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Feasibility Study of Radio Telescope Array and Communication System Development on the Far Side of the Moon

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The basis of this study is to outline a feasible and affordable method for lunar interferometery on the moon's far side. The idea of radio astronomy on the moon has been around for decades, with radio astronomy's inception in the 1930's by Karl Janskey. Coupling radio astronomy with development of lunar landers in the latter half of the 20th century brought lunar astronomy to the forefront of cutting edge research.

Basic aspects of lunar radio astronomy development are outlined in this paper. The moon's far side, where optimal research would take place, is shielded from communication with Earth. If communication is completely blocked, so is interference from the massive technological super systems on Earth. This renders the moon's far side the most practical place, possibly in the solar system, to conduct astronomy experiments. A system of two satellites is proposed to continually relay data to Earth. The paper discusses the overall mission, which includes three stages:

I. Launching and deploying the surface landers
II. Launching and injecting the communication satellites
III. Setting up receiving stations on Earth

The development of four individual ultra-light landers for each radio dish is proposed. When landed, deployment is completely automated and communication with an L2 satellite and the three other lunar telescopes are immediately set up. Before deployment, communication relay satellites are set up at L2 and L4. Validation for these respective placements will follow.

This paper does not discuss rocket selection for this mission. Any rocket capable of carrying and deploying all four telescope landers at one time would be ideal. In total, two launches would be needed, one for surface structures and one for communication satellites.

During development stages, ground-based receiving stations will need to be built. Preferably 2-3 stations so 24 hour coverage can be provided.

Communication between the surface and the satellites will be accomplished via "Light Amplification by Stimulated Emission of Radiation" (LASER) technology. This is a unique proposition and details will be analyzed. LASER technology would be optimal because it will not produce any harmful interference with the sensitive radio equipment. The paper will outline instrumentation requirements, significant values, theoretical data, pathways, and a brief breakdown of radio interferometry and communication elements. Lunar lander designs with the radio telescope attached will be proposed and analyzed.

I. INTRODUCTION

Radio astronomy on the moon is a long sought-after, yet never accomplished, mission for astronomers. The reason this opportunity is so unique is because its application is restricted to the far side of the moon. As outlined in the abstract, this placement on the far side of the moon blocks all interference from systems on Earth and from satellites in geosynchronous orbit.

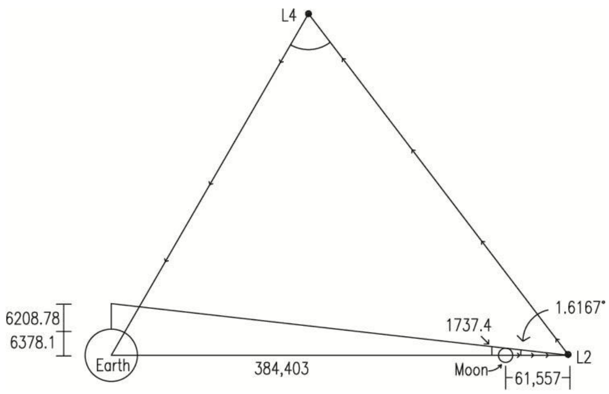

Fig. 1 - Diagram of moon shielding and L2 relays

Radio signals ranging from a few millimeters to tens of meters can easily penetrate the atmosphere. Beyond this window extraterrestrial radio signals cannot reach the ground because the ionosphere will reflect them back into space. While this effect can be good for communications on Earth, it closes off a potentially interesting region of the electromagnetic spectrum from Earth-bound telescopes. Certain regions of the radio spectrum can only be observed from space (Davies).

The feasibility of this mission is actually surprisingly simple in theory. Albeit, we should recognize the execution and success of the overall mission is limited by multiple factors.

Technology of LASER's and communication is expanding every day. The first part of this paper will discuss the LASER theory of communicating information via Free Space Optics (FSO). The layout of the telescopes and communication efforts will be outlined immediately following. This will lead to a discussion of the analytical considerations of the communication system.

Information received from the telescopes will be relayed to a system of communication satellites. After the requirements for communication are established, design requirements for the surface landers will be addressed.

Based upon the lander design and the communication system concept, we can then begin to address the design of the relay satellites. Positions for these satellites have been mentioned briefly, however, a more detailed analysis will be provided.

L2 and L4

The L2 and L4 points are also known as Lagrangian point 2 and Lagrangian point 4 (Earth-Moon Lagrangian points). Basic physics dictates that with every 2 orbiting bodies there are 5 corresponding points where the gravity from each body, cancels out the gravitational pull from each body. This gives those 5 points the ability to rotate with the body and remain relatively unperturbed. Placing an object in this location give it the ability to maintain its orbit without having to go through regular orbital maintenance maneuvers. Theoretically, whatever is placed in these locations can remain there forever, due to the negligible effects of gravity

II. THEORY - REQUIRMENTS

This section will outline the theory of the laser system that will be implemented in this communication system. The system will link the moon's far side and the Earth. With efforts to keep the far side of the moon radio quiet, laser communication will take place all the way up to the L4 point. Explanations will be chronologically ordered, starting from radio signal reception to the downlink to a ground station on Earth.

A chronological process will guide the discussion:

- An incoming radio signal will be received on the surface of the moon. Information will be sent to a central dish, where the information will be processed and analyzed.
- From the primary source on the moon, the central dish, information will be transmitted via laser to an active optics relay satellite at L2.
- Information will be received by the primary satellite, compressed, amplified, and relayed to the L4 satellite. Upon reception, the signal will be converted into a microwave beam and down-linked to the Earth's surface. This process keeps the moon's far side radio quiet.

Signal Processing and Laser relay

Using a system of four ultra-light telescopes with a minimum amount of equipment on board, it is possible to gain access to parts of the spectrum that are unavailable on the Earth. Radio signals at certain wavelengths have trouble propagating through the atmosphere due to various factors (Ghuman). Further discussion will focus on the exchange of information from data collection of the exterior dishes to a central dish, avoiding the need for large and bulky dishes. The diameter of the telescopes can range depending on the rocket payload's shroud size.

Spreading 3 dishes apart at 20km (~12.4 miles) in a Y-pattern, distributed around a central dish at 120° apart, will create a simple, yet optimal layout for observation.

This layout follows a similar layout of the Very Large Array (VLA), with the Y-pattern and a similar spread. The location of the antennas allows aperture synthesis interferometry at a maximum baseline of 40 km. This will be very high resolution.

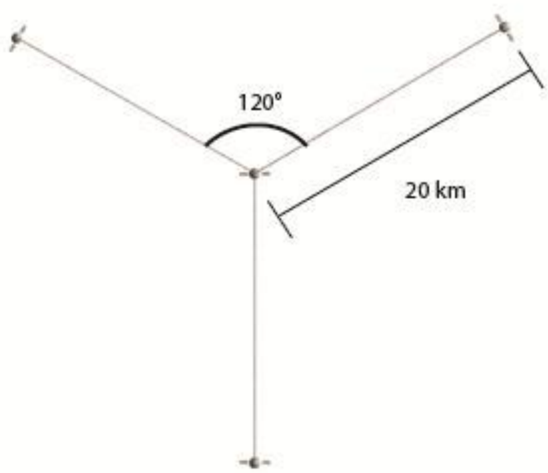

Fig. 2 – Y-Pattern Layout

Equipping each of these dishes with a small laser for communication capable of transmitting though the relatively unperturbed atmosphere will create a negligible amount of dB loss. Once the central computer receives this information, it will be collected, processed, and transmitted to the L2 satellite where it will be actively reflected onto the L4 location. At this point, the laser signal can be converted into a microwave signal that can easily and consistently penetrate Earth's atmosphere.

Resolution of the Radio Telescope

A single radio telescope's resolving power will be poor because of the long wavelength of radio waves. Combining multiple telescopes will enable the signals to be combined to mimic the effect of a single, large instrument (known as aperture synthesis). With dishes close together they can be synchronized using atomic clocks. The telescopes will record information and direct it towards the central dish to be relayed back to Earth for processing. This is known as Very Large Baseline Interferometry (VLBI) (Davies).

This layout enables assess to parts of the spectrum that have never been explored. The 20km Y-patter layout will give the equivalent of a 40km dish. With the moon's relatively slow rotation rate (about 29 ½ days) the telescope will have access to extended periods of time to observe a given object. The software used on Earth for data analysis can be put on the central dish for processing along with a computer to help power the process.

Mount and Motion of Telescope Dish

The optimal mount for the dish, in order to allow freedom to rotate, will be an alt-azimuth mount, or a "Dobsonian" mount. This will give the telescope a degree of freedom that will allow it to observe any section of the sky. An altitude and azimuth coordinate can be transmitted to the telescope, processed, and two small motors can point to the exact location in the sky. Due to the slow rotation of the moon, periodic correction will be needed to track a celestial object across the sky. Tracking an object on Earth with this type of mount is difficult because of its tilt. The moon has a tilt of about 1.5 degrees, which will not present a problem.

Location of Landers on the Moon

An equatorial site has been selected for the placement of this radio array. This will provide the telescopes with optimal access to the sky throughout its 29 1/2 day rotational period. The further we venture away from the equator; the less access it has to the sky. Finding a suitable landing site can be further explored, however, several things must be provided from the site.

Trade-offs on the location of the landers to consider are:

- Flatness - this will dictate how the lander is sitting and whether or not a communication link can be set up with the other telescopes.

- Nearness to equator - plays a huge role in the % of the sky that can be accessed.
- Depth of crater - can also be a problem. If creator walls are very high, they can cut off a portion of the sky due to elevated horizons.
- Longitude – to escape the Earth radio interference.

A site at or close to 0° N, 180° E would be optimal. This will create an easier communication link to the L2 satellite overhead. This is on the exact opposite side of the moon and directly on the equator. An example would be any mare that is relatively flat, or a larger crater, i.e. Daedalus Crater or Aitken Crater.

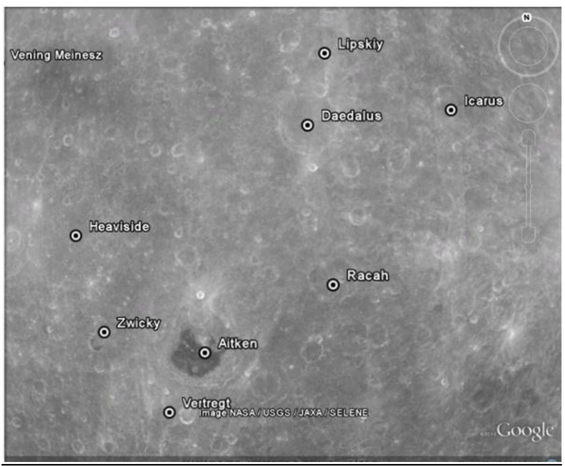

Fig. 3 - Map of Moon's Far Side at Equator

III. EQUIPTMENT AND PROCEDURE

Perimeter Dishes

The three outlying dishes vary only slightly from the central dish. Keeping with a minimum functionality approach, the design of this dish will be equipped with only the basics:

- **Dish** – the dish is parabolic in shape, as to direct the received signal on a central focus and utilizes a feed horn to help direct the signal. The feed horn serves several purposes, but the key use is to direct the radio signals between the reflecting dish and the receiver/antenna.
- **Antenna**– After the signal is directed off the dish to the feed horn, it is then directed to the focus. The focal point has a wire antenna that converts the radio wave into electric current.
- **Tuner** – Due to the massive amounts of signals hitting the dish, the tuner separates radio signals from background noise and other useless signals. The tuner matches the frequency of the incoming radio waves that are being observed.
- **Amplifier** – Boost the signal to a useful level.
- **Transmitter** – The signal is then converted in an electro-optic process, and passed to a laser transmitter where it is relayed to the central dish for data processing.

The designs of these telescopes are extremely rudiment. Nothing above and beyond proven technology will be needed for any part of the astronomy process. These techniques have been perfected on Earth so the understanding and data collection can easily be processed.

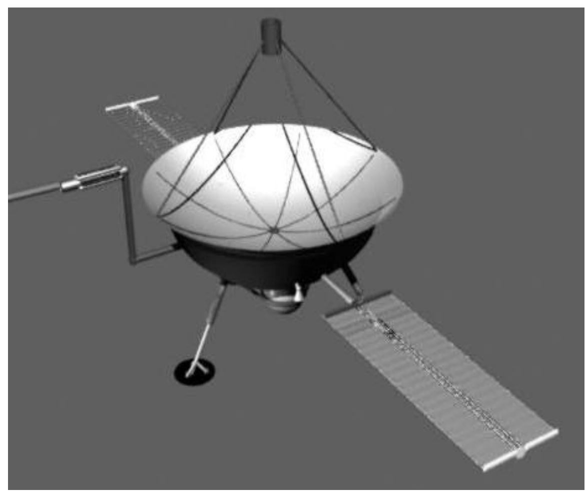

Fig. 4 - Model of Perimeter Dish

Central Dish

There are subtle differences in the central dish as compared to the perimeter dishes. The difference will be that the three receivers that will need to be arranged on the lander's frame. The central dish will also have a more powerful laser transmitter directed upward as opposed to horizontal. The transmitter will send a signal to a relay satellite about 61,500km away, so a stronger LASER will be required.

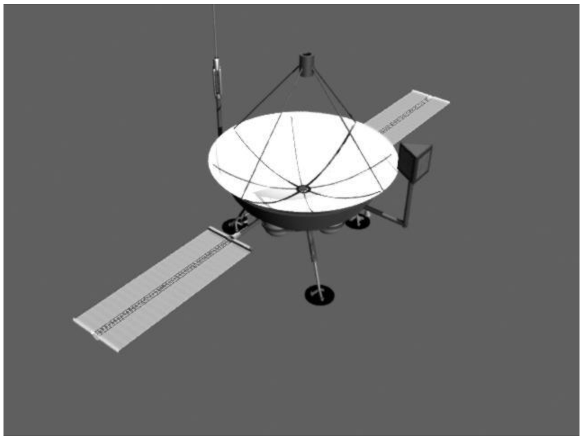

Fig. 5 - Model of Central Dish

Computers in the central lander will process all the data from the four telescopes, including itself, record that data on tapes, and condense it. This way, only useful data will be transmitted to Earth rather than the entire massive amount of raw data. This will cut down on the data package size and make transmitting easier.

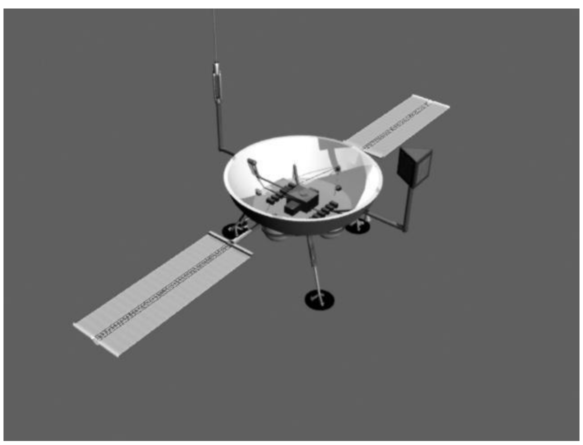

Fig. 6 - Model of Systems in Central Dish

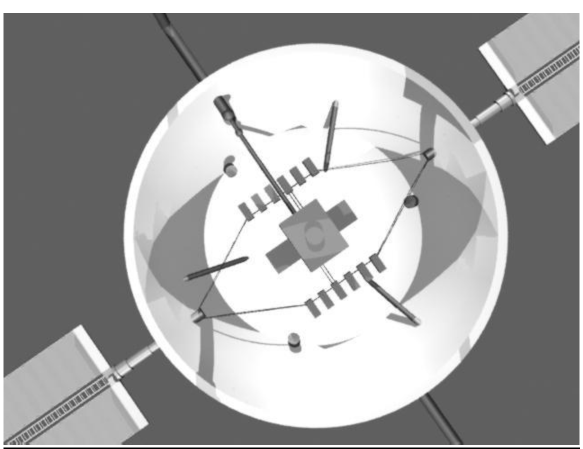

Fig. 7 - Up Close View

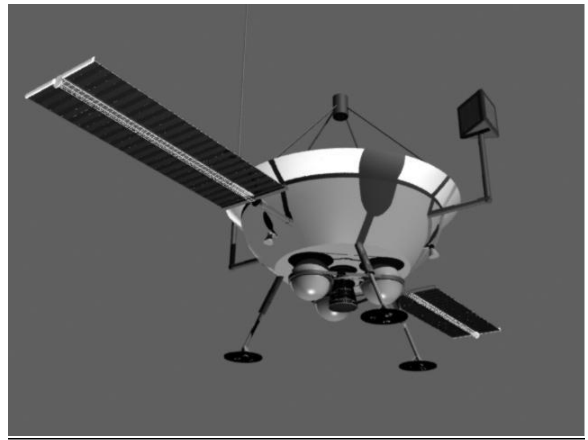

Fig. 8 - Propulsion System

Relay Satellite

The original plan was to use passive optics on the relay satellite, but applying several models and equations made this task seem near impossible due to the information that would be lost between the moon, L2, and L4. The satellite will simply receive the signal, process it, compress it, and then amplify the signal to be transmitted onto the L4 satellite. Using mirrors to reflect the signal is an idea worth examining, but as distances grow further apart, accuracy falls off tremendously. Solving this problem with active optics can complicate the scenario but in the end give a clearer picture due to the increased amount of accurate data that will be received on Earth.

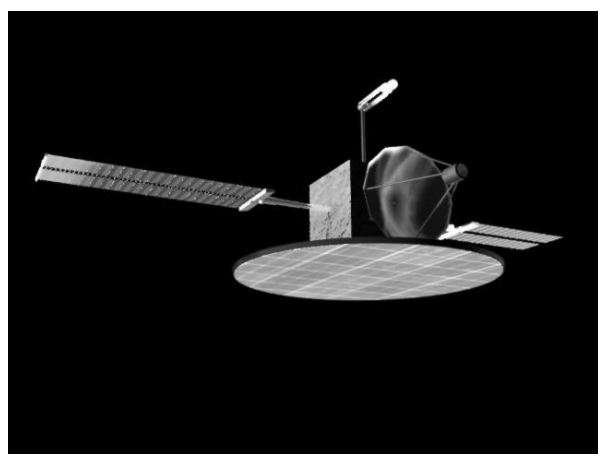

Fig. 9 - Model of L2 satellite

Connecting satellites via LASER can be solved theoretically. When put into practice, however, it becomes a big logistic problem. Transmitting between the moon - L2 and L2 - L4 will need to be addressed in more detail. The proper point-ahead angle as well as Acquisition, Tracking, and Pointing (ATP) mechanisms are all part of the equation of locking onto the given satellite. When communicating in the medium of space, very little differs in the laws and equations that are used in radiofrequency communication. There is a basic method for calculating the number of collected photons at the receiving end, using the energy emitted from the transmitter. The equation:

$$n = P/hvf \qquad [1]$$

Where:
n = number of photons per bit
P = received optical power (watts)
h = Plank's constant
v = frequency of LASER (Hz)
f = signal data rate (bits per second)

The farther the platforms are away from one another, the inherent Bit Error Rate (BER) increases. BER is the number of bits received by the receiver that have errors in them due to noise and interference. The LASER is introduced to several perturbations due to various vibrations and jitters. This causes the LASER to not focus directly on the receiver, creating errors.

When transmitting through a system of satellites the error rate of the data is cumulative, with either passive or active optics. Possible ways to prevent this issue would be to demodulate the data and apply correction factors for the error rate at each transmission point, adjust the data, and continue on with the relay transmission. This solution can be utilized for relatively low cost in weight of the system, but is made up in the monetary cost of extra software and technical complications. In the case for low cost systems, relaying and amplification systems are the main concern. Separation from the electrical noise of the tracking system and the LASER communication system are vital parts to maximizing received information, with minimal interference.

IV. RESUTS AND DATA – TECHNICAL SUPPORT

This section will address a few of the sub-systems that will be implemented for the system. Acquisition, tracking, and pointing will be analyzed as more details are developed with our communication system.

FSO on Lunar Surface

Beam divergence can be a big issue for long range transmission. For a larger separation in distance, the larger diameter the laser will have at the receiving end. This is due to "geometric path loss". A narrower beam can be used to counteract the effect. This is a feasible idea because of a ultra-stable platform that the moon's surface offers. This reduces the amount of jitter and random vibrations, yielding the communication link to be very reliable.

$$w(z) = w_0 \sqrt{1 + \left(\frac{z}{z_R}\right)^2}\ . \qquad [2]$$

Where:
W(z) = Spot Size
W_0 = Minimum Value
Z = Distance from beam waist
Z_R = Rayleigh Length = $\frac{\pi w_0^2}{\lambda}$

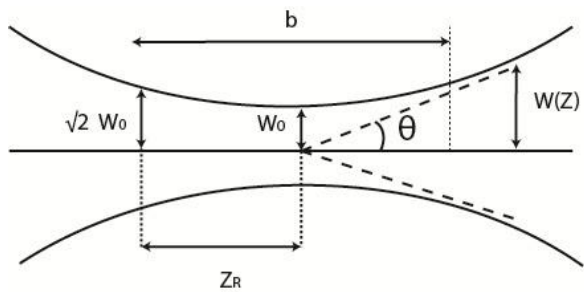

Fig. 10 – Picture Breakdown of LASER Beam Waste

This equation explains the dispersion of the beam size as it is transmitted over a certain distance.

The beauty of FSO is that it can receive and transmit information at the same time, a "duplex" operation. For digital systems, like these, the transmitter modulates the electrical input that carries the actual traffic (Fortescue). During the Electro Optic (EO) process, information is converted from an electrical signal to an optical one. This process allows for the transmission paths to stay independent and separate. The advantage of this type of system that is the separate telescopes can be programed, in near real time, where to point. Having this amount of control assures that each telescope is pointing in the same direction when needed.

Many options are available for semiconducting lasers. Main variables exist when trying to decide which source to use:

- wavelength
- modulation speed, and
- power.

Some main tradeoffs for this project, given its defined parameters:

- system weight
- bps, and
- power requirements.

Details involving specific laser designs and configurations are beyond the scope of this paper. Accordingly, it will focus on the bigger picture.

Acquisition, Tracking, and Pointing (ATP)

ATP is a vital part of maintaining constant data flow between nodes in the communication system. Implementing the proper equipment to assure that the signal can lock onto the target is vital. We can assume one common medium for propagation of the LASER due to the fact that the moon's atmosphere has a negligible impact on the LASER, much like the medium of space.

There are four major steps in the ATP process and the scenario that has been set up which makes it very easy to acquire and track, however maintaining pointing can be a problem due to the large distances. Equipping the central dish with a beacon with an optimal field of view, searching and acquiring the L2 satellite should not be a major difficulty, due to the simplicity of the orbit around the L2 point. Given a large enough Field Of View (FOV), with a small amount of error, no more than +/-1 degree, scanning can continue until the satellite passes into our beacon swath.

After the satellite is acquired, the tricky part is done. We then set up the communication link and direct the LASER towards the receiver. The L2 satellite then scans its own FOV and detects the incoming data beam. The beam is locked in and a tracking beacon is set up so the L2 satellite can track that point on the moon where the central dish is stationed.

Last, the central dish locks onto an incoming tracking beam from L2 and the link is considered closed. Now the system has an accurate pointing system that can maintain constant, strong signal flow (Aviv).

For the relaying of information to the L4 satellite, the same procedure applies. During this ATP process for each node, both the beacon beam and the communication beam must have an ability to gimbal. The motion of these systems must be independent of the motion of the satellite, so not to break the alignment the satellite has with its solar panels facing perpendicular to the sun.

Solar Power – Light vs. Dark

The light and dark cycle on the moon offers a unique set of challenges. The 29 ½ day rotational period offers 15 days of light then 15 days of darkness. In order to operate during the dark periods without having to add extra fuel or other electrical sources of energy, the lander will need to have an alternate source of energy. Batteries would be the simplest solution to this problem, but current battery technology is proven only down to about -83 degrees Celsius. The moon's dark side can get down to about -153 degrees Celsius.

Small, portable "suitcase" sized nuclear power plants could be the solution. With the ability to generate around 40 kW, this would be more than enough power to run the telescope during lunar night. This technology is being developed and tested currently. The issue of meltdown, as we commonly encounter here on Earth, would not be an issue due to the low power levels and the system would just shut down in cause of error. This deems miniature nuclear power plants very safe (Tech).

V. ANALYSIS AND CONCLUSION

In conclusion, we see that setting up this system of landers and satellites can be done with a minimalistic and sustainable mindset. This will drive down costs, while also maintaining reliability between all of the nodes. This is a very simple and affordable way to probe deeper into that part of the spectrum that remains a mystery.

Lunar astronomy is the future of the science of astronomy. Steps have already been made to rise above the major portion of the atmosphere with airborne telescopes like SOFIA, which has a price tag of 3.75 billion US dollars and operates at a cost exceeding 230 thousand US dollars per hour. This is small compared to the cost of the Hubble Space Telescope that is currently orbiting. Total cost now exceeds 14 billion US dollars and cost about 235 thousand US dollars per hour to operate.

The cost advantage of a moon based system would essentially pay for itself over a lifetime that can exceed decades. Radio astronomy is one of the simplest parts of the spectrum to observe, so the lifetime can easily surpass expectations. Equipping the systems with back up LASER, which will in all likelihood be the limiting reagent in this problem, will create a longevity that could far exceed our expectations. The ability to build onto the system also creates opportunity for expandability.

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