UNIQUE ABILITIES OF HOPPER SPACECRAFT TO ENABLE NATIONAL OBJECTIVES FOR SOLAR SYSTEM EXPLORATION

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B.S. Engineering
Harvey Mudd College, 2006

Submitted to the
Engineering Systems Division
and the
Department of Aeronautics and Astronautics
in partial fulfillment of the requirements for the degrees of

MASTER OF SCIENCE IN TECHNOLOGY AND POLICY
and
MASTER OF SCIENCE IN AERONAUTICS AND ASTRONAUTICS

at the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
February 2011

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ABSTRACT

In comparison with conventional and other conceived approaches, hopper spacecraft offer unique advantages in exploring Solar System objects beyond Earth. The present work began with a survey – based on documents from the White House, Congress, NASA, and the international planetary science community – of exploration plans and objectives in the United States. The results are presented, and lead into a representative description of goals that might be enabled by hoppers. Relevant hopper attributes are then described in comparison to other vehicle types, and these vehicle characteristics are mapped to the exploration goals to show how hoppers can facilitate achievement of policy and science objectives. Specific examples are examined by formulating and analyzing a demonstrative and timely variety of model missions on Earth's Moon, Mars, and Saturn's moon Titan. These analyses use models for both hovering and ballistic hops to produce realistic values for hopper performance including mass, fuel consumption, trajectory characteristics, and basic spacecraft subsystem characteristics. In sum, planetary hopper technology is not for every mission, but generally offers paradigm-changing mobility and flexibility for small additional mass or development costs. Mission planners should evaluate hoppers for suitability to their exploration goals. Policy recommendations are offered toward this purpose.

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Acknowledgements

I would first like to thank my thesis advisor Jeff Hoffman for his guidance and relaxed but demanding demeanor. John Danis, my Draper Laboratory Fellow advisor, deserves the next mention for his profuse helpfulness and enthusiasm for my work. Draper Laboratory as a whole has been very generous and supportive of my research. Bobby Cohanim has also been critical to my progress, success, and sanity; I thank him for his assistance and friendship. From even before my involvement with hoppers, Phillip Cunio has been a stimulating and insightful collaborator. Beyond these, I would like to thank the entire Talaris team at MIT for providing me with ideas, aid, and a fulfilling research project. Next, my colleagues Dan Fulcoly, Ben Corbin, Akil Middleton, and Wendelin Michel all offered advice and contributed to the analytical portions of this thesis.

Outside of the aerospace and astronautics world at MIT, my home has been the Technology and Policy Program. For my happy time there I have first to thank Sydney Miller, Frank Field, Ed Ballo, and Dava Newman, for bringing me in, giving me the program I was really looking for, and helping me with the details along the way. In that realm of details, I could not have managed without the helpful people scattered in financial and administrative offices across the Institute. I am also indebted to the MIT Space, Policy, and Society Group, where I began my work space policy, and the fine people in the Space and Science Branch at the Office of Management and Budget who allowed me to intern there one summer.

Above all I must express my gratitude to my friends in Cambridge and elsewhere, who have made my time here immensely rewarding, and my family, who got me off to a fine start and have been great comrades ever since. Finally, thanks to Daft Punk for writing the soundtrack to the homestretch of my master’s student career.

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Chapter I: Introduction

I.1. Introduction

This thesis presents an argument that hopper spacecraft make a capable, versatile, and worthwhile addition to the suite of conventional and proposed planetary exploration spacecraft. With the idea that space exploration is enabled by technology and analysis, but actually happens through political and institutional processes, information is presented to illustrate to all parties in the decision-making process when and how hoppers are likely to contribute a cost-effective advantage. This appeal is accomplished by (1) a thorough survey of both public and science exploration objectives, with a focus on planetary science activities in the United States, followed by (2) a technical description of hoppers and their attributes in comparison to other means of Solar System mobility, with (3) those attributes mapped to the policy and science goals, and finally supported by (4) technical performance analysis of a set of model missions that illustrates the potential of hoppers in a likely range of scenarios. Results show that hoppers are not always the most attractive mobility option, but provide a strong and novel advantage in a diverse array of conditions. A list of policy recommendations is provided for those who wish to help the effort of enabling hopper technology to fulfill its potential for exploration value.

I.2. Description of Sections to Follow

The remainder of this chapter provides the background necessary to make use of this thesis. Hopper vehicles as relevant to this thesis are defined and illuminated with some background information. Then the *Methodology* section (I.4) presents the logical structure of the thesis. This section also describes the use and limitations of the technical analyses.

Chapter II comprises a survey of the relevant exploration policy and science communities and their current-day stances and priorities regarding missions in the upcoming decades. The goal in conducting this research and writing this chapter is to give a representative and insightful snapshot of what is important to these communities, both in general for context, and in relation to the potential use of hoppers.

Chapter III describes attributes of existing and potential planetary exploration vehicle types, with special emphasis on advantages and disadvantages of hoppers. General characteristics of both mission operations and Solar System destinations, as they might be pertinent to hoppers, are also presented. Hopper attributes are then correlated to the mission and destination characteristics, as well as policy and science exploration objectives drawn from Chapter II. This process is not exhaustive, but demonstrative.

Chapter IV consists of three sections that analyze example missions to Earth's Moon, Mars, and Saturn's moon Titan, respectively. Each section is intended to function as a self-contained document presenting a realistic picture of how hoppers could facilitate exploration of the given destination. They all include a brief motivating introduction and a summary, in addition to analysis. These simulated sequences of hops are designed around attractive targets and give as much detail on hopper performance as the models permit. Values given include masses and fuel consumption, distances and altitudes attained, and hopper subsystem characteristics including basic engine design.

Chapter V summarizes the results presented in the preceding three chapters. Relevant aspects of both the exploration objectives and hopper performance analyses are presented in concert to illustrate how hoppers can and should best be utilized to increase the value of national Solar System exploration activities. A set of policy recommendations is included to present these conclusions concretely and concisely to decision makers.

A Note on References

References are included in truncated form as footnotes for the reader's convenience and to maintain the flow of the document. More complete citations for each source use the same numeric designations and are found in the *References* section at the end of the thesis. Footnotes referencing the same source refer to the first footnote citing that source. This citation style is explained in the *Chicago Manual of Style*, Chapter 14.14.[1]

I.3. Background

1.3.1 Hopper definition

In the context of this thesis, a hopper is a vehicle that visits multiple locations on a solid Solar System body with measurable gravity, by using propulsive thrust, such as a rocket, to re-launch to one or more locations on the surface after an initial landing. Movement from location to location may follow a ballistic or hovering trajectory. This thesis will not consider hoppers that travel by bouncing or spring-actuated mechanisms.

1.3.2 History of hoppers

To date, no use has been made off the Earth of hoppers as defined above. In 1967, the United States' Surveyor 6 spacecraft conducted what might be considered a hop on the moon by re-igniting its engine briefly after initial landing.[2] The Russian spacecraft Phobos 2 was designed to deploy a hopping device on the Mars moon Phobos, but contact with the spacecraft was lost before the hopper was released.[3] A number of proposed spacecraft have incorporated hopping techniques, including hoppers using a

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[1] Chicago Manual of Style

[2] NASA, *Surveyor 6*

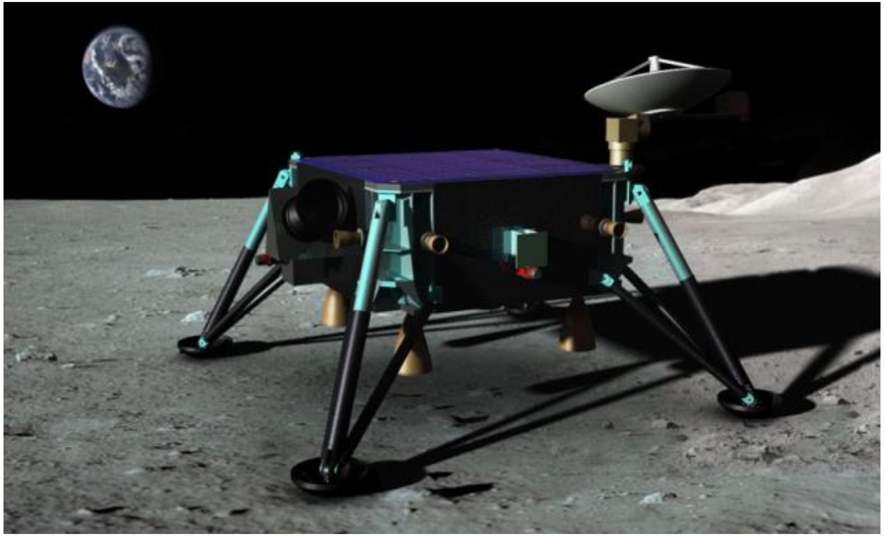
[3] NASA, *Phobos 2*

pogo-like piston for the Apollo program,[4] a Canadian design to use thermal changes to store energy in hop-enabling springs,[5] and a European Space Agency design using CO_2 harvested on Mars to oxidize a magnesium fuel for hops across Mars.[6] On Earth, NASA's Lunar Lander Research Vehicle and Lunar Lander Training Vehicle conducted multiple hovering flights using thrusters aided by a jet engine, but the purpose was to simulate aspects of Apollo lunar landings.[7] Students at the University of Southern California built and began testing a hopper device intended for science on the Moon.[8] Other hopper-like devices may have been tested, but none have operated in space.

1.3.3 Project Talaris

This thesis is motivated in part by involvement with the Terrestrial Lunar and Reduced grav-I-ty Simulator (TALARIS) hopper project at the Massachusetts Institute of Technology and the Charles Stark Draper Laboratory. Talaris, otherwise the Greek name for Hermes' winged sandal, is a component of the Next Giant Leap consortium's attempt at the Google Lunar X-Prize. A concept for the final spacecraft is shown in Figure 1.

Figure 1. Concept of Next Giant Leap hopper on the Moon[9]



Talaris is a vehicle intended to test the consortium's moon craft under Moon-like conditions within the Earth environment. The vehicle has two conceptual components: a spacecraft emulator, and gravity-canceling propulsion. The spacecraft emulator consists of a structure carrying propulsive thrusters, a flight computer, and avionics; the gravity-canceling propulsion is accomplished by fans that provide upward lift to cancel 5/6 of Earth's gravity. Draper Laboratory is responsible for vehicle guidance and control, and

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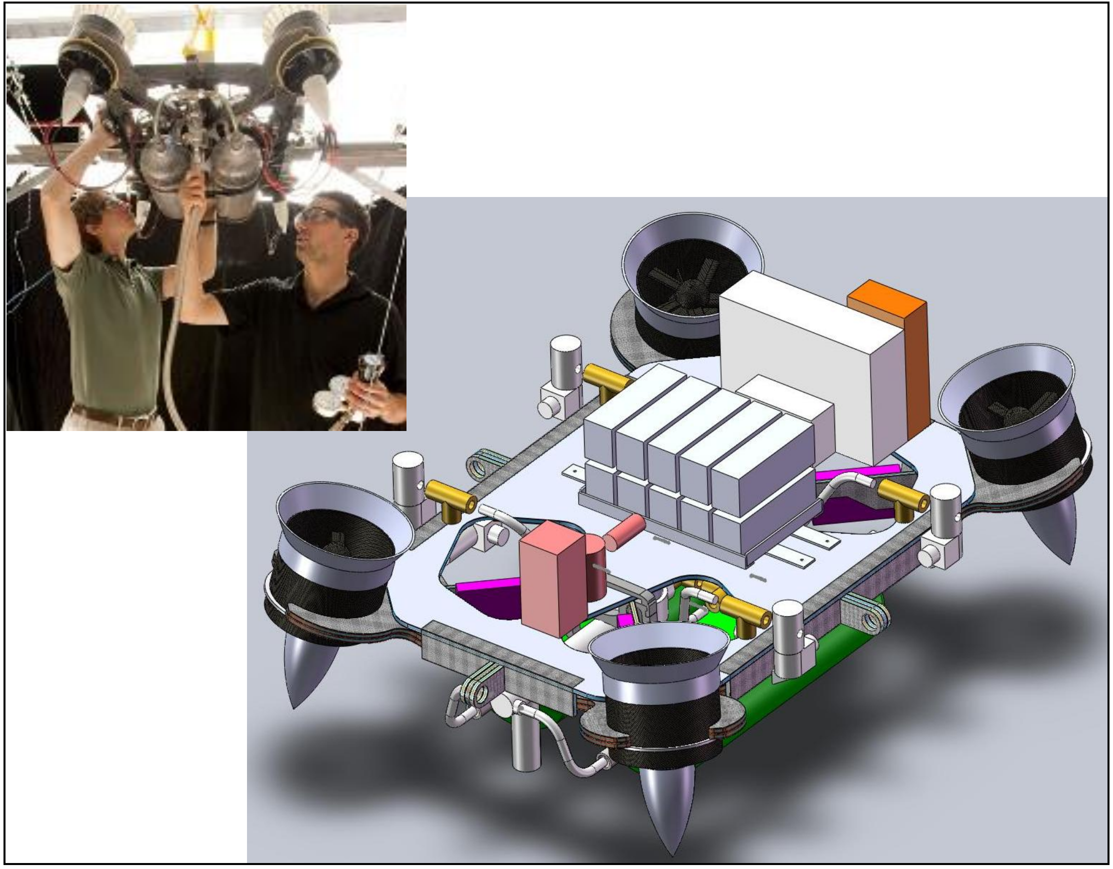
[4] Kaplan and Seifert, *Hopping Transporter for the Lunar Explorer*, 1968
[5] Soltis, "Hopping Across Mars," 2008
[6] Shafirovich et al., "Mars Hopper versus Mars Rover," 2006
[7] Matranga et al., *Unconventional, Contrary, and Ugly*, 2005
[8] Barnhart et al., *Hands-On Space Flight Risk Reduction Training...*, 2007
[9] Hornyak, "Hopper Vehicle Could Explore Mars by Jumping," 2010

MIT is building and testing the vehicle.[10] To date, the second-generation Talaris (T-2) has been designed and built and is undergoing detailed characterization and control tests.[11] The vehicle is shown being developed in Figure 2.

Figure 2. Talaris hopper with the author to the far left[12]



I.4. Methodology

This section describes both the logical methodology used to derive the basic conclusions of this thesis, and the analytical methods used to support the model mission examples.

1.4.1 The Logic and Process

In broad strokes, this thesis goes about articulating the potential advantages of hopper spacecraft by describing exploration objectives in both the policy and science domain, describing attributes of hoppers and other spacecraft for the sake of comparison, mapping those attributes to the exploration objectives, and presenting some example analyses as demonstration.

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[10] Cohanim et al., *Taking the Next Giant Leap*, 2009

[11] Cunio et al., *Further Development and Flight Testing…*, 2010

[12] (see Ref.9) Hornyak, “Hopper Vehicle Could Explore Mars by Jumping,” 2010

This logical thread carries through, but in practice some leaps are necessary due to the complicated nature of space science mission architecting and the limited scope of this effort. The process began by conducting a literature survey to understand and document objectives of planetary science stakeholders in the broadest terms. This led to a conceptual separation between exploration objectives for policy and science. As conceived here, policy objectives are at a higher level and encompass issues and motivations of a public and political nature; science objectives, though related, are presented as more objective and detailed agenda items for the planetary science community. The policy objectives are subjective and unwieldy in analysis, but a thorough description of the pertinent entities, processes, and history yields a reliable picture of the policy landscape. The science objectives are so plentiful, disparate, and detailed that they were hard to characterize exhaustively, though this presentation is soundly representative. Isolating the most relevant aspects of a broad range of conceptual vehicles – including hoppers – in a way that lends those attributes to quantitative matching with an unruly set of exploration objectives is not straightforward. The vehicle descriptions offered are intended to be thorough, which leaves the objectives mapping awkward. The resulting mapping process is therefore demonstrative rather than exhaustive.

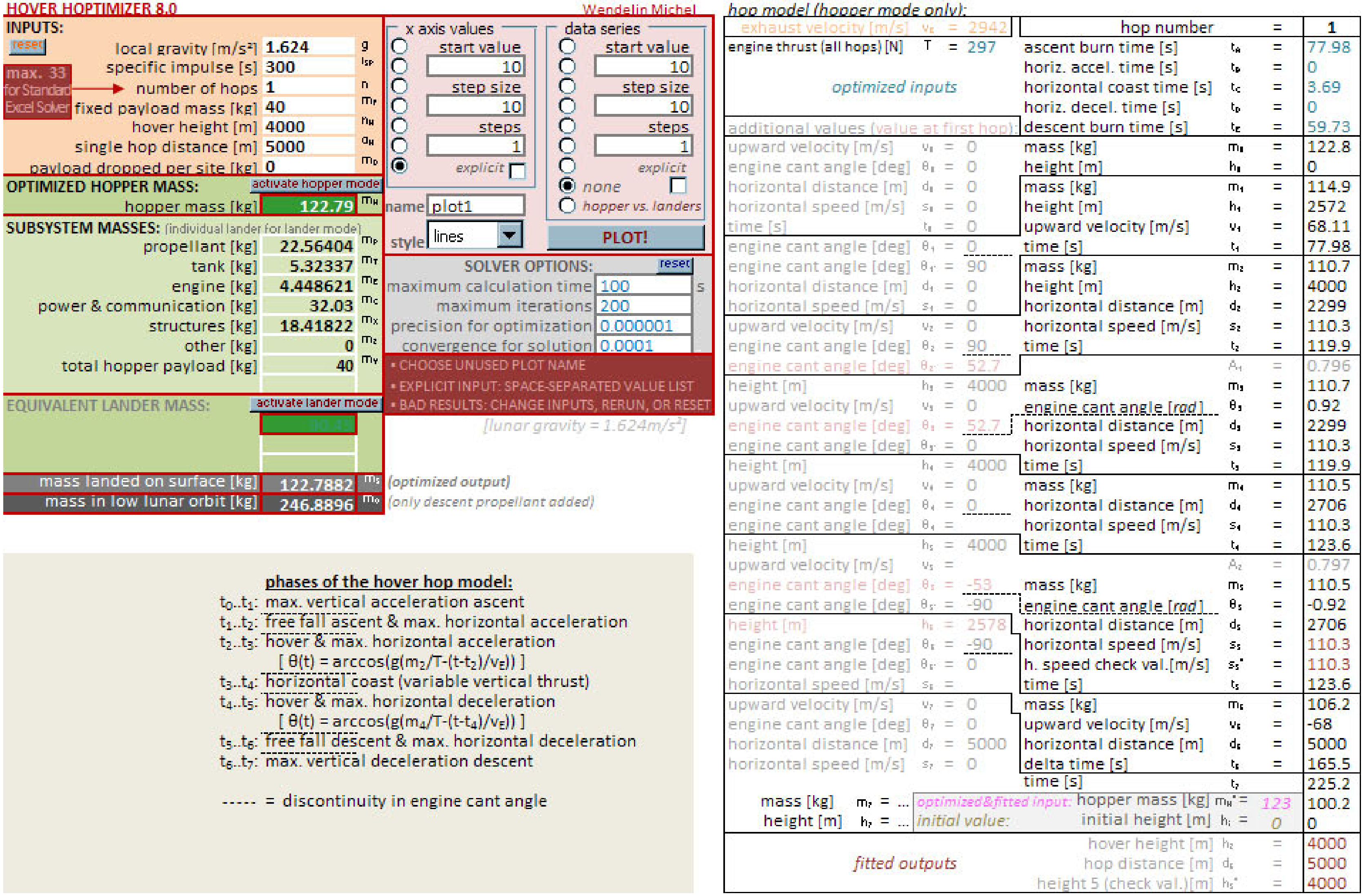
Through this process of mapping vehicle attributes to exploration objectives, it became increasingly clear that showcasing hoppers by example was not only more convenient, but an effective and expressive means for demonstrating the range of hopper capabilities and limitations. The example missions were chosen in an attempt to compromise between exhaustively analyzing every case where a hopper might possibly be used, and directly expounding hopper strengths and weaknesses. The final set of model missions leaves few urgently interesting hopper capabilities unexplored, covers a broad swath of the Solar System's hoppable worlds, and honestly portrays both disappointing and intriguing hopper performances. The methods used to analyze these missions are discussed in the next section.

Finally, all the preceding inputs and explanations are reduced into a concise set of qualitative and quantitative findings and employed in generating a set of policy recommendations to be considered by anyone hoping to promote the exciting new opportunities enabled by hopper technology.

1.4.2 "Hoptimizer" Model for Hovering Hops

Description

In his 2010 master's thesis at the Massachusetts Institute of Technology, Wendelin Michel presented a spacecraft dynamics model for hovering hoppers called "Hover Hoptimizer 8.0," henceforth Hoptimizer. The model is based in Microsoft Excel® and uses Microsoft Visual Basic® as the programming environment. The model assumes a predetermined flight profile shape that ascends, tilts to move horizontally, coasts at a hover altitude using only vertical thrust, and reverses the process to land.



HOVER HOPTIMIZER 8.0

Wendelin Michel

INPUTS:

local gravity [m/s²]	1.624	g
specific impulse [s]	300	I_{sp}
number of hops	1	n
fixed payload mass [kg]	40	m_F
hover height [m]	4000	h_H
single hop distance [m]	5000	d_H
payload dropped per site [kg]	0	m_D

max. 33 for Standard Excel Solver → number of hops

OPTIMIZED HOPPER MASS:

hopper mass [kg]	122.79	m_H

SUBSYSTEM MASSES: (individual lander for lander mode)

propellant [kg]	22.56404	m_P
tank [kg]	5.32337	m_T
engine [kg]	4.448621	m_E
power & communication [kg]	32.03	m_C
structures [kg]	18.41822	m_X
other [kg]	0	m_Z
total hopper payload [kg]	40	m_Y

EQUIVALENT LANDER MASS:

mass landed on surface [kg]	122.7882	m_S	(optimized output)
mass in low lunar orbit [kg]	246.8896	m_O	(only descent propellant added)

x axis values: start value 10, step size 10, steps 1, ● explicit ☐

name: plot1

style: lines

data series: start value 10, step size 10, steps 1, explicit, ● none ☐, ○ hopper vs. landers

SOLVER OPTIONS:

maximum calculation time	100	s
maximum iterations	200	
precision for optimization	0.000001	
convergence for solution	0.0001	

- CHOOSE UNUSED PLOT NAME
- EXPLICIT INPUT: SPACE-SEPARATED VALUE LIST
- BAD RESULTS: CHANGE INPUTS, RERUN, OR RESET

[lunar gravity = 1.624m/s²]

hop model (hopper mode only):

exhaust velocity [m/s] v_E = 2942

engine thrust (all hops) [N] T = 297

optimized inputs

hop number		=	1
ascent burn time [s]	t_A	=	77.98
horiz. accel. time [s]	t_B	=	0
horizontal coast time [s]	t_C	=	3.69
horiz. decel. time [s]	t_D	=	0
descent burn time [s]	t_E	=	59.73
mass [kg]	m_0	=	122.8
height [m]	h_0	=	0
mass [kg]	m_1	=	114.9
height [m]	h_1	=	2572
upward velocity [m/s]	v_1	=	68.11
time [s]	t_1	=	77.98
mass [kg]	m_2	=	110.7
height [m]	h_2	=	4000
horizontal distance [m]	d_2	=	2299
horizontal speed [m/s]	s_2	=	110.3
time [s]	t_2	=	119.9
	A_1	=	0.796
mass [kg]	m_3	=	110.7
engine cant angle [rad]	θ_3	=	0.92
horizontal distance [m]	d_3	=	2299
horizontal speed [m/s]	s_3	=	110.3
time [s]	t_3	=	119.9
mass [kg]	m_4	=	110.5
horizontal distance [m]	d_4	=	2706
horizontal speed [m/s]	s_4	=	110.3
time [s]	t_4	=	123.6
	A_2	=	0.797
mass [kg]	m_5	=	110.5
engine cant angle [rad]	θ_5	=	-0.92
horizontal distance [m]	d_5	=	2706
horizontal speed [m/s]	s_5	=	110.3
h. speed check val.[m/s]	s_5^*	=	110.3
time [s]	t_5	=	123.6
mass [kg]	m_6	=	106.2
upward velocity [m/s]	v_6	=	-68
horizontal distance [m]	d_6	=	5000
delta time [s]	t_6	=	165.5
time [s]	t_7		225.2
optimized&fitted input: hopper mass [kg]	m_H^*	= 123	100.2
initial value: initial height [m]	h_i	= 0	0
hover height [m]	h_2	=	4000
hop distance [m]	d_6	=	5000
height 5 (check val.)[m]	h_5^*	=	4000

additional values (value at first hop):

upward velocity [m/s]	v_0	=	0
engine cant angle [deg]	θ_0	=	0
horizontal distance [m]	d_0	=	0
horizontal speed [m/s]	s_0	=	0
time [s]	t_0	=	0
engine cant angle [deg]	θ_1	=	0
engine cant angle [deg]	θ_1'	=	90
horizontal distance [m]	d_1	=	0
horizontal speed [m/s]	s_1	=	0
upward velocity [m/s]	v_2	=	0
engine cant angle [deg]	θ_2	=	90
engine cant angle [deg]	θ_2'	=	52.7
height [m]	h_3	=	4000
upward velocity [m/s]	v_3	=	0
engine cant angle [deg]	θ_3	=	52.7
engine cant angle [deg]	θ_3'	=	0
height [m]	h_4	=	4000
upward velocity [m/s]	v_4	=	0
engine cant angle [deg]	θ_4	=	0
engine cant angle [deg]	θ_4	=	
height [m]	h_5	=	4000
upward velocity [m/s]	v_5	=	
engine cant angle [deg]	θ_5	=	-53
engine cant angle [deg]	θ_5'	=	-90
height [m]	h_6	=	2578
engine cant angle [deg]	θ_6	=	-90
engine cant angle [deg]	θ_6'	=	0
horizontal speed [m/s]	s_6	=	
upward velocity [m/s]	v_7	=	0
engine cant angle [deg]	θ_7	=	0
horizontal distance [m]	d_7	=	5000
horizontal speed [m/s]	s_7	=	0

mass [kg] m_7 = ...

height [m] h_7 = ...

fitted outputs

phases of the hover hop model:

$t_0..t_1$: max. vertical acceleration ascent

$t_1..t_2$: free fall ascent & max. horizontal acceleration

$t_2..t_3$: hover & max. horizontal acceleration

[$\theta(t) = \arccos(g(m_2/T-(t-t_2)/v_E))$]

$t_3..t_4$: horizontal coast (variable vertical thrust)

$t_4..t_5$: hover & max. horizontal deceleration

[$\theta(t) = \arccos(g(m_4/T-(t-t_4)/v_E))$]

$t_5..t_6$: free fall descent & max. horizontal deceleration

$t_6..t_7$: max. vertical deceleration descent

----- = discontinuity in engine cant angle

Figure 3. Hoptimizer interface

The interface is shown in Figure 3. Besides fixed and dropped payload masses, hop distance, and hop height, the user can input local acceleration due to gravity and the desired number of identical hops. The program incorporates very simple parametric models for propellant tanks, engine, and structure. Results are produced by varying subsystem and propellant masses along with engine thrust to optimize a single hopper design. The optimization parameters can be adjusted. The resulting design includes a fuel mass required for landing from an orbit with a specified change in velocity (ΔV) relative to the surface, assuming conformation to the ideal rocket equation and ignoring propellant tanking and extra engine mass.[13] There is also an ability, unused in this thesis, to compare a hopper mission to a set of individual landers visiting the same number of sites; this comparison ignores costs of orbital maneuvers for the landers. There are also options to plot the optimization results. A more thorough description of the program can be found in Michel's thesis.[14]

Hoptimizer includes some drawbacks that limited the analysis of model missions. First, each hop must have the same distance, height, thrust, specific impulse, and drop mass. Second, the subsystem models are simplistic and incorporate a number of assumptions that limit the model's generality. The power and communications model is discussed below. Finally, the optimization implementation is precariously tuned to analyze a small number of short hops with light masses, making it cumbersome to investigate larger-scale missions.

Modifications

Hoptimizer's Power and Communications model is based on a link budget model built by Ben Corbin for a class at MIT, which was in turn based on Chapter 13 of *Space Mission Analysis and Design* (SMAD).[15] In a personal communication, he stated that the version included in the model was based on a link constant relevant only to another project. The model also calculates power consumption only for the communications system, with no consideration for payload or other subsystem needs. Photovoltaic cells are the supply source, with rechargeable batteries available for user-specified time intervals of panel shading.

To remedy these issues while maintaining focus on the central themes of this thesis, advice from Corbin and Dan Fulcoly, another graduate student at MIT, was incorporated into a rework of the communications model. The core link calculations were retained, but more inputs were included to make the calculations relevant to any desired mission. These inputs are shown in Table 1.

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[13] Wertz and Larson, Eds., *SMAD*, 1999, p.690

[14] Michel, "Use and Sizing of Rocket Hoppers for Planetary Surface Exploration," 2010

[15] (see Ref.13) Wertz and Larson, Eds., *SMAD*, 1999

Table 1. Input values for Hoptimizer communications and power model. Rows with only one value use that value for Earth's Moon, Mars, and Titan. * indicates unreferenced estimates

	Units	*Earth's Moon*	*Mars*	*Titan*
Data rate	Mbps	5*	50	50
Communication power allotment	W	50*	10	10
Link Distance	m	$4x10^8$	$2x10^5$	$2x10^5$
Frequency	GHz	32	2	2
Required signal to noise ratio	dB		13	
Link margin	dB		3	
Transmitter antenna efficiency	ratio		0.8	
Transmitter line loss	dB		0.5	
Transmitter pointing error	degrees		1*	
Receiver antenna diameter	m	34	0.5	0.5
Receiver efficiency	ratio		0.8	
Receiver antenna pointing error	degrees	.0002	.01*	.01*
Atmospheric loss	dB	1.07	0.1*	2*
System noise temperature	Kelvin	125	200*	200*
Implementation loss	dB		2	
Transmitter mass/Power	kg/W		0.1	
Antenna mass/Area	kg/m^2		2.94	
Power converter mass/Power	kg/W		0.76	
Transmission antenna diameter	**m**	**0.1**	**0.1**	**0.2**
Power system mass	**kg**	**5**	**10**	**10**

Most of these inputs are based on typical reasonable values found in SMAD or other sources; '*' indicates other estimates. Missions on the Moon are assumed to communicate with the Deep Space Network's 34 m antennas on Earth in the K_a frequency band, which is generally recommended for future science missions.[16] Missions to Mars and Titan are assumed to communicate through those respective atmospheres with orbiting spacecraft which in turn handle communications with Earth. This uplink to orbit is assumed to use a 1 m receiver antenna and operate in the S frequency band, which has little traffic at these remote locations and is in some ways easier to implement.

After these values are input to the model, the transmission antenna mass is varied until the hopper's transmission system has an Equivalent Isotropically Radiated Power (EIRP) high enough to satisfy the required signal-to-noise ratio. An estimate for total spacecraft power system mass is also input; a more detailed power model would be mission specific and beyond the scope of this thesis to implement. Both the transmission antenna diameter and power system mass are in bold at the bottom of the table.

Usage

In the Excel file's first sheet, the user inputs local acceleration due to gravity, engine specific impulse (I_{sp}), number of hops, fixed payload mass, hover height, hop distance, and mass of payloads to be dropped at each landing site. An I_{sp} of 300 s, typical for deep space missions using hydrazine bipropellant, is used for all analyses in this thesis. The model runs automatically each time an input is adjusted. Small changes in input values are required to keep the optimization convergent. The model internally calculates a thrust value and outputs masses for propellant consumed, a corresponding propellant tank, an engine that provides the thrust, and structure. The mass of the power and communications system, described above, is also used in the optimization. The total wet (fueled) mass initially landed on the surface, is the main output.

The model also provides a pre-landing on-orbit mass; in this thesis, the ΔVs required for a soft landing on orbit are 2055 m/s for the Moon, 4100 m/s for Mars, and 2300 m/s for Titan. The format for presenting the inputs and outputs is a table such as Table 2.

---

[16] Slobin, *DSN Telecommunications Link Design Handbook: 302, Rev.B*, 2010, p.7

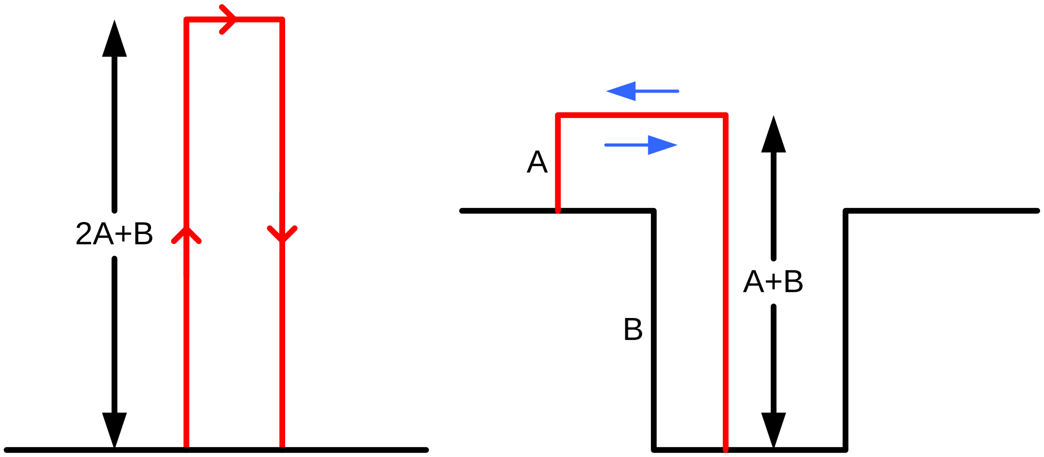
Table 2. Example table showing Hoptimizer input and output format

	Input Values
Local gravity, g (m/s^2)	1.624
Engine specific impulse, I_{sp} (s)	300
Number of hops	1
Fixed payload mass (kg)	51
Hover height (m)	10
Single hop distance (m)	1000
Payload dropped per site (kg)	0
	Output Masses (kg)
Propellant	4.7
Tank	1.9
Engine	3.8
Power	18
Communications	14
Structures	16.5
Other	0
Total hopper payload	51
Optimized hopper mass	**110**

For some of the missions described, a hopper dry (unfueled) mass is chosen prior to conducting any hop analysis. This mass is achieved iteratively by first adjusting the power and communications subsystems, and then varying the "other" mass in the outputs field so that the total hopper mass minus any propellant roughly equals the desired dry mass. The user can then provide appropriate inputs to run optimizations that determine the actual propellant and total hopper mass. The user then checks the total-minus-propellant mass and adjusts the "other" mass until the desired quantity is achieved.

Finally, some of the missions make use of the ideal case where the "hop height" can be used for travel upward or downward in either order and with arbitrary stops and starts. For an example shown on the right of Figure 4, the hopper could start on a surface, rise to a short hover height, move horizontally, and descend deep to the bottom of a pit. As long as there is a return trip, this profile is – in the vertical direction – energetically identical to a hop that starts on a surface and climbs to and immediately descends from a height equal to the first hop's hover height (multiplied by two for ascent and descent) plus pit depth.

Figure 4. Basic hop compared to round-trip hop into pit; both expend the same energy on vertical motion



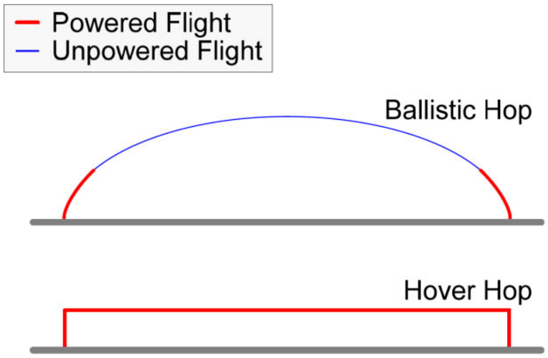
This idealization assumes no inefficiencies or unnecessary accelerations related to starting and stopping, but should provide a close approximation. The analog for horizontal motion – that starts and stops are irrelevant as long as the same round-trip distance is covered – is invalid because there is no gravity to aid with braking and fuel must be consumed for every deceleration. Still, a single horizontal leg can be assumed to use only slightly less fuel than a few horizontal legs summing to the same distance.

1.4.3 BallisticHop Model for Ballistic Hops

Description

Another 2010 thesis from the Massachusetts Institute of Technology, this one by Akil Middleton, provided a model for analysis of ballistic hops. A conceptual comparison with hover hops is shown in Figure 5.[17]

Figure 5. Ballistic and hover hops[18]



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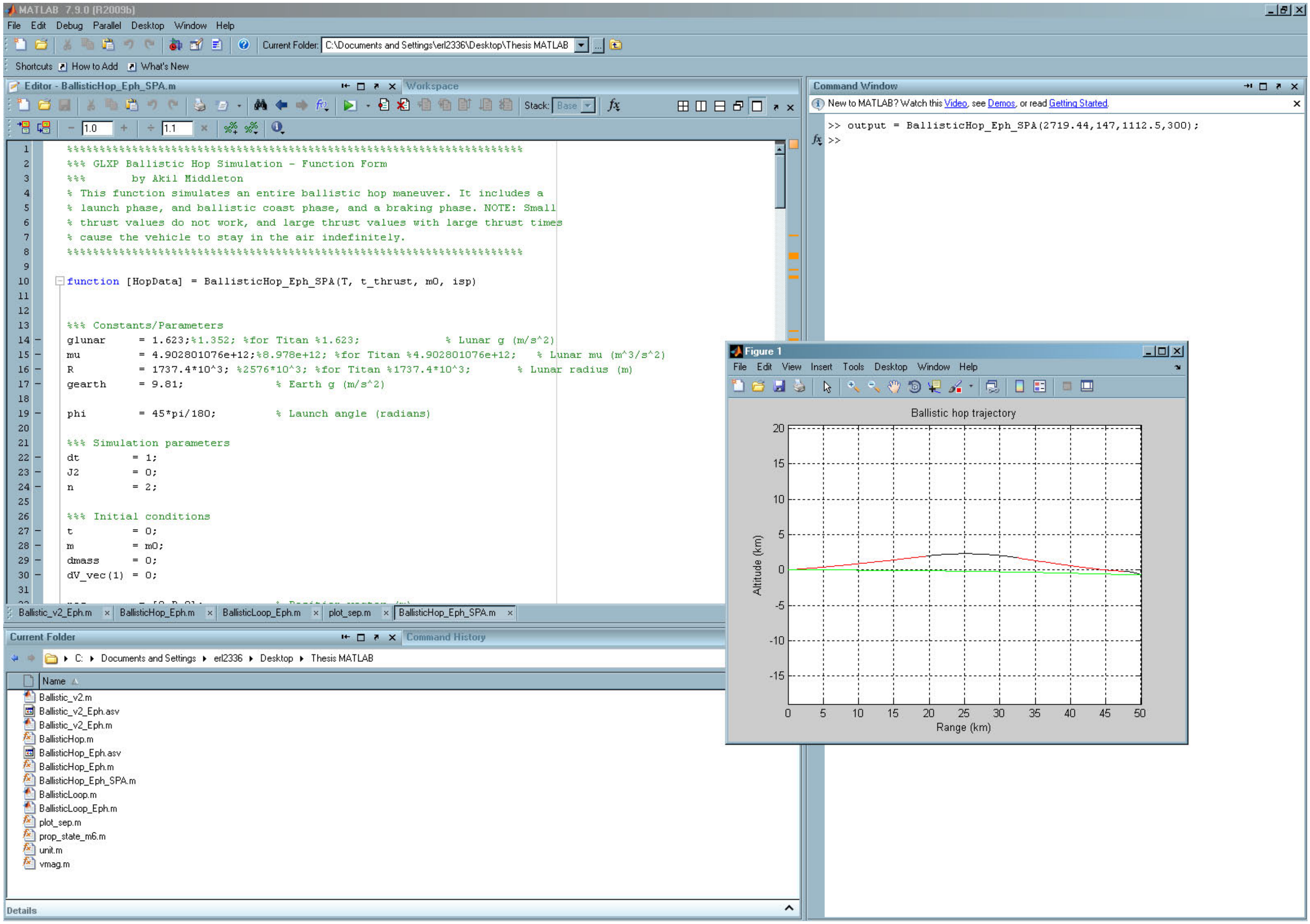
[17] Middleton, "Modeling and Vehicle Performance Analysis of Earth and Lunar Hoppers," 2010

[18] (see Ref.17) Middleton, "Modeling and Vehicle Performanc.e…," 2010, p.2

The software consists of a set of one primary MATLAB® script that references a few others for low-level computation. Though new file names were generated for each model simulation in this thesis, the name of the top-level file taken from Middleton is Ballistic_Hop.m. This script analyzes the trajectory and fuel consumption of a rocket hopper executing a ballistic hop over a curved planetary surface. The interface is shown in Figure 6.



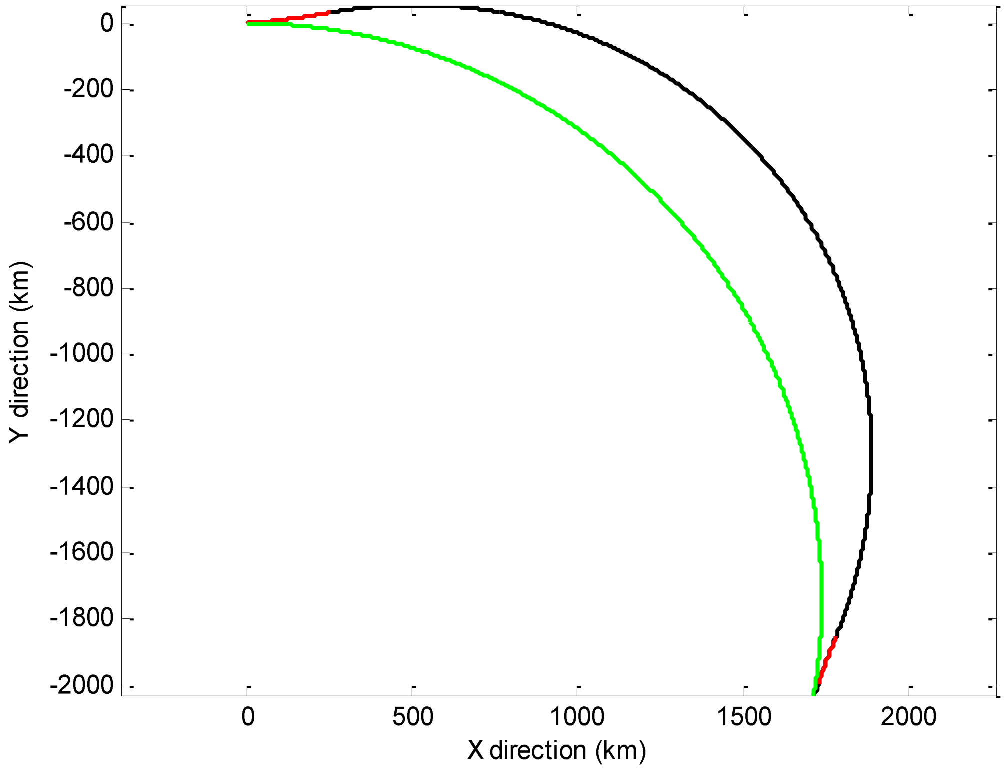
```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% GLXP Ballistic Hop Simulation - Function Form
%%%       by Akil Middleton
% This function simulates an entire ballistic hop maneuver. It includes a
% launch phase, and ballistic coast phase, and a braking phase. NOTE: Small
% thrust values do not work, and large thrust values with large thrust times
% cause the vehicle to stay in the air indefinitely.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function [HopData] = BallisticHop_Eph_SPA(T, t_thrust, m0, isp)


%%% Constants/Parameters
glunar      = 1.623;%1.352; %for Titan %1.623;             % Lunar g (m/s^2)
mu          = 4.902801076e+12;%8.978e+12; %for Titan %4.902801076e+12;   % Lunar mu (m^3/s^2)
R           = 1737.4*10^3; %2576*10^3; %for Titan %1737.4*10^3;       % Lunar radius (m)
gearth      = 9.81;                 % Earth g (m/s^2)

phi         = 45*pi/180;            % Launch angle (radians)

%%% Simulation parameters
dt         = 1;
J2         = 0;
n          = 2;

%%% Initial conditions
t          = 0;
m          = m0;
dmass      = 0;
dV_vec(1) = 0;
```

```
>> output = BallisticHop_Eph_SPA(2719.44,147,1112.5,300);
>>
```

Figure 6. BallisticHop model open in MATLAB

Each hop produces a plot of the hopper's trajectory; Figure 7 shows an example of a long hop just over a quarter of a planet's circumference. Black indicates the hopper's path, with red indicating segments with the engine on. The green line is the portion of the planet's surface directly below the trajectory. The axes show Cartesian coordinates with the origin at the launch point. Notably, the program executes with the origin at the planet's center, and the coordinates are adjusted for display. Also, the x- and y-axes have the same scale, so the plot's shape is accurate.

Figure 7. Example BallisticHop trajectory plot



The model incorporates a few limiting simplifications. First, the launch is assumed to be at an idealized launch angle rather than in a more realistic vertical direction, and this thrust angle relative to the planet's surface is maintained throughout the launch and brake phases. Thrust also remains constant over the entire hop, and no fuel is allotted for control. Next, the launch and landing are required to take place at the same altitude. And, though not a limitation inherent in the software, the program is intended for a slightly different mode of inquiry than its use here; to attain the results in this thesis, the code had to be run manually numerous times for each analysis, as discussed below.

Additionally, the braking phase is increasingly unrealistic for longer hops. The program uses the same thrust value with the same duration for both launch and braking. Since fuel is consumed and spacecraft mass is depleted as the flight progresses, the braking phase should start later for a zero-velocity (or very low velocity) landing. Before the changes discussed below were made, this led to the hopper reaching zero vertical velocity long before landing, and then reaccelerating back into space.

BallisticHop includes the relevant internal variables displayed in Table 3. The program was originally intended for analysis of lunar missions, so some values were adjusted for analysis of the Mars and Titan missions.

Table 3. Internal values for BallisticHop model. Rows with only one value use that value for all three destinations

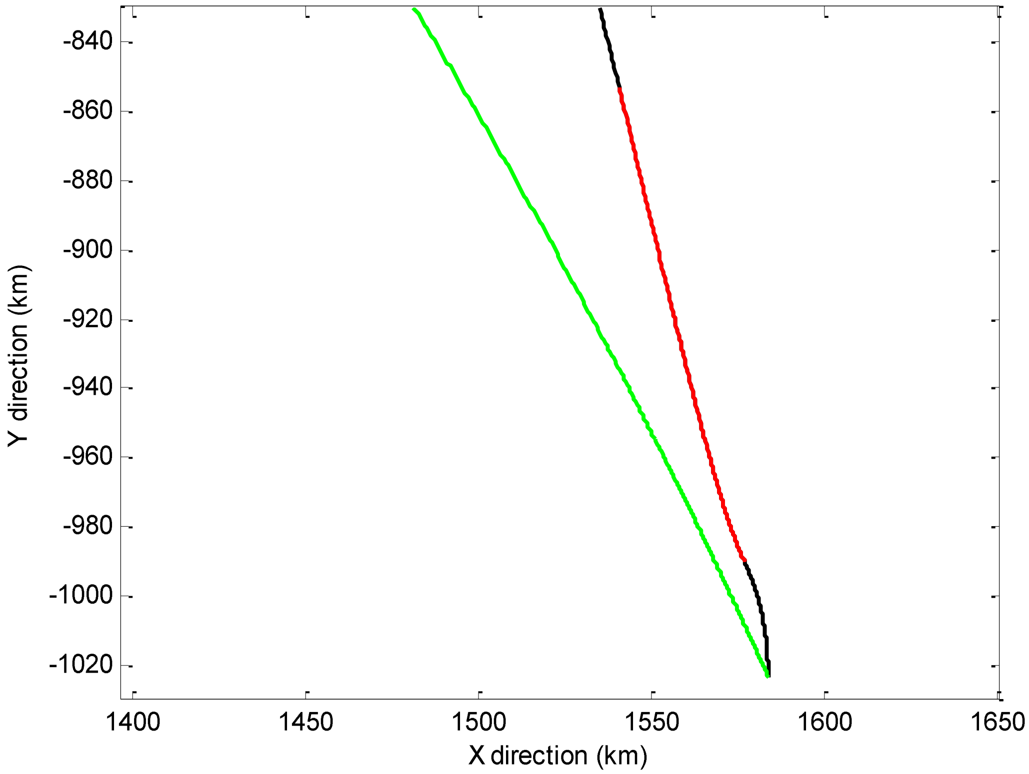
	Units	*Earth's Moon*	*Mars*	*Titan*
Local acceleration due to gravity	m/s^2	1.623	3.71	1.352
μ = GM	km^3/s^2	4.903×10^{12}	4.284×10^{13}	8.978×10^{12}
Radius of planetary body	km	1737.4	3380	2576
Earth acceleration due to gravity	m/s^2		9.81	
Time step	s		1	

Modifications

To aid with the analysis of long-distance hops in particular, a few changes were made to the code. First, code was added to display the planet's curving surface in output plots. The dynamics calculations were adjusted to enable hops almost all the way around a planet's circumference, rather than comparatively short distances where the surface can be approximated as a gradual slope. Finally, an adjustment was incorporated to address, provisionally, the landing issue discussed above in the "Description" subsection.

The implemented solution is to detect when the hopper reaches roughly zero vertical velocity, then turn off the engine. For hops of thousands of kilometers, this cutoff may occur while the hopper is still a few kilometers above the surface. BallisticHop then propagates the hopper's state under freefall until contact is made with the surface, as depicted in Figure 8. This is unrealistic and undesirable, but allows a close estimation of the total fuel required for the flight without requiring an iterative routine to calculate the beginning of the braking phase.

Figure 8. Example of freefall approximation at end of long-distance ballistic hop



Usage

First, the appropriate internal values given in Table 3 are set within the Ballistic _Hop file. Next, the function is called in MATLAB's Command Window, providing inputs for thrust, launch burn time, initial mass, and engine specific impulse (I_{sp}). As with Hoptimizer, an I_{sp} of 300 s is used for all analyses. The program outputs, in addition to a trajectory plot, a MATLAB structure that includes matrices of: ΔV for launch, braking, and total; hopper mass at every time step; range, or total distance traveled over ground; and final velocities.

The function is called repeatedly according to a strategy in order to find a near-optimal hop. The strategy consists of manually matching four variables: launch angle, initial mass (consisting of known hopper dry mass plus propellant mass), thrust, and launch thrust time. First is the launch angle. For an ideal ballistic flight over flat ground, the most efficient launch angle is 45°. But when the ground curves away appreciably, as in a long-distance hop over a planet's surface, the ideal angle becomes shallower. In opposition to a shallower launch angle is the need to provide the minimum sufficient thrust for liftoff; it is assumed that a lower-thrust engine is lighter, making the hopper more mass efficient. The tradeoff of engine thrust with acceleration loads, engine mass, and fuel efficiency resulting from shorter burn times is not further addressed in this thesis, and likely estimates were used for long hops.

Matching the other three variables is more deterministic. An initial hopper mass is guessed. Then based on that mass, the minimum thrust required for liftoff is computed to provide a vertical acceleration 1.06 times local gravitational acceleration. The thrust time is then varied to reach the desired range. Keeping that time constant, the pairing of thrust and initial mass is adjusted to find the desired final. This process should be automated for future analyses.

When this process has resulted in an appropriate launch angle and found the initial mass, thrust, and thrust time necessary for the desired end mass and distance traveled, the inputs and outputs are presented in the format demonstrated by Table 4.

Table 4. Example table showing BallisticHop input and output format

	Input Values
Launch angle, ϕ (degrees)	30
Engine thrust (N)	510
Launch thrust time (s)	356
Start mass (kg)	148
Engine specific impulse, I_{sp} (s)	300
	Output Values
Range (km)	2009
End mass (kg)	58
Velocity change, ΔV (m/s)	2749
Initial hopper mass (kg)	**148**

Aerodynamic drag

Mars and especially Titan have substantial atmospheres. High-velocity hops through this dense air would result in efficiency losses to aerodynamic drag. While less important for the short, relatively low-velocity hover hops analyzed with Hoptimizer, the ballistic hops analyzed with BallisticHop should account for these losses. Since the program was originally intended for lunar missions, it assumed no drag effects. A simple correction was implement in toward the end of this writing.

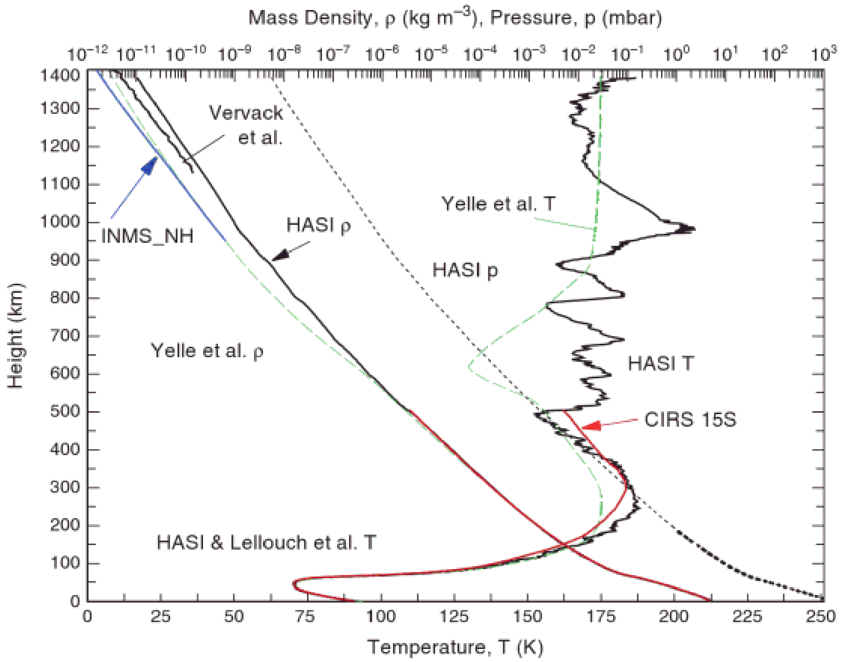
HoverHop runs by computing the accelerations experienced by the hopper due to engine thrust. It sends these accelerations to a subroutine along with the hopper's state vector, and the subroutine uses a numerical integrator to compute the next state. To account for drag, the acceleration vector due to drag force is added to the thrust acceleration vector. The force due to drag F_D is

$$F_D = \tfrac{1}{2}\,\rho V^2 C_D A,$$

where ρ is atmospheric density, V is velocity in the direction opposite the drag force, C_D is a drag coefficient, and A is the projected area exposed to the drag force. The acceleration due to this force is simply F_D / m, where m is the current mass of the hopper.

This enhancement was incorporated into the BallisticHop analysis of the Titan mission. A density of $\rho = 1.3$ kg/m^3 was taken from the red "CIRS 15S" density curve in Figure 9, itself from the book *Titan from Cassini-Huygens*. A reasonable drag coefficient of 0.05, which is conservative for terrestrial aircraft, was combined with a projected area of 0.25m^2 in the x-direction and 1m^2 in the y-direction; using the axial directions was convenient and a close approximation for a fixed-orientation hop over a distance short compared to surface curvature.

Figure 9. Titan atmosphere models and measurements[19]



The result for the same launch angle, fuel consumption, thrust, and thrust time was a much shorter hop. Figure 10 shows the results to scale with and without drag for comparison. Drag was not implemented in the coast and braking phases, so some additional ground could be gained by braking less. Inputs necessary to reach the original desired hop distance were not computed, but this demonstration is sufficient to show that drag losses are substantial and should not be neglected in future analyses.

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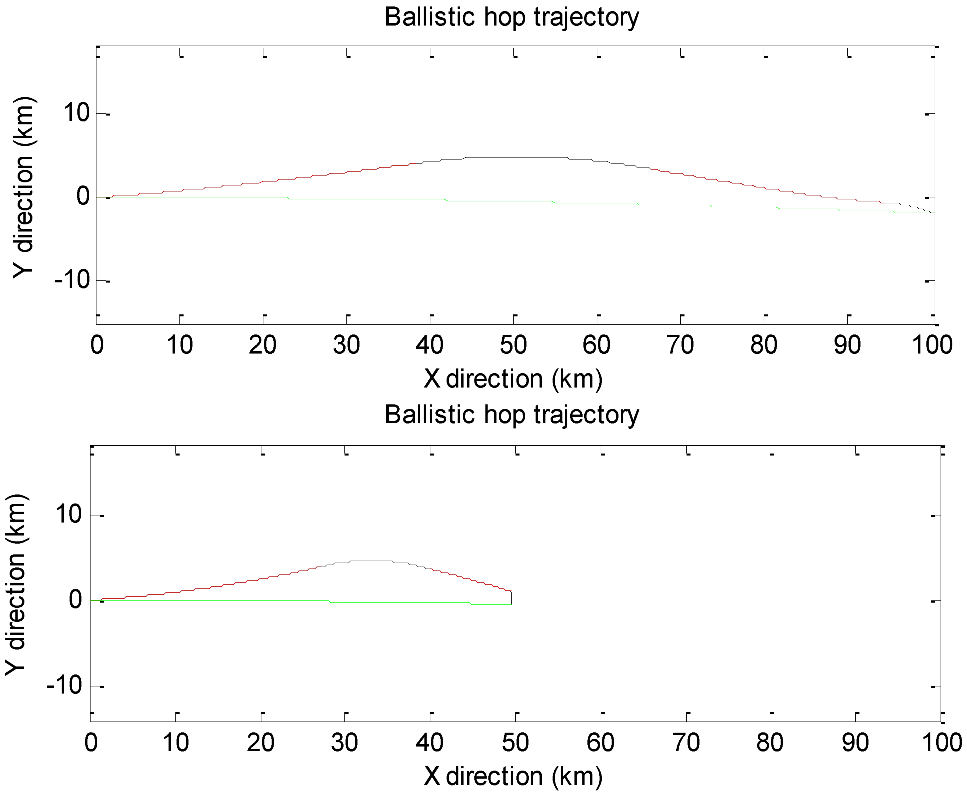
[19] Brown et al., *Titan from Cassini-Huygens, 2009,* p.237

Figure 10. Ballistic hops on Titan using same inputs, without (top) and with (bottom) aerodynamic drag during launch



Chapter II: Objectives for Solar System Exploration

The exploration objectives considered in this thesis are divided into two conceptual categories: policy and science. These categories are interrelated and could be delineated differently, but the division used here is convenient and appropriate for motivating the use of hoppers.

II.1. Policy Objectives

2.1.1 How Solar System Exploration Policy Works

The main goal of this thesis is to show why hoppers are an attractive option for Solar System exploration. Decisions about how a given exploration mission is architected, or how such missions themselves are selected in the context of competing funds for space science, other research, and all the other demands on national budgets, are largely distant from the technical merits of specific technologies. These decisions are made in a climate of fierce competition by people who operate in the realm of politics, billion-dollar budgets, and media attention. Their choices are informed by scientific and engineering knowledge, yes, but more significantly by laws, elections, and political momentum. This section offers a snapshot of this space exploration policy scene, and foreshadows the next chapter's exposition of how hopper spacecraft should appear attractive even at this level. This description is worthwhile because promoters of technologies like hopper spacecraft should be aware of how the system generally works and what promotion efforts will be most productive.

One way to illustrate this Solar System exploration policy landscape is to describe the parties who make or influence decisions that direct the course of events. Starting at the highest level is the international context. This is influenced by a handful of nations, their governing bodies, and their space agencies. The most significant entity for Solar System exploration outside the United States is the European Space Agency (ESA), which collaborates most extensively with NASA on science missions. Europe is often involved in NASA's largest missions to the planets, such as Galileo,[20] Cassini-Huygens (where ESA provided the Huygens Titan lander),[21] and a planned mission to Jupiter and its moon Europa.[22] Russia, Japan, China, India, and Canada also spend significant sums on planetary science and sometimes collaborate with other nations. Five space programs collectively operate and utilize the International Space Station: NASA, Roscosmos (Russia), ESA, JAXA (Japan Aerospace Exploration Agency), and CSA (Canadian Space Agency).[23] In total, over 60 countries have active space programs.[24]

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[20] NASA, "Galileo Mission"
[21] NASA, "The Huygens Probe"
[22] NASA 2010 Science Plan, p.56
[23] NASA, "International Space Station"
[24] Wikipedia, "List of space agencies"

Generally, international collaboration in space exploration has steadily become a more prevalent theme. The 2004 Vision for Space Exploration lists "promote international and commercial participation in exploration to further U.S. scientific, security, and economic interests" as one of four overarching goals for space exploration.[25] Of the 2008 NASA Authorization Act's 13 findings, four (numbers 4, 5, 7, and 13) promote international cooperation, and the 2010 Authorization repeatedly mentions such efforts. A tight-knit international community exists in support of an International Lunar Network.[26] In 2007, 14 space organizations collaborated to produce a framework document[27] that precipitated creation of the International Space Exploration Coordination Group (ISECG), which has vigorously pursued its founding mandate since 2009.[28]

In even broader terms, the late 20th century brought space exploration into the awareness of the collective human population. This massive, if diffuse, consciousness bears on the course of funding decisions through political processes. At the same time, many practitioners of space exploration policy are informed by profound feelings and perspectives on humanity writ large.

At the next level down, this thesis focuses on Solar System exploration by the United States, which leads the world in related activity and expenditures: Figure 11 shows global space expenditures for 2009, with the U.S. government spending (on defense, NASA, and other science) more than three times all other governments combined. Within the U.S., the legislative branch, embodied by Congress, writes into law budgets that broadly determine how exploration is funded; these appropriations for NASA are usually contained in omnibus appropriations bills such as the Consolidated/Omnibus Appropriations Acts of 2008, 2009, and 2010.[29,30,31] Congress also has the discretion to write laws with instructions for how money is spent and what initiatives are emphasized; recent examples are the NASA Authorization Acts of 2005, 2008, and 2010.[32,33,34] The executive branch, led by the president, has the authority to set the national space policy and propose budgets to Congress. An extension of the executive branch is the National Aeronautics and Space Administration, NASA. Though significant space-related activity takes place outside of NASA in the Department of Defense (DoD), the National Science Foundation (NSF), the Department of Energy (DOE), and the National Oceanic and Atmospheric Administration (NOAA), Solar System exploration,

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[25] *Vision for Space Exploration*

[26] *Statement of Intent Regarding the International Lunar Network*

[27] *The Global Exploration Strategy, 2007*

[28] "International Space Exploration Working Group"

[29] *Consolidated Appropriations Act of 2008*

[30] *Omnibus Appropriations Act of 2009*

[31] *Consolidated Appropriations Act of 2010*

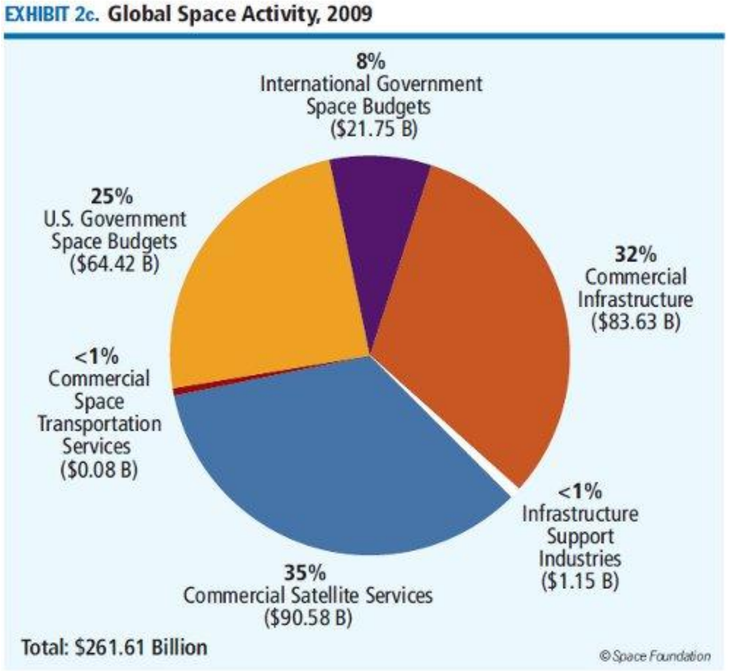
[32] *NASA Authorization Act of 2005*

[33] *NASA Authorization Act of 2008*

[34] *NASA Authorization Act of 2010*

and thus this thesis, is within NASA's purview. All activity within NASA is governed by the National Aeronautics and Space Act of 1958 and its Amendments.

Figure 11. Global space activity, 2009.[35] Note that units are U.S. dollars and do not reflect regional differences in buying power



NASA is itself headed by an Administrator who is appointed by the President and approved by Congress. As it is presently organized, NASA is divided into four major directorates, in addition to other smaller organizations; the Exploration Systems Mission Directorate (ESMD) and, primarily, the Science Mission Directorate (SMD) are the most pertinent for Solar System exploration. The SMD is divided into four "major science areas" [36] that research different aspects of the universe. The area most relevant here is Planetary Science, where focus is split among the Inner Solar System, the Outer Solar System, and small bodies of the Solar System.[37]

NASA's Planetary Science area supports three classes of missions. Discovery and New Frontiers missions are proposed – by principle investigator-led teams from the broader science community – in response to NASA announcements of opportunity. NASA manages the proposal competition and supports the development of science instruments and the spacecraft as well as testing and launch, but the proposing team retains leadership of the project overall. Discovery missions usually cost significantly less than $500 million. New Frontiers missions are intended to address robustly science questions prioritized by a decadal survey, and can cost upwards of $750 million. Finally,

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[35] The Space Foundation, "Global Space Activity"

[36] (see Ref.2222) NASA, 2010 Science Plan, p.14

[37] NASA, "Welcome to NASA Science"

flagship-class missions are major national research endeavors managed internally by NASA at an approximate rate of once per decade, at a cost over $1 billion.

Research endeavors within SMD are grouped into categories. The Lunar Quest Program, the Mars Exploration Program, and Outer Planets categories target specific sets of destinations, and the first two have significant overlap with human exploration planned by ESMD. More general categories are Planetary Science Research and Technology, both of which are Earth-based efforts.[38]

Outside the mission directorates, NASA also maintains research groups that are dedicated to study of specific regions of the Solar System. The Lunar Exploration Analysis Group (LEAG) organizes research on the Earth's moon. The Mars Exploration Program Analysis Group (MEPAG) is for Mars, and Venus Exploration Analysis Group (VEXAG) is for Venus. OPAG similarly concentrates on the Outer Planets. These Analysis Groups coordinate strongly with, and sometimes draw membership from, their respective wider science communities.

These communities, often collectively referred to as the space science community, consist of researchers at NASA, universities, and government and private research facilities. These parties interact in many ways, but for each research domain, their consensus will is focused by the Space Studies Board (SSB) of the National Research Council (NRC), which is itself a member of the National Academies. Roughly every ten years, Congress requests the NRC to conduct a "decadal survey" to prioritize that science community's objectives. This tradition began with the Astronomy and Astrophysics community in the 1960's. The first planetary science decadal survey was released in 2003, and another is scheduled for publication in spring of 2011;[39] these documents will be mentioned more extensively below. The government can also commission other reports by the National Research Council or other organizations. Recent examples include a 2009 study headed by General Lester Lyles entitled *America's Future in Space: Aligning the Civil Space Program with National Needs*,[40] a 2010 Space Studies Board Report called *An Enabling Foundation for NASA's Space and Earth Science Missions*,[41] and a pivotal 2009 report by an independent panel, *Seeking a Human Spaceflight Program Worthy of a Great Nation*,[42] often called the "(second) Augustine report" after the panel's chairman Norman Augustine.

The decadal surveys disseminate calls for "white papers" that describe reasons and means for specific exploration goals or targets. This call is open to the public. Most of the entries are from recognized scientists and institutions, some listed above, but many come from little-known scientists, interest groups, or the general public. Interest

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[38] (see Ref.22) NASA 2010 Science Plan, p.52-54

[39] NRC Space Studies Board, "Planetary Science Decadal Survey"

[40] Lyles Report, *America's Future in Space*, 2009

[41] *An Enabling Foundation for NASA's Earth and Space Science Missions*, 2010

[42] Augustine Report, *Seeking a Human Spaceflight Program Worthy of a Great Nation*, 2009

groups, such as the Lunar and Planetary Institute, or the Planetary Society, can be significant lobbying organizations; they often have prominent scientists among their membership, and serve to speak for the broader public. There are other means for informing and organizing the public, such as blogs, websites, and news sources like space.com or NASA Watch. A final contingent is the aerospace industry, which makes its will felt through lobby groups and the election process. Its influence on Solar System exploration decisions is indirect and generally considered small compared to the science community, so industry will not receive explicit consideration in this thesis.

Another important way to view the space exploration policy world is historical momentum. Though space travel and related fantasies have always contributed to the ethos of space technology development, the reasons rocket and space technology were funded and developed had to do with security and conflict. The earliest serious, government-funded rocket programs, first in Germany and then the U.S. and Russia, were all focused on missiles. NASA was set up to oversee a civilian space program, but in the context of Cold War competition with the Soviets. This “space race” framing continued to be popular through the 1960’s and 1970’s, and still comes up in reference to the space programs of China, India, and other nations; this is easy to see by typing “China space race” or “India space race” into any Internet search engine.

The history of space science is somewhat decoupled from the political intensity of the missile and moon races. Early missions to Mars and Venus had some of the same frantic showmanship, but data sharing and collaboration between scientists represented some temperance to the Cold War. This attitude climaxed in the mid-1970’s with the Apollo-Soyuz missions, which eventually developed into Russia - U.S. collaboration on both the Mir and International Space Stations.[43] In astronomy and planetary science, the U.S. has traditionally been more aligned with Europe. ESA and NASA have similar research agendas and scientific spacecraft, and many Solar System probes are funded, built, and operated collaboratively; this collaboration is on the rise:

> NASA is currently expanding partnerships with ESA in planetary science, since both agencies’ science objectives require flagship-class missions that neither can afford to implement on its own.[44]

NASA enthusiastically carries out collaborative efforts with other nations as well:

> In Planetary Science, NASA partners with established and emerging spacefaring nations to send spacecraft to asteroids, comets, and other planets, and NASA-funded scientists commonly collaborate with foreign colleagues in mission-enabling research.[45]

With the actors introduced and the historical background synopsized, the drama of the space policy process can be presented. The process is cyclical and heavily interlinked,

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[43] Harland, *The Story of Space Station Mir*, 2005

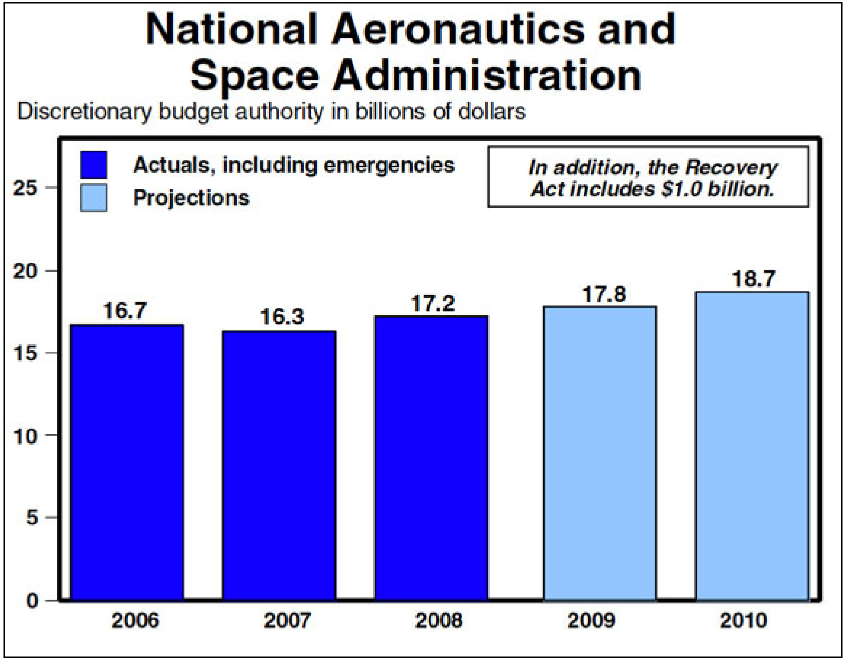
[44] (see Ref.22) NASA 2010 Science Plan, p.15.

[45] (see Ref.22) NASA 2010 Science Plan, p.8.

but a good place to begin an explanation is with the President's budget. This is generated each year by the White House's Office of Management and Budget (OMB), in collaboration with all the federal agencies, as a blueprint of the nation's annual spending. To aid the OMB and make its requests known, NASA submits a proposed budget for itself; the OMB can negotiate amounts and emphasis with the Administration before including it in the President's budget. This NASA request is itself the result of extensive effort and compromise among NASA's directorates, physical centers, and program offices.

Congress uses the President's budget proposal as a starting point for debates about what fiscal appropriations actually get written into law; this process is influenced by the executive agenda, lobbying groups (including the aerospace industry and the space science community), agency desires, and pork-barrel politics. In the end, NASA receives – typically as part of an omnibus appropriations bill – a roughly steady $17-18 billion in 2010 dollars, as shown in Figure 12. This is distributed among the mission directorates and comes attached with a few paragraphs of spending instructions and requirements for reports.[31]

Figure 12. NASA's overall budget in recent years[46]



The budget allotted to human exploration is volatile and, especially in recent years, contentious. But importantly for hoppers, the budget allotted to space science, is relatively stable and predictable. Figure 13 shows human and science expenditures through most of NASA's history, and Figure 14 demonstrates for recent years how the science budget stays relatively constant while expenditures on human-related

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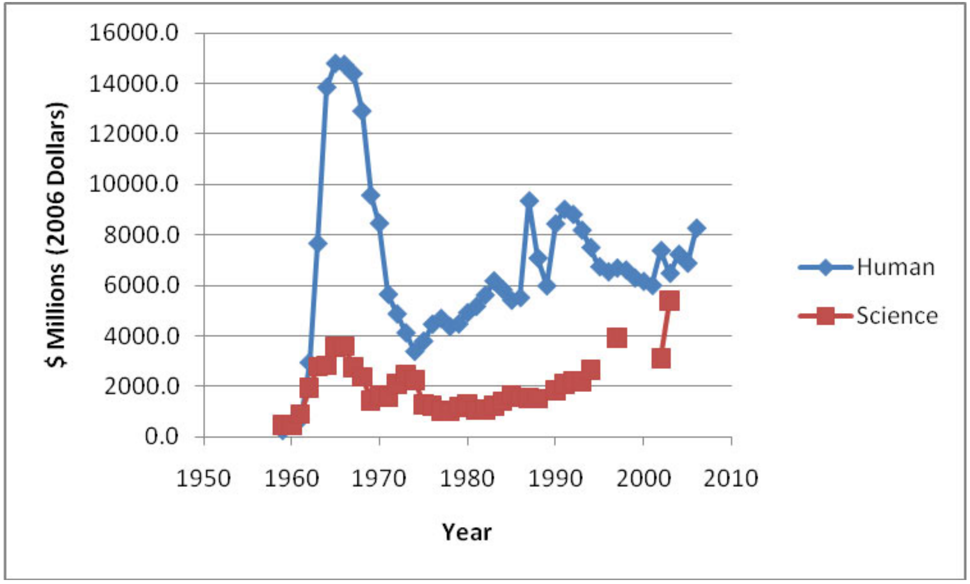
[46] OMB, *NASA 2010 Budget Highlights*

endeavors (all other layers of the chart) fluctuate. The dynamic nature of human spaceflight funding is further demonstrated by the host of historical reports (Rogers/Challenger Commission,[47] Ride Report,[48] Vest Report,[49] CAIB,[50] and Aldridge Commission,[51] by their informal names) and corresponding publicity. This media attention has in the last two years focused on the 2009 Augustine Commission,[52] the retirement of the space shuttle, and the debate about how NASA should rely on commercial contracts, international partners, and internal engineering for the next generation of space transportation.

Figure 13. Historical NASA expenditures on human and science programs. Data from NASA Historical Data Books and NASA Statistical Pocket Guide, compiled by Stephen B. Johnson for the MIT Space, Policy, and Society Research Group.[53]



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[47] Rogers/Challenger Report, *Report… on the Space Shuttle Challenger Accident*, 1986

[48] Ride Report, *Leadership and America's Future in Space*, 1987

[49] Vest Report, *Final Report to the President*, 1993

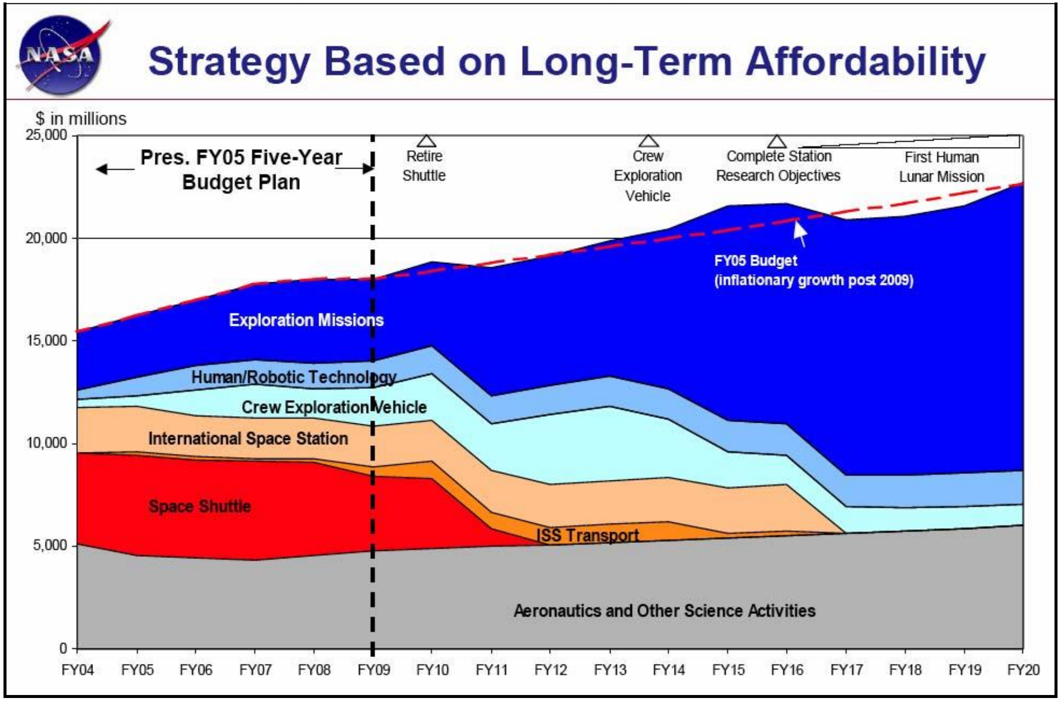
[50] CAIB, *Columbia Accident Investigation Board Report*, 2004

[51] Aldridge Commission, *A Journey to Inspire, Innovate, and Discover*, 2004

[52] (see Ref.42) Augustine Report, *Seeking a Human Spaceflight Program Worthy of a Great Nation*

[53] Johnson Email, 2008

Figure 14. Notional NASA budget projections[54]



This description of the important entities and dynamics of the space policy world lays the groundwork for an understanding of current space policy issues.

2.1.2 Important Issues in Planetary Exploration Policy

As further described in Section 2.2.2, science objective are traced back to profound mysteries of the Solar System, like the presence of life and water, how our planet and its habitable conditions came into being, and the evolution and fate of this and other star systems. These questions also impact exploration policy through popular appeal and the rhetoric of the political process. Concerns that rise to the national Congressional level can be written into laws like the Authorization and Appropriations bills mentioned in the previous section. Since NASA's formative years under Presidents Eisenhower and Kennedy, the executive administration has often had a strong space policy in place; in June of 2010 the White House issued a new National Space Policy.[55] These government-level documents often reference questions about the nature of the universe and practical reasons for the U.S. to pursue them; they can also embody concerns about the balance between civil and military space funding, or other national issues.

A range of other issues makes regular appearances in general space policy discussions, or have come into stable prominence during the last decade. One of these is hazards posed by space weather, orbital debris, and the possibility of impact from a Near-Earth Object (NEO) such as an asteroid.[56] Another is the production of plutonium-238,[57] a

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[54] NASA "Strategy Based on Long-term Affordability"

[55] National Space Policy, 2010

[56] (see Ref.34) NASA Authorization Act of 2010, Section 1202

radioactive byproduct of nuclear weapon production that serves as a very reliable long-term power supply for probes in deep space; both the U.S. and Russia have fast-dwindling supplies and have long ceased production.[58] A third issue is the difficulty in information exchange imposed by the International Traffic in Arms Regulations (ITAR), which became particularly burdensome for space science[59] in 1999 when all spacecraft were assigned to the controlled munitions list.[60]

An overlapping set of concerns and interests vie for attention specifically in the realm of human space exploration. Though this thesis does not seriously explore the possibilities of using hoppers in human missions, the potential is extensive for remote presence, astronaut assistance, and transport of people or other cargo; for this reason and for the sake of awareness, some prominent human spaceflight issues are listed in Table 5.

Table 5. Human spaceflight policy topics

Issues
Astronaut presence, remote presence, teleoperation
International cooperation and leadership
Vastly enhanced science yield humans on site
Commercial and economic interests
Biological and physiological research
Permanent settlement

Human spaceflight plans are in flux as of this writing, but the Obama administration's National Space Policy draws heavily on the Augustine Commission's "flexible path" to attaining exploration objectives that eventually build up to placing humans on Mars.[61] This is the first of three policy themes that, though still general in scope, have particular relevance to hoppers. Beyond human exploration, these themes can broadly be grouped into technology development in the national and international contexts, and public involvement.

Milestones along the flexible path might include Earth's Moon, Near Earth Objects like asteroids, Mars orbit, and the surface of Mars. Integral to this adaptive plan is the notion of "robotic precursors" to human presence. The NASA Lunar Precursor Robotics

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[57] (see Ref.34) NASA Authorization Act of 2010, Section 806
[58] Greenfieldboyce, "Plutonium Shortage Could Stall Space Exploration," 2009
[59] (see Ref.34) NASA Authorization Act of 2010, Finding 15
[60] Zelnio, *Determining the Effects of ITAR Regulation…*
[61] (see Ref.42) Augustine Report, *Seeking a Human Spaceflight Program Worthy of a Great Nation*, p.40

Program[62] has a dedicated line item in the 2010 NASA Authorization bill.[63] Hoppers could be a value-boosting component in a network of automated or remote-operated systems that demonstrate technical capabilities necessary for more complicated future with humans on-site. One such scenario using hoppers on the surface of Mars to complement a human crew in orbit was proposed by a team from MIT in 2010 and won the graduate category of the National Institute of Aerospace's Revolutionary Aerospace Systems Concepts Academic Linkage (RASC-AL) competition.[64]

A web of interrelated issues fits under the umbrella of technological leadership in the national and international contexts. Development of advanced technology is in itself a major goal of the government and NASA,[65] and this is often couched in terms of commercial or security advantage, or simply the ability to do more. Steadily advancing technology is also crucial to international leadership, where both equal collaboration and maintaining the prime position contribute to an agenda of policy influence, within exploration or other political domains.[66] The enabling factor in international technological leadership is industry[67] and workforce base,[68] including a growing high-profile commercial space sector.[69] These institutions in turn draw on the education system. This whole structure relies on space exploration to inspire and motivate students and professionals. Excerpts from *The Global Exploration Strategy*, NASA's *2010 Science Plan*, the Lyles report *America's Future in Space*, and President Obama's Florida speech announcing his new National Space Policy, respectively, illustrate this cluster of motivations:

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[62] NASA, "Exploration."

[63] (see Ref.34) NASA Authorization Act of 2010, Section 101.G

[64] Cunio et al., *Shared Human and Robotic Landing and Surface Exploration…*, 2010

[65] (see Ref.33) NASA Authorization Act of 2008, Section 402 (2) and (3)

[66] (see Ref.33) NASA Authorization Act of 2008, Finding 7

[67] (see Ref.55) National Space Policy, 2010, p.4

[68] (see Ref.34) NASA Authorization Act of 2010, Finding 6

[69] (see Ref.34) NASA Authorization Act of 2010, Finding 8

Table 6. Examples of exploration objectives within "technological leadership"

Source	*Objective*
Global Exploration Strategy: In the future, a sustained but affordable agenda of globally coordinated space exploration can serve society through:	– Securing new knowledge and solving global challenges in space and on Earth through innovative technology; – Permanently extending human presence into space, physically and culturally; – Enabling economic expansion and new business opportunities; – Creating global partnerships by sharing challenging and peaceful goal; and – Inspiring society through collective effort and personal endeavour[70]
NASA 2010 Science Plan: NASA science contributes directly and substantially to current national priorities:	– Leadership in fundamental research… – Educating the next generation and creating a world-class workforce – Driving technological innovation – Extending partnerships internationally and domestically[71]
Solar System Exploration, 2006: All six goals serve the national interest…:	– To reestablish leadership for the protection of Earth and its inhabitants through the use of space research and technology. – To sustain U.S. leadership in science by seeking knowledge of the universe and searching for life beyond Earth. – To expand the frontiers of human activities in space – To provide technological, economic, and societal benefits that contribute solutions to the nation's most pressing problems. – To inspire current and future generations. – To enhance U.S. global strategic leadership through leadership in civil space activities.[72]
Obama's speech:	What we're looking for is not just to continue on the same path – we want to leap into the future; we want major breakthroughs; a transformative agenda for NASA… Critical to deep space exploration will be the development of breakthrough propulsion systems and other advanced technologies. So I'm challenging NASA to break through these barriers.[73]

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[70] (see Ref.27) The Global Exploration Strategy, 2007, p. 7

[71] (see Ref.22) NASA 2010 Science Plan, p.7-8

[72] (see Ref.4040) Lyles Report, *America's Future in Space*, 2009, p.16-17

[73] Obama, *Remarks by the President on Space Exploration in the 21st Century*, 2010

Public engagement is part of the “technology development” objective theme, but deserves mention in its own right. The Hubble Space Telescope[74] and Mars Exploration Rovers[75] are two examples of substantial public engagement inspired through engaging new views of outer space. Hoppers might be more spectacular because they can visit many sites in a variety of conditions and move dramatically between them.

Beyond policy objectives that are expressed in current discussions, hoppers stand to offer advantages that have not been considered by the broad space policy community. Related to public engagement is the possibility of remote presence. Advancing audiovisual and transmission technologies allow for increasingly immersive experiences by the public from personal computers; hoppers’ speed and potential for responsive navigation are particularly enabling. Similar capabilities could facilitate enhanced remote operation, enabling a ground-based operator more access to the remote site. Related possibilities are being explored through the Google Lunar X Prize,[76] for which the Next Giant Leap Team is developing a hopper.[77]

Trends in increasingly complicated planetary exploration that stresses both high-resolution detail and big-picture context (whole planets, the whole Solar System) point toward using networks of diverse assets. Such networks already consist of rovers, impactors, orbiting communications relays, Earth-based antenna stations, and infrastructure and ground support all working together in tight coordination. Future exploration networks might employ surface habitats, remote observation or caching stations, and other forms of mobility including aircraft; hoppers could play a critical part in such networks.

Finally, and perhaps most importantly, is the fact that hoppers add affordable capability to the Solar System exploration portfolio. Exploration can get done much faster with the capability and flexibility to negotiate rough and vertical terrain responsively as a given mission progresses. Even the ability to sample at a handful of sites for any single landing could be game changing. In a simple scenario where ¼ of the surface area in a given region on a planet or moon contains interesting evidence, e.g. water ice, protobiological fossils, or a 4 billion-year-old rock, a lander placed in that region has a 25% chance of making the discovery and a hopper capable of 3 hops (visiting 4 sites) has a 68% chance of making the discovery.

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[74] Space Telescope Science Institute, “Hubble: Two Decades Unveiling the Universe”

[75] NASA, “Mars Exploration Rover Mission”

[76] X Prize Foundation, “About the Google Lunar X Prize”

[77] NEXT Giant Leap, “Mission: Capture the Google Lunar X Prize”

2.1.3 Policy Objectives Summary and Outlook

Table 7 summarizes the objectives discussed in this section and collects them for further analysis. It may be possible to derive a different valid set of objectives, but this one is both demonstrative and thorough.

Table 7. Space policy issues

Category	*Issue*
General space policy issues	Fundamental science questions, as described in Section 2.1.2
	Major space policy issues: hazards, Pu-238, ITAR
	Human exploration policy issues
Hopper-relevant policy issues	Relevance to "flexible path"
	Technology leadership, domestic and international
	Public engagement
Policy issues hoppers might address in the future	Remote presence/operation
	Exploration networks
	Simple added capability

Much of NASA's immediate future is currently in question. Arguments in Congress throughout 2010 have been a result of a seeming impasse between President Obama's progressive National Space Policy, which was foreshadowed by the Augustine Commission's report, and arguments that President Bush's Vision for Space Exploration was a good plan that should not be interrupted, all situated within the context of maintaining aerospace jobs, technology expertise, and infrastructure. Though this debate bears primarily on human exploration, the spillover for planetary science is significant. First, extensive planning and discussion was underway for international collaboration, particularly in Moon and Mars exploration; agreements and work have stalled. Second, NASA as a whole is in limbo, meaning that initiatives and program offices are awaiting guidance before committing resources to any given path.

The 112th U.S. Congress convened on January 3, 2011. The previous Congress, which was in session during the beginning of Democrat Obama's presidency, had a democratic majority in both the House of Representatives and the Senate and still produced the present stalemate for NASA; the present Congress has a Republican majority in the House of Representatives, and may pose more challenges to bilateral progress in space exploration policy. Still, some direction will eventually come from bills debated and passed in 2011 and 2012. Additional direction and funding stability will result from the current planetary science decadal survey, which is due to be released to the public in early 2011.

II.2. Science Objectives

2.2.1 Sources of Exploration Science Objectives

Section 2.1.1 gives a description of the space policy process. It demonstrates that, in prioritizing NASA expenditures on Solar System exploration, the most important and definitive formulation of goals takes place in the decadal surveys. This method of prioritizing objectives has for decades been generally acknowledged by both the science community and the U.S. government as effective and efficient.

For these reasons, the first reference in collecting exploration objectives pertaining to solid bodies in the Solar System is the current planetary science decadal survey, "New Frontiers in the Solar System," which was released in 2003.[78] A new survey is underway and is scheduled to appear in early 2011, with the intention of guiding planetary exploration for the decade of 2013-2020. This section can soon be updated with the actual report, but as of this writing, predictions are limited to the information made available by the Space Studies Board, which includes all the white papers submitted to the survey and a list of 28 missions from which the final report will select its top-ranked recommendations. These missions are discussed further in Section 3.4.3.[79]

Beyond the decadal survey, other authorities provide significant additional details and perspectives. Foremost among these authorities is NASA. Various organizations within the Administration, described in Section 2.1.1, organize objective-setting efforts and produce supporting documentation. Important among these documents are the *2006 Solar System Exploration Roadmap*[80] and the *2010 Science Plan*,[81] both of which reference the *2006 NASA Strategic Plan* (especially Sub-goal 3B),[82] despite its predication upon President G.W. Bush's now-outdated *Vision for Space Exploration*.[83] For planetary exploration, the *2010 Science Plan* largely defers to the 2003 decadal survey and explains that the 2011 decadal survey will finalize the next steps. The Analysis Groups NASA has organized around specific planets or groups also produce reports and conference proceedings. The MEPAG recently released a report documenting its consensus science priorities.[84] Additionally, NASA's Mars Exploration

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[78] NRC Space Studies Board, *New Frontiers in the Solar System*, 2003

[79] NRC Space Studies Board, *Missions Being Considered by the Planetary Science Decadal Survey*, 2009

[80] NASA, *Solar System Exploration*, 2006

[81] (see Ref.22) NASA 2010 Science Plan

[82] NASA, *2006 NASA Strategic Plan*

[83] (see Ref.25) Vision for Space Exploration, 2004

[84] MEPAG Goals Committee, *Mars Science Goals, Objectives, Investigations, and Priorities: 2010*

Steering Group keeps a living *Mars Design Reference Mission*, now in revision 5.0.[85] The LEAG maintains a similar *Lunar Exploration Roadmap*, which was last updated in 2009.[86]

Next, plans written by non-U.S. space administrations, or written under international collaboration, can have bearing on funding decisions and indicate where political and community pressure lies. ESA's Cosmic Vision plan for 2015-2025,[87] which follows on the Horizon 2000 initiative, helps define European cooperation with NASA. The International Lunar Network Statement of Intent similarly documents the commitments of a host of international partners to that specific mission.[88] The Global Exploration Strategy serves the same purpose for the full array of human and robot-supported Solar System exploration.[89]

Conference proceedings and publications by other professional and interest groups also come to bear. In 2007, the NASA Advisory Council hosted a Lunar Science Workshop that produced a report to advance lunar exploration.[90] NASA's Lunar Science Institute and the independent Lunar and Planetary Institute also produce both scientific, policy, and informational documentation. International groups like the Planetary and Meteoritical Societies produce documents like magazines for their membership and also submit white papers to the decadal surveys.

Finally, a body of reports by the National Research Council has a major influence on policy emphasis. The Aldridge and Lyles Reports have already been mentioned. Other examples from the Space Studies Board are *The Scientific Context for Exploration of the Moon* and *A Scientific Rationale for Mobility in Planetary Environments*.[91]

2.2.2 Fundamental Questions that Underpin Solar System Exploration

Decadal studies are grounded in the fundamental motivations that inspire exploration. The description of these motivations draws on other documents that, by various means, serve to coalesce and articulate the reasons our society uses to justify the expenditure of large sums on spacecraft. For instance, NASA's *2010 Science Plan* summarizes planetary exploration goals with "Ascertain the content, origin, and evolution of the solar system and the potential for life elsewhere."[92] A more elaborate collection of these "big questions" is presented in Table 8

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[85] NASA*, Human Exploration of Mars Design Reference Architecture 5.0*, 2009

[86] Lunar Exploration Roadmap

[87] European Space Agency, "Cosmic Vision 2015-2025"

[88] (see Ref.26) *International Lunar Network Statement of Intent*

[89] (see Ref.27) The Global Exploration Strategy, 2007

[90] NASA, *Lunar Science Workshop*

[91] NRC Space Studies Board, *A Scientific Rationale for Mobility in Planetary Environments*, 1999

[92] (see Ref.22) NASA 2010 Science Plan, p.11

Table 8.

For some background information on these sources, the ongoing planetary science decadal survey will have a list of fundamental questions that draws heavily from its predecessors. There will be traceable similarities with the “Why We Study Planets” chapter of NASA’s 1994 *Integrated Strategy for the Planetary Sciences*. The current decadal survey’s direct predecessor, still technically in effect, is the 2003 *New Frontiers in the Solar System*. NASA updated this plan in 2006 with a “roadmap” for its Science Mission Directorate, *Solar System Exploration, 2006*. The most current formalization of NASA’s science strategy is captured in the *2010 Science Plan*. Within the *Science Plan*, the section on planetary science grounds itself in a more focused list of questions.

Table 8. Fundamental questions for Solar System exploration

Source	*Question*
Integrated Strategy for the Planetary Sciences, 1994[93]	– Understand how physical and chemical processes determine the main characteristics of the planets, thereby illuminating the workings of Earth; – Learn how planetary systems originate and evolve; – Determine how life developed in the solar system and in what ways life modified planetary environments; and – Discover how the simple, basic laws of physics and chemistry can lead to the diverse phenomena observed in complex systems
New Frontiers in the Solar System, 2003: Objectives[94]	– Determine if environments capable of sustaining life exist or have ever existed beyond Earth, what parameters constrain its occurrence, how life developed in the solar system, whether life exists or may have existed beyond Earth, and in what ways life modifies planetary environments; – Understand how physical and chemical processes determine the main characteristics of solar system bodies and their environments, thereby illuminating the workings of Earth; – Learn how the Sun's retinue of planets and minor bodies originated and evolved; – Explore the terrestrial space environment to discover what potential hazards to Earth may exist; and – Discover how the simple, basic laws of physics and chemistry can lead to the diverse phenomena observed in complex systems.
New Frontiers in the Solar System, 2003: Crosscutting themes[95]	– The First Billion Years of Solar System History – Volatiles and Organics: the Stuff of Life – The Origin and Evolution of Habitable Worlds – Processes: How Planetary Systems Work

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[93] NRC Space Studies board, *An Integrated Strategy for the Planetary Sciences,* p.12

[94] (see Ref.78) NRC Space Studies Board, *New Frontiers in the Solar System*, 2003, p.156

[95] (see Ref.78) NRC Space Studies Board, *New Frontiers in the Solar System*, 2003, p.178

Source	*Question*
	…Table 8 continued
Solar System Exploration, 2006[96]	– How did the Sun's family of planets and minor bodies originate? – How did the Solar System evolve to its current diverse state? – What are the characteristics of the Solar System that led to the origin of life? – How did life begin and evolve on Earth and has it evolved elsewhere in the Solar System? – What are the hazards and resources in the Solar System environment that will affect the extension of human presence in space?
NASA Science Plan, 2010: Profound questions[97]	– How and why are Earth's climate and the environment changing? – How and why does the Sun vary and affect Earth and the rest of the solar system? – How do planets and life originate? – How does the universe work, and what are its origin and destiny? – Are we alone?
NASA Science Plan, 2010: Planetary Science[98]	– What is the inventory of solar system objects and what processes are active in and among them? – How did the Sun's family of planets, satellites, and minor bodies originate and evolve? – What are the characteristics of the solar system that lead to habitable environments? – How and where could life begin and evolve in the solar system? – What are the characteristics of small bodies and planetary environments that pose hazards or provide resources?

Recurring themes of human curiosity about the formation, function, and fate of life on our home world and in our star system are obvious. Profound curiosity about the universe's origin and existence of other intelligent life are not lacking. A more extensive exploration of the historical justifications for Solar System exploration might yield a

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[96] NASA, *Solar System Exploration*, 2006

[97] (see Ref.22) NASA 2010 Science Plan, p.4

[98] (see Ref.22) NASA 2010 Science Plan, p.50

spellbinding story, but these lists are sufficient to provide an idea for the foundational reasoning behind the more specific science goals presented next.

2.2.3 Solar System Destinations and Related Goals

Since current and foreseeable technology limits the deployment of hoppers to solid objects within the Solar System (with the possible exception of stops at non-solid entities like Lagrange points), the list of possible targets (given here in rough order of distance from the Sun) is manageable.

Generally, all accessible targets are interesting to scientists. However, certain destinations possess features that are of special interest. Additionally, the last few decades of Solar System exploration have yielded much information about where it should be most productive to look. Ranking these goals is difficult, and part of the task of the decadal surveys. This section highlights the most interesting aspects, and begins to indicate which targets are most attractive and conducive to investigation via hopper. The objectives presented are not an exhaustive list, but are demonstrative of the emphasis and interest of the community.

Mercury

Mercury is a dense, rocky planet with a cratered surface that pristinely records the impact history of the inner Solar System. But comparatively little is known about it, and it is not as intriguing or inviting as other destinations.[99] NASA's MESSENGER probe will become the first to orbit Mercury in 2011 and stands to reveal exciting new information,[100] but this innermost planet will not be considered for hoppers now.

Venus

Venus is interesting for many reasons. Its size, composition, distance from the Sun, core, tectonic and volcanic activity, and surface features make it in many ways the object most similar to Earth in the known universe. At the same time, its drastically different history of a runaway greenhouse effect may be its most valuable subject for study. But atmospheric density, pressure, and temperature at the surface are too high for a visit by the first generation of hoppers.[101] Table 9 shows some reasons that hoppers in particular might be attractive for Venus in the future, alongside the citing document. This table format is repeated for some of the other destinations in this list.

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[99] Williams, "Mercury Fact Sheet"

[100] NASA, "MESSENGER: Mission to Mercury"

[101] Williams, "Venus Fact Sheet"

Table 9. Example hopper-relevant science exploration goals for Venus

Source of Objective	*Venus Science Objectives*
Scientific Rationale for Mobility in Planetary Environments, 1999	gravity, topography, mineralogy: low-altitude flight over 100s of km; seismic stations, rock compositions, sample collection: touch-down aircraft, 10s of km
New Frontiers in the Solar System, 2003	In-situ Explorer: lander, balloon
Solar System Exploration, 2006	p.71 an air mobility platform… with long traversing would be preferred over a surface rover
Scientific Context for Exploration of the Moon, 2007	
Opening New Frontiers in Space, 2008	understand properties of Venus' atmosphere down to surface… temporal measurements over several Earth days

Earth's Moon

Off the Earth, Luna is the easiest place to go simply because it is close; fuel and communications requirements are lower than for all other destinations beyond Earth orbit. The Moon is also a vast source of unexplored information about the Earth and Solar System. Its composition and internal differentiation are similar to the Earth's. However, the lack of tectonics, magnetic field, and erosion mean that the geological and impact records are well preserved from the early days of the Solar System when the Earth and Moon's surfaces cooled.[102] Despite the quiet nature of the Moon's surface, there is a tenuous atmosphere of charged particles that interact with solar radiation and collect volatiles like water; permanently shadowed regions of the lunar poles retain these volatiles, which might someday be used for human consumption. Human outposts on the Moon have long been proposed for general exploration and lunar research, as well as for physiological research, resource extraction, and astronomy, particularly from the far where there is no radio noise from Earth. There is plentiful additional information about scientific interest in the Moon; some highlights are displayed in Table 10.

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[102] National Research Council, *The Scientific Context for Exploration of the Moon, 2007*, p.7

Table 10. Example hopper-relevant science exploration goals for Earth's Moon

Source of Objective	*Earth's Moon Science Objectives*
Scientific Rationale for Mobility in Planetary Environments, 1999	
New Frontiers in the Solar System, 2003	South Pole-Aitken Basin sample return
Solar System Exploration, 2006	
Scientific Context for Exploration of the Moon, 2007	strategic site selection - provide a thorough description of the geologic context; *in situ* compositional and structural analyses of craters and basin (via traverses); long-distance traversing, navigation, and access
Opening New Frontiers in Space, 2008	elucidate nature of moon's lower crust… characterize large lunar impact basin

Mars

Beyond its enduring place in the popular imagination, Mars has become more scientifically interesting as information has accumulated over the decades. In basic terms, Mars shares many important features with Earth like distinctive seasons, polar ice caps, erosion, and volcanism. Though surface conditions are not friendly to human life, the temperature, pressure, atmospheric composition, and presence of at least frozen water make Mars probably the easiest place other than Earth to live. These factors, combined with prevailing theories that Mars used to have a much thicker atmosphere and lots of liquid water, maintain suspicions that the planet formerly, and still might, harbor life of some kind. Some specific science objectives are listed in Table 11, but the intense focus on Mars by NASA missions, historically, presently, and in future plans, is the chief testament to persistent scientific interest.

Table 11. Example hopper-relevant science exploration goals for Mars

Source of Objective	*Mars Science Objectives*
Scientific Rationale for Mobility in Planetary Environments, 1999	spectroscopy at scales smaller than orbital; traverse over 10s of km over complex terrain
New Frontiers in the Solar System, 2003	long-lived network
Solar System Exploration, 2006	
Scientific Context for Exploration of the Moon, 2007	
Opening New Frontiers in Space, 2008	p.32: determine… the exchange of dust, water, CO_2, etc., between the atmosphere and surface

Asteroids and other small bodies

There are many categories of small objects that populate the vast interplanetary spaces of the Solar System. The familiar asteroid belt contains countless small ice, rock, and metal clumps, though about a third of its mass is contained in the asteroid Ceres. Other asteroid categories include, for example, Amors, Trojans, and Centaurs, which occupy specific types of orbits. Comets can also visit the inner solar system. There are many reasons to study these exhibits of Solar System history, composition, and dynamics, and spacecraft have made close observations of and physical contact with both comets and asteroids.[103] Some objectives for future observations are provided in Table 12.

Table 12. Example hopper-relevant science exploration goals for asteroids and others small bodies

Source of Objective	*Asteroid and Other Small Body Science Objectives*
Scientific Rationale for Mobility in Planetary Environments, 1999	m to 100s of m to 10s of km to measure variations in mineralogy and chemistry, or sample return, or deploy geophysical instruments
New Frontiers in the Solar System, 2003	Eros lander, rover, sample return
Solar System Exploration, 2006	
Scientific Context for Exploration of the Moon, 2007	
Opening New Frontiers in Space, 2008	p.42: Acquire samples with known geologic context

Outer planet moons

Jupiter, Saturn, Uranus, and Neptune hold dozens of sizeable objects in their gravitational grasp, many of which are prime targets for study. All four of Jupiter's main moons, called "Galilean" in honor of their discoverer Galileo Galilei, fall in this category. Io, with the smallest orbit around Jupiter, is intensely active with volcanism and in some ways resembles planetologists' notion of early Earth. Europa is covered in a geologically active layer of ice that likley conceals an ocean of liquid water heated by tidal forces; this moon will be a target of NASA's next flagship mission since it is one of the most likely places in the Solar Sytem to host life.[104] Ganymede is the largest moon in the Solar System and is postulated to have a fully differentiated interior including a subsurface liquid water ocean, a history of tectonic action, and its own strong magnetic field. Callisto, significantly further from Jupiter, is not exposed to the same tidal heating and surface radiation as the first three Galilean moons; it is the third largest moon in the Solar System and a likely candidate for an eventual human base.[105]

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[103] Wikipedia, "Solar System"

[104] NASA 2010 Science Plan, p.52

[105] Wikipedia, "Galilean Moons"

By far the largest and most intriguing moon around Saturn is Titan, the second largest moon in the Solar System and larger, though significantly less dense, than the planet Mercury. Enceladus is a much smaller moon that has been observed to vent gas, which is probably the source of one of Saturn's many rings. Iapetus, another small moon in the Saturn system, has very distinct light and dark sides and a huge unexplained ridge ringing part of its equator. Neptune's moon Triton is worth a final mention as one of only three confirmed volcanically active moons, and the seventh largest in the Solar System.[106] Table 13 enumerates some examples of formal outer moon exploration objectives.

Table 13. Example hopper-relevant science exploration goals for moons of outer planets

Source of Objective	*Outer Planet Moons Science Objectives*
Scientific Rationale for Mobility in Planetary Environments, 1999	Europa: geological, geochemical, geophysical measurements over 10s of km
New Frontiers in the Solar System, 2003	Ganymede orbiter, Europa lander
Solar System Exploration, 2006	Titan: p.70 Exploration of lower atmosphere winds, clouds, and precipitation and *in situ* measurements of ices and organic materials at the surface… would also be performed
Scientific Context for Exploration of the Moon, 2007	
Opening New Frontiers in Space, 2008	

Trans-Neptunian Objects

The term "trans-Neptunian object" covers a range of relatively unknown items that spend most of their time orbiting the Sun outside the orbit of Neptune. The classification covers whatever clumps of ice and rock may be undiscovered there, but more interestingly the dwarf planet Pluto and its satellites Charon, Nix, and Hydra; the more massive pair Eris and its satellite Dysomnia; and various comets and other objects that comprise the Kuiper Belt, the Scattered Disk, the Oort Cloud, and whatever other secrets the outer frontiers of the Solar System may hold.[107] Though they collectively stand to reveal valuable information about the nature and evolution of the Solar System and stellar systems in general, they are hard to access. They are also relatively small and dissimilar with Earth, so they are not considered in further detail.[108]

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[106] Wikipedia, "Moons of Saturn"

[107] Remo, "Classifying Solid Planetary Bodies," 2007

[108] Wikipedia, "Trans-Neptunian Object"

2.2.4 Science Objectives Summary

Venus and Mars are interesting because of accessibility, similarity to Earth, habitability, and potential for past or present life. Earth's moon is appealing for similarity to Earth (composition, history, differentiation/core), accessibility, pristine preservation of Solar System and Earth history, and habitability and resources. The outer planet moons are intriguing because of dynamism, similarity to Earth, and information about Solar System dynamics. Finally, there is increasingly strong interest in small Solar System objects, including asteroids, comets, and trans-Neptunian objects, because of well-preserved information about Solar System origins and evolution. Studies of these small bodies may provide insight on the origins of life or the general lines along which other star systems develop.

The research conducted for this thesis indicates that the best way to forecast future planetary science research emphasis is to have a basic understanding of the possible destinations and what makes them interesting, keep track of discoveries and publications, understand the political context of exploration funding including underlying exploration themes and agendas, follow the science community's dialogue – particularly through the decadal surveys, and maintain a picture of the basic state of technologies needed for exploration tasks. Space science enthusiasts are not shy about using their imagination to picture ways of conducting exploration far in the future. But noticing the near-term appeal of new developments like hopper technology requires persistent exposure.

Chapter III: Matching Vehicle Attributes to Exploration Objectives

This chapter begins by enumerating the relevant attributes of exploration vehicle types in the abstract, and proceeds to discuss hoppers in detail. Then a general list of attributes for destination worlds and missions is presented. The next section maps hopper attributes first to these characteristics of Solar System destinations and missions that hoppers can address, and then to exploration policy and science goals that were developed in the previous chapter. The attributes of other vehicle types are used for comparison with hoppers where possible.

III.1. Planetary Exploration Vehicles and Their Attributes

A variety of use-tested and proposed types of vehicles exist for exploring planetary bodies from their own neighborhood, as opposed to using Earth-based instruments. The purpose of this section is to mention these vehicle types briefly, solely to provide a basis of comparison to hoppers. These vehicle types are broad, general categories, and each one can incorporate extensive diversity. A more exhaustive comparison of all possibly relevant attributes of planetary exploration vehicle types should consider the next level of detail: individual system characteristics. All planetary exploration spacecraft have systems for power supply, communication with Earth, thermal management, on-board computation, and navigational control. Each also includes some means of reaching and, usually, stopping at the world of interest. Many of the vehicles employ an additional form of mobility once in the target's vicinity; these modes of mobility are the defining characteristic of categories like rovers and aircraft.

Fly-by

The most basic way to explore a planet close-up is to fly by it on the way to somewhere else. This method provides the least opportunity for observation because the vehicle passes by just once, usually at a great distance. Examples include Voyager 2, which flew by Jupiter, Saturn, Uranus, and Neptune on its present course into interstellar space,[109] and the Galileo probe when it made the first close pass of an asteroid on the way to its final orbit around Jupiter.[110]

Orbiters

A spacecraft dedicated to a destination can be placed in orbit around it, providing potentially global, long-term observations, as well as communications capability for other spacecraft in the vicinity. Two examples are the Lunar[111] and Mars[112] Reconnaissance Orbiters, which are presently gathering data from orbits about their respective namesakes.

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[109] NASA, *Voyager 2*

[110] Astrobiology Magazine, "Galileo Flyby: Extreme Explorers Hall of Fame"

[111] NASA *Lunar Reconnaissance Orbiter*, 2008

[112] NASA, Mars Reconnaissance Orbiter "Overview"

Impactors/Penetrators

The next step is to make contact with the object of interest. An impactor descends to the surface and is often destroyed on impact. Some designs, including penetrators, which burrow into the surface by piercing it at very high velocities, can continue to make measurements and provide data after impact. Regardless, the descent can provide valuable information through atmospheric sampling and close-range observation. The Soviet Luna 2 was the first spacecraft to impact another world in 1959,[113] and in 2010 LCROSS struck the moon again, this time kicking up a plume of debris that was analyzed for its chemical composition by other spacecraft.[114]

Landers

A craft designed to survive a controlled, "soft" landing is generally called a lander. Often brought to the object's vicinity by another spacecraft component that stays in orbit, a lander typically provides all the benefits of an impactor and adds the dimension of extended surface presence for sampling or other data collection. For instance, Viking 1 famously landed on Mars in 1976 and continued collecting and transmitting data until 1982.[115] The Huygens lander became the first human-made object on Titan after delivery by the Cassini spacecraft in 2005.[116]

Rovers

For surface mobility, the most common approach has been a wheeled rover. These can make observations over a potentially large area, but have thus far been limited by speed and range. Even at their maximum potential, wheeled rovers will be limited by terrain. Well-known examples of rovers are the three Apollo Lunar Rovers[117] and the two Mars Exploration Rovers, Spirit and Opportunity.[118]

Walkers

Walkers also provide surface mobility, and can negotiate more severe terrain than rolling vehicles. They are limited by speed, range, and mechanical complexity. No walkers have been deployed in space, but NASA is developing an Earth-based prototype called ATHLETE.[119]

Aircraft

Aircraft, which depend on an atmosphere to operate, provide a different class of mobility. This includes powered airplanes, gliders, and buoyant vessels like balloons and airships. These have abundant opportunity to sample the atmosphere and can cover

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[113] NASA, *Luna 2*.

[114] Braukus, "NASA Missions Uncover the Moon's Buried Treasures," 2010

[115] NASA "Viking: Trailblazer for All Mars Research," 2006

[116] European Space Agency, "Landing on Titan, Saturn's Mysterious Moon," 2005

[117] Williams, *The Apollo Lunar Roving Vehicle*, 2005

[118] NASA, *Mars Exploration Rover*

[119] NASA, "The ATHLETE Rover"

wide areas, potentially for long durations. They provide little or no direct contact with the surface, and are largely dependent on developing technology. The Soviet Vega 1 balloon on Venus provides one of only a few examples of aircraft that have been deployed in space.[120] A very different type of aircraft is the NASA-proposed Ares, which would utilize powered aerodynamic flight in the Mars atmosphere.[121]

Subsurface vehicles

This untested type of vehicle includes drillers, “thermal drills,” and submarines. They can provide access to subsurface features, including likely oceans, but pose significant technical challenges. One early proposal is for a probe to drill through Europa’s icy outer layer to the suspected liquid ocean below.[122]

Other possibilities

Novel concepts offer unique and intriguing exploration capabilities. Tiny devices may provide large arrays of small samples; ballistic-impact vehicles could provide tight seismological or thermal coupling with the surface; ball-shaped objects may provide very efficient mobility over large distances. There will always be new possibilities.

III.2. Hopper Attributes

The definition of hoppers used in this thesis is given in Section 1.3.1. They inherently offer certain capabilities, and can possess additional attributes depending on specific design. This section does not give an exhaustive description of all forms that a hopper might take, or all characteristics that a hopper might manifest, but it does offer a strong foundation for comparison with other vehicle types. For a more rigorous characterization of hoppers, efforts are underway at MIT to conduct an exhaustive analysis of hopper capabilities and quantify where and when they are desirable over other vehicle types. As background for this work, Michel’s thesis presents Table 14, which subjectively compares the versatility of vehicle types.

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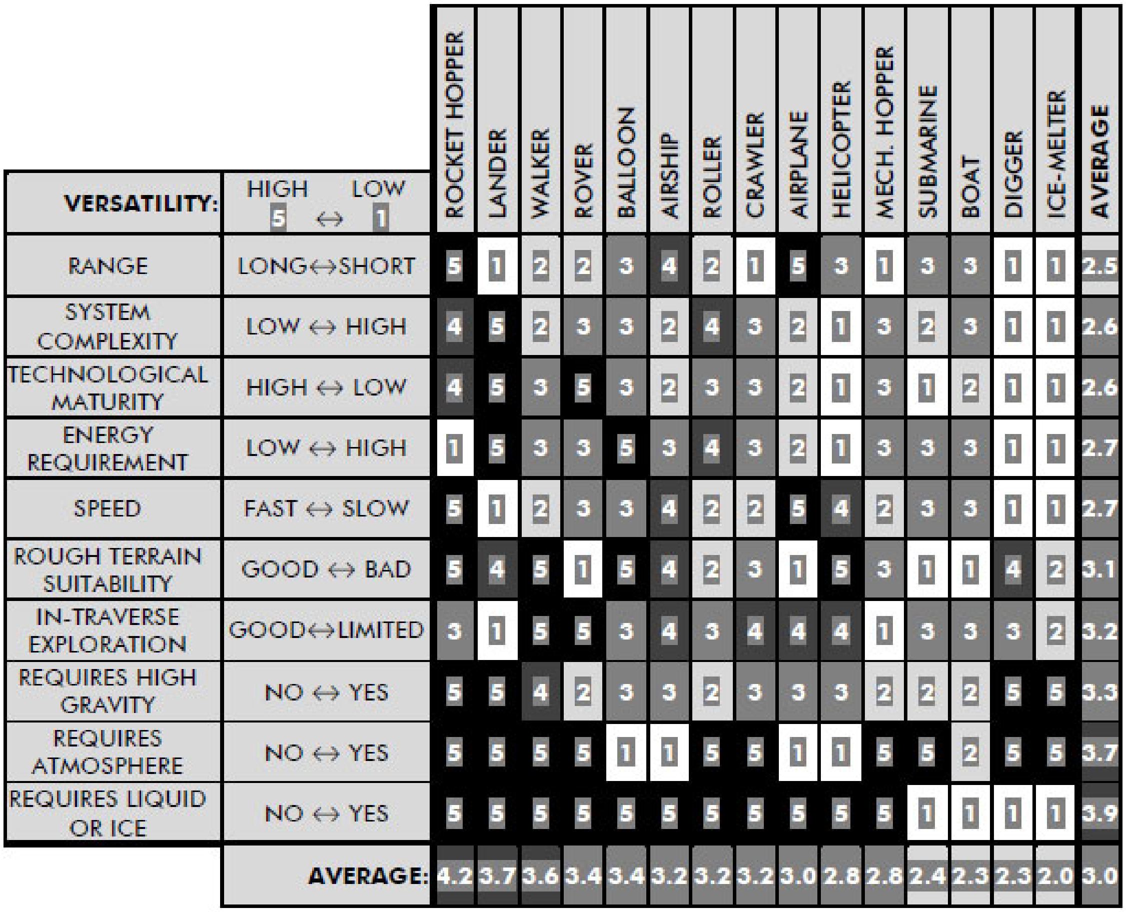
[120] NASA, *Vega 1 Balloon*

[121] Levine “ARES… A Proposed Mars Scout Mission”

[122] Hsu, “Dual Drill Designed for Europa’s Ice,” 2010

Table 14. Versatility of hoppers compared to other spacecraft, from Wendelin Michel's thesis[123]



VERSATILITY:	HIGH LOW 5 ↔ 1	ROCKET HOPPER	LANDER	WALKER	ROVER	BALLOON	AIRSHIP	ROLLER	CRAWLER	AIRPLANE	HELICOPTER	MECH. HOPPER	SUBMARINE	BOAT	DIGGER	ICE-MELTER	AVERAGE
RANGE	LONG↔SHORT	5	1	2	2	3	4	2	1	5	3	1	3	3	1	1	2.5
SYSTEM COMPLEXITY	LOW ↔ HIGH	4	5	2	3	3	2	4	3	2	1	3	2	3	1	1	2.6
TECHNOLOGICAL MATURITY	HIGH ↔ LOW	4	5	3	5	3	2	3	3	2	1	3	1	2	1	1	2.6
ENERGY REQUIREMENT	LOW ↔ HIGH	1	5	3	3	5	3	4	3	2	1	3	3	3	1	1	2.7
SPEED	FAST ↔ SLOW	5	1	2	3	3	4	2	2	5	4	2	3	3	1	1	2.7
ROUGH TERRAIN SUITABILITY	GOOD ↔ BAD	5	4	5	1	5	4	2	3	1	5	3	1	1	4	2	3.1
IN-TRAVERSE EXPLORATION	GOOD↔LIMITED	3	1	5	5	3	4	3	4	4	4	1	3	3	3	2	3.2
REQUIRES HIGH GRAVITY	NO ↔ YES	5	5	4	2	3	3	2	3	3	3	2	2	2	5	5	3.3
REQUIRES ATMOSPHERE	NO ↔ YES	5	5	5	5	1	1	5	5	1	1	5	5	2	5	5	3.7
REQUIRES LIQUID OR ICE	NO ↔ YES	5	5	5	5	5	5	5	5	5	5	5	1	1	1	1	3.9
	AVERAGE:	4.2	3.7	3.6	3.4	3.4	3.2	3.2	3.2	3.0	2.8	2.8	2.4	2.3	2.3	2.0	3.0

The relative versatility scores of 1-5 are unsupported and contain some lack of generality; for instance, a hopper's range is heavily dependent on available fuel, and an unpowered balloon transported by atmospheric winds may cover a much greater distance despite its lower ranking in the "range" category. Similarly, the "requires atmosphere" category may be too simplistic since the presence of an atmosphere actually imposes a penalty on fast-moving airborne vehicles due to aerodynamic drag. Still, the table is both insightful and helpful for visualization. It suggests that rocket-propelled hoppers perform better than the average across vehicle types in all categories except "energy requirement," due to a heavy dependency on combustible fuel, and "in-traverse exploration," since ground-based and slower vehicles have more opportunity for higher-resolution observation. Most significantly, hoppers score as the most versatile vehicle overall.

A general list of relevant and distinctive hopper attributes is presented in Table 15.

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[123] (see Ref.14) Michel, "Use and Sizing of Rocket Hoppers for Planetary Surface Exploration," 2010, p.13

Table 15. Hopper attributes

Advantages described in forthcoming MIT paper[124]
Rapid terrain coverage
Access to sites in rough or steep terrain
Ultraprecision landings
Potentially reduced system development cost (due to commonality with landers)
Shifted operational complexity (due to lack of need to reconfigure upon initial landing)
Other Advantages
Generally precise navigation
Mid-hop or inter-hop course changes
Low-altitude ground coverage and fixed hover
Temporary presence in unfavorable conditions
Repeated samples of atmosphere AND surface
Disadvantages
Unproven concept
More costly than static landers and possibly some mobile vehicles
Major dependence on heavy, expendable fuel
Every hop increases opportunities for problems
Launch or landing can cause disturbance or contamination of site
Mission duration

With these attributes established, further qualitative comparison with other vehicle types is possible. Table 16 shows how, for each of the performance attributes listed above, a typical notional hopper compares to the other vehicle types described in Section III.1. This display focuses on hoppers, ignoring special traits specific to other

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[124] Cunio et al., "Options in the Solar System for Planetary Surface Exploration via Hopping," forthcoming

vehicle types, like the ability of orbiters to observe a planet's entire surface. The table is also not amenable to making summary conclusions about hoppers; its purpose is to compare hoppers with alternative options one attribute at a time.

Table 16. Comparison of notional typical hopper to other vehicle types. + indicates a hopper would perform better; ++ indicates much better; - indicates worse; -- indicates much worse; 0 indicates roughly the same performance

Advantages	*Fly-by*	*Orbiter*	*Impactor*	*Lander*	*Rover, etc.*	*Aircraft*	*Subsurface*	*Notes*
Rapid terrain coverage	--	--			++	+	++	Some types of aircraft, like balloons, would be much slower
Rough and steep terrain					++	+		Aircraft are similar, but likely require more landing space
Precision navigation	++	++	++	++	-	+		
Navigational flexibility	++	++	++	++	0	0		Rovers are slower and aircraft may be hard to control
Low-altitude observation and hover	++	++				+		Hovering applies to ability to move over ground at any speed
Repeated access to surface and atmosphere	++	++	++	++	++	+	++	Hoppers require fuel to fly, but aircraft require flat space to land
Disadvantages								
Unproven concept	--	--	-	-	-	0	+	Hoppers still have an advantage from being similar to landers
Complexity and cost	--	--	-	-	+	++	++	Use of a hopper likely implies orbiter and lander on same mission
Dependence on fuel	--	--	--	--	-	-		Aircraft types have a wide range of fuel dependency
More hops increase risk	--	--	--	--	-	-		
Site disturbance or contamination	--	--	+	0	-	-	-	

In their basic conceptual forms, hoppers are both more capable and more complicated and costly than landers. For a given mission where both vehicle types are viable, some trade study must be conducted to determine which is most advantageous. Michel's thesis offers an analytic methodology for such a comparison.[125] For rovers and other ground-based vehicles such as those employing legs or tank-style tracks, the comparison is more straightforward. Hoppers are well-suited to precision navigation, but rovers and

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[125] (see Ref.14) Michel, "Use and Sizing of Rocket Hoppers for Planetary Surface Exploration," 2010, p.56

other ground-based vehicles like walkers are generally more stable and can be more precise. Hoppers fundamentally offer more range and speed. Hoppers are also likely to be simpler and cheaper than ground-based vehicles since they employ the same basic functionality as landers whereas rovers, walkers, etc., which likely employ a lander to reach their destination surface, rely on additional complicated systems like drive trains. Designs for hoppers that are more complicated and costly than ground-based systems are possible, but the basic nature of each vehicle type indicates that, in general terms, hoppers are a more dynamically capable option than ground-based vehicles.

Some further observations should be considered. One disadvantage of rocket hoppers is their heavy dependence on expendable fuel. One way to ameliorate this drawback is to generate or retrieve fuel from the hopper's surroundings. "*In situ* Resource Utilization" for hoppers is described generally by Powell et al.,[126] and for Mars in particular by Landis and Linne.[127]

It is worth pointing out, separately from other advantages, that hoppers use the same core technology as landers. Features may be added, such as a more capable guidance and control system, a lower-thrust engine, or drop-away fuel tanks, but in essence a lander only has to take off and re-land after its initial touch-down to become a hopper. For the extra capability, the development cost should be low. For the same reason, some development and operational risks will be lower for hoppers than for other vehicles.

Another implied advantage of hoppers is the ability to dwell temporarily in unfavorable conditions. A slower solar-powered vehicle may not have battery capacity to penetrate deep into a shadow. A similar scenario could exist for thermal or radiative stress. A hopper may also be able to reach deeper into areas with poor communication coverage.

The hopper concept is inherently versatile in both the destinations and objectives it can achieve. A core hopper spacecraft could be fitted with modular, mission-specific add-on features, suiting the same central design to targets as diverse as the Moon versus Mars, a global versus regional network, or a specific versus open-ended Solar System exploration architecture. Though not different from other vehicle types in this regard, the hopper is a categorically new class of platform, able to pass over any terrain with speed and precision.

III.3. Destination and Mission Attributes

First, the exploration objectives researched and analyzed in this thesis were generally formulated without consideration of hoppers and their capabilities. As this new concept gains momentum both in theoretical and empirical settings, expectations for planetary exploration spacecraft will change. Though the open, community-based approach to

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[126] Powell et al., *The MITEE Hopper*, 1998

[127] Landis and Linne, "Mars Rocket Vehicle Using In Situ Propellants," 2001

establishing and developing exploration objectives is proficient at both focusing on goals rather than means, and incorporating novel ideas, the mindset is dominated by the expectation that there are orbiters, landers, rovers, and other more expensive options. As the planetary science and space engineering communities become more familiar with the advantages and peculiarities of the hopper concept, some effect on the formulation of Solar System exploration objectives is likely.

To demonstrate where and when hoppers are most advantageous, the pertinent attributes of both hoppers and other varieties of planetary exploration vehicle should be compared to vehicle needs arising from exploration objectives. Once a set of exploration objectives is formulated and, potentially, clustered into a mission concept, many factors influence the choice of the best type of vehicle for attaining those objectives. Some factors derive from the character of the world being explored, and some from the nature of the observations to be made. The forthcoming MIT paper mentioned in the previous section lists the three most important planetary body characteristics when considering use of a hopper; they are reproduced in Table 17.

Table 17. Destination attributes

Attribute
Gravity
Atmospheric density
Surface roughness

A list of salient mission attributes is given in Table 18. To elaborate on them, high surface gravity means more fuel will be used to counteract it. High atmospheric density means more fuel will be used to counteract aerodynamic drag. High surface roughness, on the other hand, means that hoppers are likely to be more favorable than other vehicles. Hopper performance is not worse for smoother surfaces, but stays similar as roughness increases while other vehicles’ performance declines.

Table 18. Mission attributes

Attribute
Spatial distribution of potential sites
Dependency of hop landing site selection on in-situ observation
Number of sites
Ability to sample various altitudes for various durations
Nature and difficulty of interface with target site (sampling, docking, etc.)
Mission duration

An additional consideration might be surface stability; loose rubble could affect the suitability of potential landing slopes, or a small asteroid may not have enough cohesion to support a hopper's landing. Other factors derive not just from the mission's goals or the destination, but both in combination, as in Table 19.

Table 19. Attributes of destination-mission combinations

Attribute
Potential for harmful environmental variability, e.g. corrosion, wind, dust
Vulnerability of site to disruption and contamination, e.g. exhaust, dust, vibration
Ease of communication with Earth
Radiation exposure
Access to solar power
Suitability for astronomical observations

There may be other characteristics of a destination or mission that pertain to selection of exploration vehicle, and these descriptions do not purport to be exhaustive or rigorous. They do provide a summary view of the relevant issues and enable the following analysis and comparison of vehicle capabilities.

III.4. Vehicle Attributes Mapped to Exploration Objectives

3.4.1 Mapping Hoppers to Destination and Mission Attributes

Before hopper attributes are mapped to the policy and science objectives that determine how and how much Solar System exploration is conducted, the same set of attributes can be mapped to a more general set of destination and mission characteristics. Of those attributes that are described in the previous section, those related to the character of the mission are most conducive to mapping. This correlation is presented in

Table 20, which is followed by an explanation of each meaningful intersection in the table.

Table 20. Mapping hopper attributes to mission/destination attributes

	Rapid terrain coverage	*Rough and steep terrain*	*Precision navigation*	*Navigational flexibility*	*Low-altitude observation and hover*	*Repeated access to surface and atmosphere*
Distribution of potential sites	1		2		3	
Dependency of site selection on in-situ observation			4	5	6	
Number of sites	7		8		9	
Ability to sample various altitudes						10
Nature/difficulty of target interface		11	12	13		

1. For distant sites, hoppers cut down on mission time, enabling more activity for the same resources.
2. For distant sites, hoppers can reach the target with greater precision than blind vehicles. For nearby sites, hoppers can fine tune their location with great precision.
3. The farther apart the sites, the more opportunity a hopper has for near-ground observations during transit.
4. Hoppers can be selective in picking very specific sites, such as a small pit or a cliff edge. It can also make observations of a potential site from multiple vantage points.
5. Hoppers can redirect their course mid-hop or between hops.
6. Hoppers can provide observations with higher resolution and longer duration than an orbiter or some types of aircraft, and over a wider and longer swath than a typical rover.
7. For many sites, similarly to (1), hoppers cut down on mission time, enabling more activity for the same resources.
8. For a chain of many hops, hoppers do not build up error as they progress.
9. The more sites there are, similarly to (3), the more opportunity a hopper has for near-ground observations during transit.
10. Hoppers are more versatile in sampling both the surface and atmosphere than other vehicle types.
11. Hoppers can position themselves in many types of terrain.
12. Hoppers can position themselves precisely relative to a target.
13. Hoppers can retry positioning themselves or redesignate targets.

Without quantifying hopper ability to enable exploration of these site characteristics, these observations illustrate in detail why hoppers offer so much new potential to the planetary exploration toolkit. Other vehicle types could be mapped in a similar way, with completely different results, and some would appear impressive. However, this set of hopper capabilities is distinctive and enables a novel set of exploration tasks.

3.4.2 Mapping Hoppers to Policy Objectives

Major policy issues were described in Section 2.1.2, with current topics relevant to hoppers given in the middle of Table 7. Table 21 shows how hoppers can address those issues, in comparison to other vehicle types. Each line of the table should be read as an independent comparison of hoppers to other vehicle types for applicability to that issue. Because the issues were selected for amenability to the use of hoppers, this comparison does not summarily show that hoppers are superior to the other vehicles. However, the table does demonstrate that hoppers can be very attractive when aiming to address national-scale space policy concerns.

Table 21. Comparison of notional typical hopper to other vehicle types in fulfilling exploration policy objectives. + indicates a hopper would perform better; ++ indicates much better; - indicates worse; -- indicates much worse; 0 indicates roughly the same performance

Policy Objectives	*Fly-by*	*Orbiter*	*Impactor*	*Lander*	*Rover, etc.*	*Aircraft*	*Subsurface*	*Notes*
Flexible path	+	+	+	+	0	+		Hoppers cover a broad range of surfaces of interest for astronauts
Technological leadership, domestic and international	++	++	++	++	+	+		Tech., intl., industry/workforce, commercial, education
Public engagement	++	++	++	++	+	0	++	Hoppers can visit a variety of sites and move dramatically between
Remote presence/operation	++	++	++	++	0	0	0	

3.4.3 Mapping Hoppers to Science Objectives

Mapping vehicle attributes, even for hoppers, to a list of all important science objectives for the Solar System is beyond the scope of the present effort. There are too many objectives. Section 2.2.3 provides a representative set of examples and references the important sources. To demonstrate how hoppers map to this nebula of objectives, this section relies on the decadal survey process. The planetary decadal that will be released in early 2011 has released a list of 28 missions that serve to summarize the breadth of the missions most likely to be executed in coming years.

Table 22 shows which of these missions might be improved by incorporating a hopper and thereby serves to illustrate hoppers' appeal and versatility.

Most of the decadal mission study documents have a traceability matrix showing a list of basic goals, measurements proposed to meet those goals, and instruments proposed to take those measurements. This list of goals and measurements, in conjunction with the existing mission concept, can determine whether a hopper might be worth further investigation. Consideration is given to missions that have a corresponding study document available from the decadal survey's website, and that already have some plan for soft contact with the object's surface. Because with unlimited resources a hopper would add benefit to almost any mission, the table only indicates where a hopper would be likely to augment exploration capability for similar complexity and cost.

Table 22. Potential benefit of hoppers to missions being considered by 2011 decadal survey. Note that most missions with landed components retain a communications relay in orbit. * indicates a similar mission is discussed in Chapter IV

	Current Proposed Mobility Type	*Does hopper value merit further analysis?*	*Reasoning*
Mercury Lander	lander	no	Only lander necessary
Venus Mobile Explorer	aircraft	no	Only aircraft necessary
Venus Tessera Lander	lander	no	Only lander necessary
Venus Climate Mission	balloon with gondola, mini-probe, and drop sondes	no	Hoppers provide insufficient global coverage
Lunar Network	landers	no*	Hop distances yield excessive mass
Lunar Polar Volatiles Mission	rover	yes*	
Mars Trace Gas Orbiter	orbiter		Orbiter only
Mars 2018 Skycrane Capabilities	rovers	yes	
Mars Network	lander	no	Hop distances yield excessive mass
Mars Polar Mission	lander	yes	
Mars Astrobiology Explorer-Cacher	2 rovers	yes	
Mars Ascent Vehicle	Insufficient information		
Mars Sample Return Orbiter	orbiter	no	Orbiter only
Asteroid Sample Return	lander	no	Only lander necessary
Comet Surface Sample Return	Insufficient information		
Europa Jupiter System Mission	orbiter, impactor	no	Orbiters and impactors only
Io Observer	orbiter	no	Orbiter only
Ganymede Observer	orbiter	no	Orbiter only

	Current Proposed Mobility Type	*Does hopper value merit further analysis?*	*Reasoning*
		…Table 22 continued	
Trojan Tour	fly-by	no	Fly-by only
Saturn Probe Mission		Insufficient information	
Titan Lake Lander	lander	no	Focus on lakes
Titan Saturn System Mission	lander, aircraft	yes*	
Enceladus Flyby/Sample Return	orbiter, impactor, or lander	no	Orbiter and impactor/lander only
Chiron Orbiter	orbiter	no	Orbiter only
Uranus System Mission		Insufficient information	
Neptune/Triton Mission	fly-by or orbiter	no	No contact with Triton

Hoppers appear to offer an advantage for five of the proposed missions. Of the 28, four have insufficient information for this comparison, and another eight are scoped for no soft contact with the target's surface, leaving 15 viable possibilities. Of them, another four missions can be achieved with a stationary lander; hoppers may require little additional expense and would likely offer more performance, but the trade-off would require more research. A deeper analysis might show that hoppers are worthwhile for more of the missions' given science goals from an objective viewpoint, but this shallow evaluation relies on the proposed baseline concepts for the mission scope and implementation scheme. As such, hoppers are shown to be advantageous, not in all circumstances, but for a substantial variety of exploration science goals.

III.5. Chapter Summary

The chapter opens with a brief description of the classes of vehicles that can be used for Solar System exploration. A more detailed description of hopper attributes follows, and the other vehicle types are compared to each relevant hopper attribute. Hoppers are shown to offer rapid terrain coverage, ability to handle rough, precision navigation, navigational flexibility, and other advantages and disadvantages. Next, pertinent general, hopper-related characteristics of planetary destinations and missions are presented, and hopper performance advantages with respect to those characteristics described. The following sections refer to the previous chapters to show how hopper attributes help address major space policy issues first, and then planetary science objectives. The policy mapping offers a cursory comparison with other vehicle types. The science mapping uses missions that are highly ranked by the current planetary science decadal survey to illustrate how versatile hoppers can be for high-priority exploration goals. In total, the contents of this chapter are not meant to be exhaustive, but thoroughly show where and how hoppers are a helpful new exploration tool in relation to other vehicle classes.

Still, the intersection of Solar System destinations, science questions, mobility techniques, and policy-level interests is not easy to model. Possible destinations are fairly few (planets, their moons, and a variety of small objects), but very diverse in their demands and their potential for scientific discovery. Destinations, mission attributes, and the characteristics of hoppers that make them attractive are not amenable to general, theoretical analysis, at least at the level of this thesis, because any actual space mission is a complicated and delicate balance of capabilities and compromises. For these reasons, the best way to demonstrate how hoppers can be useful is with some examples, as in the next chapter.

Chapter IV: Model Missions

IV.1. Introduction

The selection of model missions was a balance between portraying hoppers in the most general conditions where they could operate, and showcasing both the capabilities and versatility of the hopper concept. It was also important to keep the missions grounded in current, high-profile exploration objectives for the sake of comparison – in this document and by future readers in their work – to existing, well developed proposals. The locations and mission profiles ultimately selected represent close to the widest variety of conditions where a hopper as currently conceived could operate; analysis showed that some missions were poorly suited to hoppers, while others demonstrated significantly better capability or performance for a hopper over conventional approaches.

Earth's Moon is a straightforward place to begin. It is the most easily accessible extraterrestrial body, and the subject of intense scientific observation and research. With relation to hoppers, the Moon has medium gravity and virtually no atmosphere, making it easy to fly. Four missions on the Moon lend themselves to analysis, with the most detailed examining a journey across the South Pole-Aitken Basin ending in a return of samples to Earth.

Mars, arguably the most Earth-like and popular destination in the Solar System, is another compelling choice. There is a wide variety of landscapes and weather, significant gravity, and a thin but non-negligible atmosphere. With many exploration objectives proposed for Mars, three low-detail hopper missions provide a survey of tasks a hopper might be expected to facilitate.

Saturn's moon Titan provides an intriguing destination in the Outer Solar System. Titan has a unique combination of moderate gravity similar to Earth's Moon, a cold atmosphere more dense than Earth's, and stable bodies of liquid pooled on the surface. For these and other reasons, Titan is both a highly prioritized exploration target and an extreme case for modeling hopper capabilities.

Asteroids, comets, and other small bodies of the system supply a very different form of potential mission, with a hopper landing on one, hopping around its surface, and potentially moving to another body, all for small fuel costs. Spacecraft dynamics in this environment are not well understood, and only brief mention is given to point out the possibilities for future hopper missions.

The methodology for these model mission analyses begins with a brief review of science exploration goals for the world in question. For some of the more detailed analyses, comparable missions using plans for conventional spacecraft are discussed to provide a baseline for comparison, as well as a reference set of payload specifications and spacecraft masses. Next, simple hopper models are generated and subjected to flight dynamics analysis as described in Sections 1.4.2 and 1.4.3. Finally, technical and programmatic results are discussed, with reference to baseline missions where appropriate.

IV.2. Earth's Moon

As Earth's closest sizeable neighbor and the target of an intense competition between cultural ideologies in the middle of last century, the Moon is a compelling – and relatively easily reached – target for exploration. Lunar science flourished during the 1950s and 1960s. Though no spacecraft were sent to the Moon's vicinity between Russia's Luna 24 in 1976 and Japan's Hiten probe in 1990,[128] analysis of lunar samples and meteorites continued alongside theoretical work incorporating knowledge about the Moon into Earth and Solar System formation models.[129] The U.S. sent the Clementine probe into lunar orbit in 1994 and Lunar Prospector in 1998. In the first decade of the 21st century, the E.U., Japan, China, India, and the U.S. all sent missions to the Moon.[130] Plans to return humans to the surface were discussed but remained unfunded.

The Space Shuttle Columbia was lost during reentry on February 1, 2003.[131] The tragedy precipitated a shift in direction for the U.S. human space program. NASA and the White House collaborated to formulate a new direction, which was embodied in the G.W. Bush administration's *Vision for Space Exploration* (VSE), released in February 2004.[132] This document prioritized returning astronauts to the Moon in the 2010s and precipitated the Exploration Systems Architecture Study (ESAS). This intensive summertime effort by NASA outlined an architecture of space vehicles that would enable VSE-inspired access to low Earth orbit, the Moon, and eventually Mars. Congressional support coalesced around the resulting Constellation program.[133] By the end of 2006, Constellation essentially consisted of four spacecraft: the Ares I rocket for sending humans to low Earth Orbit (LEO), the Ares V rocket for sending heavy loads to orbit and the Moon, the Orion capsule as a general purpose human transport, and the (later named) Altair lunar lander.[134]

Following the transition to Barack Obama's administration, the Constellation program was formally challenged by the Augustine Commission, who found that it lacked sufficient funding to meet its goals.[42] As of this writing, disputes among Obama's administration and key players in Congress leave the status of the U.S.'s present focus

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[128] Lunar and Planetary Institute, "Lunar Mission Summaries: Lunar Exploration Timeline"

[129] Todd, Ed., "Lunar Sample Laboratory Facility"

[130] NASA*,* "Lunar Exploration Timeline"

[131] (see Ref.50) CAIB, *Columbia Accident Investigation Board Report*, 2004, p.6

[132] NASA. *The Vision for Space Exploration*, 2004

[133] (see Ref.33) NASA Authorization Act of 2008, Finding 8

[134] Connolly, *Constellation Program Overview*, 2006

on Moon exploration indeterminate. However, even if humans are not directed there in the upcoming decades, U.S. space science decision makers, as well as the international space community at large, are eager for more access to and understanding of our cratered neighbor. The Lunar Reconnaissance Orbiter (LRO) was sent into lunar orbit in 2009 to conduct mapping and scouting for future missions; the same launch positioned the Lunar Crater Observation and Sensing Satellite (LCROSS), which ultimately confirmed water ice in a dark crater near the Moon's south pole.[135] The U.S. National Research Council's planetary science decadal survey is considering three Moon missions in its final round: the International Lunar Network, polar volatiles sampling, and a sample return mission to the South Pole-Aitken Basin.[136]

This section analyzes four potential Moon missions using hoppers. The first shows that using a single hopper to emplace an International Lunar Network is costly in terms of mass, but offers the advantage of a single vehicle and close-range observations over thousands of kilometers of moonscape. The second builds on Michel's master's thesis to postulate a realistic hopper mission in and around Shackleton Crater, whose rim is home to the lunar south pole. The third postulates a simple mission to explore the depths of recently discovered pits, which may provide access to ancient lava tubes or caverns. The most in-depth consideration is given to the final mission, which offers a hopper-enabled alternative to executing a South Pole-Aitken Basin sample return.

4.2.1 A Hopper to Emplace the International Lunar Network?

A network of science stations distributed across the Moon would address a handful of profound and highly prioritized questions about the Moon, the Earth-Moon system, the inner Solar System, and possibly the origins of life. However, the network nodes should be distributed broadly over the Moon's surface, and hover hops are not efficient for long distances. Even ballistic hops entail large changes in velocity which, for such distances, are comparable to that required to reach the Moon from Earth. For instance, an efficient ballistic hop of 3000 km on the Moon, a generous but fair distance between ILN nodes, requires just over 3000 m/s of ΔV. Because a typical trans-lunar injection from low Earth orbit also uses just over 3000 m/s of ΔV, it would almost certainly be cheaper to launch each ILN node from Earth orbit separately. But because using a single vehicle still offers strong advantages, this subsection analyzes a lunar network emplaced by a hopper.

Though progress in lunar exploration largely stalled in 2009 as the White House began to redirect NASA's human spaceflight program, the International Lunar Network (ILN) is a well-developed mission concept with strong backing from the lunar science community, both in the United States and abroad.[137] In the likely eventual situation that U.S. political interest in lunar exploration, via humans or robots, returns to a threshold level, a hopper could emplace the Network with a single vehicle while offering substantial additional scientific opportunities.

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[135] NASA, "LCROSS Overview"

[136] Shearer et al., *Lunar Polar Volatiles Explorer (LPVE) Mission Concept Study*

[137] (see Ref.26) *Statement of Intent Regarding The International Lunar Network*

The science objectives that motivate the ILN and its support are rooted in the “big questions” of the evolution of the solar system and the origin of life, as well as testing some fundamental physics. The core issues involve the development of differentiated bodies, the bombardment history of the inner Solar System, the history of the Earth-moon system, and details of the moon’s history and present state. Based on years of community-wide deliberation, the ILN Science Definition Team released in January 2009 its report specifying the first “anchor” node locations and the instruments to be placed there.[138] The Team recommended a six-year lifetime, which will be assumed throughout this section. The core instruments in order of decreasing priority are seismograph, interior thermal probe, atmospheric/electric field sensor, and, for Earth-facing nodes, retroreflector mirrors. Salient specifics of these instruments are included in Table 23.

Table 23. ILN node instruments[139]

	Mass (kg)	*Power (W)*	*Data (Mb/day)*	*Emplacement details*
Seismograph	6	2 (peak)	100	coupled to ground
Thermal sensor	1	3	0.05	**adds +2kg**, **+10Mb**
Atmosphere/electric field sensor	5	6	100	
Retroreflector	1	none	none	**adds +1kg**, directional
Summary	**16**	**11**	**210.05**	

A minimum of four nodes is recommended to address all the prioritized questions, with rapidly decreasing benefit returned from a network with fewer nodes. Mostly based on the location of a deep moonquake nest located by Apollo and Russian Luna missions, these sites are shown in Figure 15.[138] Nodes 1 and 2 are about 3000 km apart on the near side. Nodes 3 and 4 are on the far side of the Moon, and with node 1 form a rough equilateral triangle about 2000 km to a side. These far-side nodes also provide access to feldspathic highlands for magnetic observations.[140]

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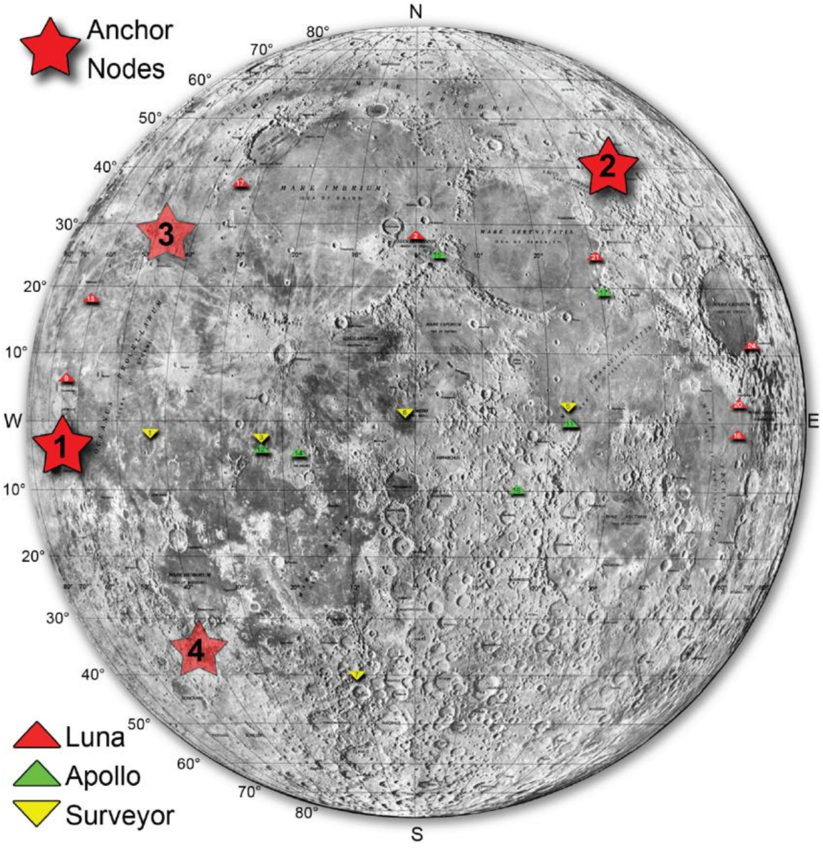
[138] NASA, *Final Report, Science Definition Team for the ILN Anchor Nodes*, Washington, D.C., 2009, p.28.

[139] International Lunar Network Core Instruments Working Group, *Final Report*, 2009.

[140] NASA, *Final Report, Science Definition Team for the ILN Anchor Nodes*, Washington, D.C., 2009, p.31.

Figure 15. ILN node locations.[141] Note that the Moon's near side is shown; nodes 3 and 4 are on the far side.



This information is sufficient for comparing two methods to achieve such a network: four individual landers, or a single hopper. This analysis makes a few common assumptions for both methods. For communications back to Earth, the nodes on the far side never have line of sight to the Earth and so will always be dependent on an orbiting relay. It is assumed that the near-side nodes have equal access to this relay, but all nodes are designed for communication directly to Earth since this is a more stringent criterion and would likely be handy or required for some nodes. For power, any location on the Moon except a few small features near the poles experience a diurnal cycle of about 29.5 Earth-days, implying roughly 15 days of darkness each cycle. For any architecture relying on solar power, this entails massive batteries. Since a moon orbiter is required for communications, beaming power via x-rays or lasers from the same orbiter has been studied.[142] The efficacy of this approach is uncertain and in any case dependent on undeveloped technology, so the present analysis falls back on radioisotope generator technology. These devices include radioactive plutonium-238, but provide a very viable power supply. Based on General Purpose Heat Source Radioisotope Thermoelectric Generator (GPHS-RTG) technology under study for

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[141] NASA, *Final Report, Science Definition Team for the ILN Anchor Nodes*, Washington, D.C., 2009, p.30.

[142] Borer et al., "Characterization… Lunar Surface Science Network using On-Orbit Beamed Power," 2010.

downsizing by NASA, a 4.4 kg model providing at least 21.9 W of electrical power[143] over a 6-year mission was employed for both scenarios in this section.[144] Finally, both the hopper and the individual landers begin in Low Lunar Orbits (LLO) that are matched to the that spacecraft's landing site so that descent involves no orbital maneuvers.

The first means for implementing the ILN is the baseline mission that would employ individual landers to emplace each node. Such a lander spacecraft, including the ILN science package, was parametrically designed using the Hoptimizer model and is summarized in Table 24.

Table 24. Mass of ILN node emplaced by dedicated lander

	Mass (kg)
Instruments	16
Power (RTG derivative)	4.4
Guidance	10
Engine	2.6
Tanking	9.6
Communication	3.7
Structure	15% of total dry mass = 8.1
Total	**54**

Starting with the instrument mass of 16 kg and the 4.4 kg power supply, another 10 kg was added for guidance, navigation, and control, with related computation, during descent. Power needs are met by the power unit during both surface operations and descent (before the instruments are active). Hoptimizer's communication model uses up to 10 W for communication and a 10 cm parabolic antenna, contributing 8.1 kg. A thrust-to-weight ratio of 1.5 at landing is used to compute an engine mass of 2.6 kg and a tank mass of 9.6 kg. Assuming that structure consumes 15% of the final dry mass, Hoptimizer gives 54 kg for the mass of an emplaced node.

This result bears comparison to actual moon landers. United States, Russian, and Indian missions involving impactors, rovers, sample return, or astronauts have understandably been much heavier. The U.S. Surveyor missions in the 1960s are the only stationary, soft

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[143] Abelson, Ed., et al., *Enabling Exploration with Small Radioisotope Power Systems*, 2004

[144] Wikipedia, "Plutonium-238"

lunar landings in history, and were all around 300 kg landed on the surface, which generally validates the 54 kg mass for a minimalist modern science payload.[145]

Each individual lander requires 55 kg of propellant to reach the surface from orbit. With four such spacecraft, this scenario results in a mass in LLO of 436 kg. An important further penalty arises from the choice between launching each 109 kg mission separately from Earth, or launching them on one Earth-departure rocket and placing them in different lunar orbits, either by separate injection burns or non-trivial maneuvers in the Moon's vicinity.

The alternative scenario uses a single hopper spacecraft to descend from orbit and hop from node-site to node-site, leaving an instrument package at each. First, each instrument package must be massed both for its instruments and its supporting structure, power source, and communications equipment; the results are in Table 25.

Table 25. Mass of ILN node emplaced by single hopper

	Mass (kg)
Instruments	16
Power (RTG derivative)	4.4
Communication	3.7
Structure	15% of total dry mass = 4.2
Total	**28**

Now Middleton's ballistic hop model can be employed to design a hopper with three drop payloads of 28 kg and an identical payload remaining on-board for the fourth location. A supplementary science payload of 10 kg is added for unprecedented close-range observations during the long-distance hops. In addition, there is another 10 kg for guidance, navigation, and control, with related computation, as in the multiple-lander scenario. Similarly, power during descent from LLO can be supplied by the payload. This gives a hopper base mass, without fuel or the three stations to be dropped, of 58 kg.

The ballistic trajectory between nodes 1 and 2 (or 2 and 1 in the order they are visited), covering 3000 km, is shown in Figure 16. This hop, launched at 30° from the initial landing site, requires 380 s of thrust at 4608 N, as described in Table 26.

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[145] NASA, "Spacecraft Query"

Figure 16. Trajectory for first hop of ILN mission: 3000 km along surface

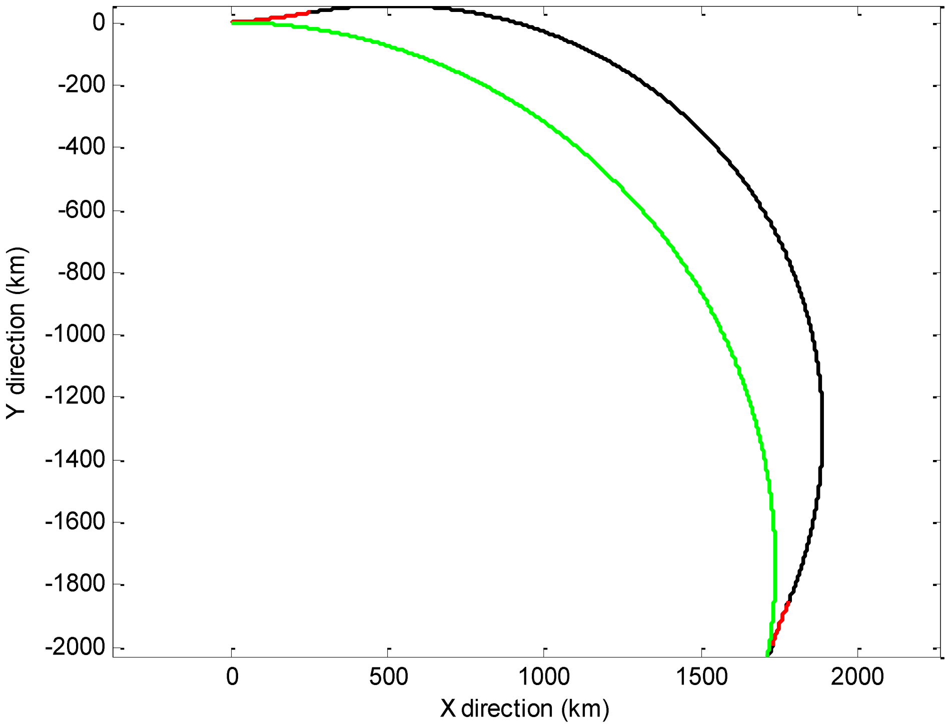


Figure 17. Trajectory for second and third hops of ILN mission: 2000 km along surface

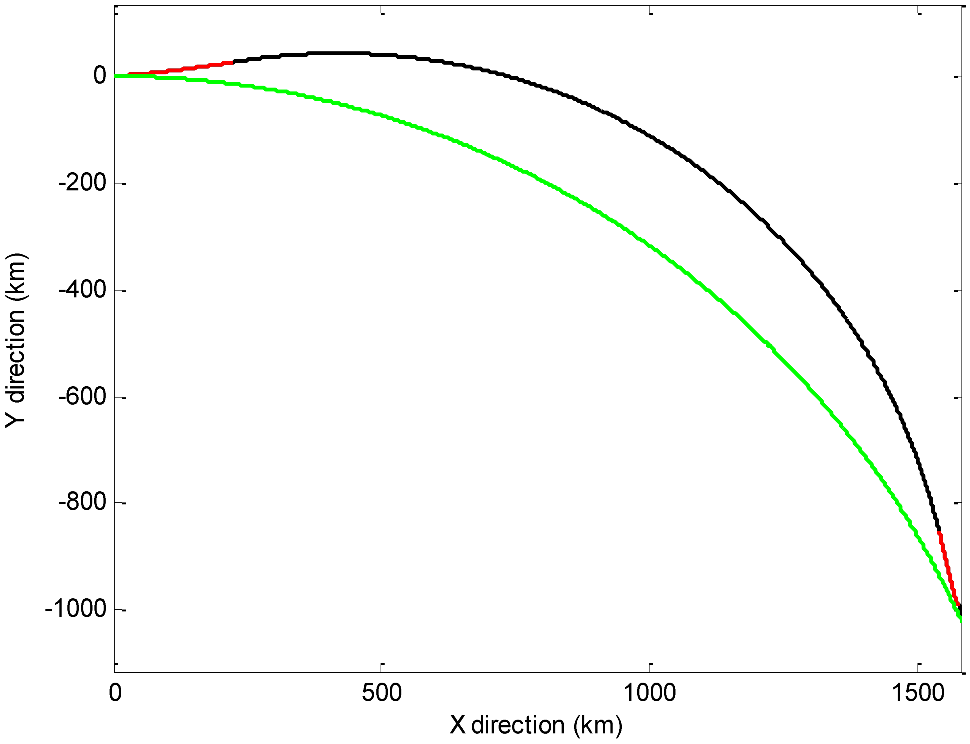
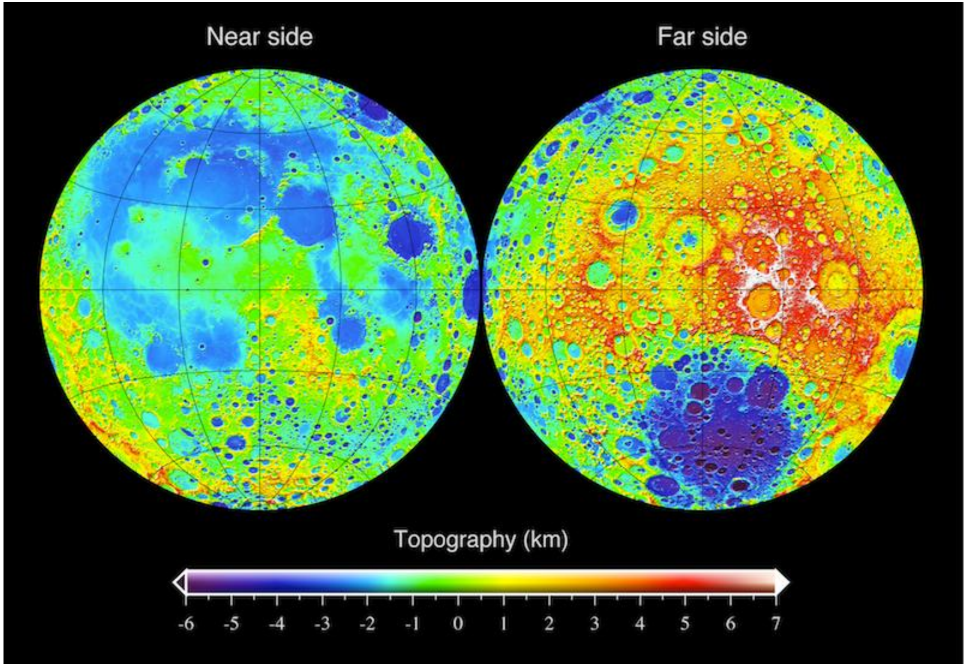


Table 26. BallisticHop inputs and outputs for first ILN hop

	Input Values
Launch angle, ϕ (degrees)	30
Engine thrust (N)	4608
Launch thrust time (s)	380
Start mass (kg)	1339
Engine specific impulse, I_{sp} (s)	300
	Output Values
Range (km)	3022
End mass (kg)	476
Velocity change, ΔV (m/s)	3037
Initial hopper mass (kg)	**1339**

The next two hops, each of 2000 km and shown in Figure 17, clear the 3-5 km of topographic variation between the mid-lowlands on the near-side and the mountainous terrain toward the far right of the "Far side" map in Figure 18, as prescribed by the node locations in Figure 15 above. These two hops, also at a launch angle of 30°, each have a launch burn time of 356 s. The remaining parameters are shown in Table 27 and Table 28. Thrust is incrementally lower for each hop, and the final hop's thrust is 510 N, meaning the engine needs to throttle down to about 11% of its original output or operate in pulses.

Figure 18. Lunar topography[146]



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[146] Wikipedia, "MoonTopoLOLA"

Table 27. BallisticHop inputs and outputs for second ILN hop

	Input Values
Launch angle, ϕ (degrees)	30
Engine thrust (N)	1542
Launch thrust time (s)	356
Start mass (kg)	448
Engine specific impulse, I_{sp} (s)	300
	Output Values
Range (km)	1993
End mass (kg)	176
Velocity change, ΔV (m/s)	2744
Initial hopper mass (kg)	**448**

Table 28. BallisticHop inputs and outputs for third ILN hop

	Input Values
Launch angle, ϕ (degrees)	30
Engine thrust (N)	510
Launch thrust time (s)	356
Start mass (kg)	148
Engine specific impulse, I_{sp} (s)	300
	Output Values
Range (km)	2009
End mass (kg)	58
Velocity change, ΔV (m/s)	2749
Initial hopper mass (kg)	**148**

The resulting hopper spacecraft, including 4 node stations and propellant for all 3 hops, comes in at 1367 kg landed on the surface, implying 2748 kg in low lunar orbit. This is nearly six times the 436 kg required in LLO for the lander mission. The lander mission mass does not account for fuel required to attain the different orbits required by the four landers, or the benefits of additional close-range observations conducted during hops. Still, there is a significant mass penalty for such long-range hops.

4.2.2 Hopping in and out of Permanently Shadowed Regions on the Moon

The region around the Moon's south pole includes a number of craters that always view the sun from a shallow angle. Figure 19 shows Shackleton Crater; in lunar winter when it receives the least sunlight, a few locations still receive direct illumination up to 70% of the time; these sites are promising for a human outpost or any other system that requires solar power. Within less than 10 km, parts of the crater's floor *never* receive direct sunlight, and have not for billions of years. These regions have deposits of volatiles that have accumulated over time; Figure 20 shows probable water ice in and around Shackleton Crater. Water and other chemicals are of great interest both for science and human consumption.

Figure 19. Winter sun illumination at the lunar south pole[147]

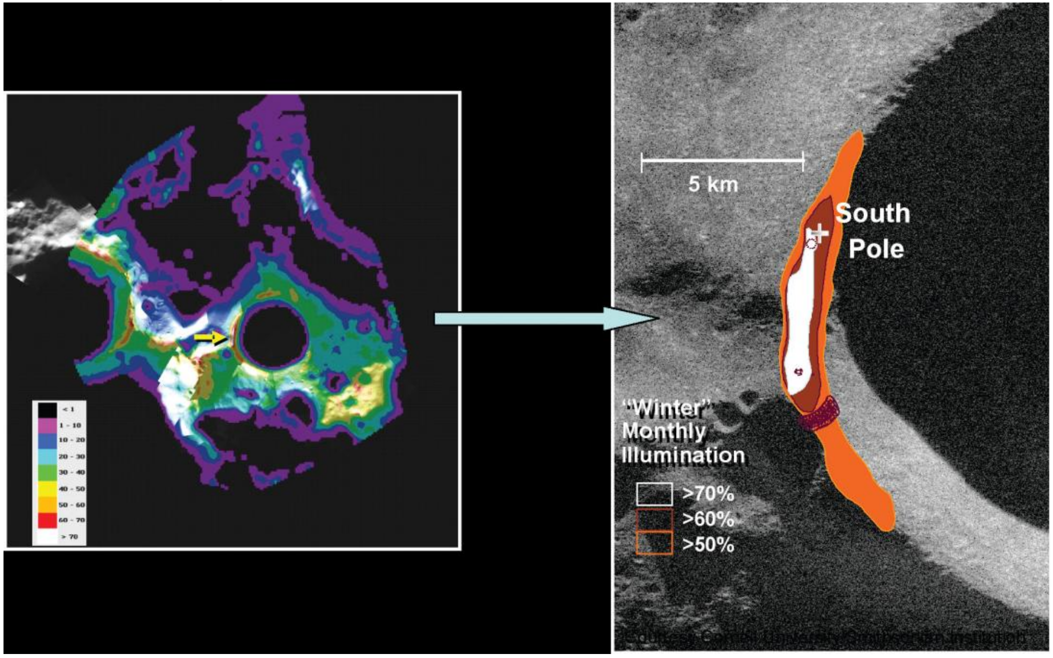
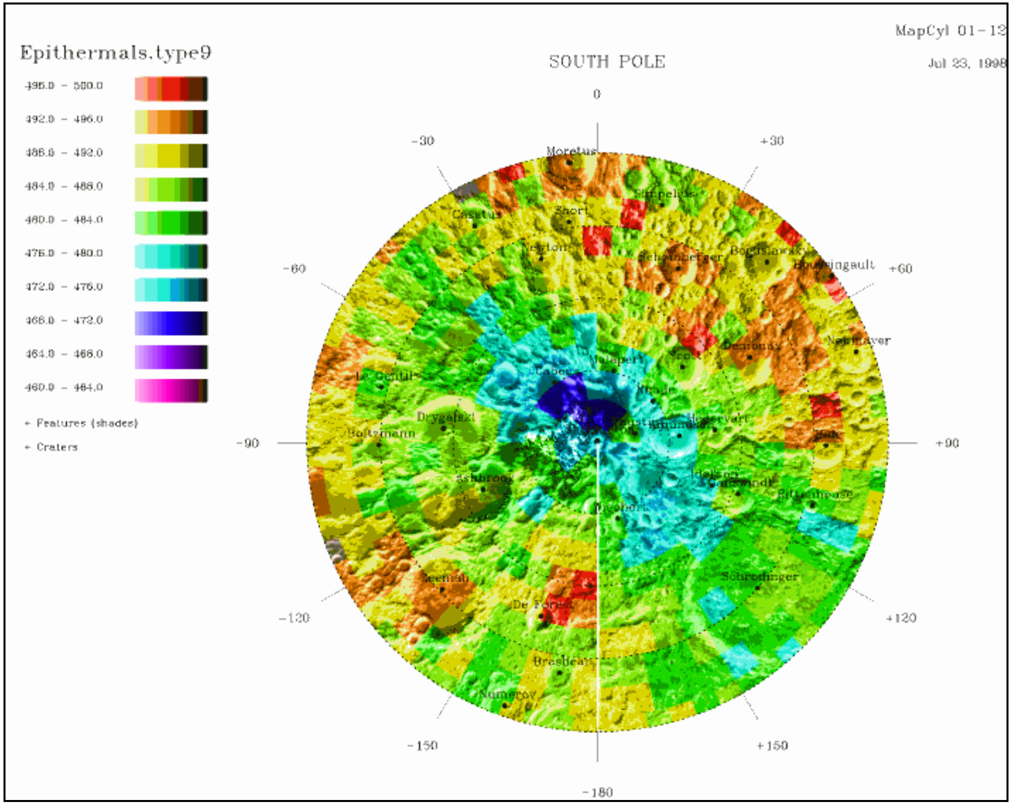


Figure 20. Neutron spectrometer data showing likely water ice (blue and purple) around the lunar south pole[148]



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[147] NASA, Lunar Science Workshop 2007, p. 29

[148] NASA, "Neutron Spectrometer Experiment Results"

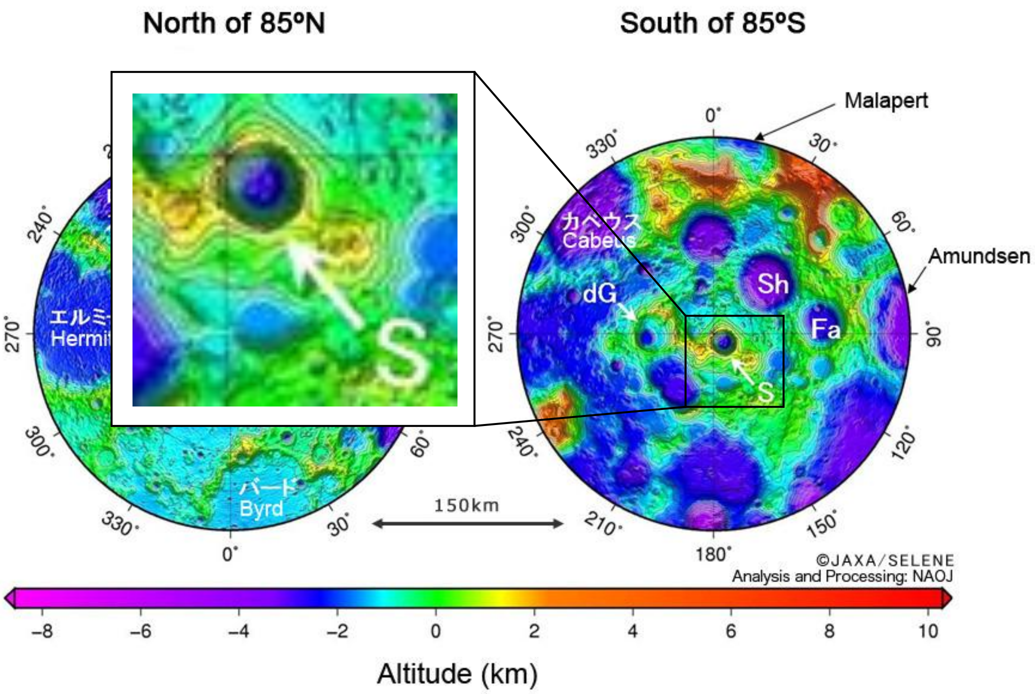
Section IV.5.1 of Michel's thesis investigated the use of a hopper in prospecting this region. However, that analysis allowed for hops at a height of only 10 m. Figure 21 shows that Shackleton itself varies by about 4 km from floor to rim. Traversing this height could be desirable in a scenario with an outpost on the rim sending sorties for sample-collection to the floor, or for a probe investigating the dark floor and returning to the sunny rim to soak its solar panels.

Michel's model was employed here to analyze a hopper for this journey. The hopper could start on the crater rim and descend to the floor, and return; it could also start at the floor and hop to the rim and return; the two scenarios are energetically equivalent. A dry mass of 100 kg was chosen as approximately appropriate; considering necessary subsystems, the model ultimately allows 55 kg for payload. The hop height was set to 4 km for descent and ascent each, with a total lateral traverse of 10 km allowing 5 km in each direction. This hop consumes 25.3 kg of fuel, yielding an initial wet mass of 126 kg, as shown in Table 29. This analysis results in an engine thrust of 323 N.

Table 29. Hoptimizer inputs and outputs for a hop into Shackleton Crater; thrust = 323 N

	Input Values
Local gravity, g (m/s^2)	1.624
Engine specific impulse, I_{sp} (s)	300
Number of hops	1
Fixed payload mass (kg)	55
Hover height (m)	4000
Single hop distance (m)	10,000
Payload dropped per site (kg)	0
	Output Masses (kg)
Propellant	25.3
Tank	5.8
Engine	4.7
Power	5
Communications	11
Structures	18.9
Other	0
Total hopper payload	55
Optimized hopper mass	**126**

Figure 21. Lunar south pole topography, inset showing Shackleton Crater[149]



This grade of terrain is not likely to be navigable by a ground-based vehicle, but a hopper can make the round trip in 246 s, just over 4 minutes. For this short amount of time spent in shadow, without sunlight or line of sight to Earth, a small battery would suffice. The capability to make this kind of hop could be useful anywhere that two attractive locations exist in close proximity with a comparatively large altitude difference.

4.2.3 Lunar Pits

Permanent human habitation of the Moon has long been both a fantasy and a serious long-term exploration objective; one of a few daunting obstacles is the intense radiation environment on this airless orb. Effective shielding with any material from Earth requires exorbitant mass. However, a 2-5 m layer of lunar regolith has been estimated to be an effective long-term radiation shield.[150]

Fortunately, the Moon hosts some geological formations that may include underground caverns. These may be lava tubes, which are former lava channels whose walls hardened before the lava drained. Photographs from the Lunar Reconnaissance Orbiter, including Figure 22 and Figure 23, show pits in the Moon's surface that may be openings to such tubes or other form of underground formation. The holes appear to have

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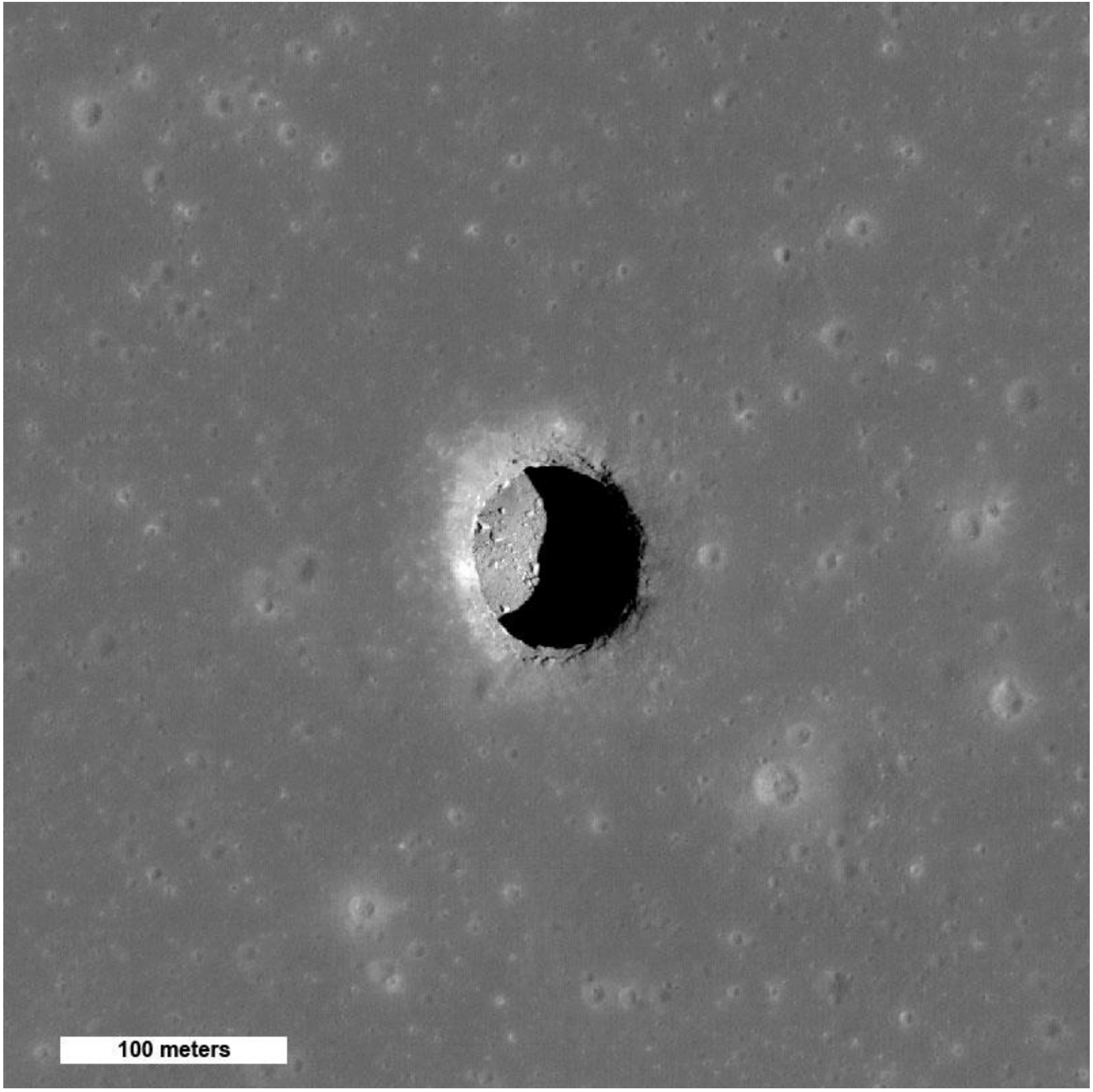
[149] Japanese Aerospace Exploration Agency, "Kaguya's Major Scientific Results So Far," 2007

[150] Lindsey, "Lunar Station Protection: Lunar Regolith Shielding," 2003

overhanging edges, inviting speculation that the caverns within may be wider than the openings. Regardless of their origin or exact nature, any access to underground features would be a valuable and interesting exploration target.

Figure 22. Mare Tranquillitatis pit[151]



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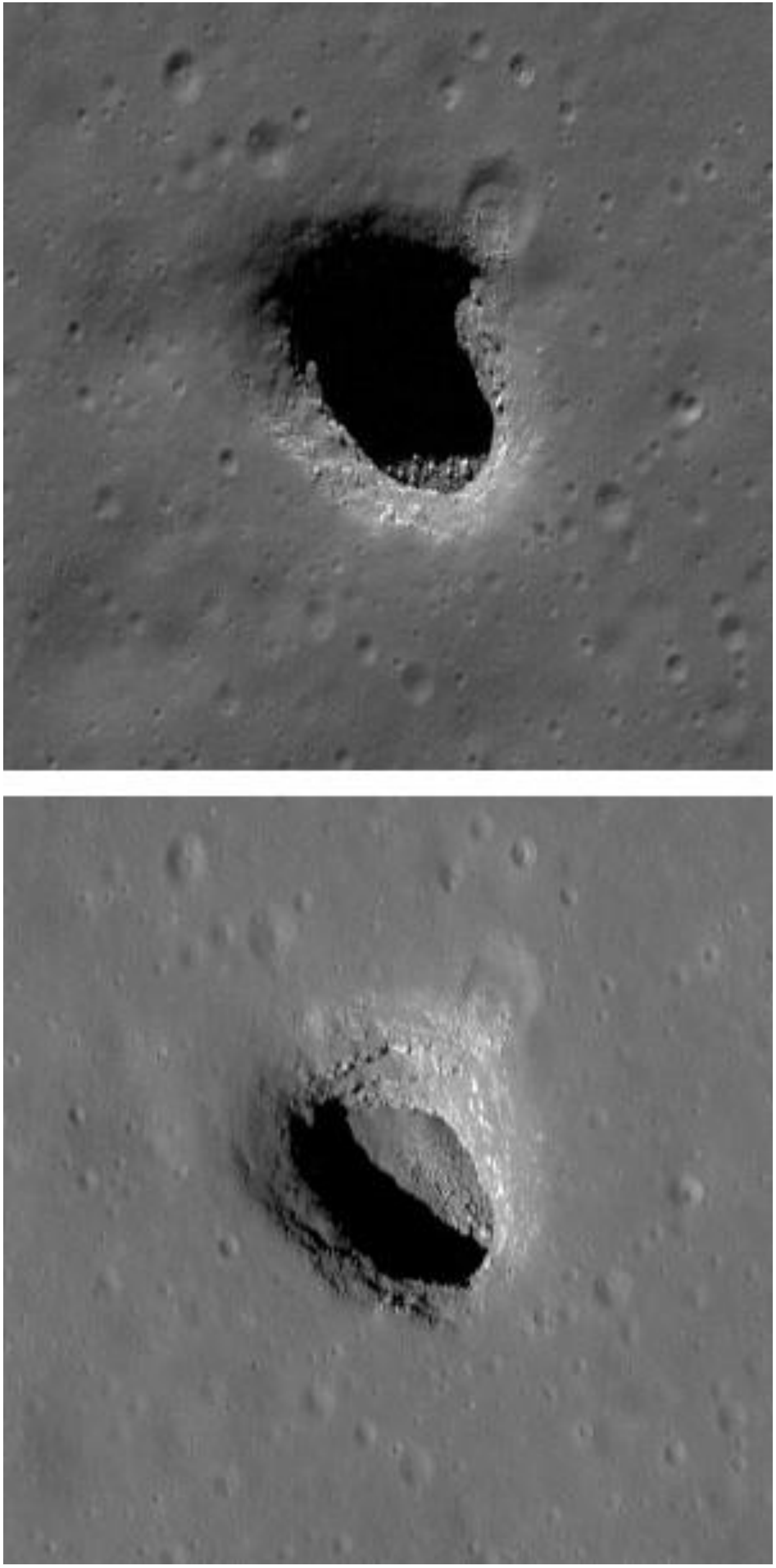
[151] NASA, “New Views of Lunar Pits”

Figure 23. Mare Ingenii pit under two lighting conditions[151]



A hovering hopper could land near such a hole and then hop to its bottom. This would facilitate investigation of the cavern's interior, and on the way down afford a unique view of the stratified lava layers, which are particularly evident for the Mare Ingenii pit in Figure 23. For such a mission, a dry mass of 100 kg is again estimated as a starting point. The mission includes two hops, one to move from the initial landing site to the pit's edge, and the other to descend to the pit's floor and return to the surface.

The first hop can traverse up to 1000 m, based on the ability of all the Apollo moon landings after Apollo 11 to touch down within 600 m of their target.[152] A hover height of 10 m would clear the flat local terrain. This hop also carries fuel needed for the subsequent hop into and out of the pit. Michel's Hoptimizer model produces the inputs and outputs show in Table 30.

Table 30. Hoptimizer inputs and outputs for hop to edge of Tranquillitatis pit1; thrust = 238 N

	Input Values
Local gravity, g (m/s^2)	1.624
Engine specific impulse, I_{sp} (s)	300
Number of hops	1
Fixed payload mass (kg)	63
Hover height (m)	10
Single hop distance (m)	1000
Payload dropped per site (kg)	0
	Output Masses (kg)
Propellant	4.7
Tank	1.9
Engine	3.8
Power	5
Communications	11
Structures	16.5
Other	3.9
Total hopper payload	63
Optimized hopper mass	**110**

A second hop – actually computed first to find fuel mass – allows the hopper to reach the middle of the opening, descend to the bottom, and reach the surface again, as depicted in Figure 24. The Mare Tranquillitatis pit is the larger of the two shown, with an opening of 100-115 m and an estimated depth of roughly 100 m; allowance for a 200 m horizontal traverse and 120 m for both descent and ascent provides more than enough capability.

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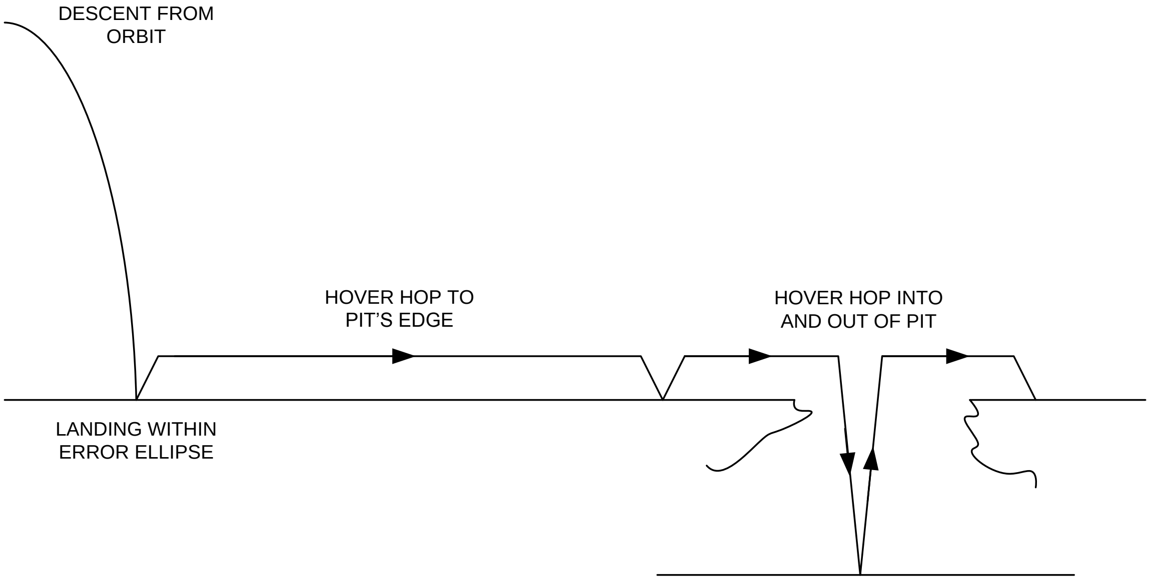
[152] Orloff, "LM Lunar Landing," 2004

Figure 24. Hop profile for lunar pit mission, NOT TO SCALE



The Hoptimizer inputs and outputs are shown in Table 31. The descent and ascent time are each about 14 s; additional observation from a slow or stationary hover could be achieved with more fuel. The hopper designed would have capacity for a generous 63 kg payload. It would use a maximum thrust of 244 N and be 221 kg in low lunar orbit.

Table 31. Hoptimizer inputs and outputs for hop to bottom of Tranquillitatis pit and back to surface; thrust = 244 N

	Input Values
Local gravity, g (m/s^2)	1.624
Engine specific impulse, I_{sp} (s)	300
Number of hops	1
Fixed payload mass (kg)	63
Hover height (m)	120
Single hop distance (m)	200
Payload dropped per site (kg)	0
	Output Masses (kg)
Propellant	3.9
Tank	1.6
Engine	3.9
Power	5
Communications	11
Structures	15.6
Other	0
Total hopper payload	63
Optimized hopper mass	**104**

This simple example demonstrates a straightforward way that a hopper could offer, in a way no other vehicle could, an unprecedented exploration opportunity.

4.2.4 South Pole-Aitken (SPA) Basin Sample Return

SPA Basin Mission Motivation

Likely the Moon's clearest path to answering fundamental questions about the Solar System is through returning samples to Earth from the South Pole – Aitken (SPA) Basin. This enormous dent in the Moon's far side is about 2500 km in diameter and up to 8.2 km deep,[153] making it one of the largest impact craters in the Solar System (only Mars is known to have larger[154]). Of more interest is the Basin's profound – but not precisely known – age. Because the Moon's surface has changed so little over the last 4 billion years, information from this time in the Solar System is pristinely preserved on the Basin's floor.

At a March 2009 meeting hosted by NASA's Lunar Exploration Analysis Group (LEAG), the lunar science community agreed concerning SPA sample return:

- Still a very important high priority for constraining the impact flux of the inner solar system and is part of the last decadal survey that has not yet been addressed.
- Age of potentially the oldest giant impact on the Moon is a vital scientific goal not only for the impact history of the Moon, but also for understanding the evolution and impact history of the inner solar system.
- The SPA impact excavated the crust deeply, maybe even exposing the upper mantle. Returning samples could shed light on the nature of the lower lunar crust and possibly the upper mantle.
- Mare patches and cryptomare within SPA allow the examination of the diversity of mantle sources by returning basalts from the lunar far side.
- Determination of the ages of the large craters *within* SPA will potentially give a definitive test to the cataclysm hypothesis.[155]

Toward this end, LEAG's2009 Lunar Exploration Roadmap has "understand the impact history of the inner Solar System as recorded on the Moon" as its first objective under Science Theme B, "Use the Moon as a 'witness plate' for Solar System evolution."[86]

Outside LEAG and NASA, the 2003 planetary decadal survey report listed SPA Basin sample return as one of three missions that would be most relevant to answering the first of its twelve top-level questions: "What processes marked the initial stages of planet and satellite formation?"[156] More recently, the 2007 report by the National

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[153] Petro and Pieters, "Surviving the Heavy Bombardment," 2004, p.1

[154] *Science Daily*, "Largest Crater in Solar System Revealed by NASA Spacecraft," 2008

[155] Lunar Exploration and Analysis Group, "Community Forum on Future Lunar Science Mission, 2009, p.3

[156] New Frontiers in the Solar System, 2003, p.179

Research Council, *The Scientific Context for the Exploration of the Moon*, gave as the first of their priority-ranked goals:

> 1a. Test the cataclysm hypothesis by determining the spacing in time of the lunar basins.
>
> 1b. Anchor the early Earth-Moon impact flux curve by determining the age of (perhaps) the oldest and largest lunar basin (South Pole-Aitken Basin).[157]

A white paper to the current planetary decadal survey comments on goal 1a:

> As we have no ages for ≥29 older, pre-Nectarian basins, we still have no idea if they are part of a lunar cataclysm or are instead part of the declining bombardment... this makes any basin older than Serenitatis a ripe target for sample return, with the highest priority being unaltered impact melt from the South Pole-Aitken (SPA) Basin… Because SPA may be the oldest and may be the largest basin, it defines the beginning of the basin-forming epoch.[158]

There is consensus that a sample return mission is the most effective way to resolve these issues because detailed, complicated, and high-precision investigations are necessary:

> To determine if this lunar cataclysm was real, one needs precise ages of the lunar basins (better than ±0.02 Ga, by multiple methods, emphasizing the oldest and youngest basins (South Pole - Aitkin & Orientale). This level of precision is achievable only in terrestrial laboratories.[159]

Despite the inherent complexity in a sample return mission compared to *in situ* experimentation, this option is not only being considered as one of the current decadal's three Moon missions,[160] but is one of three finalists announced in 2009 for NASA's next New Frontiers mission.[161] This finalist mission is called Moonrise, and serves as a source of baseline information.

SPA Basin Mission Concept Design

The Moonrise project would, for about $1.1 billion in projected 2015 dollars, land on the Moon's surface, collect about 1 kg of mostly rock fragments and some regolith, and return the sample to Earth.[162] A hopper could improve upon this mission's science return for little additional cost. Simply being able to sample multiple locations – locations that can be evaluated and redesignated *in situ* – greatly magnifies the likelihood that returned samples will answer all the priority questions about the Basin. Though the Moonrise mission assumes that all rock types of interest are well distributed

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[157] The Scientific Context for Exploration of the Moon, 2007, p.54

[158] Bottke et al., *Exploring the Bombardment History of the Moon*, 2009, p.4

[159] Treiman et al., *Sample Return from the Earth's Moon*, 2009, p.4

[160] NRC Space Studies Board, *Missions Being Considered by the Planetary Science Decadal Survey*

[161] NASA, *NASA Chooses Three Finalists for Future Space Science Mission…*

[162] Jolliff et al., *Moonrise: South Pole-Aitken Basin Sample Return Mission for Solar System Science*, 2010

over the target region,[163] sampling multiple distant sites gives, at the very least, definitive access to known rock types and features like crater rims and floors. At most, hopper access to multiple sites allows for mission success even if something is wrong or anomalous about some of the sites – knowledge which might not surface until the samples are in an Earth lab. In the same vein, the flexibility of a hopper allows adaptation to discoveries made at early touchdown sites.

The additional cost for a hopper comes from assuming the same amount of mass landed on the moon as Moonrise, but having to move it around the surface. Most of this mass consists of the hardware and fuel needed to send the samples back to Earth. The end of this section considers a scenario where a small sample-collecting hopper separates from the heavy lunar ascent vehicle, including its Earth return stage, and returns after collecting samples. But for now the entire mass including, the Earth return stage, moves with the hopper during each hop. The Moonrise mission has not published a total spacecraft mass; a misread of a presentation to NASA's Lunar Exploration Analysis Group produced a figure of 900 kg.[164] While this is actually the mass of a scientific payload remaining after Moonrise's Earth return stage has departed – meaning that Moonrise in total will be significantly heavier – 900 kg remains a reasonable starting point for the following analysis. To keep growth from this starting mass minimal while allowing access to a variety of the most interesting terrains in the basin, this scenario considers 5 ballistic hops, each of 50 km, meaning 6 sample sites.

The route shown in Figure 25 lands in a patch of pre-Nectarian (typically over 4 billion years old[165]) cryptomare (formerly buried lava field). It then makes one hop within this earliest type of ejecta deposit, hops into the deep floor of Bose crater, and makes two stops in typical SPA Basin terrain on its way to a final position in the Lower Imbrian ejecta plain just southeast of Alder crater. This route gives access to a variety of surface types, including the representative "average" for the Basin as well as the oldest kinds of impact ejecta, and grants access to the inside of a crater where mantle material may be exposed. To clear the topographic variation along this path of about 5 to 7 km below the lunar average, as indicated in the bottom of Figure 25, each hop reaches about 2.5 km in altitude. This maximum altitude results from optimizing fuel consumption, but can be increased for little cost. An illustration of the trajectory common to each hop is show in Figure 26.

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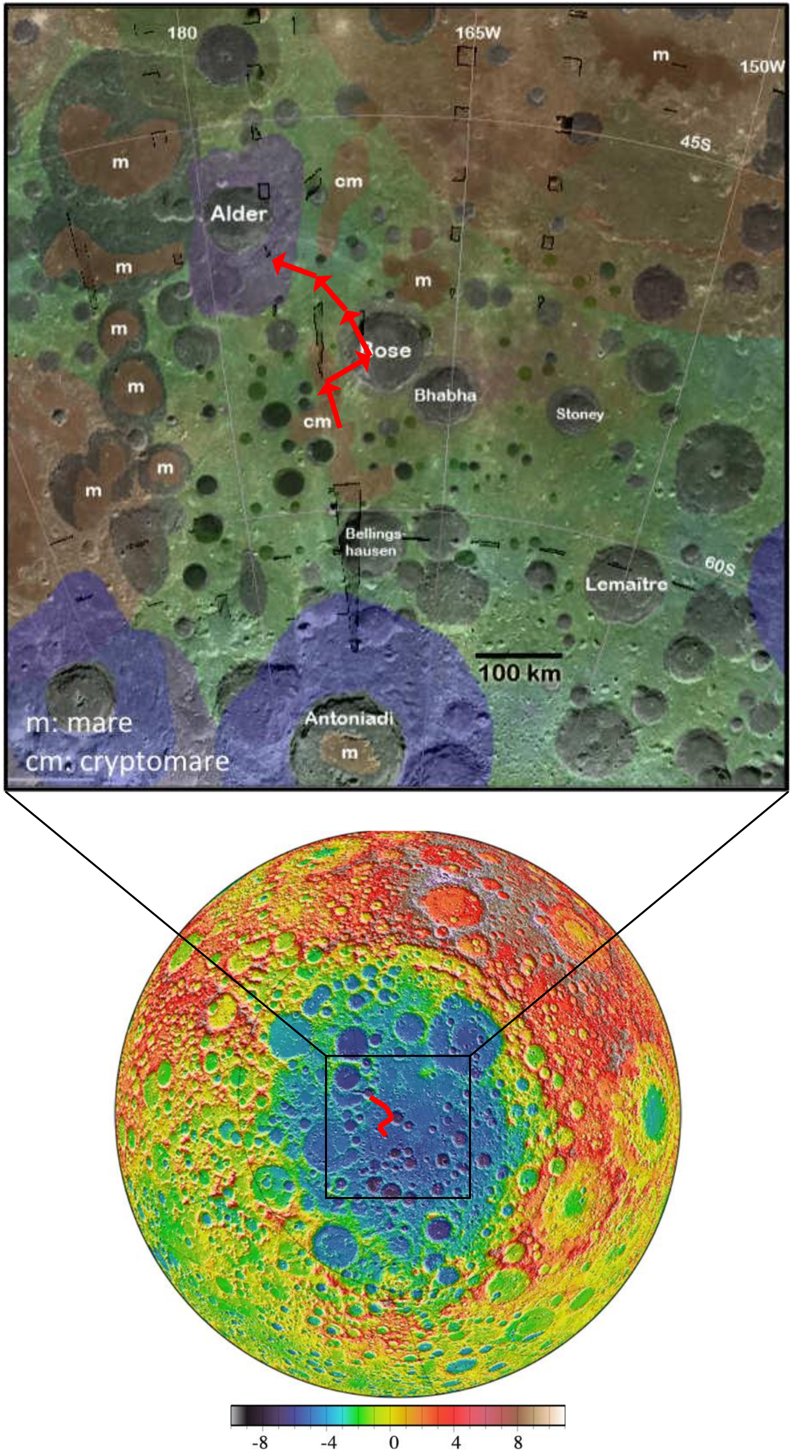
[163] Jolliff et al., *Moonrise: A Sample-Return Mission to the South Pole-Aitken Basin*, 2010

[164] Jolliff et al., *MoonRise: SPA Basin Sample Return Mission for Solar System Science*, 2010, slide 20

[165] Harland et al., *A Geologic Timescale 1989*, 1990, p.23

Figure 25. Two views of possible hopper path across SPA Basin, with stops indicated by arrows. TOP: "Interior of the SPA Basin showing locations of large craters, mare (m) and cryptomare (cm). Ejecta deposits: light brown, Pre-Nectarian; gray, Nectarian; purple, Upper Imbrian; magenta, lower Imbrian; olive green, Eratosthenian."[166] BOTTOM: SPA Basin topography (in km).[167]



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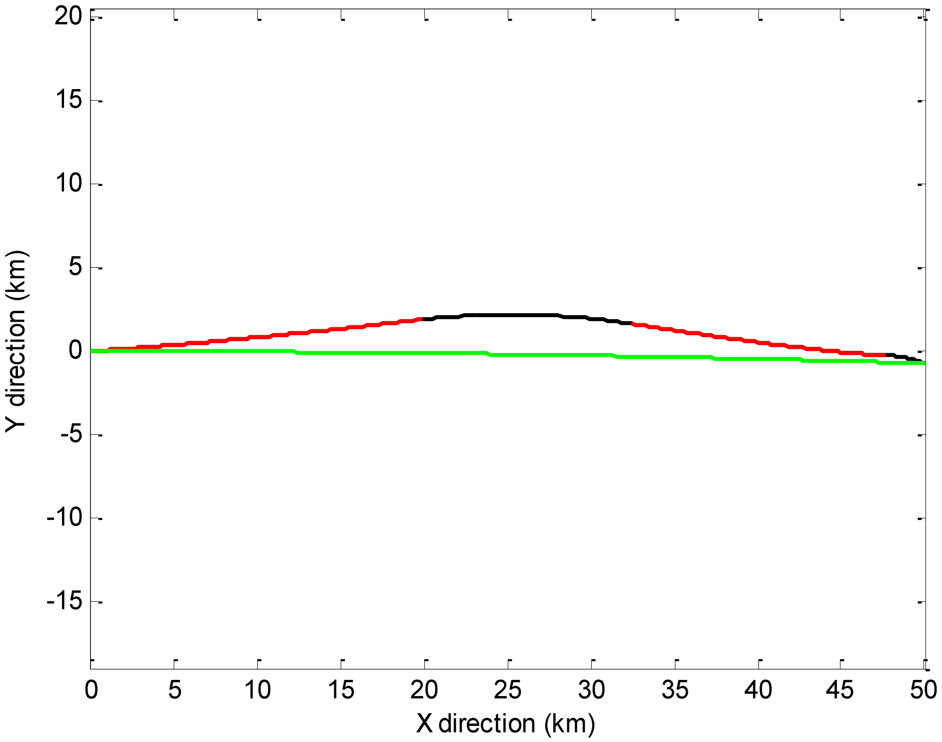
[166] (see Ref.162) Jolliff et al., *Moonrise: South Pole-Aitken Basin Sample Return Mission…*, 2010, p.4

[167] http://www.nasa.gov/mission_pages/LRO/multimedia/lroimages/lola-20100409-aitken.html

Figure 26. Hop trajectory in the South Pole-Aitken Basin



SPA Basin Mission Analysis

To calculate the parameters for these hops, the modified version of Middleton's MATLAB model was employed. The analysis assumes that after all 5 hops the vehicle mass should be 900 kg, which is the mass estimated by Moonrise to be necessary for sample collection and return to Earth. A very nearly optimal launch angle of 45° is employed. The hopper engine is assumed to be able to throttle down to 43%. If this engine can also be used for lunar orbit capture or initial descent to the surface, significant mission mass and development savings would result. Fuel mass and thrust decrease in proportion as the hopper travels, while the each hop follows trajectory with the same range, altitude, and engine burn time. The launch burn time to achieve the desired hop for this scenario is 148 s; the resulting trajectory is illustrated in Figure 26. For a mass of 900 kg at the end of the fifth hop, including samples from each site that total to 1 kg, an initial mass landed on the Moon's surface is 2601 kg. The details are in Table 32.

Table 32. **BallisticHop inputs and outputs for 5 hops in the South Pole-Aitken Basin**

	Input Values
Launch angle, ϕ (degrees)	45
Engine thrust (N)	2708-6329
Launch thrust time (s)	148
Start mass (kg)	2601
Engine specific impulse, I_{sp} (s)	300
	Output Values
Range (km)	5 x 50
End mass (kg)	900
Velocity change, ΔV (m/s)	5 x 623
Initial hopper mass (kg)	**2601**

This is almost 3 times the mass that Moonrise proposed to land on the surface. Though commensurate added costs for technology development, Earth launch vehicle, and fuel should be small compared to the mission cost, especially relative to the advantages gained, it may still be possible to avoid this mass growth. The instrumentation for sample collection and storage, navigation, and hopping might be contained within 100 kg, a reasonable amount considering both the hardware required and the fact that most of the 900 kg mass landed on the moon by Moonrise would be for returning the sample to Earth. If 800 kg of Earth return hardware stays at the initial landing spot, a smaller sample-collecting hopper could make 5 hops and return with a mass of 100 kg. Some additional technology would be needed for docking and sample transfer, but such precision targeting is not a problem for a hover-capable hopper. For this scenario, each launch burn time would still be 148 s, with each hop trajectory still the same as in Figure 26, but the route would return to its start point. Such a hopper would need to start at 289 kg. This implies only 189 kg added to Moonrise's 900 kg, for a total landed on the Moon of 1089 kg. This mass growth of 21% is an attractive compromise considering the additional sampling it enables.

4.2.5 Moon Missions Summary

The Moon is an attractive target for exploration, with strong enthusiasm from scientists and policymakers. This section analyzed four hopper-enabled Moon missions: an International Lunar Network, the rim and floor of a polar crater such as Shackleton, lunar pits, and sample return from the South Pole-Aitken Basin.

Concept studies for an International Lunar Network currently under consideration by NASA prescribe at least 4 nodes and a science package of about 16 kg at each node. Using individual landers to emplace each node from low lunar orbit would entail a mass of 54 kg landed mass per node, or a total of 436 kg in orbit, without considering orbital maneuvers to reach each node site. A node station with no propulsion system would be 28 kg; a hopper using ballistic trajectories to drop four stations at sequential distances of 3000, 2000, and 2000 km would require 1367 kg on the Moon's surface, and 2748 kg in orbit. This is six times the lunar orbit mass of the individual-lander mission. However, the hopper is a single self-contained vehicle, allows for close-range observations throughout the long-distance hops, and entails more flexibility as the hopper can adjust its trajectory or add short hops for precise positioning.

Craters in the Moon's polar regions offer sites of both permanent shadow and near-permanent sunlight. A hopper with a conveniently chosen dry mass of 100 kg, of which 40 kg could be used for payload, could access both the rim and floor of such a crater. Shackleton Crater is at the Moon's south pole and varies by about 4 km from floor to rim. A hovering hopper could execute such a hop with capacity to redirect itself from unwelcoming terrain. With capacity to traverse 5 km horizontally throughout the hop, such a hopper would be 123 kg before conducting the hop.

Recent photographs show pits in the Moon's flat mare terrain at least 100 m deep. A hovering hopper could land within 1 km of the pit, conduct a precise hovering hop to the hole's edge, and hop once more to the cavern's floor to observe its structure. Again starting with a 100 kg hopper dry mass, this hopper would include 47 kg for payload. Its mass would be 110 kg at the beginning of the first hop, and 221 kg in lunar orbit.

A sample return mission to the interior of the South Pole-Aitken Basin is a high priority in current discussions. The leading proposal calls for a single lander, relying on impact-facilitated mixing of all rock types throughout the Basin over the millennia to ensure the sample contains the desired information. This lander would be 900 kg on the Moon's surface. A hopper visiting 6 diverse and promising sites, with the option to redirect at any point, would facilitate a more robust mission than a single lander. Two variants were considered for this hopper mission, both capable of returning 1 kg of the Moon back to Earth. The first variant carries 900 kg of sample-processing and Earth-return hardware of the NASA baseline mission to all 6 sites. This hopper would be 2601 kg at initial landing, almost three times NASA's baseline for a single site. The second variant would use a smaller hopper of 100 kg dry mass to leave the 800 kg lander, collect each sample, and return for sample delivery to the Earth return stage. This approach is 1089 kg upon initial landing, only 189 kg (21%) more than the baseline.

Because hoppers rely almost entirely on technology that is already integral to the missions they stand to improve, and provide substantial unprecedented capability, they are an attractive concept. This section specifies their performance in four likely lunar mission concepts. Hoppers always provide advantages, and in at least some of the cases presented offer a compelling alternative worthy of further investigation.

IV.3. Mars

There are many objectives for Mars exploration. Interest is strongest for sample return, remote measurements, a global geophysical network, and diversity of samples. Many of the objectives could be met by orbital spacecraft. Some require coverage of the entire planet. There are also many local-scale objectives where hoppers could provide a new level of maneuverability, terrain negotiation, and navigational precision. However, the nature of planning for Mars exploration – an idea that attracts strong excitement but is technically difficult and distant on the time and budget horizons – means that thoroughly planned mission profiles are not available for comparison to a hopper mission. Rather than detailing a specific mission, this section presents a set of example hops that demonstrate the range of capabilities a Mars hopper could offer.

The missions considered all assume a communications relay in orbit around Mars, and use of solar power, including the ability to store energy in batteries through Martian night, dust storms, and other weather events. Aerodynamic drag from Mars' thin atmosphere is ignored.

4.3.1 Hop into Valles Marineris

Mars boasts extreme topographic features, the deepest of which is the vast Valles Marineris.[168] Aside from demonstrating a large vertical hop, a mission into the Valles could observe the exposed rock layers in the ancient cliff walls. An initial ballistic hop can move the hopper from anywhere in its landing ellipse to the valley's brink. The Mars Science Laboratory plans to land within an ellipse about 25 km long and 20 km at its widest.[169] Assuming similar landing precision for this mission, a 25 km ballistic hop along the surface of Mars is shown in Figure 27. The BallisticHop input and output values are given in Table 33. Starting at 256 kg, 203 kg remain after the hop. This value derives from the hovering hop to the valley's floor, which itself assumes a 50 kg payload.

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[168] United States Geological Survey, "Valles Marineris: The Grand Canyon of Mars" 2008

[169] NASA *MSL Landing Site Selection User's Guide*, 2007, p.5

Figure 27. Hop trajectory from Mars landing ellipse to edge of Valles Marineris

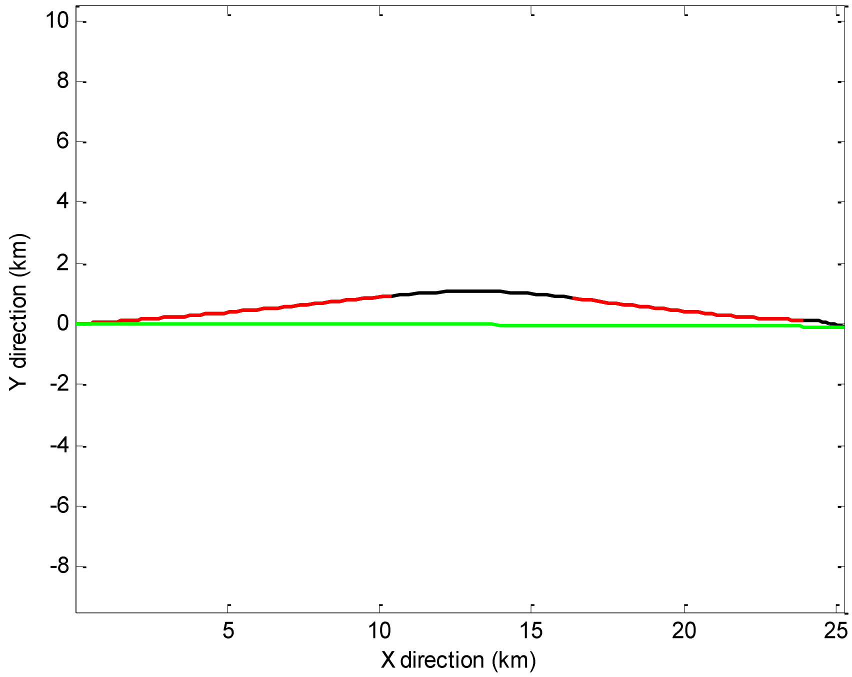
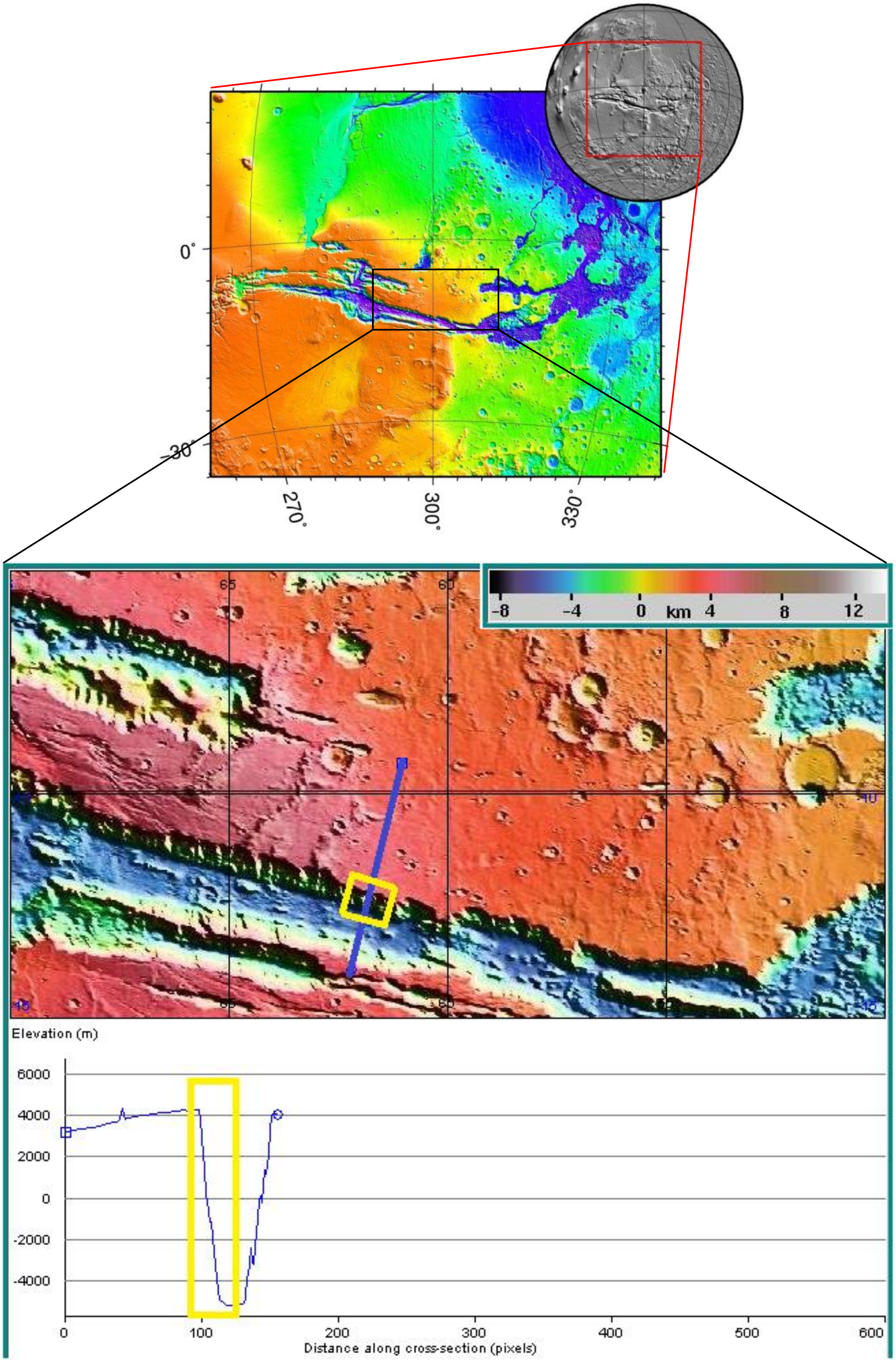


Table 33. BallisticHop inputs and outputs for hop to the edge of Valles Marineris

	Input Values
Launch angle, ϕ (degrees)	45
Engine thrust (N)	1424
Launch thrust time (s)	70
Start mass (kg)	256
Engine specific impulse, I_{sp} (s)	300
	Output Values
Range (km)	25.3
End mass (kg)	203.7
Velocity change, ΔV (m/s)	670
Initial hopper mass (kg)	**256**

The hop to the valley floor also moves 25 km horizontally, but covers a greater altitude change of 10 km. Figure 28 illustrates a possible location for such a hop in the eastern Coprates Chasma, which features some of the greatest depth and steepest cliff faces in Valles Marineris. The blue line in the zoomed image of the Chasma is displayed in vertically exaggerated profile at the bottom of the figure. The yellow boxes indicate the segment covered by the hovering hop, while the rest of the blue profile is for context. Note that the x-axis of the profile has meaningless units of 'pixels,' while the actual distance traveled is 25 km. Hoptimizer must calculate a hop that begins and ends at the same altitude; a hopper that remains at the bottom would use roughly half the fuel calculated here.

Figure 28. Hop into Valles Marineris[170]



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[170] NASA, "Interactive Mars Data Maps: MOLA"

The results, shown in Table 34, result from a hopper using 1101 N of thrust; this implies an engine that can throttle down from 1424 N required for the ballistic hop. The descent into the Valles takes 40 s; an optional ascent back to the start height, for which this hopper is designed, takes 79 s.

Table 34. Hoptimizer inputs and outputs for hop into Valles Marineris; thrust = 1101 N

	Input Values
Local gravity, g (m/s^2)	3.71
Engine specific impulse, I_{sp} (s)	300
Number of hops	1
Fixed payload mass (kg)	50
Hover height (m)	10,000
Single hop distance (m)	25,000
Payload dropped per site (kg)	0
	Output Masses (kg)
Propellant	85.6
Tank	12.9
Engine	10.7
Power	10
Communications	3.7
Structures	30.5
Other	3.9
Total hopper payload	50
Optimized hopper mass	**203**

In summary, this hopper carries a 50 kg payload from anywhere in a landing error ellipse to the edge of Valles Marineris, and then to its floor 10 km below. The hopper is designed to return to the canyon’s rim, but considerable savings would result from remaining at its bottom. The initial landed mass of the hopper would be 256 kg, implying 1031 kg in low Mars orbit.

4.3.2 Intriguing Features on Arsia Mons

Shown in the top left of Figure 29, a fitting counterpoint to the lowest region of Mars would be Olympus Mons, the highest known mountain in the Solar System. However, its neighbor to the southeast, Arsia Mons, offers some intriguing and unique features. Figure 30, an image from Google Earth®’s global map of Mars, shows chains of pits that may indicate lava tubes of the type discussed in Section 4.2.3, and are certainly an unexplained and intriguing volcanic feature.

Figure 29. Olympus Mons and the Tharsis Montes, including Arsia Mons in the bottom center[171]

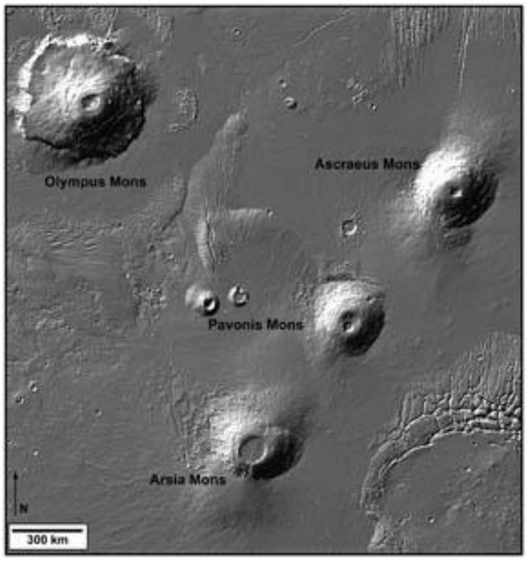
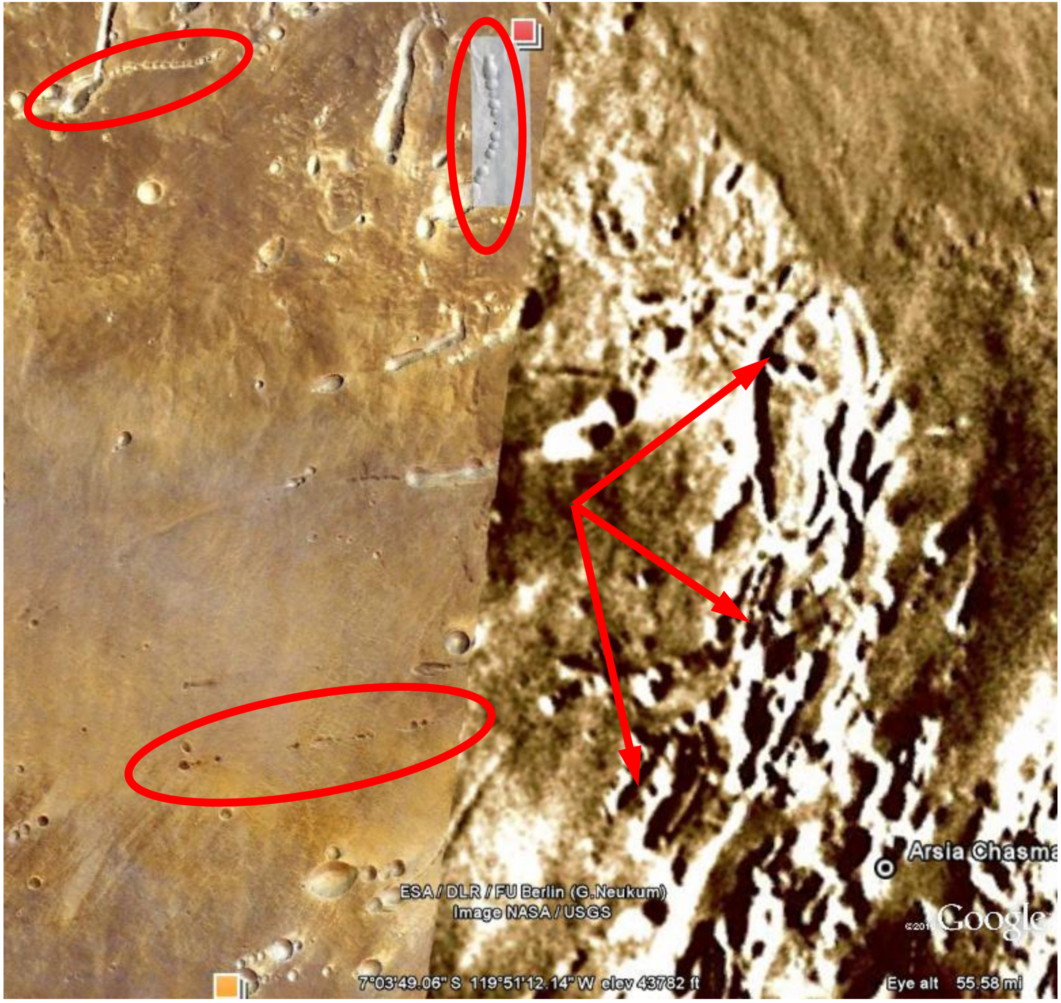


Figure 30. Pit chains on the north slope of Arsia Mons



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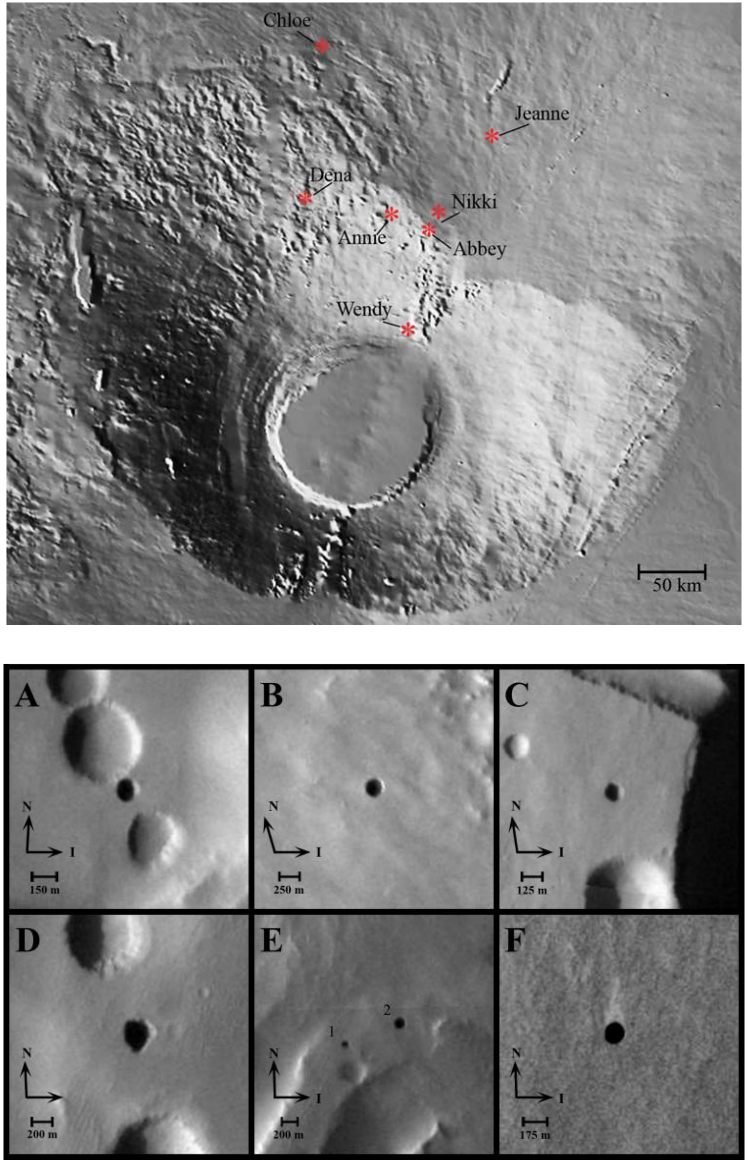
[171] NASA, "Hawaii Reveals Steamy Martian Underground," 2007

A zoomed out view including the same region is shown in Figure 31. Discovered in 2007, these 7 holes have diameters ranging from 100 m to 255 m in diameter; their optical and thermal properties suggest they could be entrances to larger caverns that may reach over 100 m deep based on limited observations of shadows.[172] If these attractions are not enough, Figure 32 shows geological features on the volcano's west flank that have been proposed as a target for human exploration.[173]

Figure 31. Possible cave skylights on Arsia Mons: (A) Dena, (B) Chloë, (C) Wendy, (D) Annie, (E) Abby and Nikki, and (F) Jeanne



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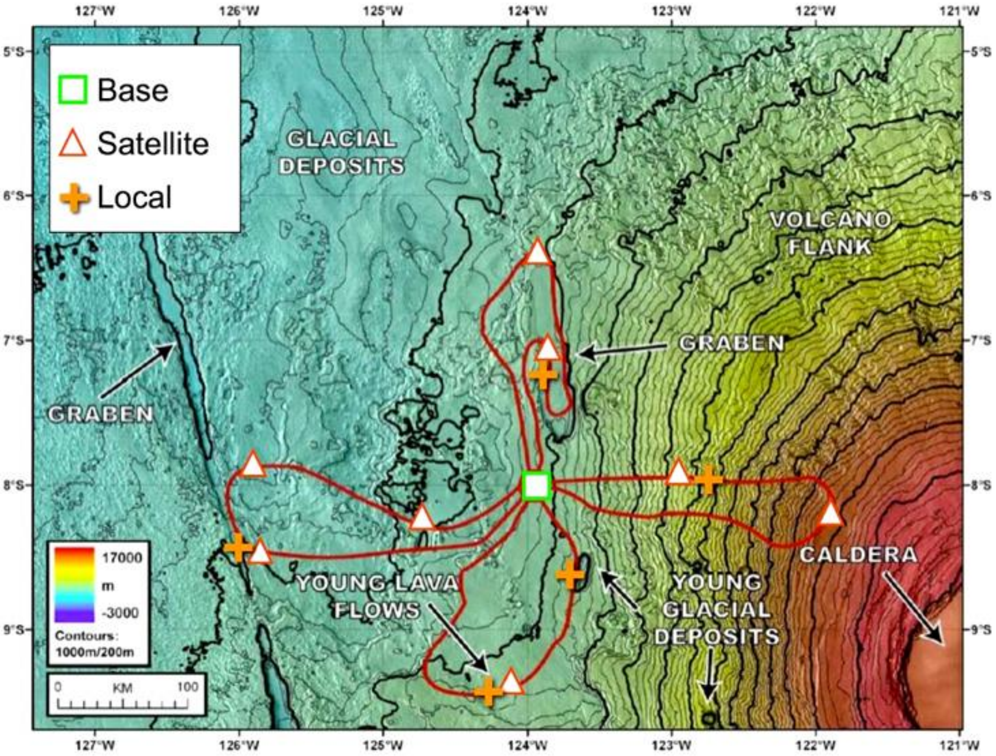
[172] Cushing et al., "THEMIS Observes Possible Cave Skylights on Mars," 2007

[173] Levine et al., "Martian Geophysics Investigations," 2010

Figure 32. Geological targets on the west slope of Arsia Mons



Some of the targets mentioned are hundreds of kilometers apart, but a single hopper could explore any one of them thoroughly, or possibly a group such as pits Abby and Nikki. Such a hopper was designed for three hops, each of 15 km, at a hover height of 1 km to handle the dynamic topography. This hopper arbitrarily begins with a reasonable 25 kg payload. The Hoptimizer data is in Table 35.

Table 35. Hoptimizer input and output for 3 hops on Arsia Mons; thrust = 1364 N

	Input Values
Local gravity, g (m/s^2)	3.71
Engine specific impulse, I_{sp} (s)	300
Number of hops	3
Fixed payload mass (kg)	25
Hover height (m)	1000
Single hop distance (m)	15,000
Payload dropped per site (kg)	0
	Output Masses (kg)
Propellant	148
Tank	18.7
Engine	12.3
Power	10
Communications	3.7
Structures	38.4
Other	0
Total hopper payload	25
Optimized hopper mass	**256**

This mission would have mass of 1031 kg in orbit and enable any hop maneuvers that fit within its fuel capacity.

4.3.3 Human Mission at Edge of Isidis Planatia

To illustrate a mission where hoppers carry humans, a hopper in the northwest of Isidis Planatia makes a good example. Levine et al. propose a geological expedition that would be based near the center of an impact crater that may once have been a lake; a map of the site is shown in Figure 33 with context. In addition to the diversity of features labeled in the figure, heat flux measurements from this area could complete a three-node network for studying Mars' interior on a global scale.[174]

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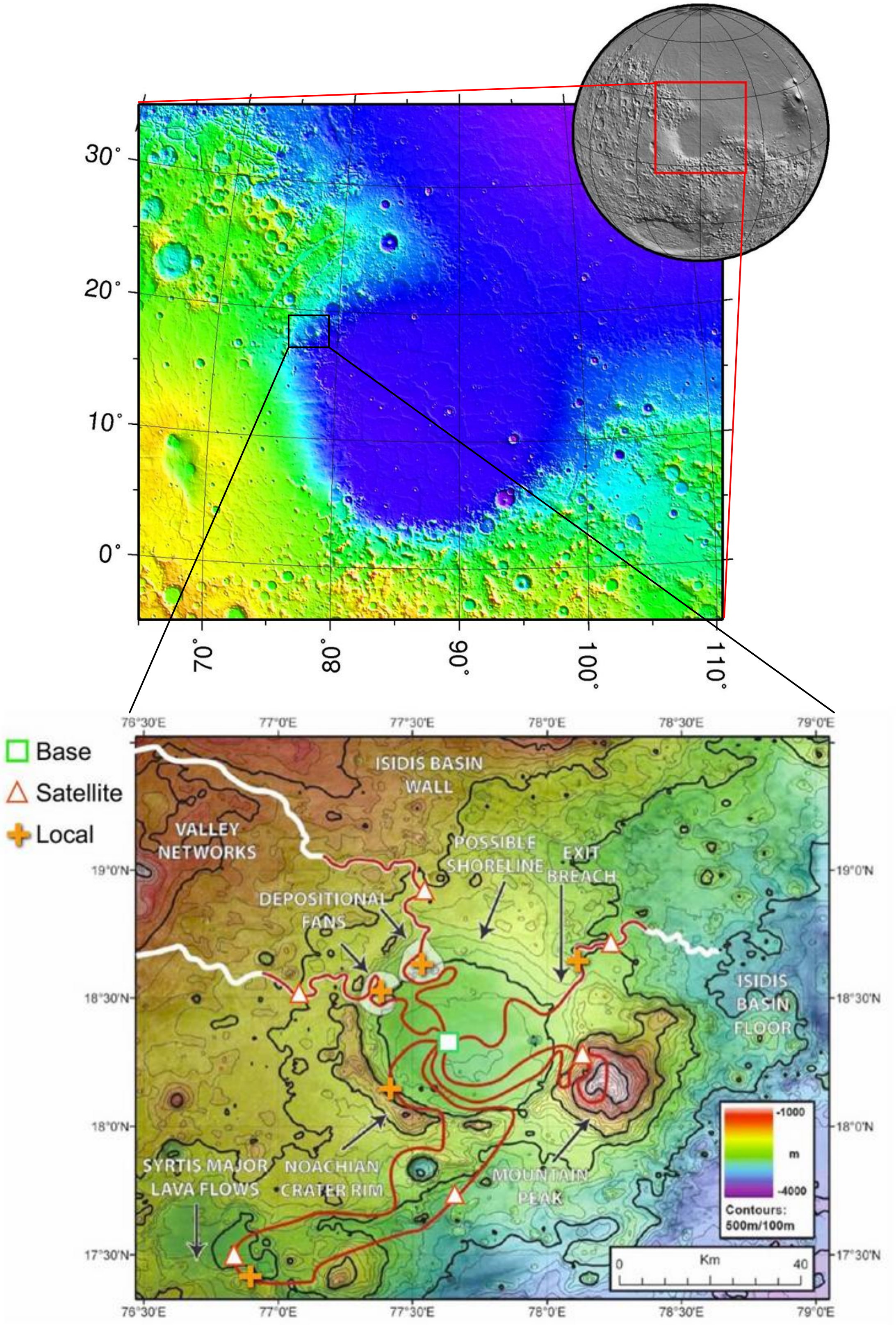
[174] (see Ref.173) Levine et al., "Martian Geophysics Investigations," 2010, Section 6

Figure 33. Proposed human expedition at edge of Isidis Planatia[174,175]



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[175] Wikipedia, "Isidis_basin_topo.jpg"

Any hopper carrying a human in a pressurized chamber is likely to be more massive than those with small instrument packages throughout the rest of this chapter. The Apollo Lunar Module was about 15,000 kg; plans for the Altair Lunar Lander cited a mass of over 43,000 kg.[176] The present hopper is assigned a payload of 10,000 kg for a habitat, in addition to the usual subsystems. The power system is assigned 50 kg. With capacity for two hops of 40 km – pushing the limits of Hoptimizer for this heavy vehicle – each "satellite" station in Figure 33 except the one furthest southwest can be reached from the "base" in a round trip. If a fuel source, derived from Earth or Mars, can be stored at the home base, more hops would be possible. A hover height of 1 km clears all the topography along the flight paths and most of the surrounding terrain; it also allows detailed measurements from the hopper throughout each traverse. This hopper would use a thrust of 170 kN. As shown in Table 36, it would have a total initial mass of over 42,000 kg, of which ab0ut 17,000 kg is dry mass including the 10,000 kg habitat. Using a conventional landing, this hopper would be 86,000 kg in Martian orbit.

Table 36. Hoptimizer inputs and outputs for human expedition to Isidis Planatia; thrust = 171,000 N

	Input Values
Local gravity, g (m/s^2)	3.71
Engine specific impulse, I_{sp} (s)	300
Number of hops	2
Fixed payload mass (kg)	10,000
Hover height (m)	1000
Single hop distance (m)	40,000
Payload dropped per site (kg)	0
	Output Masses (kg)
Propellant	25,619
Tank	579
Engine	308
Power	50
Communications	3.7
Structures	6452
Other	0
Total hopper payload	10,000
Optimized hopper mass	**43,012**

These mass values make bringing such a vehicle from Earth, even without fuel, a task for some time in the future. The same will be true of any pressurized human vehicle, but a hovering hopper has an unparalleled ability to negotiate terrain and could be piloted by an astronaut to explore and respond to emergent information *in situ*.

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[176] NASA, *The Altair Lunar Lander*

4.3.4 Mars Missions Summary

A range of example hop scenarios were explored to demonstrate the utility of hoppers on Mars. The first analyzed a hop to the floor of the deepest feature on the planet, Valles Marineris. After a ballistic hop to reach the valley's brink from anywhere in a landing uncertainty ellipse, the hopper would descend to its bottom, observing the steeply-sloped valley walls. This hover hop would traverse 25 km horizontally and 10 km vertically. Designing for a 50 kg payload, the hopper would have a dry mass of 117 kg; this pair of hops would cost 138 kg in fuel, yielding a total wet mass of 256 kg.

The second example was exploration of some of Arsia Mons' many intriguing features. For a 25 kg payload moving through 3 hops of 15 km horizontally at a hover height of 1 km, a hopper with 108 kg dry mass would be required. It would begin the mission at 256 kg, using 148 kg of fuel.

A final example was human exploration of a region on the edge of Isidis Planatia. Moving a 10,000 kg pressurized habitat 40 km at a 1 km altitude on both legs of a round trip from a base would require a hopper dry mass of about 17,000 kg and propellant mass of about 25,600 kg. The resulting initial mass of 43 metric tons is not within the capacity of current means for getting to Mars, but the mobility advantages may prove worthwhile when human exploration finally begins.

Hoppers provide a good match for such a variety of destination characteristics. Each mission is inherently flexible, and the capabilities demonstrated could be applied to a plethora of other enticing targets. The abilities to clear rough terrain and adapt to discoveries on the ground, all with little new technology, are what makes hoppers broadly appealing for the highly variable terrain of Mars. Future capabilities like utilization of *in situ* carbon dioxide to oxidize propellant brought from Earth, as discussed in Shafirovich et al., will only make hoppers on Mars more attractive. [6]

IV.4. Titan

4.4.1 Titan Mission Motivation

Titan is inarguably one of the most interesting places in the Solar System, and there are numerous reasons to prioritize its exploration. The most compelling relate to the dense (about 4.5 times Earth's[177]) nitrogen atmosphere with a rich and varied composition of organic compounds,[178] and the presence of stable liquid bodies in the form of ethane lakes and streams. Despite an uninviting surface temperature around 94 K,[177] Titan's active weather and plentitude of surface water ice, complex chemistry, and likely subsurface water ocean make it a promising site for research in proto-biology. Tectonic and cryovolcanic action have occurred in the past and likely continue. Ethane and methane also constitute a potential fuel source.

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[177] Yelle, *Engineering Models for Titan's Atmosphere*, 1997 p.13

[178] Yelle et al., *Prebiotic Atmospheric Chemistry on Titan*, 2009, p.1

For these and other reasons, Titan has been the target of steady investigation since the 1940s[179]. The Cassini-Huygens mission continues to give the moon special attention since it arrived in the Saturn system in 2004 and in 2005 landed the Huygens probe on its surface.[180] Even after having directed this attention to Titan, the planetary science community is anxious for more.

Though missions to Jupiter's moon Europa, the total Jupiter and Saturn systems, and the further planets are prominent in discussions about the next outer Solar System probes, Titan remains a major target. The Titan Explorer[181] and Titan Saturn System Mission[182] are two detailed options that have been extensively developed and considered. The National Research Council's current planetary science decadal survey is considering 11 outer Solar System missions, of which two focus explicitly on Titan (Titan Lake Lander and Titan Saturn System Mission); no other single target has multiple missions under consideration[160]. NASA's Outer Planets Assessment Group (OPAG) also continues to emphasize missions to Titan[183]. Their recommendations to the decadal survey state:

> 4) OPAG also advocates the need for a focused technology program for the next Outer Planet Flagship Mission, which should be to Titan and Enceladus, in order to be ready for a launch in the mid-2020s.
>
> 5) New Frontiers class missions that should be considered in the interim include... a shallow Saturn probe, a Titan in-situ explorer or probe, a Neptune/Triton/KBO flyby, and a Uranus orbiter[184]

Consensus in this and other submissions to the current planetary science decadal survey for a holistic investigation of Titan is that an orbiter, lander, and airborne component are all necessary.[185,186,187,188] As the 2003 decadal survey report puts it:

> The key elements of the proposed exploration are mobility within the atmosphere so that different levels, weather, and processes can be studied in detail with *in situ* experimentation… In addition, the system is assumed to be capable of making high-resolution remote observations of the surface from various altitudes and of descending to the surface multiple times during the mission to make close-range and possibly *in situ* measurements of surface composition and properties.[189]

These specifications for multiple atmosphere and surface samples invite investigation of the use of hoppers.

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[179] Coustenis and Taylor, *Titan: Exploring an Earth-like World*, 2008, p. 13.

[180] Munsell, "Mission Overview: Introduction"

[181] Johns Hopkins University Applied Physics Laboratory. *Titan Explorer Flagship Mission Study*, 2008

[182] NASA, European Space Agency. *Final Report on the NASA Contribution to a Joint Mission with ESA*, 2009

[183] *Outer Planets Assessment/Analysis Group Meeting Report*, 2010, p.5

[184] McKinnon et al., *Exploration Strategy for the Outer Planets 2013-2020*, 2009, p. 5

[185] Beauchamp et al., *Technologies for Outer Planet Missions*, 2009

[186] Waite, Jr. et al. *Titan Lake Probe*, 2009

[187] Allen et al., *Astrobiological Research Priorities for Titan*, 2009

[188] Coustenis et al., *Future In Situ Balloon Exploration of Titan's Atmosphere and Surface*, 2009

[189] (see Ref.78) NRC Space Studies Board, *New Frontiers in the Solar System*, 2003, p. 132

4.4.2 Titan Mission Concept Design

Proposed missions including a lander would incorporate an orbiting mother ship as a communications link and large-scale observational capability, so an orbiting component is assumed for the current study. Much work has been done to demonstrate the utility of a balloon in the cold, dense atmosphere, and a hopper would have difficulty making comparable upper-atmosphere in-situ observations[190]. However, a hopper could execute sounding flights to any altitude, provided it has sufficient propellant; such a scenario is treated at the end of this section. Even without capability overlap with a balloon, balloon proposals consistently acknowledge the need for a presence on the surface; a hopper can provide this in multiple locations, and take extensive samples of the lower atmosphere. Thus even a hopper without a separate aerial vehicle would address the priority questions of atmospheric, surface, and lake chemistry.

Some proposals call for a network distributed widely over the moon's surface[191]; such a mission would be similar to the lunar network considered in Section 4.2.1 due to Titan's surface gravity being close to that of the Moon's. Other priority objectives include understanding Titan's likely cryovolcanoes and mid-latitude sand dunes; hoppers may well be enabling for these missions. However, because a visit to the polar lakes seems more highly prioritized, versatile, and interesting, the present study will examine a lander at Titan's largest known body of liquid – indeed the largest known body of surface liquid off the Earth – Kraken Mare.

The priorities for any Titan mission are atmospheric observation via mass spectrometry and sample analysis, and compositional analysis of a liquid body such as a lake or river. ESA's proposal for the balloon and lake lander components of the Titan Saturn System Mission lists as the instruments for its lander an imager with lamp, a chemical analyzer, a meteorological and electrical observation package, a surface properties package with acoustic and magnetic sensors, and a radio science package. These instruments sum to 27 kg[192]. Since the lander portion of TSSM is only designed to last 9 hours, including 6 hours of descent from the orbiter, and because a hopper may be used to conduct some of the balloon's mission, some instruments from the balloon are added for the present analysis. These are an imaging spectrometer and a radar sounder, adding approximately 10 kg[193]. Allowing 3 kg more for configuration differences, the on-board instrument mass considered here will be 40 kg. An additional unspecified 10 kg can be dropped at each landing site before the final, yielding a total of 80 kg for scientific payload.

Mass needs for propellant, engine, and structure depend on the subsequent analysis, which results in a total vehicle wet mass landed on the surface of 235 kg. To estimate needs for interface to the orbiter and an entry, descent, and landing (EDL) system, the

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[190] NASA, "Titan Saturn System Mission Backgrounder"

[191] Lorenz, *The Case for a Titan Geophysical Network Mission*, 2009

[192] European Space Agency. *TSSM In Situ Elements*, p. iii

[193] (see Ref.192) European Space Agency. *TSSM In Situ Elements*, p. 31-35

TSSM in-situ balloon and lake lander can be used as a baseline. All these probes would descend from the orbiter and use aerobraking in Titan's thick atmosphere as the exclusive means of decelerating. Front and back heat shields and a set of parachutes with support systems collectively eliminate the need to fire a landing engine during this phase. The balloon uses 52% of its on-orbit mass for orbiter-interface and landing[194], while the lake lander uses 55%[195]. Since the hopper is more similar in size and EDL needs to the lander, this analysis will assume 55% of on-orbit mass is used for orbiter-interface and EDL, giving an on-orbit hopper mass of 427 kg.

Though the emphasis of this section is not on hopper subsystems, some mention should be given to power, communication, and propulsion. At Saturn's distance from the Sun and considering Titan's hazy atmosphere, photovoltaic power is not attractive. The leading alternatives are battery and radiothermal generator. The latter will provide more power for much longer using less mass, though the former may be more desirable considering international regulation and the dwindling supply of necessary plutonium-238. Regarding communication, the hopper will only have to uplink to the orbiting relay, which will facilitate transmissions to and from Earth. A reasonable estimate of 10kg is allotted to the hopper for power and communications.

The hopper's engine is assumed to be gimbaled to provide guidance and attitude control, and capable of throttling to make both ballistic and hover hops efficient. Even more than at Earth's surface, thrust from a rocket engine designed to operate in a vacuum will be reduced because of Titan's high ambient surface pressure. However, since a parachute is sufficient for slowing the hopper on entry and no propulsion is needed above the lower atmosphere, an engine can be optimized for these conditions. Next, while hydrazine is frequently preferred as a propellant for space missions because of its simplicity, reliability, and performance, due consideration should be given to contamination of the area around the hopper, as well as engine performance and other spacecraft effects from the exhaust's chemical and physical interaction with the cold, high-density volatiles in Titan's crust and atmosphere. On this note, Titan's air has high concentrations of ethane and methane, both of which could conceivably be employed as a propellant if utilization technology were sufficiently mature. Such a fuel supply would extend a hopper's mission duration to depend on power supply or parts lifetimes; many high-altitude hops to makes extensive *in situ* observations of Titan's entire atmosphere then become viable. Finally, the calculations in this section have ignored aerodynamic drag and wind, which will necessitate a significant increase in propulsion capability.

4.4.3 Titan Mission Analysis

For a mission profile, one possibility is for the hopper to land at the closest possible safe distance from a lake as determined by orbital reconnaissance shortly before the landing.

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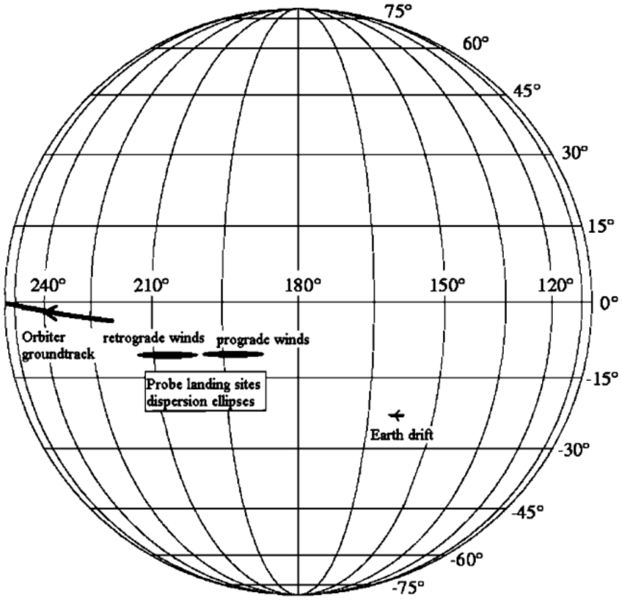
[194] (see Ref.192) European Space Agency. *TSSM In Situ Elements*, p. 73

[195] (see Ref.192) European Space Agency. *TSSM In Situ Elements*, p. 109

One hop could be included to correct for any error or unexpected discoveries in the initial landing. A worst case for this hop distance can be derived from the landing uncertainty ellipse of the Huygens probe, shown in Figure 34. Two ellipses are shown, one for retrograde atmospheric winds, and the other for prograde. Huygens itself confirmed that the winds are prograde (in the direction of Titan's rotation)[196] and ultimately landed very near the center of that ellipse at 10.3°S and 192.4°W[197].

Figure 34. Huygens landing uncertainty ellipses on Titan[198]



The ellipses are about 600 km long, but less than 100 km at the widest. If a straight stretch of lake coast about this long could be identified in the north-south direction, in-line with a likely polar orbit from which the hopper would be released, the hopper would never have to hop more than the ellipse's width. Such an ellipse is shown along the coast of Kraken Mare in Figure 35. This scenario accounts for no improvement in landing precision after the Huygens mission, but allows limitation of the hop distance to 100 km. Refinements in landing precision or site selection could ensure negligible chances of landing in the lake or being unable to reach it in the first hop.

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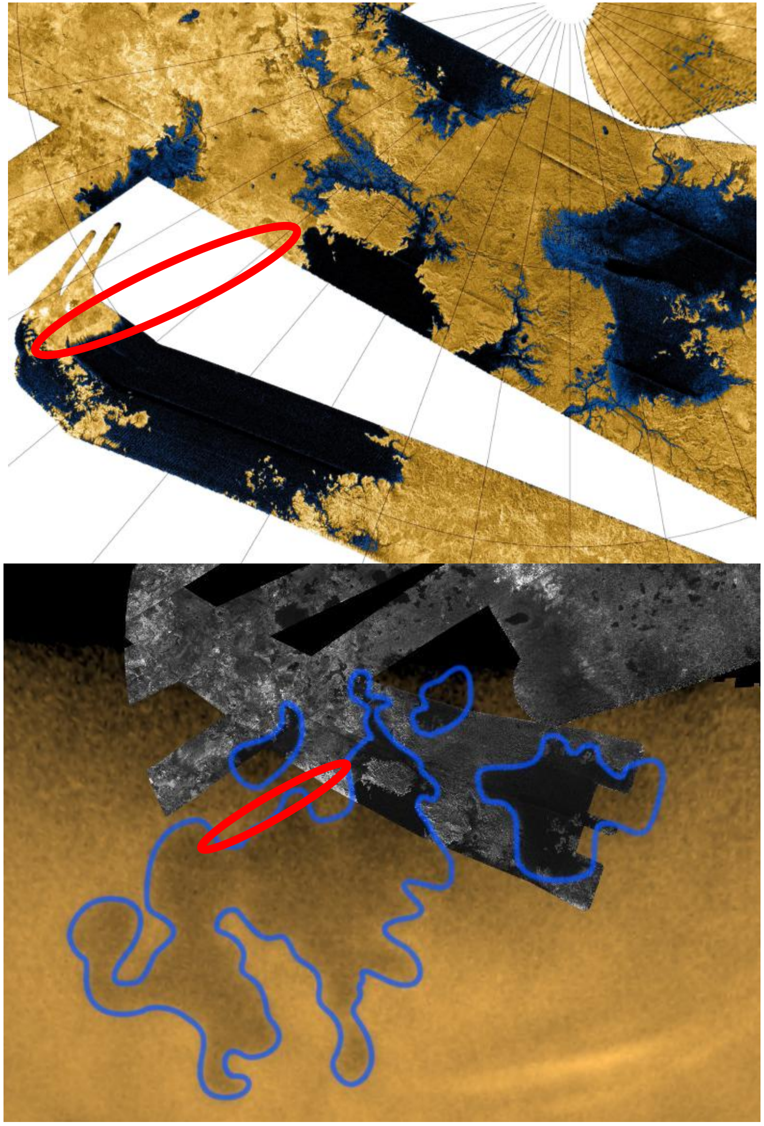
[196] Bird, "The Vertical Profile of Winds on Titan," 2005

[197] Lebreton, "An Overview of the Descent and Landing of the Huygens Probe on Titan," 2005

[198] Lebreton and Mason, *The Huygens Probe: Science, Payload and Mission Overview*, 1997, p. 88

Figure 35. Two views of possible hopper landing site along the coast of Kraken Mare[199,200]



For such a long hop, the trajectory should be ballistic. With a 45° launch angle, manipulation of Middleton's hop model indicates an engine thrust of 440 N and a burn time of 224 s. The hop trajectory is shown in Figure 36, with the BallisticHop inputs in outputs in Table 37 just below.

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[199] NASA/Jet Propulsion Laboratory/United States Geological Survey, "…Titan's North Polar Region," 2007

[200] NASA/Jet Propulsion Laboratory/United States Geological Survey, "…Wetlands of Titan," 2007

Figure 36. Ballistic hop trajectory on Titan

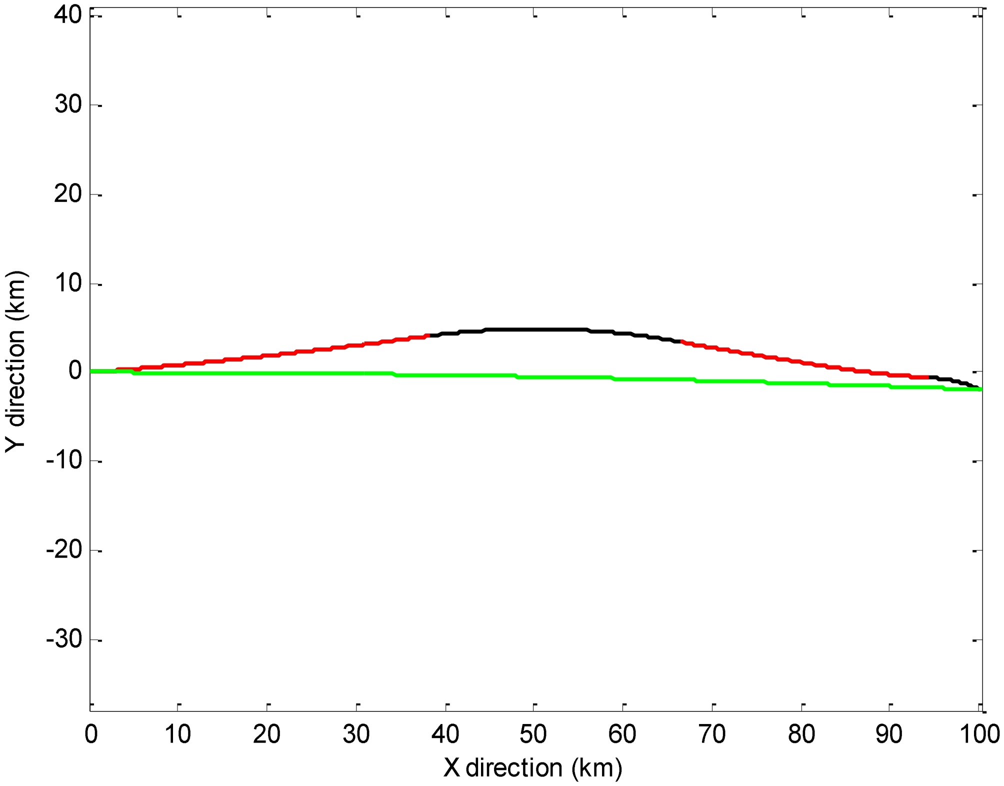

Table 37. BallisticHop inputs and outputs for hop from anywhere inside Titan landing ellipse

	Input Values
Launch angle, ϕ (degrees)	45
Engine thrust (N)	440
Launch thrust time (s)	224
Start mass (kg)	217
Engine specific impulse, I_{sp} (s)	300
	Output Values
Range (km)	100
End mass (kg)	166
Velocity change, ΔV (m/s)	785
Initial hopper mass (kg)	**217**

Thereafter the hopper, using the same engine, could execute a precision low-altitude hover hop to cover up to 10 km and land literally on the brink of the lake, enabling liquid sample collection and analysis. This would be achieved by throttling the engine down to 330 N (75% of the 440 N needed for the ballistic hop) and hovering at a constant height of150 m to clear local terrain,[201] which enables close-range observation of the surface

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[201] Lorenz et al., "Titan's Shape, Radius, and Landscape from Cassini Radar Altimetry," 2007

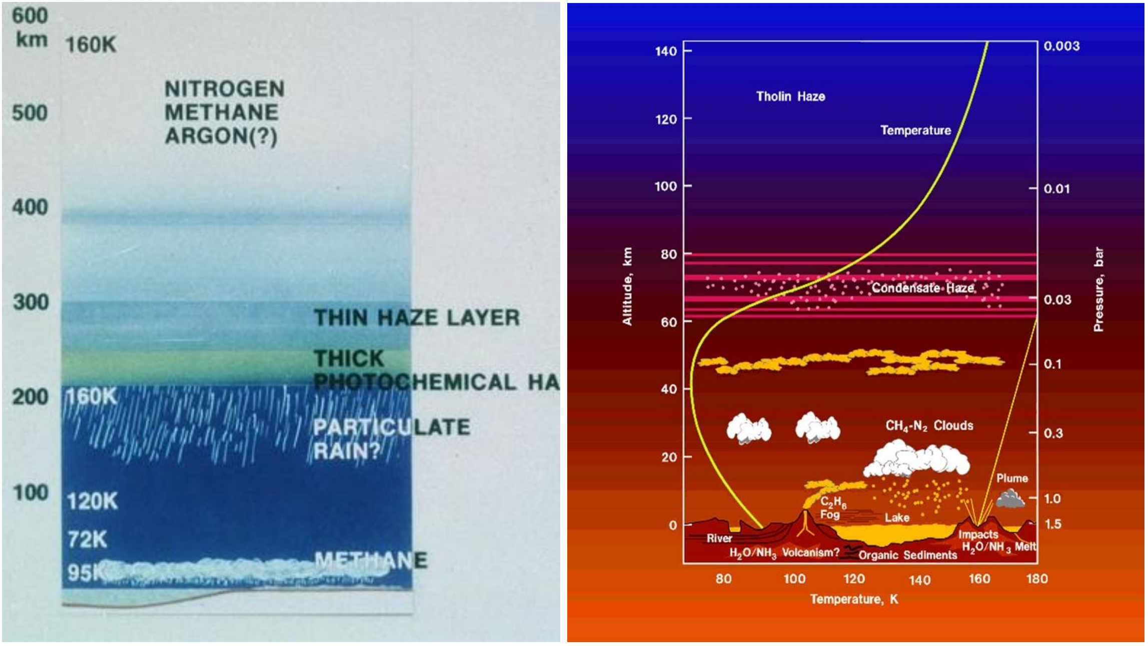
and in-flight determination and adjustment of the landing site. After these two hops, another could be made to an island in the lake, a stream flowing into or out of the lake, another point along the shore, or any other destination that appears interesting based on information gathered *in situ*. Next, capacity is included for one more hover hop; this capability gives the mission significant flexibility and robustness. The Hoptimizer inputs and outputs for this set of hover hops are listed in Table 38.

Table 38. Hoptimizer inputs and outputs for 3 hovering hops on Titan; thrust = 330 N. * indicates these values account for Hoptimizer's "drop mass" being part of the 40 kg payload

	Input Values
Local gravity, g (m/s^2)	1.352
Engine specific impulse, I_{sp} (s)	300
Number of hops	3
Fixed payload mass (kg)	40
Hover height (m)	150
Single hop distance (m)	10,000
Payload dropped per site (kg)	10
	Output Masses (kg)
Propellant	44.4
Tank	8.4
Engine	4.8
Power	10
Communications	3.8
Structures	24.9
Other	-10*
Total hopper payload	80*
Optimized hopper mass	**166**
End mass (no spent fuel or drop loads)	**92**

After these maneuvers, additional capacity may be added to allow the hopper to sound the atmosphere. The TSSM balloon was planned to drift at a nominal altitude of 10 km, for at least 6 months. Figure 37 shows how this altitude range fits into Titan's total atmosphere, which was assumed by the Huygens mission to end at its "entry" altitude of 1270 km[197]. While this sustained presence at altitude is not possible with a hopper, visits to the balloon design altitude can be achieved with the addition of more fuel and tanking.

Figure 37. Titan's atmosphere: (LEFT)[202] ground to 600 km, (RIGHT)[203] ground to 140 km



By this point in the mission, the hopper will already have had the opportunity to observe this range of the atmosphere once during initial descent. The first hop after landing then follows a ballistic trajectory that achieves about 5 km in height; the launch angle could be adjusted to reach slightly higher for little fuel cost. Addition of one final ballistic hop to 10 km altitude, as shown in Figure 38, will require about 130 kg more total mass in orbit; this value could be reduced if the hopper neglected the final braking phase and crash landed. Such a hop with braking would launch at 89° relative to the horizon and cover 0.9 km over the ground, assuming no wind. Saving this hop for the end of the mission entails carrying the requisite fuel throughout the earlier phases, putting the hopper at 120 kg at the end of the hover hop sequence (up from 92 kg), 289 kg at initial landing before the first ballistic hop (up from 217), and 525 kg in orbit with the heat shield and parachute system (up from 395 kg). The engine thrust will have to be increased to 586 N (up from 440 N) to accommodate the added mass. Additional sounding hops could be added for similar costs that trickle back according roughly to the rocket equation.[13]

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[202] NASA/Jet Propulsion Laboratory, “Atmosphere Comparison”

[203] NASA/Jet Propulsion Laboratory, “Model of Titan’s Atmosphere”

Figure 38. Final ballistic hop to sound atmosphere

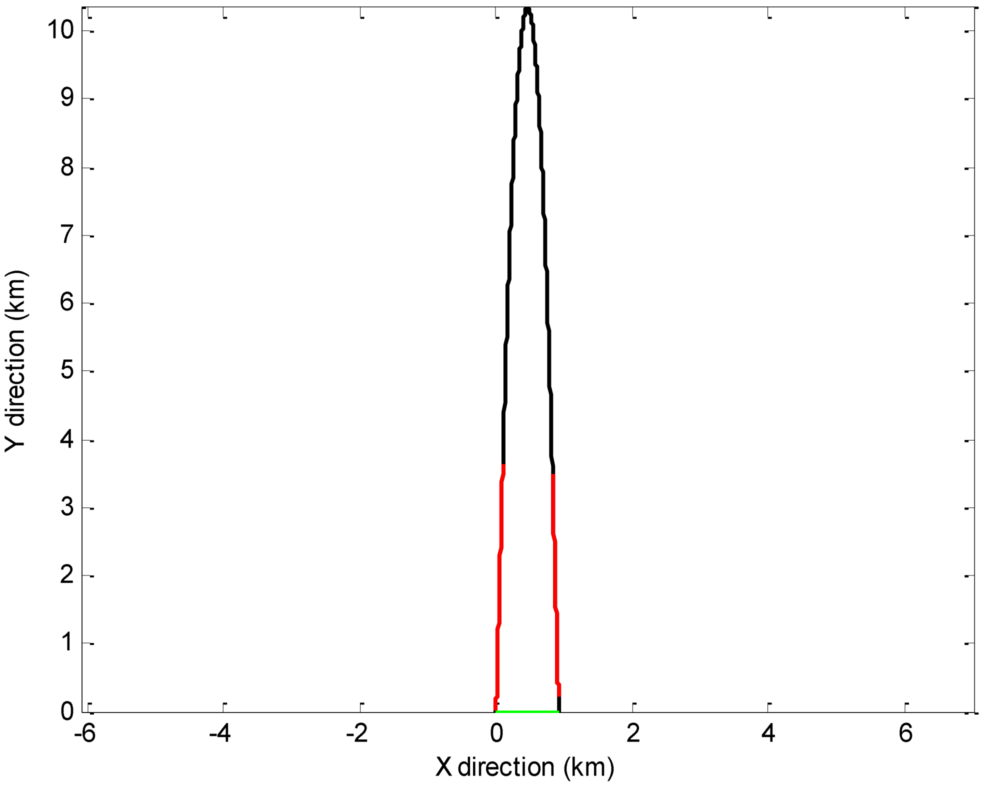

Figure 39 shows the hop profile of this mission. Table 39 through Table 41 show the ballistic, hover, and ballistic hop model inputs and outputs in the order they occur in the mission.

Figure 39. Titan mission profile, NOT TO SCALE

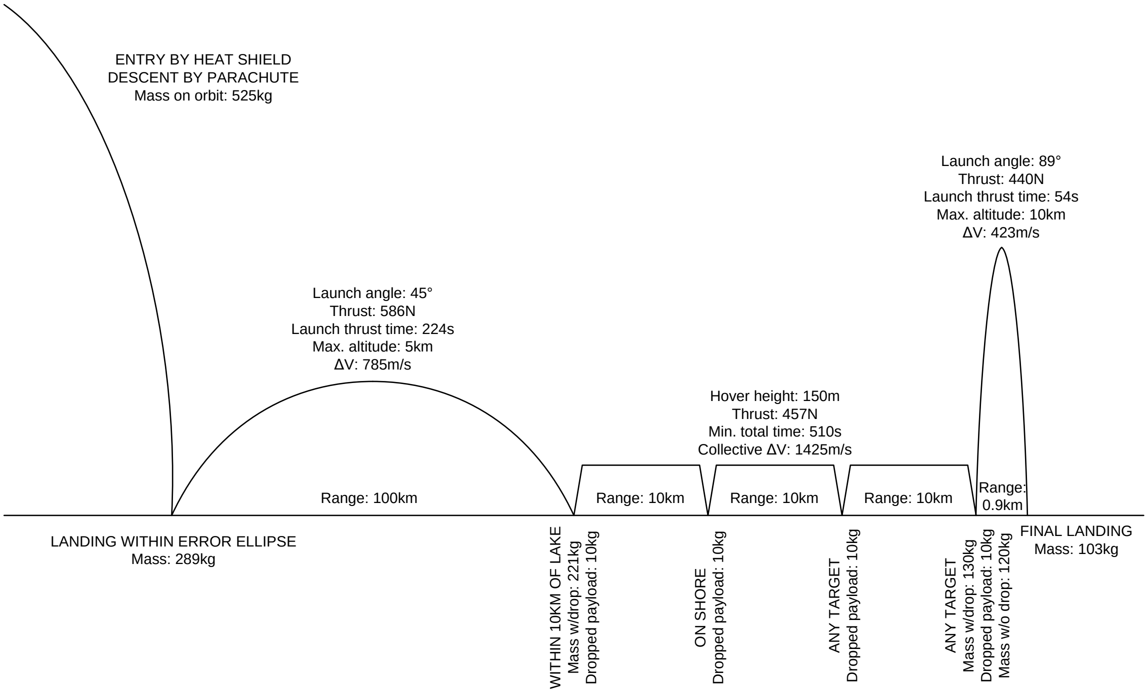

Table 39. BallisticHop inputs and outputs for initial ballistic hop on Titan with fuel for final sounding hop

	Input Values
Launch angle, ϕ (degrees)	45
Engine thrust (N)	586
Launch thrust time (s)	224
Start mass (kg)	289
Engine specific impulse, I_{sp} (s)	300
	Output Values
Range (km)	100
End mass (kg)	221
Velocity change, ΔV (m/s)	785
Initial hopper mass (kg)	**289**

Table 40. Hoptimizer inputs and outputs for hovering hops on Titan with fuel for final sounding hop; thrust = 457 N

	Input Values
Local gravity, g (m/s^2)	1.352
Engine specific impulse, I_{sp} (s)	300
Number of hops	3
Fixed payload mass (kg)	40
Hover height (m)	150
Single hop distance (m)	10,000
Payload dropped per site (kg)	10
	Output Masses (kg)
Propellant	61.2
Tank	10.4
Engine	5.9
Power	10
Communications	3.8
Structures	33.2
Other	17
Total hopper payload	80
Optimized hopper mass	**221**
End mass (no spent fuel or drop loads)	**103**

Table 41. BallisticHop inputs and outputs for altitude sounding hop on Titan

	Input Values
Launch angle, ϕ (degrees)	89
Engine thrust (N)	440
Launch thrust time (s)	54
Start mass (kg)	120
Engine specific impulse, I_{sp} (s)	300
	Output Values
Range (km)	0.917
End mass (kg)	103
Velocity change, ΔV (m/s)	423
Initial hopper mass (kg)	**120**

4.4.4 Titan Mission Summary

Exploration priorities for Titan are chemical analysis of the atmosphere and lakes; existing proposals assume an orbiter, an aerial vehicle, and a lake lander employed simultaneously. Using a hopper as the landing component, and at least parts of the aerial component, will give the mission much more capability and flexibility, for little additional mass or cost. This section analyzed a hopper mission to the coast of Kraken Mare, near Titan's north pole, and showed that it could offer the same science opportunities and results as the combined balloon and lake lander segments of the TSSM, except sustained presence high in the atmosphere as with a balloon. With 130 kg added to the hopper's on-orbit mass, a sounding hop to the same height as the proposed balloon is possible. The science payload is assumed the same as the TSSM lake lander, with portions of the balloon payload and extra allowance for changes, plus 10 kg of unspecified equipment dropped at every landing except the last, where the onboard payload continues operating as long as the power supply lasts.

This mission profile would begin with the hopper separating from the Titan orbiter with a mass of 395 kg and descending to the surface. Descent using a heat shield and parachutes would place the hopper within a 600 km by 100 km ellipse with a mass of 217 kg. This landing ellipse would be along the coast of Kraken Mare, offering the hopper guaranteed access to its coast with a ballistic hop of 100 km or less. Such a hop would execute 785 m/s of ΔV, leaving the hopper at a mass of 166 kg. From this landing site, a relatively short hover hop could place the vehicle literally on the brink of the lake, allowing direct contact with the liquid. This and the remaining hover hops would cover 10 km or less, hovering at a height of 150 m. After the first lake sample, the hopper may move to an island in the lake or any other nearby target. Next, there is capacity for one additional hop. The final dry mass of the hopper is 92 kg, 40 kg of which is the on-board science package. The hover hops undergo a collective ΔV of 1737 m/s, giving a propelled ΔV for the hopper mission of 2522 m/s. Addition at mission's end of a single ballistic hop to sound the atmosphere at 10 km would increase the total propelled ΔV to 2633 m/s and increase the on-orbit hopper mass to 525 kg, as illustrated in Figure 39.

TSSM's lake lander has an on-orbit mass of 190 kg, and the balloon is 571 kg, for a total of 761 kg. At 525 kg (2/3 the mass), a hopper mission could accomplish most of the same exploration objectives and add significant capability and flexibility. A hopper might also require less technology development than a balloon and lake lander together, or possibly for either alone. Beyond similar entry, descent, and landing systems, a hopper would require for minimum functionality a throttling engine with associated navigation and control avionics, in comparison to the deployed buoyant systems on the other two vehicles. This trade-off is worth further investigation in light of the scientific capabilities of each approach.

IV.5. Asteroids and Other Small Objects

A dramatically different implementation of hoppers would be on small bodies like asteroids or comets. A hopper could land on such a body and visit multiple locations, making observations or collecting samples. For targets in the asteroid belt or among, for example, groups of near-Earth Amor asteroids, a hopper could visit one and then move to another. Such a mission might fit well into the "flexible path" approach for human exploration. Another target might be Ceres, a dwarf planet that composes a third of the asteroid belt's mass and contains substantial water.[204]

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[204] NASA, *Dawn: A Journey to the Beginning of the Solar System*

Moving from object to object could continue as long as sufficient propellant remained. A study for the 2011 planetary science decadal survey of a mission to Jupiter's Trojan asteroids (defined by their location at the L4 and L5 Lagrange points of Jupiter's orbit) requires 1.6 km/s of ΔV for the total mission post-launch.[205] This includes maneuvers to acquire the desired orbit and fly by a multiple asteroids; it can be inferred that movement between is possible for much less ΔV than the mission total.

Maneuvering operations in the proximity of a small, irregularly shaped object constitute a novel and analytically intense problem. Work to analyze these dynamics is exemplified by a study on orbits about elliptical asteroids by Bellerose and Scheeres.[206] While there is theoretical work to be done in optimizing flights of this nature, the technology is available. Using the hopper concept could change a mission from a fly-by or single visit to a more productive multi-world tour. This thesis does not include further analysis of hoppers on and among small bodies, but the idea merits further investigation.

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[205] Brown, *Trojan Tour Decadal Study*, p.39

[206] Bellerose and Scheeres, *Dynamics and Control for Surface Exploration of Small Bodies*, 2008

Chapter V: Findings

V.1. Results Summary

5.1.1 Solar System Exploration Objectives

The first part of Chapter II gives a detailed description of the space policy process. Next, major space policy issues are presented; Table 7, reproduced here, summarizes them.

Category	*Issue*
General space policy issues	Fundamental science questions, as described in Section 2.1.2
	High profile space policy issues: hazards, Pu-238, ITAR
	Human exploration policy issues
Hopper-relevant policy issues	Relevance to "flexible path"
	Technology leadership, domestic and international
	Public engagement
Policy issues hoppers might address in the future	Remote presence/operation
	Exploration networks
	Simple added capability

From here, science exploration objectives are described. This begins with a description of the most important sources for science objectives, and then summarizes fundamental questions that underlie the entire Solar System science enterprise in

Table 8 on page 46, which is too large for this summary. With this foundation, destinations where hoppers could potentially be useful are listed and described, with accompanying science objective examples for each. This is not copied here due to its length, but can be found in Section 2.2.3 beginning on page 48.

5.1.2 Mapping Vehicle Attributes to Exploration Objectives

This chapter opens with a quick description of possible planetary exploration vehicle types and proceeds with a more detailed presentation of hopper characteristics. Table 16, copied here *without hopper disadvantages*, shows how other vehicles compare to hoppers in the performance categories described.

Advantages	*Fly-by*	*Orbiter*	*Impactor*	*Lander*	*Rover, etc.*	*Aircraft*	*Subsurface*	*Notes*
Rapid terrain coverage	--	--			++	+	++	Some types of aircraft, like balloons, would be much slower
Rough and steep terrain					++	+		Aircraft are similar, but likely require more landing space
Precision navigation	++	++	++	++	-	+		
Navigational flexibility	++	++	++	++	0	0		Rovers are slower and aircraft may be hard to control
Low-altitude observation and hover	++	++				+		Hovering applies to ability to move over ground at any speed
Repeated access to surface and atmosphere	++	++	++	++	++	+	++	Hoppers require fuel to fly, but aircraft require flat space to land

Next, pertinent aspects of Solar System missions and destinations are developed, and the subsequent section shows how hoppers stand to address them, as summarized in Table 20 on page 64. The chapter proceeds to compare hoppers with other vehicles in their suitability to exploration policy goals, as this copy of Table 21 describes.

Policy Objectives	*Fly-by*	*Orbiter*	*Impactor*	*Lander*	*Rover, etc.*	*Aircraft*	*Subsurface*	*Notes*
Flexible path	+	+	+	+	0	+		Hoppers cover a broad range of surfaces of interest for astronauts
Technological leadership, domestic and international	++	++	++	++	+	+		Tech., intl., industry/workforce, commercial, education
Public engagement	++	++	++	++	+	0	++	Hoppers can visit a variety of sites and move dramatically between
Remote presence/operation	++	++	++	++	0	0	0	

The chapter concludes by describing how hoppers stand to satisfy established goals of the science community. A list of 28 high profile missions released by the current planetary science decadal survey is employed to synopsize these community goals; this matching is located in

Table 22 on page 67.

5.1.3 Model Missions

Earth's Moon

Four model missions are considered. Using a single hopper to implement a 4-node lunar network is shown to be an attractive concept, but requires a 2989kg hopper landed on the Moon, implying 6013kg in low lunar orbit, as compared to a total of 1080kg in orbit for four stationary lander nodes. The hopper option seems prohibitively massive. But for accessing both the nearly-permanently sunlit rim of Shackleton Crater and its permanently shadowed floor 4 km below, a 123kg hopper appears desirable. Next, newly discovered pits on the Moon offer enticing access to potential underground caverns, and a hopper with slightly over 110 kg of landed mass could easily descend, make observations, and return to the surface.

The most detailed consideration is given to a sample return mission to the Moon's South Pole-Aitken Basin. A NASA proposal for a 900 kg stationary lander is used as a baseline. A similar payload placed on a hopper making 5 hops, and therefore visiting 6 sites, offers greatly increased chances of observing all the desired geological materials, but has a mass of 2598 kg at initial landing. For some added complexity, a lander with a small hopper that collects samples and return to place them in an Earth-return vehicle could offer similar results for only 189kg (21%) more than the baseline mission.

Mars

Because Mars is the subject of extensive curiosity and study, a set of three moderately-defined missions serves to illustrate broadly the extent of services a hopper could render. First, a 256 kg hopper could descend to the bottom of Valles Marineris, making a unique set of observations including the surrounding highlands, the 10 km cliff face, and the valley floor itself. Second, a set of intriguing destinations on the slopes of Arsia Mons provides an array of targets for a 256 kg hopper capable of making three 15km hops. Finally, a series of hops in the vicinity of a conceptual human base on the edge of Isidis Planatia demonstrates that a hopper's utility comes at a high cost – about 42.5 metric tons – when a pressurized human habitat is transported.

Titan

NASA's Titan Saturn System Mission is used as a baseline to evaluate a hopper that would land near the edge of the moon's liquid ethane lake Kraken Mare, make a few hops to and along its shore, and finish with at least one hop to sound the atmosphere up to 10km. This mission could accomplish most of the goals of TSSM for a mass of 509kg in orbit, compared to TSSM's on-orbit payload 761 kg, which includes a lake lander and atmospheric balloon.

Asteroids and Other Small Objects

Though no analysis was conducted for this class of Solar System bodies, mention is made of how hoppers could enable novel productivity in exploring multiple small targets.

V.2. Policy Recommendations

This thesis has described the ingredients needed for a push to promote hopper technology toward fulfilling its potential to enable Solar System exploration. Such an effort is needed because, as with many beneficial novel technologies, a strong force of demonstration will be required before the benefit is broadly recognized. Hoppers are indeed such a beneficial technology because, for little change in the way spacecraft are built, they offer a very capable new mode of surface mobility. This section explains specific recommendations.

Follow the process

In the U.S., the science community, the Presidential administration, and Congress each year contend in a process to produce budgets for NASA, the National Science Foundation, and other agencies that conduct space science. The President also sets the national posture for exploration policy, which can bear on international and commercial involvement, NASA's plans, and willingness to spend money in Congress and as a public. NASA maintains a plan working plan for exploration that, with extensive collaboration with the science community, is founded in the decadal surveys.

Historically, this process is well established and more stable and predictable in space science than in human space exploration. Knowing – and playing to – the parties and dynamics of this process will get hoppers into the arena. Hoppers should be explained in simple, honest terms that make clear where and how they offer benefits.

Attract attention

The Next Giant Leap team, particularly Draper Laboratory and MIT, are well on their way to establishing the hopper concept in the space technology community by publishing papers, presenting at conferences, and attracting media attention. Multimedia information should be made available to investors, scientists, academics, and as broad a public base as possible. Technical papers and articles stir attention, and demonstrations attract new audiences and drive home the reality of hopper capabilities.

Submit proposals

Possibly not long in the future, the hopper concept and specific capabilities will be developed to a point that they can be explicitly incorporated first into grant and research proposals, and then into space missions. Some of the model missions discussed in this thesis may provide material for a NASA Discovery or New Frontiers mission. The last round of New Frontiers competition resulted in three finalists being selected in 2009. By the time another announcement of opportunity is released, a hopper-enabled mission should be ready to compete. Only the best win, but hoppers have unique inherent strengths.

Look ahead

Hoppers should be a central part of planetary networks that include orbiters, stationary surface installations, rovers, aerial vehicles on worlds with atmospheres, and eventually human bases. These networks also include the space transportation, communication, and Earth-based services needed to support in-situ exploration. The most productive route to fitting into future exploration initiatives is to understand how all these elements work together, and what in particular hoppers can contribute.

V.3. Future Work

First, the entire policy outlook of this thesis should be updated with the outcome of the NRC Space Studies Board planetary science decadal survey, which is scheduled for release in early spring, 2011. This thesis anticipates the results with all publicly available information, but the finalized set of Solar System exploration priorities for 2013-2020 is not available and will be the strongest authority for directing planetary exploration missions for the decade.

Of only slightly less relevance are the lingering results of the stalemate between the 111th U.S. Congress and the Obama administration regarding future plans for NASA. These plans primarily concern human exploration, but space transportation systems, the structure of the aerospace industry and commerce, and funding and organizational priorities within NASA are all hanging in the balance. With the 112th Congress entering session the month of this writing's release, some way forward should become clear over the next year.

Further regarding science objectives for planetary exploration, a more exhaustive and parameterized collection of priorities including the 2011 decadal results could provide a more satisfying grounding for the justification of hoppers as a desirable exploration tool.

For hoppers themselves, work should continue as planned to characterize intrinsic hopper attributes rigorously, and to extend the present work into a comprehensive general, theoretical framework for determining, in quantitative terms, when and where a hopper is desirable in comparison to other space vehicle types. Work should also continue to develop and characterize real hopper systems on physical testbeds like Talaris.

In aid to this hopper characterization effort, and to continue the work begun with the model missions in Chapter IV, the analytical models for hopper design and dynamics should be further developed. The first priorities should be incorporating higher-fidelity models for the individual spacecraft systems like power and propulsion, and making more realistic dynamical models to include aerodynamic drag, life-like landing sequences, optimized ballistic launch angle, and allowance for thruster gimbaling and flight phase transition limitations. Determination should be made of when a hovering or ballistic hop is appropriate; this effort should incorporate both technical concerns like fuel and speed, and broader mission-architecture level considerations such as added science from low-altitude hovering and navigational flexibility.

Finally, an additional model mission examining the use of a hopper in visiting multiple small bodies like asteroids would make the presented suite of hopper examples more comprehensive and compelling. Such a mission analysis would showcase a hopper's ability to land on a few targets of no atmosphere and low gravity that are separated by large distances yet have small needs for velocity-change thruster burns.

V.4. Conclusion

Hopper spacecraft provide an extensive new category of capability to the Solar System exploration enterprise. Under specific circumstances, advantages easily outweigh the price of unproven technology and heavy dependence on fuel. Analysis of hypothetical missions – that are technically and programmatically plausible in the near-term – to Earth's Moon, Mars, and Saturn's moon Titan demonstrate that hopper performance is desirable over other modes of transportation in many but not all cases. The organizations and people who determine the future direction of Solar System exploration are generally unaware of the benefits afforded by hoppers, but analysis of the present and foreseeable national exploration science and policy landscapes indicates that hoppers can and should play a role in missions during this and upcoming decades. Policy recommendations are provided toward that end.

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Gaps in the sequence indicate footnotes that cross-reference other references listed here. “NASA” signifies the National Aeronautics and Space Administration.

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