Conceptual Framework for a Rapid Space Launch Capability

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Dedication

TO MY WIFE and DAUGHTER

Susanne and Jane, for all of their love, encouragement, and enduring patience throughout this journey

IN DEDICATION TO MY PARENTS and LITTLE BROTHER

Who were always a great inspiration in my endeavors, but passed away during this journey, yet got to see it through to the end smiling down from heaven.

Beloved parents, Robert C. Reid (2016) and Joan E. Reid (2017), and wonderful Brother, David H. Reid (2014)

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Abstract of Praxis

Conceptual Framework for a Rapid Space Launch Capability

Launches of satellites require years of advance planning leading to lower national and economic security posture. A new construct is required for rapidly enabling access to space for global urgent mission needs. A new construct is required for effectively enabling a launch of a satellite to orbit in 24 hours or less. This long duration and high cost process is resulting in a barrier and congestion in placing crucial space assets into space. The current space mission planning process takes on an average of 24 months to plan, from customer initial meeting with launch provider to launch day, for new missions, with launch activities taking several weeks. Current satellite customers require launches of their satellites in 24 hours or less in response to natural disasters, rescue missions, communications outages, or urgent military tactical needs. So, what activities could be performed in advance of launch day, able to be placed "on the shelf" in a launch readiness storage state, enabling a rapid launch to orbit mission (e.g. 24 hours or less)? Assuming those prior efforts have been successfully accomplished and maintained, in the form of agreements, mission associated data, satellites built and sitting in flyable storage, what launch process construct could be developed to enable a rapid launch to orbit with a critical payload(s)? This latter problem statement is the focus of this study, a rapid launch process for space.

Practical applications of this proposed construct include, in response to a natural disaster, an agency would be able to restore communications over a region for medical and rescue personnel with orbital cell-towers, or be able to place electro-optical sensors

over a region for rapid damage assessments with orbital telescopes. Other examples include timely delivery of supplies directly to personnel in need, or in response to volcanic eruptions threatening populated areas, unattended sensors can rapidly be delivered to around the rim of the volcanoes (suborbital payloads example, using reentry coronal capsules).

Research methodologies performed include modeling of rapid launch process Monte Carlo simulations and expert elicitation for model validation. An executable timeline model has been developed for simulating this framework.

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List of Acronyms

6DOF	Six Degrees of Freedom
AFB	Air Force Base
AFSS	Autonomous Flight Safety System
AI	Artificial Intelligence
ALASA	Airborne Launch Assist Space Access
ASAT	anti-satellite
ASPEN	Automated Scheduling and Planning ENvironment
BIT	built-in-test
BM/C3	Battle Management/Command, Control, and Communications
BMDO	Ballistic Missile Defense Organization
C2	Command and Control
CA	Conjunction Assessment
CASPER	Continuous Activity Scheduling Planning Execution and Replanning
CCAFS	Cape Canaveral Air Force Station
CEO	Chief Executive Officer
CFR	Code of Federal Regulations
CIA	Central Intelligence Agency
COA	Course of Action
COLA	Collision avoidance
Comm	Communications
Constra	Constraints

COTS	Commercial off the shelf
CSV	comma-separated values
cubesat	cube satellite
CYBINT	cyber intelligence
DARPA	Defense Advanced Research Projects Agency
DCAPS	DATA-CHASER Automated Planner/Scheduler
DC-X	Delta Clipper Experimental (SDIO)
DC-XA	Delta Clipper Experimental-Revision A (NASA)
Deconf	Deconflictions
DES	discrete-event system
DHS	Department of Homeland Security
DIGS	Delta inertial guidance system
DISA	Defense Information Systems Agency
DISP	Dispersions
DoC	Department of Commerce
DoD	Department of Defense
DOF	Degrees of Freedom
DoS	Department of State
DoT	Department of Transportation
DOT&E	Director, Operational Test and Evaluation
Ec	Expected Casualties risk quantity
e-CFR	electronic code of federal regulations
EMA	electromechanical actuators

EO	electro-optical
EO-1	Earth Observing-1
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
FEMA	Federal Emergency Management Agency
FTS	Flight Termination System
GAO	Government Accountability Office
GEOINT	Geospatial intelligence
GN&C	Guidance, Navigation and Control
GPO	Government Publishing Office
GR&A	Ground Rules and Assumption
GRIB2	GRIdded Binary Edition 2
GSE	ground support equipment
HW	Hardware
IC	Intelligence community
ICAO	International Civil Aviation Organization
ICD	Interface Control Document
IIP	instantaneous impact points
INIT	Initialization
JCS	Joint Chiefs of Staff
JFCC	Joint Functional Component Command
JFCOM	Joint Forces Command
JPL	Jet Propulsion Laboratory

JSpOC	Joint Space Operations Center
KE	kinetic energy
km/s	Kilometer per second
KSC	Kennedy Space Center
LAAC	launch assist aircraft
LEO	low Earth orbit
LLC	Limited Liability Company
LNM	Local Notices to Mariners
LRR	Launch Readiness Review
LV	Launch Vehicle
MAPGEN	Mixed Initiative Activity Planning Generator
MASINT	Measurement and signature intelligence
MDA	Missile Defense Agency
MDA-W	McDonnell Douglas Aerospace West
MDL	Mission Data Load
MECO	Main Engine Cutoff
MEXAR2	Mars Express Scheduling Architecture version 2
mins	minutes
MOU	Memorandum of understanding
MP	Mission Planning
mph	miles per hour
MS	Microsoft
MUSE	Multi-User Scheduling Environment

NASA	National Aeronautics and Space Administration
NCEI	National Centers for Environmental Information
NDAA	National Defense Authorization Act
NGA	National Geospatial-Intelligence Agency
NOAA	National Oceanic and Atmospheric Administration
NOTAM	Notice to Airmen
NRO	National Reconnaissance Office
NSA	National Security Agency
NSF	National Science Foundation
NtMs	Notices to Mariners
NWS	National Weather Service
ODNI	Office of the Director of National Intelligence
ODR	Orbital Data Request
OPORD	Operations Order
OPS	Operations
OSD	Office of the Secretary of Defense
PIV	particle image velocimetry
PL	Payload
RAPIDS	Rapid Prototyping and Integrated Design System
RAXEM	Reverse of MEXAR
Rel Pts	Release points
RF	Radio frequency
RIFCA	Redundant Inertial Flight Control Assembly

RLP	Rapid launch process
RSO	Range Safety Officer
RUG	Range Users' Guide
SDIO	Strategic Defense Initiative Organization
SECO	Second (Stage) Engine Cutoff
Sep	Separation
SI	Sensitivity Index
SIGINT	Signal Intelligence
Sims	Simulations
SKeyP	SOHO Keyhole Planner
SLS	Space Launch System
SME	subject matter experts
SpaceX	Space Exploration Technologies Corporation
SPO	system program office
SSA	Space Situational Awareness
SSN	Space Surveillance Network
Stdev	Standard Deviation
STO	Space Tasking Order
STRATCOM	United States Strategic Command
SW	Software
SWPC	Space Weather Prediction Center
TA	Technology Area
TRAJ	Trajectory

TRANS	Transformed proposal instructions from RPS2
TTO	Tactical Technology Office
U.S.	United States
ULA	United Launch Alliance
US	United States
USAF	United States Air Force
USCG	United States Coast Guard
USN	United States Navy
USSTRATCOM	United States Strategic Command
VAFB	Vandenberg Air Force Base
WAFCs	World Area Forecast Centers
WAFS	World Area Forecast System
Wi-Fi	Wireless Internet

List of Symbols / Nomenclature

1.	%	Percent
2.	3D A*	Three-dimensional A* algorithm
3.	A*	Optimized path search algorithm
4.	D*	Informed incremental search algorithm
5.	DurationX	Task duration fields for dispersion analysis
6.	E_c	Expected Casualty risk quantity
7.	hrs	hours
8.	mins	minutes
9.	NORM.INV	Normally distributed random number generator, MS Excel
10.	NORMINV	Normally distributed random number generator, MS Excel
11.	R^2	Correlation Coefficient
12.	rand	Uniformly distributed random number generator, MATLAB
13.	RAND	Uniformly distributed random number generator, MS Excel
14.	RANDBETWEEN	Uniformly distributed random number generator, MS Excel
15.	randn	Normally distributed random number generator, MATLAB

Chapter 1 - Introduction

1.1 Background

Timely launches of satellites are critical for a variety of organizations, to include branches of the military, intelligence agencies, civil agencies, other government agencies, universities, and commercial companies. In an age of shrinking budgets and other countries' continual evolving capabilities, rapid, routine and affordable "access to space is increasingly critical for both national and economic security. Current satellite launch systems, however, must schedule many years in advance for a very limited inventory of available launch facility resources" (DARPA TTO, 2014).

Satellites today are typically launched from on top of a much larger rocket, or multiple rocket stages. There are a very limited number of terrestrial launch sites, most with contested resources, except for air launch. "Launch costs are driven in part today by fixed-site aging infrastructure, non-evolving processes, testing, and a large set of flight safety rules. Fixed-launch sites can be rendered idle by something as innocuous as a boat in the area or rain. They also limit the direction and timing of orbits satellites can achieve, also greatly impacting mission planning and performance" (DARPA TTO, 2014).

"Several companies that are developing lower cost small launch vehicles or who are providing lower cost rideshare launch services say they expect new Chinese launch vehicles to drive down launch prices, raising concerns in the community of unfair competition. If is very possible that the Chinese are going to drive an order of magnitude

reduction in launch costs, building satellites and operating satellites in the next five years" (Foust, 2018).

New launch processes and frameworks are required for the space missions of the future and for increasing our national and economic security posture. A picture of the stakeholders that could benefit from this new construct is shown in Figure 1.1-1. They include military, intelligence community, civil agencies, and commercial space.

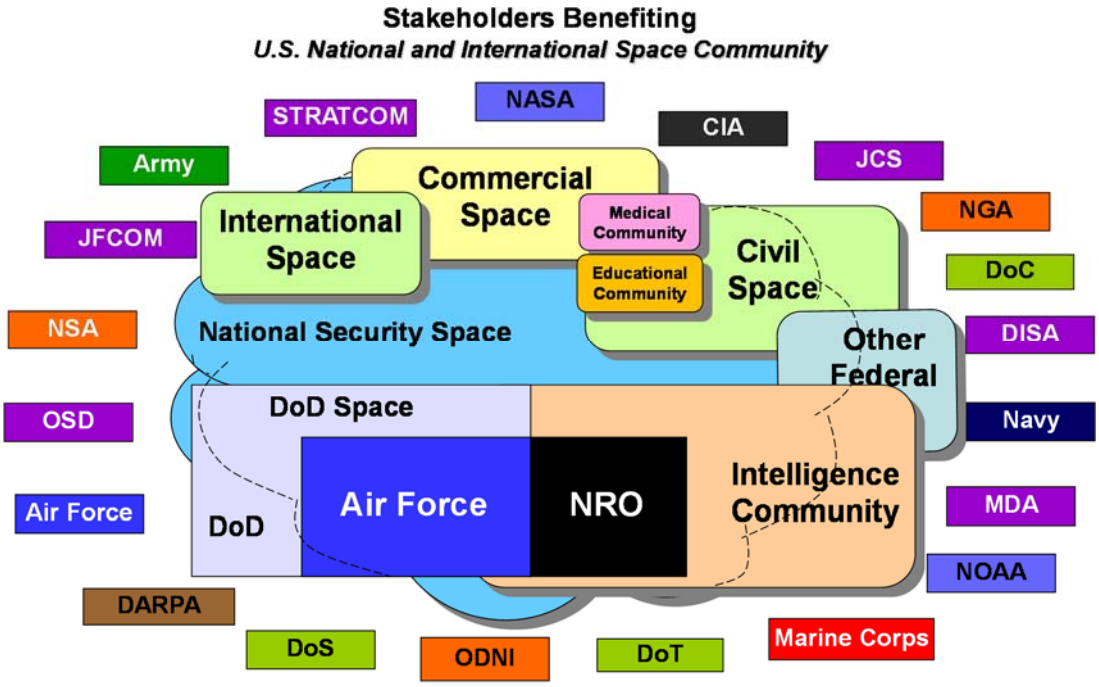
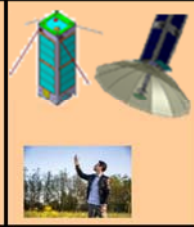
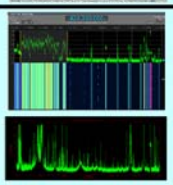


Figure 1.1-1 Stakeholders that could Benefit from this Research

Specific missions that could be enabled by rapid access to space include disaster response. Natural disasters from earthquakes, tsunami, landslides, avalanches, sinkholes, floods, volcanic eruptions, hurricanes, tornadoes, or blizzards may require a rapid damage assessment, especially if an existing space asset is not over that region or is inadequate to sense the required phenomenon. The Federal Emergency Management Agency, Red Cross, and local response teams could benefit from rapidly deployed

modern electro optical hyper-spectral sensors targeted for over the exact geographical region of interest. Additionally, communications could be restored over a region with temporary cellular or Wi-Fi services. Humanitarian efforts could deliver food, communications equipment, unattended sensors in remote or hazardous regions, and medical supplies from sub-orbital parachute coronal capsule drops. Remote medical diagnoses, treatment, critical care support could also be enabled, as shown in Table 1.1-1.

Table 1.1-1 Missions Enabled by Rapid Access to Space

Civil Agencies		Military & Intelligence	
Disaster Response-Damage Assessment *[FEMA, Red Cross]* EO sensors, Rapid disaster response team support teams		**Security** *[Military, DHS, FEMA]* Monitor security zones, integrate agencies, communications support, covert launches, jamming	
Disaster Response-Restore Communications *[Mobile Cell, Wi-Fi]* Cellular service, Wi-Fi, provided from space		**Data Exfiltration** *[IC, NSF, NASA, NOAA]* Unattended ground sensors delivery and early warning data extraction supporting seismic and weather	
Disaster Response-Supplies Delivery *[Humanitarian, FEMA]* Rapid delivery of food, communications, medical (Sub-orbital mission)		**Intelligence Gathering** *[NRO, NGA, CIA, DHS, Military]* *GEOINT*, SIGINT, MASINT, CYBINT data gathering	
Virtual Medical *[Humanitarian]* Remote diagnosis, treatment, and critical care support		**Early Warning** *[NRO, Military]* Missle early warning, nuclear explosion detection, new foreign launch	
Commercial & Health Industries			
Package Delivery-Hyper Logisitics *[Commercial Companies]* Material that needs to be any place on the planet in 90 minutes or less (suborbital mission)		**Health Industry-Organ Delivery** *[Hospitals]* Package delivery of organ to any place on the planet in 90 minutes or less (suborbital mission)	

Military and intelligence agencies can more rapidly respond to dynamic security threats and to friendly troops with urgent needs, with new signal intelligence (SIGINT), geospatial intelligence (GEOINT), cyber intelligence (CYBINT) and, measurement and signature intelligence (MASINT) sensors not currently over that region. Communications support and jamming could also be rapidly deployed.

1.2 Problem Statement

Launches of satellites require years of advance planning leading to lower national and economic security posture. A new construct is required for rapidly enabling access to space for global urgent mission needs.

This long duration and high cost process is resulting in a barrier and congestion in placing crucial space assets into space (DARPA, 2015). From a survey of launch providers, the current space mission planning process takes an average of 24 months to plan, from customer initial meeting with launch provider to launch day, for new missions (United Launch Alliance, LLC, Delta IV, 2013) (United Launch Alliance, Atlas, 2010) (Space Exploration Technologies Corp, Falcon, 2015) (Orbital ATK, Pegasus, 2015).

General Hyten, commander of United States Strategic Command, oversees the nation's nuclear and space missions and has been outspoken in his criticism of the Pentagon's procurement methods and technology choices. Hyten recently commented, "to keep the edge in space, military needs cheaper launch costs, and faster satellite development." The Pentagon's current leadership is motivated to change the acquisition and procurement culture. They understand the need to speed up the modernization of space systems (Erwin, 2018).

The Defense Advanced Research Projects Agency (DARPA) has been striving to drive industry to a more rapid, lower cost space launch technology since the 1990's. The commercial space industry can mass produce satellites that are small but quite sophisticated for the price. Launch vehicles are getting better and cheaper. So, it only makes sense for the United States military to ride that wave. DARPA has been vocal about the need to get the Pentagon to become less dependent on large, complex satellites in geostationary Earth orbit. It's time for the Department of Defense to shift future spending to constellations in low Earth orbit made up of dozens or hundreds of small satellites (Erwin, DARPA, 2018).

The Department of Defense, civil agencies, and the commercial sector currently have "very exquisite satellites. They are high-performance systems but cost too much, and take too long to build and launch." DARPA wants to see a shift to low Earth orbit (LEO), get capabilities in larger constellations. The more satellites in the system, the harder it will be for the enemy to take it down (Erwin, DARPA, 2018).

There are many different mission planning groups within a typical launch organization, each with a unique methodology of communication and integrating their critical products to the other groups. Each group has evolved over time to become more comfortable with a variety of different work flow process tools, such as paper, telephone voice, technical interchange meetings, email, share points, or links to server folders. Most organizations lack an integrated and consistent approach to making available the data to the whole system even though they are highly interdependent. Given the long time periods involved in planning for a launch mission, it is easy to become accustomed

to poor information flow. In contrast, during the final days of critical launch operations, the flow of information is usually excellent (Hammond, 1999).

1.3 Thesis Statement

Statistical Monte Carlo models applied to launch vehicle mission simulations are required to reduce the launch mission planning and operations processes.

Engineering management is required for development of novel approaches to launch stakeholders' coordination and approval processes. Engineering management is required for integration and automation of traditional stove-piped mission planning domains. Rapid mission planning management enables rapid and low-cost launch operations, key to making tactical space practical.

There must be significant reductions in access to space time and costs if our country is going to reach the urgent orbital mission demands of the future (Hammond, 1999). Due to the complex nature of space transportation and the growing number of approving and service providing agencies involved, it is critical that a new construct is developed for more rapidly planning and executing future space launch missions.

1.4 Research Questions

Research questions include: 1. How do the processes by which launch missions are planned today, differ? 2. What pre-launch planning activities can be done in parallel that are currently done in series? 3. Which manually intensive planning activities could be automated or accelerated with new methodologies? 4. What pre-launch planning activities could be performed well in advance of launch day, automatically updated daily waiting for launch order, and then require only minor updates on launch day? 5. What methods of launching, e.g. terrestrial- launch vs. air-launch, could contribute a significant

role in rapid launch processes (RLP)?

1.5 Research Objectives

Research objectives include evaluation of data to determine if a launch to orbit is achievable in 24 hours or less. Specifically, the research will identify a set of manually-intensive mission planning tasks that can be automated with statistical models and algorithm development applied to launch vehicle timeline simulations. The research can then develop an executable framework for mission managers which uses these new timelines, and automation constructs.

1.6 Research Hypotheses

The research hypotheses are as follows:

1. Space launch mission planning timelines can be reduced to <24 hours for supporting emerging tactical and responsive space missions.

2. A rapid mission planning framework can be developed that future project managers can use for their space missions.

3. The long duration and manually intensive tasks can be automated with statistical models and algorithms applied to launch vehicle simulations.

4. The required launch coordination with stakeholders, approving authorities and service providers can be accelerated with modern collaboration tools that support rapid launch goals.

1.7 Limitations

Launch campaigns can be organized into four launch mission phases, space system development, readiness, employment, and execution phases. The focus of this research is

on the latter two phases with a goal of both phases being accomplished on launch day.

It is acknowledged that in order for this new construct to be successful, it comes at a cost, added readiness effort is required to be ready for a rapid deployment and produce this valuable capability. Proprietary cost data has not been added as part of this research, but nothing prevents the engineering manager from resource loading this model for cost and schedule analyses.

Two key aspects of this responsive and rapid on-orbit capability will be the ability to first, rapidly plan and implement the launch process and, secondly, autonomously check out and enable the payload within a few orbits after launch. The emphasis of this Praxis will be on the first aspect, real-time mission planning and launch activities required on launch day. However, requirements can be discovered for the payload and launch vehicle designs that will further enhance the overall process timeline.

A focus on air-launch mission type was assumed for this research in order to narrow the scope. Additionally, this construct is focused on missions requiring a rapid launch capability. However, this construct can be applied to a variety of launch systems, for process improvements and further savings.

1.8 Document Organization

This document is organized into five chapters. The first chapter is an introduction to the research, which provides an overview with the background, problem and thesis statements, research objectives, research questions, research hypotheses, and limitations of the research. The second chapter sets the foundation and context for the research with a review of the literature available in this domain. A review of the current processes associated with launch platform providers, launch platform types, launch day required

approvals and coordination processes, and space launch automation technologies are analyzed. The third chapter describes the research methodology, including data collection and analyses and the model refinement and validation process. The fourth chapter presents the results of the research, to include the simulations results and resulting construct architecture. The fifth chapter summarizes the conclusions of the research, contributions, and offers recommendations for future research.

Chapter 2 - Literature Review

In order for a mission to launch a payload into Earth's orbit, the launch vehicle must produce a forward velocity in free-fall that achieves a trajectory arch that matches the curvature of Earth. In other words, for a satellite to orbit the Earth, a booster rocket lifting the satellite must achieve a horizontal velocity large enough for its path to match the curvature of the Earth, in free-fall without thrusting. Given the Earth's size, for every 8000 meters along the surface, the Earth's curvature drops a vertical distance of 5 meters. So in order to achieve Earth's orbit, a rocket "must travel 8000 meters in the time it takes to fall 5 meters. Given this 8000 meter tangent with Earth curving downward 5 meters, a projectile traveling horizontally at 8 km/s, or 17,896 mph, will fall 5 meters in that time and follow the curve of the Earth" (Hewitt, 2016). This is in contrast to a missile or suborbital mission that follows a ballistic trajectory, only achieving some fraction of this velocity, less than 8 km/s.

To place a satellite into orbit requires precise control over the speed, direction, orientation, and timing of the rocket's flight. Most orbital destinations require a specific time to reach their "slot" in orbit, for the purpose of maintaining separation from other nearby satellites, or achieving specific overflight times of required locations on Earth.

In order to set a foundation and begin the development of a rapid mission planning and launch process, the assessment of existing launch processes is warranted. Existing commercial launch operations, military space operations, civil space operations, space launch processes, to include terrestrial-, sea-, and air-launch comparisons, launch approval stakeholders, and current launch automation technologies have been examined.

2.1 Commercial Launch Operations

A launch vehicle payload user's guide contains recommended schedules for a generic mission integration schedule. Payload user or planner guides for commercial companies were examined, such as, "United Launch Alliance Delta IV" (United Launch Alliance, LLC, Delta IV, 2013), "United Launch Alliance Atlas" (United Launch Alliance, Atlas, 2010), "Space Exploration Technologies Corporation (SpaceX) Falcon 9" (Space Exploration Technologies Corp, Falcon, 2015), "Orbital ATK Taurus II and Antares" (ATK, Orbital, 2009), "Orbital ATK Pegasus" (Orbital ATK, Pegasus, 2015), "Orbital ATK Minotaur" (Orbital ATK, 2015), "International Launch Services (ILS) Proton" (International Launch Services, 2009), and "Rocket Lab Electron" (Rocket Lab Payload User Guide, 2017). Each guide shows an average of 24 months recommended for typical mission planning activities, and several weeks of lengthy launch preparation activities at the launch site, as shown in Table 2.1-1.

Table 2.1-1 Launch Vehicle Mission Typical Timelines

Company	Launch Vehicle	Time to Orbit (Months)	Launch Campaign
United Launch Alliance (ULA)	Delta IV	24	9-weeks
United Launch Alliance (ULA)	Atlas	24-36	4-weeks
Space Exploration Technologies Corporation (SpaceX)	Falcon 9	24	4-weeks
Orbital ATK	Taurus II, Antares	24	16-weeks
Orbital ATK	Pegasus	24-30	4-weeks
Orbital ATK	Minotaur	24	3-weeks
International Launch Services (ILS)	Proton	17-23	4-weeks
Rocket Lab	Electron	TBD	4-weeks

The primary activity drivers observed over most of these launch vehicles are the preparation of the guidance and resulting software mission constants for the specific mission and the system performance analyses to insure requirements are met. Analyses required in preparation for launches include: system performance, guidance, flight

software, controls, mass properties, electrical, mechanical, propulsion, structural loads, thermodynamics, and data engineering. This process could be simplified by reduction or further automation of the generation of many of these required analyses products.

For example, Delta rocket had 52 internal major products to generate for each launch, as shown in Table 2.1-2 (United Launch Alliance, LLC, Delta IV, 2013). Some of these products could be eliminated or reduced in size with vehicle changes resulting in increased flight constraint margins.

Table 2.1-2 Mission Analyses Activities Summary (Delta Rocket, 2001)

	Activities	Hours	Products	Interfaces	Comments
Program Office	7	0	1	31	Program office hours were accounted for elsewhere
System Performance	19	1929	11	42	Has the most products and interfaces
Guidance, Flight SW	27	2652	9	34	The majority effort is in the preparation of mission constants
Controls	7	375	7	37	This effort increases substantially for new vehicle configurations
Mass Properties	10	568	8	21	Analysis needed due to limited vehicle flight margins
Electrical	3	24	3	6	This activity has changed with the replacement of DIGS with RIFCA
Mechanical	2	16	2	3	Delta III, IV have additional EMA second stage actuation
Propulsion	5	950	5	14	Measure engine performance used
Structural Loads	2	45	2	8	This effort increases substantially for new vehicle configurations
Thermodynamics	9	360	4	9	Analysis needed due to limited vehicle flight margins
Data Engineering	4	499	0	10	Routine, unless anomalies
Total	95	7418	52	215	

2.2 Military Launch Operations

In the military domain, air-launched anti-satellite (ASAT) programs' rapid launch processes were examined. These historical rapid launch programs had to be developed and launched quickly due to an emerging and urgent need, namely, protection of our high-value and critically relied upon satellites. An "F-15 Eagle fighter aircraft" air-launched an "ASM-135 ASAT missile" during a final test and successfully destroyed the Solwind P78-1 satellite in orbit, a United States gamma ray spectroscopy satellite. Although successful, this ASAT program was cancelled in 1988, but the tactical weapon system rapid launch process documents can be examined, such as the Space Defense

Operations Center/Mission Control Center Interoperability document (The Boeing Company, 1984).

ASAT had a unique reason for rapidly launching. During the cold war the Russians had an ASAT system that was estimated by our intelligence as being approximately 50% effective. If we were successful in our testing, our national leadership feared that would escalate Russian ASAT capability, and the arms race in this area would continue. So, the team had a deadline to launch before the program was going to be canceled (Croslin, 2018).

Similarly, the terrestrially-launched kinetic energy anti-satellite (KE ASAT) program from the early 1990s has declassified 171 documents. Several of the documents give insight into their tactical launch processes, such as ASAT Battle Management/Command, Control, and Communications (BM/C3) Concept of Operations document (BA&E Electronics, 1990), the System Specification for the Antisatellite (ASAT) System (Rockwell International Corporation, 1989), and the System Design Document for the "Kinetic Energy Anti-Satellite (KE ASAT) Weapon System" (Rockwell International, 1991).

The United States Department of Defense's Strategic Defense Initiative Organization (SDIO) required a suborbital and recoverable rocket with the capability of "lifting up to 3,000 pounds of payload to an altitude of 1.5 million feet, then returning to the launch location for an autonomous landing, producing a the turn-around capability to launch for another mission in under seven days" (Ballistic Missle Defense Organization (BMDO), 1992). SDIO's most notable launch program with this mission goal was the "Delta Clipper Experimental (DC-X), which was a prototype reusable single-stage-to-orbit

launch vehicle built by McDonnell Douglas under SDIO from 1991 to 1993. Starting 1994 until 1995, test flights continued through funding of the United States (US) civil space agency, National Aeronautics and Space Administration (NASA). In 1996, the DC-X technology was transferred to NASA, which ordered upgrades to the design for performance increases to create the DC-XA" (Sponable, 2004). Both the DC-X and DC-XA rocket programs produced very rapid launch timelines and turnaround times, improving their timelines over 12 successful flights. The focus was on demonstrating "aircraft-like" operations for launch vehicles, with turnaround time threshold requirement of 26 hours, and objective requirement of 8 hours. Additionally, call-up/alert response time requirement of 2-3 hours (Sponable, 2004). Review of the operations timelines shows DC-X was routinely powered-up, checked out, propellant loaded and flown in a 3 hour period (Ball, 1998). Examples of automated processes that enabled these rapid launch turnaround times included extensive on-board automation and multiple layers of built-in-test (BIT), workload reduced to initiating automated processes and monitoring progress with abort options, electronic checklists with time-tags eliminating paper manuals, on-board six degrees of freedom simulation capability enabled "test like you fly" training, mission planning, range safety approval, post-flight data analysis, autonomous pre-flight BIT, propellant load, purge, chill down, engine start/checkout, post-liftoff ground support equipment (GSE) securing, post-flight on-board auto-staffing, securing, post-flight BIT, and rapid post-flight data retrieval and analysis is essential for fast-paced flights (Ball, 1998).

Studying lessons learned from the DC-X/XA programs reveals that "aircraft-like" operations and supporting systems are actually compatible with rocket-powered reusable

launch systems, and automated ground support systems help to reduce overall processing times and size of required support personnel (Leisman, 2000). These historical rapid launch programs serve as an excellent foundation for a rapid launch capability construct and can inform the modern launch processes in place today. For example, a "build a little, test a little" iterative approach lead to shorter development cycle because implementation problems are discovered sooner. This resulted in a shorter schedule (x-axis) and greater quality product (y-axis) produced in the end. This innovative process is compared against the traditional "waterfall" development processes in Figure 2.2-1 (Riel, 1999).

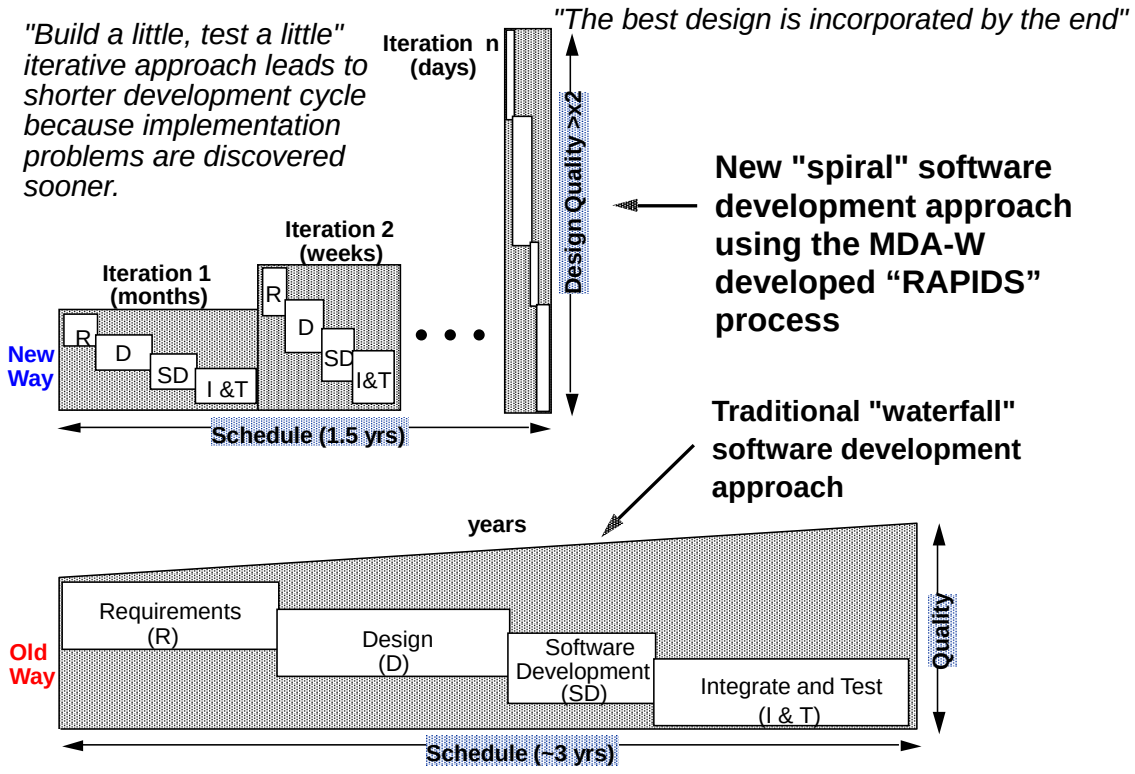


Figure 2.2-1 Rapid Development Process Developed on DC-X and DC-XA Programs

It is interesting to note, the DC-Y program would have been the orbital follow-on to the successful DC-X/DC-XA flight demonstration programs, applying the rapid launch,

reusability, and "aircraft-like" operations construct to a full-size orbital launch vehicle. But, several decades later commercial companies capitalized on this development performed by SDIO, NASA, and McDonnell Douglas and produced the reusable commercial version of vertical takeoff and vertical landing rocket systems, with rapid launch timelines (e.g. SpaceX and Blue Origin).

In comparison to terrestrial-launch platforms, air-launch is valued highly as the most potential launch methods for responsive aerospace launch missions because of quick response, high maneuverability and great adaptability (Zhang, 2017). This launch platform has a high potential for achieving the greatest rapid mission planning responsive launch goals given decreased reliance on contested and costly terrestrial range assets. The Defense Advanced Research Projects Agency (DARPA) attempted to demonstrate this on the Airborne Launch Assist Space Access (ALASA) development contract. ALASA's goal was to propel up to "100-pound satellites into low Earth orbit (LEO) within 24 hours of mission call-up" (DARPA TTO, 2014). The United States Air Force and DARPA are supportive of rapid, flexible launch readiness within hours of call-up (Horais, 2004), and intend to spin-off this capability to other military and commercial industries once it is developed. A key component to this construct is a rapid mission planning and operations capability.

DARPA initially awarded launch system design and development contracts to The Boeing Company, Virgin Galactic, and Lockheed Martin, to not only develop air-launch systems that can launch 100 pound payloads into low Earth orbit for under $1 million, but in just 24 hours or less from mission call-up to integrate, test and launch the payload, with the ability to re-plan the launch in-flight and send the aircraft to a different base or

airport on short notice. The launch assist aircraft must be able to operate from military airfields as well as civil, anywhere in the world, in a crisis. Key enabling technologies development contracts were awarded to Northrup Grumman, Space Information Laboratories LLC, and Ventions LLC, in order to burn-down risk in key areas, such as automated mission planning, automated range safety systems, and space-based range communications. These are key technologies required for before any rapid launch capability can become a reality (Clapp, 2012).

2.3 Civil Space Operations

NASA Jet Propulsion Laboratory (JPL) has developed highly autonomous mission planning and operations technologies that could be adapted for the launch industry. Many of their spacecraft, probes, and rover missions take advantage of highly autonomous mission planning processes, such as with the Earth Observing-1 (EO-1) mission. The EO-1 was the first satellite to routinely rapidly replan and measure a facility's methane leak from space, the "first to map active lava flows from space, and the first to track re-growth in a partially destroyed Amazon forest from space. EO-1 captured scenes such as the ash clouds after the World Trade Center attacks and flooding in New Orleans after Hurricane Katrina" (JPL, 2017). Technologists developed "autonomy software onboard EO-1 that enabled the Earth sensing satellite to make its own decisions based on the content of the collected data. For instance, if a scientist requested EO-1 to take a picture of an area where a volcano was actively erupting, the mission planning software could decide to automatically take a follow-up image the next time it passed over the region" (JPL, 2017). EO-1 grew to be highly autonomous, ultimately able to operate daily without the assistance of the traditional human-intensive and costly ground

segment controlling the spacecraft. It was able to be tasked directly by scientists from all over the world. Scientists would turn in their science-gathering desires each day based upon global urgent needs and the EO-1 autonomous ground software would adjudicate the priorities and science gathering opportunities, publish the daily mission plan, and uplink to the space vehicle for the next day's scheduled activities. EO-1 would then send the data directly to the scientist requesting the data. "By automating the daily sequence generation process and by encapsulating the system operation specific knowledge, this allowed spacecraft commanding by untrained, non-operations personnel, hence allowing significant reductions in mission operations workforce, cost and schedule. This achieved the goal of allowing direct user commanding, commanding by scientists globally" (JPL, 1999).

EO-1 used autonomous mission planning and mission management software that operated on-aboard the spacecraft, called Continuous Activity Scheduling Planning Execution and Replanning (CASPER) mated with a component on the ground to take scientists' daily inputs from around the globe and close the autonomy loop, called Automated Scheduling and Planning ENvironment (ASPEN). CASPER leverages iterative repair techniques to guide continuous updating and modification of a current mission plan in reaction to dynamic and developing operating context, in support of automated planning and scheduling, planning and execution, and replanning (JPL, AI at JPL CASPER, 2017). ASPEN, based on AI algorithm techniques, "is a modular, reconfigurable application framework which is capable of supporting a wide range of mission planning and scheduling domains. ASPEN provides a set of reusable software components that implement the elements found in complex planning and scheduling

systems, including a resource management system, an expressive modeling language, a temporal reasoning system, plan optimization, heuristic search, iterative repair, scalable autonomy, reconfigurable framework, and a user-friendly graphical interface" (Alex S. Fukunaga, 1997). These mission planning automation innovation examples are well documented and detailed in over 29 peer-reviewed publications for use on future systems (JPL, 1999).

A current launch system in development by NASA and many global contractors is the Space Launch System (SLS). The SLS program has not yet completely defined specific mission or affordability requirements beyond its initial development test flights but the program is identifying opportunities to promote affordability moving forward (GAO, 2014) This is an excellent opportunity for applying the results from this research.

2.4 Space Launch Processes

The "process of placing a payload into Earth orbit is not a simple or speedy task. Lieutenant Colonel David E. Lupton in his book, *On Space Warfare: A Space Power Doctrine*, describes the launch process as similar to building an ocean liner from scratch, sailing it from Europe to the United States, and when within sight of land, using a rowboat to reach the shore while scuttling the ocean liner" (Lupton, 1988). This is an excellent analogy of the space launch process in place today.

Rocket launches have traditionally been accomplished from terrestrial sites, from at sea, and from the air. Once the mission is identified, followed by the payload and mission orbit required, the launch system and appropriate launch site(s) become apparent.

The United States federal government has available the "electronic code of federal regulations (e-CFR) that covers Aeronautics and Space, under Title 14. The Code of

Federal Regulations (CFR) is the codification of the rules published in the Federal Register by the various departments and agencies of the Federal Government. The Office of the Federal Register updates the material in the e-CFR daily. It is divided into 50 titles that represent broad areas that are subject to Federal regulation" (U.S. Government Publishing Office (GPO), 2018). Chapters 1 through 6 cover regulations for the various aeronautics and space domains, with chapters 1, 3, and 4 applicable to space launch, as summarized in Table 2.4-1.

Table 2.4-1 Federal Regulations – Title 14 Aeronautics and Space (eCFR, 2018)

Title	Volume	Chapter	Browse Parts	Regulatory Entity
Title 14 Aeronautics and Space	1	I	1-59	FEDERAL AVIATION ADMINISTRATION, DEPARTMENT OF TRANSPORTATION
	2		60-109	
	3		110-199	
	4	II	200-399	OFFICE OF THE SECRETARY, DEPARTMENT OF TRANSPORTATION (AVIATION PROCEEDINGS)
		III	400-1199	COMMERCIAL SPACE TRANSPORTATION, FEDERAL AVIATION ADMINISTRATION, DEPARTMENT OF TRANSPORTATION
	5	V	1200-1299	NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
		VI	1300-1399	AIR TRANSPORTATION SYSTEM STABILIZATION

2.4.1 Terrestrial-Launch Processes

Terrestrial range costs are rising significantly. "Terrestrial range costs have escalated as the ground-based infrastructure has aged. Range services now account for up to 35% of launch costs" (Aviation Week & Space Technology, 2012). The key United States launch sites are on the Eastern Range located at Cape Canaveral Air Force Station (CCAFS), Florida, which serves Kennedy Space Center (KSC) next to it, and on the Western Range located at Vandenberg Air Force Base, California. Additionally, the Wallops Island facility in Virginia can launch a number of smaller commercial launch

vehicles and sounding rockets (James R. Wertz, 2011). Each have their own legacy processes and aging infrastructure.

"The National Defense Authorization Act (NDAA) mandates the Department of Defense to undertake a program to modernize the infrastructure and improve support services on the Eastern and Western launch ranges in Florida and California" (Messier, 2017). The measure has been approved by Congress and signed by the President (U.S. Congress, 2017).

The 2018 act reads, "The program shall include investments to improve operations at the Eastern and Western Ranges that may benefit all users, to enhance the overall capabilities of ranges, to improve safety, and to reduce the long-term costs of operations and maintenance. The act also includes measures to improve operations processes across both ranges to minimize the burden on launch providers and improvements in transparency, flexibility, and, responsiveness for launch scheduling" (U.S. Congress, 2017).

Issues at ranges are numerous. "The Eastern Range, was recently closed for two weeks to catch up on 85 high-priority maintenance projects. The Western Range at Vandenberg Air Force Base in California uses radar range tracking systems that were built in the 1950's" (Messier, 2017).

These launch site locations were originally selected based upon public safety, weather, and orbital access energy considerations. The United States continues to hold human safety in the highest regard, so launch sites have been selected in remote regions or along coast lines in order to produce flight paths away from populated regions when

low in the atmosphere. Both ranges have allowable launch azimuths that prevent fly over habitable areas for safety and political considerations.

However, at least one other country has demonstrated launches over highly populated regions and many civilian injuries and deaths have occurred. China, for example, has three out of its four primary launch sites located deep inland, hundreds of miles from open water (Koren, 2018). The nominal expendable stages have fallen onto towns as well anomaly missions raining debris onto towns. A large part of United States launch site policy, processes, and planning deal with human safety and impact overall timelines.

The Eastern Range extends from the "launch pads at Cape Canaveral Air Force Station and the adjacent John F. Kennedy Space Center, and extends eastward over the Atlantic Ocean to 90 degrees East longitude in the Indian Ocean, where it meets the Western Range. Range safety limitations restrict launches from CCAFS to orbital inclinations from 28.5 to 57 degrees to prevent overflights of the Bahamas and Newfoundland, or launch limits between 37° and 114° azimuth. As of 2017, the Eastern Range has supported and managed more than 3,500 launches" (45th Space Wing, 2017).

The Eastern Range is managed by the United States Air Force, 45th Space Wing, headquartered at nearby Patrick Air Force Base, and maintains a new customer information web site for customers wishing to conduct operations on the Eastern Range. The new customer process flow chart, new customer worksheet, new customer survey, and Range Users' Guide (RUG) are among the resources available (45th Space Wing, 2018). The 45th Space Wing has instituted Range 2020 initiatives to examine current range operations and develop new innovative methods to support the commercial space industry, which this research could support.

The Western Range "extends from the West Coast of the United States to 90 degrees East longitude in the Indian Ocean where it meets up with the Eastern Range. The primary site, Vandenberg Air Force Base (VAFB), is ideally suited for polar and retrograde launches with inclinations from 70 to 104 degrees," or launch limits between 201° and 158° azimuth (Vandenberg Air Force Base, 2018).

The Western Range is managed by the Air Force, 30th Space Wing, located on VAFB. They maintain a new customer information web site, as well, for customers wishing to conduct operations on the Western Range (USAF VAFB, 2018).

Many states are now developing their own commercial space ports, for the purpose of enabling business in commercial space, special events, and tourism. The FAA-licensed spaceports in development today are listed in Table 2.4-2 (Sheetz, 2017).

The FAA gave Houston authority to build America's 10th commercial space port in 2017. The states are supporting space tourism, targeting sub-orbital flights. "Thanks to the early excitement and momentum, spaceport projects have attracted international attention, and countries around the world have announced plans for building commercial launch facilities" (Launchspace Staff, 2017). These state and commercial partnerships could help develop additional rapid launch technologies and processes.

"Ten spaceports are quietly driving the commercial space industry, and the FAA says another half-dozen locations are knocking on the door. The FAA is working to resolve the enduring conflict between aircraft and spacecraft, as the number of rocket launches increases exponentially. Spaceports are economic drivers. One CEO says the money really is in the vehicle operators" (Sheetz, 2017). More efficient processes will be critical to their success.

Table 2.4-2 FAA-Licensed Spaceports

	Operator	Space Port	Location	License Expires
1.	New Mexico Spaceflight Authority	Spaceport America	Truth or Consequences, NM	Dec. 14, 2018
2.	Mojave Air & Space Port	Mojave Air and Space Port	Mojave, CA	Dec. 14, 2018
3.	Virginia Commercial Space Flight Authority	Mid-Atlantic Regional Spaceport	Wallops Flight Facility, VA	Dec. 18, 2017
4.	Jacksonville Aviation Authority	Cecil Field	Jacksonville, FL	Jan. 10, 2020
5.	Oklahoma Space Industry Development Authority	Oklahoma Air and Space Port	Burns Flat, OK	Jun. 11, 2021
6.	Houston Airport System	Ellington Airport	Houston, TX	Jun. 25, 2020
7.	Space Florida	Cape Canaveral Air Force Station	Kennedy Space Center, FL	Jun. 30, 2020
8.	Midland International Airport	Midland International Air and Space Port	Midland, TX	Sept. 14, 2019
9.	Harris Corporation	California Spaceport	Vandenberg Air Force Base, CA	Sept. 18, 2021
10.	Alaska Aerospace	Pacific Spaceport Complex	Kodiak Island, AK	Sept. 23, 2018

2.4.2 Sea-Launch Processes

The unique Sea Launch Zenit-3SL system was created in the post-cold war era to attract rocket scientists from Russia in a joint venture with the United States, before they went to other countries. Sea Launch's secondary goal was to "address the commercial satellite market need for more reliable and affordable launch services. The unique multi-national system draws on the considerable engineering experience of the aerospace

industry leaders from the Russian Federation, the Ukraine, the United States, as well as the extensive maritime expertise from Norway" (Sea Launch SA, 2018).

"The Sea Launch Zenit-3SL launch system is comprised of three system segments: the Rocket Segment, the Marine Segment, and the Home Port Segment. Each of these segments are required at some point during the launch campaign in order to launch the customer's spacecraft into space" (Sea Launch SA, 2018). Sea launch has the advantage of being able to vary its launch point, optimizing the energy to orbit. Most of its payloads have been geostationary communications satellites, launching from the equator, which optimizes the energy required and saves cost. Customers include "DirecTV, XM Satellite Radio, PanAmSat, Thuraya, and EchoStar. The rocket and its payload are assembled on a converted cruise ship called Sea Launch Commander in Long Beach, California. It is then transferred to a converted ocean oil platform to on top of the self-propelled Ocean Odyssey and both sail to the equatorial Pacific Ocean for launch. The Sea Launch Commander serves as the command center. The sea-based launch system means the rockets can be launched from the optimum location on Earth's surface, considerably increasing payload capacity while reducing launch costs compared to fixed terrestrial-based systems" (Amos, 2011).

"Advantages of equatorial launch sites include the rotational speed of the Earth is greatest at the equator, providing an extra launch energy boost. By launching from zero degrees latitude on the surface, the need for an orbital plane change to the zero degree inclination of geostationary orbit is eliminated, providing a major extra launch energy advantage. This allows 17%-25% more mass to be launched to geostationary orbit than

the same rocket launched from Cape Canaveral, for example, which is located at 28.5 degrees north latitude" (Amos, 2011).

Another important attribute of launch location selection is providing better safety to the public. Ocean-based has an advantage over conventional land-based launch locations due to it reduces risk related to launching over populated areas. "Also, almost no range conflicts with other launch systems, a near total absence of overhead air or ship traffic," and minimal contention for communication and tracking resources and frequencies that would constrain launch (Amos, 2011).

However, the sea system travels slowly to the launch point. The command ship travels the 3,000 mile journey in 8 days on average, whereas the platform in 11 days, on average. The weather along the journey and at the equator can be a concern. These constraints can greatly impact overall mission timelines, especially important for precise launch time missions (Amos, 2011).

2.4.3 Air-Launch Processes

Air-launch processes have the potential of being abstracted from contested terrestrial resources, launch azimuth constraints, fixed launch points, timing constraints, and some required approving and service providing agencies. "The unique mobile capability of an air-launch system provides versatility, flexibility, reduced constraints, and speed to the payload customer. The air-launch vehicle can optimize desired orbit requirements based on the initial launch location, as well as accommodate integration of the spacecraft at a customer desired location anywhere in the world" (Orbital ATK, Pegasus, 2015).

For example, after final buildup of the rocket the Pegasus air-launch system "was mated to the Orbital ATK Carrier Aircraft and ferried to Madrid, Spain, to integrate Spain's MINISAT-01 satellite in 1997. Pegasus was then ferried to the island of Gran Canaria for launch, following integration of the satellite payload. The successful launch of Spain's MINISAT-01 satellite demonstrated Pegasus' ability to accommodate the payload provider's processing and launch requirements at locations better suited to the customer rather than the launch vehicle" (Orbital ATK, Pegasus, 2015).

Air-launch systems can also fly to the optimal launch point for optimized energy, mission timing, and ultimately launching sooner. Terrestrial fixed launch sites must wait for the orbit to pass over head or expend additional energy to chase the desired orbit from a fixed-site.

However, traditional air-launch systems that have relied on heavily modified aircraft have turned out to negate some of the cost savings and other benefits. Orbital Sciences Corporation Pegasus uses a "heavily modified Lockheed L-1011 airliner and is one of most expensive ways to launch small payloads to space" (Aviation Week & Space Technology, 2012). The Pegasus launch system unique aircraft, called Stargazer, is dedicated to just a few uses, conducting launches or scientific research. So it must bear the full cost of maintenance, take time to fly from its home hangar to a launch range, and is not always available being just a single contested and aging asset.

The Scaled Composites White Knight and White Knight Two series are a jet-powered custom built carrier aircraft used to launch experimental spacecraft, such as the Scaled Composites' SpaceShipOne, SpaceShipTwo, and SpaceShipThree series. This carrier aircraft is primarily dedicated to the launch mission, so again, launch missions must bear

the cost of the non-recurring and recurring aircraft costs. This system is the world's first passenger carrying spaceship to be operated in commercial service and built by a private company, in collaboration with Virgin Galactic (Malik, 2008), although targeting suborbital missions. "Virgin Galactic is a space tourism spaceflight company within the Virgin Group. It is developing commercial spacecraft with the goal to provide suborbital spaceflights to the space tourism market, as well as suborbital launches for high altitude science missions" (Malik, 2008)

Virgin Galactic is developing an orbital version of an air-launch system, using a Boeing 747, called Cosmic Girl. As a former passenger airplane operated by Virgin Atlantic, she was purchased by Virgin Galactic in 2015 to be used as the first stage launch platform, or mother ship, for the air-launch stage of the small satellite orbital launch vehicle, the Mark II LauncherOne. The aircraft was transferred to the orbital launch subsidiary, Virgin Orbit, and her livery updated to Virgin Orbit livery in 2017. Her first LauncherOne launch is planned for late 2018 (RocketLaunch.Live, 2018).

Virgin Orbit is "competing against companies like Rocket Labs, which performed its first flight test in May, and Vector Space, which flew a prototype rocket the same month. These companies want to be the first to provide rapid launches to small satellite-makers, a market that remains underserved by companies like SpaceX and Arianespace that built businesses around flying the largest, heaviest satellites into orbit. Analysts suspect competing on the low-end could be a billion dollar opportunity. Virgin Orbit's goal is to allow customers to go from contract to launch in just six months, compared to the 18 months or 24 of lead-time common in the launch industry" (Fernholz, 2017).

The air-launched ASAT system in the 1980's successfully demonstrated rapid launch processes with a minimally modified "F-15 Eagle fighter aircraft" and an "ASM-135 ASAT missile." A minimally modified carrier aircraft allows it to be used for other purposes until needed for the launch mission, greatly reducing cost. Additionally, with over 200 in the inventory spread out over the globe, the chances are high that one will be available when needed and close to a desired launch point (Grier, 2009).

2.5 Launch Approvals and Launch Day Service Providers

A significant series of collaborative efforts required in the launch process deals with launch approvals from government agencies and coordination with various launch service providers. Stakeholders that can have a significant impact on the schedule leading up to and during the day of launch include the following for terrestrial launches; range safety, range operations, United States Coast Guard (USCG), National Geospatial-Intelligence Agency (NGA), the Joint Space Operations Center (JSpOC), Federal Aviation Administration (FAA), payload provider(s), communications relay providers (e.g. NASA), weather reporting agencies (e.g. NOAA, NWS, USAF), and factory support companies. For air-launches, assuming launch release from greater than 100 nautical miles (nm) off the coast, the first three stakeholders are not required. The USCG supports any keep-out zones up to 100 nm off our coasts, whereas, NGA controls our waters beyond 100 nm from the coast lines. Air-launches do add a unique stakeholder, the launch assist aircraft (LAAC) provider (e.g. F-15E Strike Eagle System Program Office), for asset and crew scheduling, and aircraft mission planning. A summary of the stakeholder coordination required for a typical launch is shown in Figure 2.5-1

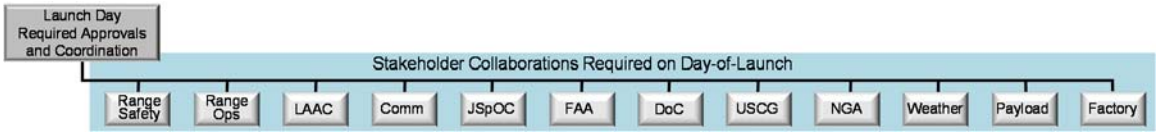


Figure 2.5-1 Launch Approvals and Coordination Required for Day-of-Launch

A new player in the launch process has been announced, United States Department of Commerce, Office of Space Commerce. Their goals cover development of a new space mission authorization framework and improvements to the commercial remote sensing licensing process covering all United States commercial space activities beyond the jurisdictions of FAA and FCC. Additionally, their goals include improvements regarding export controls affecting commercial space activities, communications spectrum policy, and improvements in commercial space transportation licensing (Office of Space Commerce, 2018). Commerce pledges support for the commercial space industry, and helping to speed up the access to space process (U.S. Department of Commerce, 2018).

Space situational awareness is currently provided by the Defense Department, e.g. JSpOC. The Department of Commerce will be responsible for providing "space situational awareness for public and private use." Government and private organizations will share data, technical guidelines, and safety standards (FAA, 2018).

The National Space Council has four recommendations signed into effect in the near future: Streamlined launch licensing to allow the same license at multiple sites, Secretary of Commerce oversees "non-traditional" space activities, spectrum coordination for ease of space activities, and review of export control policy (FAA, 2018).

2.5.1 Range Safety Coordination and Approvals

Range Safety organizations are in place "to protect people and assets on both the launch range and downrange under the trajectory path in cases when a launch vehicle might endanger them. For a rocket deemed to be off course, range safety may be implemented by something as simple as commanding the rocket to shut-down the propulsion system or by something as sophisticated as an independent Flight Termination System (FTS) that has redundant transceivers in the launch vehicle that can receive a command to self-destruct then set off charges in the launch vehicle to combust the rocket propellants at altitude. Range safety is usually the responsibility of a Range Safety Officer (RSO) affiliated with either the civilian space program led by NASA or the military space program led by the Department of Defense, through its subordinate unit the Air Force Space Command. At NASA, the range safety goal is for the general public to be as safe during range operations as they are in their normal day-to-day activities" (NASA Office of Safety and Mission Assurance, 2018).

Safety modeling and analysis that must occur prelaunch includes, nominal trajectory and expected variations from nominal, vehicle component reliability, vehicle failure modes, probabilities, and effects, wind modeling and debris-dispersion modeling, population modeling, debris-effect modeling, computation and application of safety metrics, flight hazard and flight caution area, blast effect modeling, toxic-effect modeling, impact limit lines, instantaneous impact point, destruct lines, and collision avoidance (Committee on Space Launch Range Safety, 2000). These analysis packages need to be further automated to reduce the turnaround time, or performed well in advance and rapidly updated on launch day for current conditions and specific mission.

"For the first time of launches from the Eastern Range, responsibility for commanding self-destruct of the rocket, if necessary, lay with computers on board the launch vehicle, not a human-in-the-loop on the ground. If done correctly, an automated system is actually safer, more reliable than having a human in the loop, said Kennedy Space Center Director Bob Cabana" (Dean, 2017). "The successful launch with an Autonomous Flight Safety System (AFSS), was a historic game-changer, demonstrating technology that will improve safety, lower costs and enable more launches from the Eastern Range, said Brig. Gen. Wayne Monteith, commander of the Air Force's 45th Space Wing" (Dean, 2017).

With more users demanding rapid and efficient access to space, both the "Eastern and the Western Ranges have been faced with developing more innovative solutions to launch rockets without compromising public safety while accounting for aging infrastructure and recognizing that the wing has fewer resources and personnel accomplishing comparable and greater launch rates than before" (Herman, 2017). The Air Force and industry have been working to provide the capability to enhance the "ability to support more launches by expediting range turnaround times with more stringent safety standards and fewer people on console while reducing overall launch costs," while reducing reliance on aging range infrastructure (Herman, 2017). A recent innovation example helping to make this a reality is the AFSS.

2.5.2 Range Operations Coordination and Approvals

Range operations coordinates range assets that are available to support a launch, to include security, facilities, scheduling, data, voice, video networks, Radio Frequency (RF) communications, and tracking services (Patrick AFB, 2016). There may also be

multiple ranges involved in the coordination, e.g., launch range, take-off range, landing range, abort sites, and overflights over other ranges.

2.5.3 Launch Assist Aircraft (LAAC) Coordination and Approvals

For air-launch missions, an aircraft must be selected from the inventory and scheduled, as well as the mission plan developed for the flight crew based upon the launch mission plan received. For example, the F-15E Strike Eagle has a system program office (SPO) that coordinates the flight vehicles, flight crews, ground support equipment, and ground crews. The flight mission planners develop their flight plan to support the launch mission with their internal mission planning system, which ultimately tasks base assets, crews, and produces mission data loads for their aircraft. Aircrews "conduct detailed mission planning to support the full spectrum of missions, ranging from simple training to complex combat scenarios. Aircrews save the required aircraft, navigation, threat, and weapons data on a data transfer device that they load into their aircraft before flight" (DOT&E Office of the Secretary of Defense, 2013).

2.5.4 Communications Services Coordination

The launch vehicles requires support services such as space-to-ground communication resources. This can be accomplished by either ground tracking networks or space-based networks. If telemetry health and status information and commanding is required during assent, reliable RF communications is required. If something goes wrong, data will be required on the ground to be reconstructed and the anomaly cause or causes determined. Data received and recorded in either real-time, or received later from a "black-box" that survives the catastrophic event, is critical for engineering to fix the

issue(s) before next flight, and for gaining approval to fly again. Very little data or commands need to be sent to the launch vehicle during flight due to its autonomous nature. A command (or high powered series of tones) may need to be sent from the ground to the on-board flight termination subsystem (FTS) to self-destruct or terminate the engines if the vehicle goes off course and passes pre-established trajectory boundaries. However, with recent developments in the area of FTS, autonomous FTS (AFTS) systems, or autonomous flight safety systems (AFSS), are on the rise and are being tested and flown on vehicles, helping to eliminate one more communications link.

Due to the high velocities, accelerations, and altitudes, associated with rocket launches, few communications services can service launch vehicles. High velocities impact ground-tracking antenna slew rates and precision-pointing capabilities. High velocities also impact space-based communication relay services given antenna beam cone geometries, and beam-to-beam rapid switch over time capabilities. High accelerations impact receive and transmit frequency Doppler shifts so continuous frequency adjustment must be made at either end (Irfan Ali, 2001). High altitudes can result in flying outside of the space-based antenna cone angle, since the beams are normally oriented to overlap on the ground, for land/air/sea communications, typically not for high altitude vehicles. As for the ground-tracking systems, high altitude impacts signal strength link margin and auto-tracking abilities (Elbert, 2001).

2.5.5 JSpOC Coordination

JSpOC coordinates the continuous detection, tracking, and identification of "all artificial objects in Earth orbit. JSpOC accomplishes this by tasking the Space Surveillance Network (SSN), a worldwide network of 30+ space surveillance sensors, to

observe the objects. These sensors includes radar and optical telescopes, both military and civilian systems." Launch systems coordinate with JSpOC prior to each launch, to ensure planned trajectories do not come near other orbiting objects. JSpOC performs conjunction assessment (CA) prior to launch and the results are an input into the final mission planning process and launch go/no-go decision (U.S. Strategic Command, 2016).

The JSpOC's CA process identifies close approaches between active satellites and other cataloged space objects. Collision avoidance (COLA) is the process of planning and possibly executing a maneuver in response to a close approach identified during the CA process. The JSpOC performs CA and provides COLA support for all satellite operators as an emergency service to ensure spaceflight safety. Owner/operators who have signed a Space Situational Awareness (SSA) Sharing Agreement with USSTRATCOM may request Advanced CA and COLA through the Orbital Data Request (ODR) process.

If the Owner/operator designates it as "Special" the JSpOC will treat it as high-interest and screen it as soon as possible. If it is designated as "Operational" the JSpOC will screen it according to the routine daily schedule. Results for Special ephemeris are provided within 1-4 hours of receiving the ephemeris, and Operational results are provided within 4-8 hours of the scheduled screening times (JFCC SPACE, 2017).

For our rapid launch construct, the "Special" category would support the turnaround times needed for evaluating several candidate trajectories (several nominal, and several off-nominal), according to the latest Spaceflight Safety Handbook for Satellite Operators, version 1.3, January 2017, published by the "Joint Functional Component Command for Space (JFCC Space)," and JSpOC (JFCC SPACE, 2017).

Given the recent decisions by the National Space Council, there will be a tight partnership for the Space Traffic Management mission between JSpOC, the Department of Commerce, and the FAA (FAA, 2018).

2.5.6 FAA Coordination and Approvals

The FAA has an "Office of Commercial Space Transportation which handles launch licenses and permits." Its mission is to "ensure protection of the public, property, and the national security and foreign policy interests of the United States during commercial launch or reentry activities, and to encourage, facilitate, and promote United States commercial space transportation" (FAA, 2018).

On launch day the resulting air keep-out zone determined by mission planning must be sent to the FAA. The FAA will in turn "issue a notice to airmen (NOTAM)" about the area closure. "A Notice to Airmen (NOTAM) is a notice filed with the FAA to alert aircraft pilots of potential hazards along a flight route or at a location that could affect the safety of the flight," such as a rocket launch (FAA, 2018). An example of the information that must be sent to the FAA is shown in Figure 2.5-2 (DOT FAA, 2018).

Will provide to the local FAA control center the hazard areas and the associated start/stop time in the following format (sample latitude and longitudes included) :

FAA

Description (Area Number)	Hazardous Area (Area enclosed by connecting following points in order:)	Closure Time (Minutes From Liftoff, Normal)	Closure Time (Minutes From Liftoff, Malfunction)
(1) Launch Danger Zone - Air Craft Hit Area	(1) 28° 35′ N, 80° 36′ W (2) 28° 35′ N, 80° 23′ W (3) 28° 25′ N, 78° 16′ W (4) 28° 22′ N, 78° 16′ W (5) 28° 30′ N, 80° 27′ W (6) 28° 32′ N, 80° 36′ W and to the beginning.	3	23 (if malfunction occurs during first 3 minutes of flight)
(2) First Stage, Skirt Ring & Payload Fairing Impact Area (a)	(1) 28° 01′ N, 73° 33′ W (2) 28° 02′ N, 73° 00′ W (3) 27° 47′ N, 71° 00′ W (4) 27° 34′ N, 70° 00′ W (5) 27° 12′ N, 71° 00′ W (6) 27° 16′ N, 71° 00′ W (7) 27° 32′ N, 73° 00′ W (8) 27° 45′ N, 73° 53′ W and to the beginning.	27	27

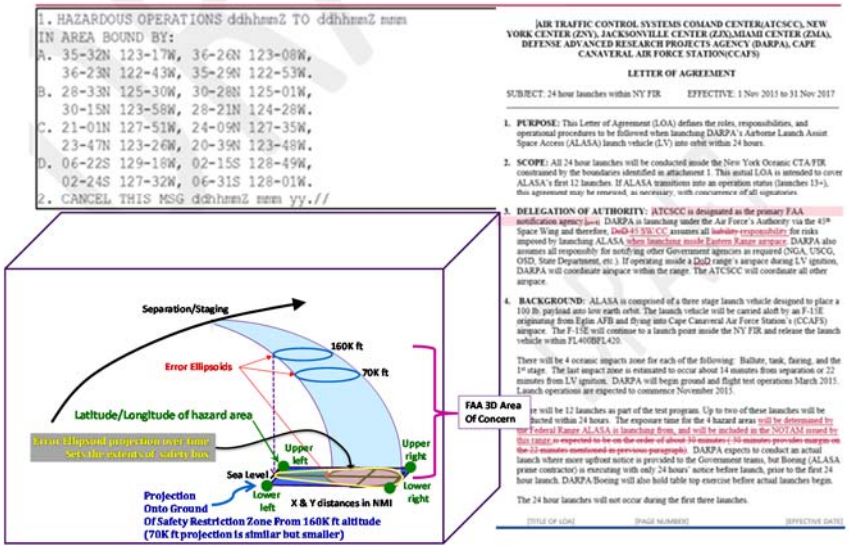
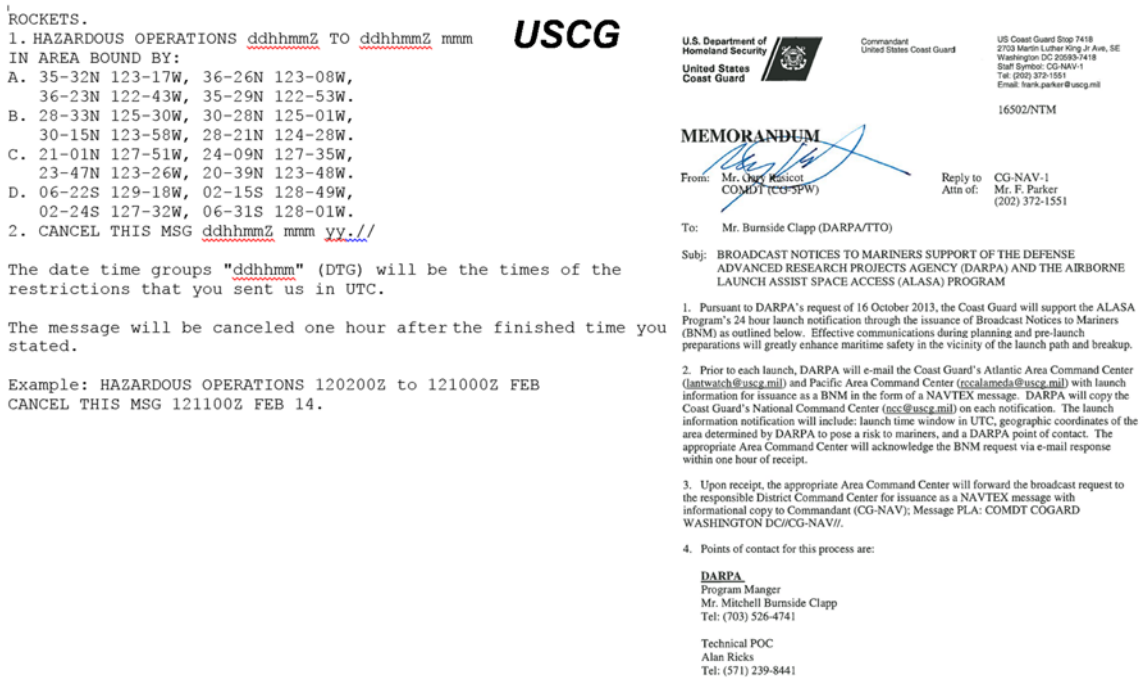


Figure 2.5-2 FAA NOTAM Data Content and Format with MOU Example

The United States "commercial space-launch industry has experienced significant growth in the past half-decade. The FAA reported in 2016 that its licensed launches have increased 60% and industry revenue has increased 471% since 2012" (GAO, 2016). The GAO reported "that the industry has experienced growth in the number and complexity of launches and growth in demand for space launches" (GAO, 2016). The FAA is currently evolving to adapt to the rapidly changing space industry that is "developing new types of reusable launch vehicles which could reduce launch costs" (GAO, 2015).

2.5.7 United States Coast Guard (USCG) Coordination

The USCG supports launches by notifying ship traffic of upcoming launches and the associated keep out zones on the sea surface. The launch vehicle mission planning function generates Monte Carlo nominal and off-nominal trajectories that generate instantaneous impact points (IIP) maps on the Earth surface in the case of an anomaly. This resulting surface area keep-out zones and timing information is sent to USCG in order for Local Notices to Mariners (LNM) to be issued. The USCG issues LNMs and they are updated weekly and available for download by the marine community, as shown in Figure 2.5-3.



ROCKETS.
1. HAZARDOUS OPERATIONS ddhhmmZ TO ddhhmmZ mmm
IN AREA BOUND BY:
A. 35-32N 123-17W, 36-26N 123-08W,
36-23N 122-43W, 35-29N 122-53W.
B. 28-33N 125-30W, 30-28N 125-01W,
30-15N 123-58W, 28-21N 124-28W.
C. 21-01N 127-51W, 24-09N 127-35W,
23-47N 123-26W, 20-39N 123-48W.
D. 06-22S 129-18W, 02-15S 128-49W,
02-24S 127-32W, 06-31S 128-01W.
2. CANCEL THIS MSG ddhhmmZ mmm yy.//

The date time groups "ddhhmm" (DTG) will be the times of the restrictions that you sent us in UTC.

The message will be canceled one hour after the finished time you stated.

Example: HAZARDOUS OPERATIONS 120200Z to 121000Z FEB
CANCEL THIS MSG 121100Z FEB 14.

USCG

U.S. Department of Homeland Security
United States Coast Guard

Commandant
United States Coast Guard

US Coast Guard Stop 7418
2703 Martin Luther King Jr Ave, SE
Washington DC 20593-7418
Staff Symbol: CG-NAV-1
Tel: (202) 372-1551
Email: frank.parker@uscg.mil

16502/NTM

MEMORANDUM

From: Mr. Gary Rasicot
COMDT (CG-5PW)

Reply to Attn of: CG-NAV-1
Mr. F. Parker
(202) 372-1551

To: Mr. Burnside Clapp (DARPA/TTO)

Subj: BROADCAST NOTICES TO MARINERS SUPPORT OF THE DEFENSE ADVANCED RESEARCH PROJECTS AGENCY (DARPA) AND THE AIRBORNE LAUNCH ASSIST SPACE ACCESS (ALASA) PROGRAM

1. Pursuant to DARPA's request of 16 October 2013, the Coast Guard will support the ALASA Program's 24 hour launch notification through the issuance of Broadcast Notices to Mariners (BNM) as outlined below. Effective communications during planning and pre-launch preparations will greatly enhance maritime safety in the vicinity of the launch path and breakup.

2. Prior to each launch, DARPA will e-mail the Coast Guard's Atlantic Area Command Center (lantwatch@uscg.mil) and Pacific Area Command Center (rccalameda@uscg.mil) with launch information for issuance as a BNM in the form of a NAVTEX message. DARPA will copy the Coast Guard's National Command Center (ncc@uscg.mil) on each notification. The launch information notification will include: launch time window in UTC, geographic coordinates of the area determined by DARPA to pose a risk to mariners, and a DARPA point of contact. The appropriate Area Command Center will acknowledge the BNM request via e-mail response within one hour of receipt.

3. Upon receipt, the appropriate Area Command Center will forward the broadcast request to the responsible District Command Center for issuance as a NAVTEX message with informational copy to Commandant (CG-NAV); Message PLA: COMDT COGARD WASHINGTON DC//CG-NAV//.

4. Points of contact for this process are:

DARPA
Program Manger
Mr. Mitchell Burnside Clapp
Tel: (703) 526-4741

Technical POC
Alan Ricks
Tel: (571) 239-8441

Figure 2.5-3 USCG LNM Data Content and Format with MOU Example

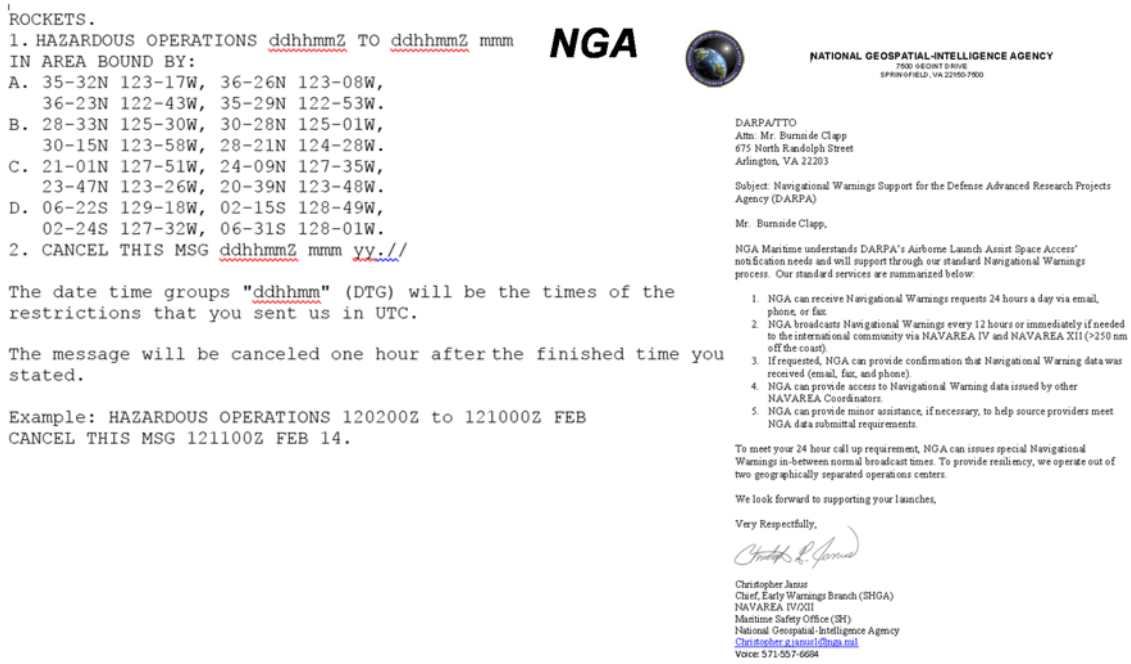
The USCG manages waters close to our coast lines. It operates under the United States Department of Homeland Security during peacetime (USCG, 2018). The National Geospatial-Intelligence Agency (NGA) manages the waters beyond the USCG domain.

2.5.8 National Geospatial-Intelligence Agency (NGA) Coordination

NGA "delivers geospatial intelligence that provides a decisive advantage to warfighters, first responders," intelligence professionals, and policymakers. Any user who flies a United States aircraft, sails a United States ship, is engaged in national conflicts, searches for targets, responds to natural disasters, makes national policy decisions, or even navigates with a hand held device, relies on NGA (NGA, 2018). NGA, "as a member of the Intelligence Community and the Department of Defense, enables all of these critical actions and influences decisions that impact our world through the key discipline of geospatial intelligence (GEOINT). NGA ensures safety of navigation on the seas and in the air by maintaining the most current information and highest data integrity for government and commercial users, such as United States military forces and global transport networks. NGA also assists in disaster relief and humanitarian efforts by working directly with the lead federal agencies responding to earthquakes, floods, fires, hurricanes, landslides or other natural or manmade disasters" (NGA, 2018).

The Maritime Safety Office gathers, analyzes, organizes, and provides "worldwide marine navigation products and databases. It is responsible for maritime safety and hydrographic activities including support to the worldwide portfolio of NGA and National Oceanic and Atmospheric Administration (NOAA) standard nautical charts and hardcopy and digital publications. The office coordinates the worldwide Navigational Warning Service's NAVAREA IV and NAVAREA XII safety messages, an essential part of the Global Maritime Distress and Safety System" (NGA, 2018).

Similar to the USCG, the launch vehicle mission planning function generates Monte Carlo nominal and off-nominal trajectory dispersions that generate instantaneous impact points (IIP) maps on the Earth surface in the case of an anomaly. This surface area keep-out zones and timing information is sent to NGA in order for Notices to Mariners (NtMs) to be issued. The NGA issues NtMs and they are updated weekly and available for download by the marine community, as shown in Figure 2.5-4.



ROCKETS.
1. HAZARDOUS OPERATIONS ddhhmmZ TO ddhhmmZ mmm
IN AREA BOUND BY:
A. 35-32N 123-17W, 36-26N 123-08W,
36-23N 122-43W, 35-29N 122-53W.
B. 28-33N 125-30W, 30-28N 125-01W,
30-15N 123-58W, 28-21N 124-28W.
C. 21-01N 127-51W, 24-09N 127-35W,
23-47N 123-26W, 20-39N 123-48W.
D. 06-22S 129-18W, 02-15S 128-49W,
02-24S 127-32W, 06-31S 128-01W.
2. CANCEL THIS MSG ddhhmmZ mmm yy.//

The date time groups "ddhhmm" (DTG) will be the times of the restrictions that you sent us in UTC.

The message will be canceled one hour after the finished time you stated.

Example: HAZARDOUS OPERATIONS 120200Z to 121000Z FEB
CANCEL THIS MSG 121100Z FEB 14.

NGA

NATIONAL GEOSPATIAL-INTELLIGENCE AGENCY
7500 GEOINT DRIVE
SPRINGFIELD, VA 22150-7500

DARPA/TTO
Attn: Mr. Burnside Clapp
675 North Randolph Street
Arlington, VA 22203

Subject: Navigational Warnings Support for the Defense Advanced Research Projects Agency (DARPA)

Mr. Burnside Clapp,

NGA Maritime understands DARPA's Airborne Launch Assist Space Access' notification needs and will support through our standard Navigational Warnings process. Our standard services are summarized below:

1. NGA can receive Navigational Warnings requests 24 hours a day via email, phone, or fax.
2. NGA broadcasts Navigational Warnings every 12 hours or immediately if needed to the international community via NAVAREA IV and NAVAREA XII (>250 nm off the coast).
3. If requested, NGA can provide confirmation that Navigational Warning data was received (email, fax, and phone).
4. NGA can provide access to Navigational Warning data issued by other NAVAREA Coordinators.
5. NGA can provide minor assistance, if necessary, to help source providers meet NGA data submittal requirements.

To meet your 24 hour call up requirement, NGA can issues special Navigational Warnings in-between normal broadcast times. To provide resiliency, we operate out of two geographically separated operations centers.

We look forward to supporting your launches,

Very Respectfully,

Christopher Janus
Chief, Early Warnings Branch (SHGA)
NAVAREA IV/XII
Maritime Safety Office (SH)
National Geospatial-Intelligence Agency
Christopher.j.janus1@nga.mil
Voice: 571-557-6684

Figure 2.5-4 NGA NtM Data Content and Format with MOU Example

2.5.9 Weather Services Coordination

Current and future prediction weather data is critical to the launch mission planning and operations process, to include terrestrial and space weather. Data can be received from local range weather stations, for surface weather near the launch, take-off, or landing sites, and from civil and military weather agencies for winds and weather aloft along the planned flight path. Space weather data is also important as an input to the mission planning process.

NOAA is a scientific civil agency within the United States Department of Commerce that focuses on the conditions of our planet, including the oceans and the atmosphere, from the ocean floors to the surface of the sun. NOAA's National Weather Service (NWS) analyzes weather data and provides weather forecasts, other weather-related products, and warnings of hazardous weather to organized groups and the public in order to provide general information and timely protection (DOC NOAA NWS, 2018).

An example of weather data products available is aviation weather data, experimental World Area Forecast System (WAFS) grids. The NWS produces "WAFS grids for wind, turbulence, cumulonimbus cloud, and icing is a graphical representation of the grids issued jointly by the World Area Forecast Centers (WAFCs) in the United States and the United Kingdom. These grids are approved by the FAA and the ICAO for use in flight planning. They are available for various altitudes from forecast 6 to 36 hours, in three hourly time step resolutions" in useful formats, such as GRIB2 (NOAA NWS, 2018).

Nearby ranges also periodically release high altitude weather balloons that can help give higher fidelity localized winds aloft, temperature, and humidity information to fold into mission planning and launch go/no-go decisions. Weather data from three meters altitude up through the various atmospheric layers are considered upper air or weather balloon data. "These data are received from balloon radiosondes, which are instrument packages tethered to balloons that are launched from the ground, ascend through the atmospheric layers, as high as 115,000 feet, and transmit back to a ground receiving station. These routine observations include vertical profiles of wind speed and direction, temperature, humidity, atmospheric pressure, and geopotential height" (NOAA NCEI, 2018).

Space weather is also a key component of mission planning. The NOAA NWS "National Centers for Environmental Prediction, Space Weather Prediction Center (SWPC)" provides timely data that could impact a launch decision or help select between multiple possible launch times (NOAA SWPC, 2018).

In addition to government weather agencies, commercial organizations such as spaceweather.com maintain real-time space weather forecast data compiled from a variety of sources and can provide frequent notifications (spaceweather.com, 2018).

2.5.10 Payload Provider(s) Coordination

The payload provider(s) may require health status and maintenance services while waiting for launch. Depending upon their power state and maintenance required on day of launch, the payload providers may have a role in the go/go decision for launch. As satellites are getting smaller with advancements in technology, more satellites are able to fit in the launch vehicle. Multiple payload providers is becoming the norm on most launches today. NASA reports, "in 2014, one hundred and thirty seven small spacecraft were launched versus forty eight larger spacecraft. Forecasts show that the balance will shift even more towards small spacecraft in the near future. State of the art technologies in launch vehicles, integration, and deployment systems are responding to the changing small spacecraft market to support new, advanced missions with diverse technologies that will take small spacecraft further into both space and the future" (NASA, 2018).

The housekeeping portion of a satellite that provides services to the payload, usually referred to as the satellite "bus", is decreasing is size every year. Many small spacecraft buses are becoming available from small as well as large aerospace companies in the United States, such as Millennium Space Systems, Ball Aerospace, Spaceflight

Industries, and Sierra Nevada Corporation in the United States, and Astro- und Feinwerktechnik Adlershof, Surrey Satellite Technology Ltd, Berlin Space Technologies GmbH in Europe. Very small "cubesat" buses, made up in units of 10 centimeter cubes, are available from Blue Canyon Technologies LLC, Pumpkin Inc, Tyvak Nanosatellite Systems Inc., and The Boeing Company in the United States, and many European companies, such as GomSpace ApS. "There are many suppliers providing space engineering services to design a turnkey small or miniaturized spacecraft platform customizable to your specific mission requirements" (NASA, 2018).

2.5.11 Factories Coordination

On launch day, if issues arise, cautionary or severe, timely reach back to the various factories or product manufacturers may be of critical importance. Factories maintain detailed design, testing, and performance data that could be useful to solve launch day issues. Leading up to launch day, factories assist in maintenance and status reporting. Maintaining communication with the factories and manufacturers associated with all of the ground and flight subsystems, hardware and software, can play a key role in timely mission execution.

2.6 Space Launch Automation Technologies

Launch vehicle work flow planning is a relevant and urgent application of planning and scheduling of complex systems requiring automation. "Space mission planning often requires modeling of complex operations constraints including instrument and subsystem timing, synchronization, power, thermal, geometry, data volume, communications, visibility, and space vehicle trajectory and pointing" (Steve A. Chien, 2012). Additionally, because spacecraft are high cost and present a high value to the end-users,

"a planning system must be highly reliable," robust and resilient, and produce operational products that "do not endanger the valuable system" or create collateral damage. Because of the complex and interdependent nature of launch operations, "priority, collaboration, and optimization are often involved, either implicitly or explicitly. Because of the vast potential for automated planning, collaboration, and operations tools to improve space missions, a long line of planning systems have been applied in a wide range of space missions planning applications. Examples include "ASPEN, Spike, TRANS, DCAPS, MAPGEN, Flexplan, MEXAR2, RAXEM, SKeyP, MUSE, and TerraSAR-X/TanDEM-X" mission planning systems (Steve A. Chien, 2012).

"Most of the mission planning systems share a common temporal or timeline-based approach to mission planning. In this timeline–based approach, the overall system being planned (the spacecraft and relevant ground systems state) is represented by a set of timelines. Each timeline tracks the reported (past) or projected values of the spacecraft states and resources. These planning systems therefore are performing some form of modeling and simulation of the target system being planned. This timeline-based modeling is then used to plan the target system in a manual, semi-automated, or fully automated scheme" (Steve A. Chien, 2012).

Areas for process acceleration can be identified and solutions developed for responsive space (Horais, 2004). "Many space mission planning problems may be formulated as hybrid optimal control problems, that is, problems that include both real-valued variables and categorical variables" (Englander, 2012). Petri nets, Bayesian networks, D*, and 3D A* algorithms are among the many approaches applied in mission planning automation (Lin Zhang, 2001) (Dicheva, 2014).

Technologies are available to improve ground support functions and can be used to enable rapid launch processes, examples of which are summarized in Table 2.6-1 (Hammond, 1999).

Table 2.6-1 Ground Technologies Available for Launch Systems

Ground Support	
Technology Family	**Desired Features**
Automated data management system	Reduce processing time, increase accuracy
Automated test and inspection	Reduce costs, decrease delays
Automated payload and launch system handling	Reduce costs, decrease delays
Built-in test equipment	Reduce costs, decrease delays
Artificial intelligence, expert systems	Reduce ground support resources
Augmented reality	Reduce training cost and schedule
Automated software development	Reduce timing, cost
Fault detection, isolation, and course of action	Reduce required resources, timing
Software automation and machine learning	Reduce required resources, timing

Technologies are available to improve mission control and operations functions and can be used to enable rapid launch processes, examples of which are summarized in Table 2.6-2 (Hammond, 1999).

Table 2.6-2 Mission Control and Operations Technologies Available for Launch Systems

Mission Control and Operations	
Technology Family	**Desired Features**
Computer integrated assembly, integration, test	Reduce assembly cost, schedule
Automated launch system handling, mission control	Reduce human activities, cost, schedule
Artificial intelligence, expert systems	Reduce human activities, cost, schedule
Augmented reality	Reduce training cost and schedule
Handling, servicing by robotic systems	Reduce human activities, cost, schedule
Automated training and logistics systems	Reduce training cost and schedule
Software automation and machine learning	Reduce human activities, cost, schedule

NASA's latest technology roadmap for "ground and launch systems" was published in 2015. "This technology area 13 (TA-13), for Ground and Launch Systems, is a roadmap that considers a wide range of needed technologies and development pathways required for the next 20 years" (through 2035). The guidance focuses on applied research

and development in critical need areas. "The clearest benefit from improved TA-13 technology candidates are reduced ground operations and maintenance costs to NASA programs at major launch sites, as well as the off-site test venues and command centers that support launch campaigns" (NASA, 2015).

Applied technologies that inspire and drive increased "automation, conservation, and ground operations team situational awareness will result in improvements across a broad range of tasks, in addition to reduced costs. These improvements include reduced costs of propellants and other fluids reduced logistics costs, reduced times required for ground processing and launch, reduced mission risk, reduced hazards exposure to personnel, and reduced areas cleared for launches" (NASA, 2015).

An example of requested technologies called out TA-13 is, "Autonomous Command and Control for Integrated Vehicle and Ground Systems. This includes intelligent planning and scheduling systems, multi-mission control rooms, immersive training systems, real-time data and voice loops connecting control rooms with remote operators, automated fault detection and isolation systems, system access personal confirmation technology, and concurrent multi-user three-dimensional situational information environment control rooms." Other examples includes autonomous radio frequency identification wireless instrumentation systems, ground software and test algorithms, integrated vehicle health management systems, temperature and pressure-sensitive paints, deployable advanced sensor networks for launch systems monitoring, "sensors for ground test facilities such as Rayleigh scattering, particle image velocimetry (PIV), and advanced non-conventional Schlieren photography techniques" (NASA, 2015).

Chapter 3 - Research Methodology

3.1 Research Questions and Research Objectives

Research questions include, 1. How do the processes by which launch missions are planned today differ? 2. What pre-launch planning activities can be done in parallel that are currently done in series? 3. Which manually intensive planning activities could be automated or accelerated with new methodologies? 4. What pre-launch planning activities could be performed well in advance of launch day, updated daily automatically waiting for launch order, and then require only minor updates on launch day? 5. What methods of launching, e.g. terrestrial-launch vs. air-launch, could contribute a significant role in rapid launch processes (RLP)?

Research objectives include evaluation of data to determine if a launch to orbit is achievable in 24 hours or less. Specifically, the research will identify a set of manually-intensive mission planning tasks that can be automated with statistical models and algorithm development applied to launch vehicle timeline simulations. The research can then develop an executable framework for mission and engineering managers which use these new timelines, and automation constructs.

Our hypotheses are as follows:

1. Space launch mission planning timelines can be reduced to <24 hours for supporting emerging tactical and responsive space missions.

2. A rapid mission planning framework can be developed that future project managers can use for their space missions.

3. The long duration and manually intensive tasks can be automated with statistical models and algorithms applied to launch vehicle simulations.

4. The required launch coordination with stakeholders, approving authorities and service providers can be accelerated with modern collaboration tools that support rapid launch goals.

Research Methodologies performed include modeling of a rapid launch process Monte Carlo simulation, with expert elicitation for model validation. A timeline executable model has been developed that enables a Monte Carlo simulation to be performed on the timing dispersions for launch day work tasks. This construct enables a project manager or engineer to run a statistical simulation of possible project outcomes based on optimistic, most likely, and pessimistic estimates. The results can be used as feedback to the project manager to adjust the timing and activity linkages until a 24-hour or less worst-case timing goal is achieved. Expert elicitation methodology is used for aggregating expert judgment inputs, to refine the data distribution and timing dispersion data, and validate the model. "Executing this model should be used to quantify uncertainty and improve decision-making. The goal should be to quantify uncertainty, not to remove it from the decision process" (Aspinall, 2010). A model sensitivity analysis was also performed. A methodology roadmap used in this research is shown in Figure 3.1-1.

Multiple launch system timelines were analyzed for the major tasks required on launch day. Tasks that could be accomplished well in advance of launch day and able to be placed "on-the-shelf" in preparation for launch day were identified and placed into the "non-recurring" activity bin. The remaining tasks required to be accomplished on launch

day were captured and analyzed. Mission requirements must be analyzed for each type of mission in order to refine launch day required tasks and task durations. A focus on air-launch mission type was assumed for this research in order to narrow the scope.

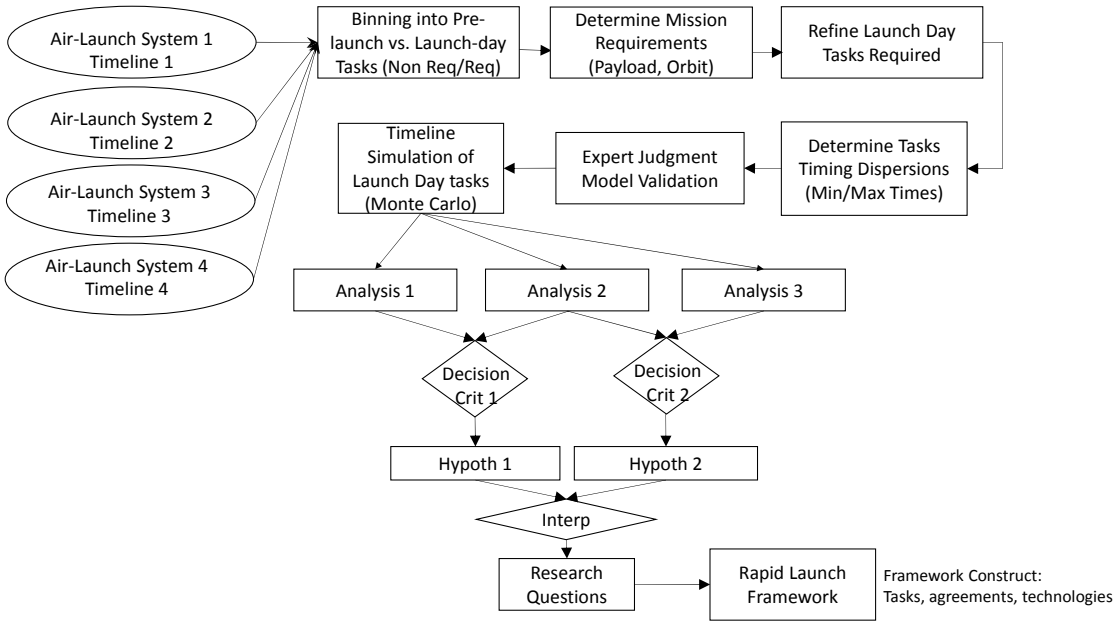


Figure 3.1-1 Methodology Map – Rapid Space Launch Operations

Work task timing dispersions are then determined, minimum (optimistic) and maximum (pessimistic) time estimates per task, based upon review of previous rapid launch mission data and experts elicitation inputs. The total mean times of all the tasks are then verified to add up to less than the mission schedule goal (e.g. ≤ 24 hours) before beginning the dispersions analysis process. Otherwise, serial vs. parallel tasks are analyzed, or task durations adjusted to reasonable values, with assumptions captured. Expert solicitation is iteratively used to validate the set of tasks for completeness and the values of each minimum and maximum time for accuracy, for a given set of assumptions. Experts in the field of space mission planning and launch operations were used.

First, a static model had to be constructed in order to serve as an input to the Monte Carlo simulation model later on. The method used to record, manage, and refine the launch day process static model was building the launch day plan in a project management software tool, using Microsoft Project. It is designed to assist a project manager or engineer in developing a plan, analyzing workloads, establishing linkages between tasks, and hence, determine the total duration of the plan.

In this tool environment the discrete tasks are able to be listed, organized, grouped, linkages established in the form of predecessors and successors, minimum and maximum task durations recorded, and then launch day mission duration determined more easily. The input data was obtained from historical rapid launch mission data and subject matter expert inputs. This process was iterated on until a mission duration fell under the timing goal, using expert elicitation during this refinement process, ensuring reasonable values and linkages were maintained. This resulting static architecture for a rapid launch mission could then be used as in input to a dynamic simulation.

Secondly, a dynamic model was built in a simulation environment for the purpose of determining if the overall timing goal can be met given uncertainty estimates for each task (e.g. launch in 24 hours or less). The Mathworks MATLAB Simulink, Microsoft Excel Visual Basic macros, and Microsoft Project with Full Monte (version 2017) plug-in simulation environments were used to analyze timing dispersions established for each task from expert elicitation.

A MATLAB Simulink simulation was developed for ingesting the schedule data and performing a dispersion analysis and worst-case analysis on mission timing. The timeline modeling construct development was conducted using MATLAB Simulink

SimEvents simulation. SimEvents provides a component library and discrete-event simulation engine for analyzing event-driven system models, such as user actions or received sensor inputs, and optimizing performance characteristics such as throughput, latency, and packet loss. Servers, routers, switches, queues, and other predefined blocks enable modeling routing, processing delays, and prioritization for communication and scheduling. Embedded timers measures time to launch and a Monte Carlo simulation is required to determine average time to launch.

Discrete-event state modeling techniques have been applied to space mission planning. Discrete-event simulations can be useful to model non-deterministic, discrete-event systems. They can be useful in analyzing resource contention, for example, congestion/bottlenecks/processing delays, system throughput, scheduling and routing. A discrete-event system (DES) is a system whose state changes based upon the occurrence of discrete-events. DES is used to model the movement of some physical "entity" through a process. Applications of DES include mission planning and business and operational processes, manufacturing processes, and service scheduling.

Mathworks provides a tool called SimEvents that leverages the power of MATLAB and Simulink to extend DES simulation and analysis capabilities. Additionally, the Optimization Toolbox can be leveraged to incorporate optimization into the simulation. The user can drive simulations from MATLAB scripts to perform parameter sweeps and sensitivity analysis (Ning, 2014). The high level simulation in MATLAB Simulink SimEvents Monte Carlo block diagram is shown in Figure 3.1-2.

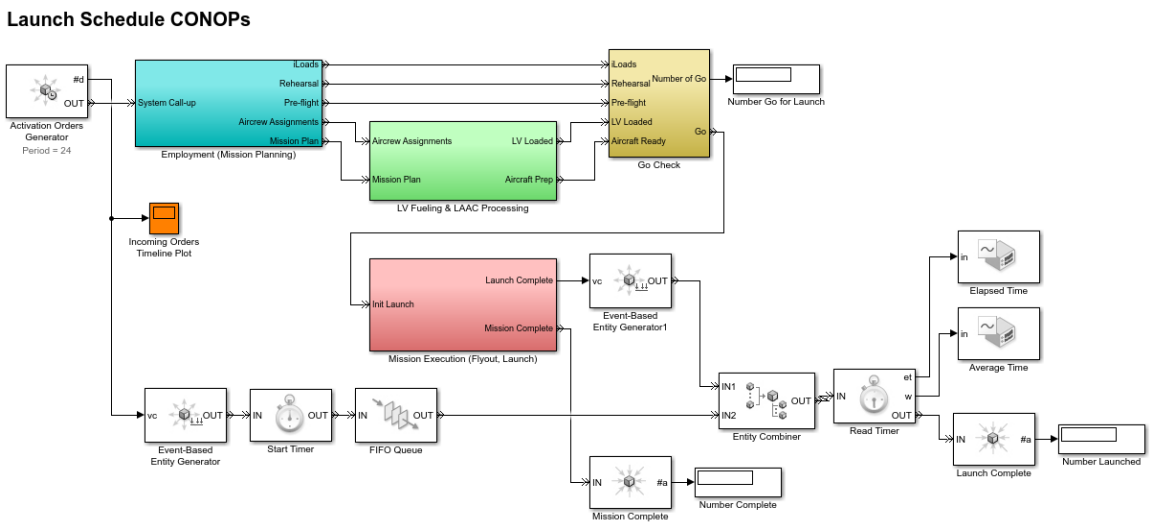


Figure 3.1-2 High Level Simulation Block Diagram

The employment of mission planning simulation block diagram detail is shown in Figure 3.1-3.

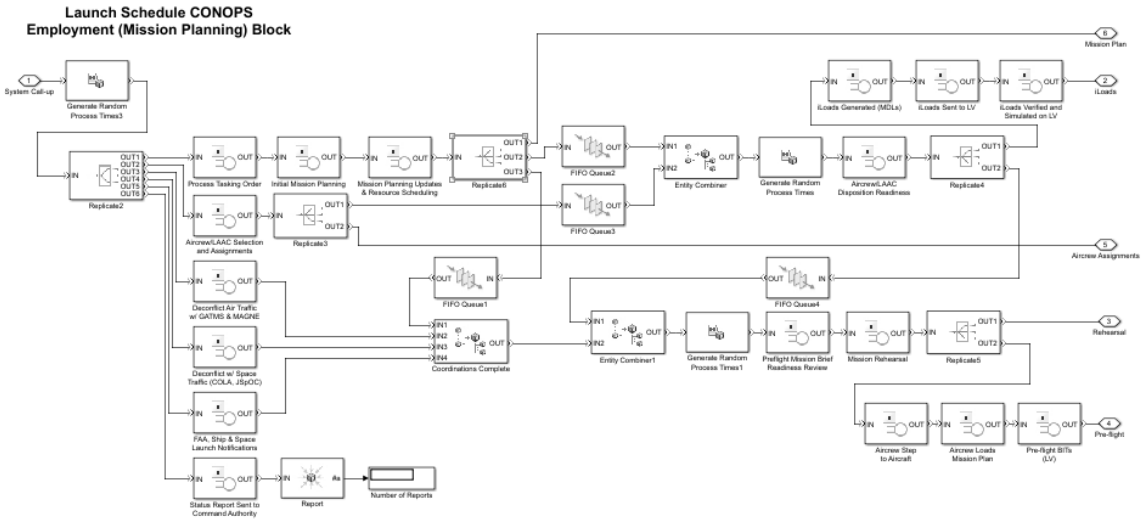


Figure 3.1-3 Employment - Mission Planning Simulation Block Diagram

The execution of launch vehicle fueling simulation block diagram detail is shown in Figure 3.1-4.

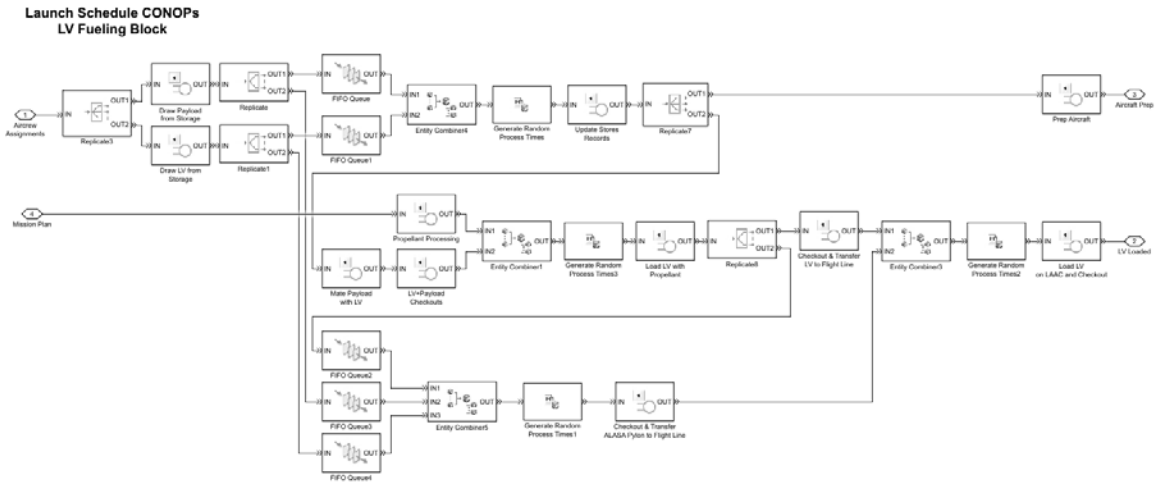


Figure 3.1-4 Execution - Launch Vehicle Fueling Simulation Block Diagram

The execution of launch block diagram detail is shown in Figure 3.1-5.

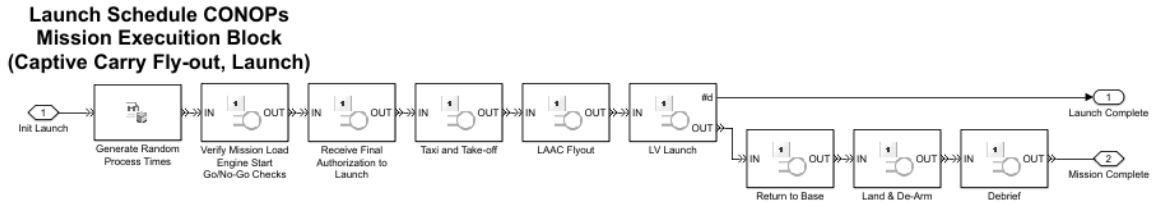


Figure 3.1-5 Execution - Launch Operations Block Diagram

The schedule is first built in a full project management COTS tool environment, Microsoft Project, for the purpose of achieving a completely linked schedule. The data is then exported to a CSV file for import into the MATLAB for simulation of schedule dispersions and performing of analyses, as illustrated in Figure 3.1-6.

Furthermore, a Microsoft (MS) Excel environment was then created to facilitate data-gathering and the subject matter experts reviewing of the data. A Visual Basic macro created within MS Excel allowed the experts to execute the model themselves during their review for immediate feedback allowing them to visualize the overall mission-timing and their change impact. The user simply has to enter the number of missions to iterate on and then type "Alt+F8" to execute the simulation themselves.

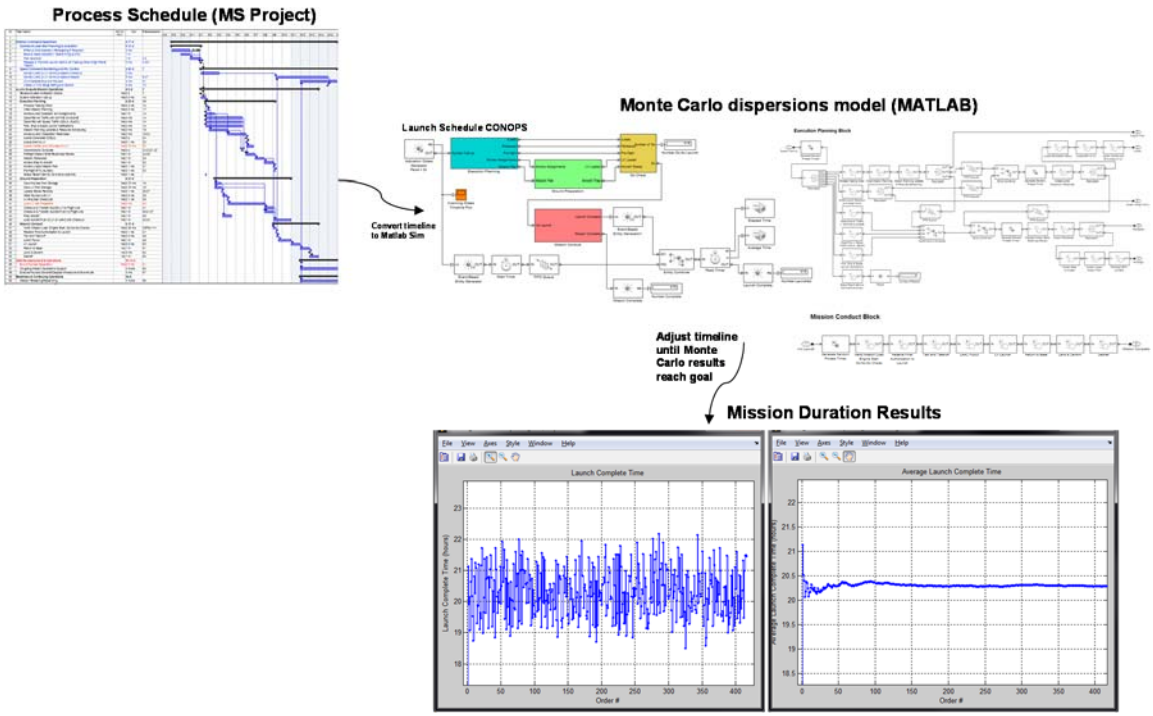


Figure 3.1-6 Timeline Modeling of Schedule Dispersions Using MATLAB Simulink

The macro loop counter represents the total number of missions specified as an input and the "Calculate" command performs a "calculate the entire workbook now" function, which regenerates a new random-draw for every task, records the resulting total mission duration on the next row down, and builds a plot during execution, plotting total mission time duration vs. mission number.

The inputs to the model are input times (minimum and maximum values for each task), total mission duration goal, and total number of mission to simulate. The model first calculates the mean and standard deviation for each task based upon the minimum and maximum task times. Then a random time is generated that falls between each minimum and maximum task time limits. The model then executes a Monte Carlo simulation on the entire schedule, generating new random draws for each task before each iteration loop is repeated for N number of missions. A sufficient number of mission

iterations is chosen in order to achieve a reasonable linear regression trend-line and consistent results.

The simulation then combines the N number of missions and calculates the percentage of those missions that exceed the timing goal, the standard deviation of the n mission times, and the probability of meeting the expected launch timing goal.

A summary of the model Monte Carlo simulation flow is shown in Figure 3.1-7.

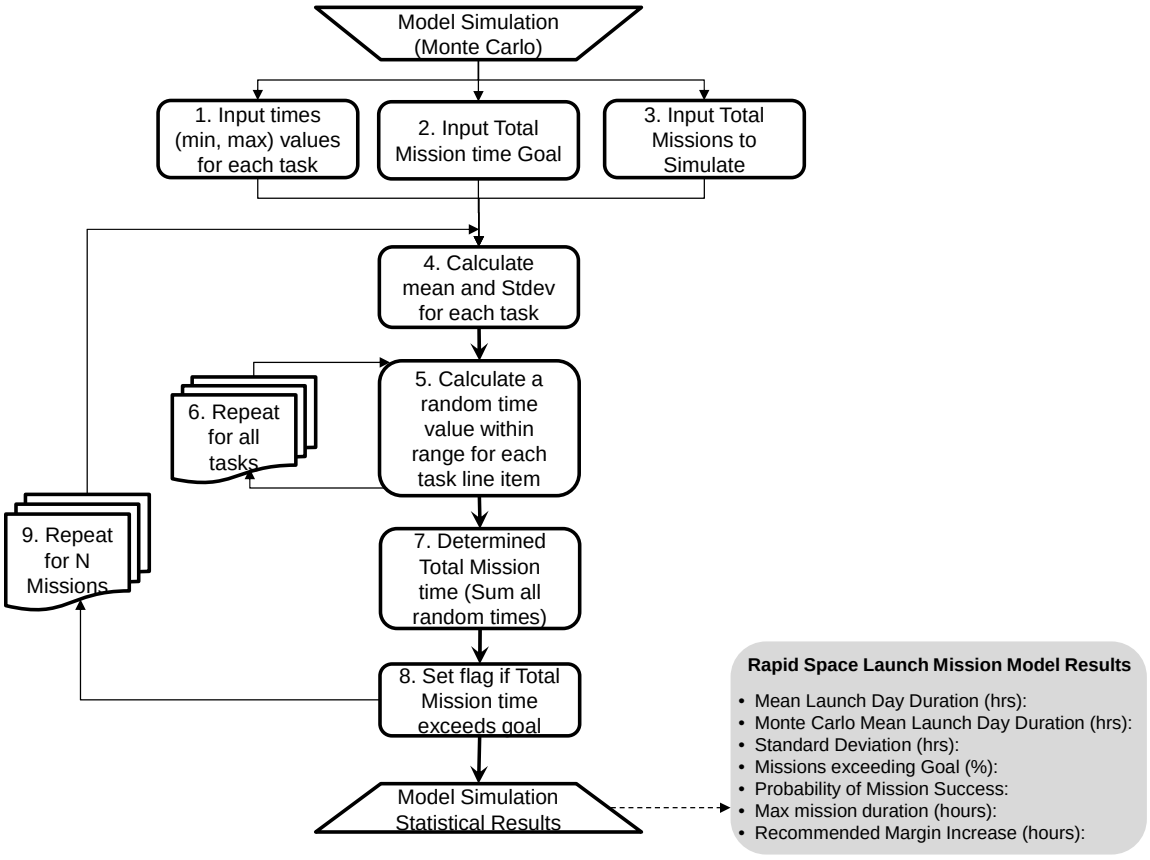


Figure 3.1-7 Model Monte Carlo Simulation Flow

The maximum value over the goal of the resulting data-set can then be used to size the required schedule margin, usually in the form of the “built-in hold” time during the count-down sequence, increasing the chances of mission success. Today, this “built-in hold” margin incorporated in most launches is manually selected and not statistically

determined as could be with this methodology. This insight can also be used to motivate reduction of the larger dispersions in the timeline, through further automation, targeted technologies or process improvements.

The Monte Carlo technique was used for several reasons. If one subsystem performs off-nominal, then that can easily be simulated. As a number of subsystems perform off-nominal, they need to be simulated as combinations. If the number is large, the number of simulations needed experience a combinatorial explosion. Rather than simulating individual cases for all combinations, which could be large, the performance of each subsystem is modeled statistically, then drawn randomly many times. The central limit theorem states that as the number of draws increases, the system performance will approach a Gaussian where the mean is the expected value and the variance defines off nominal performance. Monte Carlo is an efficient way to analyze very complex systems if the individual subsystem uncertainties are reasonably well known. "Monte Carlo is also well adapted to situations requiring an approximation of the stochastic influences often found in real world operating and decision systems. Monte Carlo simulation is not a substitute for proper theoretical model construction, nor is it a substitute for proper experimental design and statistical analysis. Rather Monte Carlo simulation is a method of performing experiments on functionally expressed models" (J. F. Willis, 1969), as performed in this researched.

Stochastic approaches to solving problems appear to be useful, and sometimes essential, in the following context. "One cannot expect that very complex phenomena lead to perfectly calibrated mathematical models, or even to perfect mathematical models, so that uncertainties or stochastic components are involved in the equations.

Stochastic numerical methods allow one to solve deterministic problems, of which the high dimension or singularities render classical deterministic methods of resolution intractable or inaccurate, provided that the solutions can be represented in terms of probability distributions of random variables or stochastic processes" (Graham, 2013).

Several random number generator methods were analyzed. Random numbers can be uniformly sampled between the minimum and maximum time values or use a normally distributed (Gaussian) random number draw from the mean and standard deviation for each task. A Gaussian random number generator was first selected based upon the nature of this research, where task durations are assumed to bias about the mean. Both MS Excel and MATLAB simulation environments have these types of random number generators. Uniformly distributed random numbers can be generated in MATLAB with the *rand* function or in MS Excel with the *RAND* or *RANDBETWEEN* functions. In comparison, normally distributed random numbers can be generated in MATLAB with the *randn* function or in MS Excel with the *NORMINV* or *NORM.INV* functions. Experimenting with both types yielded minor changes in the overall results when simulated over a large number of missions, as shown in Figure 3.1-8.

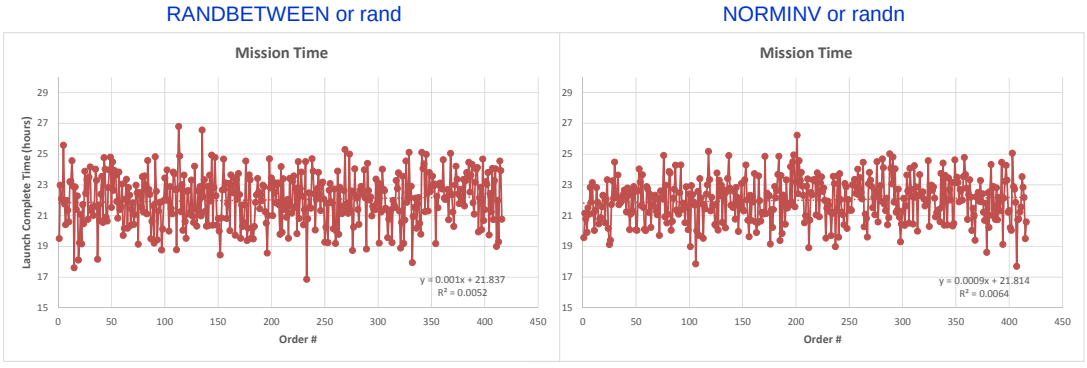


Figure 3.1-8 Different Random Number Generator Functions Analyzed

Sensitivity and uncertainty analyses were also conducted. The uncertainty analysis can be used "to describe the entire set of possible outcomes, including their associated occurrence probabilities. The analysis was used to determine the change in model output values that results from modest changes in model input values. The analysis thus measures the change in the model output in a localized region of the input space. However, one can often use the same set of model runs for both sensitivity analyses and uncertainty analyses. It is valid to carry out a sensitivity analysis of the model around a current solution, and then use it as part of a first order uncertainty analysis" (Daniel P. Loucks, 2005).

Full sensitivity analysis for a particular task entails doing two risk analysis "simulations, one with the duration of the task set to its optimistic value and one with it set to its pessimistic value." In both cases, the other tasks are allowed to vary randomly as defined by their distributions. A full analysis was performed for all the tasks, and for individual tasks. A plug-in tool to Microsoft Project, called *Full Monte 2017* was used to assist in the sensitivity analysis (Barbecana, 2017).

The methods typically used to estimate the measures of sensitivity were statistical techniques based on a comparison of the inputs (the durations sampled for each activity) and outputs (the "early finish of the sensitivity target") as if the project network were a "black box." They were therefore vulnerable to being misled by correlations. If activity A and B are correlated and if activity A is sometimes critical but activity B is not, then a correlation will nonetheless be observed between the target date and the duration of task B, and this could result in a spurious indication that the target date is sensitive to the duration of B (Barbecana, 2017).

The new technique used in the Full Monte plug-in is based upon the relationship "between the task duration and the project finish date" (or other specified target milestone date) only when the task is critical, avoiding any errors due to correlation. It is still the case however that the only way to get completely reliable estimates of the sensitivity to a particular task duration, while all other task durations are uncertain, is to do two full-risk analyses. The "sensitivity index field is intended to give a rough guide of how sensitive the schedule early finish of the sensitivity target is to variation in the activity's duration." It is calculated as the standard deviation of the duration multiplied by the percent critical and then "divided by the standard deviation of the schedule early finish of the sensitivity target" (Barbecana, 2017).

3.2 Data Collection and Data Analyses

Data sources include launch preparation timelines for several launch vehicle systems. These can be found in readily available payloads planner's guides available from each launch vehicle manufacturer. These include launch preparation timelines for rocket systems from Boeing, "United Launch Alliance (ULA)" (United Launch Alliance, Atlas, 2010) (United Launch Alliance, Atlas, 2010), "Space Exploration Technologies Corporation (SpaceX)" (Space Exploration Technologies Corp, Falcon, 2015), "Orbital Sciences Corporation Alliant Techsystems (Orbital ATK)" (Orbital ATK, Pegasus, 2015), and "Defense Advanced Research Projects Agency (DARPA)." The timeline simulation developed from these data sources produced data and insight for the research.

The nature of the data is schedule timeline of launch mission planning and operations required tasks, with timing dispersions and dependences. Examples of data includes task description, start-time, end-time, predecessor(s), successor(s), earliest start-time, and

latest end-time (timing dispersions) data distribution. An initial data-binning exercise determines which tasks can be accomplished in advance of launch and "placed on the shelf" until launch day, and which tasks have to absolutely take place on launch day. This plays a key role in determining how rapid a given launch mission type can be, assuming the added cost of placing product and analyses in storage and maintained in a launch readiness state is acceptable. This construct is organized into four launch mission phases, space system development, readiness, employment, and execution phases, as shown in Figure 3.2-1.

The space system development phase is focused on developing the system hardware, software, and operational tools. The readiness phase is focused on developing proactive mission plans for testing, readiness, training, and rehearsals. Continuous review of mission capabilities against preselected sets of orbits is accomplished as well as deliberate non-crisis planning procedures to develop pro-active courses of action and operational procedures for use in future crisis situations.

The employment phase begins with the receipt of a warning, planning, alert, or execute order to activate the system. Mission planning follows with detailed mission execution plans and mission data loads for the various launch subsystems being produced. The execution phase includes the execution of the launch plans, launch operations, while monitoring, assessing, and dynamically re-planning, as needed. The focus of this research is on the employment and execution phases, with a goal of both phases being accomplished on launch day.

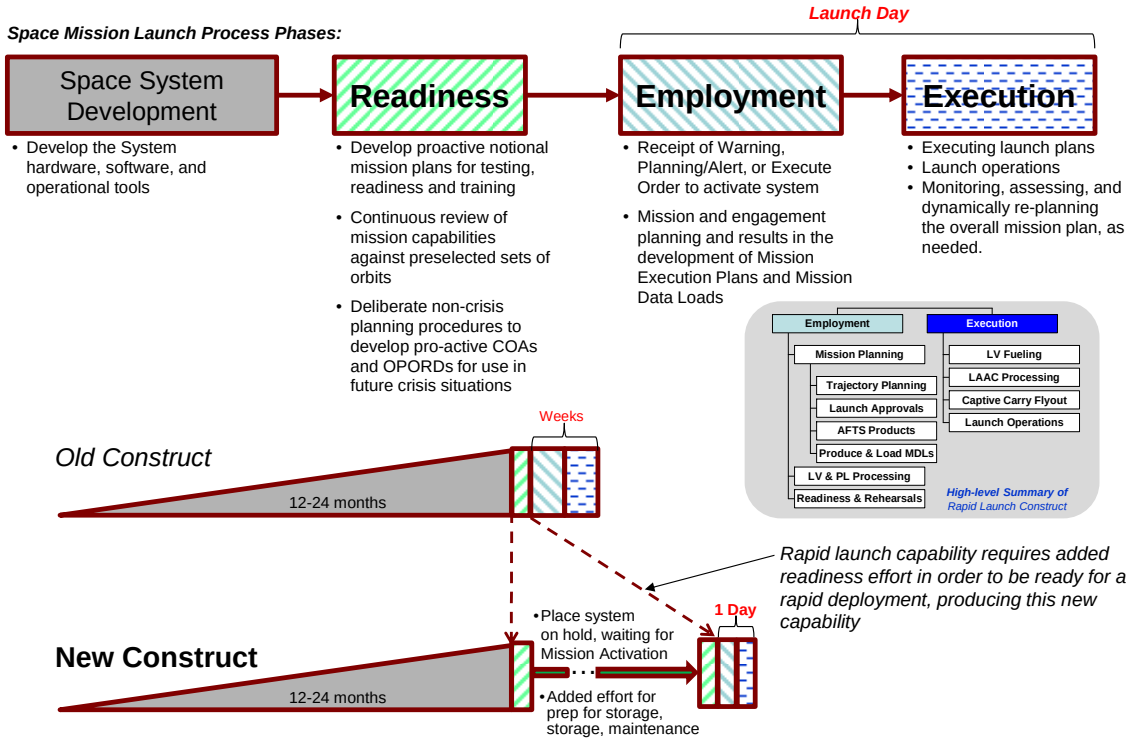


Figure 3.2-1 Space Mission Launch Process – Cost and Schedule Considerations

In this new construct, the space system development and readiness phases includes all tasks required to be completed ahead of time and placing them "on shelf," maintained, in readiness state, waiting for the launch order. The satellites are prebuilt, tested, in flyable storage, preplanning accomplished, and preliminary agreements and approvals in place for a given mission. Then, during the employment phase, on day of launch, the systems are pulled out of flyable storage, planning updates for the received specific mission requirements and timing are accomplished, along with pre-approvals updated and finalized, launch processing, final mission plan development, approvals, notifications, software mission constants developed and loaded on-board the launch vehicle and satellite(s), satellite mating to launch vehicle, and final checks. Then, the execution phase conducts the launch operations.

It is acknowledged that in order for this new construct to be successful, it comes at a cost, added readiness effort is required to be ready for a rapid deployment and produce this valuable capability.

3.3 Model Validation

A total of 26 experts in launch mission planning and space operations have been elicited to validate the model, as listed in Appendix A. These subject matter experts have experience ranging from dozens to hundreds of missions each, covering various portions of the launch day process. The use of expert judgment elicitation and use of appropriate statistical modeling techniques reduces uncertainty and bias in the analyses, and provides insights from a wide range of expertise.

The experts were used during three phases of the research. The first phase was to gather the building blocks, survey literature and the subject area experts for the process components (full set of tasks required on launch day). The second phase was to gather timing information for each component, minimum and maximum durations for each process task, from the literature and the subject area experts for their domain of expertise. Key ground rules and assumptions required to achieve any of the more challenging timing goals were captured. The third phase was to review the overall created construct. A summary of the expert elicitation process used for model validation is shown in Figure 3.3-1.

In the first phase, survey cycle-1, the experts were asked, "*Are the components correct (Y/N), for your areas of expertise?*" The purpose of this phase was to get the process model components correct and achieve a first level of the architecture. The experts were used with varying domain expertise in launch operations in order to cover

each diverse area of the launch process. Experts provided feedback for their domain of expertise. Results were collected in a table containing the building blocks as rows, required work tasks in the process, with each expert response assigned to a column. A "yes" entry signifies that the expert responded that the task must belong on launch day. A "yes" was recorded as a "1" for counting of total feedback responses received for each line item, ensuring sufficient feedback was collected on all tasks. A "no" resulted in either elimination of a task or discussing it further with the expert. Each line item received sufficient feedback counts, with an average of 6.9 experts/line item verified task description. The survey cycle-1 results are summarized in Appendix-B.

In the second phase, survey cycle-2, the experts were asked, "*What are the work task values (minimum and maximum time duration values)*?" The experts could report their best estimates in units of durations (minutes) or a most likely duration (minutes) with a +/– confidence interval (+/- %) for the minimum and maximum time duration values, or optimistic and pessimistic values. For example, if a task most likely will take 3 hours, it could have an optimistic confidence percent of 90% and a pessimistic confidence percent of 110%. This process should be how schedules are developed on future programs, enabling statistical analysis on the plan.

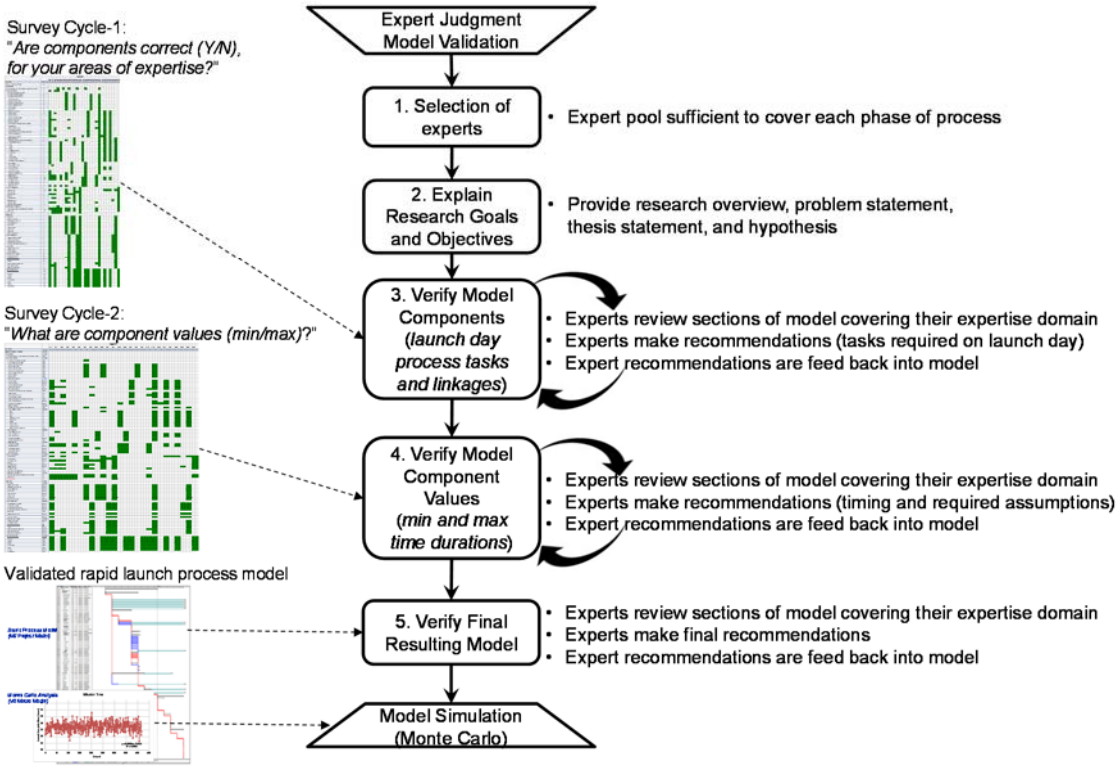


Figure 3.3-1 Expert Elicitation Process Key to Model Validation

The experts, once again, only responded to the line items they had expertise in, reporting what they believed to be maximum and minimum time duration values. The responses were then averaged for determination of each work task's minimum and maximum duration. The purpose of collecting data in the form of a range is to be able to perform statistical simulation on the timing dispersion estimation for each task.

In the third phase, experts were asked to verify the resulting model. Various data formats were provided to elicit feedback, namely, the various architecture views in chart form, schedule timeline form, and simulation results presented in spreadsheet form. They could run a form of the Monte Carlo simulation themselves in the spreadsheet form by easily executing a Visual Basic embedded macro for increased understanding and immediate feedback. All duration values were converted to the same units, in this case "minutes". While 1 hour is equivalent to 60 minutes, the schedule is easier to read when

the durations are expressed in the same unit as it keeps the reader from having to do mental conversions while reviewing the schedule.

When collecting data for a new construct such as this, it is best to collect timing data in the form of 3-point estimates, not a single duration value. If a single value is collected, it is not known what is behind that estimate, an optimistic duration, or most likely duration, or a pessimistic duration. The 3-point duration estimates can be collected by using a parametric or values consistent with previous similar programs or interviewing subject matter experts (SME) for their assessment. If the value in the duration field represent the SME's best estimate or most likely duration, it shouldn't use the normal distribution curve as it ignores this value and has a natural tendency to reduce the standard deviation. In this case the triangular distribution is recommended because it uses the SME's most likely as the mode value and tends to spread the standard deviation a bit to allow for occurrences in the extremes or tails of the distribution curve. An example for the launch zone analysis task 3-point duration estimates normal vs. triangular distribution is shown in Figure 3.3-2.

It was found best to capture the optimistic and pessimistic duration ranges from the beginning using a "DurationX" field, for example, optimistic duration goes in Duration1, most likely in Duration2 and the pessimistic in Duration3. The data can then be imported into the other simulations, such as Full Monte, more easily for analysis.

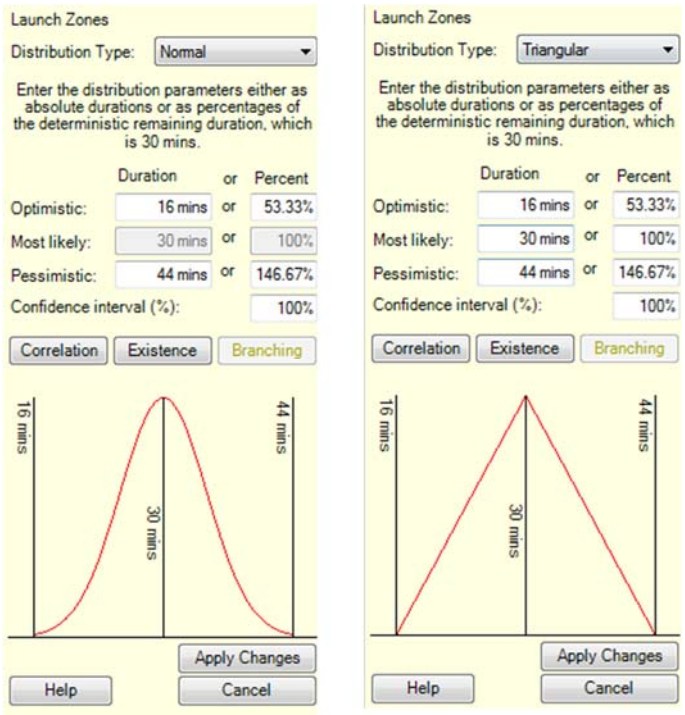


Figure 3.3-2 Normal vs. Triangular Distribution for the 3-point Duration Estimates

Checks that were performed on task ranges that appear tight were to ensure that they represented automated sequences and not require human intervention. If this is largely an automated sequence, the risk ranges may be rather narrow, however, if human intervention is required (i.e. to make a decision), the ranges should be much wider.

It is important to ask the SME's about any correlation between the tasks. Adding in correlation between tasks in each grouping is key if they are more likely to all increase during the same iteration as opposed to the randomness causing a canceling effect when some are shorter and some longer. Correlation allows us to offset some of the canceling effect by defining pairs or groups of tasks whose durations tend to increase or decrease together (positive correlation) or move in opposite directions as when one increases, another decreases (negative correlation).

Another critical data capture to accompany this construct is any required ground rules and assumptions (GR&As) associated with the activities in order to insure the task duration achievability. These GR&As associated with tasks have also been assessed for if any significant investment is recommended. This list could serve as a foundation for future research. The GR&As associated with this construct are summarized in Appendix E, with the subset listing of the significant investment required flagged items listed in Table 3.3-1.

Table 3.3-1 Further Investment Recommended Tasks to Support this Construct

Task Name	Duration	Ground Rules & Assumptions required to enable timing goals	Investment Required
Rapid Air Launch Mission	**0.99 days**		
Employment	**0.59 days**		
Mission Planning	**0.38 days**		
Trajectory Planning	**0.3 days**		
Launch Zones	30 mins	Trajectory Planning Automation	X
Release Points	30 mins	Trajectory Planning Automation	X
Launch Time/Window	10 mins	Trajectory Planning Automation	X
Constraints Analysis	2 hrs	Trajectory Planning Automation	X
Dispersions Analysis	3 hrs	Mission Monte Carlo Automation	X
Produce Plan Reports	30 mins	Stakeholder ICDs Finalized	X
Launch Approvals	**0.04 days**		
Final Deconflictions	**0.04 days**		
FAA	60 mins	MOU in place, ICD established	X
USCG	60 mins	MOU in place, ICD established	X
NGA	60 mins	MOU in place, ICD established	X
Communications	60 mins	MOU in place, ICD established	X
LAAC Base	60 mins	MOU in place, ICD established	X
JSpOC	60 mins	MOU in place, ICD established	X
LAAC Range	60 mins	MOU in place, ICD established	X
Launch Range	60 mins	MOU in place, ICD established	X
AFTS Products	**0.06 days**		
Run anomaly cases	60 mins	Trajectory Monte Carlo Automation	X
Final IIP Analysis	60 mins	IIP Monte Carlo Automation	X
Final Ec Analysis	60 mins	Ec Monte Carlo Automation	X

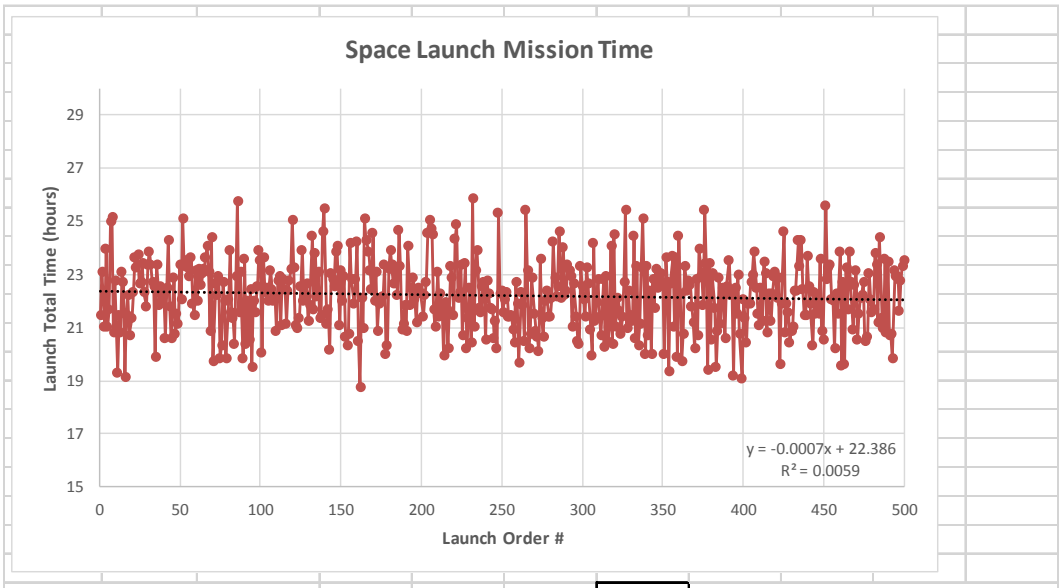
Chapter 4 - Results

4.1 Simulation Results

In summary, an executable timeline framework and model has been developed for simulating this construct and refining the mission planning tasks and providing immediate feedback to the experts for improved decision making.

An example of 500 missions simulated over a 24-hour period goal was analyzed. This example covers a satellite that must be on-orbit over an area of interest on the globe in 24 hours or less, from a start time of being notified (receiving a space tasking order). The mean launch day duration was 22.18 hours, so the initial timing construct seemed successful. But when the timing dispersions are incorporated within a Monte Carlo simulation 43 out of 500 (8.6%) missions exceed the 24-hour goal, as shown in Figure 4.1-1.

This 8.6% of the time failure rate can be interpreted as a 0.91 probability of mission success, which may be acceptable depending upon the mission. This 8.6% risk can either be accepted or reduced by folding it back into the initial timeline planning until the simulation results approach 0% risk. The maximum value mission time was 25.85 hours, so a recommended schedule reduction would be on the order of 1.85 hours. Targeted process change examples include reducing task dispersions, the durations of selected tasks, or paralyzing additional tasks.



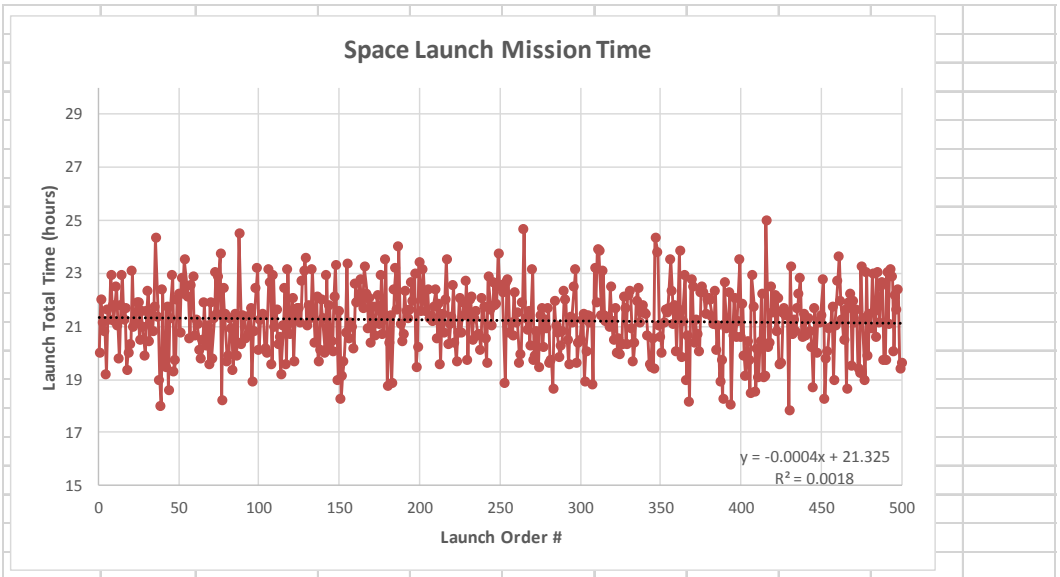
Mean Launch Day Duration (hours):	22.18	24	Launch Day Max Duration Goal (hours)
Monte Carlo Mean Launch Day Duration (hours):	23.70	500	Missions
Standard Deviation (hours):	1.34		
Missions exceeding Goal (%):	8.60%		
Probability of Mission Success:	0.91		
Max mission duration (hours):	25.85		
Recommended Margin Increase (hours):	1.85		

Figure 4.1-1 Rapid Space Launch Mission Time Durations Monte Carlo Results-1

Next, the model was used in achieving this greater probability of mission success, i.e., making coordinated changes then executing the Monte Carlo simulation. This readily resulting in meeting the mission timing goal (<24 hours). An acceptable single line item was changed, the "built-in hold" time was reduced from 2 hours to 1 hour. This achieved favorable results. This count-down buffer is used on launch day as a schedule-float to reduce the impact of any pre-launch issues that may arise. This "built-in hold" margin incorporated in most launches is manually selected and not statistically determined as could be with this methodology.

The mean launch day duration reduced to 21.18 hours. When the timing dispersions are incorporated within a Monte Carlo simulation only 6 out of 500 (1.2%) missions exceed the 24-hour goal, as shown in Figure 4.1-2. This 1.2% of the time failure rate can

be interpreted as a 0.99 probability of mission success, which may be acceptable depending upon the mission. This 1.2% risk can either be accepted or reduced by folding it back into the timeline planning until the simulation results approach or exceed 0% goal. The maximum value mission time was 24.98 hours.



Mean Launch Day Duration (hours):	21.18	24	Launch Day Max Duration Goal (hours)
Monte Carlo Mean Launch Day Duration (hours):	20.02	500	Missions
Standard Deviation (hours):	1.28		
Missions exceeding Goal (%):	1.20%		
Probability of Mission Success:	0.99		
Max mission duration (hours):	24.98		
Recommended Margin Increase (hours):	0.98		

Figure 4.1-2 Rapid Space Launch Mission Time Durations Monte Carlo Results-2

A sensitivity analysis was executed on the model. As expected, the longer duration activities yielded the greatest impact when varied. Values could be varied in MATLAB, MS Excel or MS Project model to see the sensitivities.

Sensitivity analysis was more exhaustively performed using the Full Monte plug-in within the MS Project representation of our model. A split tornado chart could be produced, sorted on greatest sensitive task first, as shown in Table 4.1-1 and Appendix F. The bars indicate the range of the expected finish time based on possible variation in the

duration of each task. It was based on 10,000 iterations, so this research can be fairly sure that this is a definitive list. It does not list activities for which the sensitivity is not statistically significant.

Table 4.1-1 Split Tornado Chart

ID	Task Name	Sensitivity Index	Schedule Sensitivity Bar Basis	Optimistic Finish of Project	Jan 2019 02 02:00 03:00 04:00 05:00	Pessimistic Finish of Project
20	JSpOC COLA	61%	Estimated	01/02/19 02:59		01/02/19 05:38
71	LV Fueling	44%	Estimated	01/02/19 03:18		01/02/19 05:18
17	Constraints Analy...	41%	Estimated	01/02/19 03:24		01/02/19 05:12
85	Fly to Launch Zone	22%	Estimated	01/02/19 03:48		01/02/19 04:48
84	LV Comm Checks1	22%	Estimated	01/02/19 03:48		01/02/19 04:48
62	Built-In Hold	13%	Estimated	01/02/19 04:02		01/02/19 04:35
66	Movement to Fue...	11%	Estimated	01/02/19 04:03		01/02/19 04:33
65	Power transition	11%	Estimated	01/02/19 04:03		01/02/19 04:33
24	Finalize Trajectori...	11%	Estimated	01/02/19 04:03		01/02/19 04:33
57	LV Simulations	11%	Estimated	01/02/19 04:03		01/02/19 04:33
42	Produce AFTU M...	11%	Estimated	01/02/19 04:04		01/02/19 04:33
14	Launch Zones	11%	Estimated	01/02/19 04:04		01/02/19 04:32
15	Release Points	9%	Estimated	01/02/19 04:05		01/02/19 04:31
25	Produce Plan Re...	9%	Estimated	01/02/19 04:06		01/02/19 04:30
74	LV Movement to ...	7%	Estimated	01/02/19 04:08		01/02/19 04:28
75	LV Mating to LAAC	7%	Estimated	01/02/19 04:08		01/02/19 04:28
83	Climb to Altitude	7%	Estimated	01/02/19 04:08		01/02/19 04:28
76	Aircrew Step to A...	7%	Estimated	01/02/19 04:08		01/02/19 04:28
40	Final IIP Analysis	6%	Estimated	01/02/19 04:16		01/02/19 04:35
39	Run anomoly cas...	6%	Estimated	01/02/19 04:16		01/02/19 04:35
41	Final Ec Analysis	6%	Estimated	01/02/19 04:17		01/02/19 04:35
97	PL Sep	4%	Estimated	01/02/19 04:13		01/02/19 04:23
69	Fueling Lines	4%	Estimated	01/02/19 04:13		01/02/19 04:23
68	Vent Lines	4%	Estimated	01/02/19 04:13		01/02/19 04:23
77	Aircrew Confirms ...	4%	Estimated	01/02/19 04:13		01/02/19 04:23
67	Attach Umbilical	4%	Estimated	01/02/19 04:13		01/02/19 04:23
81	Taxi & Take-off	4%	Estimated	01/02/19 04:13		01/02/19 04:23
79	Remove Vent Lin...	4%	Estimated	01/02/19 04:13		01/02/19 04:23
72	Vent fueling lines	4%	Estimated	01/02/19 04:13		01/02/19 04:23
70	Purge Lines	4%	Estimated	01/02/19 04:13		01/02/19 04:23
91	Launch Manuever	4%	Estimated	01/02/19 04:13		01/02/19 04:23
47	AFTU MDL Load...	4%	Estimated	01/02/19 04:13		01/02/19 04:23
86	Tanker	4%	Estimated	01/02/19 04:13		01/02/19 04:23
88	Mission Selection	4%	Estimated	01/02/19 04:13		01/02/19 04:23
16	Launch Time/...	4%	Estimated	01/02/19 04:13		01/02/19 04:23

The chart is shown in descending order of the bar lengths, and the other measures of sensitivity are in line. The times upon which the bars are based are also shown in the columns on either side of the bar chart. The bars are split by color at the expected finish-time of the target. Bars are stacked in order of highest sensitivity. These bars show the relative impact of the task on the program finish or key activity. The bars are split in

color to illustrate Optimistic versus Pessimistic swing in duration impact. Longer bars mean changes to the duration in this task cause greater impact to the program.

The Tornado chart is used to visualize and identify the activities having the most impact on a key milestone or end-date of the project. As expected, the tornado plots points out the longer duration activities are the most sensitive. Often the tasks driving the risk are the longer duration tasks in the project, but not always. If you want to improve the likelihood of meeting a key milestone date, reducing the risk or impact of these tasks at the top of the Tornado will improve your project's chances of supporting a key date. Once these tasks are identified, you can adjust their risk duration range, confidence level and/or potentially alternate networking to drive results. Make appropriate adjustments to the network or risk information and rerun the simulation.

A summary of key metrics to use as feedback back into the model are listed in Table 4.1-2 (Barbecana, 2017). A Tornado chart with these metrics is shown in Table 4.1-3.

Table 4.1-2 Tornado Chart Metrics

· Percent Critical	Identifies the percentage of time the task was on the critical path during the multiple simulation runs.
· Sensitivity Index	Indicates the relative impact of this task's changes in duration to impact on the key activity or program Early Finish date. (They don't add up to 100% - they are a relative index to compare the impact of one task to another. For example, a task with an SI of 40% would have twice the impact of a task with an SI of 20%.)
· Optimistic Finish	Relates to the most Optimistic Early Finish date (green bars) representing the earliest finish of the activity during the simulation.
· Pessimistic Finish	Relates to the most Pessimistic Early Finish date (red bars) representing the latest early finish of the activity during the simulation.
· Tornado bars	Stacked in order of highest sensitivity, these bars show the relative impact of the task on the program finish or key activity. The bars are split in color to illustrate Optimistic versus Pessimistic swing in duration impact. Longer bars mean changes to the duration in this task cause greater impact to the program.

Table 4.1-3 Tornado Chart with Metrics

ID	Task Name	Remaining Duration	Percent Critical	Percent Critical (Sensitivity)	Sensitivity Index	Sensitivity Index 25.00 50.00	Optimistic Finish of Project	Pessimistic Finish of Project	Jan 2019 02 02:00 03:00 04:00 05:00	Early Finish Histogram	Schedule Sensitivity Bar Basis
0	Rapid Air Launc	20.17 hrs	100%	0%	NA		NA	NA		Graph	Estimated
1	Employment	12.22 hrs	100%	0%	NA		NA	NA		Graph	Estimated
62	Built-In Hol	1 hr	100%	100%	13%		1/2/2019	1/2/2019		Graph	Estimated
3	Mission Pla	9.22 hrs	100%	0%	NA		NA	NA		Graph	Estimated
44	Produce (	1.85 hrs	0%	0%	NA		NA	NA		Graph	Estimated
47	AFTU M	10 mins	99%	99%	4%		1/2/2019	1/2/2019		Graph	Estimated
49	Loads \	10 mins	100%	100%	4%		1/2/2019	1/2/2019		Graph	Estimated
46	LV MDL	10 mins	0%	0%	0%		1/2/2019	1/2/2019		Graph	Estimated
48	LAAC M	10 mins	1%	1%	0%		1/2/2019	1/2/2019		Graph	Estimated
45	Produc	1 hr	0%	0%	0%		1/2/2019	1/2/2019		Graph	Estimated
13	Trajector	7.33 hrs	100%	0%	NA		NA	NA		Graph	Estimated
20	JSpOC	3 hrs	100%	100%	61%		1/2/2019	1/2/2019		Graph	Estimated
17	Constra	2 hrs	100%	100%	41%		1/2/2019	1/2/2019		Graph	Estimated
24	Finalize	30 mins	100%	100%	11%		1/2/2019	1/2/2019		Graph	Estimated
14	Launch	30 mins	100%	100%	11%		1/2/2019	1/2/2019		Graph	Estimated
15	Releas	30 mins	100%	100%	9%		1/2/2019	1/2/2019		Graph	Estimated
25	Produc	30 mins	100%	100%	9%		1/2/2019	1/2/2019		Graph	Estimated
18	Weathe	10 mins	100%	100%	4%		1/2/2019	1/2/2019		Graph	Estimated
16	Launc	10 mins	100%	100%	4%		1/2/2019	1/2/2019		Graph	Estimated
26	Launch A	61 mins	1%	0%	NA		NA	NA		Graph	Estimated
28	Final D	1 hr	1%	0%	NA		NA	NA		Graph	Estimated
35	LAAC	1 hr	1%	1%	0%		1/2/2019	1/2/2019		Graph	Estimated
38	AFTS Pro	91 mins	99%	0%	NA		NA	NA		Graph	Estimated
42	Produc	30 mins	99%	99%	11%		1/2/2019	1/2/2019		Graph	Estimated
40	Final IIF	1 hr	35%	35%	6%		1/2/2019	1/2/2019		Graph	Estimated
39	Run an	1 hr	35%	35%	6%		1/2/2019	1/2/2019		Graph	Estimated
41	Final E	1 hr	34%	34%	6%		1/2/2019	1/2/2019		Graph	Estimated
50	LV & PL Pro	10.18 hrs	0%	0%	NA		NA	NA		Graph	Estimated
57	LV Simul	1 hr	100%	100%	11%		1/2/2019	1/2/2019		Graph	Estimated
63	Execution	8.95 hrs	100%	0%	NA		NA	NA		Graph	Estimated
64	LV Fueling	3.83 hrs	100%	0%	NA		NA	NA		Graph	Estimated
71	LV Fuelin	2 hrs	100%	100%	44%		1/2/2019	1/2/2019		Graph	Estimated
66	Movemen	30 mins	100%	100%	11%		1/2/2019	1/2/2019		Graph	Estimated
65	Power tra	30 mins	100%	100%	11%		1/2/2019	1/2/2019		Graph	Estimated
68	Vent Line	10 mins	100%	100%	4%		1/2/2019	1/2/2019		Graph	Estimated
69	Fueling L	10 mins	100%	100%	4%		1/2/2019	1/2/2019		Graph	Estimated
67	Attach Un	10 mins	100%	100%	4%		1/2/2019	1/2/2019		Graph	Estimated
70	Purge Lin	10 mins	100%	100%	4%		1/2/2019	1/2/2019		Graph	Estimated
72	Vent fueli	10 mins	100%	100%	4%		1/2/2019	1/2/2019		Graph	Estimated
73	LAAC Proc	90 mins	100%	0%	NA		NA	NA		Graph	Estimated
74	LV Mover	20 mins	100%	100%	7%		1/2/2019	1/2/2019		Graph	Estimated

The sensitivity index is used to indicate the relative impact of the task's changes in duration to impact on the key activity early finish date. Adjustments can then be made to the network and rerun the simulation until timing goals are achieved.

4.2 Architecture Results

The resulting timeline architecture diagram view, with goal times shown for an air-launch mission example, is shown in Figure 4.2-1. Events are leveraged from past rapid military missions, then brought current with expert judgment. Times are based upon top-down analyses, to be balanced with the bottoms-up detailed analyses and simulation for specific missions.

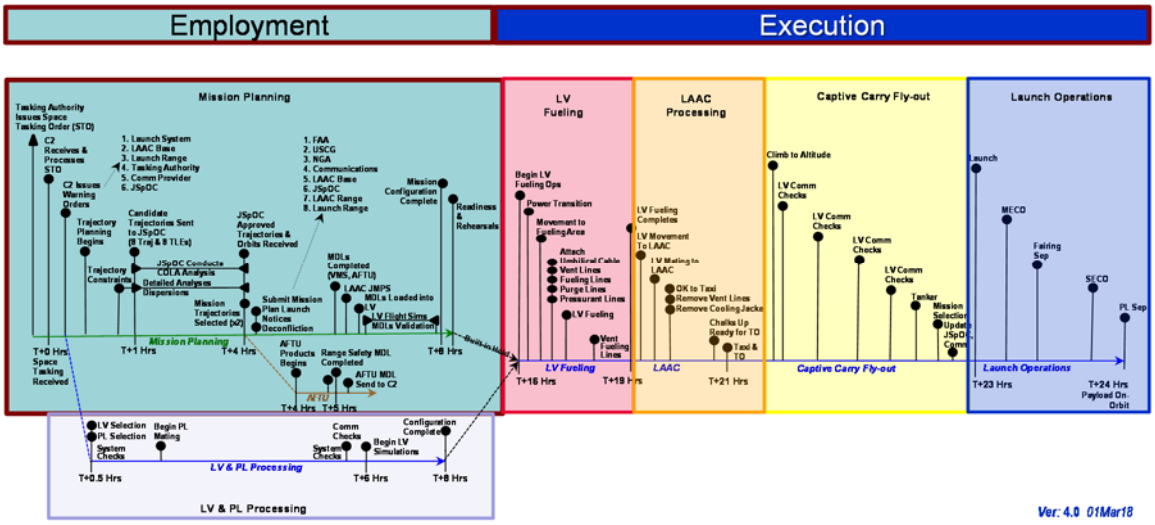


Figure 4.2-1 Rapid Launch Timing Framework (24-Hour Air-Launch Day Example)

The resulting simulation architecture diagram view, with schedule data and task dispersions as inputs, is shown in Figure 4.2-2. Receipt of a space tasking order initiates the launch process, with the employment phase simulated by the launch mission planning task, readiness and rehearsals tasks, and launch vehicle and payload (satellite) processing tasks. Those results flow into the execution phase simulated by the launch vehicle fueling, launch assist aircraft processing, captive carry fly-out, and launch operations activities.

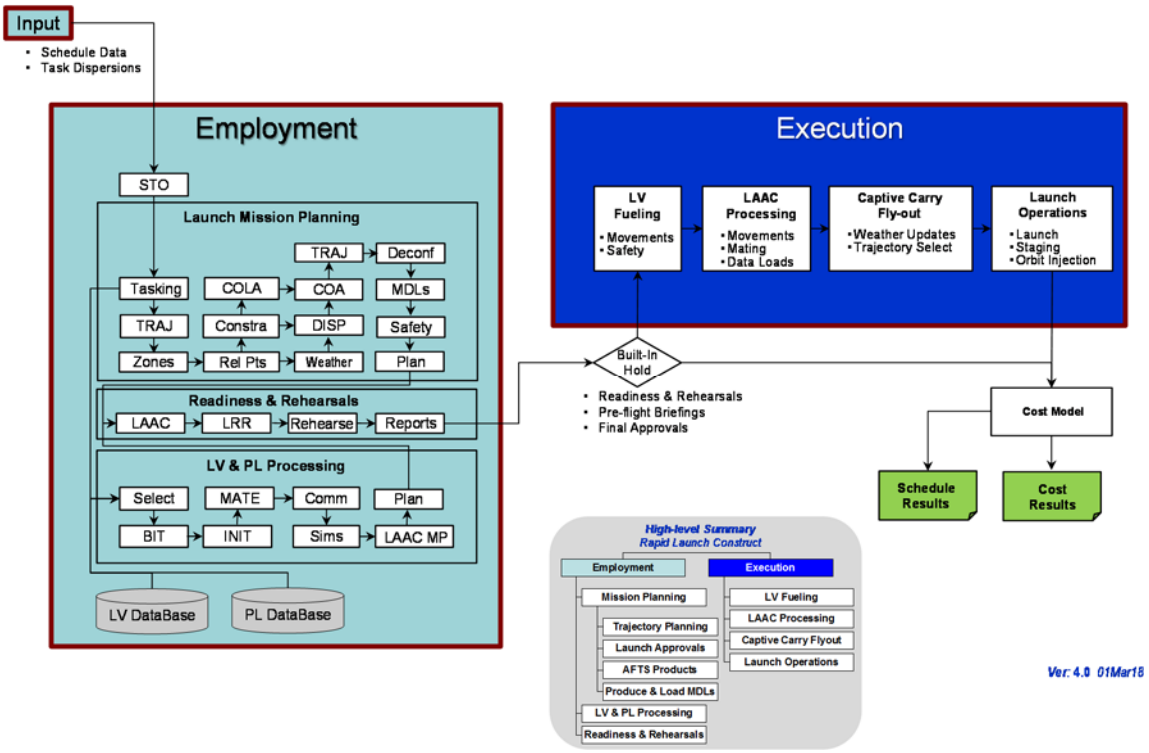


Figure 4.2-2 Rapid Launch Simulation Architecture

A resulting MS Project linked schedule architecture view has been produced, as shown in Appendix D. This captures the rapid launch model in an environment that assists a project engineer in developing a plan forward, resource loading to tasks, tracking progress, analyzing workloads, and managing the budget. MS Project provides a plug-in for a Monte Carlo simulation directly within MS Project. This plug-in, Full Monte, "addresses the issue of cost and schedule risk analysis by replacing single-point estimates with probability distributions and using Monte Carlo simulation to provide a much more realistic assessment of likely project outcomes" (Barbecana, 2017), similar to what was performed in our research.

All of these architecture viewpoints are available as tools and insight for future program managers and planners to use for developing and managing rapid launch missions.

Chapter 5 - Conclusions and Recommendations

A new construct has been developed for rapidly enabling access to space for global urgent mission needs. A new construct has been developed for effectively enabling a launch of a satellite to orbit within 24 hours or less. An executable timeline model construct has been developed for simulating this rapid launch capability framework.

An air-launch system has the advantages of being able to achieve rapid timing goals more readily. This is due to reduced risk to public safety by being able to launch over the oceans, reducing several of the mission planning safety constraints and planning products required. Additionally, air-launch systems naturally optimize mission launch timing by being able to fly to the optimal launch point, optimizing both mission launch timing and orbital energy.

Once air-launch systems are realized and proven these constructs can be folded back into heritage terrestrial launch systems for process improvements and further savings. Sometimes major process changes need to be demonstrated successfully on smaller scales with less constraints, first, before larger system are willing to adopt.

Ultimately, realizing this as a systems problem, rapid launch mission planning being part of a larger system, requirements can be feedback to the launch vehicle domain, as an added benefit, for changes that could occur on-board future launch vehicle designs for further mission operations performance increases.

Recommended technology maturation and further investment areas have been identified to further support this rapid launch construct. Technologies targeting reductions in operational crew sizes and turn-around times are key to achieving a rapid launch process.

5.1 Contributions

This research contributes to the military, intelligence, civil, and commercial space engineering management and mission planning communities. Timely satellite launch processes are critical for a variety of organizations, to include branches of the military, intelligence agencies, civil agencies, other government agencies, universities, and commercial companies.

This research also contributes to the general engineering management community involved in planning a program from beginning to end, or just for the next planning cycle. A Monte Carlo simulation of schedule and cost risk associated with a project plan can provide a much more realistic assessment of likely project outcomes.

5.2 Future Research

Recommendations for future research include cost risk data added to the model by resource loading proprietary cost data from a given launch provider. This should achieve further insights into rapid launch processes risks and opportunities. Current and future systems could optimize their process based upon schedule and cost risk Monte Carlo analyses.

Further research into the identified technology maturation areas should be conducted in order to ensure construct success. This includes research in automated trajectory mission planning, automated collaboration tools with the approving authorities and service providers, and further automation of safety systems, as listed in Appendix E.

Given that launch campaigns can be organized into four launch mission phases, space system development, readiness, employment, and execution phases, and the focus of this

research has been on the latter two phases, future research can focus on the first two phases, as well.

Lastly, future research should include applying this construct to a variety of launch systems. Large and small terrestrial launch systems using the Eastern or Western launch ranges could benefit with process improvements and further savings from this construct.

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Appendix A - Subject Matter Experts Elicited

Table A-1 Subject Matter Experts Elicited

Expert	Expertise	Years Experience
1.	Flight Systems Lead for 25 Delta II launches, Air Launch Chief Engineer, GN&C Engineer	41
2.	Delta II control analysis, Delta IV Launch System Chief Engineer,	36
	Aerospace Corporation, multiple contractors	
3.	Automated Mission Planning, Delta Rocket GN&C, DC-X/XA	33
4.	Delta Rocket Mission analysis	35
5.	Delta Rocket launch operations, Aerospace Corp launch support	32
6.	Initial mission requirements	35
7.	Ground segment launch systems, multiple contractors,	32
	C2 lifecycle launch architecture, DC-X/XA	
8.	Space Shuttle missions, DARPA Missions, GN&C lead	34
9.	Range Safety and Ground Safety	36
10.	Lead for all Delta II Iridium launches, USAF Launches, USN	34
11.	Advanced space missions architecture	35
12.	Delta Rocket Mission Operations Lead	33
13.	Delta Rocket launch operations, Aerospace Corp launch support	28
14.	Delta Rocket, Aerospace Corp, multi-launch contractor oversight	37
	Delta Mission Analysis Verification	
15.	Delta, Universal Space Lines, Mission Planning	36
16.	Aerospace Corp, Ground Segment and Operations lead	33
17.	Space Shuttle, DARPA orbital missions, GN&C Technical Fellow	32
18.	DC-X/XA GN&C Lead, Design Certification Review Delta	40
	Delta Mission Assurance	
19.	Aerospace Corporation, Launch missions lead	36
20.	Mission Analysis Group Lead, Delta Rocket, 150 missions	37
21.	Trajectory planning, 3 & 6 degrees of freedom simulations	41
22.	Director, GMD Booster, Delta rocket	37
23.	Trajectory planning, 3 & 6 degrees of freedom Simulations	36
24.	Space advanced hardware and software sales expert	32
25.	Eastern Range Launch Operations, DC-X/XA launches	31
26.	Shuttle, Flight lead, Mission Operations Lead Engineer	34
	Average	***35***

Appendix B - Survey Cycle-1 Results Summary

Survey Cycle-1 Results:

Purpose:

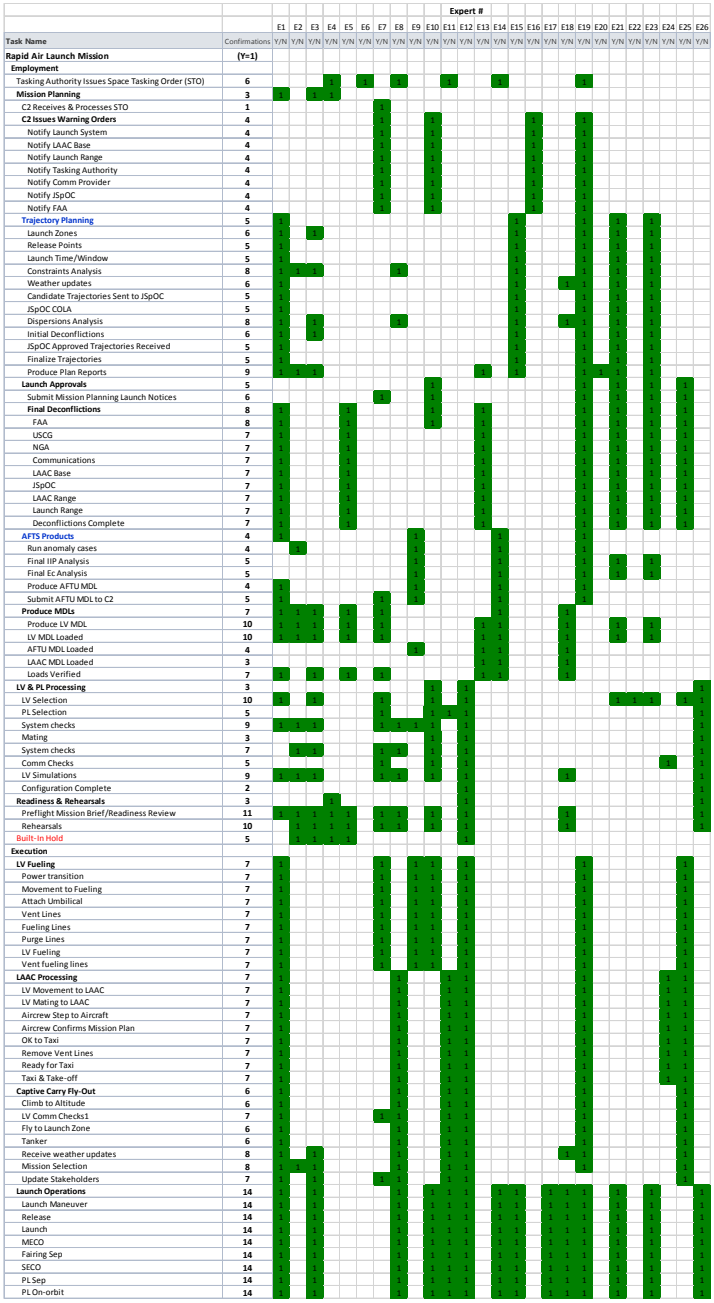
1. Get process model components correct
2. Achieve first level of architecture

"*Are components correct (Y/N), for your areas of expertise?*"

Results:

1. 26 Experts used, with varying domain expertise in launch operations, in order to cover each area of the process
2. Experts provided feedback for their domain of expertise
3. Each line item received sufficient feedback counts
   - Average = ~7 experts/line item verified task (description and if required)

Table B-1 Survey Cycle-1 Results Summary



Task Name	Confirmations	Expert # E1 Y/N	E2 Y/N	E3 Y/N	E4 Y/N	E5 Y/N	E6 Y/N	E7 Y/N	E8 Y/N	E9 Y/N	E10 Y/N	E11 Y/N	E12 Y/N	E13 Y/N	E14 Y/N	E15 Y/N	E16 Y/N	E17 Y/N	E18 Y/N	E19 Y/N	E20 Y/N	E21 Y/N	E22 Y/N	E23 Y/N	E24 Y/N	E25 Y/N	E26 Y/N
Rapid Air Launch Mission	(Y=1)																										
Employment																											
Tasking Authority Issues Space Tasking Order (STO)	6			1		1		1				1			1				1								
Mission Planning	3	1		1	1																						
C2 Receives & Processes STO	1							1																			
C2 Issues Warning Orders	4							1			1					1			1								
Notify Launch System	4							1			1					1			1								
Notify LAAC Base	4							1			1					1			1								
Notify Launch Range	4							1			1					1			1								
Notify Tasking Authority	4							1			1					1			1								
Notify Comm Provider	4							1			1					1			1								
Notify JSpOC	4							1			1					1			1								
Notify FAA	4							1			1					1			1								
Trajectory Planning	5	1													1				1		1		1				
Launch Zones	6	1		1											1				1		1		1				
Release Points	5	1													1				1		1		1				
Launch Time/Window	5	1													1				1		1		1				
Constraints Analysis	8	1	1	1					1						1				1		1		1				
Weather updates	6	1													1			1	1		1		1				
Candidate Trajectories Sent to JSpOC	5	1													1				1		1		1				
JSpOC COLA	5	1													1				1		1		1				
Dispersions Analysis	8	1		1					1						1			1	1		1		1				
Initial Deconflictions	6	1		1											1				1		1		1				
JSpOC Approved Trajectories Received	5	1													1				1		1		1				
Finalize Trajectories	5	1													1				1		1		1				
Produce Plan Reports	9	1	1	1									1		1				1	1	1		1				
Launch Approvals	5										1								1		1		1			1	
Submit Mission Planning Launch Notices	6							1			1								1		1		1			1	
Final Deconflictions	8	1				1					1			1					1		1		1			1	
FAA	8	1				1					1			1					1		1		1			1	
USCG	7	1				1								1					1		1		1			1	
NGA	7	1				1								1					1		1		1			1	
Communications	7	1				1								1					1		1		1			1	
LAAC Base	7	1				1								1					1		1		1			1	
JSpOC	7	1				1								1					1		1		1			1	
LAAC Range	7	1				1								1					1		1		1			1	
Launch Range	7	1				1								1					1		1		1			1	
Deconflictions Complete	7	1				1								1					1		1		1			1	
AFTS Products	4	1								1					1				1								
Run anomaly cases	4		1							1					1				1								
Final IIP Analysis	5									1					1				1		1		1				
Final Ec Analysis	5									1					1				1		1						
Produce AFTU MDL	4	1								1					1				1								
Submit AFTU MDL to C2	5	1						1		1					1												
Produce MDLs	7	1	1	1		1		1							1				1								
Produce LV MDL	10	1	1	1		1		1					1	1	1				1		1		1				
LV MDL Loaded	10	1	1	1		1		1					1	1	1				1		1		1				
AFTU MDL Loaded	4								1					1	1				1								
LAAC MDL Loaded	3													1	1												
Loads Verified	7	1		1		1		1						1	1				1								
LV & PL Processing	3										1		1														1
LV Selection	10	1		1				1			1	1										1	1	1		1	1
PL Selection	5							1			1	1	1														1
System checks	9	1	1	1				1	1	1	1		1														1
Mating	3										1		1														1
System checks	7		1	1				1	1		1		1														1
Comm Checks	5							1			1		1												1		1
LV Simulations	9	1	1	1				1	1		1		1						1								1
Configuration Complete	2												1														1
Readiness & Rehearsals	3				1								1														1
Preflight Mission Brief/Readiness Review	11	1	1	1	1	1		1	1		1		1						1								1
Rehearsals	10		1	1	1	1		1	1		1		1						1								1
Built-In Hold	5		1	1	1	1							1														
Execution																											
LV Fueling	7	1						1		1	1		1						1							1	
Power transition	7	1						1		1	1		1						1							1	
Movement to Fueling	7	1						1		1	1		1						1							1	
Attach Umbilical	7	1						1		1	1		1						1							1	
Vent Lines	7	1						1		1	1		1						1							1	
Fueling Lines	7	1						1		1	1		1						1							1	
Purge Lines	7	1						1		1	1		1						1							1	
LV Fueling	7	1						1		1	1		1						1							1	
Vent fueling lines	7	1						1		1	1		1						1							1	
LAAC Processing	7	1							1			1	1						1						1	1	
LV Movement to LAAC	7	1							1			1	1						1						1	1	
LV Mating to LAAC	7	1							1			1	1						1						1	1	
Aircrew Step to Aircraft	7	1							1			1	1						1						1	1	
Aircrew Confirms Mission Plan	7	1							1			1	1						1						1	1	
OK to Taxi	7	1							1			1	1						1						1	1	
Remove Vent Lines	7	1							1			1	1						1						1	1	
Ready for Taxi	7	1							1			1	1						1						1	1	
Taxi & Take-off	7	1							1			1	1						1						1	1	
Captive Carry Fly-Out	6	1							1			1	1						1							1	
Climb to Altitude	6	1							1			1	1						1							1	
LV Comm Checks1	7	1						1	1			1	1						1							1	
Fly to Launch Zone	6	1							1			1	1						1							1	
Tanker	6	1							1			1	1						1							1	
Receive weather updates	8	1		1					1			1	1						1	1						1	
Mission Selection	8	1	1	1					1			1	1							1						1	
Update Stakeholders	7	1		1				1	1			1	1													1	
Launch Operations	14	1		1					1		1	1	1		1	1		1	1	1		1		1			1
Launch Maneuver	14	1		1					1		1	1	1		1	1		1	1	1		1		1			1
Release	14	1		1					1		1	1	1		1	1		1	1	1		1		1			1
Launch	14	1		1					1		1	1	1		1	1		1	1	1		1		1			1
MECO	14	1		1					1		1	1	1		1	1		1	1	1		1		1			1
Fairing Sep	14	1		1					1		1	1	1		1	1		1	1	1		1		1			1
SECO	14	1		1					1		1	1	1		1	1		1	1	1		1		1			1
PL Sep	14	1		1					1		1	1	1		1	1		1	1	1		1		1			1
PL On-orbit	14	1		1					1		1	1	1		1	1		1	1	1		1		1			1

Appendix C- Survey Cycle-2 Results Summary

Table C-1 Survey Cycle-2 Results Summary

Survey Cycle-2 Results:

Purpose:

1. Get process model components time values correct
2. Achieve an executable architecture to verify timing goals

"*What are component values (min/max)*?"

Results:

1. Received time min/max values for each line
2. Calculated means and Stdev's for each line
3. Calculated a random time value within range for each line item
4. Determined Total Mission time
5. Repeated for 500 missions (Monte Carlo simulation)

Appendix D - Survey Cycle-2 Results Summary

Table D-1 Timeline Linked Schedule Framework

ID	Task Name	Remaining Duration	Early Finish Histogram	Duration Distribution Type	Duration Optimistic	Duration Most Likely	Duration Pessimistic	Predecessors	Successors	Percent Critical (Sensitivity)	Sensitivity Index
0	Rapid Air Launch Mission	20.17 hrs	Graph	Normal	90%	100%	110%			0%	NA
1	Employment	12.22 hrs	Graph	Normal	90%	100%	110%			0%	NA
2	Tasking Authority Issues Space Tasking Order	0	1/1/2019	Normal					4	100%	0%
3	Mission Planning	9.22 hrs	Graph	Normal	90%	100%	110%			0%	NA
4	C2 Receives & Processes STO	1 min	1/1/2019	Triangular	90%	100%	110%	2	6, 7, 8, 9, 10, 11,...	100%	0%
5	C2 Issues Warning Orders	1 min	1/1/2019	Normal	90%	100%	110%			0%	NA
6	Notify Launch System	1 min	1/1/2019	Normal	90%	100%	110%	4	14, 51, 52	100%	0%
7	Notify LAAC Base	1 min	1/1/2019	Normal	90%	100%	110%	4		0%	0%
8	Notify Launch Range	1 min	1/1/2019	Normal	90%	100%	110%	4		0%	0%
9	Notify Tasking Authority	1 min	1/1/2019	Normal	90%	100%	110%	4		0%	0%
10	Notify Comm Provider	1 min	1/1/2019	Normal	90%	100%	110%	4		0%	0%
11	Notify JSpOC	1 min	1/1/2019	Normal	90%	100%	110%	4		0%	0%
12	Notify FAA	1 min	1/1/2019	Normal	90%	100%	110%	4		0%	0%
13	Trajectory Planning	7.33 hrs	Graph	Normal	90%	100%	110%			0%	NA
14	Launch Zones	30 mins	Graph	Triangular	16 mins	30 mins	44 mins	6	15	100%	11%
15	Release Points	30 mins	Graph	Triangular	17 mins	30 mins	43 mins	14	16	100%	9%
16	Launch Time/Window	10 mins	Graph	Triangular	5 mins	10 mins	15 mins	15	17	100%	4%
17	Constraints Analysis	2 hrs	Graph	Triangular	64 mins	118 mins	172 mins	16	18	100%	41%
18	Weather updates	10 mins	Graph	Triangular	5 mins	10 mins	15 mins	17	19	100%	4%
19	Candidate Trajectories Sent to JSpOC	0	Graph	Normal				18	20, 21, 22	100%	0%
20	JSpOC COLA	3 hrs	Graph	Triangular	102 mins	182 mins	262 mins	19	23	100%	61%
21	Dispersions Analysis	3 hrs	Graph	Triangular	102 mins	182 mins	262 mins	19		0%	0%
22	Initial Deconflictions	3 hrs	Graph	Triangular	102 mins	182 mins	262 mins	19		0%	0%
23	JSpOC Approved Trajectories Received	0	Graph	Normal				20	24	100%	0%
24	Finalize Trajectories	30 mins	Graph	Triangular	15 mins	30 mins	45 mins	23	25	100%	11%
25	Produce Plan Reports	30 mins	Graph	Triangular	18 mins	30 mins	42 mins	24	27, 39, 40, 41, 45	100%	9%
26	Launch Approvals	61 mins	Graph	Normal	90%	100%	110%			0%	NA
27	Submit Mission Planning Launch Notices	1 min	Graph	Normal	90%	100%	110%	25	29, 30, 31, 32, 3...	1%	0%
28	Final Deconflictions	1 hr	Graph	Normal	90%	100%	110%			0%	NA
29	FAA	1 hr	Graph	Triangular	30 mins	1 hr	90 mins	27	37	0%	0%
30	USCG	1 hr	Graph	Triangular	30 mins	1 hr	90 mins	27	37	0%	0%
31	NGA	1 hr	Graph	Triangular	30 mins	1 hr	90 mins	27	37	0%	0%
32	Communications	1 hr	Graph	Triangular	30 mins	1 hr	90 mins	27	37	0%	0%
33	LAAC Base	1 hr	Graph	Triangular	30 mins	1 hr	90 mins	27	37	0%	0%
34	JSpOC	1 hr	Graph	Triangular	30 mins	1 hr	90 mins	27	37	0%	0%
35	LAAC Range	1 hr	Graph	Triangular	30 mins	1 hr	90 mins	27	37, 48	1%	0%
36	Launch Range	1 hr	Graph	Triangular	30 mins	1 hr	90 mins	27	37	0%	0%
37	Deconflictions Complete	0	Graph	Normal				29, 30, 31, 3...		0%	0%
38	AFTS Products	91 mins	Graph	Normal	90%	100%	110%			0%	NA
39	Run anomoly cases	1 hr	Graph	Triangular	38 mins	59 mins	81 mins	25	42	35%	6%
40	Final IIP Analysis	1 hr	Graph	Triangular	38 mins	59 mins	81 mins	25	42	34%	6%
41	Final Ec Analysis	1 hr	Graph	Triangular	38 mins	59 mins	81 mins	25	42	35%	6%

Table D-2 Timeline Linked Schedule Framework, cont.

ID	Task Name	Remaining Duration	Early Finish Histogram	Duration Distribution Type	Duration Optimistic	Duration Most Likely	Duration Pessimistic	Predecessors	Successors	Percent Critical (Sensitivity)	Sensitivity Index
42	Produce AFTU MDL	30 mins	Graph	Triangular	15 mins	30 mins	45 mins	39, 40, 41	43	99%	11%
43	Submit AFTU MDL to C2	1 min	Graph	Normal	90%	100%	110%	42	47	99%	0%
44	⊟ Produce & Load MDLs	1.85 hrs	Graph	Normal	90%	100%	110%			0%	NA
45	Produce LV MDL	1 hr	Graph	Triangular	38 mins	59 mins	81 mins	25	46	0%	0%
46	LV MDL Loaded	10 mins	Graph	Triangular	5 mins	10 mins	15 mins	45	49	0%	0%
47	AFTU MDL Loaded	10 mins	Graph	Triangular	5 mins	10 mins	15 mins	43	49	99%	4%
48	LAAC MDL Loaded	10 mins	Graph	Triangular	5 mins	10 mins	15 mins	35	49	1%	0%
49	Loads Verified	10 mins	Graph	Triangular	5 mins	10 mins	15 mins	46, 47, 48	57	100%	4%
50	⊟ LV & PL Processing	10.18 hrs	Graph	Normal	90%	100%	110%			0%	NA
51	LV Selection	10 mins	Graph	Triangular	5 mins	10 mins	15 mins	6	53	0%	0%
52	PL Selection	10 mins	Graph	Triangular	5 mins	10 mins	15 mins	6	53	0%	0%
53	System checks	20 mins	Graph	Normal	90%	100%	110%	51, 52	54	0%	0%
54	Mating	1 hr	Graph	Normal	90%	100%	110%	53	55	0%	0%
55	System checks	20 mins	Graph	Normal	90%	100%	110%	54	56	0%	0%
56	Comm Checks	30 mins	Graph	Normal	90%	100%	110%	55	58	0%	0%
57	LV Simulations	1 hr	Graph	Triangular	45 mins	1 hr	75 mins	49	58	100%	11%
58	Configuration Complete	0	Graph	Normal				57, 56	60, 62	100%	0%
59	⊟ Readiness & Rehearsals	2 hrs	Graph	Normal	90%	100%	110%			0%	NA
60	Preflight Mission Brief/Readiness Review	1 hr	Graph	Normal	90%	100%	110%	58	61	0%	0%
61	Rehearsals	1 hr	Graph	Triangular	90%	100%	110%	60		0%	0%
62	Built-In Hold	1 hr	Graph	Triangular	45 mins	62 mins	78 mins	58	65	100%	13%
63	⊟ Execution	8.95 hrs	Graph	Normal	90%	100%	110%			0%	NA
64	⊟ LV Fueling	3.83 hrs	Graph	Normal	90%	100%	110%			0%	NA
65	Power transition	30 mins	Graph	Triangular	15 mins	30 mins	45 mins	62	66	100%	11%
66	Movement to Fueling	30 mins	Graph	Triangular	15 mins	30 mins	45 mins	65	67	100%	11%
67	Attach Umbilical	10 mins	Graph	Triangular	5 mins	10 mins	15 mins	66	68	100%	4%
68	Vent Lines	10 mins	Graph	Triangular	5 mins	10 mins	15 mins	67	69	100%	4%
69	Fueling Lines	10 mins	Graph	Triangular	5 mins	10 mins	15 mins	68	70	100%	4%
70	Purge Lines	10 mins	Graph	Triangular	5 mins	10 mins	15 mins	69	71	100%	4%
71	LV Fueling	2 hrs	Graph	Triangular	1 hr	2 hrs	180 mins	70	72	100%	44%
72	Vent fueling lines	10 mins	Graph	Triangular	5 mins	10 mins	15 mins	71	74	100%	4%
73	⊟ LAAC Processing	90 mins	Graph	Normal	90%	100%	110%			0%	NA
74	LV Movement to LAAC	20 mins	Graph	Triangular	10 mins	20 mins	30 mins	72	75	100%	7%
75	LV Mating to LAAC	20 mins	Graph	Triangular	10 mins	20 mins	30 mins	74	76	100%	7%
76	Aircrew Step to Aircraft	20 mins	Graph	Triangular	10 mins	20 mins	30 mins	75	77	100%	7%
77	Aircrew Confirms Mission Plan	10 mins	Graph	Triangular	5 mins	10 mins	15 mins	76	78	100%	4%
78	OK to Taxi	0	Graph	Normal				77	79	100%	0%
79	Remove Vent Lines	10 mins	Graph	Triangular	5 mins	10 mins	15 mins	78	80	100%	4%
80	Rady for Taxi	0	Graph	Normal				79	81	100%	0%
81	Taxi & Take-off	10 mins	Graph	Triangular	5 mins	10 mins	15 mins	80	83	100%	4%
82	⊟ Captive Carry Fly-Out	3 hrs	Graph	Normal	90%	100%	110%			0%	NA
83	Climb to Altitude	20 mins	Graph	Triangular	10 mins	20 mins	30 mins	81	84	100%	7%
84	LV Comm Checks1	1 hr	Graph	Triangular	30 mins	1 hr	90 mins	83	85	100%	22%
85	Fly to Launch Zone	1 hr	Graph	Triangular	30 mins	1 hr	90 mins	84	86	100%	22%
86	Tanker	10 mins	Graph	Triangular	5 mins	10 mins	15 mins	85	87	100%	4%
87	Receive weather updates	10 mins	Graph	Triangular	5 mins	10 mins	15 mins	86	88	100%	4%
88	Mission Selection	10 mins	Graph	Triangular	50%	100%	150%	87	89	100%	4%
89	Update Stateholders	10 mins	Graph	Triangular	5 mins	10 mins	15 mins	88	91	100%	4%
90	⊟ Launch Operations	37 mins	Graph	Normal	90%	100%	110%			0%	NA
91	Launch Manuever	10 mins	Graph	Triangular	5 mins	10 mins	15 mins	89	92	100%	4%
92	Release	1 min	Graph	Normal	90%	100%	110%	91	93	100%	0%
93	Launch	1 min	Graph	Normal	90%	100%	110%	92	94	100%	0%
94	MECO	5 mins	Graph	Triangular	50%	100%	150%	93	95	100%	2%
95	Fairing Sep	5 mins	Graph	Triangular	50%	100%	150%	94	96	100%	2%
96	SECO	5 mins	Graph	Triangular	50%	100%	150%	95	97	100%	2%
97	PL Sep	10 mins	Graph	Triangular	50%	100%	150%	96	98	100%	4%
98	PL On-orbit	0	Graph	Normal				97		100%	0%

Appendix E - Process Tasks GR&As Recommended

Table E-1 Task GR&As Recommended to Support this Construct

Task Name	Duration	Ground Rules & Assumptions required to make timing possible	Investment Required
Rapid Air Launch Mission	**0.99 days**		
Employment	**0.59 days**		
Mission Planning	**0.38 days**		
Trajectory Planning	**0.3 days**		
Launch Zones	30 mins	Trajectory Planning Automation	X
Release Points	30 mins	Trajectory Planning Automation	X
Launch Time/Window	10 mins	Trajectory Planning Automation	X
Constraints Analysis	2 hrs	Trajectory Planning Automation	X
Dispersions Analysis	3 hrs	Mission Monte Carlo Automation	X
Produce Plan Reports	30 mins	Stakeholder ICDs Finalized	X
Launch Approvals	**0.04 days**		
Submit Mission Planning Launch Notices	1 min	C2 Tasking Automation	
Final Deconflictions	**0.04 days**		
FAA	60 mins	MOU in place, ICD established	X
USCG	60 mins	MOU in place, ICD established	X
NGA	60 mins	MOU in place, ICD established	X
Communications	60 mins	MOU in place, ICD established	X
LAAC Base	60 mins	MOU in place, ICD established	X
JSpOC	60 mins	MOU in place, ICD established	X
LAAC Range	60 mins	MOU in place, ICD established	X
Launch Range	60 mins	MOU in place, ICD established	X
Deconflictions Complete			
AFTS Products	**0.06 days**		
Run anomaly cases	60 mins	Trajectory Monte Carlo Automation	X
Final IIP Analysis	60 mins	IIP Monte Carlo Automation	X
Final Ec Analysis	60 mins	Ec Monte Carlo Automation	X
Produce AFTU MDL	30 mins	AFTU ICD Finalized	
Submit AFTU MDL to C2	60 mins	C2 Automation	
Produce MDLs	**0.08 days**		
Produce LV MDL	60 mins	LV ICD Finalized	
LV MDL Loaded	10 mins	C2 Automation	
AFTU MDL Loaded	10 mins	C2 Automation	
LAAC MDL Loaded	10 mins	C2 Automation	
Loads Verified	10 mins	C2 Automation	
LV & PL Processing	**0.42 days**		
LV Selection	10 mins	Logisitics Automation	
PL Selection	10 mins	Logisitics Automation	
System checks	20 mins	C2 Automation	
Mating	60 mins	Trained technicians	
System checks	20 mins	C2 Automation	
Comm Checks	30 mins	C2 Automation	
LV Simulations	60 mins	6DOF Simulations Automation	
Configuration Complete	0 days		
Readiness & Rehearsals	**0.08 days**		
Preflight Mission Brief/Readiness Review	60 mins	Trained crew	
Rehearsals	60 mins	Mission Simulation Automation	
Built-In Hold	60 mins		

Table E-2 Task GR&As Recommended to Support this Construct, cont.

Task Name	Duration	Ground Rules & Assumptions required to make timing possible	Investment Required
Execution	**0.4 days**		
LV Fueling	**0.16 days**		
Power transition	30 mins	Trained technicians	
Movement to Fueling	30 mins	Trained technicians	
Attach Umbilical	10 mins	Trained technicians	
Vent Lines	10 mins	Trained technicians	
Fueling Lines	10 mins	Trained technicians	
Purge Lines	10 mins	Trained technicians	
LV Fueling	120 mins	Trained technicians	
Vent fueling lines	10 mins	Trained technicians	
LAAC Processing	**0.06 days**		
LV Movement to LAAC	20 mins	Trained technicians	
LV Mating to LAAC	20 mins	Trained technicians	
Aircrew Step to Aircraft	20 mins	Trained crew	
Aircrew Confirms Mission Plan	10 mins	Trained crew	
OK to Taxi			
Remove Vent Lines	10 mins	Trained technicians	
Ready for Taxi			
Taxi & Take-off	10 mins	Trained crew	
Captive Carry Fly-Out	**0.16 days**		
Climb to Altitude	20 mins	Trained crew	
LV Comm Checks1	60 mins	Trained crew	
Fly to Launch Zone	60 mins	Trained crew	
Tanker	10 mins	Trained crew	
Receive weather updates	10 mins	Trained crew	
Mission Selection	10 mins	Trained crew	
Update Stakeholders	10 mins	Trained crew	
Launch Operations	**0.02 days**		
Launch Maneuver	10 mins	Trained crew	
Release	1 min	Trained crew	
Launch	1 min		
MECO	5 mins		
Fairing Sep	5 mins		
SECO	5 mins		
PL Sep	10 mins		
PL On-orbit			

Appendix F - Split-Tornado Chart

Table F-1 Split-Tornado Chart Metrics Assisting in Sensitivity Analyses

ID	Task Name	Remaining Duration	Percent Critical	Percent Critical (Sensitivity)	Sensitivity Index	Sensitivity Index 25.00 50.00	Optimistic Finish of Project	Pessimistic Finish of Project	Jan 2019 02 02:00 03:00 04:00 05:00	Early Finish Histogram	Schedule Sensitivity Bar Basis
0	Rapid Air Launc	20.17 hrs	100%	0%	NA		NA	NA		Graph	Estimated
1	Employment	12.22 hrs	100%	0%	NA		NA	NA		Graph	Estimated
62	Built-In Hol	1 hr	100%	100%	13%		1/2/2019	1/2/2019		Graph	Estimated
3	Mission Pla	9.22 hrs	100%	0%	NA		NA	NA		Graph	Estimated
44	Produce (	1.85 hrs	0%	0%	NA		NA	NA		Graph	Estimated
47	AFTU M	10 mins	99%	99%	4%		1/2/2019	1/2/2019		Graph	Estimated
49	Loads V	10 mins	100%	100%	4%		1/2/2019	1/2/2019		Graph	Estimated
46	LV MDL	10 mins	0%	0%	0%		1/2/2019	1/2/2019		Graph	Estimated
48	LAAC M	10 mins	1%	1%	0%		1/2/2019	1/2/2019		Graph	Estimated
45	Produc	1 hr	0%	0%	0%		1/2/2019	1/2/2019		Graph	Estimated
13	Trajectory	7.33 hrs	100%	0%	NA		NA	NA		Graph	Estimated
20	JSpOC	3 hrs	100%	100%	61%		1/2/2019	1/2/2019		Graph	Estimated
17	Constra	2 hrs	100%	100%	41%		1/2/2019	1/2/2019		Graph	Estimated
24	Finalize	30 mins	100%	100%	11%		1/2/2019	1/2/2019		Graph	Estimated
14	Launch	30 mins	100%	100%	11%		1/2/2019	1/2/2019		Graph	Estimated
15	Release	30 mins	100%	100%	9%		1/2/2019	1/2/2019		Graph	Estimated
25	Produc	30 mins	100%	100%	9%		1/2/2019	1/2/2019		Graph	Estimated
18	Weathe	10 mins	100%	100%	4%		1/2/2019	1/2/2019		Graph	Estimated
16	Launc	10 mins	100%	100%	4%		1/2/2019	1/2/2019		Graph	Estimated
26	Launch A	61 mins	1%	0%	NA		NA	NA		Graph	Estimated
28	Final D	1 hr	1%	0%	NA		NA	NA		Graph	Estimated
35	LAAC	1 hr	1%	1%	0%		1/2/2019	1/2/2019		Graph	Estimated
38	AFTS Pro	91 mins	99%	0%	NA		NA	NA		Graph	Estimated
42	Produc	30 mins	99%	99%	11%		1/2/2019	1/2/2019		Graph	Estimated
40	Final IIF	1 hr	35%	35%	6%		1/2/2019	1/2/2019		Graph	Estimated
39	Run an	1 hr	35%	35%	6%		1/2/2019	1/2/2019		Graph	Estimated
41	Final E	1 hr	34%	34%	6%		1/2/2019	1/2/2019		Graph	Estimated
50	LV & PL Pro	10.18 hrs	0%	0%	NA		NA	NA		Graph	Estimated
57	LV Simula	1 hr	100%	100%	11%		1/2/2019	1/2/2019		Graph	Estimated
63	Execution	8.95 hrs	100%	0%	NA		NA	NA		Graph	Estimated
64	LV Fueling	3.83 hrs	100%	0%	NA		NA	NA		Graph	Estimated
71	LV Fuelin	2 hrs	100%	100%	44%		1/2/2019	1/2/2019		Graph	Estimated
66	Movemen	30 mins	100%	100%	11%		1/2/2019	1/2/2019		Graph	Estimated
65	Power tra	30 mins	100%	100%	11%		1/2/2019	1/2/2019		Graph	Estimated
68	Vent Line	10 mins	100%	100%	4%		1/2/2019	1/2/2019		Graph	Estimated
69	Fueling L	10 mins	100%	100%	4%		1/2/2019	1/2/2019		Graph	Estimated
67	Attach Un	10 mins	100%	100%	4%		1/2/2019	1/2/2019		Graph	Estimated
70	Purge Lin	10 mins	100%	100%	4%		1/2/2019	1/2/2019		Graph	Estimated
72	Vent fueli	10 mins	100%	100%	4%		1/2/2019	1/2/2019		Graph	Estimated
73	LAAC Proce	90 mins	100%	0%	NA		NA	NA		Graph	Estimated
74	LV Mover	20 mins	100%	100%	7%		1/2/2019	1/2/2019		Graph	Estimated
75	LV Mating	20 mins	100%	100%	7%		1/2/2019	1/2/2019		Graph	Estimated
76	Aircrew S	20 mins	100%	100%	7%		1/2/2019	1/2/2019		Graph	Estimated
77	Aircrew C	10 mins	100%	100%	4%		1/2/2019	1/2/2019		Graph	Estimated
81	Taxi & Ta	10 mins	100%	100%	4%		1/2/2019	1/2/2019		Graph	Estimated
79	Remove V	10 mins	100%	100%	4%		1/2/2019	1/2/2019		Graph	Estimated
82	Captive Car	3 hrs	100%	0%	NA		NA	NA		Graph	Estimated
85	Fly to Lau	1 hr	100%	100%	22%		1/2/2019	1/2/2019		Graph	Estimated
84	LV Comm	1 hr	100%	100%	22%		1/2/2019	1/2/2019		Graph	Estimated
83	Climb to A	20 mins	100%	100%	7%		1/2/2019	1/2/2019		Graph	Estimated
86	Tanker	10 mins	100%	100%	4%		1/2/2019	1/2/2019		Graph	Estimated
87	Receive v	10 mins	100%	100%	4%		1/2/2019	1/2/2019		Graph	Estimated
88	Mission S	10 mins	100%	100%	4%		1/2/2019	1/2/2019		Graph	Estimated
89	Update St	10 mins	100%	100%	4%		1/2/2019	1/2/2019		Graph	Estimated
90	Launch Ope	37 mins	100%	0%	NA		NA	NA		Graph	Estimated
91	Launch M	10 mins	100%	100%	4%		1/2/2019	1/2/2019		Graph	Estimated
97	PL Sep	10 mins	100%	100%	4%		1/2/2019	1/2/2019		Graph	Estimated
94	MECO	5 mins	100%	100%	2%		1/2/2019	1/2/2019		Graph	Estimated
96	SECO	5 mins	100%	100%	2%		1/2/2019	1/2/2019		Graph	Estimated
95	Fairing Se	5 mins	100%	100%	2%		1/2/2019	1/2/2019		Graph	Estimated