A Condominium of Observatories on the Moon

Study examples and general considerations of an integrated approach

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Abstract

This paper discusses many aspects of founding a condominium of observatories on the Moon. It discusses an integrated approach strategy and gives a study example. ISRU Intensive lunar development will be mandatory for any sustainable human exploration of the solar system, including the Moon. Advantages of a common utilities Infrastructure will be discussed and why observatories on the Moon make more sense than "Fast Food"-throw-away space-based telescopes. On the Moon, environmental considerations come into play that are different than in space, it is explained that none of these pose a problem with proper engineering and planning. Expansion of the initial telescope to a condominium is briefly discussed and Human-Robot cooperation required for construction and operations. A foundation example and construction sequence is shown and cost and risk factors are discussed based on assurance and continuity of observations, maintenance, repair and updating capabilities of instruments and facilities. Last but not least, synergy projects, precursors and experiments are listed.

Introduction

With the tragedy of the Columbia accident basic issues as to the purpose and scope of the Space program have been revisited. An intensive “in house” assessment resulted in **President Bush's Vision for U.S. Space Exploration** announced publicly on **January 14 2004.** (Heiss 2003)

The President's first and foremost goal – beyond the immediate issues at hand (the Space Shuttle and the International Space Station (ISS)), is a return of Humans to the Moon, this time to stay. To quote:

“America will return to the Moon as early as 2015 and no later than 2020 and use it as a stepping stone for more ambitious missions. A series of robotic missions to the Moon, similar to the Spirit Rover that is sending remarkable images back to Earth from Mars, will explore the lunar surface beginning no later than 2008 to research and prepare for future human exploration. Using the Crew Exploration Vehicle, humans will conduct extended lunar missions as early as 2015, with the goal of living and working there for increasingly extended periods.

o The extended human presence on the Moon will enable astronauts to develop new technologies and harness the Moon's abundant resources to allow manned exploration of more challenging environments. An extended human presence on the Moon could reduce the costs of further exploration, since lunar-based spacecraft could escape the Moon's lower gravity using less energy at less cost than Earth-based vehicles. The experience and knowledge gained on the Moon will serve as a foundation for human missions beyond the Moon, beginning with Mars.
o NASA will increase the use of robotic exploration to maximize our understanding of the solar system and pave the way for more ambitious manned missions. Probes, landers, and similar unmanned vehicles will serve as trailblazers and send vast amounts of knowledge back to scientists on Earth."

ESA Aurora program

"Aurora's step-by-step approach means that missions will increase in complexity over time, culminating - if all goes well - in a human expedition to Mars by the year 2030. Steps on the way to Mars will probably include **exploration of the Moon** as well as:

* remote sensing of the Martian environment
* robotic exploration and surface analysis
* Mars sample return missions
* a robotic outpost

Not all these steps towards the ultimate goal of sending humans to Mars will necessarily be part of the Aurora Programme. As the result of international cooperation, various collaborating agencies will make a contribution to those missions that best meet their particular requirements and areas of expertise."

Japan has plans for several robotic missions to the Moon including the soon to be launched Lunar-A and a year later Selene. There is interest in a Lunar base but no plans have been approved as of yet.

India has a lunar orbiter called Chandrayaan-1 planned for launch in 2007-2008

China has tentative plans for a lunar base by 2020

Reasons to go the Moon vary greatly depending on the source and range from 'The exploration spirit of humanity needs to be satisfied' to 'We need a higher ground to control CIS-Lunar space'. I believe that mostly it is a combination of all reasons. Independently of why it will be decided to go back to the Moon, there are many things to be done once there. The Moon offers a capability to observe the Universe, CIS-Lunar space and Earth from its surface. Dr. Klaus Heiss organized a panel discussion hosted by the Washington Academy of Science about this topic. This paper talks about what an integrated approach could mean for lunar exploration and observations from the Moon in particular by using a large lunar telescope design example.

Vision: An Integrated Approach with the ISS Partners?

A lot of functions can be performed on the Moon. Every interested party has different plans and interests. Some functions may seem to have conflicts of interest at first, but can be reconciled with careful planning and an integrated approach. An example of this would be to plan telescope sites more than ten kilometers away from mining sites and launch and landing zones. A list of possible functions and parties is shown below.

Functions:
- Test bed for exploration technologies and strategies,
- In Situ Resource Utilization and production (construction materials, fuel and oxidizer, water and other consumables) (ISRU)
- Observations ,
- In Situ Science,
- Higher ground

Parties:
- Government, (NASA, airforce, spaceforce?)
- Industry, (Lockheed, Boeing, etc.)
- Academia, (Universities)
- Private sector, (Scaled Composites, Virgin Galactic, etc.)
- International partners (ESA, ISRO, JAXA, companies, etc.)

Suffice to say that each party has its own strengths and weaknesses and not just ONE party or function is sufficient or capable to achieve the goals set by president Bush in 2004 in a sustainable way. In other words, it has to be a cooperative synergistic effort between parties while pursuing and building multiple functions. This would lead to the building of a sustainable infrastructure which would give humanity a permanent base of operations on the Moon performing several functions such as In Situ Resource Utilization (ISRU) from where the exploration of the solar system can really pick up speed.

Examples of an Integrated Approach

Some project examples of successful integrated approaches are among others, the European Southern Observatory (ESO) who has built the Very Large Telescope Interferometer (VLTI) in Chile over the past 20 years and successfully operates it now, all the parties involved in the condominium of observatories on the peak of Mauna Kea in Hawaii, the European Space Agency (ESA), which has undertaken and is undertaking many successful international space projects, the International Space Station (ISS) which is still underway, and the massive civil engineering works on Earth such as highway networks, air traffic control across nations, etc. During each project, lessons were learned, but whether or not some of the projects original goals, costs and timelines were met, great things were accomplished despite long time-lines, changing politics and finances. All of these projects in the past 30 years have laid groundwork, created partnerships, and established networks that can be used to find alternate organizational structures that could speed up the timelines common in NASA projects. An example of the renewed spirit of alternate exploration is the flight of Space Ship One in 2004 which illustrates another tool that can be used to speed up and stimulate technical maturation of the required techniques for manned exploration of the solar system.

Figure 1: The Very Large Telescope Interferometer of ESO in Chile (courtesy of ESO)

Of all these examples the ISS must rank first and foremost: through all the travails and setbacks the ISS has forged a unique "technology management know-how", ranging from mundane issues such as language, management styles and customs to complex systems such as how to "dock" space systems designed by entirely different technology, industrial standards and specifications, such as Soyuz-Apollo, Soyuz-Space Shuttle and Soyuz-ISS. The resources expended, in terms of funding but also in terms of scientific, engineering and management man-hours have created an invaluable "human capital" base uniquely suited to continue and apply this expertise to returning to the Moon, establish a first permanent human base with the task of deploying a Condominium of Observatories – ultimately across the electromagnetic spectrum and with a multitude of applications including scientific, and environmental monitoring tasks.

Architecture Integrated with Intensive ISRU Lunar Development

Concurrent with a decision to establish a Moon Base and the deployment of a Condominium of Observatories a sustained Research Development of Technology & Engineering (RDT&E) program for the "In-Situ Resources Utilization" (ISRU) has to be initiated. For a sustainable human exploration of the Moon, CIS-lunar Space and ultimately the Solar System, the development of a transportation infrastructure including ISRU production of oxidizer and other elements is mandatory. (hydrogen, oxygen, other elements (M.B. Duke, et. al). Detailed plans have been laid out, including the development of the initial steps on the Moon by demonstration missions and robots starting in 2008 with the purpose of testing exploration technologies and developing extensive ISRU capabilities to prepare for human missions to the lunar surface (2015 and beyond) toward an early permanent manned lunar base. Once the RDT&E, deployment and operation of Lunar facilities have been accomplished and issues of Human health and productivity assessed and resolved one may then proceed with Human exploration missions beyond the Moon, to Mars and other destinations in the Solar system.

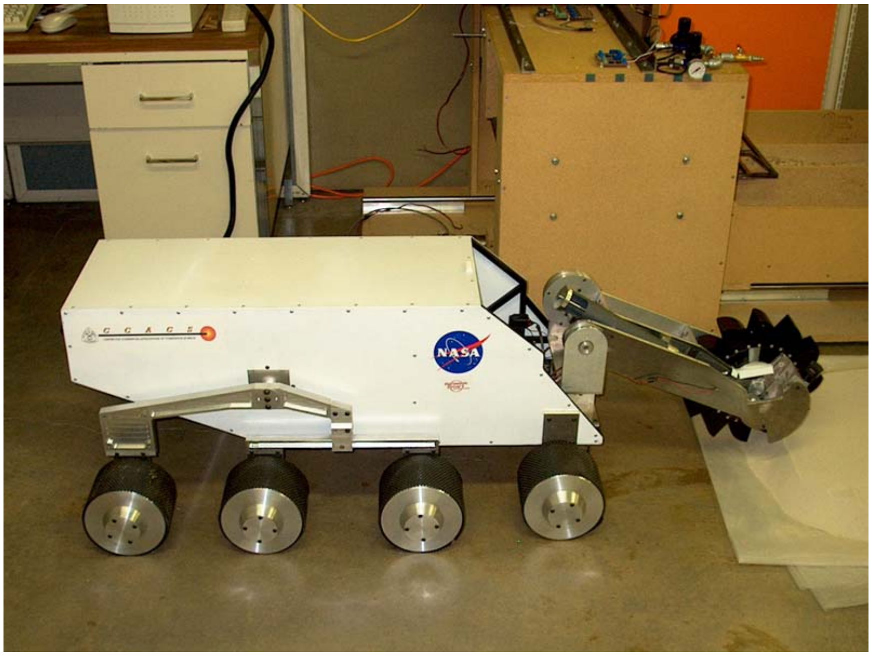


Figure 2: The bucket wheel excavator as designed and build at CSM

Critical for the efficient operation and expansion of human activities on the Moon will be the development of Closed Ecological Life Support Systems and of ISRU technologies. As to the latter, it appears from simulations done at the Colorado School of Mines (CSM) that with extensive use of ISRU, resource-"self-sufficiency" can be achieved on the Moon. More extensive ISRU production can be developed such that structures for on the lunar surface and in space can be made on and launched from the lunar surface. This will reduce substantially the initial deployment costs of the first Lunar Observatory outlined later, which can be accomplished without any in-situ production of components. With the establishment of a permanent human presence on the Moon and experience with local construction has been gained, many additional activities and functions can be developed on the lunar surface. One of the most interesting ones is the expansion of the initial observatory proposed herein toward a condominium of (large, distributed aperture) observatories in combination with extensive lunar science while expanding human presence across the Moon (2020-). Once 'self-sufficiency' has been achieved this will lead to an exponential growth of activities on the lunar surface which would benefit all mankind: the science, exploration, Earth, environment and climate monitoring and resource allocations, private industry, national and international stability and security and many others.

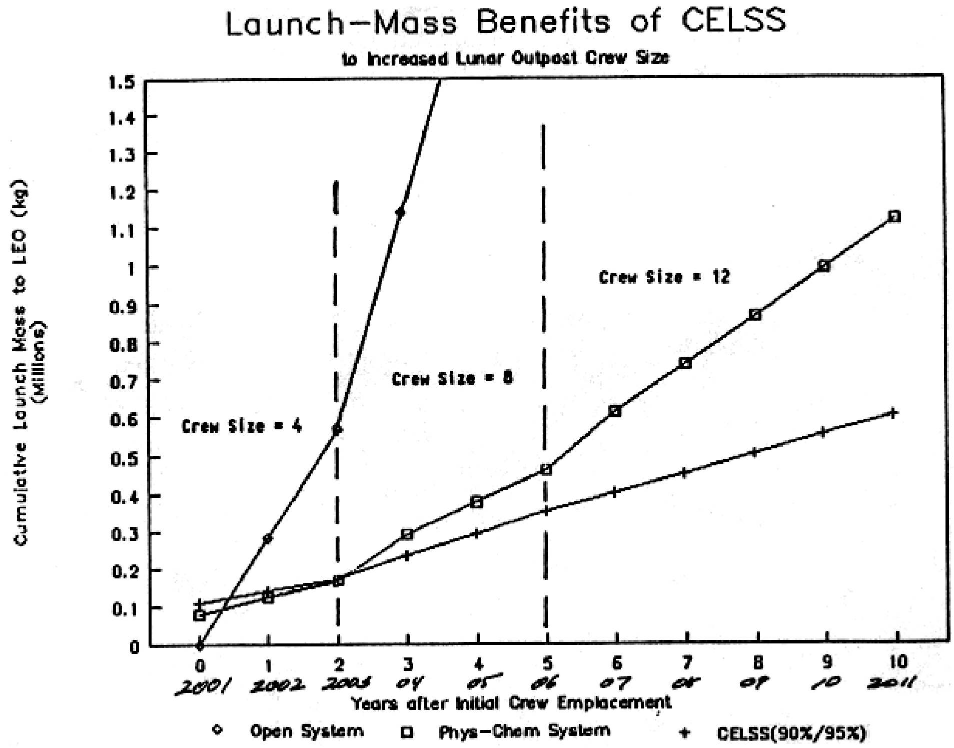


Figure 3: illustration of the importance of development of a CELSS system

As shown in Figure 3 the impact of CELLS and ISRU (Physical and Chemical "in-situ" systems) are major when measured in total mass needed for supporting such operations from Earth until one has learned how to avail ourselves of the Lunar resources and their recirculation and reuse. When deployment of observatories are added to the logistics of these operations, the advantage of CELSS and ISRU technologies is even more pronounced and mandatory.

The results shown in Figure 3 are of extensive Monte Carlo simulations performed in the late 1980'a and 1990's by one of the authors and are based on assumptions not dissimilar of current CELLS and ISRU requirements, but also on extensive use of US submarine data as regards human health requirements and logistics. (Heiss 1992)

Infrastructure required

Robotic missions will lay the groundwork of the main infrastructure of ISRU demonstration missions and delivery of the initial factories to manufacture sufficient oxygen needed for launching and landing operations on the Moon, in low lunar orbit (LLO) and in Lagrange point 1 (L1). These capabilities will be built-up incrementally and require re-usable descent/ascent vehicles. With this part of the infrastructure in place, the logistics and operations costs of the ground infrastructure required for a permanent human base can be reduced substantially from the initial deployment, including transportation, habitats and other buildings, power generation and management, thermal management, radiation shielding, communication infrastructure and others. Once a permanent local ISRU production, transportation, power and communication infrastructure is established, this can be expanded to other areas for particular needs in mining, scientific sites of interest and construction sites for observatories.

Why observatories on the Moon

Without (and even with) Reusable (Heavy Lift) Launch Vehicle (R(HL)LV) development that have a significantly larger payload capacity than present day launch vehicles, there are limits to the physical size and mass of space based telescopes. A good example of present day capabilities is the James Webb Space Telescope (JWST) which is currently under development for launch in 2011 and will have a diameter of roughly 6.2 meters and a nominal lifetime of 5 years. The successor of the JWST will have to be an improvement of at least an order of magnitude in scientific achievement. Since the instruments are reaching their quantum limits of sensitivity this can only be achieved by increasing the size of the collecting area. An order of magnitude improvement would lead to a collecting surface with a diameter of approximately 20 meters. The time frame of the successor of the JWST will be approximately 10 years after its (successful) launch which would place it around the time of the first set of human missions to the Moon in this vision for space exploration by President Bush. By that time the Shuttle will have been phased out and the support to the ISS will be limited. Construction of large telescopes in space is possible, but is very complicated and full of risk. The Moon is a natural platform in space that has many similar characteristics as free space (e.g. vacuum), but is much safer to work on and allows for regular maintenance and upgrading which placement of telescopes in far away Lagrange points does not, or at least will make it very cumbersome, time consuming and risky, since these are conceptual and as yet unproven in design and operations in a hostile Space environment constantly affected, among others, by Solar climate/weather events. Since by 2020 new telescope capabilities will be required because current telescopes will be at the end of their lifetime and successors will be too large to deploy or extremely complicated and risky to achieve in free space (e.g. interferometry formation flying constellations of telescopes), the lunar surface is an excellent place to construct the next and following generations of telescopes.

Environmental Considerations

The idea of lunar telescopes is not new and over time many ideas have been put forward. Ever since the conception of the Apollo lunar program and even far before, the Moon was considered an ideal site to perform astronomy from. Because for the past thirty-some years no robot or human has landed on the Lunar surface, astronomy has been presented as a reason to go back. Some in the community of Space astronomers have of late (Lester et al. 2004) raised environmental concerns regarding Lunar observatories.

These environmental characteristics presented by some as insurmountable problems, can be quite easily mitigated; some are even an advantage (Susante 2004). Gravity, temperature, dust, meteoroids and lunar seismic activity are the most often perceived problems.

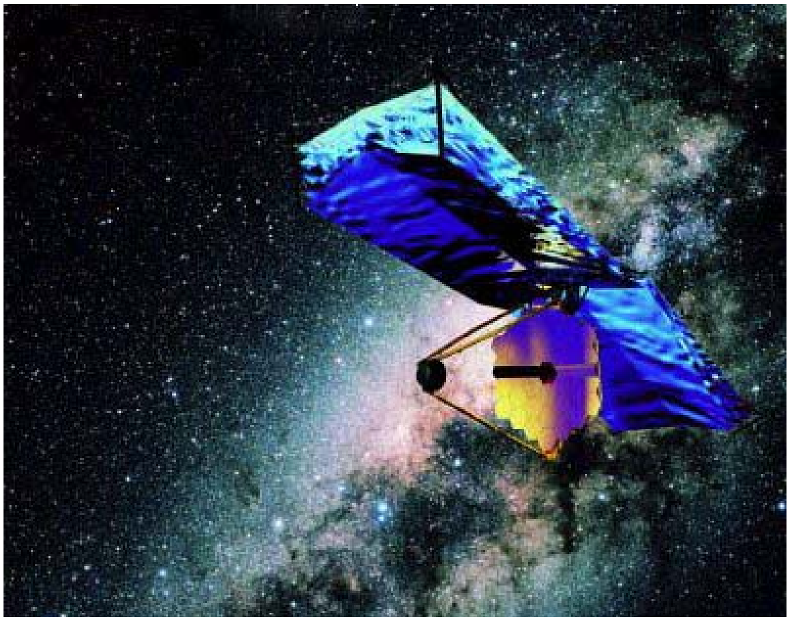


Figure 3: The NGST (now JWST) as envisioned (6 m diameter primary mirror) (courtesy: ESA)

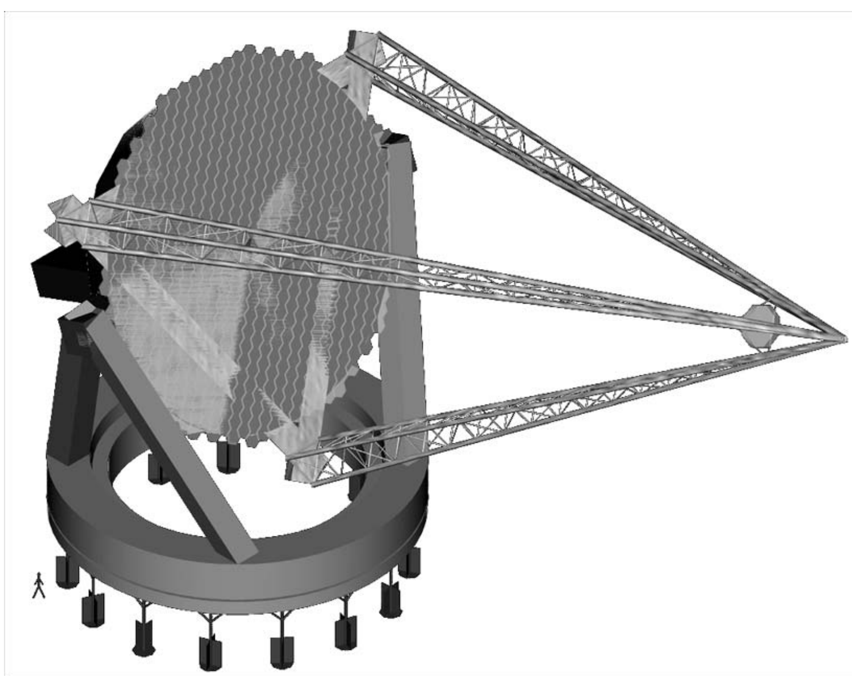


Figure 4: a rendering of an alt-azimuth telescope as designed for the lunar surface (25 m diameter primary mirror)

Gravity on the Moon is one sixth of Earth's gravity so one kilogram on Earth would exert a force of about 100 Newton on the floor, on the Moon this same mass of one kilogram would only exert a force of 16.7 Newton on the floor. Inertia of a body's mass is a good thing because it makes construction easier (you can walk on the surface as opposed to float away into space if not being careful) and it gives the structure something to push against. In other words, moving the telescope to a different position is easier on the Moon than in free space. Rotating the telescope generates vibrations in the structure that have to dampen out. This is comparable to holding the camera still before taking a picture. If you do not hold the camera still it will result in a blurry picture. On the Moon these vibrations die out sooner because there is more damping and more mass available than in free space. The Hubble Space Telescope had a ten minute transient vibration time which meant that during those ten minutes no observations could be made. The lunar surface is capable of absorbing these forces which will result in more observation time per day and it will make sure construction, inspection, maintenance and upgrading is much safer and easier to do than in free space. Another aspect of gravity that is considered negative is the fact that it causes deformations by 'pulling' on the telescope elements. This effect, however, is predictable and repeatable. We can deal with it in Earths' gravity field so why not in the benign one sixth gravity of the Moon. So gravity is not a negative factor but is even an asset, light enough to make great things and structures possible and make it safer, but not so much that it becomes limiting.

The temperature range that can be found on the lunar surface differs greatly from Earth because there is no atmosphere. The surface temperature behavior is very similar to behavior of surfaces in free space and is determined by the angle with respect to the incoming solar energy. Most of the lunar surface receives sunlight for roughly 14 Earth-days and then is in darkness for about the same amount of time. During the lunar day the temperature at the equator is as high as 390 K and during the night it will get as low as 110 K. In the north and south polar areas of them Moon, craters exist in which the sunlight never reaches. This unique situation means that the temperature in those areas is very low and doesn't change much. Exact temperatures have never been measured, but models suggest that the temperature could get as low as 30 K with a variation of 10 K over a month. These permanently shaded craters exist to about 10 degrees off the poles and are suspected to contain concentrations of hydrogen that are many times larger than anywhere else on the lunar surface. The hydrogen is a potential resource that could be used for oxidizer in rockets, water for drinking, chemical processes, and many other things. The cold areas can become mining areas, but also can be used to place very sensitive infrared telescopes as described by Van Susante (2001, 2004). Operations in very cold areas are an engineering challenge, but expected problems such as lubrication issues for moving parts, can be solved. On most places on the lunar surface, the temperatures are similar as to in free space and a lot of experience to working in that environment is available, as of course the experience from the Apollo missions.

Dust is perhaps the greatest problem for exploration, operations and science on the surface of planets including the Moon and Mars. Some experience with dust and its effects was gained during the Apollo missions and the properties of the lunar dust have been and will be studied on Earth laboratories and on the lunar surface. The Martian dust has other characteristics then lunar dust, among others the Martian dust is toxic for humans since it consists of peroxides. The lunar dust problem is known and thus can be mitigated. The exact behavior of dust is not well known and will be subject of several studies that will be performed by NASA and universities, among others at the Colorado School of Mines. For telescope applications, dust can be a problem, but mitigation measurements that are implemented from the design phase will be able to greatly reduce its impact on telescope operations. Among other measures to be taken are minimizing ground transportation's dust production by good fenders, wheel enclosings, driving slowly so that kicked up dust does not travel far, also locating mining, launching and landing operations and other dust producing activities at least ten kilometers away from the telescope sites. Some other measures are described in Van Susante (2004).

Meteoroids are considered by some to have a higher impact concentration on the Moon because its gravity captures meteoroids that in free-space would have flown by. The amount of meteoroids that is expected to hit the Moon is about twice as high as in free space. Nothing definite is known about the impact density on the lunar surface since no measurements have been done and the estimate is based on counting craters and estimating the age of each one. However, the Moon's planetary body not only attracts meteoroids, it also shields a structure on or under the surface from meteoroids that would have hit a structure in free space.

Seismic activity on the Moon is several orders of magnitude less than on Earth, many of the most powerful telescopes currently in operation are located on the Mauna Kea volcano in Hawaii next to an active one called Mauna Loa. For individual telescopes seismicity on the lunar surface is not a problem. For interferometry it might pose a problem during local very short seismic events, but overall the lunar surface is much more stable than the Earth surface and thus will not pose a problem for interferometry if properly designed/engineered. A revisit of Apollo collected seismic data shows this (Mendell, 1998)

Telescopes on Lunar Surface

Van Susante (2001, 2003, 2004) shows that a basic infrastructure to and on the lunar surface will be required before very large telescopes can be constructed there. This infrastructure such as transportation capability, basic construction capability and a small manned lunar base can then support many activities including telescope construction. This infrastructure and the presence of other activities and functions will facilitate the building/maintenance and upgrading of the telescope facilities over decades. Many telescopes can be constructed this way and once a few are built, the threshold will be very low to construct many more, especially once some (structural) parts can be manufactured on the Moon. A careful balance and coordination must be warranted such that present and future lunar activities would not disturb ongoing observations. The planning and coordination should not be a complex issue in itself, but requires willingness from all involved parties. Two of the main effects that could influence telescope operations are dust generation and vibration generation. Since dust travels in parabolic trajectories due to the vacuum conditions its impact area can be calculated and zones of influence can be established. Vibrations generated by other activities such as mining that are transport through the lunar surface will require more research locally, but is expected not to give many problems.

However, with an initial deployment of the infrastructure for a large telescope, in particular the utility-infrastructure for the management and operations of the facility, other instruments and structures can be added at substantially reduced total costs when compared to "stand-alone" facilities. These range from simple items such as communications, command and control (CCC) infrastructure to climate/environmental controls, power supplies, in-situ data pre-processing and processing, storage and even archiving, broad-band communications to and from Earth and to other CIS-lunar facilities, to maintenance tasks, updating, repair and spare parts inventories. Most important, hardware not needed on the Moon such as attitude controls, fuel to maintain orbits, gyros etc. can not fail and need not be maintained, repaired or replaced – or worse, can not lead to loss of facility and, hence, termination of a whole field of research and teams of researchers. The cost/risk/assurance of continuity aspects are dealt with separately below in the Cost and Risk Factor Determination" paragraph.

Another advantage of an established infrastructure on the lunar surface is the added inherent advantages in "standardization" that will be the inevitable result of a common operation and maintenance of a Condominium of Observatories. This has been demonstrated in the ISS (at great initial expense and effort), but also in many other Space programs, be they transportation, logistics or Space craft – commonly summarized under the heading "payload effects".

Human-Robot teams

Figure 5: Astronaut and Robonaut prototype working together in truss construction in Earth laboratory (courtesy of NASA)

Operations on the lunar surface will, where possible, be done by robots, either remotely or (semi-)autonomous. However, when direct assessment, adaptation, interpretation and evaluation is required with myriads of “unknown unknowables” a central, enabling role for humans in the deployment, operation and maintenance of such Condominium facilities is mandatory, just as such human presence is required by integrated terrestrial facilities to assure continuity of operations. The strengths of robots and humans should be used where it will be most beneficial and in a way such that they complement each other. Robots are good at repetitive and well defined activities within a certain operational range. Humans are far more versatile and can adapt relatively fast and easy to new or unexpected circumstances. Most well planned construction can be done by robots while humans supervise and problem solve when required. Every construction process has unexpected occurrences that need to be dealt with. Humans are also required for the commissioning phase which entails the testing of all parts of the telescope such that it all works together flawlessly. If parts are misaligned, malfunctioning or an instrument doesn't work properly, troubleshooting will be necessary. Humans are invaluable and irreplaceable by current state of the art robots because some processes such as the commissioning phase will require knowledge, feeling, intuition, a multitude of tools and local ingenuity to solve issues that can not be foreseen. Robots and humans, however, need to be able to work well together as NASA has been exploring in many research projects, among others in the Robonaut project.

Foundation Example

An example of how to design and place a foundation for a large lunar telescope can be found in Van Susante (2001, 2004). A first step will be to use robots to install some sort of geo-measurement system that can be used with a geographical information system such that planned and actual positioning can be checked since precision is of utmost importance when building telescopes. Laser rangefinders can be used as such a local geographical measurement tool. After these are installed, the construction process can begin with digging of foundation holes in the designated and confirmed locations. The foundation poles can then be placed inside the holes which will be filled and compacted. Calculations and foundation details can be found in Van Susante (2001).

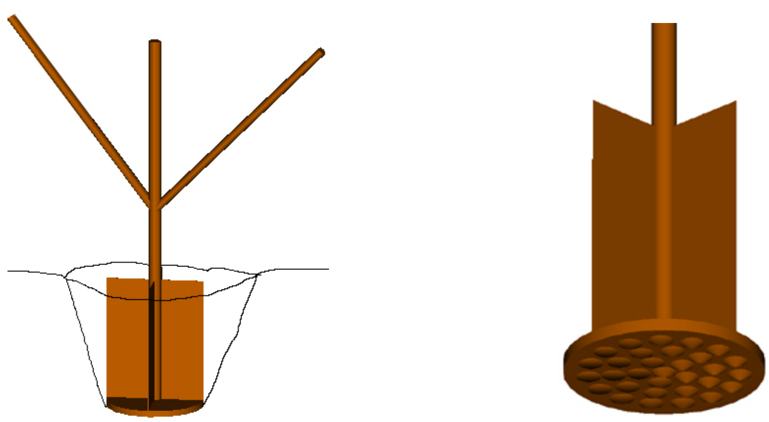
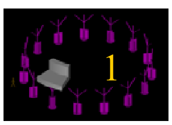


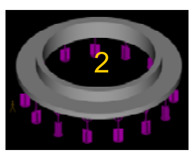
Figure 6: Foundation poles for the large telescope

Construction Sequence

A possible overall construction sequence of a large Altitude-Azimuth telescope on the lunar surface can be found in Van Susante (2001, 2004). First and foremost the overall lunar surface transportation and lunar base infrastructure need to be set up. Then the foundation can be installed in the chosen location. In the case where the telescope would be cold enough, super-conducting bearings could be used to make the azimuth ring on top of the foundation. These bearings are uniquely suited for telescopes in locations where the temperature is lower than 90 K. They could function with virtually no energy losses, be very precise, have no friction and most importantly be impervious to dust clogging. The rings would have to be installed in two sections, the lower half and the upper half. When the upper half is constructed and resting on the lower half, the main support struts can be installed. These main support struts will carry the housing for the instruments, the counter weight and the altitude axis on which then the primary mirror support will be built on which the secondary mirror support struts will be built. Once the main structure is in place, the delicate parts will be installed beginning with the secondary mirror, followed by the primary mirror and the instruments. The commissioning phase can then begin.



1) Placement of foundation

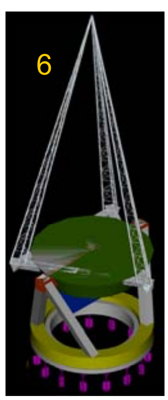


2) First super-conducting magnet ring

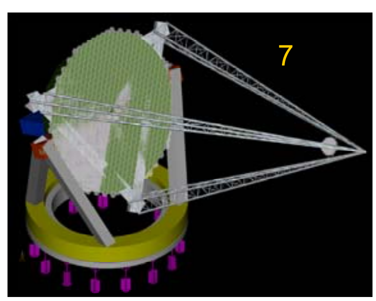
3) Second ring & main supports

4) Main axis, contra weight & instrument housing

5) Main mirror support structure



6) Secondary mirror supports



7) Mirrors and Instruments Installed

8) Commissioning phase

Figure 7: A large altitude-azimuth telescope construction sequence

Expansion Sequence beyond the first Observatory.

A first observatory should have demonstration capabilities in a way so that it not only provides science but also demonstrates techniques that will be required by subsequent, larger observatories. A three to six meter primary mirror would be a good start. The wavelength should be chosen for convenience and contribution to science. For a first observatory it would probably be best to choose radio or optical wavelengths followed by infrared and all the shorter wavelengths in UV, microwave, x-ray, etc.

Cost and Risk Factor Determination

An incredible amount of factors play a role in the determination of cost. However, not only the cost in dollars determines if something is expensive or cheap. It depends on what you get for it in return. Is it better to spend $1 billion on a free flying space telescope that might not work once in orbit and will be discarded after a few years, or is it better to spend $5 billion on a telescope on the lunar surface that will allow the construction of many more telescopes in the same area for a marginal cost because the infrastructure is already there and each successive telescope will cost less than the first one. In addition to expansion, it is possible to do maintenance and upgrade the existing telescopes such that instead of a lifespan of a few years, they have a lifespan of decades or more. On Earth, even the oldest, smallest telescope is capable of performing good science, so why discard it? Another advantage of building telescopes on the lunar surface with a manned lunar base in the vicinity is that fast and close-by quality control and trouble shooting can be done on the spot by sending robots and/or humans. In free space this would take much longer because of the travel times and difficulties involved. The long travel times would also lead to long unproductive down-times of the telescope. Overall, a lunar based telescope can do more science per year than a free-based telescope. A large lunar telescope would be easier and safer to construct than its free-space counterpart. The risk of fatal malfunctions or irreparable damage on the lunar surface is also considerably lower. Overall this leads to the preliminary conclusion that lunar based observations are more efficient than the ones located in free-space. If a comparison is made between one telescope in free-space versus one on the lunar surface, these advantages are not enough to warrant the building of all the infrastructure required, just for one telescope. If, however, most of the infrastructure required will be built for one or more of the functions described earlier, and not one, but many telescopes are considered, it becomes a very clear picture that the Moon is the only logical place to build telescopes.

A rough major cost breakdown structure for large astronomical spacecraft is shown in Table 1. As can be seen from those data, about half of the cost of astronomical spacecraft go to “household" (utility) chores and half to the scientific instruments themselves. As a first order of magnitude approximation one can say that a commonly provided utilities infrastructure on the Moon could save at least half the costs of these facilities.

Programs	Instruments	Housekeeping
Chandra	58%	42%
GRO	48%	52%
HST (original)	53%	47%
HST after modifications and enhancements	62%	38%
SIRTF	49%	51%
Average	**54%**	**46%**

Table 1: Percentage of total cost per observatory by distribution between instruments and housekeeping.

Obviously this is but a first ballpark estimate – but nonetheless it appeals to common sense.

Things become even more advantageous for deployment(s) on the Moon when one looks at the degradation of these facilities after deployment in Space, their lifecycle costs, risks and assurance of continuity of observations and programs. A quick review of such issues certainly includes the following:

- Compton (GRO) failed because of problems with a few gyros – these are not needed on the Moon and – if accessible to humans like Hubble with the Space Shuttle, could easily have been repaired if designed from the start for such human instrument-spacecraft services;
- Chandra as of late had "fogging" problems (degradation of its optics) with 'out-gassing' suspected as the culprit. Again a human servicing mission could easily have taken care of this (minor) problem to save a multi-billion dollar mission;
- Hubble – the ONLY major space craft specifically designed for human (Space Shuttle) servicing and repairs – actually had failed totally after the initial launch due to faulty optics. It was with the ingenuity of Hubble engineers and the ability to indeed revisit this facility with the Space Shuttle that "enabled" Hubble to begin with and made possible the most spectacular and successful astronomical facility ever operated by man.

  Then, in the course of Hubble operations, this facility was radically updated and improved over time – the HST Modifications & Enhancements – to yield additional capabilities at relatively little added cost and risk. Indeed the outcry over termination of Hubble by nearly all astronomers and the public at large is testimony to the success of human tended Space observatory operations, maintenance and modernization(s).

Last and not least, with a deployment of permanent observatories on the Moon the age-old "discontinuities of Space astronomy "life-cycles"" are avoided once and for all. Taking the Hubble Space Telescope as an example: it was in the early 1970's that the Space Transportation assessment team of Mathematica visited with Prof. Spitzer in

Princeton and the Hubble was born. Lockheed Missiles and Space Corporation (LMSC) did the Shuttle compatible design of Hubble to allow for human visits and repairs in the 1970's. Yet it still took another decade – to the late 1980's, before the Hubble would be launched. And then it turned out to be unusable for the designated missions. It took another two to three years to see to the repair of the flaws in the Hubble Telescope and since then it operated successfully for now one and a half decade. But even that included a major Hubble Modification and Enhancement mission to prolong its useful life. Without that, Hubble would have been terminated years ago. Now indeed the decision seems to have been made to terminate Hubble in favor of other follow-on programs. Had the revisit capability not existed there would have been ZERO output from this major investment program. More importantly, any follow-on would have required another "decadal" definition and procurement cycle, all the while the careers of initially young astronomers would have advanced to the ripe old age of prospective retirement.

> A deployment of Observatories on the Moon will end these discontinuities and uncertainties and bring Space closer to the well established operations and career paths for astronomers experienced here on Earth in "condominium" facilities such as ESO and on Mauna Kea in Hawaii.

By combining the historical cost and risk experiences with operational requirements and the need for assurance a comparison can be made between Space based and Moon based observatories. A rather complex set of issues arises which in combination seem to give observatories deployed on the Moon a considerable "life-cycle" cost, risk and assurance of service advantage. First order of magnitude Monte Carlo simulations using historical data and requirements indicate the following (see Table 2)

Astronomy Life Cycle	**Risk Cost Schedule Assessment**	
Probabilities	**Space Based**	**Moon Based**
Launch success	0.92	0.99
Infant Mortality	0.27	0.01
Operational	0.2	0.1
Repair/ Refurbishment	N.A.	0.9
Updating/ Evolution	N.A.	0.9
Replacement	0.4	N.A.
Assurance of Continuity of Observations		
Combined - Standard	0.37	1
Combined -"NRO" Type	0.98	1
RoM Cost Assessment		
One Life Cycle	205	100
Assured "NRO"	525	100

Table 2: Probability, assurance of Continuity and Cost assessment of Space Based observatories vs. Moon based observatories.

All these calculations use an existing manned Lunar Base and a Space Transportation infrastructure as specified in the various Space Task Forces over the past decades needed for the operation and maintenance of such permanent presence of humans on the Moon. That is, the observatory costs are evaluated as "additive" to an existing Lunar infrastructure. With modern means and innovative approaches, these numbers probably improve to be even more in favor of observatories on the Moon.

What stands out are the substantial cost and risk advantages of Lunar deployment if indeed the required observations have to be "assured", that is the probability of cessation or outright failure due to loss of spacecraft or instrument is unacceptable. Other than with extraordinary duplication – indeed 'tripling" of capabilities in orbit, on the ground and in the procurement pipeline such assurance is seldom accomplished – and even with such a management approach "force majeur" sometimes intervenes to deny observation capabilities even under such rigorous management approaches – see the post-Challenger grounding of all US launch capabilities for over a two year period (Titans, Atlas-Centaur, Delta) and Ariane.

Observatories deployed on the Moon will not "fall off" the Moon – nor will they cease to operate even with extended interruptions of service missions if properly designed and provided for – short of an asteroid taking out the complex.

These RoM Monte Carlo simulations and the historical data set used have to be updated – but if done on a comparable basis with the requirement of an assurance of observations the cost-risk-assurance advantages of Lunar deployment will persist. With the evolution of ISRU, CELLS, robotics and human capabilities across the Moon and CIS-lunar Space these advantages can only increase by order of magnitudes

Synergies

Possible cooperation and synergies can be found in a variety of groups and parties. Some examples of projects that could be done from the Moon are the Comet Asteroid Protection System (CAPS), the tracking of moving objects capability (a National Research Council decadal study of planetary exploration recommendation), observation of Earth, the Solar system and the rest of the universe for science and other reasons. On the Moon, the development of exploration technology and a research / testbed for Mars and other planetary bodies will be put in place. Mining operations for In Situ Resource Utilization and manufacturing operations will be developed and performed on an increasing scale. Next to all this, the science on and of the Moon will not be forgotten an even commercial development will be possible.

Precursors and Experiments

Before the first large telescope can be constructed on the Lunar surface, more research and technology development needs to take place. Some of these required research projects can only be performed on the lunar surface, others can be done from lunar orbit or even on Earth. A list of some of the more important research and knowledge gaps is listed below.

* More topographical information with sufficient resolution (<1m) needs to be available, this can be done from lunar orbit, however, some local ground reconnaissance will probably be required before final locations for construction can be chosen.

* More information on seismic stability is needed which hopefully will be provided by a successful Lunar-A mission by the Japanese in 2006. Local seismic data will probably have to be collected before and during operations, if only to determine which data might be influenced by seismic events.
* Confirmation about the presence of ice and its composition etc. in the permanently shadowed craters is required so strategic decisions for mining and lunar base siting can be made. This can only be guaranteed by a lunar surface ice detection mission.
* Knowledge about the exact temperature regime in the permanently shadowed craters is necessary for design and modeling purposes and the effectiveness of different kinds of shielding (including regolith cover) must be examined for thermal control of telescopes and other structures to be built on and under the lunar surface.
* More and direct in-situ knowledge about lunar dust is required before effective designs can be made. Mitigation measurements need to be implemented and studied for effectiveness.
* More knowledge about the extent of the influence of human presence on the lunar environment (atmosphere, dust, vibrations) will be required. Human presence will influence the surroundings by leaking of gases from buildings, landing and launching of rockets, dust production and vibration generation. The extent of these effects need to be studied and mitigation measurements studied.
* High temperature super-conducting magnetic bearings need to be further developed.
* Human-robot construction interaction studies need to be performed. Intuitive methods of working together need to be studied and implemented. Safety aspects need to be integrated from the start such that human risk will be as low as possible.
* New versatile and autonomous robots need to be developed and tested
* ISRU needs to be developed and implemented on the lunar surface to speed up development and independence of the lunar base and other lunar activities.
* Small telescopes in different wavelengths need to placed to test their effectiveness and get experience with construction on the lunar surface.
* Interferometry needs to be implemented and tested on the lunar surface.

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