WOLF

***W**hat's **O**n the **L**unar **F**arside?*

SALEH Space And Lunar Exploration for Humanity

ESDM Systems Engineering Paper Competition

3/10/2008

WOLF

What's On the Lunar Farside?

Mission Overview

WOLF (What's On the Lunar Farside?) is a lunar sample return mission to the South Pole-Aitken (SPA) Basin, located on the farside of the moon, seeking to answer some of the remaining questions about our solar system. Through the return and analysis of SPA samples, scientists can constrain the period of inner solar system late heavy bombardment and gain momentous knowledge of the SPA basin. WOLF provides the opportunity for mankind's progression in further understanding our solar system, its history, and unknowns surrounding the lunar farside.

Mass Breakdown Structure

Element	Mass (kg)
Dry Mass of Single Lander	634.2
Propellant Mass of Lunar Descent	774.3
Dry Mass of Orbiter	204.1
Propellant Mass of Lunar Orbit Insertion	631.5
Boosted Mass	4327.7
Total Margin	2072.3
Launch Capability of HLV	6400

ΔV Budget

Atlas V HLV			
	Launch	9.5	km/s
	Trans-lunar	3.3	km/s
WOLF Spacecraft			
	Orbit	0.55	km/s
	Descent	2.05	km/s
	Return	2.65	km/s

WOLF Payload

Lander		Orbiter
Drill	Microscopic imager	Magnetometer
Storage Container	Mass spectrometer	Visible/NIR Spectrometer
Extendable Arm w/ Scoop	Visible/NIR Spectrometer	
Panoramic Imager	Descent Imager	Gamma Ray Spectrometer

DSN Specifications

Antenna Diameter	26 m
Uplink Freq	7 GHz
Downlink Freq	8 GHz

Communications

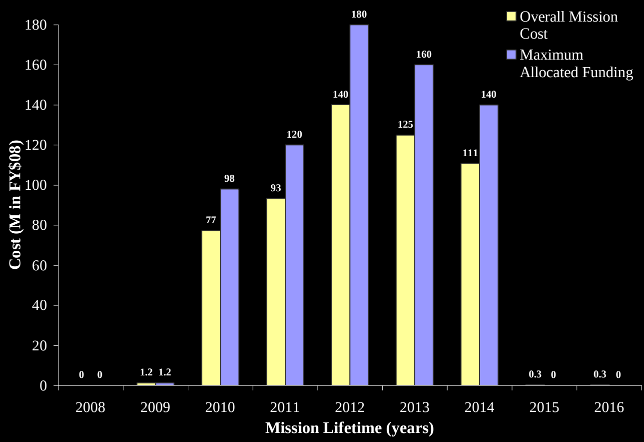
The orbiter will provide intermittent, direct communication between the lander and ground operations via the Deep Space Network (DSN). Received images and spectrometry will aid in real-time sample selection.

WOLF

SALEH Team Structure

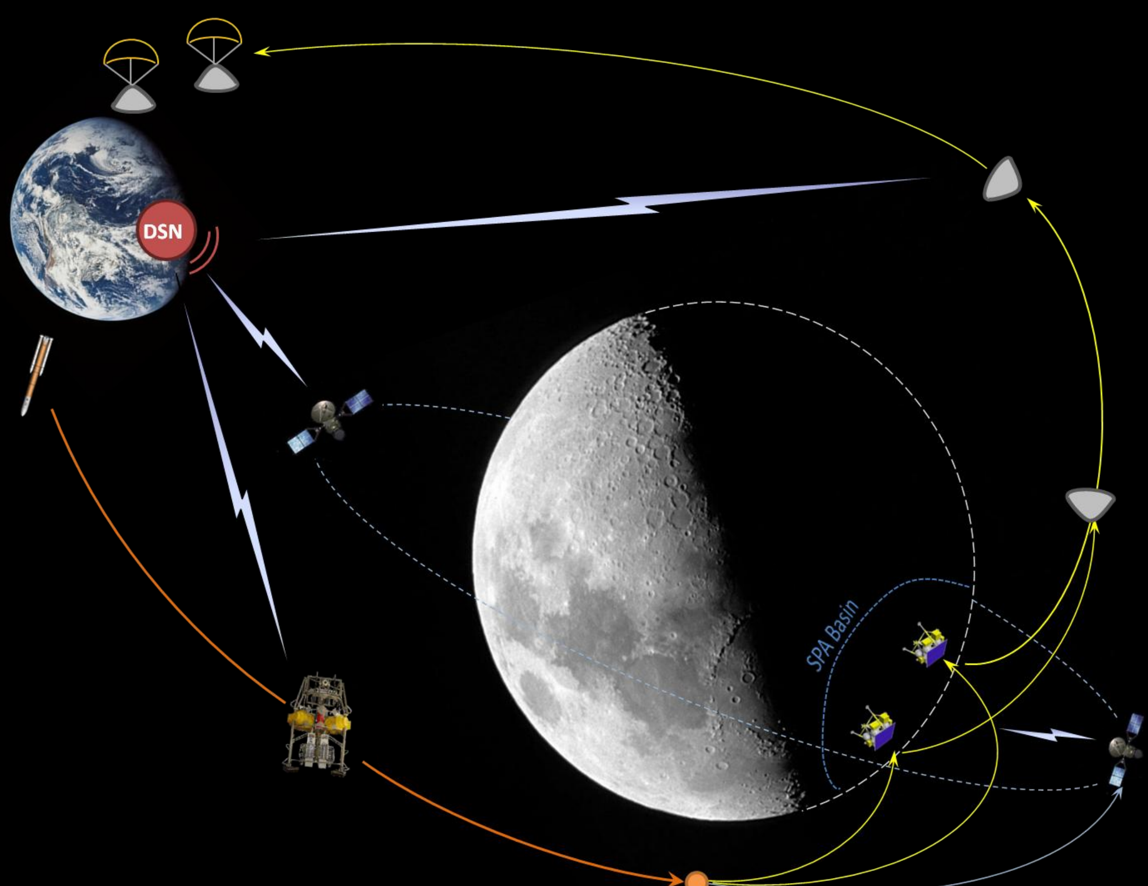
Michael Bernatovich	Project Manager
Nicholas Daily	Mission Engineer
Jonathan Keim	Systems Engineer
Laura Place	Project Engineer
Jennifer Rome	Payload Engineer

Cost Schedule



Cost Breakdown	Mil of FY$08
(2) Lunar Landers	336
Communication Relay Satellite	78
Atlas V HLV	130
Ground Operations	1.7
NASA Curatorial Facility	1.3
Phase-A Concept Study	1.2
Overall Mission Cost	***548.1***

WOLF OV-1 Diagram



Executive Summary

Space and Lunar Exploration for Humanity (SALEH, pronounced “SAY-LEE”) is a team of undergraduate Aerospace Engineering students from Georgia Institute of Technology designing a mission in response to an Announcement of Opportunity (AO) from the National Aeronautics and Space Administration (NASA). SALEH was chosen by professors of a Space Systems Design course to represent Georgia Institute of Technology in the NASA Exploration Systems Mission Directorate (ESMD) Systems Engineering Paper competition. Our team is comprised of Michael Bernatovich (Project Manager), Laura Place (Project Engineer), Jonathan Keim (Flight Systems Engineer), Jennifer Rome (Payload Engineer), and Nicholas Daily (Mission Engineer).

As a part of NASA’s New Frontiers program, an AO was released for the scientific investigation of a Lunar Sample Return (LSR) mission to the South Pole-Aitken (SPA) Basin, a crater on the farside of the moon believed to be the largest crater in our solar system. Through the collection and return of these samples, WOLF can elucidate mysteries surrounding SPA geochemical anomalies and the period of inner solar system late heavy bombardment. WOLF provides the opportunity for mankind’s progression in further understanding our solar system, its history, and unknowns surrounding the lunar farside.

SALEH has designed the proposal mission WOLF (What’s On the Lunar Farside?) using carefully defined systems engineering processes and developing various tools detailed in this report. Specific systems engineering approaches were defined on both a subsystem level and mission level for the design of the WOLF mission. Looking at the smaller scale, SALEH takes several different approaches which are individually tailored for the design decision at hand. In making a decision for mission architecture, a Morphological Matrix isolates the four most favorable architectures we’ve considered based on various criteria. These top architectures are then placed in an Analytical Hierarchy Process (AHP) which gives a quantitative assessment for our final mission architecture decision. With tens of thousands of options for a payload combination, SALEH developed a Pareto Optimization tool which significantly reduces the combinations to consider and analyze. Upon comparison with the AO requirements and objectives, a baseline and performance floor payload combination is defined to simplify the descoping process if necessary. Cost analysis was accomplished using a unique integration between two types of top-down models. All the while, these tools are considered crucial links of a chain which represents the complete WOLF mission design effort. Using traceability and transparency with the AO, we are able to methodically approach our design choices.

In short, we have a great mission architecture which fully qualifies for the AO; but more importantly, we have a systematic qualitative & quantitative Systems Engineering approach that guides us through the mission design process and can be used in a wide range of applications beyond a LSR mission.

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4. Nomenclature

AHP	Analytical Hierarchy Process
AIAA	American Institute of Aeronautics and Astronautics
AO	Announcement of Opportunity
CDR	Concept Design Review
CRS	Communication Relay Satellite
ΔV	Orbital Maneuver Cost (change in velocity)
DSN	Deep Space Network
ESDM	Exploration Systems Mission Directorate
LHB	Late Heavy Bombardment
LSR	Lunar Sample Return
NASA	National Aeronautics and Space Administration
OV-1	Operational View Diagram
SALEH	Space And Lunar Exploration for Humanity
SPA	South Pole-Aitken
STK	Satellite Tool Kit
TRL	Technology Readiness Level
WOLF	“What’s On the Lunar Farside?” Mission

5. Contributors

SALEH would like to thank the following professors, professionals, specialists, and students for their assistance in the design of WOLF.

Peter Isaacson	Brown University
Ian Garrick-Bethell	Massachusetts Institute of Technology
Dr. Carlee Bishop	Georgia Institute of Technology
Dr. Joseph Saleh	Georgia Institute of Technology
Dr. Robert Braun	Georgia Institute of Technology
Dr. Ryan Russel	Georgia Institute of Technology
Chris Cordell	Georgia Institute of Technology
Bala Radharamanan	Georgia Institute of Technology

6. Mission Introduction

This mission proposal is in response to the NASA Announcement of Opportunity (AO) through the New Frontiers Program for a LSR mission from the Moon's SPA Basin. The mission must launch by the end of 2014, return at least 1 kg of lunar samples, and stay within the cost cap of $700M (FY$08).

6.1. South Pole-Aitken Basin

SPA Basin is the largest known basin in the solar system, as well as the oldest and deepest impact structure preserved on the Moon. Located on the lunar farside, it spans 2500 km, has a maximum depth of 13 km, and contains some of the lowest and highest elevations on the lunar surface. Farside spectrometry has revealed that the basin has higher concentrations of iron oxide and thorium than surrounding landscapes. In addition, its crustal thickness of 15 km is lower than the global average of about 50 km. For these reasons, SPA Basin is an extremely interesting target for a sample return mission.

First, because SPA is the oldest lunar impact structure, its age constrains the beginning of the period of Late Heavy Bombardment (LHB). It is hypothesized that during this period (approximately 4.1 to 3.8 billion years ago), a spike occurred in the flux of large impactors in the inner solar system, and many large impact basins were formed. A more precise determination of the time at which the LHB period began would aid understanding of the formation of the Earth and the inner solar system. Therefore radiometric age dating of samples returned from SPA would be of great scientific value.

SPA Basin also has unusually high concentrations of iron oxide and thorium, observed through remote sensing. While thorium is abundant in the nearside maria, most of the farside thorium is concentrated in SPA. It is possible that these materials were indigenous to SPA and were exposed after the basin was formed, or that the materials were ejected from a nearby impact such as Mare Imbrium. Since thorium is a heat-producing element, it is likely tied to lunar thermal evolution and differentiation. Studying samples returned from SPA could help elucidate the nature of this geochemical anomaly.

Since SPA Basin is the deepest structure on the Moon and has a lower than average crustal thickness, it allows access to the interior of a small, differentiated body. The floor the basin is considered to be representative of the Moon's lower crust. It is also possible that the impact that formed the basin may have churned up mantle rocks along with other ejected material, or that mantle materials may exist as clasts in breccia rocks. Samples of such materials would allow scientists to determine, using gamma ray and visible/near-infrared spectrometry, the mineralogy and composition of the Moon's lower crust and mantle. The composition of these samples would also help characterize the lunar farside, since current Apollo and Luna samples are biased by nearside impact basins. In addition, the composition and origin of the impacting object could be determined through trace-element and isotopic analyses.

6.2. Announcement of Opportunity (AO) Breakdown

The top-level AO requirements and objectives can be broken down as shown in Figure 6-1. The team managers must develop a work breakdown structure to define the project's scope and objectives. They must also identify the mission, cost and schedule risks and appropriate mitigation strategies.

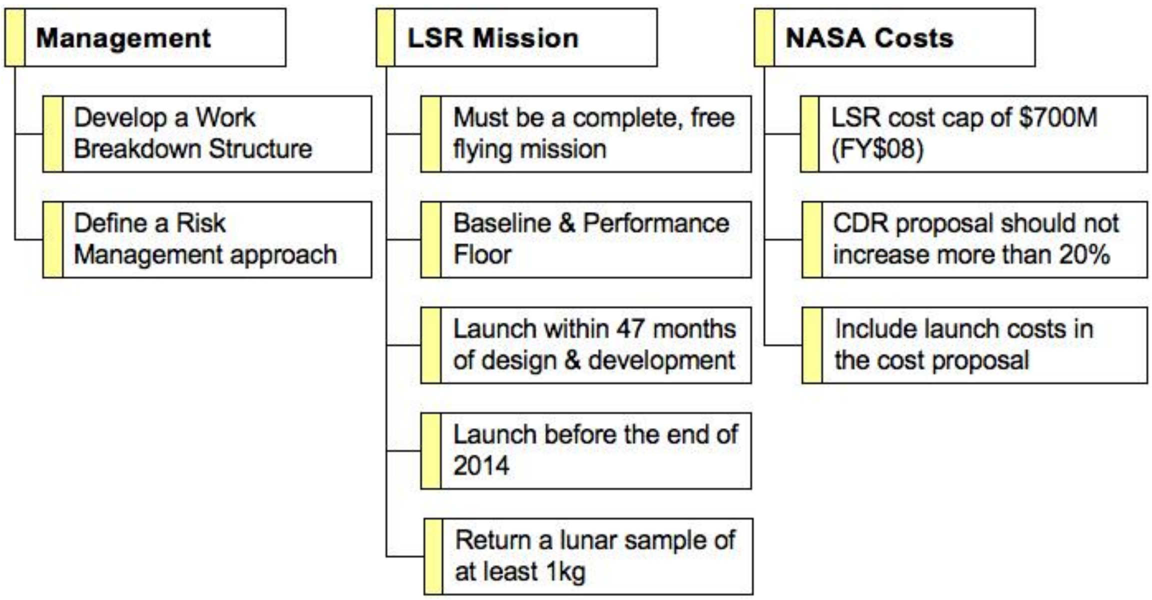

Figure 6-1. Breakdown of top-level AO requirements.

The mission itself must be a complete, free-flying mission capable of returning 1 kg of lunar sample. A baseline and performance floor must be clearly defined; the baseline mission should be capable of accomplishing all scientific objectives proposed in the AO, while the performance floor mission would achieve the minimum science return for which the mission cost is justifiable. The sample return mission must launch within 47 months of the commencement of design and development, and no later than the end of 2014.

The cost cap defined by NASA is $700M (FY$08), which covers all mission costs, including the cost of launch services. In addition, the mission cost presented to NASA at the Concept Design Review (CDR) cannot experience a growth of more than 20% over the course of the project.

7. Systems Engineering Methodology

In attempting to complete any complex project, the complexity of the schedule, project development, and team integration can become such a daunting task that project success can seem impossible. Not only must team members efficiently complete their respective duties, but each of these duties must be completed in an organized fashion which benefits mission design as a whole. This approach taken to approach optimal project progression is known as Systems Engineering. Systems Engineering is the effort taken to formalize an approach to accomplish project development while exploring new ideas and maximizing team productivity.

As one can see in Figure 7-1, WOLF is designed through a high level Systems Engineering structure using a progression in decisions and tasks necessary to approach full mission development. Beginning with a complete breakdown of the AO objectives and requirements, the necessary milestones are laid out in a way which defines a step by step guideline moving toward a detailed mission design process. This figure represents the large scale SE effort formulated for designing WOLF. On a smaller scale, each of the blocks can individually be broken down to an individually tailored SE approach. This chapter describes the breakdown of the design methodology and tools developed for the most critical blocks (Mission Architecture Selection, Payload Optimization, Orbit Determination, Mass Model, and Cost Models).

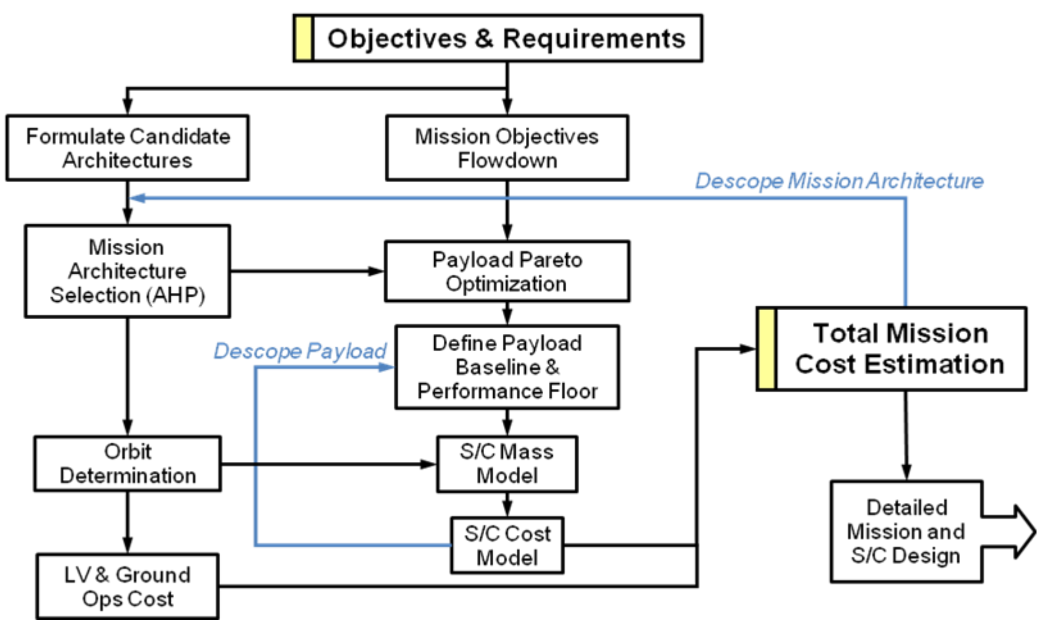

Figure 7-1. SALEH's SE approach towards designing WOLF is represented by a framework of milestones which decreases the amount of reworking and design changes.

7.1. Mission Architecture Selection

Defining the mission architecture is critical to the mission design process. It drives all other trades and systems engineering decisions that are encountered throughout the design process. Candidate architectures must first meet the requirements specified in the AO. Second, these architectures must be weighed against each other, not only in terms of variable with concrete significance such as cost and mass, but also in abstract values such as risk and science. It is through the consideration of all of these variables that the optimal mission architecture is chosen. The Wolf mission architecture was designed using multiple system engineering tools that take all of these considerations into account. Each of these tools was specifically chosen to refine the number of candidate architectures from many to a single architecture.

A Morphological Matrix was used, first, to define all possible combinations of architectures that were considered and second to narrow down the field into plausible options. The Morphological Matrix, or Morph Matrix for short, decomposes the system into various options so that the options may be identified and considered for further analysis. In the preliminary stages of mission design many architectures were considered. These candidate architectures ranged from architectures of historical missions to those that have never been tested. All of the possibilities were listed and divided into two categories: a moon surface element and a moon orbiting element. In Table 7-1, the surface element is listed the vertical axis and the orbiting element is listed on the horizontal axis. An “X” denotes that the surface element/orbiting element combination is plausible from both an engineering perspective and from the requirements defined in the AO.

Table 7-1. The Morphological Matrix used to identify all plausible mission architecture combinations

Candidate Architectures	Orbiting Sample Return Carrier	Comm. Relay	Orbiting Sample Return Carrier and Comm. Relay	2-Phase Orbiter
Lander	X	X	X	X
Landers	X	X	X	X
Rover	X	X	X	X
Rovers				
Lander + Rover	X	X	X	
Impactor + Rover				
Rapid Impactor				

SALEH Space And Lunar Exploration for Humanity

A lander refers to a stationary sample gathering device ("multiple landers" is assumed to mean two landers due to cost limits); a rover is a sample gathering device that can travel across the surface of the moon. An impactor is a probe that travels at high speeds and hits the moon, creating a crater that a rover can investigate. The Rapid Impactor is a vehicle that releases an inert piece of metal that will send dust into the air, the vehicle will then fly into the dust and gather it. An orbiting sample return carrier waits in orbit for a sample return capsule to jettison from the surface. The capsule then docks with the orbiter and the orbiter returns the sample to Earth. A communications relay satellite provides a communications link between the Earth and the surface element. A 2-phase orbiter is a single vehicle that firsts orbits the moon and then descends to the surface. The requirements defined in the AO required that the mission bring, to Earth, 1 kg of sample. Because the rapid impactor is not capable of gathering 1 kg of sample, it was not considered for further analysis. The impactor and rover architecture does not add any practical gain to the science requirements in the AO, therefore it was also not considered for further analysis.

Table 7-2. The Down-selection Matrix takes the outputs from the Morph Matrix and assigns the candidates scores based on their rating in certain categories and those categories weightings relative to each other.

Candidate Architectures	Requirements: > 1 kg samples	Variety of samples	Quality of samples	samples	Risk**	Cost**	**Score Without Cost**	**Score With Cost**
Weight	**5**	**3**	**3**	**1**	**3**	**5**		
Orbiter + Lander	9	1	1	1	3	3	**61**	**76**
Orbiter + Landers	9	9	1	1	3	3	**85**	**100**
Orbiter + Rover	9	3	3	3	1	1	**69**	**74**
Orbiter + Lander + Rover	9	3	3	3	1	1	**69**	**74**
CRS + Lander	9	1	1	1	9	9	**79**	**124**
CRS + Landers	9	9	1	1	9	3	**103**	**118**
CRS + Rover	9	3	3	3	3	3	**75**	**90**
CRS + Lander + Rover	9	3	3	3	3	3	**75**	**90**
Orbiter/CRS + Lander	9	1	1	1	3	3	**61**	**76**
Orbiter/CRS + Landers	9	9	1	1	3	3	**85**	**100**
Orbiter/CRS + Rover	9	3	3	3	1	3	**69**	**84**
Orbiter/CRS + Lander + Rover	9	3	3	3	1	1	**69**	**74**
2-phase Orbiter/Lander	9	1	1	1	9	9	**79**	**124**
2-phase Orbiter/Landers*	9	9	1	1	9	9	**103**	**148**
2-phase Orbiter/Rover	9	3	3	3	3	3	**75**	**90**

Next, all 15 combinations that were said to be plausible were given ratings in multiple categories in a Down-Selection Matrix. The Down-Selection Matrix uses the ratings of each candidate and the weight of each category to assign each candidate a "mission score." The categories used were based on the science requirements given in the AO, plus a separate risk and cost category. The cost and ability to gather at least 1 kg of sample were determined to be most important to mission success (refer to Table 7-2). Other science objectives are how much area the candidate architecture can cover (variety of samples), the candidate architecture's ability to choose what samples to collect (quality of samples) and the ease to which each candidate can avoid contaminating samples (uncontaminated samples). Each alternative is given a rating in the requirements and risk category a score of high (9), medium (3) and low (1) was used.

Every category, except cost, was relatively simple to rate. There are too many variables in cost alone to simply rate it on a scale of low, medium and high. To give each candidate architecture a cost rating, a separate Down-selection Matrix was used (refer to Table 7-3).

Table 7-3. The cost Down-selection Matrix generates a score based on 5 variables of cost. The score is then turned into a ranking that can be inputted into the overall Down-selection Matrix.

Candidate Architecture	Autonomous	Rover	Docking	Normalized Different Pieces	Normalized Total Pieces	Score	Norm. Score	Rank
Weight	1	3	3	3.5	4.5			
Orbiter+Lander	1	0	1	0.67	0.67	9.33	0.62	3
Orbiter+Landers	1	0	1	0.67	1.00	10.83	0.72	3
Orbiter+Rover	1	1	1	0.67	0.67	12.33	0.82	1
Orbiter+Lander+Rover	1	1	1	1.00	1.00	15.00	1.00	1
CRS+Lander	0	0	0	0.67	0.67	5.33	0.36	9
CRS+Landers	0	0	0	0.67	1.00	6.83	0.46	3
CRS+Rover	0	1	0	0.67	0.67	8.33	0.56	3
CRS+Lander+Rover	0	1	0	1.00	1.00	11.00	0.73	3
Orbiter/CRS+Lander	0	0	1	0.67	0.67	8.33	0.56	3
Orbiter/CRS+Landers	0	0	1	0.67	1.00	9.83	0.66	3
Orbiter/CRS+Rover	0	1	1	0.67	0.67	11.33	0.76	3
Orbiter/CRS+Lander+Rover	0	1	1	1.00	1.00	14.00	0.93	1
2-phase Orbiter/Lander	1	0	0	0.33	0.33	3.67	0.24	9
2-phase Orbiter/Landers*	1	0	0	0.33	0.67	5.17	0.34	9
2-phase Orbiter/Rover	1	1	0	0.33	0.33	6.67	0.44	3

The cost Down-selection Matrix broke cost down into five variables. The first three, the use of automation, the use of a rover, and the use of orbital docking (used with an "orbiter" for the moon orbiting element) are given a Boolean rating (1 for yes, 0 for no). The second two cost variables are the number of different pieces (a Comm. relay satellite and a lander are two different "pieces") and the number of total pieces (two identical landers are two total pieces).

Once a score is generated, it is then normalized by the maximum score. Finally, the architecture candidates were separated into three groups, based on the normalized score. With these cost scores, the overall Down-selection Matrix scoring process is complete. The Down-selection Matrix is useful for taking a large number of choices and identifying which are “better” in terms of the weighted categories. The top four mission candidates determined by the Morph Matrix are the communications relay satellite with one or multiple landers and the 2-phase orbiter with one or multiple landers. Qualitatively, these selections are reasonable. A lander is less complex and therefore has less risk than a rover. An architecture with multiple landers is able to gather samples in extremely different locations in the SPA Basin, where a rover is limited to a certain area around its landing site. A communications relay satellite allows commands to be sent from Earth to the surface element, which lowers risk. The 2-phase orbiter should be cheaper than other architecture simply because there is no communications relay to design and launch. To make the distinction as to which candidate is “best”, however, requires a more refined comparison tool.

An Analytical Hierarchy Process (AHP) not only weighs each alternative in a series of categories, but it weighs each alternative relative to the other alternatives. This process determines the best alternative for the given categories. Table 7-4 depicts the AHP used for the WOLF mission architecture selection. Science, risk and cost are the parameters that determine the “best” mission. Of these, science and cost are the most important. Each of the four candidate architectures, then, is rated against each other in the category of science, risk and cost. The summary of their ratings is shown the bottom figure in Table 7-4. Once the AHP is completed, two architectures have virtually identical scores: The communications rely with multiple landers and the 2-phase orbiter with multiple landers. Having multiple landers increases the ability of your mission to gather “better” science (meaning that the mission has more selection for sample gathering).

Table 7-4. The Analytical Hierarchy Process takes the top four candidate architectures from the Morph Matrix and rates them against each other in performance in science, risk and cost.

Prioritization Matrix	Science	Risk	Cost	Normalized Science	Normalized Risk	Normalized Cost	**Weighting**
Science	1	3	1	3/7	3/7	3/7	3/7
Risk	1/3	1	1/3	1/7	1/7	1/7	1/7
Cost	1	3	1	3/7	3/7	3/7	3/7

Summary	Science		Risk		Cost		**Final Score**
	Weighting	Score	Weighting	Score	Weighting	Score	
2-phase Orbiter/Landers	3/7	3/8	1/7	2/7	3/7	1/5	0.29
CRS + Lander	3/7	1/8	1/7	1/5	3/7	2/7	0.21
2-phase Orbiter/Lander	3/7	1/8	1/7	8/53	3/7	24/71	0.22
CRS + Landers	3/7	3/8	1/7	11/30	3/7	12/71	0.29

Now, the task comes to selecting one architecture over the other. Both of the architectures that the AHP rates highest have two landers. Therefore the amount of science is not an issue that will be consider in choosing which of the two architectures is better than the other. From a perspective of risk though, there is a distinction between the two architecture candidates. The 2-phase architecture relies on the automation build into the landers for the entire mission. If some part of the automation protocol were to fail, Earth based controllers would have no ability to correct the failure. However, the landers, with the communications relay satellite, can receive commands from Earth. Also, were the communications relay satellite to fail, the landers could be programmed with basic automation protocol that would enable them to function without the communications relay satellite. This redundancy reduces the risk of the landers with the communications relay satellite architecture.

7.2. Payload Selection

Using the requirements breakdown from the AO, SALEH developed a list of instruments that support mission success. Though the AO only has one main requirement of returning at least 1 kilogram (kg) of lunar sample back to Earth, it will be beneficial to incorporate additional instruments which increase the likelihood of obtaining desirable samples. These desirable samples include the lunar mantle, lunar crust, and samples containing thorium or iron oxide. The additional instruments which can identify these samples include different variations of imagers and/or spectrometers. WOLF also incorporates a science package into the Communication Relay Satellite (CRS) to provide a regional context for science. As one can see from Table 7-5, each of the payload instruments considered in this trade are mapped to their respective mission objective.

Table 7-5. Every payload instrument considered supports the collection of lunar samples and the likelihood of obtaining desirable samples.

Priority	Objective		Payload Instrument
1	Sample Collection		Drill Extendable Arm with Scoop
2	Sample Selection	Identification	Panoramic Imager Microscopic Imager
		Composition	Visible/NIR Spectrometer Mass Spectrometer
3	Sample Context (Lander)	Imagery	Descent Imager Panoramic Imager
		Environment	Thermometer Dosimeter
4	Sample Context (CRS)	Composition	Gamma Ray Spectrometer Visible/NIR Spectrometer
		Mapping	Visible Imager Laser Altimeter
		Environment	Magnetometer

Pareto-to-Morph Matrix Tool

In order to make a knowledgeable decision of which instruments to incorporate into the spacecraft, each of the 32,767 possible payload combinations must be evaluated over multiple criteria. To perform this trade study, SALEH developed a Pareto Optimization tool using MATLAB computational software. In our application, Pareto Optimization can be considered a method used to rate a large number of options based upon multiple criteria and finding the best available option. By plotting every rating a Pareto front is formed—each option along this front can gain no further optimality in either criterion without loss in another criterion. Each of the options along the Pareto front are analyzed through the use of a Morph Matrix. The Morph Matrix is a tool which gives further insight as to how each option compares to the rest. Each option is evaluated based upon how much quality is gained with the necessary increase in resources. For a visual reference of how our Pareto Optimization-to-Morph Matrix tool works, please refer to Figure 7-2 below.

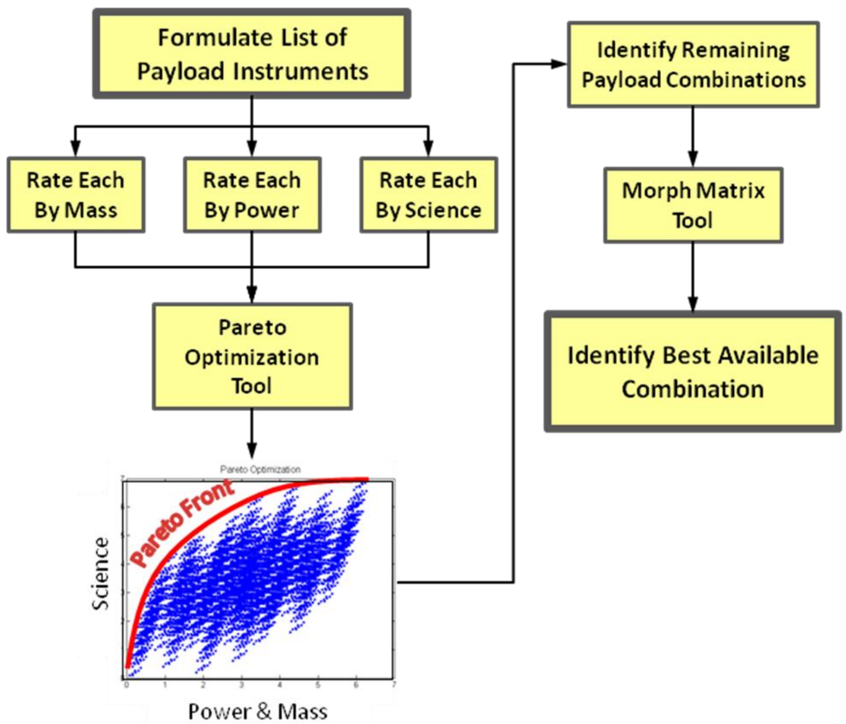

Figure 7-2. SALEH's Pareto-to-Morph Matrix tool is used to identify the best available payload combination available for the WOLF mission.

WOLF Payload Optimization

For the case of our payload combinations, we've considered mass, power, and quality of science for the evaluation criteria. Before running the Pareto Optimization tool, each of the payload instruments are individually rated over each criterion. Since we are have not chosen our exact payload instruments, the power and mass values are estimated using historical examples. Our quality of science ratings, are based upon extensive discussion with Peter Isaacson, a lunar science specialist from Brown University. Once the Pareto Optimization tool is finished, the results are plotted with the y-axis representing the quality of science ranking and the x-axis representing a rating that combines both the mass and power values. Thus ideally, the best solution would be located toward the upper left corner of the plot—the area of highest science and lowest cost. Represented by the red curve in Figure 7-3, 21 payload combinations are located on the Pareto Front and require further consideration. Nine of these combinations did not meet mission requirements since they did not include a sample collection device (drill or extendable arm); therefore only 12 of the 32,676 combinations need further individual evaluation. These 12 combinations are compared to each other through a Morph Matrix. The Morph Matrix calculates the gain in quality of science for the increase in mass and power from the next "cheaper" combination. The Pareto-to-Morph Matrix tool is finished once this best available payload combination is identified in the Morph Matrix. Represented by the star in Figure 7-3, the chosen payload combination is summarized in Table 7-6.

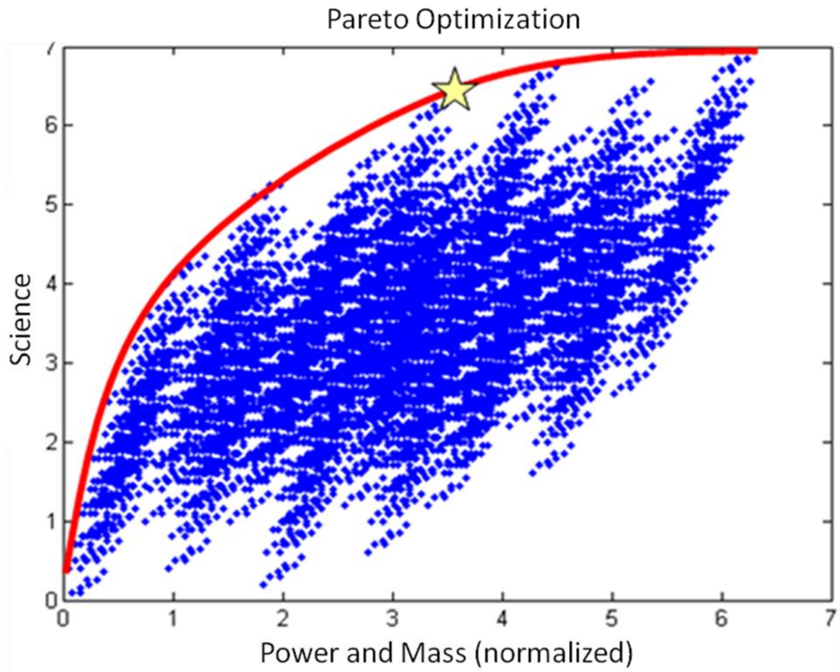

Figure 7-3. The Pareto Optimization tool reduces the number of possible payload combinations from 32,676 to 12. These 12 options cannot gain optimality in either criterion without loss of optimality in the other.

Table 7-6. The payload combination chosen using the Pareto-to-Morph Matrix tool satisfies mission requirements and provides science in both a local (lander) and regional (CRS) context.

Lander	Communication Relay Satellite (CRS)
Drill	Visible/NIR Spectrometer
Extendable Arm (w/ scoop)	Gamma Ray Spectrometer
Descent Imager	Magnetometer
Panoramic Imager	
Visible/NIR Spectrometer	
Mass Spectrometer	
Microscopic Imager	
Storage	

Defining a Baseline and Performance Floor

During the design of WOLF, there is the possibility that we may reach a situation where the mission exceeds NASA's cost cap or otherwise proves impractical. SALEH fully realizes this possibility and takes steps to minimize the effect these occurrences may have on the mission design process. One of the first mitigation measures considered in these situations is the descoping of WOLF's payload in an effort to reduce spacecraft mass, power, and/or cost. Our method of descoping the payload was carefully scrutinized in relation to the AO requirements and objectives. This was done to make sure that the process of descoping instruments is in the order of least to most necessary for mission success. Three critical levels of payload descoping are defined starting with a baseline science mission and ending with the performance floor. The baseline mission can be considered the "luxury" WOLF payload design, whereas the performance floor represents the most basic payload that can still accomplish mission success. Table 7-7 shows the specific payload combinations for each critical level of descoping.

Table 7-7. SALEH's process of payload descoping provides the capability of making changes to the mission with minimal effect to the overall mission design. This acts as mitigation to the risk of cost growth or other changes making certain instruments impractical.

Baseline Science Mission	Mid-Range Mission	Performance Floor
Drill	Drill	Drill
Storage	Storage	Storage
Descent Imager	Descent Imager	
Panoramic Imager	Panoramic Imager	
Gamma Ray Spectrometer	Gamma Ray Spectrometer	
Visible/NIR Spectrometer	Visible/NIR Spectrometer	
Extendable Arm w/Scoop		
Visible/NIR Spectrometer		
Mass Spectrometer		
Microscopic Imager		
Magnetometer		

7.3. Orbit Determination

While considering many orbital paths, mission cost and risk were minimized. To ensure accuracy, multiple models were utilized and the results were compared to independently developed models. A number of possible paths exist which were evaluated based on fuel cost, stability, time, and synergy with the sample collection. Research showed that exotic orbits have some advantages and disadvantages over traditional orbits.

Orbital Evaluation Criteria

To downselect to the final orbit path, the complexity and readiness of each path is the most important factor. By using many experimental techniques, the fuel cost is less than conventional methods. However, development cost for these advanced techniques is significantly higher as more resources must be committed to ensure that they are mission ready. To evaluate the relative costs of developing each technique, the ability to correct for uncertainty and minor errors is critical. Descriptions of this uncertainty were obtained from various independent studies.

Determination Tools

Independent studies and previous missions provide a thorough list of probable options that should be investigated further. Apollo and unmanned missions like Lunar Prospector provide a basis to understand basic transfers to the moon. The parameters of these missions allow range of focus of direct methods to be narrowed fairly effectively. Studies discussing future missions and theoretical possibilities show wide range of other possibilities. They also explain additional challenges and benefits related to using the more exotic options.

By using a number of models, many different results and their agreement can be investigated. First, a simple patched conic model estimated the maneuvers needed for a direct transfer with moderate accuracy. Lambert's solution to Gauss' problem allowed for a more accurate, iterative solution; initial solutions for this model were derived from the historical missions. Figure 7-4 shows a sample result from this model with launch date, time of flight, and maneuver cost to be compared.

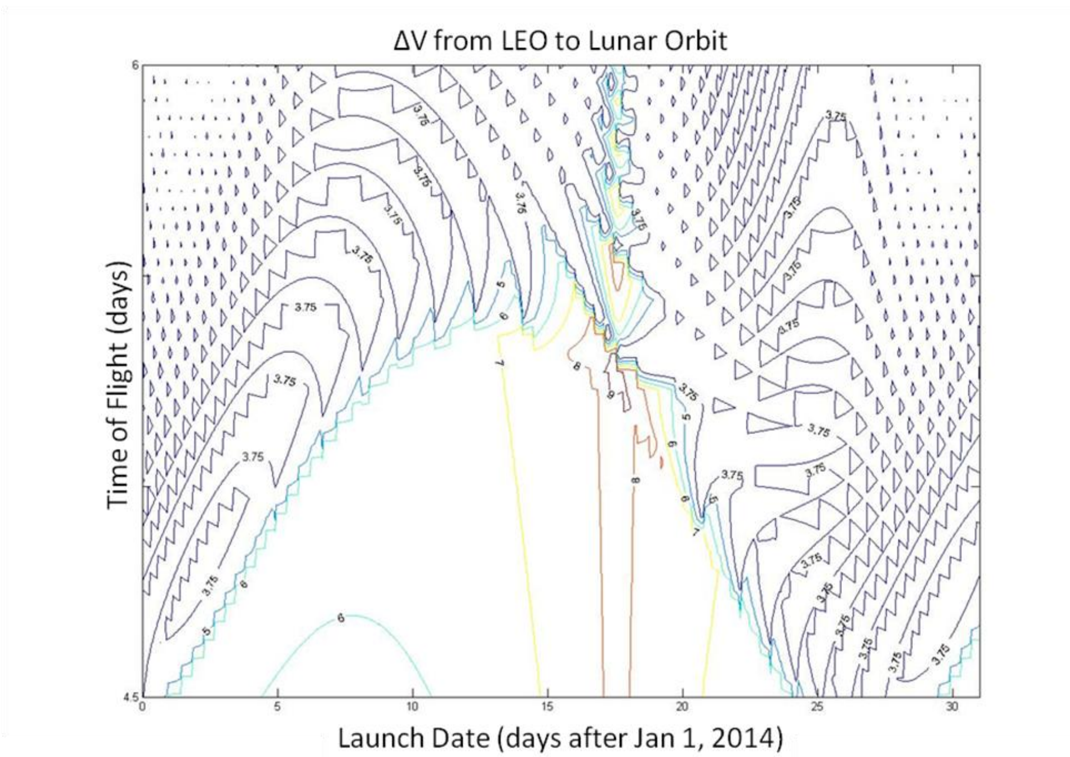

Figure 7-4. Results of Lambert's solution code. This plot allows launch/arrival dates, time of flight, and maneuver cost to be traded.

Finally, a high fidelity simulation tool, Satellite Tool Kit's (STK) Astrogator, calculated the final path to 3-σ accuracy. This tool also allows lighting conditions and communication durations to be calculated. Specific times of flight for each portion of the path are available. The specific parameters of the orbit at the moon are inputs so that trades with orbit altitude and communications can be conducted easily. Figure 7-5 was generated using the communication data over a wide range of altitudes.

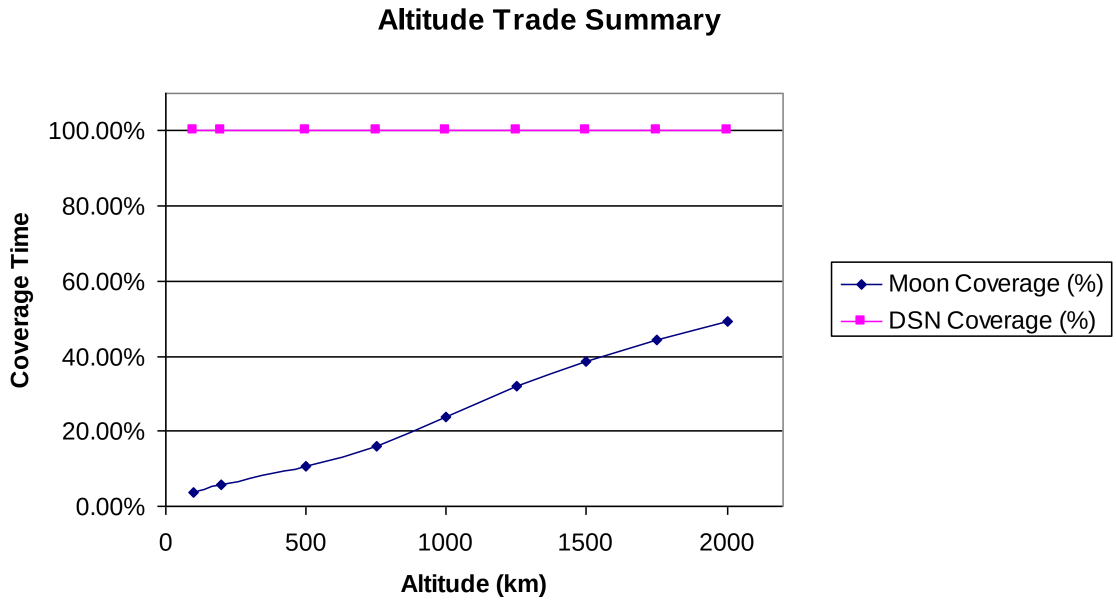

Figure 7-5. Communication coverage percentage as function altitude. Increasing altitude tends to increase the size of communication system but provides more coverage time.

Results

The direct path from the earth to the moon, like that of the Apollo missions, is the simplest. While the minimum fuel cost is slightly higher, considerably less development work is needed to finalize the trajectory. A number of other possible paths also exist. By using gravitational anomalies such as Lagrange points, it is possible decrease fuel cost slightly if much larger times of flight are permissible. A similar trade exists if electromagnetic propulsion methods are used instead of conventional chemical rockets. Both of these methods entail considerably more risk. Electrical propulsion is still highly experimental, and performance parameters of electromagnetic engines are much more uncertain than conventional engines. A path taking advantage of a Lagrange point would require several small, precise burns. The same physical laws that allow less fuel to be required also amplify errors during burns significantly.

A mission architecture that allows for intermittent communication greatly decreases the cost and risk associated with CRS. To obtain uninterrupted contact with the landers, a constellation of satellites or a very high altitude halo orbit is required. Using multiple orbiters consumes considerable resources and does not greatly increase the value of the collected sample. The halo orbit is at an twice that of geosynchronous orbit about the Earth; communication across that distance requires much larger and more powerful antennas than the low altitude orbits.

The return path is also direct so that development resources can be committed elsewhere. The fuel savings from using exotic return trajectories are even smaller. These savings are proportionally more significant for boosted mass, but the much higher performance of the launch vehicle offsets these costs on a program level.

7.4. Mass Estimation Model

Another crucial step in the early design process is the mass estimation model. An accurate mass estimation will increase the accuracy of other aspects of the design processes such as cost estimation. Therefore, the more accurate a model is, the more beneficial it is to the design process. The best fit for this criterion is a bottom up approach where each individual component mass is measured. However, the ability to quickly change the inputs of the model is also vital. This ability will allow a new mass estimation to be developed with ever new decision that is made in the design process. A balance between these two ideals is reached with the Wolf mass estimation model.

In the mission architecture selection process, the mission was broken down into two elements: the moon orbiting element and the moon surface element. This breakdown is also used in developing the mass estimation model. First, masses of historical mission with a similar architecture were gathered. For the orbiting element, masses of orbiting space craft that were either communications relay or communications relay with an additional science payload were considered. These masses were then broken down into percentages based on the dry mass of the space craft. An average mass percentage of each subsystem was then obtained. Table 7-8 gives the orbiting element historical calculation). A similar average was developed for the surface element.

Table 7-8. Historical averages of each subsystem pass as a percentage of the overall dry mass of the spacecraft.

Historical Data (with Science payload)									
Tab	Power	Comm.	ADCS	Prop	Structure	Thermal	Payload	C&DH	Total
Lunar 1							10.0%		10.0%
Asteroid 1	18.9%	8.2%	10.1%	30.0%	17.3%	3.4%	9.1%		97.0%
Mars 2	18.18%		13.64%	22.73%	26.52%		18.94%		100.0%
Mars 2	14.80%		8.18%	12.94%	43.48%		20.70%		100.1%
Europa 1	3.82%	2.55%	5.73%	16.56%	53.18%	12.74%	5.10%	0.32%	100.0%
Mars 4	10.32%	7.42%	4.19%	23.23%	25.81%	5.03%	19.35%	2.58%	97.9%
Lunar 2	15.10%	24.05%	5.84%	11.31%	32.29%	2.58%		8.82%	100.0%
Average	**13.5%**	**10.6%**	**7.9%**	**19.5%**	**33.1%**	**5.9%**	**13.9%**	**3.9%**	**108.3%**
Normalized	**12.5%**	**9.8%**	**7.3%**	**18.0%**	**30.6%**	**5.5%**	**12.8%**	**3.6%**	**100.0%**

The science payload of the orbiter is then used as an input into the model. The model, based on the historical percentages then estimates the dry mass and the mass of each subsystem based on the mass of the science payload. After the dry mass has been calculated, a thirty percent contingency is added to the mass of the orbiter to accommodate any uncertainty in the estimation process. The surface element mass estimation is developed in the same way. The main difference is in the inputted payload. The payload of the lander is not only its own science equipment, but also the sample return capsule that will take the samples gathered and return them to Earth. Once the dry mass of the lander is calculated, a thirty percent contingency is also placed on the entire estimation. The mass breakdown structure (MBS) of both the lander and orbiter can be found in Table 7-9.

Table 7-9. The lander and orbiter MBS with subsystem mass breakdown and an overall contingency of 30% for both elements.

Lander MBS		
System	**mass (kg)**	**% of Dry M**
Payload	122.53	25.12%
Comm.	10.51	2.16%
Data Handling	22.86	4.68%
Structure	88.31	18.10%
Thermal	16.51	3.38%
GN&C	7.86	1.61%
Propulsion	42.28	8.67%
Power	176.99	36.28%
Dry mass w/o cont	487.86	
Contingency	146.36	30.00%
Dry Mass of 1 lander	**634.21**	

Orbiter MBS		
System	**mass (kg)**	**% of Dry M**
Payload	20.10	12.80%
Power	19.61	12.49%
Comm.	15.32	9.75%
ADCS	11.52	7.34%
Prop	28.21	17.97%
Structure	48.00	30.57%
Thermal	8.60	5.48%
C&DH	5.66	3.61%
Dry Mass w/o cont	157.02	
Contingency	47.11	30.00%
Dry Mass of Orbiter	**204.13**	

7.5. Cost Estimation Models

We considered our mission cost to be a key factor in driving our overall mission development, and so used a variety of tools to reduce the uncertainty in our initial cost estimate (all values in FY$08). The first approach we took was to look at the information provided to us in the AO to determine what our unknown factors were.

We began by setting the $700 M NASA cost cap as our base value. Next, we knew the cost of our launch vehicle must be taken into account, so we subtracted the $130 M cost of the Atlas V HLV from our cost cap, leaving us with $570 M. Then, we took into account the 25% margin required to be reserved from Phase B to Phase E, leaving us a new balance of $427 M. We decided to take this margin into account in advance so that the final value obtained for our spacecraft and landers budget would be the absolute maximum available to spend. Next, using the equation provided in *NASA's Mission Operations and Communications Services*, we determined the maximum cost for using the DSN over a period of 21 days (notice this is 3x longer than our mission is planned to last) to be $1.7 M. Using the *Anticipated Costs and Capabilities of the NASA Curatorial Facility* we determined the cost incurred by the NASA Curatorial Facility to be $1.3 M. Taking these two factors into account along with the amount of $1.2 M allocated to us for our Phase-A Concept Study our maximum spending budget for the development and production of our spacecraft and landers to be $422.8 M.

This maximum spending budget allowed us to use a cost model to determine whether or not our current mass estimate fell within our allotted budget. We used NASA's Advanced Missions Cost Model because it took into account the most number of user inputs which decreased the uncertainty in the cost estimation output. Before using the cost model, we tested its accuracy by using the dry weight and cost of a previously flown mission. Using NASA's Phoenix lander mission which cost $420 M in FY$07, we inputted its dry weight of 770 lb. into the cost model, converted the cost into FY$07 and determined the model to be accurate within ~2%. For our lander we used the Lunar Rover mission which over estimates the cost of our lander, and the Earth Observing Satellite which underestimates the cost of our CRS. With these assumptions, we considered this 2% difference to be covered in our estimate of our second lander; therefore the model is valid for our purposes.

Out of the five inputs required for the cost model, only two remained unknown; the Block Number which represents the level of inheritance of the mission design and Difficulty which represents the complexity of the mission. By varying these two inputs, the model provided us with 1250 different possible costs for our mission for a specific dry weight of the spacecraft and landers. The main advantage in having so many possible combinations is that we were able to look at trends created by varying the block number and difficulty and conclude where our mission could realistically fall within their respective ranges so as to determine whether or not our maximum spending budget was met or busted.

Once a target combination was selected (being Block Number of 3 and Difficulty of Average) we compared the cost obtained by the model with that of the spending budget. If the model cost fell under the maximum spending budget, then the current payload selection and mass estimates were considered to be valid, otherwise we began descoping payload instruments, obtaining new mass estimates for the descope, and inputting that dry weight into the model. This iteration process was continued until our target combination fell below the cost allowed for the Atlas V HLV launch vehicle and met the boosted mass criteria. From here, we were able to not only proceed with selecting subsystems and science instruments, but we also were aware of how the complexity of the subsystem and/or s/c design and the level of new technology will affect us in terms of cost, therefore reducing the potential of straying away from our initial cost estimates throughout mission design. With our mass estimate of 216 kg for our CRS and 629.6 kg for each lander, we obtain an estimated development and production cost of $414 M for all three spacecrafts, and an overall mission cost of $548.1 M. This cost estimate provides us with an additional 2% margin, leaving us with a total cost margin of 27% for our mission.

Table 7-10. Breakdown of WOLF mission cost.

Cost Parameter	Value (M in FY$08)
(2) Lunar Landers	336
Communication Relay Satellite	78
Atlas V HLV	130
Ground Operations	1.7
NASA Curatorial Facility	1.3
Phase-A Concept Study	1.2
Overall Mission Cost	***548.1***

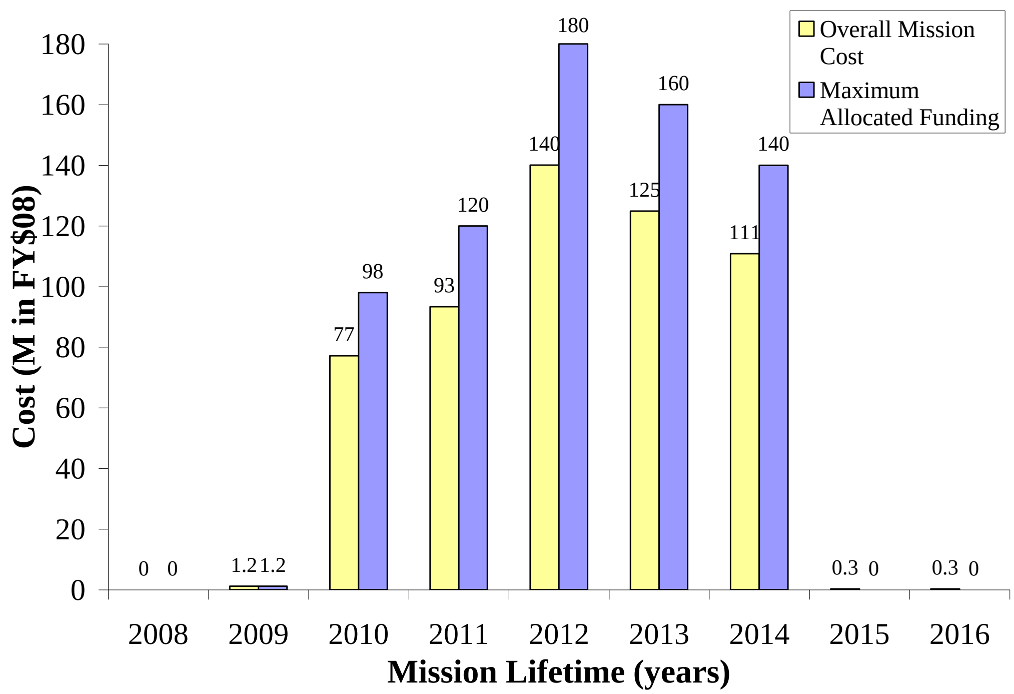

Figure 7-6. WOLF mission cost schedule as it relates to the New Frontiers Program funding profile.

8. WOLF Mission Architecture

WOLF Mission Architecture Overview

Now that the methodology and tools developed through the systems engineering process have been described, the specifics and timeline of the WOLF mission can be discussed in a more complete manner.

After launch, the WOLF spacecraft communicates with DSN while performing its lunar transfer. The spacecraft inserts into a low lunar orbit as a triple module spacecraft (CRS and both landers) and prepares for separation of both landers. The landers consecutively detach from the CRS and descend toward different locations on the SPA surface for science operations. After the landers detach, the CRS is repositioned into a higher lunar orbit in order to provide better communication coverage between the DSN and the landers. Throughout surface operations, the landers intermittently communicate with the DSN by sending & receiving data when the CRS is within line of sight. Once sample collection and storage is accomplished, the landers consecutively launch their respective sample return capsules (SRC) from the surface and into a trajectory approaching Earth. During Earth approach, each SRC communicate with ground operations through the DSN. Upon entry, descent, & landing (EDL) each capsule deploy several stages of parachutes before performing a dry landing. Each capsule is then recovered and their contents transported directly to the curatorial facility. This entire mission architecture is illustrated with a two phase (Earth-to-moon and moon-to-Earth) Operational View (OV-1) diagram in the Appendix. A complete breakdown of the entire WOLF spacecraft can also be found in the Appendix.

Benefits of Multiple Landers

By obtaining samples from two separate SPA landing sites, WOLF provides a more representative sample than having both a single lander and lunar rover. WOLF's multiple landers architecture shares benefits of low cost and obtaining valuable samples. Of particular interest are the samples which contain iron oxide or thorium. Through remote sensing, scientists have determined that the locations of these two composition deposits are not overlapping—in fact, they are hundreds of kilometers away from each other. WOLF provides a low cost and high TRL method to obtain samples from both locations, thus providing a more valuable lunar sample than single lander or rover collection methods

The inherent mission redundancy for incorporating multiple landers is especially critical in the overall WOLF design. With a second lander, the mission can encounter a catastrophic failure in either lander and still accomplish mission success when the second lander returns at least 1 kg of lunar sample.

9. Project Management

9.1. Organization

SALEH is broken down into an interacting structure of several positions that work together towards the common goal of designing WOLF. Each position has a specific set of responsibilities that provide a balance between individual and team oriented effort.

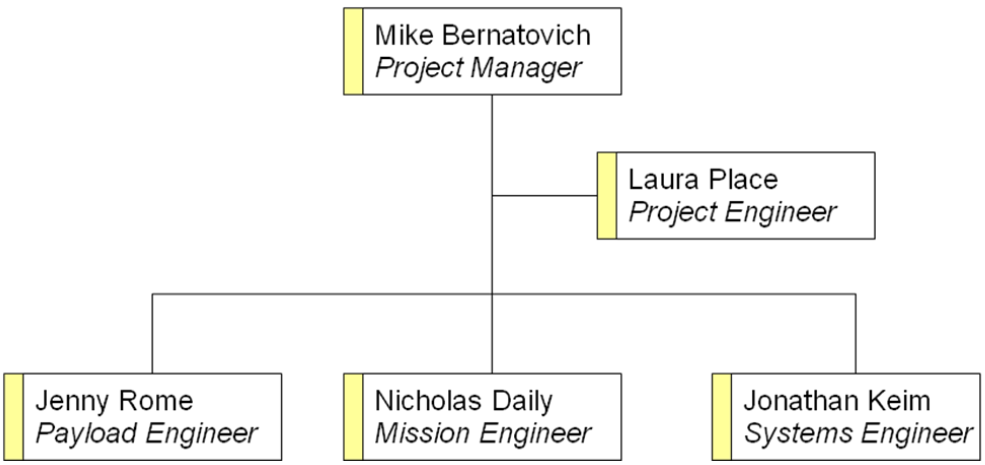

Figure 9-1. The organizational structure of SALEH is designed in a way which promotes an efficient and interacting environment during the design of WOLF.

Acting as the functional leader, the Project Manager (Michael Bernatovich) is responsible for overall success of the team. The Project Manager calls and leads team meetings, balances risk and cost of the design at hand, serves as primary interface with the course instructors, and has final decision making authority for all project decisions.

The Project Engineer (Laura Place) is foremost responsible for the development and flowdown between subsystem development and mission requirements & objectives. Overall coordination of technical and programmatic margins, cost models analysis and development, and working with the Project Manager in implementing key trades are some of the other major responsibilities for the Project Engineer,

The Systems Engineer (Jonathan Keim) is responsible for the complete development of all aspects of the spacecraft flight subsystems. Since this area of design closely relates to the overall mass estimation and development, the Systems Engineer is also responsible for developing the mass estimation model.

The Payload Engineer (Jenny Rome) is responsible for all aspects of payload design and analysis. Payload Engineer responsibilities also extend to the mission requirements flowdown in relation to the payload and the development of a post-mission data analysis & archiving plan.

The Mission Engineer (Nicholas Daily) is primarily responsible for orbit determination and its relation to the communication architecture. The Mission Engineer performs launch vehicle trades, develops a mission operation timeline, and performs telecom & ground data systems trades.

9.2. Schedule

The WOLF mission design, development, and testing schedule incorporates margin for every task that needs to be completed before and after launch. As taken from the AO, the schedule must include phase A through E as described in Table 9-1. When designing the schedule, SALEH places contingency on every task that needs to be completed in order to mitigate possible schedule growth. As one can see in Figure 9-2, SALEH has developed a detailed Gantt chart that shows the expected time for completion (dark blue) and the incorporated contingency time (beige). This was developed to provide a visual tool to monitor and assure that the requirement of launching within 47 months of Phase B completion is met.

Table 9-1. WOLF design, development, testing, & operations is broken up into six phases as described by NASA's AO

WOLF Phase	Task
Phase A	Concept study
Phase B	Preliminary design
Phase C	Final design & development of all flight and ground hardware and software
Phase D	S/C assembly, testing, & launch operations
Phase E	Mission operations & data analysis
Phase F	Extended mission operations (if necessary)

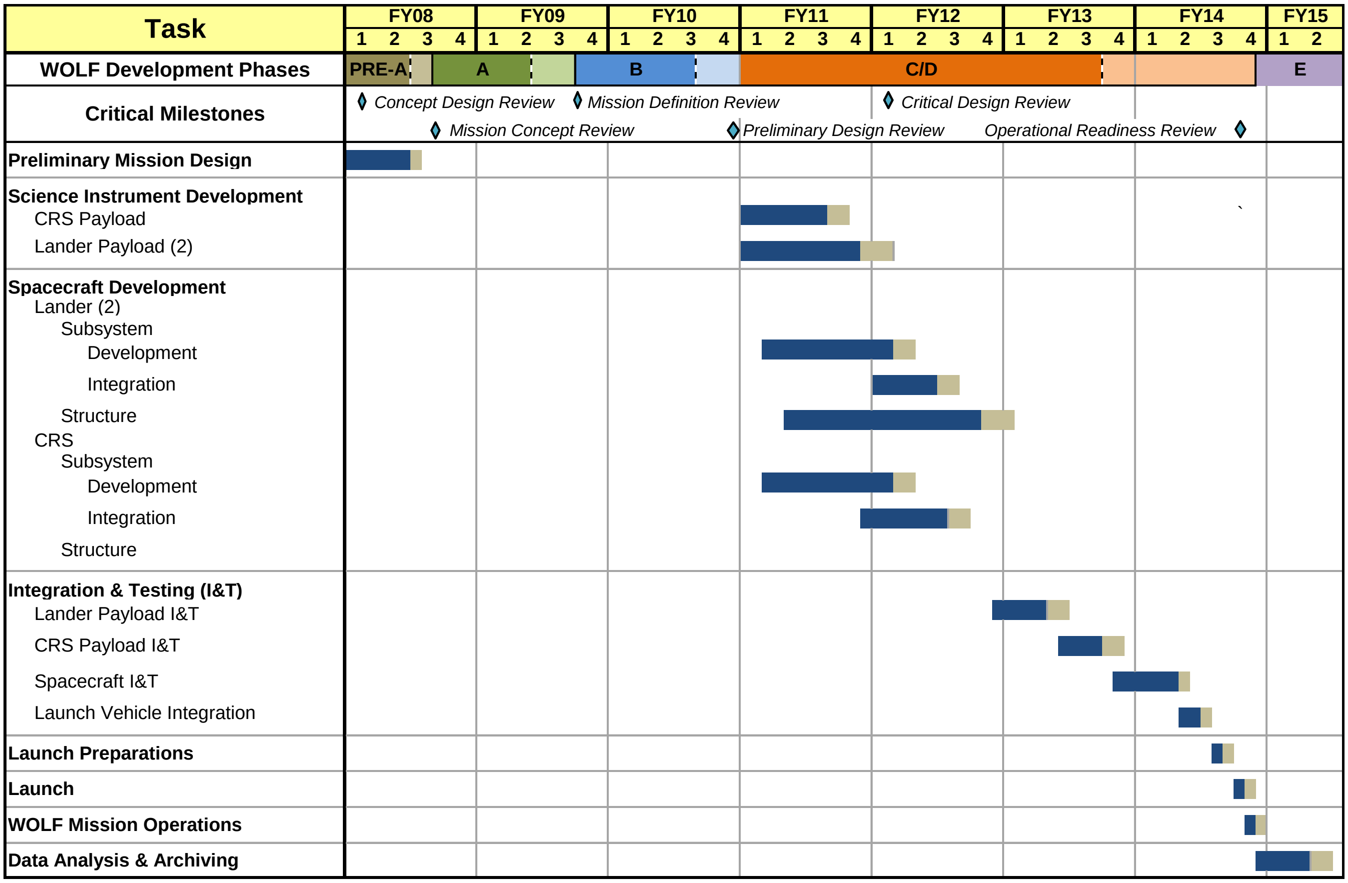

Figure 9-2. The WOLF Gantt chart illustrates that SALEH has a complete schedule with contingency that meets the AO requirement to launch within 47 months of the completion of Phase B.

9.3. Risk

Being confident about one's own mission design is very common and important given the amount of work dedicated to its development; however, it is equally important to consider the weakest links of the design as well. These weakest links are considered risks within the mission design and its processes. Risks can be present in various forms—ranging from Systems Engineering models to physical failures during real-time mission operations. SALEH has taken risk into consideration throughout the design process and developed an appropriate mitigation approach for each risk element. A summary of which can be found in Table 9-2 below.

Table 9-2. Extensive research & discussion has been performed on the inherent risks of WOLF. Equal research has also been applied to the mitigation plan for each of these risks.

Risk	Mitigation Approach	Impact	Probability
Lander failure during Lunar operations or Earth return	• Use an additional lander for redundancy	High	Low
Sample collection device failure during science operations	• Include both a drill and arm w/ scoop devices for redundancy	High	Low
Communication relay satellite failure	• "Safe Mode" Automation Override • Redundant subsystem design	High	Low
Cost growth	• Include sufficient margins • Prepare descoping options	Medium	High
Schedule growth and/or variation	• Include sufficient margins • Designate multiple launch dates	Low	High

Though the probability of a catastrophic failure for a lander is considered low, it would cause an overall failure for a LSR mission. SALEH realized this risk early in the design phases and decided to propose a mission which provides an inherent redundancy by using multiple landers, rather than a single lander. By using multiple landers, there can be a catastrophic failure within one of the landers and mission success can still be accomplished by the second lander returning at least 1kg of lunar sample.

In the event of a mechanical or electronic failure with the sample collection device, the mission would not be able to accomplish mission success since no method of sample collection would be available. Given that many historical missions have proven these devices to be very reliable, the likelihood of this occurring is very low. Nonetheless this risk must be fully appreciated with such a high impact on the mission. To mitigate this risk, we have incorporated two independent sample collection devices for redundancy—a drill and an extendable arm with scoop. Though the extendable arm is not included in the Performance Floor payload design, it is the last instrument to be descoped given its significance for risk mitigation.

Given that the SPA basin is on the farside of the moon, the communication architecture becomes of utmost sensitivity. With a single point failure of the CRS, ground operations can no longer send or receive any command or data to/from the landers. This would result in a complete loss of mission. In designing the mitigation approach for this risk, SALEH considered multiple options which included incorporating an additional CRS, a fully autonomous mission, or programming a Safe Mode, a quick "sample-and-go" automated mission, in the event of a loss of communication. The additional CRS was found to be infeasible with the increase in mission cost. A fully autonomous mission was found to be too risky with such a low TRL and since no control for sample collection can be provided. Though the Safe Mode option would require additional time for software development and additional Command & Data Handling capabilities, these increases are found to be negligible compared to the overall mission cost. In the event of a communication failure, the lander determines that a loss in communication has occurred which triggers it to enter Safe Mode. Once Safe Mode is activated, both landers initiate the drill sequence for sample collection, store the sample, and they consecutively launch into lunar orbit until communication with the ground is obtained. This mitigation approach also acts as a test for technology of future autonomous missions.

Cost and schedule growth and/or variation are unpredictable, yet expected, to occur at some point(s) along Phase A through Phase E of the mission design schedule. It is very difficult to avoid these types of events so the next best option is to provide contingencies and margins throughout cost and schedule estimations. SALEH has incorporated contingencies and margins into account throughout each aspect of the design process which allows for cost and schedule growth to occur with minimal effect to the overall mission design.

10. Closing Remarks

Using various Systems Engineering tools & techniques, SALEH is able to design a very worthy mission in response to NASA's AO with sufficient research and analysis to support our results. Decisions made on a subsystem, mission, and system level are scrutinized through the use of Pareto Optimality theory, Morphological Matrices, Analytical Hierarchy Processes, and in-team developed tools which are individually tailored for the decision at hand. In the event that a change in mission design is necessary, SALEH previews multiple options available for descoping on subsystem and mission levels which allow a seamless transition in the design process with minimal design backtracking. These various tools and methods build together to provide a strong foundation for the overall WOLF mission design.

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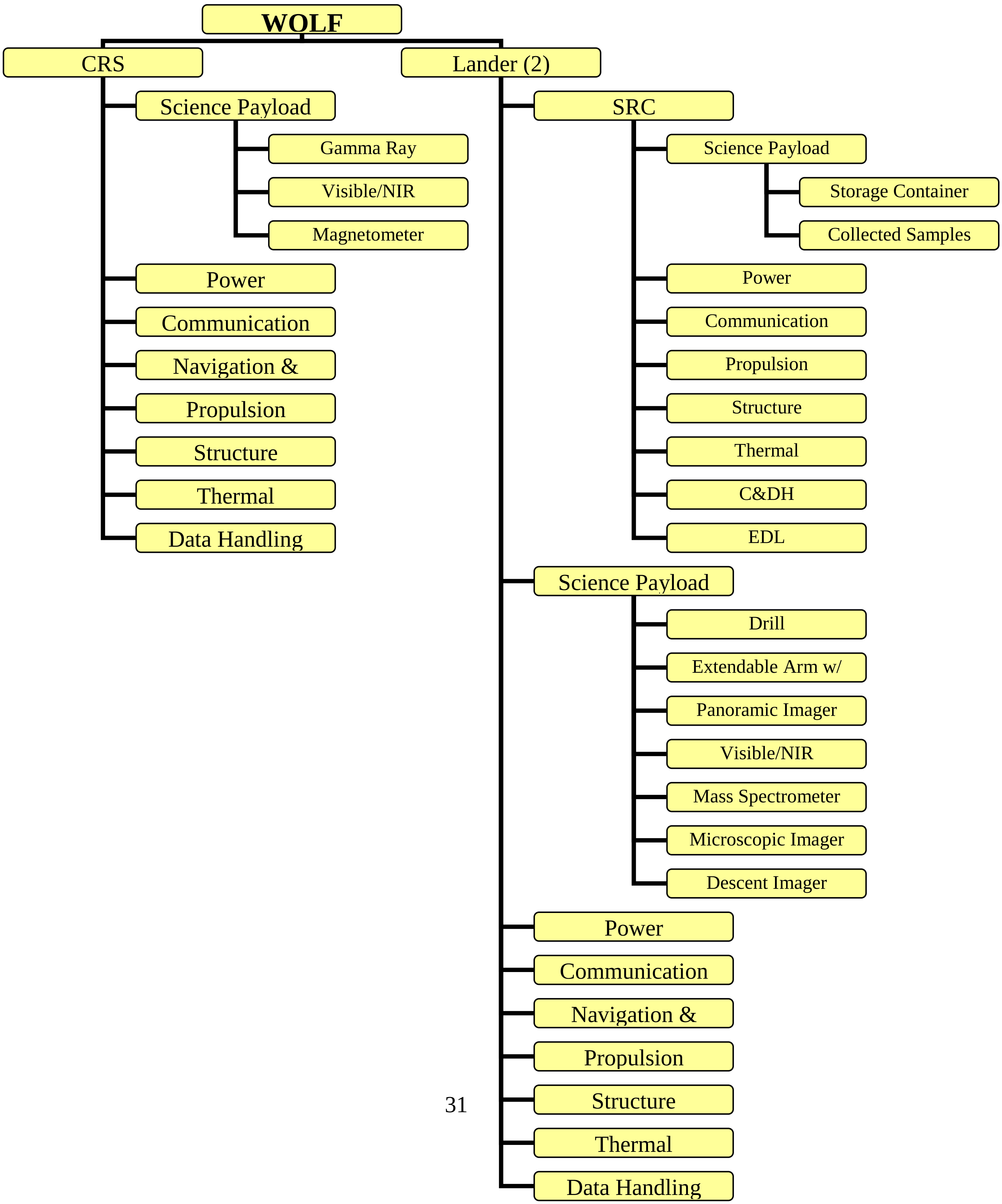
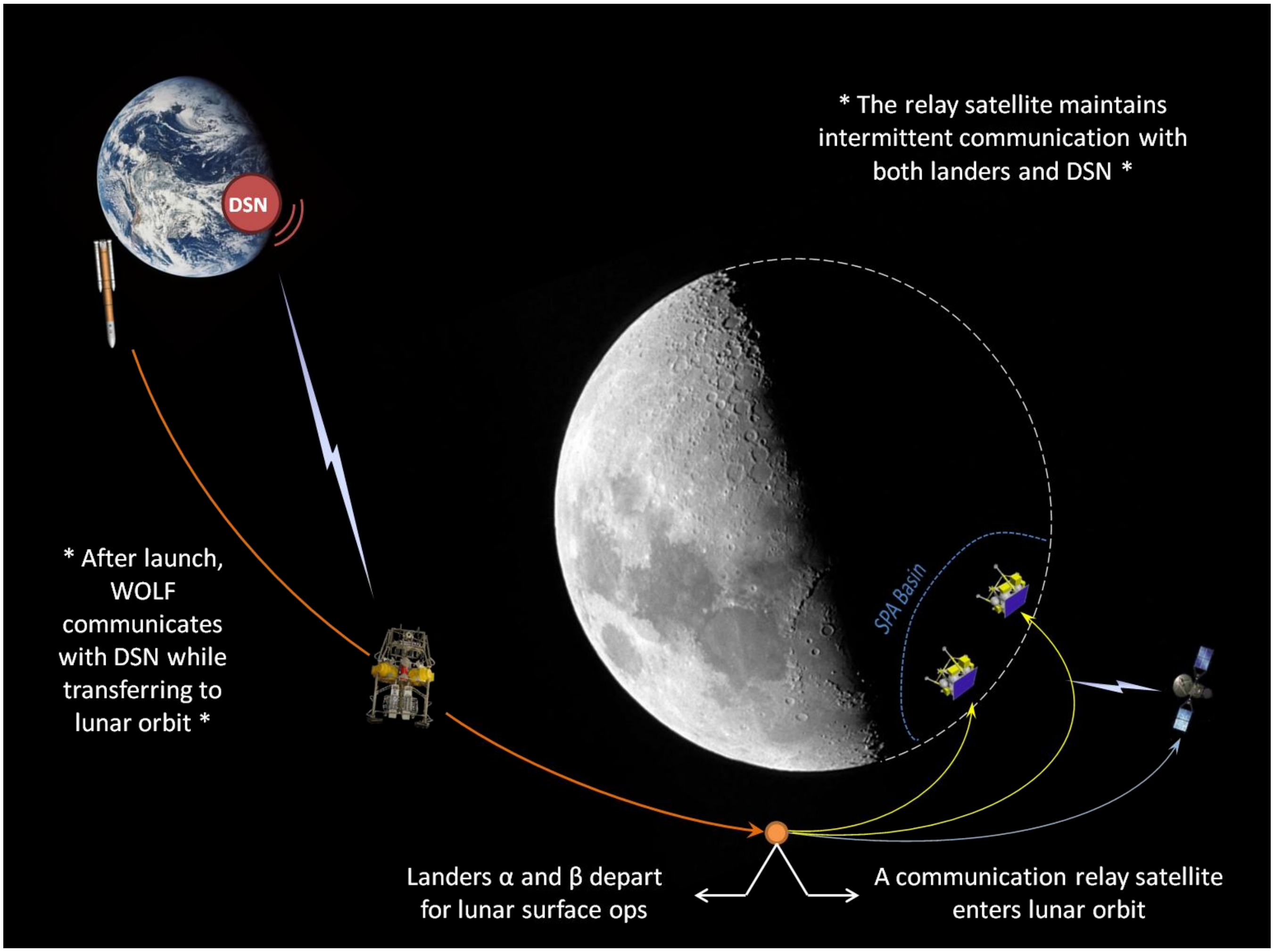
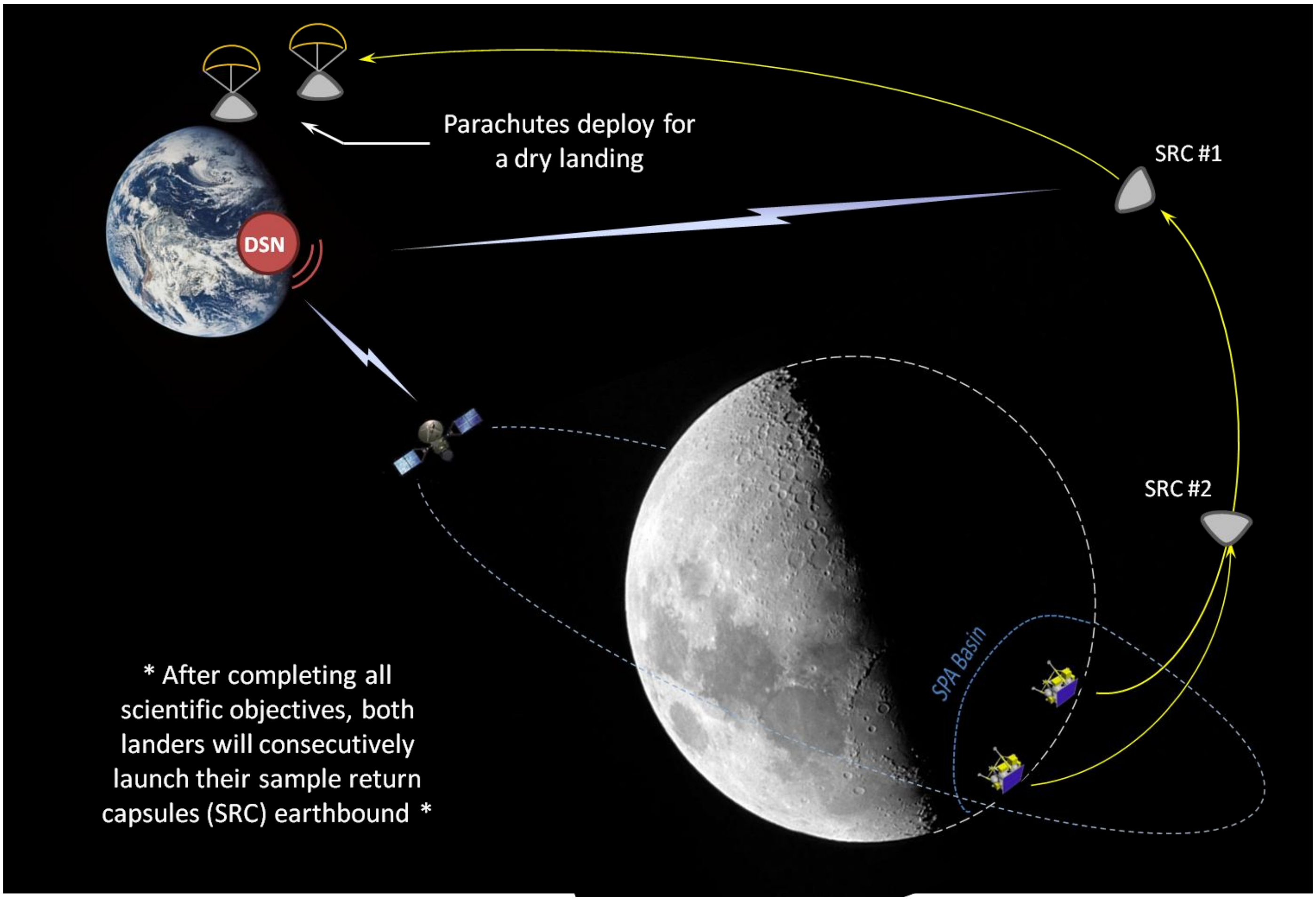
12. Appendices




* The relay satellite maintains intermittent communication with both landers and DSN *
DSN
* After launch, WOLF communicates with DSN while transferring to lunar orbit *
SPA Basin
Landers α and β depart for lunar surface ops
A communication relay satellite enters lunar orbit



Parachutes deploy for
a dry landing
SRC #1
DSN
SRC #2
SPA Basin
* After completing all
scientific objectives, both
landers will consecutively
launch their sample return
capsules (SRC) earthbound *