Lunar Interferometric Radio Array
L.I.R.A.

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Abstract

The Lunar Interferometric Radio Array (LIRA) is a performance driven design, with emphasis on utilizing the unique attributes of the far-side of the moon as a platform for radio astronomy. LIRA consists of three independent Lunar Telescope Units (LTUs), autonomously landed on the moon, and a communications relay satellite orbiting at libration point two (L2). Each LTU deploys a large inflatable spheroid, whose underside has been impregnated with a reflective coating. The spheroid is then gradually hardened into a shell by the sun's ultraviolet radiation.

LIRA achieves broadband capabilities by operating each LTU independently (tuned to offset frequencies), or provides high resolution observations as a three-element interferometer. The interferometer is functional with as few as two elements, yet will achieve greater resolution with additional elements. Thus, LIRA delivers both redundancy and the possibility for future expansion. Data processing, including interferometric synthesis, occurs at an earth-based ground station, eliminating the need for complex onboard data manipulation.

Definitions and Constants

CEI – Connected Element Interferometry

GN – Ground Network

HPBW – Half-Power Beamwidth

IBS – Inflatable Balloon-like Structure

ISM – Interstellar Medium

k – Boltzman's constant, 1.38×10^{-23} J/K

L2 – Libration point two

LIRA – Lunar Interferometric Radio Array

LPDA – Log Periodic Dipole Array

LTU – Lunar Telescope Unit

OFW – Operational Frequency Window (defined as 150 – 330 MHz)

RTG – Radioisotope Thermoelectric Generator

S – flux density, in Jansky (1 Jy = 10^{-26} Watts/(m^2 Hz))

SNR – Signal-to-Noise Ratio

T – Temperature, in Kelvin unless noted otherwise

VLBI – Very Long Baseline Interferometry

η – Antenna efficiency

λ – Wavelength

σ = feed spacing factor

τ = feed scale factor

Mission Introduction

In the electromagnetic spectrum, radio photons have the lowest energy. Therefore, they are emitted in larger numbers for the same energy radiated. This imparts a fundamental advantage to radio astronomy in the detection of distant objects, which is essential to understanding the nature and origin of the universe.

As radio spectra are extended to longer wavelengths, many tend to show radical changes, suggesting that different mechanisms are dominant in different parts of the spectrum[3]. The three important mechanisms of radio emission are blackbody radiation, plasma thermal emission and synchrotron radiation. The first two mechanisms are attributed to Planck's radiation law, which states that all objects at temperatures above absolute zero radiate energy in the form of electromagnetic waves. However, synchrotron radiation is a non-thermal emission (not due to temperature), and originates from relativistic electrons moving in the presence of a magnetic field of a star.

Manmade broadcast prohibits broadband terrestrial observations at frequencies from a few kilohertz to hundreds of gigahertz. Additionally, the earth's highly dynamic ionosphere and the presence of water vapor affect the propagation of radio signals, inhibiting high-resolution observations at particular frequencies internationally allotted to radio astronomy.

Engineering Considerations on the Lunar Far-Side

In order to effectively engineer an astronomical system on the lunar far-side, it is important that the nature of its environment be understood. The moon's weak gravitational constant ($g_{moon} \sim 1.6$ m/s^2) and lack of atmosphere (and hence weather-imposed loading such as wind, rain, etc.) allow for innovative approaches to structural design not possible on the earth. However, the magnetic field of the moon is variable and weak, and does not provide protection from the solar radiation during the lunar day,[4] inducing structural degradation. Micrometeorites also impact the surface at cosmic velocities due to the lack of a lunar atmosphere. The above factors are likely to serve as the fundamental limitations to the mission longevity.

Lunar equatorial temperatures range from 100 K to 385 K (-170 ^{o}C to 110 ^{o}C). The cold nighttime temperatures allow the cooling of many systems without the use of cryogenics, as the LIRA will be operational only during the lunar night.

The lunar regolith is fine grained, cohesive and has a low thermal diffusivity[5]. These properties indicate that thermal control problems could arise as a result of excessive regolith blown by rocket exhaust onto structures during descent to the surface. Also, the low diffusivity prohibits efficient thermal control by conduction to the surface.

The motion of the moon can be predicted more easily than the motion of the earth due to characteristics associated with the lack of an atmosphere and oceanic tides. Although the moon does experience solid body tides due to the gravitational attraction of the earth, the main tidal bulge is fixed. This makes the moon an ideal location for an interferometer. Additionally, lunar seismographs indicate that the moon experiences only a few hundred quakes yearly, with the majority of their magnitudes within the earth's seismic background noise level[4].

Mission Drivers

The lunar far-side offers two primary advantages over the earth as a site for astronomical observations in the radio spectrum. First, the lunar-far side is the only place in the solar system perpetually shielded from manmade broadcast, as the moon rotates about the earth at the same rate it rotates about its own axis. Secondly, the moon does not have an appreciable atmosphere or ionosphere to adversely affect incoming signals[4].

The LIRA shall be sensitive to frequencies ranging from 150 MHz to 330 MHz, defined as the Operational Frequency Window (OFW). This enables observation at frequencies allocated to the observation of pulsars (150.05 to 150.03 MHz) and deuterium (at 327.38 MHz), in addition to continuum thermal and non-thermal emission at frequencies never before reliably observed on earth due to manmade broadcast.

The LIRA design is driven by the following objectives:

- To provide sensitivity from 150 to 330 MHz
- To achieve high angular resolution
- To provide instantaneous 30 MHz bandwidth broadband capabilities

Approach

The LIRA project was approached in a top-down fashion, seeking scientific performance while being limited by current or near-future technologies. After researching previously proposed lunar observatories, it was determined that a simple antenna (such as a dipole) array would require significant onsite processing and too vast an area to be viable. Alternately, a very large aperture dish could be supported in a crater, similar to Arecibo. However, deployment without a human presence seems unlikely.

Telescopes in an array, known as elements, receive radiation from a distant source with a time delay due to the distance between them, known as the baseline. The time delay can be accounted for if the baseline and the orientation of the source with respect to the baseline are well known. As the source drifts through the reception pattern, the amplitude of the superimposed signal varies periodically as the constituent signals interfere. The true brightness distribution of a source may be obtained as the Fourier transform of this signal, yielding higher resolution than from any single element.

There are two broad categories of radio interferometry: Very Long Baseline Interferometry (VLBI), and Connected Element Interferometry (CEI). VLBI utilizes independent array elements, which is desirable to allow for future expansion or the failure of an element.

A lunar-based VLBI array, with medium sized apertures, can achieve high angular resolution, or by tuning the elements to offset frequency ranges, broadband observations of a given source are possible. The LIRA shall operate in this manner.

The next phase in the LIRA mission was to identify the number of elements and the aperture size required for acceptable scientific results within the limits of feasibility. The LTU was designed around a Titan IV or Ariane V class launch vehicle, with attention given to the physical dimensions and mass budget to accommodate three units on a single launch.

Subsystem designs for the LTU and relay satellite were given secondary importance to the scientific performance due to the complex and detailed nature of subsystem design. However, significant, yet somewhat generalized, consideration was given to subsystems directly related to the performance and longevity of the mission.

LIRA Mission Outline

LIRA is an unmanned mission that consists of three Lunar Telescope Units (LTUs) and a communications relay satellite. The LTU is a semi-autonomous spacecraft, with a deployable telescope aperture. Each LTU will land at a predetermined destination near the equator on the far-side of the moon. Near-equatorial placement allows observations of sources in both the northern and southern skies. Because interferometers are largely self-calibrating, deviations from the desired landing site may be accounted for by observing a known source. However, the surface curvature of the moon imposes a maximum LTU separation of 10 km for interferometric purposes[4]. Upon landing, the LTUs establish a communications link with the ground network via the communications relay satellite.

A relay satellite is necessary because the lunar far-side is never in view of the earth. A suitable orbit for the satellite lies at libration point two (L2). This orbit remains in constant line of sight with the lunar far-side and the surface of the earth. The communications relay satellite requires two antennas and three independent transceivers to relay the telescope data in real-time. Additionally, ground controllers may uplink commands, such as steering position to the LTUs.

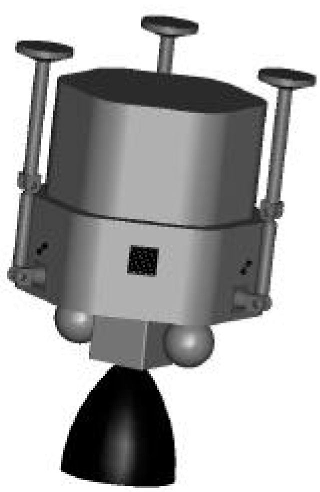


Figure 1: LTU in packed configuration

Figure 2: LTU with IBS fully deployed

Telescope Design

The moon's weaker gravitational attraction and its lack of an atmosphere enable the deployment of a large Inflatable Balloon-like Structure (IBS), which may serve as a telescope aperture by impregnating the underside with a metallic coating.

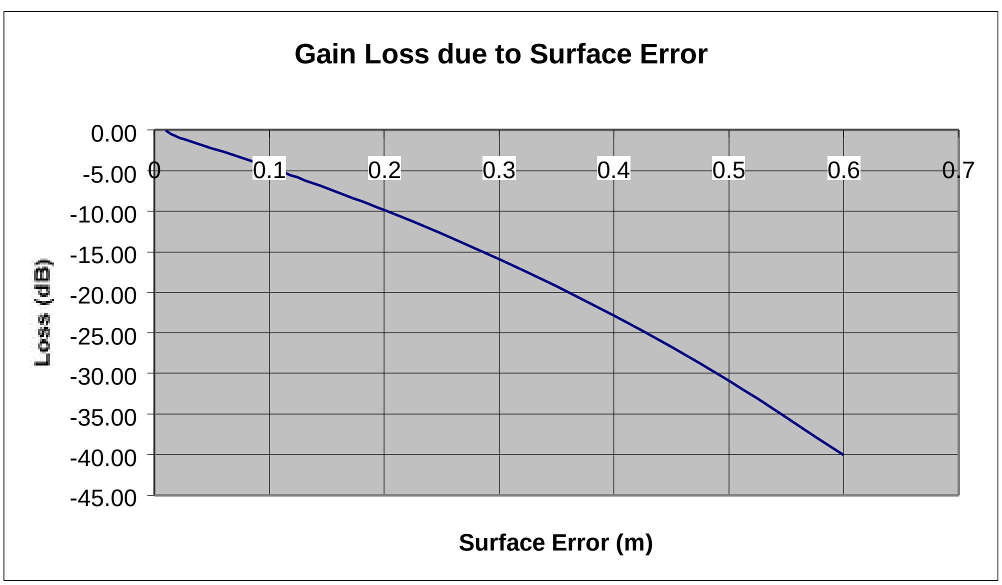
The IBS is compactly stored atop the LTUs in transit to the moon. Once on the surface, deployment of each IBS is delayed to allow the cloud of lunar regolith stirred by the LTU engine exhaust to settle, to avoid increased thermal absorption. After approximately 48 hours, the IBS is inflated with helium gas. It is desirable that the IBS harden into a shell structure to reduce maintenance associated with diffusion and temperature induced pressure variations. This is achieved by manufacturing a cross-linking chemical agent, activated by exposure to ultra-violet solar radiation, into the IBS material.

A control loop, involving pressure regulators and a calibration source, ensures that the dish takes its proper geometry as the lunar day progresses. Since the IBS will be in solar exposure for 336 continuous hours (the duration of one lunar day), the hardening process can be gradual. Off-axis steering from the sun, and the introduction of a catalyst gas may also be used to encourage homogeneous hardening. Once the shell is cured, the helium gas is vented, and a thorough calibration is performed.

A high-performance synthetic material will be required to realize the IBS. However, the capabilities of current materials suggest that such a suitable material could be produced should an initiative to develop it be taken.

Surface errors are less critical for the longer wavelength signals for which the LIRA is designed. Additionally, minor structural deviants, such as wrinkles from packing, may be accounted for by identifying critical points for each instrument, and correcting for them electronically. These initial errors, combined with structural degradation over time, result in an attenuation of the signal. It can be seen below that a surface error greater than 10 cm will significantly impact the telescope gain.

Graph 1 : Surface Error Losses



The aperture of the telescope must be on the order of several wavelengths to avoid diffraction. An aperture of 20 meters will allow acceptable resolution for signals within the OFW.

An important feature of telescope design is the focal length to diameter ratio (f/D). Side level radiation introduces noise to the signal, but is attenuated by a high f/D ratio. However, a low f/D ratio increases cross-polarization performance, which is important because sources are generally random emitters. A f/D ratio of 0.5 is a satisfactory compromise to these factors, which yields a focal distance of 10 m.

The height of the dish determines its shape and can be calculated by the following equation:

$$H = \frac{D}{16\frac{f}{D}}$$

where H is the height of the dish from the base to the top of the rim, D is the aperture and f is the focal distance.

With a dish diameter of twenty meters and a f/D ratio of 0.5, the dish height is found to be 2.5 m.

Gain is a multiplication factor by which the dish performs better than an isotropic receiver or transmitter given by:

$$Gain = \frac{4phA}{l^2}$$

where A = 314 m^2 is the area of aperture, $\eta = 0.65$ (typical[9]).

Table 1. Telescope gain as a function of wavelength (150 to 300 MHz)

Gain (dB)	**Wavelength (m)**	**Frequency (MHz)**
28.07	2.00	150
29.41	1.71	175
30.57	1.50	200
31.59	1.33	225
32.50	1.20	250
33.33	1.09	275
34.09	1.00	300

The feed receives the reflected signal from the dish. Each LTU will utilize two log periodic dipole arrays (LPDAs), oriented perpendicularly to provide reception for randomly polarized signals. The LPDAs are located at the focal point of the dish, 10 meters above the base and within the IBS. An individual LPDA consists of ten separate antennas, which are sized for different frequency sensitivities. With optimal scale and spacing factors ($\tau = 0.917$ and $\sigma = 0.169$, respectively) it will yield an additional 9 dB gain. The feed is 2.21 m in length. Below is a chart showing the length and spacing between each feed element. Additionally, the angle of the feed can be defined, and is equal to 38.88^o.

Table 2. Feed element characteristics

Feed Element	Length (m)	Spacing Distance (m)
L1	1	0.34
L2	0.92	0.31
L3	0.84	0.28
L4	0.77	0.26
L5	0.71	0.24
L6	0.65	0.22
L7	0.59	0.20
L8	0.55	0.18
L9	0.50	0.17
L10	0.46	--

To help account for all polarizations, the two LPDA feeds can themselves be circularly polarized electronically. This is accomplished by sending one of the pre-amplified LPDA signals through a phase shifter. Switches placed in the circuit of each LPDA permit each signal to be observed individually, thereby allowing observation of all polarizations.

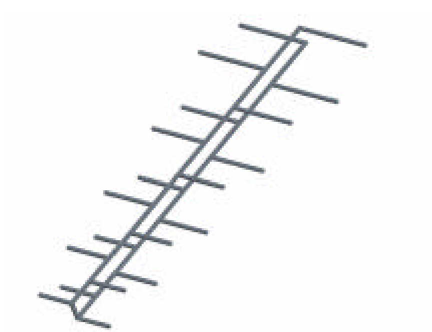


Figure 3: A single LDPA feed

Once a signal enters the feeds, it is sent to a receiver. The LTU receiver has the responsibility to amplify the incoming signal, change the polarity of the feeds, and to integrate and output a signal to the data relay transmitter. This process is handled by the following circuitry:

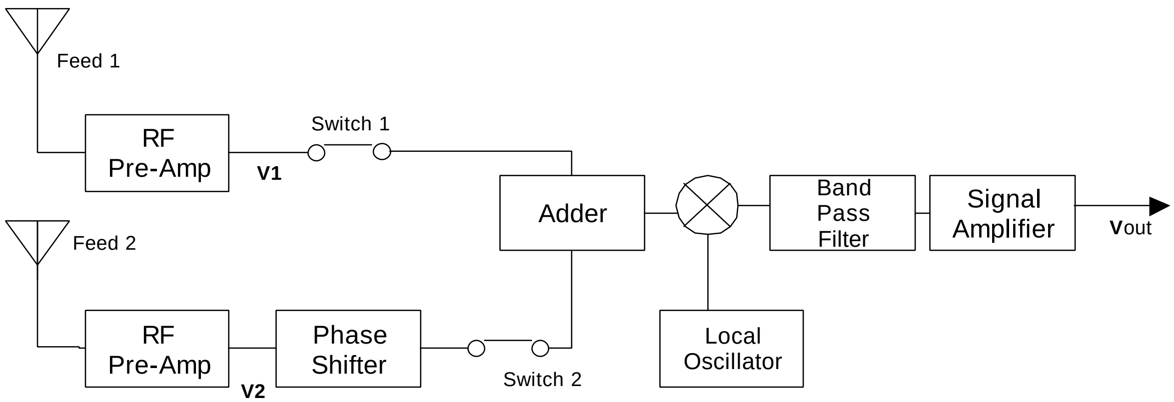


Figure 4 : Phase Switching Receiver Schematic

The incoming signal from Feed 2 can be phase shifted from –90 to 90 degrees to cover all polarizations. The switches will allow each feed to be selected individually, providing an even greater range. The final signal voltage can then be sent to an amplitude modulator to be transmitted to the relay satellite.

To conduct successful interferometry, the three LTUs must be spaced far enough apart to create helpful diffraction gratings which eliminate sideband noise. The baseline will also increase the resolution of the system. However, the baseline will be limited to a 10 km maximum due to the curvature of the moon[4]. The incoming direction of the wave plane can be found by analyzing the diffraction patterns and phase shifts between elements for a given frequency. The resolution is calculated by:

$$\frac{57.3^o}{d_l}$$

where d_λ is the distance between elements in wavelengths.

The resolution and the directivity of the antenna dictate the amount of elements needed in an array to achieve specific results. The following spreadsheet compares baseline separation to maximum resolution (in degrees) for two elements at 150 MHz:

Table 3. Angular resolution between two elements at 150 MHz

Angular Resolution

λ = wavelength (m)

D = Dish Diameter (m)

L = distance between LTUs

R = Resolution (deg)

n= number of elements

Input: Distance Between LTUs, in Wavelength

n	L (m)	λ	Aperture	Resolution
3	100	2	20	0.382
	250			0.153
	500			0.076
	750			0.051
	1000			0.038
	1250			0.031
	1500			0.025
	2000			0.019

For multiple elements, the resolution can be calculated by dividing the above resolution by (n-1), where n is the number of elements. Thus, the three-element LIRA, operating at 300 MHz and at the maximum baseline of 10 km, is capable of 3.44 arcsec resolution.

Mechanical control of the LTU aperture is very important to conduct successful interferometry. The LIRA is movable up to 15 degrees off vertical and able to rotate 180 degrees about the vertical (thereby allowing +/- 15 degrees off vertical in all directions). This is accomplished by mounting the support plate of the IBS to a rotational swivel and a curved track. A simple gear, pulley and chain assembly will drive the IBS. Additionally, motion in right ascension can be achieved by meridian-transit scanning. However, the rate of right ascension is quite slow (~2.6×10^{-6} rad/s), due to the moon's long rotational period.

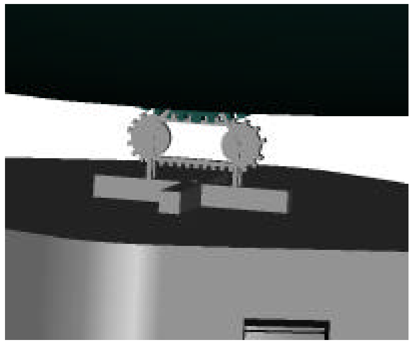


Figure 5: Drive steering mechanism

Case Study – CASSIOPEIA A:

In order to understand the broadband performance of the telescope, a well known source, such as Cassiopeia A will be examined in a case study.

First, the minimum detected temperature is calculated by

$$\frac{K_s\, T_{sys}}{(B_w\, t)^{1/2}}$$

where Ks is a receiver constant, t is the output time constant and Bw is the bandwidth.

The output time constant will be taken as one second for integration. Ks will be assumed to be 2 using a phase-switching interferometer[3]. The maximum bandwidth will be 10 MHz and the system temperature for the telescope is 100 K, the lunar nighttime temperature. This provides a minimal detectable temperature of 0.06325 K, which leads to the minimum detectable flux density given by:

$$S_{min} = \frac{2\, k\, T_{min}}{A_e}$$

$$S_{min} = 0.55618 \text{ Jy}$$

With this knowledge in hand, a Cassiopeia A may be used as a calibration source. It is situated 11,000 light years from the moon and has a flux density of 11,600 Jy at 178 MHz. The signal to noise ratio can now be calculated as:

$$SNR = S_{cass}/S_{min}$$

$$SNR = 43.19 \text{ dB.}$$

The Half-Power Beamwidth (HPBW) of the telescope and the source's subtended solid angle must be known. The HPBW telescope is 0.08587 ster, and Cassiopeia A subtends a solid angle of $1.66x10^{-6}$ ster. This provides a multiplication factor of 51179, which is used to measure the temperature of Cassiopeia A at a particular frequency. To accomplish this, the temperature factor is multiplied by the temperature increase in the antenna at that frequency. In other words, if the antenna temperature changes by 0.1 K while focused on Cassiopeia A at 178 MHz, then it can be deduced that the apparent brightness temperature of Cassiopeia A at 178 MHz is 5172.9 K.

Astronomical data from the telescope receiver will be handled by analog processing, due to limitations imposed by the performance of space certified computers. Data from the receiver will be combined with coherence data, important for the interferometric synthesis, modulated and transmitted to the relay satellite in real-time for processing and analysis at an earth based ground station. The achievable bandwidth is limited by the telescope electronics taken to be 10 MHz. As each LTU is capable of 10 MHz bandwidth, operating individually, a maximum instantaneous bandwidth of 30 MHz within the OFW can be obtained.

Communications Link Budget

The communications link budget must account for three independent channels from each LTU to the relay satellite then to the ground network. The link budget calculations were done with a spreadsheet, where inputs are given in dark gray boxes, and outputs given in yellow (or light-gray). The parameters of frequency and transmitter power are based on small deep space mission transceivers in the Ka band[6] (~30 GHz). Optimization of the Signal to Noise Ratio (SNR) can be achieved by modifying the input parameters. Calculations for the link budget from the ground station to the LTU are not included, as the LTU to ground station link is the limiting performer.

The LTU communications dish has a 1 m aperture and is placed on top of the IBS. The dishes of the LTU must be able to track the position of the 1.5 m dish of the relay satellite. The receiver temperature is kept at 303 K (30 ^{o}C), the presumed temperature inside the relay satellite. Results are listed in Table 4.

The satellite relay dish positioned towards the ground network has a diameter of 1 meter, and broadcasts to a ground network. The NASA Deep Space Network receiver temperature and aperture are used for this calculation, found in Table 5.

Both calculations are based on the maximum 10 MHz analog bandwidth (introducing the most noise), and thus are link minimum performances.

Table 4. LTU to relay satellite communications link budget

LTU-Satellite Communications Link

Ka-band communications:

Carrier Frequency (GHz) =	30.0	Lambda =	0.01 m
Transmitter Power =	5.0 W		

LTU

Inputs	
Dish Aperture =	1
Antenna efficiency =	0.7
Effective Area =	0.55
Gain =	69087.23
Gain (dB) =	48.39

Free Space Loss (FSL)

Input	
Distance between LTU and Satellite =	67500000
FSL =	7.19E+21
FSL (dB) =	218.57

Incidental Losses (Li, in DECIMAL)

Input	
Li =	1.2

Satellite

Inputs	
Dish Aperture =	1.5
Antenna efficiency =	0.7
Effective Area =	1.24
Gain =	155446.27
Gain (dB) =	51.92

Receiver Noise (Nr)

Inputs	
Temperature of receiver (K) =	303
Bandwidth (MHz) =	10
Nr =	4.18E-14
Nr (dB) =	-133.78

Signal to Noise (SNR)

SNR =	148.67
SNR(dB)=	21.72

Table 5: Relay satellite to GN communications link budget

Satellite-Ground Network Communications Link

Ka-band communications:

Carrier Frequency (GHz) =	30.0		
Transmitter Power =	5.0 W		

Input		
Lambda =	0.01	m

Satellite

Inputs	
Dish Aperture =	0.5
Antenna efficiency =	0.7
Effective Area =	0.14
Gain =	17271.81
Gain (dB) =	42.37

Ground Network (Using NASA DSN)

Inputs	
Dish Aperture =	34
Antenna efficiency =	0.41
Effective Area =	372.25
Gain =	4.68E+07
Gain (dB) =	76.70

Free Space Loss (FSL)

Input	
Distance between Satellite and GN =	4.49E+08
FSL =	3.18E+23
FSL (dB) =	235.03

Incidental Losses (Li, in DECIMAL)

Input	
Li =	1.2

Receiver Noise (Nr)

Inputs	
Temperature of receiver (K) =	28.8
Bandwidth (MHz) =	50
Nr =	1.99E-14
Nr (dB) =	-137.02

Signal to Noise (SNR)

SNR =	531.87
SNR(dB)=	27.26

Electrical Power and Thermal Control

The LTU electrical power subsystem must be operational for 336 continuous hours in absence of the sun. This, in addition to the logistical problems associated with the deployment of solar array panels beyond the IBS, suggests that a Radioisotope Thermoelectric Generator (RTG) be used.

Due to the geometry of the IBS, the electronics and main structural components of the LTUs are constantly shielded from solar radiation. Since the moon has no atmosphere, and the surface is a poor conductor of heat, the LTUs remain essentially at the lunar nighttime temperature of 100 K, and the region of space in the shadow of the IBS may be used as a heat sink. (If the periods of time when the sun is close to the horizon are neglected, and the lunar albedo received by the LTU is not significant.) Space radiators, modulated by louvers, control the thermal environment of the LTU, which is always in an excess of thermal energy generated by the RTG[9].

Mission Lifetime

Micrometeoroid flux measurements indicate 300 impacts per square meter per year, with average diameters of 10 microns[4]. At this flux, the upper structure of the IBS will incur over 94,000 such impacts per year. Additionally, craters 100 microns in diameter will form at the rate of about 150 per year.

The LTU dish will be the only structure directly exposed to the sun. The thermal control of such a large area would ideally be achieved through the use of thermal coatings, to avoid complexities associated with active controls. Due to the solar ultraviolet radiation, the degradation of these coatings is exponential in nature[9]. The upper limit for functional performance of thermal coatings is 44,000 hours[9]. This corresponds to a continuous exposure time of five years. Since only half of the time is spent in exposure, the upper limit of mission lifetime is 10 years. A more realistic approximation would be a maximum exposure time of 22,000 hours (allowing for thermal coatings of a lesser performance and micrometeoroid impacts), corresponding to a maximum five-year mission lifetime.

The mission is scheduled to launch in the year 2005, or any consecutive period less than 2.5 years before the solar activity minimum. This will minimize the solar wind flux and ultimate thermal degradation of the IBS.

Conclusions and Recommendations

The LIRA design may be expanded to include a scientific impact study to determine more specific mission objectives and their relevance to science. From this point, the LIRA concept could be modified to meet those objectives. This would also enable a more detailed subsystem analysis and reasonable cost estimates to be performed.

Due to the scientific nature of the LIRA mission, the only likely sources of funding will be governmental. LIRA was designed with an emphasis on as-simple-as-possible design principles to address the NASA initiative of "faster, cheaper, better" missions. However, the inherent complexities of a lunar-based interferometer seem to disqualify LIRA from this philosophy, unless international sources can help defray the costs.

The invasion of restricted frequencies by the communications industry seriously threatens the future of radio astronomy,[3] and already prevents very broadband observations. In the future, the lunar far-side may become the only suitable place from which to conduct observations. In such a case, the costs of a LIRA-class mission would be justified.

A possible political motivation for an international lunar-based interferometer, aside from sharing industrial technologies, could be stimulated by the Search for Extra-Terrestrial Intelligence (SETI). Current large-scale SETI projects presume that an extra-terrestrial civilization is intentionally broadcasting on significant frequencies[7]. However, our civilization itself does not continuously broadcast at these frequencies. Instead, our broadcast occurs all along the radio spectrum, *except* at those significant radio astronomy frequencies.

Outreach

LIRA team members have maintained an Internet site since early October, from which progress reports, presentation slides and pictures are accessible. The site will remain active as part of a showcase of Embry-Riddle Engineering Physics design projects, and also as a HEDS-UP resource.

In September, members presented preliminary design concepts to Engineering Physics freshmen as guest lecturers in the PS109 course. Team members were also present to give a project summary and show Pro/Engineer models (contained in this report) to prospective students at the Fall Open House. The results of the first semester were presented to colleagues in the senior design course in December. The final presentation occurred in the Miller Auditorium on April 12, before an audience of 150 students, professors and the general public.

A LIRA project summary, and a photo of team members, appeared on the cover of the Spring 2000 Engineering Physics Newsletter, distributed to over 300 Engineering Physics students professors and alumni. Embry-Riddle's campus newspaper, The Avion, also has a forthcoming article about the LIRA project and the HEDS-UP forum.

Each outreach activity was designed to increase awareness and understanding of the basic principles of radio astronomy, the drivers for a lunar far-side based observatory, the lunar environment and the LIRA design, with levels of complexity adjusted for the audience.

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