Conceptual framework for a rapid space launch capability

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ABSTRACT

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)? What type of launch vehicle offers the greatest probability of success for meeting 24-hour payload to orbit timelines? 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). Rapid launches of SSA sensors to space or suborbital launches to other geographical regions (sub-orbital point-to-point SSA sensors delivery) will be critical to meet the rapidly changing geo-political space environment.

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 k, and available to future missions. This framework can be extended to solving space traffic management and space sustainability challenges, in support of SSA/SDA architectures.

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 systems. "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.

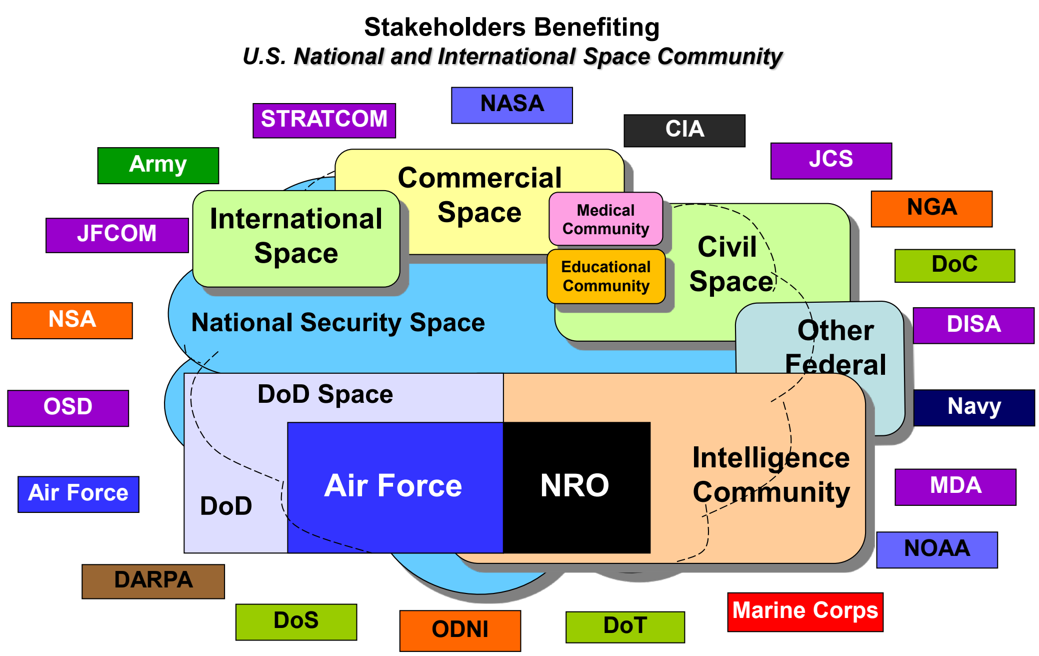
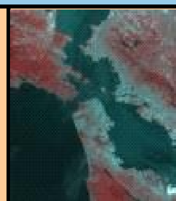
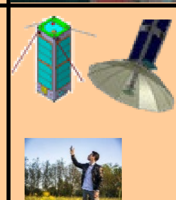
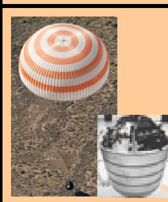
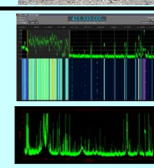
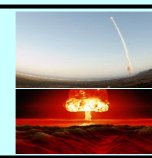


Figure 1.1-1 Stakeholders that could Benefit from this Research

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 Benefits - 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 Logistics *[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 Space Launch Timeliness Problem

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 (ret), former Vice Chairman of the Joint Chiefs of Staff, and Commander of United States Strategic Command, oversaw the nation's nuclear and space missions, has been outspoken in his challenging of the Pentagon's procurement methods and technology choices. Hyten 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 Rapid Launch Proposition

Statistical Monte Carlo models applied to launch vehicle mission simulations are required to reduce the launch mission planning and operations processes. Development of novel approaches to launch stakeholders' coordination and approval processes is required. Integration and automation of traditional stove-piped mission planning domains is required. 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 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.

1.5 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.

1.6 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. 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.

2. Current State Analysis

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 a fraction of this velocity, less than 8 km/s.

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 planner guides for commercial companies were examined. 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 (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 and Civil 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).

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).

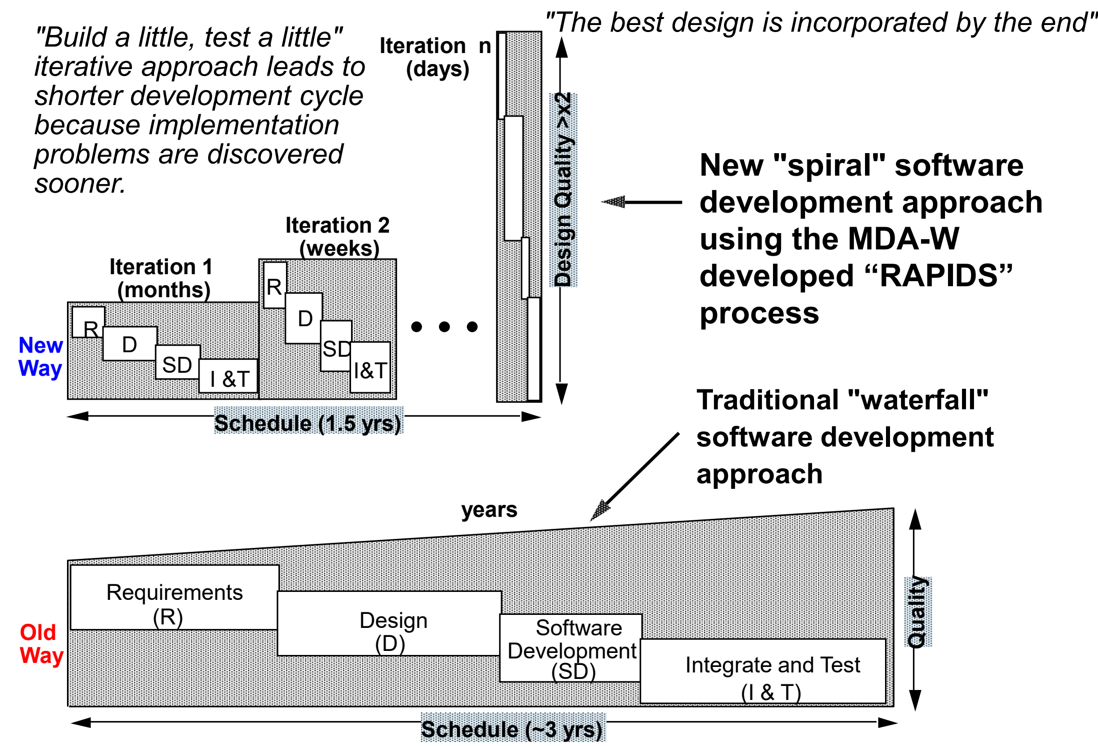


Figure 2.2-1 Innovative Rapid Development Process Developed on DC-X & DC-XA Programs

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 USAF 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.

Civil space operations examples include NASA Jet Propulsion Laboratory (JPL) where they 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 re-plan 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.

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.

2.3 Space Launch Processes

Terrestrial, Sea, and Air space launch processes were analyzed. 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 “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.

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). “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.

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).

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.

2.4 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), Combined Space Operations Center (CSpOC), Federal Aviation Administration (FAA), payload provider(s), communications relay providers (e.g. NASA), weather reporting agencies (e.g. NOAA, NWS, USAF), factory support companies and the United States Department of Commerce, Office of Space Commerce. 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.

3. Research Methodology

3.1 Research Objectives

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.

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.

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 expert's 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. 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. The user can drive simulations from MATLAB scripts to perform parameter sweeps and sensitivity analysis, as shown in the MATLAB Simulink SimEvents Monte Carlo simulation block diagram, Figure 3.1-1.

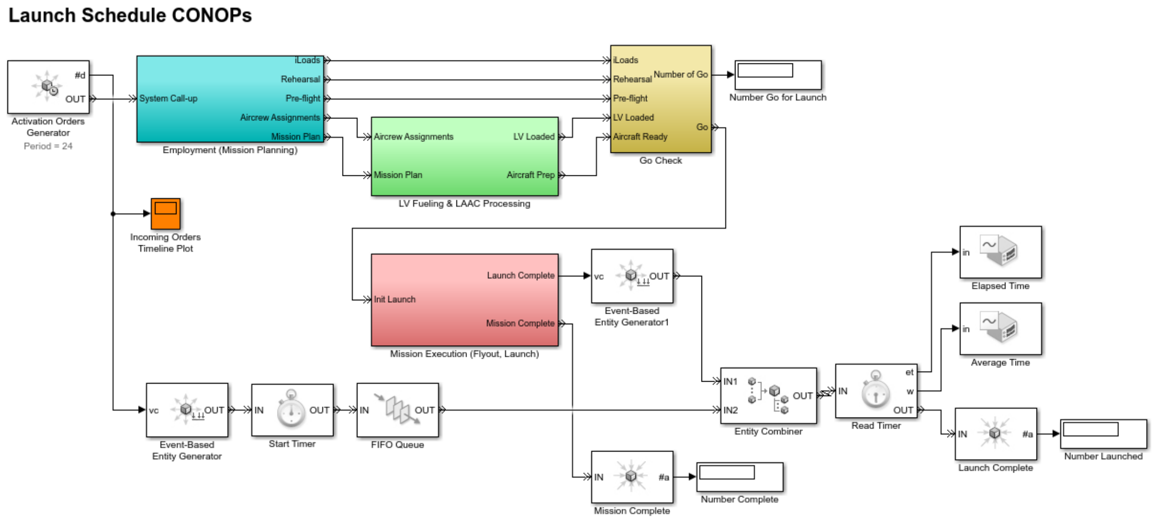


Figure 3.1-1 High Level Simulation Block Diagram

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. 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 missions 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.

Monte Carlo schedule simulations are valuable for improving mission goals and validating planning.

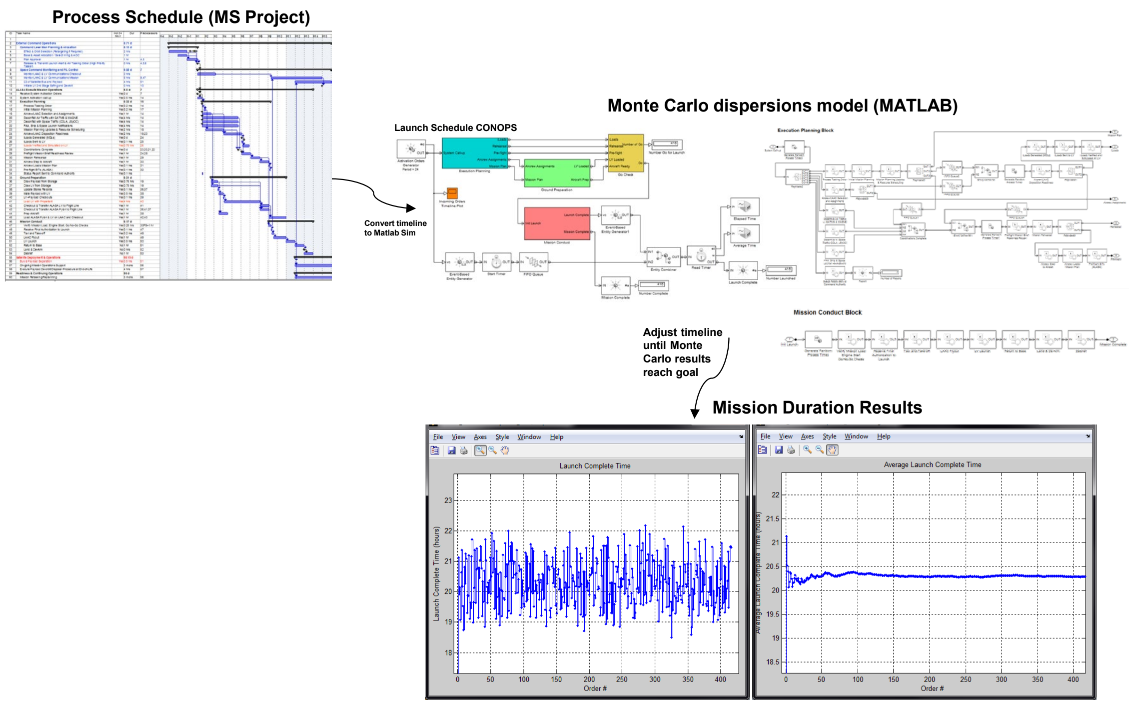


Figure 3.1-2 Timeline Modeling of Schedule Dispersions Using MATLAB Simulink

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

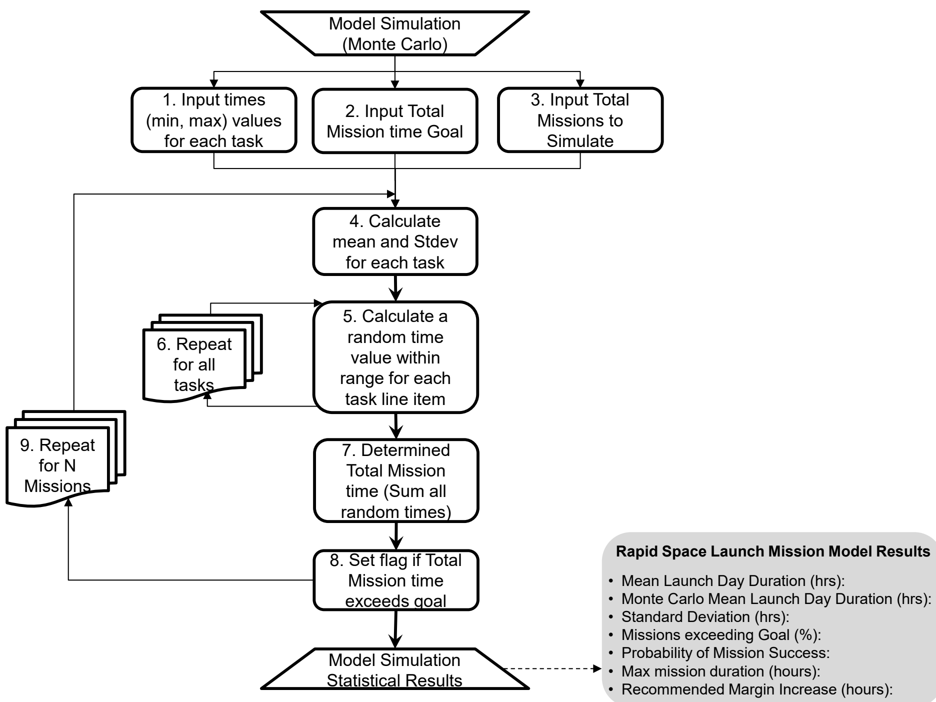


Figure 3.1-3 Model Monte Carlo Simulation Flow

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).

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).

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.

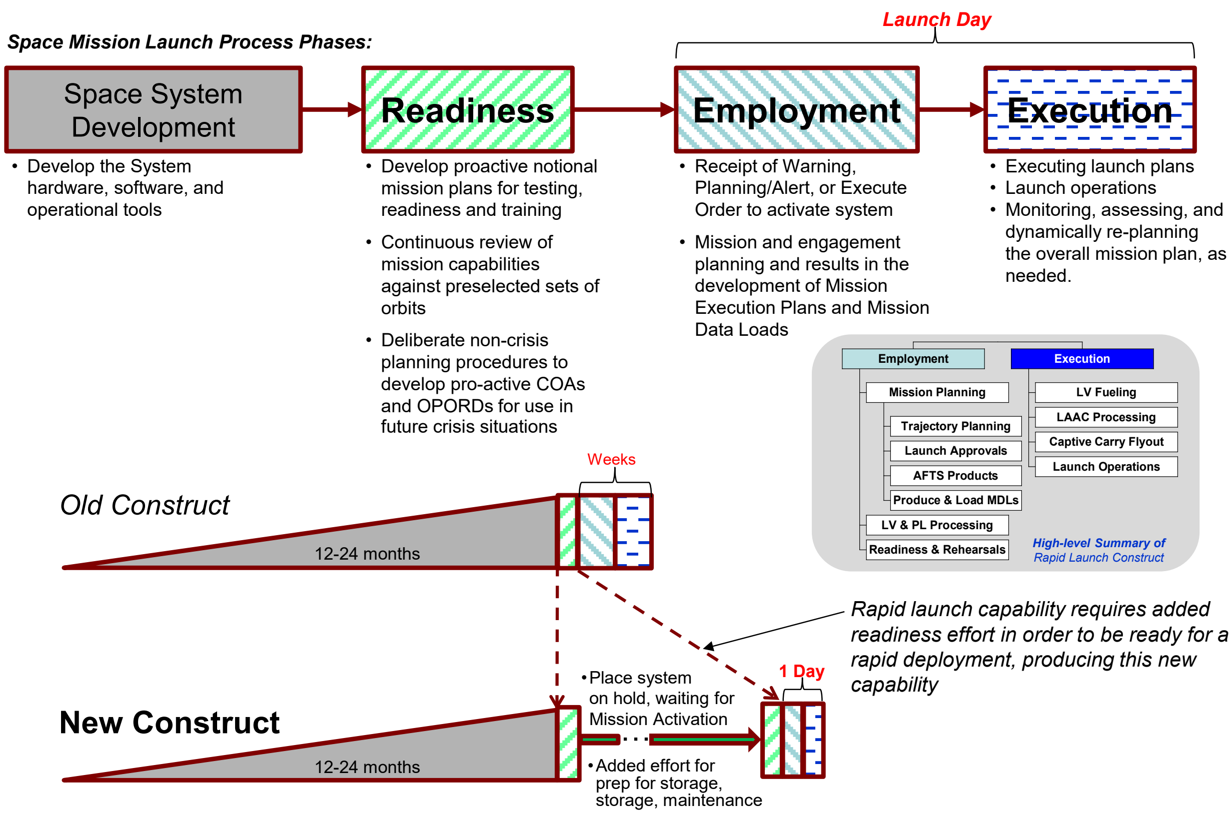


Figure 3.2-1 Space Mission Launch Process – Cost and Schedule Considerations

In this new construct, the space system development and readiness phases include 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.

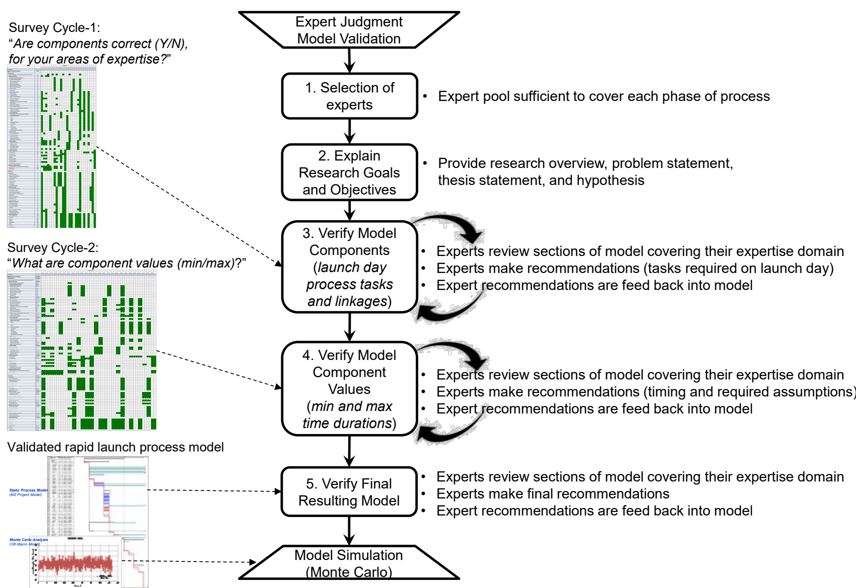


Figure 3.3-1 Expert Elicitation Process Key to Model Validation

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. The launch zone analysis task 3-point duration estimates could have a normal or triangular distribution.

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.

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.

4. Results

4.1 Simulation Results

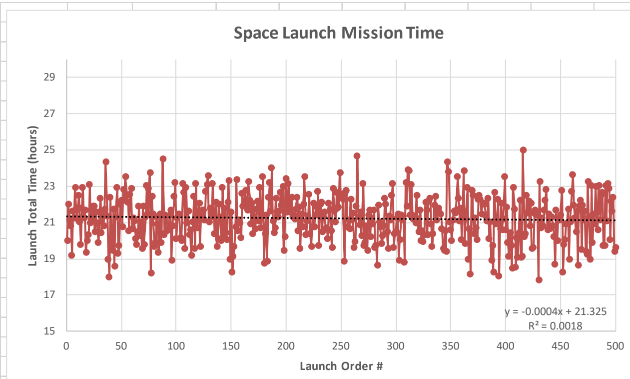
In summary, an executable timeline framework and model has been developed for simulating this construct and refining the mission planning tasks and providing immediate feedback to the experts for improved decision making.

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.

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.

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 4.1-1. 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 4.1-1 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. 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. Adjustments can then be made to the network and rerun the simulation until timing goals are achieved.

4.2 Architecture Results

The resulting 24-hour 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.

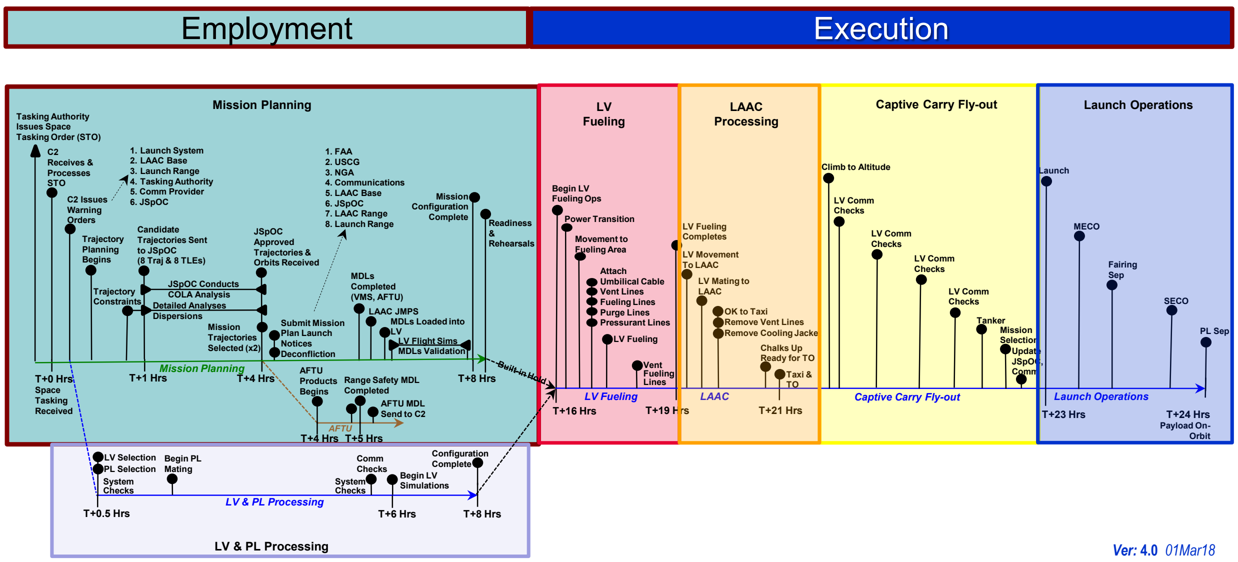


Figure 4.2-1 Rapid Launch Timing Framework (24-Hour Air-Launch Day Example)

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 air-launch vehicle offers the greatest chance of success for meeting this challenging timeline. An executable timeline model construct has been developed for simulating a rapid launch capability framework. This framework can be extended to solving space traffic management and space sustainability challenges, in support of SSA/SDA architectures.

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. A non-dedicated air-launch system (stage-0) has an even greater advantage of further reducing mission costs, substantially. 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.

Satellite buses and rapidly "plug-able" payloads should be built in advance and placed/maintained in flyable storage until call-up. Thousands of mission plans are automatically updated daily in anticipation for a 24-hour call-up. Launch day mission planning selects closest plan to one already approved for rapid approvals and coordination activities.

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 systems 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.

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