hammock)	6/30/2012	11/20/2013	350d	0%	539d	1	$1,240.00	0	Tri*(95,100,105,10,90)	Flat	$1,523.00	Tri*(95,100,105,10,90)	Flat	
107	883151.05.05.11	8807	Flight Science Algorithms (Hammock)	6/30/2012	6/28/2013	251d	0%	638d	1	$0.00	0			$1,057.00	Tri*(95,100,105,10,90)	Flat	
111	883151.05.05.12	8808	Power Systems (Hammock)	6/30/2012	9/18/2013	307d	0%	582d	1	$2,919.00	0	Tri*(95,105,110,10,90)	t Loaded	$2,194.00	Tri*(95,100,105,10,90)	nt Loaded	
115	883151.05.05.16	8809	Detector Array Assembly (Hammock)	6/30/2012	1/2/2014	378d	0%	511d	1	$643.00	0	Tri*(95,105,110,10,90)	t Loaded	$1,019.00	Tri*(95,100,105,10,90)	nt Loaded	
121	883151.05.05.17	8810	Optical Filter Assembly (Hammock)	6/30/2012	12/13/2013	366d	0%	523d	1	$1,826.00	0	Tri*(95,105,110,10,90)	t Loaded	$1,780.00	Tri*(95,100,105,10,90)	arly Peak	
125	883151.05.05.18	9333	Materials Eng (Hammock)	6/30/2012	2/24/2014	413d	0%	476d	1	$0.00	0			$509.00	Tri*(95,100,105,10,90)	Flat	
129	883151.05.05.19	9204	ODS (Hammock)	6/30/2012	12/7/2012	111d	0%	778d	1	$52.00	0	Tri*(95,100,105,10,90)	Flat	$378.00	Tri*(95,100,105,10,90)	Flat	
133	883151.05.05.21	9205	FLATLAS (Hammock)	6/30/2012	5/31/2013	231d	0%	658d	1	$31.00	0	Tri*(95,100,105,10,90)	Flat	$146.00	Tri*(95,100,105,10,90)	Flat	
137	883151.05.05.22	9208	Harness (Hammock)	6/30/2012	4/16/2013	199d	0%	690d	1	$232.00	0	Tri*(95,105,110,10,90)	rly Peak	$883.00	Tri*(95,100,105,10,90)	Late Peak	
141	883151.05.05.23	9220	Parts Mgmt	6/30/2012	2/25/2013	163d	0%	726d	1	$1,080.00	0	Tri*(95,100,105,10,90)	Flat	$0.00			
145	883151.05.05.24	9211	TAMS (Hammock)	6/30/2012	10/1/2013	316d	0%	573d	1	$242.00	0	Tri*(95,100,105,10,90)	t Loaded	$645.00	Tri*(95,100,105,10,90)	arly Peak	
149	883151.05.05.25	9214	Optical Fibers (Hammock)	6/30/2012	5/14/2013	219d	0%	670d	1	$27.00	0	Tri*(95,105,110,10,90)	Flat	$700.00	Tri*(95,100,105,10,90)	Flat	
153	883151.05.05.26	9217	AMCS (Hammock)	6/30/2012	10/1/2013	316d	0%	573d	1	$50.00	0	Tri*(95,100,105,10,90)	Flat	$1,376.00	Tri*(95,100,105,10,90)	Flat	
157	883151.05.05.09	8811	ATLAS I&T	6/3/2013	2/13/2015	427d	0%	64d	0	$0.00	0			$0.00			
158	883151.05.05.09	9123	ATLAS I&T (Hammock)	6/14/2013	2/13/2015	418d	0%	231d	1	$1,933.00	0	Tri*(95,105,110,10,90)	ate Peak	$23,616.00	Tri*(95,100,110,10,90)	Late Peak	
189	883151.06	755	Spacecraft Development	6/30/2012	10/28/2014	585d	0%	0d	0	$0.00	0			$0.00			
190	883151.06	8793	Spacecraft Management (OSC TD Work)	6/30/2012	10/28/2014	585d	0%	0d	0	$0.00	0			$0.00			
191	883151.06	9132	Spacecraft Management (OSC TD Work) (Hamm	6/30/2012	10/28/2014	585d	0%	0d	1	$95,468.90	0	Tri*(95,105,110,10,90)	Turtle	$0.00			
202	883151.06	8836	Spacecraft Systems Engineering (LOE) (In House TD Work)	6/30/2012	10/28/2014	585d	0%	0d	0	$0.00	0			$0.00			
203	883151.06	9129	Spacecraft Systems Engineering (LOE) (In House TD Work) (Hammock)	6/30/2012	10/28/2014	585d	0%	0d	1	$0.00	0			$2,057.00	Tri*(95,100,105,10,90)	Turtle	
215	883151.08	5678	Launch Vehicle (Procurement)	6/30/2012	10/9/2015	824d	0%	0d	0	$0.00	0			$0.00			

Figure 2. Mapping of Cost Elements to Schedule Activity

4.2 Analysis Schedule Development

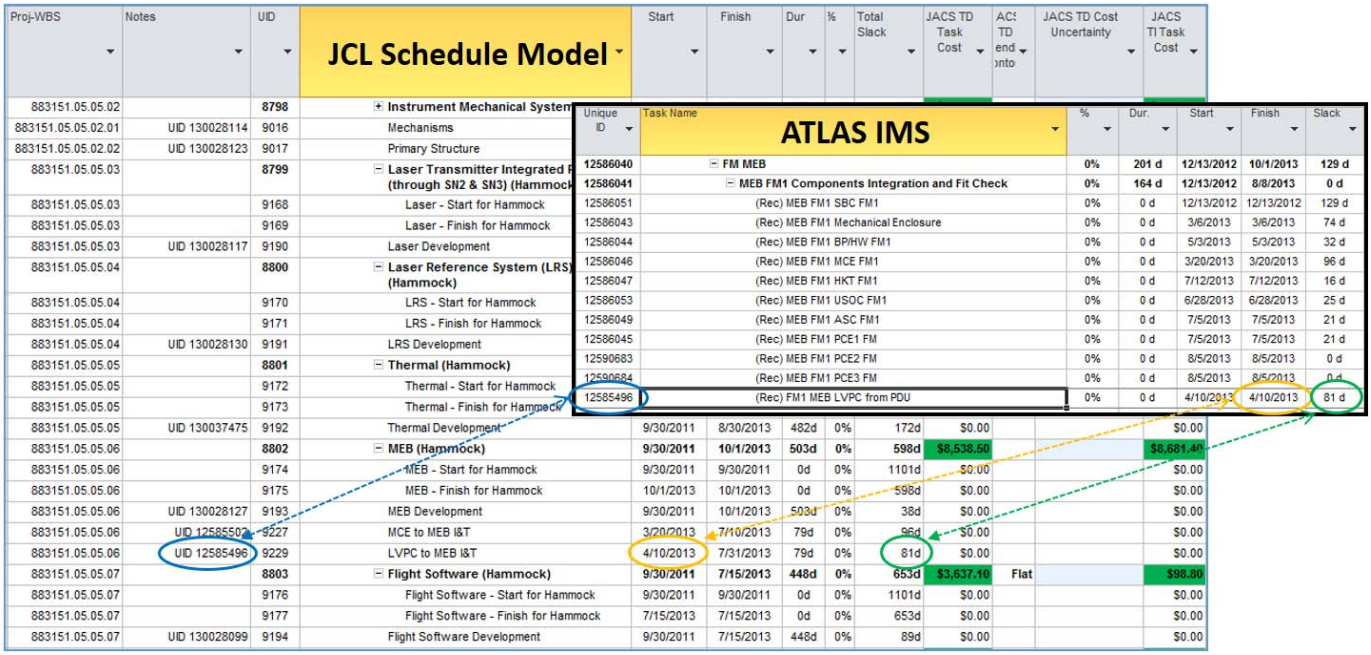
The following section will capture the pertinent steps involved with the development of the JCL Analysis Schedule.

The ICESat-2 IMS is a fully detailed schedule, from start to finish, for each subsystem. The Analysis Schedule was built directly from the IMS detail. The Analysis Schedule was constructed at a level of detail that effectively supports cost loading and risk integration. Moreover, the project allowed for the risks to dictate the level of detail within the Analysis Schedule. The durations used in the Analysis Schedule encompass the duration of the entire development of their respective subsystems. Approximately 300 activities are included in the model.

All pertinent IMS hand-offs between subsystems are reflected within the JCL model. Use of the unique identifier (UID) within the ICESat-2 IMS ensures the model accurately reflects the finish dates and slack within the IMS, as can be seen in Figure 3. Great attention to detail ensured correct slack for each of the subsystem deliveries was correctly captured within the model. The Analysis Schedule was set up with "as-soon-as-possible" tasks with no constraints.

The activities in the mPDR model began on June 30, 2012 and continued through the LRD at the time, July 2016.

All schedule margin activities were identified in the Analysis Schedule, but were removed from the model by assigning zero days of duration.



Proj-WBS	Notes	UID	JCL Schedule Model	Start	Finish	Dur	%	Total Slack	JACS TD Task Cost	JACS TD Cost Uncertainty	JACS TI Task Cost
883151.05.05.02		8798	Instrument Mechanical System								
883151.05.05.02.01	UID 130028114	9016	Mechanisms								
883151.05.05.02.02	UID 130028123	9017	Primary Structure								
883151.05.05.03		8799	Laser Transmitter Integrated (through SN2 & SN3) (Hammock)								
883151.05.05.03		9168	Laser - Start for Hammock								
883151.05.05.03		9169	Laser - Finish for Hammock								
883151.05.05.03	UID 130028117	9190	Laser Development								
883151.05.05.04		8800	Laser Reference System (LRS) (Hammock)								
883151.05.05.04		9170	LRS - Start for Hammock								
883151.05.05.04		9171	LRS - Finish for Hammock								
883151.05.05.04	UID 130028130	9191	LRS Development								
883151.05.05.05		8801	Thermal (Hammock)								
883151.05.05.05		9172	Thermal - Start for Hammock								
883151.05.05.05		9173	Thermal - Finish for Hammock								
883151.05.05.05	UID 130037475	9192	Thermal Development	9/30/2011	8/30/2013	482d	0%	172d	$0.00		$0.00
883151.05.05.06		8802	MEB (Hammock)	9/30/2011	10/1/2013	503d	0%	598d	$8,538.50		$8,681.40
883151.05.05.06		9174	MEB - Start for Hammock	9/30/2011	9/30/2011	0d	0%	1101d	$0.00		$0.00
883151.05.05.06		9175	MEB - Finish for Hammock	10/1/2013	10/1/2013	0d	0%	598d	$0.00		$0.00
883151.05.05.06	UID 130028127	9193	MEB Development	9/30/2011	10/1/2013	503d	0%	38d	$0.00		$0.00
883151.05.05.06	UID 12585502	9227	MCE to MEB I&T	3/20/2013	7/10/2013	79d	0%	96d	$0.00		$0.00
883151.05.05.06	UID 12585496	9229	LVPC to MEB I&T	4/10/2013	7/31/2013	79d	0%	81d	$0.00		$0.00
883151.05.05.07		8803	Flight Software (Hammock)	9/30/2011	7/15/2013	448d	0%	653d	$3,637.10	Flat	$98.80
883151.05.05.07		9176	Flight Software - Start for Hammock	9/30/2011	9/30/2011	0d	0%	1101d	$0.00		$0.00
883151.05.05.07		9177	Flight Software - Finish for Hammock	7/15/2013	7/15/2013	0d	0%	653d	$0.00		$0.00
883151.05.05.07	UID 130028099	9194	Flight Software Development	9/30/2011	7/15/2013	448d	0%	89d	$0.00		$0.00

Unique ID	Task Name	%	Dur.	Start	Finish	Slack
	ATLAS IMS					
12586040	FM MEB	0%	201 d	12/13/2012	10/1/2013	129 d
12586041	MEB FM1 Components Integration and Fit Check	0%	164 d	12/13/2012	8/8/2013	0 d
12586051	(Rec) MEB FM1 SBC FM1	0%	0 d	12/13/2012	12/13/2012	129 d
12586043	(Rec) MEB FM1 Mechanical Enclosure	0%	0 d	3/6/2013	3/6/2013	74 d
12586044	(Rec) MEB FM1 BP/HW FM1	0%	0 d	5/3/2013	5/3/2013	32 d
12586046	(Rec) MEB FM1 MCE FM1	0%	0 d	3/20/2013	3/20/2013	96 d
12586047	(Rec) MEB FM1 HKT FM1	0%	0 d	7/12/2013	7/12/2013	16 d
12586053	(Rec) MEB FM1 USOC FM1	0%	0 d	6/28/2013	6/28/2013	25 d
12586049	(Rec) MEB FM1 ASC FM1	0%	0 d	7/5/2013	7/5/2013	21 d
12586045	(Rec) MEB FM1 PCE1 FM	0%	0 d	7/5/2013	7/5/2013	21 d
12590683	(Rec) MEB FM1 PCE2 FM	0%	0 d	8/5/2013	8/5/2013	0 d
12590684	(Rec) MEB FM1 PCE3 FM	0%	0 d	8/5/2013	8/5/2013	0 d
12585496	(Rec) FM1 MEB LVPC from PDU	0%	0 d	4/10/2013	4/10/2013	81 d

Figure 3. Analysis Schedule Development from IMS

5. Risk Register & Threats

The ICESat-2 Risk Register is included within the analysis schedule, in a dedicated section beneath the model. Comprised of approximately 70 risks, this list was taken straight from the ICESat-2 risk database. These risks were linked into the analysis schedule as activities using predecessor and successor relationships, but with zero days' duration.

The subsystem PDLs were interviewed for their assessment of the risks, which were quantified in terms of likelihood of occurrence, as well as cost and schedule consequences. Schedule and cost impacts were provided as three-point estimates: low, medium, or high.

The PDLs were asked to characterize the total risk impact beyond the current time-dependent costs (overtime, double shifts, additional parts and materials, additional tests, etc.).

Inputs and assumptions were reviewed by management and the systems engineering team for consistency and accuracy.

Risks were quantified in terms of likelihood of occurrence (%), schedule consequence (work days), and cost consequence ($). Project issues and liens, not associated with a discrete risk, were included in the model as additional entries in the risk register or accounted for by applying greater uncertainty to those subsystems which would be impacted, if the risk were realized.

Post-mitigation "Performance risks" were included in the model, but had no impact to cost or schedule.

Figure 4 provides a visual of a small subset of the Risk Register, as it was in 2012 for the mPDR. These top risks focused on the ATLAS hardware and development schedules:

2012 Top Risks

Rank/ Trend	ID	Title	Approach
1 ↔	ICESat-2 -Risk-INSTR-0080	Laser Diode Reliability	Mitigate
2 ↔	ICESat-2 -Risk-MISSION-0042	Daily Data Volume Modeling Uncertainty	Mitigate
3 ↔	ICESat-2-Risk-SPACE-0107	Fault Management Process on Spacecraft	Mitigate
4 ↔	ICESat-2-Risk-SPACE-0108	Spacecraft Component Supplier Performance	Mitigate
5 ↔	ICESat-2-Risk-INSTR-0043	Uncorrectable On-Orbit Alignment Elements	Watch
6 ↔	ICESat-2 -Risk-INSTR-0079	Optical Damage in Frequency Doubling Crystal	Mitigate
7 ↔	ICESat-2-Risk-INSTR-0100	Flight Laser Build in Parallel with qualification laser Life Testing	Mitigate
8 ↓	ICESat-2-Risk-MISSION-0002	Undefined SC to Launch Vehicle; Technical Interface Uncertainties	Mitigate

Figure 4. 2012 mPDR Top Risks from the Risk Register

6. Estimating Cost & Schedule Uncertainty

6.1 Cost Uncertainty

All estimated costs have some level of uncertainty. The cost uncertainties are further broken down based on the time-dependent and time-independent nature of the costs. Time dependent costs scale with activity durations, whereas time independent costs are associated with a specific activity and do not scale with duration.

The project broke down uncertainty into three levels:

- Low (green) 10%
- Medium (yellow) 20%
- High (red) 30%

The table in Figure 5 shows how we quantified uncertainty ranges: Low, Medium, and High.

Cost Uncertainty (Time Dependent Costs)			
	Green (95%, 100% 105% variance)	Yellow (98%, 110%, 120% variance)	Red (100 %, 120%, 135% variance)
Cost Confidence	Confident in meeting the required cost cap. Have ample margin and overall a low cost risk.	Little confidence in meeting the required cost cap. Have little margin and overall a risky cost estimate.	Not very confident in meeting the required cost cap. No margin and overall a high risk cost estimate.

Cost Uncertainty (Time Independent Costs)			
	Green (90%, 100% 110% variance)	Yellow (95%, 100%, 135% variance)	Red (99 %, 100%, 155% variance)
Cost Confidence	Confident in meeting the required cost cap. Have ample margin and overall a low cost risk.	Little confidence in meeting the required cost cap. Have little margin and overall a risky cost estimate.	Not very confident in meeting the required cost cap. No margin and overall a high risk cost estimate.

Figure 5. 2012 mPDR Cost Uncertainties

These cost uncertainty ratings were based on the opinion of the PDLs and task complexity. These uncertainties were reviewed by the management team to ensure uncertainty ratings were applied uniformly and consistently across the mission elements. Finally, these cost uncertainty distributions are in-line with historical JCL models.

6.2 Duration Uncertainty

All planned durations have some level of uncertainty.

Similar to cost uncertainty, we developed these three levels of duration uncertainty and applied them to the subsystems according to discussions with the PDLs. We did not load duration uncertainty to level-of-effort (LOE) tasks.

Similarly to the cost uncertainty, we developed these three levels of duration uncertainty, which can be seen in Figure 6, and applied them to the subsystems according to discussions with the PDLs.

Duration Uncertainty			
	Green (90-100-110)	Yellow (95-100-135)	Red (99-100-155)
Schedule Confidence	Confident in meeting the required delivery date. Have ample margin and overall a low risk schedule.	Little confidence in meeting the required delivery date. Have little margin and overall a risky schedule.	Not very confident in meeting the required delivery date. No margin and overall a high risk schedule.

Figure 6. 2012 mPDR Duration Uncertainties

In developing the uncertainties, we reviewed data from the NASA Cost Analysis Data Requirement (CADRe), referenced other Goddard projects, reviewed literature on developing uncertainty ranges, and utilized input received from members of the NASA Cost Analysis Division.

The project made sure not to apply excessive duration uncertainty to tasks that already had an associated risk that impacted duration. The uncertainty applied to tasks were broadly based on the complexity of the work, slack assumptions, and confidence in meeting the plan.

6.3 Uncertainty Definition Development

In an attempt to allow the 2012 mPDR model to be as conservative as possible, with respect to high uncertainty ratings, the project held multiple discussions regarding uncertainty distributions.

Figure 7 is an example of standard triangular distribution for a high uncertainty, showing the 30% chance of either falling above or below the nominal value.

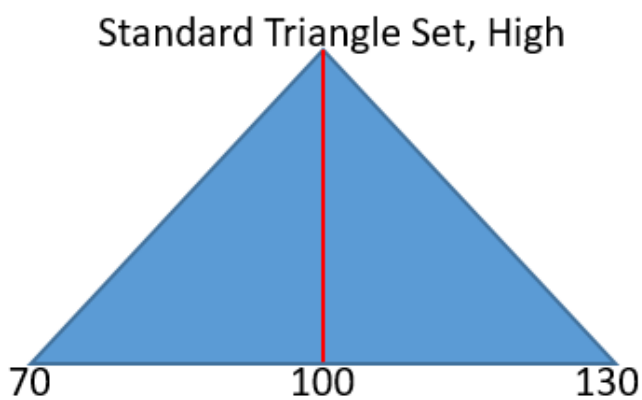


Figure 7. Standard Triangular Distribution for High Uncertainty

However, the project realized that this high uncertainty distribution allows for elements to have a greater probability of having lower values (70%) than that of the low uncertainty set (90%), as can be seen in Figure 8.

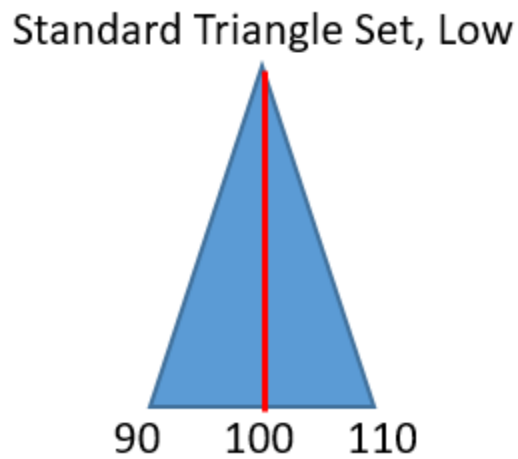


Figure 8. Standard Triangular Distribution for Low Uncertainty

The low end of the high uncertainty is 70% versus the 90% on the low end of the low uncertainty.

With that in mind, a conservative approach was taken where the project implemented new conservative distributions. Here, in Figure 9, is an example of the new high uncertainty triangular distribution (for both duration and TI cost U).

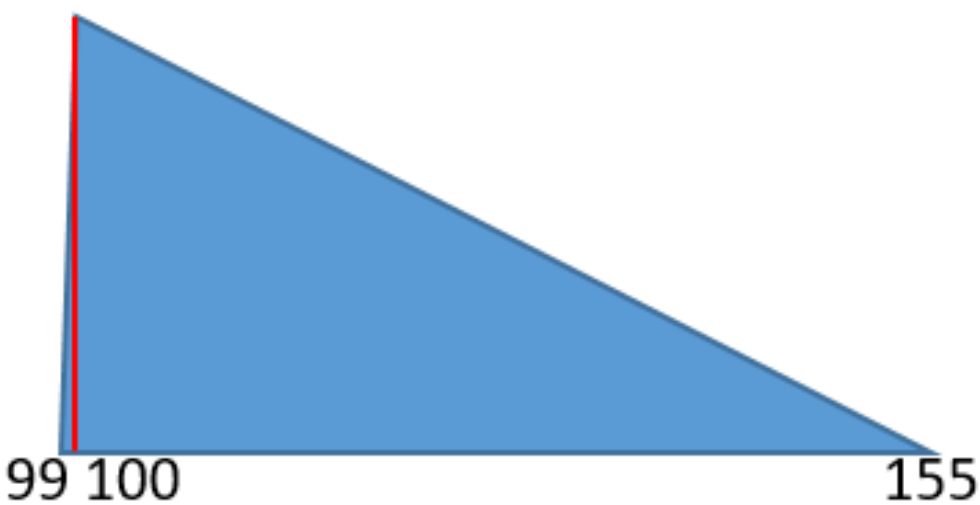


Figure 9. Conservative Triangular Distribution for High Uncertainty

Moreover, the previous high uncertainty with values of 70, 100, 130 is now 99, 100, 155. Now, high risk items will now only have a 1% probability of falling below the point estimate, while having a 55% probability of going beyond the point estimate.

8. mPDR JCL Model Results

8.1 mPDR Summary of Results

Now that the Analysis Schedule was complete with duration uncertainties, cost uncertainties, risks, and costs to date, the project was ready to get the JCL results. Performing the mPDR JCL involved running 3500 Monte Carlo simulations, or probability simulations, to produce the scatterplot seen in Figure 10.

Oct 2012 mPDR Model	LRD = July 2016	mPDR Model = 2/3/2017 at $830M

Duration Uncertainty	Green (90, 100 110)	Yellow (95, 100, 135)	Red (99, 100, 155)
Time Dependent Cost Uncertainty	Green (95, 100, 105)	Yellow (98, 100, 120)	Red (100, 120, 130)
Time Independent Cost Uncertainty	Green (90, 100, 110)	Yellow (95, 100, 135)	Red (99, 100, 155)

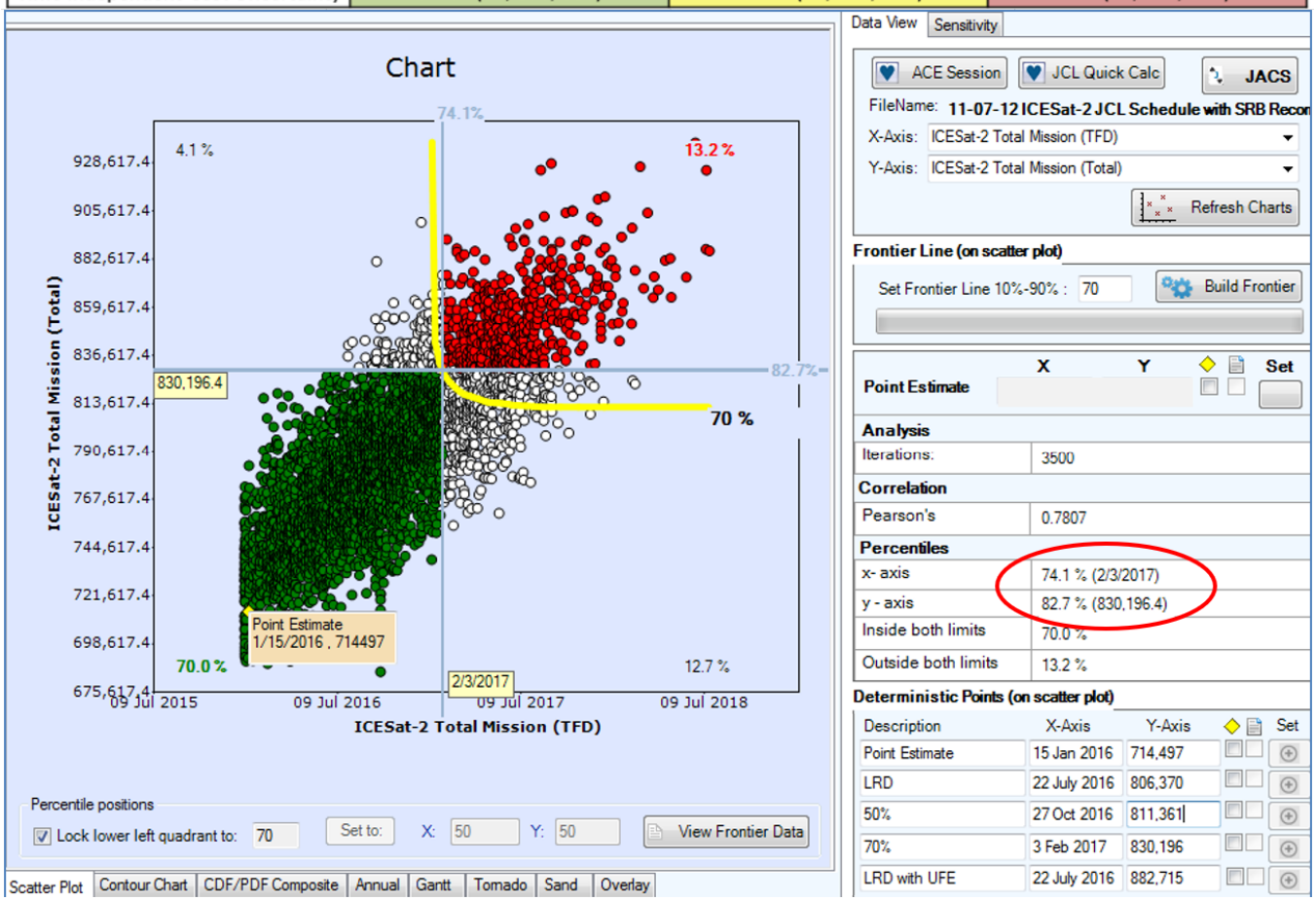


Figure 10. mPDR JCL Results

Each scatterplot dot represents a specific result from the simulation calculation. Therefore, within this shotgun blast there are 3500 iterations of cost and schedule risk analysis. The x-axis represents the final completion date and the y-axis represents the final cost.

The yellow frontier curve specifies all the cost/schedule combinations that will meet the 70% joint confidence of cost and schedule. The project selected this point on the knee of the curve, as it's recommended to be as close as possible to the center of the cluster.

Recapping the results, with 70% confidence, the LRD would be February 2017 at $830M. This was about 12 months beyond our point estimate, which was launch date minus the 6 months of margin we were holding at the time.

The mPDR JCL results were consistent with previous parametric cost and schedule estimates.

These results came from many adjustments of the model, to yield results that the project management team agreed with. During the testing period, we had learned that uncertainty distributions drive the schedule durations much more than discrete risks or cost uncertainty. Moreover, duration uncertainty impacts the results much more than discrete risks, as duration uncertainty impacts the entire model, if applying an overall uncertainty to all work elements, while the discrete

risks will impact only specific elements and their subsequent downstream elements.

The mPDR results were able to produce a list of schedule uncertainty drivers, which indicate the elements that influenced the model, as seen in Figure 11.

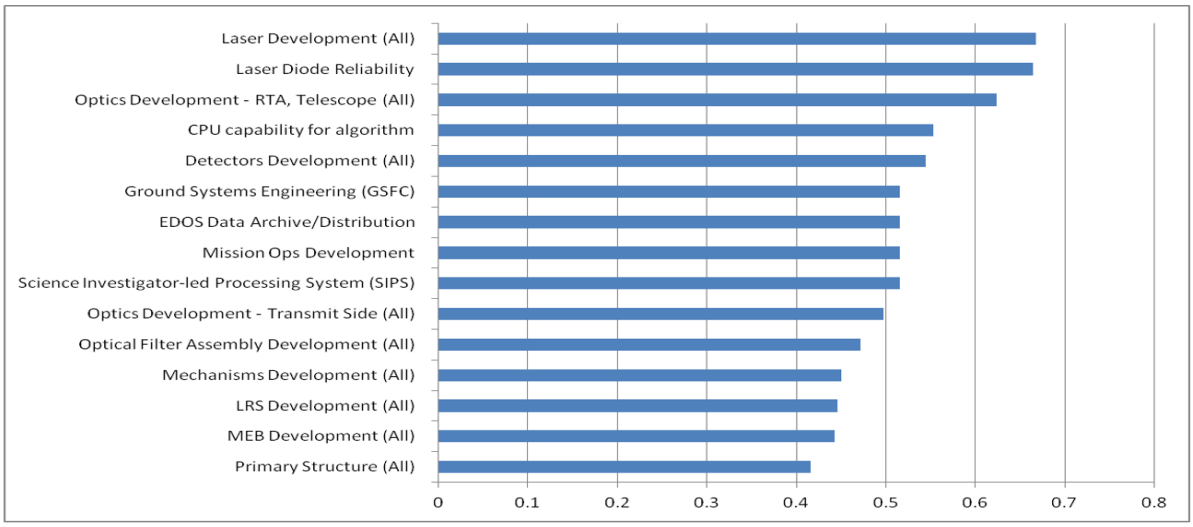


Figure 11. Schedule Uncertainty Drivers

Similarly, the model was able to provide a list of the discrete risks that would appear on the critical path of the model, indicating that these items were the top drivers of the analysis schedule. This complete list can be seen in Figure 12.

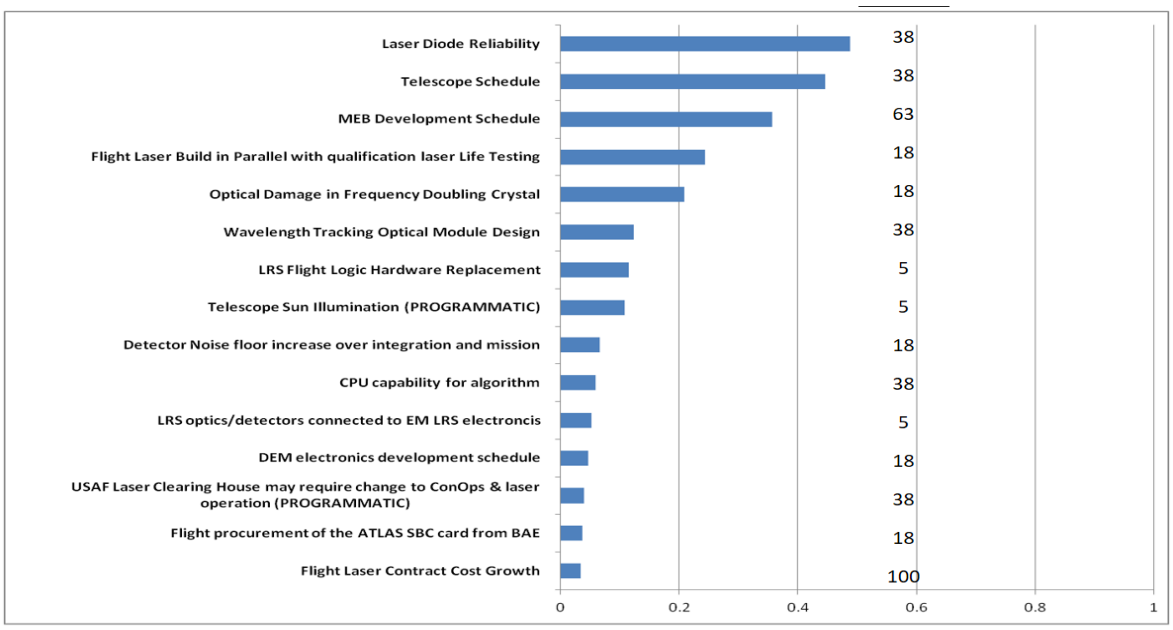


Figure 12. Schedule Risk Drivers

9. Schedule Slip and Model Adjustments

The year following the mPDR, the project had sustained a one-year slip in the LRD due to problematic systems engineering requirement issues which impacted all project subsystems. In short, the project team was not making progress towards their critical design.

This slip moved the project planned LRD from July 2016 to July 2017, which was an additional 5 months beyond the 2012 model's 70% JCL result for the LRD of February 2017.

As the project was quickly approaching mCDR, the need for reliable JCL results increased significantly.

The project held discussions on the JCL modeling process and focused on the input uncertainty distributions.

Specifically, to identify the uncertainty distributions that the 2012 mPDR model would have needed to produce a 70% LRD result of July 2017. The project wanted to use past performance and historical data from the schedule slip to improve our parametric model.

This led the project to develop uncertainty distributions that incorporated the project's past performance and historical data to improve our parametric model.

Figure 13 shows how the slip looked when plotted on a timeline.

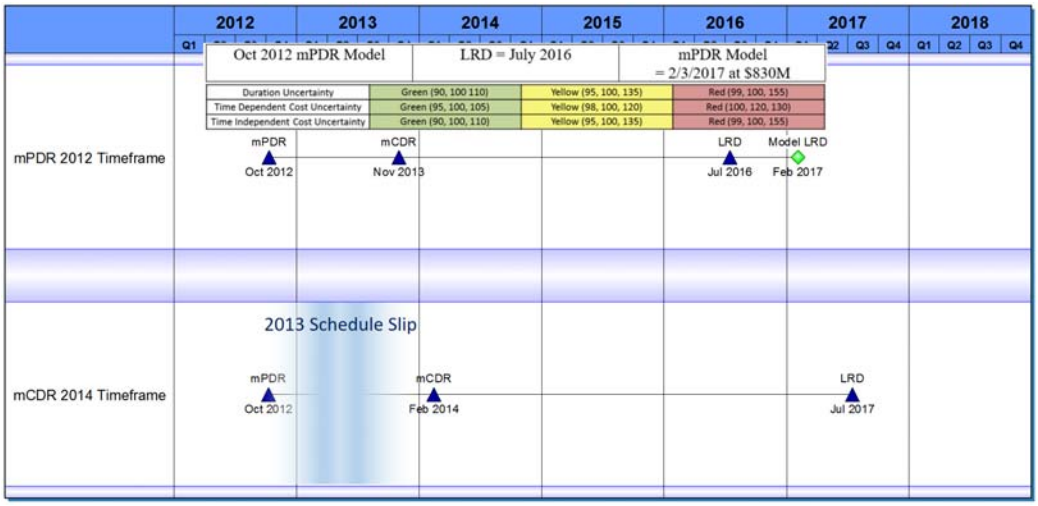


Figure 13. 2013 Schedule Slip

The top row is the schedule as it was during the mPDR timeframe and the second row is the mCDR timeframe. The blue milestones were the actual milestone dates from the schedules. The green diamond is the model projection.

Looking at the mCDR timeframe, the blue area, 2013 schedule slip, indicates the timeframe of the slip. Also, one can see how the one-year slip, from July 2016 to July 2017, jumped right over our model LRD.

Obviously the model needed to be updated and improved with better data, derived from this post-slip knowledge. Moreover, the project needed to identify the uncertainties that should have been included in the mPDR model, to yield a 70% confident LRD of July 2017.

Therefore, after many adjustments within the model, the project increased the uncertainties for the top schedule drivers in the model to reach the LRD of July 2017 at $946M.

A new color coding system was developed to easily see the changes in uncertainties between models, as can be seen in Figure 14. Green changed to yellow. Yellow changed to red. Red changed to black.

Oct 2012 mPDR JCL Uncertainties:

Oct 2012 mPDR Model	LRD = July 2016		mPDR Model = 2/3/2017 at $830M
Duration Uncertainty	Green (90, 100 110)	Yellow (95, 100, 135)	Red (99, 100, 155)
Time Dependent Cost Uncertainty	Green (95, 100, 105)	Yellow (98, 100, 120)	Red (100, 120, 130)
Time Independent Cost Uncertainty	Green (90, 100, 110)	Yellow (95, 100, 135)	Red (99, 100, 155)

The Oct 2012 mPDR Model, needed the following uncertainties in order to yield a 70% confident LRD of July 2017 at $946M:

Oct 2012 mPDR Modified Model w/ Post Knowledge Uncertainties	LRD = July 2016		Oct 2012 mPDR Model w/ Post Knowledge Uncertainties = 7/21/2017 at $946M
Duration Uncertainty	Green (90, 100 110)	Yellow (95, 100, 135)	Red (99, 100, 155)
Time Dependent Cost Uncertainty	Yellow (98, 100, 120)	Red (100, 120, 130)	Black (180, 210, 240)
Time Independent Cost Uncertainty	Green (90, 100, 110)	Yellow (95, 100, 135)	Red (99, 100, 155)

Tri(200,220,240,10,90) replaced the schedule duration uncertainty for the following discrete risks:

Duration Uncertainty	Risk Name
	ATLAS Level 3 Requirement TBRs and TBDs (S/C Related) (PROGRAMMATIC)
Tri(20,80,100,10,90)	MEB Development Schedule
Tri(30,60,120,10,90)	DEM electronics development schedule
Tri(10,40,120,10,90)	Flight Laser Build in Parallel with qualification laser Life Testing
	Detector Electronics schedule (PROGRAMMATIC)
Tri(40,60,80,10,90)	Mechanisms
Tri(20,30,40,10,90)	Requirements changes outside of PDU control will impact PDU design changes
Tri(20,40,120,10,90)	Telescope Schedule
	Flight Laser Contract Cost Growth
Tri(10,20,30,10,90)	Aggressive CDA Dates

Figure 14. 2013 Schedule Slip Model Adjustments

The October 2012 mPDR model, modified with this post-knowledge information, needed these new October 2012 mPDR modified model with post-knowledge uncertainties, to yield a 70% confident LRD of July 2017.

Black was applied to the laser subsystem development, ATLAS integration and test (I&T), and observatory I&T. We wanted to increase the uncertainties so that the model date and cost would be equal to our current estimate. The rationale for this decision was based on the laser subsystem, which was the new technology and historical schedule driver.

Then, the project aggressively increased the schedule duration uncertainty for the discrete risks that were related to developmental issues. This approach is known as a data-driven method or a performance method to updating a model.

Figure 15 shows that PDR uncertainties in the mPDR timeframe needed the updated uncertainties in the mCDR timeframe to move the model LRD from February 2017 to July 2017, shown at the orange diamond.

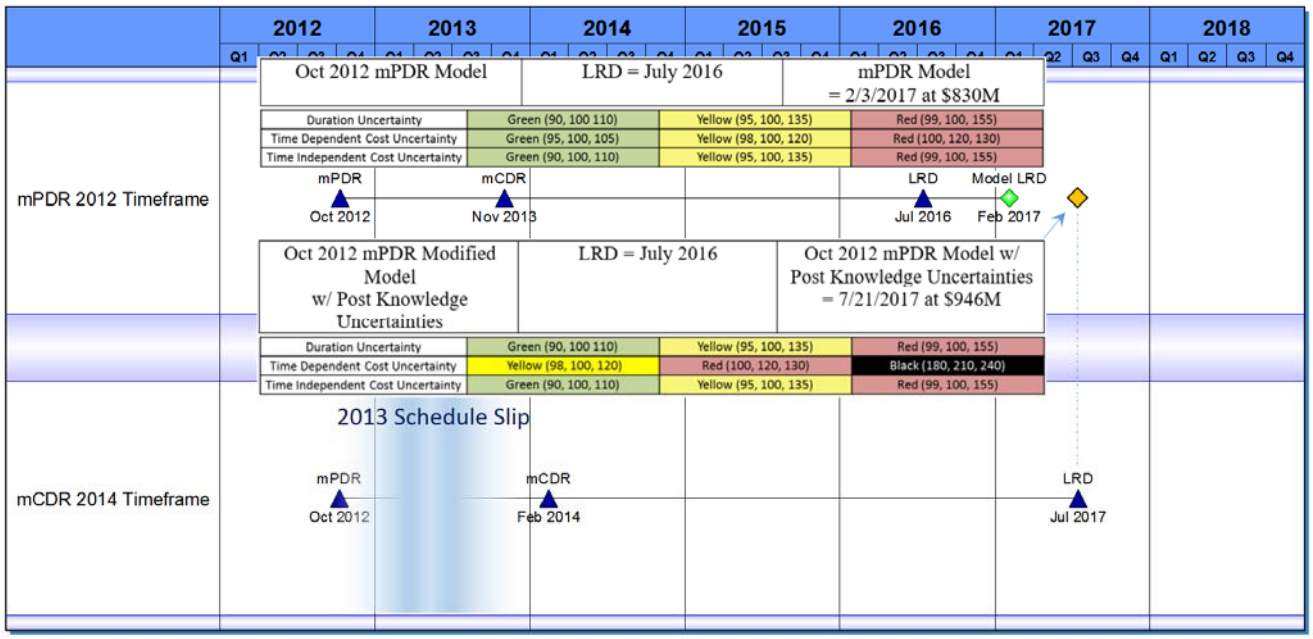


Figure 15. Uncertainty Adjustments

The project increased the time-dependent cost uncertainty to align with the new costs. However, the project did not modify the duration uncertainty nor the time-independent cost uncertainty as we wanted the discrete risks associated with the cause of the slip (i.e., having developmental schedule issues), to push out the model date.

10. mCDR JCL Model Results

Now that our uncertainties were updated to reflect the project's past performance, the final step involved creating a new February 2014 mCDR Analysis Schedule to reflect the new one-year slipped IMS and new LRD of July 2017. These new post-knowledge uncertainties were then applied to this new February 2014 mCDR model with the new costs and actuals (for February 2014) and the new LRD of July 2017.

Again running 3500 simulation iterations, the February 2014 mCDR model results informed that with 70% confidence, the ICESat-2 mission would launch in August 2018 with a cost of $1,044, as seen in Figure 16.

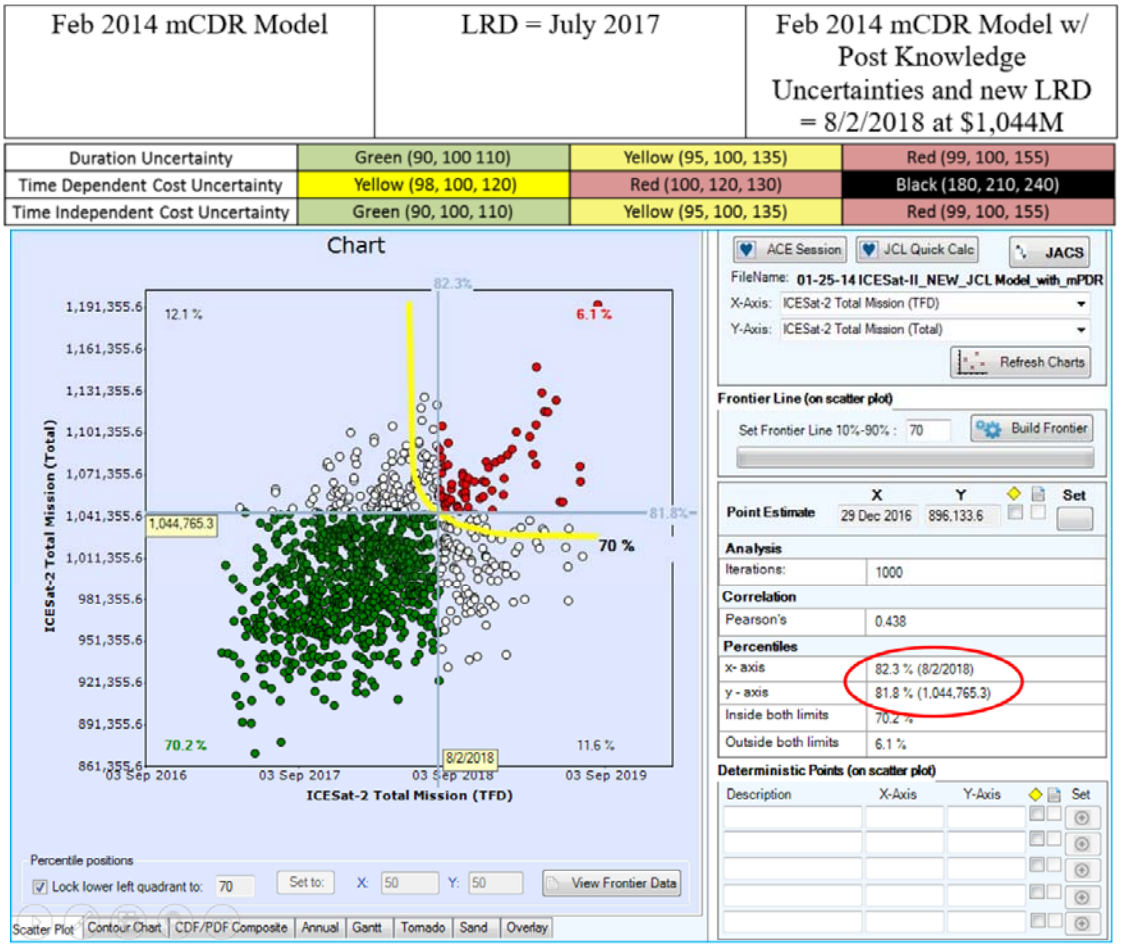


Figure 16. mCDR JCL Results

This February 2014 mCDR model informed that the slip would be due to a laser failure, the top schedule driver within the model.

The mCDR model shifted the LRD from July 2017 to August 2018 for a total of 13 months.

Plotting this mCDR result of August 2018 on the mCDR timeline allows for easy comparison to the mPDR results, as seen in Figure 16. With these new post-knowledge uncertainties applied to our new model, we see the result on the mCDR timeline, in the green diamond.

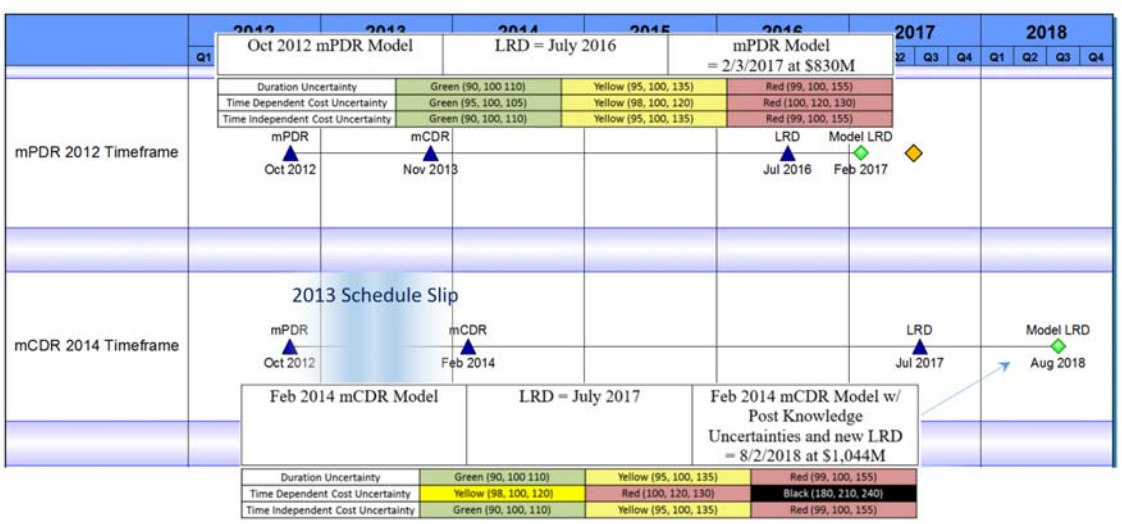


Figure 17. Results of mPDR compared to the mCDR

11. mCDR Results & the ICESat-2 Launch

ICESat-2 successfully launched on September 15, 2018 with a PM agreement of $1B and $56M.

Recapping the model's results, the project's mCDR model from 4-1/2 years ago, suggested that with 70% confidence, the ICESat-2 LRD would move from July 2017 to August 2018 and would be due to the laser subsystem.

Adding an additional row to the comparison chart and looking at the ICESat-2 final schedule row in Figure 17, we can see how the model nearly anticipated the 2017 schedule slip.

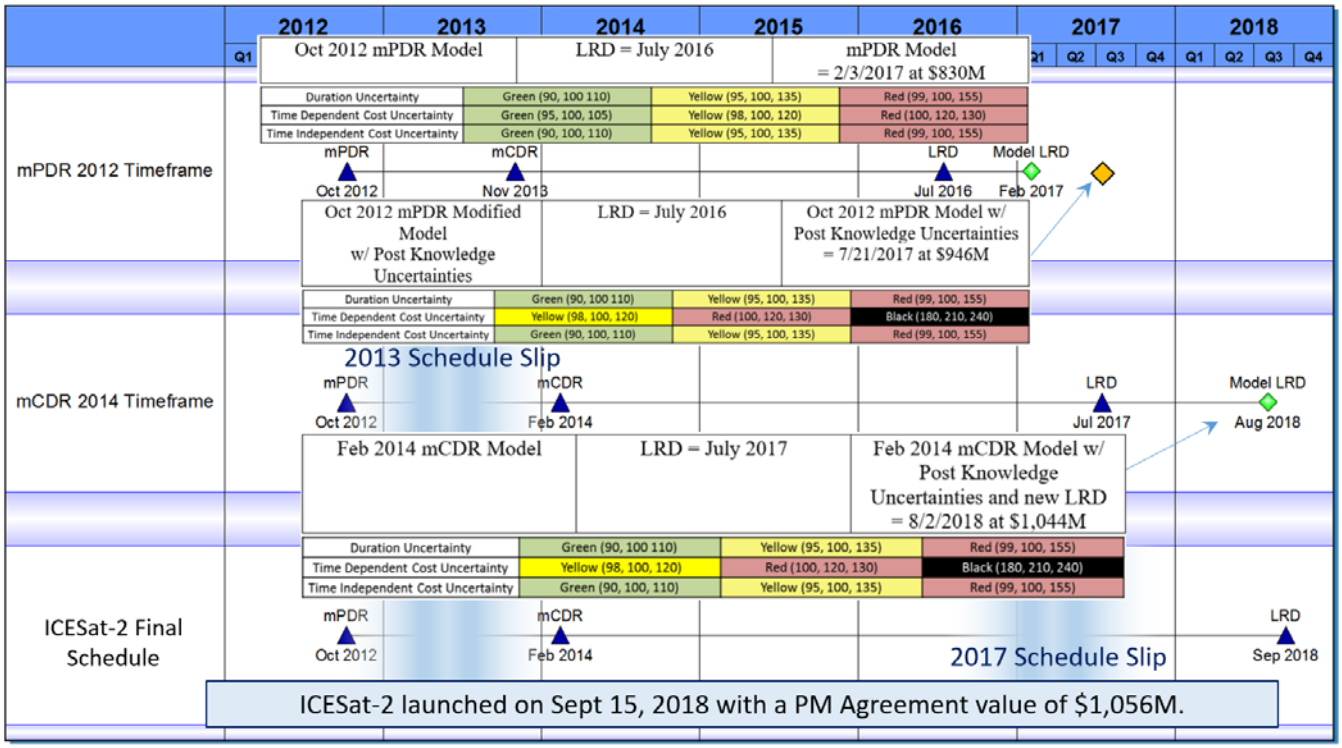


Figure 18. mCDR Results with the ICESat-2 LRD

Addressing this 2017 schedule slip, the project had a laser failure, which was the highest discrete risk and uncertainty driver within the model.

The laser failure was due to an anomaly that hadn't been seen before. Intermetallic growth between the Gold and Indium in the housing caused the laser slab crystal to fracture. This fracture was attributed to new laser technology, involving the variable energy laser. Lowering the laser energy actually causes more heat and a faster chemical reaction between the Gold and Indium. To be clear, Gold and Indium have been used on many laser missions to date without an issue. This was a true anomaly that had previously never occurred on a laser.

The laser fell to the dreaded "unknown unknown." The team had to fabricate new lasers using different materials. This fix pushed out the project an entire year.

12. Summary and Lessons Learned

The goal of this paper is to provide insight that an advocate JCL can predict and quantify issues on new technology missions.

The information provided supports the notion that projects should revisit their parametric models on a recurring basis so the project, and all stakeholders, have a better understanding of the probability of completion.

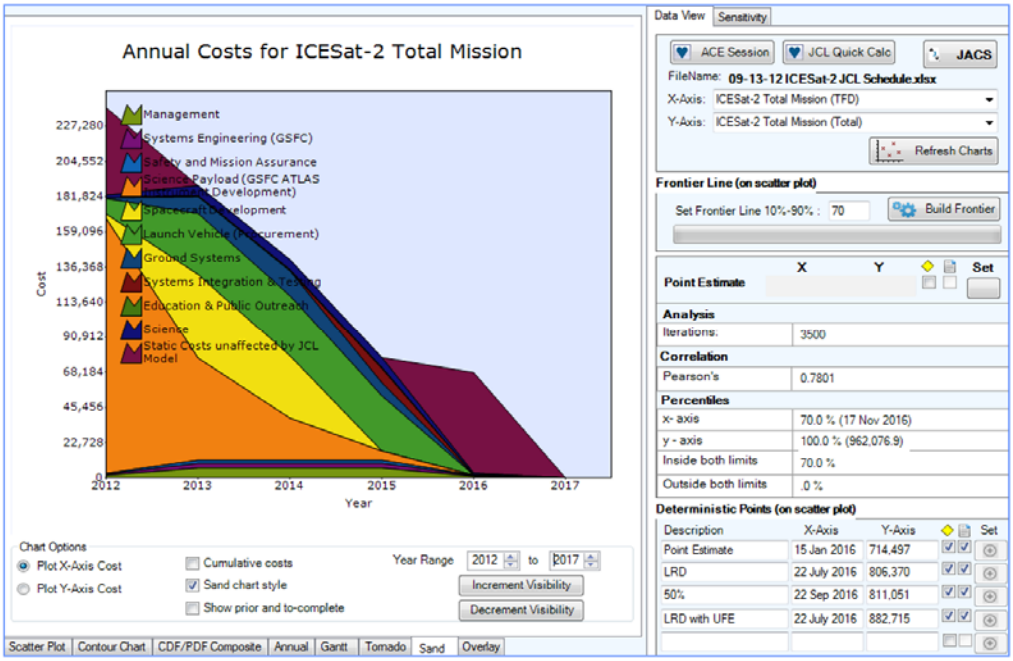
In the instance of ICESat-2, the 2013 schedule slip was the impetus to revisit and update the model. However, a project does not need a slip to occur to update their model. A project could continuously improve their parametric models using various scheduling performance metrics, or integrate the project's earned value management performance data into the model.

The majority of work and effort has already been accomplished in the setup of the original model. The analyst would need to update the analysis schedule to align with the current IMS, update the performance data for the uncertainties, as well as the cost actuals and risk register.

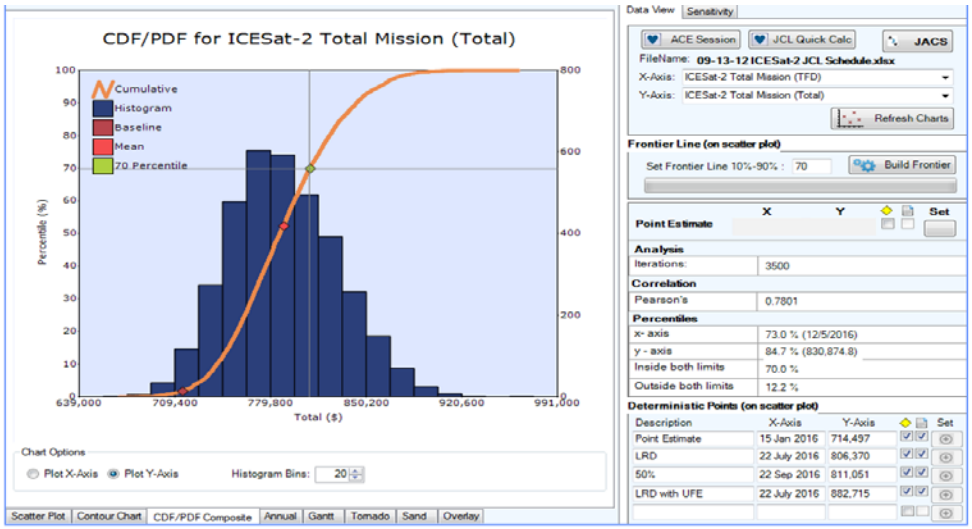
In conclusion, this illustrates how a parametric model can be continuously improved to produce valuable results for a project, even in cases of LRD delays.

APPENDICES

A. MPDR RESULTS: RISK ADJUSTED ANNUAL COST

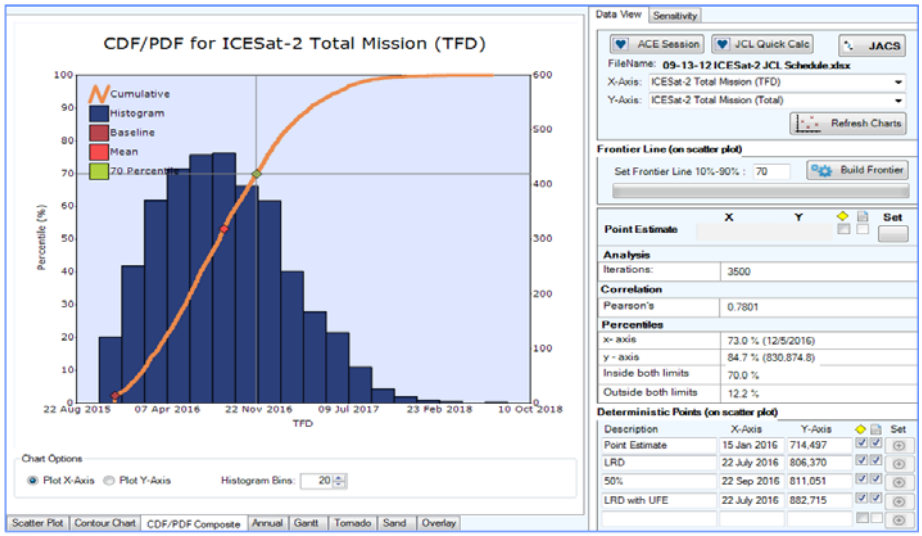


B. MPDR RESULTS: COST S-CURVE



50% Confidence Level LCC	$811 M
70% Confidence Level LCC	$831 M
Project Budget + Reserves	$806 M
Project Budget + Reserves + HQ UFE	$880 M

C. mPDR Results: Finish Date S-Curve



Project Baseline LRD w/ Reserve	**July 22, 2016**
50% Confidence Level LRD	**Sept 22, 2016**
70% Confidence Level LRD	**Dec 5, 2016**

Acknowledgements

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Param Nair, NASA Goddard Space Flight Center, Resource Analysis Office

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Biography

Joseph Krygiel After receiving his Bachelor of Science in Industrial Engineering from Penn State University in 1999, he has supported various customers and clients at the NASA Goddard Space Flight Center, holding an array of positions.

His career began as a Mechanical Systems Integration Engineer, where he managed spaceflight hardware for the Hubble Space Telescope. Over the years, he progressed to Project Engineer, to now providing Analytical Project Management Consultation. He served as the Planning and Schedule Manager on ICESat-2 for the entire life cycle of the mission, culminating to more than 10 years of service, on one project alone.

He currently supports NASA Headquarters as the Agency Scheduling Community of Practice (SCoPe) representative for NASA GSFC, the GSFC Earth Science Projects Division as the Program Planner, as well as an Integrated Program Team Leader supporting the Program Analysis and Control contract. His current positions allows him to manage both at the project and program levels through the use of process planning and controls management, while at the same time, allowing him to develop new methods of facilitating NASA Agency communication.