A lunar explorer self-contained PicoRover

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In this paper some results of the study group of the Team FREDNET is presented, which designs a lunar rover for an open source mission to the Moon within the Google Lunar X-Prize (GLXP). Team FREDNET (TFN) is an open source non-profit program that combines the talents of scientists, engineers, and technologists to create a viable solution for the continued exploration of the lunar environment.

A relatively simple model that fulfills all basic GLXP mission requirements of lunar rovers is presented. This design is based on a sphere that is able to roll in a regolith slope and steer over the surface. This is possible thanks to a very light weight self-enclosed device, that is the result of having selected Commercial-Off-The-Shelf (COTS) components to conform the basic subsystems inside the box. This model has a diameter smaller than 0.15 meters and weights less than 500 grams. Moreover, it has a large payload area inside that is occupied by an Elphel model High Definition (HD) camera.

The study of the Team FREDNET rover group involves a minimal number of subsystems. Each subsystem is afford by the technical expertise of the open source community. These subsystems are communications, thermal control, radiation protection, power supply, image processing, attitude determination, positioning and disposal. The communication and thermal issues as well as the duration of the mission are optimized in order to minimize the exposure to solar radiation and to the extreme effects of the Moon's thermal environment.

I. Introduction

Imagine to design, to build and to operate a complete lunar mission by the global community. This can be the first step inside a contest to initialize the Moon exploration promoted neither the government not the industry but by an universal team.

According to The New York Times, Chang [1] reports, "President Obama will end NASA's return mission to the moon and turn to private companies to launch astronauts into space when he unveils his budget request to Congress next week, an administration official said Thursday." The unnamed official said NASA would be given a "more sustainable path," but according to the article this has "angered some members of Congress, particularly from Texas...and Florida." Even though NASA would receive about $6 billion more over five years, it is "much less" than that recommended by the Augustine Commission. The article notes this plan "would further dismantle what remains of the human spaceflight initiative started by the Bush administration," but Augustine panel member Sally Ride complemented the plan as an 'innovative approach for NASA."

It seams that manned Moon exploration may wait a few decades. For this reason, private sector must take action. Is the Moon exploration an activity for the industry or is a governmental responsibility? In one hand, it is clear that industry only will take profit when the balance between cost and benefits decays to the benefit band and seams that for the moment is not the case. In the other hand government is focused in other priorities. Who goes to explore the Moon and give a feasible response to the industry about the valorous resource that the Moon is for the humanity? To answer this question we want to raise the option of the Open Source approach.

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In between, private industries are trying to take the first step in this issue. Of course, first investors will take bigger benefit because its privileged position. A good example of this is the Google initiative of promoting the space exploration through the innovation. Companies like the Google preferred partners [12] that give many discounts to the private Moon exploration inside the Google Lunar X PRIZE (GLXP) contest. GLXP is a 30 million dollar competition for the first privately funded team to send a robot to the Moon, travel 500 meters and transmit video, images and data back to the Earth.

The community have demonstrated in the history that have enough power to develop and implement complex projects. Team FREDNET want demonstrate that this is the way to win the Google Lunar X-Prize (GLXP) as a first step to the human colonization. Government missions are based in huge budgets supported by nation interests. Opposite, commercial missions are based on narrow budgets as a product of a good market interest. A GLXP mission to the Moon is not neither governmental nor commercial. First, the commercial cost is higher than the prize it self. Second, no government is allowed to participate in the GLXP contest. For these reasons, Team FREDNET believes in the Open Source approach. Investment has to be based on a future product that makes the space exploration cheaper for those companies, universities and partners that are investing in this open source project. The benefit of this investment will be reached when travel to the Moon become a weekly activity.

Team FREDNET is a group of scientists, technologists, and engineers who are using their combined talents to create a solution to compete in the Google Lunar X Prize based on the Open Source model. This kind of organization, contestant for a GLXP mission to the Moon, requires a very low budget and a good strategy to raise founds. It is translated in a Team FREDNET directive of *Absolute minimums*. What is the minimum mission architecture to achieve the GLXP mission to the Moon? KISS stands for *Keep It Simple and Safe*. The design will be based on the so called *Single fault systems*. No redundant subsystems demand reliable hardware allowing lower the price. For this reason it is mandatory to implement the well known *Use what we testing and test what we use*; developing, implementing, testing and validating some news technologies but also reusing old well known technologies when required. A cheap mission can't base its design in a high level of qualification. Quality assurance means high cost; the higher the quality, the higher the cost; for this reason, instead of use redundancy, for this kind of mission, it is better to use reliable components and use as less components as possible. In Figure 1 there is an example of design that meets this idea of simplicity; it is a lunar explorer, self-contained pico-rover that has less than one kilogram of mass. This ball-like rover uses a counterweight to roll over the Moon's surface. Inside there is a large volume for the payload. Laterally it has a mast that holds and antenna and a external camera. This design do not needs wheels or any external part to climb small slopes while the stability is guarantee in any circumstance.

The question we arise here is: what is the minimum mission architecture to achieve the GLXP mission to the Moon and then the Moon exploration market? We want to explore traditional and non traditional approaches in order to know what is the best cost-effective architecture and propose some real solutions to the open community. Some trade studies done by the community are presented.

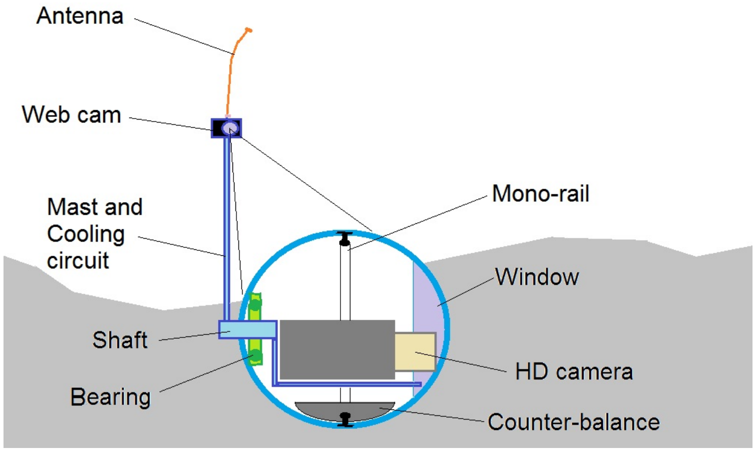


Figure 1. Prototype design. Distribution of main components inside the shield and the antenna

II. Direct lunar descent vs parking orbit

In this section a trade study is presented based on the use of direct lunar descent vs parking orbit in a very high level of analysis. The launch path is, perhaps, one of the most expensive cost for a mission to the Moon except for the development cost. A reduction of cost based on some trajectory techniques are proposed.

II.A. Nomenclature in brief

A nomenclature list and related concepts [9] used in this section is presented in brief.

ΔV The so called *Delta V* parameter (measured in m/s) is related to the escape velocity from the gravity well generated by the huge Earth mass. ΔV_{tot} is the total, ΔV_l is the launch and ΔV_d is the descent increment of velocity for the lunar lander approaching, landing and a margin propellant (Margin prop) not burned. In order to increase the spacecraft speed, thrust is required and this thrust is generated by the engine burning the propellant, a propellant that the spacecraft carries on board. The thrust stages are marked as Stg_1, Stg_2, Stg_3 and Stg_{Lander}. The total mass m_{tot} consist of the launcher structure mass, the launcher propellant mass, additional tanks and its propellant mass for upper stages, the micro lunar lander mass (9.5 kg) and the pico lunar rover mass (0.5 kg). Mass ratios are the distribution of total mass m_{tot} minus the lunar lander mass and minus the lunar rover mass. The lunar lander is designed with a Margin propellant greater than 3% for unscheduled corrections and for safety margin. The mini launcher size is scaled as a function of the propellant mass and the number of engines, keeping a ratio of 10 times the length to the diameter. The structural analysis can modify this ratio having an impact in the frontal section and then in the aerodynamic launcher performances.

Isp Engines [8] use the so called *specific impulse* parameter; having units of seconds, is proportional to the thrust (a force measured in Newtons or N for short) and inverse proportional to the fuel flow (measured in kilograms per second also m for short). As the rocket burn the propellant, the rocket mass is lower and lower each time. Acceleration become higher and higher for same engine conditions. In addition, engines usually have less Isp in the atmosphere than in vacuum when they are in the space. The main propellant quantity is burned in the initial stages but the higher velocity is reached in the last stages. If an engine has a low Isp then a large tank of propellant is required to exit from the Earth. Generally speaking, solid propellant engines have low Isp (less than 300 seconds) but they are easy to build, easy to operate, easy to storage and they are cheap. Opposite, liquid propellant engines have greater Isp (less than 500 seconds) but they are complex and very expensive due to mobile parts. Because they have large performances, improve an important reduction in the propellant tank size.

L_{cost} Commercial launchers are based on high quality, large payloads. The question we raise here is: what is better, pay for a launcher or develop a cheaper new one? The answer is related to mainly two factors: the payload mass cost and the time of development versus its development cost. The payload mass could be too small for commercial launchers but also the time to develop more adequate launchers is very limited by the GLXP contest. It is true that the market trend to adapt to the new consumers with smaller payloads and to develop such a launchers that is, in fact, a good long term investment beyond the GLXP contest. A good example of this is the Falcon 1 launcher [2] developed and operated by a private commercial organization called SpaceX [11]. Perhaps, for this reason, SpaceX is a preferred GLXP partner [12]. The most expensive component in a liquid propellant based launcher is the engine due to the high performance mobile parts and high temperature resistant materials used. Also, the fact that these engines are used once, it hampers profitability. In fact, reused engines have a very costive maintenance is to replace the most expensive parts. For solid propellant based launchers, engines are less expensive than liquid ones. The cost of the propellant ($Prop_{cost}$ measured in \$) has a big impact in the cost and the total mass (m_{tot} measured in kg) due to the Isp that provides. In fact, propellant direct cost is not the most large in the launcher budget cost.

t_{flight} Is the time of flight measured in seconds from the liftoff to the touchdown. Escape velocity is reached very soon, near the earth in a few minutes from the liftoff. Time of flight depends mainly on the escape velocity, the time of parking and less important in the launch path respect to the *Zenith* measured in degrees.

II.B. Basic parameters for a GLXP mission to the Moon

Following, the cost impact of these parameters: staging, solid or liquid propellant, straight trajectory, launch site latitude, direct launch, parking orbit, direct descent and parking to descent, over a GLXP mission to the Moon is considered. The Table 1 shows a comparison between all of them for some parameters like mission parameters, construction parameters, Delta V and engine thrusts. The simulations were made with a dedicated tool called *Moon2.0 Simulator* [10] for a GLXP mission to the Moon based on a home made small launcher, a micro lunar lander and a pico lunar rover. The launcher, typical size is 6 meters in length, 0.63 meters in diameter and typical wet mass is about 1,700 kg for a multi stage launcher. Except for the single stage case, a launcher first stage has been selected of a solid propellant like *Ammonium Perchlorate Composite Propellant* (APCP) having an Isp at sea level of 220 s and 260 s in vacuum, the engine has between 20 and 50 kN of thrust. The last stage, which is also the micro lunar lander, wet mass 9.5 kg and dry mass 2.5 kg for all cases, is based on a liquid bi-propellant like *Mono Methyl Hydrazine* and *Nitrogen Tetroxide* as an oxidizer (N2O4/MMH) having an Isp at sea level of 288 s and 336 s in vacuum, the engine has between 1.6 and 6.2 kN of thrust for the lunar transfer injection, 700 N of thrust for direct landing and 50 N of thrust for lunar parking obit and landing. The pico lunar rover mass is 0.5 kg.

Preset	1Stage	2Stages	3Stages	Direct	DirectN	Park	ParkM
Zenith (deg)	46 to 88	47 to 88	46 to 88	0 to 0	32 to 32	47 to 88	47 to 88
Launch	Direct	Direct	Direct	Direct	Direct	LEO_{150km}	LEO_{150km}
Descent	Direct	Direct	Direct	Direct	Direct	Direct	LMO_{1000km}
t_{flight} (s)	2:12:00:02	2:12:01:12	2:12:03:19	2:12:03:59	2:12:03:54	2:13:29:27	2:21:16:15
m_{tot} (kg)	32,000	1,417	2,091	1,703	1,705	1,445	1,445
size (m)	D1.7x16.6	D0.6x6	D0.67x6.7	D0.63x6.3	D0.63x6.3	D0.6x6	D0.6x6
L_{cost}	USD6M	USD2M	USD3M	USD2M	USD2M	USD2M	USD2M
$Prop_{cost}$	\$ 295,787	\$ 47,831	\$ 70,364	\$ 57,539	\$ 57,607	\$ 48,781	\$ 48,781
ΔV_{tot} (km/s)	14.93	15.09	15.05	15.48	15.51	15.14	16.52
ΔV_l (km/s)	11.99	12.18	12.13	12.50	12.50	12.22	12.22
ΔV_d (m/s)	2,937	2,908	2,922	2,986	3,018	2,922	4,295
I_{SP} (s)	288_{SL}	220_{SL}	220_{SL}	220_{SL}	220_{SL}	220_{SL}	220_{SL}
Engine	Merlin 1C	APCP	2 APCP	APCP	APCP	Masten	Masten
Mass ratios	100 : 0 : 0	90 : 10 : 0	80 : 16 : 4	90 : 10	90 : 10	90 : 10	90 : 10
Stg_1 (kN)	470.7_{SL}	20.8_{SL}	30.8_{SL}	50.1_{SL}	50.2_{SL}	21.3_{SL}	21.3_{SL}
Stg_2 (kN)		2.6_{Vac}	7.4_{Vac}	6.2_{Vac}	6.2_{Vac}	2.6_{Vac}	2.6_{Vac}
Stg_3 (kN)			1.6_{Vac}				
Stg_{Lander} (N)	588_{Vac}	687_{Vac}	687_{Vac}	687_{Vac}	687_{Vac}	687_{Vac}	50_{Vac}
Margin prop.	22.4%	22.9%	22.6%	21.6%	21.1%	22.6%	4.2%

Table 1. Comparative between orbits strategies for a minimal architecture from the Earth to the Moon

II.C. Discussing orbit strategies

The Table 1 shows seven equivalent simulations called presets. Figure 2 shows five trajectories. All missions carrying the same payload: a micro lunar lander of 9.5 kg wet mass and a Pico-lunar rover of 0.5 kg. The time of flight is 2.5 days in all cases. These presets are the result of a series of simulations with smooth changes in main parameters in order to reach the most optimized case for each set of simulations. The case of using a Geosynchronous Transfer Orbit *GTO* is not considered because a license under an international agreement and a slot assigned is required [3].

Moon 1Stage is a simulation based on a single stage launcher. This procedure is so low efficient that a huge amount of propellant and a large engine is required to reach the escape velocity. In addition, a better *Isp* and a very light structure is required to be possible the mission. Single stage don't allows low specific impulse like many solid propellants.

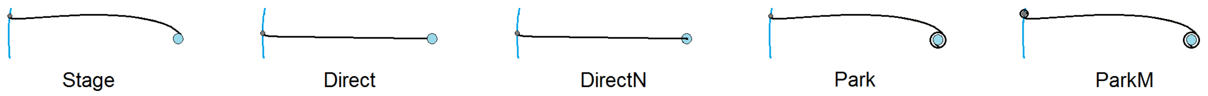

Stage Direct DirectN Park ParkM

Figure 2. Trajectories for each preset: Stage, Direct, DirectN, Park and ParkM

Moon 2Stage is the same mission as *Moon 1Stage* but using two stages launcher. This is the best efficiency of all cases in terms of cost and total mass but not in terms of operation. The launch window is very narrow because the hour of launch depends on the Moon position and the day of the month. This technique allows a very small reduction of propellant respect to the LEO parking orbit based technique.

Moon 3Stage is the same mission as *Moon 2Stage* but using three stages launcher. There is a large increment of cost and also in total mass. For small payloads is not good to use an excessive staging technique because the cost of extra engines. Multistage technique is efficient when liquid propellant based engines are used.

Moon Drect is the same mission as *Moon 2Stage* but using a direct trajectory, it is to say, without orbiting, maintaining the zenith angle during the launch. Using this technique, an extra fuel of 286 kg (over 1,417 kg of minimum) and a bigger engine is required but same launch ground station use during the main critical parts of the launch is allowed.

Moon DrectN is the same mission as *Moon 2Stage* but having latitude 0 in the North pole. Using this technique, an extra fuel of 288 kg (over 1,417 kg of minimum) and a bigger engine is required but you can launch in any day of the year without need a parking orbit. This large amount of extra fuel is due to the fact that other techniques profit the Earth rotation speed which is greatest in the equator when easting launch.

Moon Park is a similar mission as *Moon 2Stage* but based on a Low Earth Orbit *LEO* parking orbit. Using this technique, only an extra fuel of 28 kg (over 1,417 kg of minimum) is required but has a wide launch window; any hour of the day can be selected for launch. This technique requires a compatible parking orbit with other satellites and a bigger time of exposure to radiation.

Moon ParkM is the same mission as *Moon Park* but in addition uses a Low Moon Orbit *LMO* parking orbit before descent. Using this technique, some extra fuel is required which is extracted from the propellant margin, 1.4 kg (over 1.7 kg of remaining propellant in other missions) is required but moment and descent site can be chosen.

II.D. First trade study summary

In the aerospace science, the analysis of launch cost is difficult to manage due to the high number of parameter that are playing. The authors, during these six months of simulations, tried to take into account the most relevant parameters, not only from the traditional point of view of the *Delta V* but also being sensible to the improvements that today's technology allows for these kind of missions. Open source tools were used for this purpose. The reason for choose this size of vehicles is because authors understand that are the very limits that today's technology can improve. Having into account some differences, this problem can be scaled to the real operating needs or commercial components selection.

Recommendations for the next low level detail design are as follows:

- Select a two stage launcher. Liquid propellant second stage mandatory.
- A solid propellant first stage are much more cheap for small payloads.
- A liquid propellant first stage is much more efficient for large payloads.
- Select a launcher site as near the equator as possible and easting launch.
- For small payloads use the lunar lander engine for trans lunar injection with an extra tank.
- Use a Low Earth Orbit *LEO* parking orbit if a wide launch window is desired.
- Use a Low Moon Orbit *LMO* parking orbit if a exact landing site is desired.

III. Initial approach to the lunar trajectory

The second trade study is based on the two body problem in order to define an initial approach of the trajectory and the required DeltaV budget.

A minimal mission trajectory to the Moon is shown in figure 3 based on the author [4] budget. The mission architecture is composed by the Launcher, the Trans Lunar Injection bus, the Lunar Lander, the Lunar Rover and the Ground Network. The trajectory starts from a LEO parking orbit of 300 km, a trans lunar injection and a direct landing to the Moon. In this budget, lunar lander DeltaV is 2631 m/s and transfer lunar injection (lunar bus) DeltaV is 3010 m/s. Total DeltaV budget is 5461 m/s for a lunar rover of 1.5 kilograms.

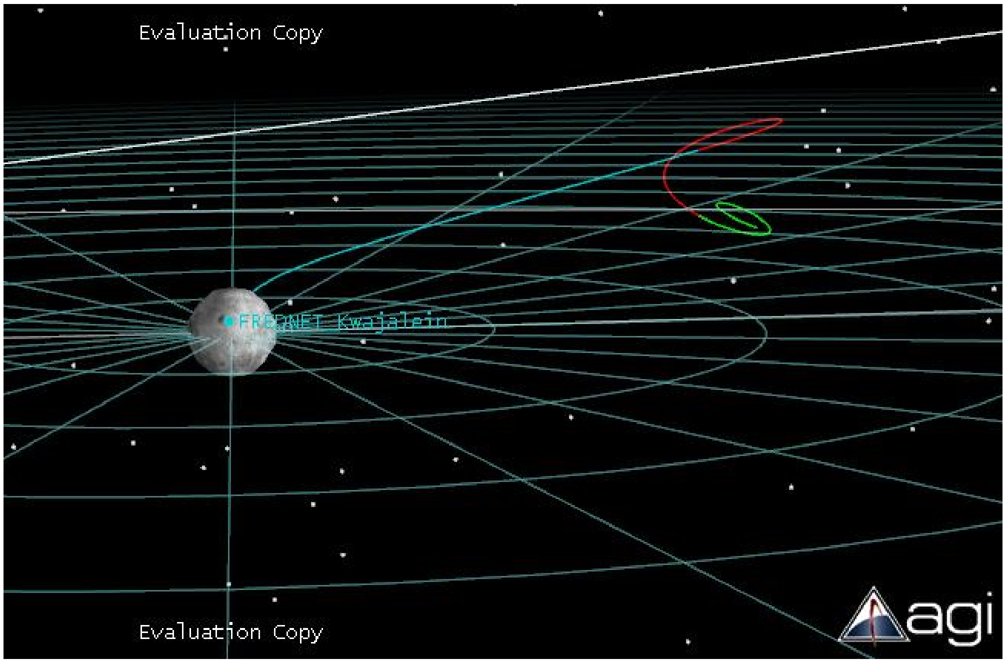


Figure 3. Initial trajectories for a minimal mission to the Moon using AGI software

In Table 3 a minimum subsystem list for a GLXP missions to the Moon will be presented. The roles for the mission agents are:

- A Launcher able to put the lunar bus in a parking orbit
- A Lunar Bus able to provide DeltaV for the trans lunar injection
- A Lunar Lander able to land in the Moon
- A Lunar Rover able to meet the minimum GLXP requirements
- A Ground Network able to receive the mooncast

IV. Minimum number of subsystems for a GLXP mission

The third trade study is based on the communications between the spacecraft and mission control using a commercial network vs global amateur network. A propellant combination trade study were done. Results are presented. A minimum number of subsystems are selected will be selected in the next chapter in order to complete the mission. These subsystems should meet any constrain imposed in the trajectory.

Restrictions to the orbit and trajectory are constrained by:

- Communication network
- Available launch sites
- Available parking orbit altitudes
- Commercial Engines vs Custom Engines
- Propellants and specific impulse

In the following section, Communication network constrains and propellant constrains is discussed.

IV.A. Ground communication network

The following link budget [5] was done by an open source author. The baseline trade study is based on a commercial network vs global amateur network. The main difference is the use of commercial frequencies or amateur frequencies. When a commercial frequency is dedicated to the mission, there is a high cost related to the frequency registration, and reservation of two years before the launch is mandatory. Opposite to this, amateur frequencies are always available but some restrictions are imposed as well; encryption is not allowed and transmitted power is limited. The best option that the author [5] has selected is to use GLXP preferred partners network like USN/SSC or SETI. These networks can not be use for tracking because they are receiver only. Tracking is done by the launcher provider. During trans lunar injection maneuver tracking is required for trajectory correction only for the first moments, a few moments during correction maneuvers and when landing. A minimum deep network installation of three ground stations could be enough like:

- Canberra (35.2192S, 148.9814E, 554 m)
- Madrid (40.2389N, 4.2489W, 493 m)
- Goldstone (35.1186N, 116.8056W, 560 m)

The Moon will always be visible to at least one of the ground stations as showed in figure 4. The safe conclusion is that this deep network of three ground stations can provide lunar communication for 97% of the time during a 30 day period.

Following, a commercial network budget is presented with the assumption of no separate bus and lander, we aim for real-time transmission of HD video and lunar rover uses lunar lander as relay. Terminology and a basic overview are defined before the link budget conclusions.

IV.A.1. Terminology

Payload data:	Data required to complete the requirements of the GLXP. This includes images, videos, etc.
Telecommand:	Commands sent from Earth to the lunar lander or lunar rover.
Telemetry:	Housekeeping telemetry from the various subsystems of the lunar lander and lunar rover.
EIRP:	Equivalent isotropically radiated power is the amount of power in the same maximum antenna gain direction that a theoretical isotropic antenna would emit.
G/T:	Gain of the receiving antenna to its noise temperature ratio.
mooncast	Is the streaming of images and videos from the Moon's surface.

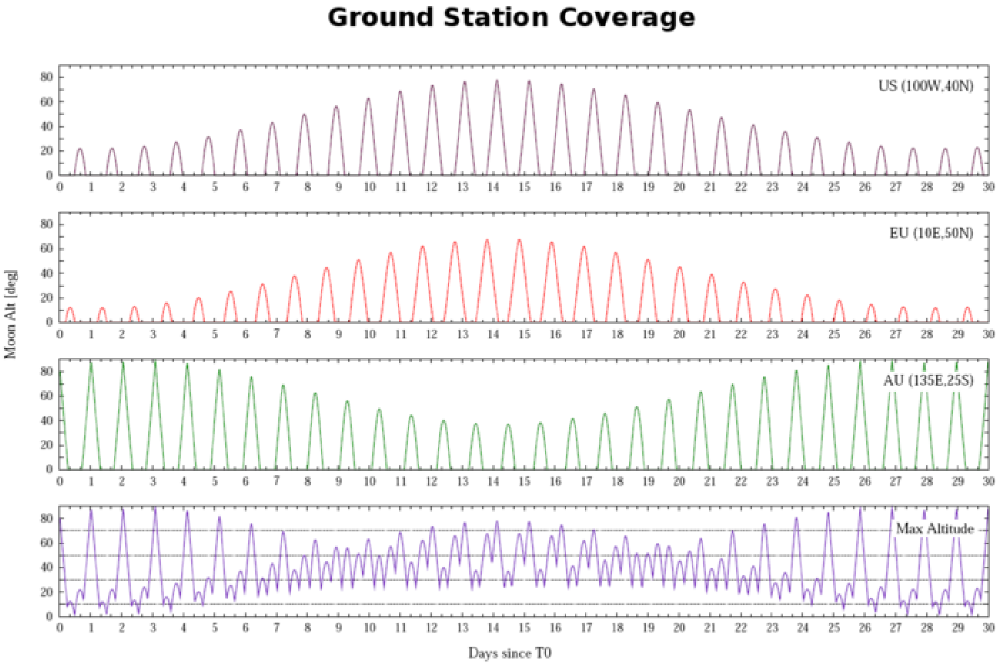


Figure 4. Basic deep network coverage based on three ground stations

IV.A.2. Overview

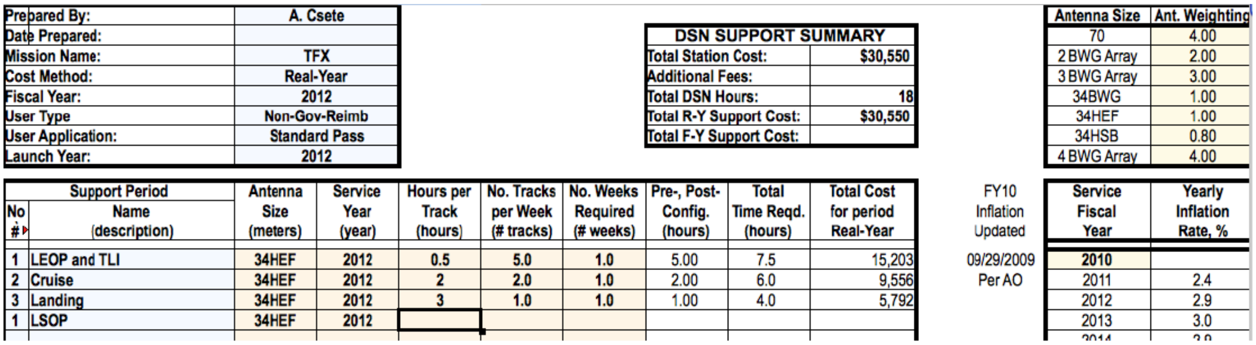
Communications are required in all phases of the mission after launch. The functional requirements for the communication system depend on the mission phase:

- LEOP: Telecommand, telemetry and tracking
- TLI/TLC: Telecommand, telemetry and tracking
- Landing: Telemetry and tracking
- LSO: Telecommand, telemetry and payload data downlink

The lunar rover communicates with Earth using the lunar lander as relay station. Payload data and telemetry from all vehicles is multiplexed into a single downlink channel by the lunar lander. Telecommands from Earth to the lunar rover are forwarded by the lander. Data rate for uplink are 30 bps for telecommand and 50 bps for Team FREDNET upload. Data rate for downlink are 600 bps engineering mode (telemetry only) and 600 kbps imaging mode (telemetry + payload data). Frequencies for lunar lander to Earth: S-band or X-band. Frequencies for lunar lander to lunar rover: Any chosen between 2 and 5 GHz due to availability of parts. Frequencies for lunar lander to Earth communications consists of a low rate uplink channel and a variable rate downlink channel. The data rate on the downlink channel depends on the mission phase. Ground stations have an EIRP 1.1 and a G/T = 4.8 dB. In case of direct lunar insertion, three ground stations distributed around the world can provide sufficient coverage.

IV.A.3. Link budget conclusions

Results of SPLAT [7] analysis shows that for a trans lunar injection cruise, it is allocated 5 passes of 30 min each up to and included lunar injection. Also it is allocated 2 passes of 2 hours each during the cruise for monitoring and trajectory correction and one pass of 3 hours for the landing. It should be noted, that the number of passes/tracks has much more influence on the price than the length of each pass/track. Table 2 shows a Deep Space Network (DSN) standard network cost study prepared by A. Csete. The cost per year is about 30,550 dollars and 18 hours per year of DNS use. The conclusion is that it is better to use any GLXP preferred partners network like USN/SSC or SETI instead of use a commercial DSN standard network.



Prepared By:	A. Csete
Date Prepared:	
Mission Name:	TFX
Cost Method:	Real-Year
Fiscal Year:	2012
User Type	Non-Gov-Reimb
User Application:	Standard Pass
Launch Year:	2012

DSN SUPPORT SUMMARY	
Total Station Cost:	$30,550
Additional Fees:	
Total DSN Hours:	18
Total R-Y Support Cost:	$30,550
Total F-Y Support Cost:	

Antenna Size	Ant. Weighting
70	4.00
2 BWG Array	2.00
3 BWG Array	3.00
34BWG	1.00
34HEF	1.00
34HSB	0.80
4 BWG Array	4.00

Support Period		Antenna	Service	Hours per	No. Tracks	No. Weeks	Pre-, Post-	Total	Total Cost
No #	Name (description)	Size (meters)	Year (year)	Track (hours)	per Week (# tracks)	Required (# weeks)	Config. (hours)	Time Reqd. (hours)	for period Real-Year
1	LEOP and TLI	34HEF	2012	0.5	5.0	1.0	5.00	7.5	15,203
2	Cruise	34HEF	2012	2	2.0	1.0	2.00	6.0	9,556
3	Landing	34HEF	2012	3	1.0	1.0	1.00	4.0	5,792
1	LSOP	34HEF	2012						

FY10
Inflation
Updated
09/29/2009
Per AO

Service Fiscal Year	Yearly Inflation Rate, %
2010	
2011	2.4
2012	2.9
2013	3.0

Table 2. DSN standard network cost study prepared by A. Csete

IV.B. Propellants and the specific impulse

Based on a David Masten study about the propellant combination trades, the trades look like H2O2/RP1 is the winner. Mostly because it does not require topping while sitting on the pad waiting for launch, it has hypergolic like ignition reliability, and it allows really lightweight composite tanks. Also gives the most options for propellant acquisition. Extra details were provided in a public communication where David Masten said:

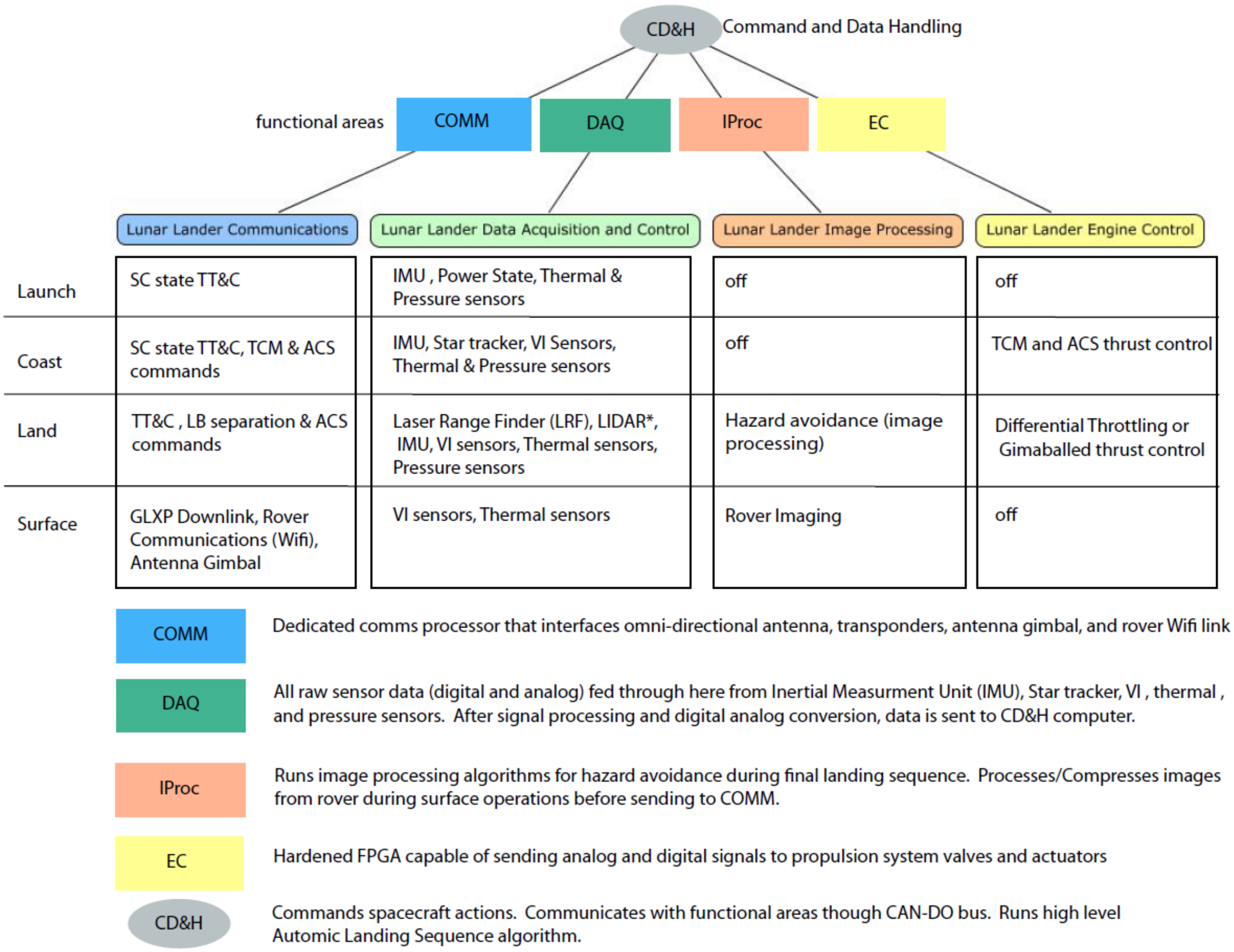
> *I'm still getting up to speed on the numbers you have. I am noticing a difference between my assumptions and everyone elses.*
> *The biggest difference I noticed is the assumption that a particular mass budget worked for some previous spacecraft, therefore something similar will work for us. As an open source project we should be aware that the JPL machine shops (or other shops of similar quality) and NASA test facilities are not available to most people (possibly including us), and therefore we might want to take a different look at the solution space. Often times this means we'll do things a bit heavier, and hopefully simpler and cheaper. That worked well for the Soviets; Soyuz is still doing the job at much less cost than most American birds.*
> *As part of the propellants trade study, I've been doing some preliminary designs. Nothing very detailed, but enough to know that it is workable. What I have done is started with 50 kg for rover and rover support gear as payload. The team said 30 kg, I took a page from the Saturn V program and assumed it will increase. I then put in a guess for what a dry mass would be and determined how much of each propellant combination it would require. Then I determined the tank masses for the propellants, and add in structures and other size variable items. Then I add all the items that are of fixed mass (for example, avionics) At that point things do not add up, so I adjust the dry mass estimate and try again until everything converges.*
> *I have converged on a workable solution for H2O2/RP-1 that masses 970 kg on a Falcon 1, and has dV to spare in both stages. Remember this represents a configuration that is conservative in every element, so we should be able to do much better as each (sub-)system design is solidified.* (Mojave - USA. January, 2010)

V. Mission architecture

The forth trade study is related to the minimal architecture that the Team FREDNET is able to design and build. This capability is based on community skills. The more relevant interest is on the Lunar Lander Architecture that is presented following and the minimal list of subsystems to achieve a Google Lunar X-Prize mission like.

V.A. Lunar Lander Architecture

Figure 5 shows a detailed Lunar Lander architecture. The Lunar Lander is divided in functional areas: Communications, Data acquisition and control, Image processing and finally Engine control. A sequence of use for each subsystem is showed in this figure for each flight phase that are: Launch, Coast, Land and Surface.



	Lunar Lander Communications	Lunar Lander Data Acquisition and Control	Lunar Lander Image Processing	Lunar Lander Engine Control
Launch	SC state TT&C	IMU , Power State, Thermal & Pressure sensors	off	off
Coast	SC state TT&C, TCM & ACS commands	IMU, Star tracker, VI Sensors, Thermal & Pressure sensors	off	TCM and ACS thrust control
Land	TT&C , LB separation & ACS commands	Laser Range Finder (LRF), LIDAR*, IMU, VI sensors, Thermal sensors, Pressure sensors	Hazard avoidance (image processing)	Differential Throttling or Gimaballed thrust control
Surface	GLXP Downlink, Rover Communications (Wifi), Antenna Gimbal	VI sensors, Thermal sensors	Rover Imaging	off

COMM	Dedicated comms processor that interfaces omni-directional antenna, transponders, antenna gimbal, and rover Wifi link
DAQ	All raw sensor data (digital and analog) fed through here from Inertial Measurment Unit (IMU), Star tracker, VI , thermal , and pressure sensors. After signal processing and digital analog conversion, data is sent to CD&H computer.
IProc	Runs image processing algorithms for hazard avoidance during final landing sequence. Processes/Compresses images from rover during surface operations before sending to COMM.
EC	Hardened FPGA capable of sending analog and digital signals to propulsion system valves and actuators
CD&H	Commands spacecraft actions. Communicates with functional areas though CAN-DO bus. Runs high level Automic Landing Sequence algorithm.

Figure 5. Lunar Lander Architecture and working sequence

V.B. Minimal List of Subsystems

The minimum number of agents in this mission are five: the Launcher, the Lunar Bus, the Lunar Lander, the Lunar Rover and the Ground Station. The minimal list of systems or elements for these proposed parts or vehicles is presented in Table 3 having each a main requirement or basic role inside the mission.

1. A launcher able to put the lunar bus in a parking orbit
1.1 A system able to add speed to escape some Earth's gravity field
1.2 A system able to know the launcher position for maneuver corrections
1.3 A system able to know the launcher attitude for thrust vector
1.4 A system able to control the launcher attitude
1.5 A system used as an interface between the lunar bus and the launcher
1.6 A system able to release the lunar bus
1.7 A system able to communicate with ground for tracking and tele-commanding
1.8 A system able to control the thermal requirements
1.9 A system able to feed and control the electrical requirements
1.10 A system able to protect susceptible subsystems from radiation
1.11 A system able to protect susceptible subsystems from acoustic noise
1.12 A well known Earth parking orbit

2 A lunar Bus able to provide deltaV for the Trans Lunar Injection
2.1 A system able to add speed to escape most of the Earth's gravity field
2.2 A system able to know the spacecraft position for maneuver corrections
2.3 A system able to know the attitude for the communication antenna
2.4 A system able to control the spaceship attitude
2.5 A system able to release the lunar lander
2.6 A system able to rely the payload communications
2.7 A system able to control the thermal requirements
2.8 A system able to feed and control the electrical requirements
2.9 A system able to protect susceptible subsystems from radiation

3 A lunar lander able to land in the Moon and meet GLXP requirements
3.1 A system able to brake the remaining speed from the Earth and the Moon's gravity field
3.2 A system able to know the altitude to the Moon in order to start the land sequence
3.3 A system able to know the attitude for the communication antenna and altimeter correction
3.4 A system able to control the spaceship attitude
3.5 A system able to absorb impacts with the Moon
3.6 A system able to deploy the lunar rover
3.7 A system able to rely the lunar rover communications
3.8 A system able to control the thermal requirements
3.9 A system able to feed and control the electrical requirements
3.10 A system able to protect susceptible subsystems from radiation

4 A lunar rover able to meet the minimum GLXP requirements
4.1 A system able to thrust the lunar rover
4.2 A system able to know the position for 500 meters race
4.3 A system able to know the attitude
4.4 A system able to control the lunar rover attitude for the communication antenna
4.5 A system able to protect the lunar rover from the Moon's environment
4.6 A system able to record the mooncast
4.7 A system able to control the thermal requirements
4.8 A system able to feed and control the electrical requirements
4.9 A system able to protect susceptible subsystems from radiation

5 A ground network able to receive the mooncast
5.1 A system available during the mission for tele-commanding
5.2 A system able to provide good tracking to the lunar bus
5.3 A robust system able to keep the confidence of the mooncast

Table 3. Minimal subsystem list for a GLXP mission to the Moon

VI. Conclusions

VI.A. Conclusions for this work

In this work, some trade studies done by the community were presented in order to set a baseline design for a Google Lunar X-Prize like, mission to the Moon and based on a lunar explorer, self-contained pico-rover.

Recommendations derived from the *Absolute minimum* directive and *KISS* principle of Keep It Simple and Safe are: Single fault tolerant systems, no redundancy subsystems, use as less components as possible but using reliable components and finally the rule *Fly what we test and test what we fly.*

For the link budget, the number of passes/tracks has much more influence on the price than the length of each pass/track.

The preferred propellant to be used in the lunar lander is H2O2/RP1.

This minimal mission architecture is composed by the Launcher, the Trans Lunar Injection bus, the Lunar Lander, the Lunar Rover and the Ground Network. A minimal list of subsystems for a these minimum number of vehicles were presented.

VI.B. Acknowledgments

The authors want to thanks the special collaboration of the open source community and Team FREDNET members.

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