Lunar Surface Arrays

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Short title: LUNAR SURFACE ARRAYS

Abstract. During the latter half of the 1980's, three concepts for low frequency arrays on the Moon were independently studied for NASA, leading to two workshops in 1990. Perhaps not surprisingly, when one considers the constraints, the concepts were all quite similar. Each consisted of tens to hundreds of dipoles deployed over tens of kilometers. Each element had a superheterodyne receiver, a digitizer, and a data transmitter and antenna mast. Each team envisioned that the array would start small and grow with time. The main technical challenges were those of deploying the array on the Moon, and of correlating the data on the Moon or returning all the raw data to Earth. We review these lunar low-frequency array concepts and note possible alternative approaches to some of the concept features.

1. INTRODUCTION

In 1984, Jim Douglas and Harlan Smith presented a concept for very low frequency radio observatory (VLFRO) on the Moon at a NASA-sponsored conference [*Douglas and Smith*, 1985]. They noted the advantages which the Moon offers:

- It can hold any number of elements in perfectly stable relative positions.
- It can start modestly and be expanded with time.
- The antenna element wires can be laid directly on the regolith.
- Lunar rotation provides full sky coverage.
- The lunar farside is shielded from terrestrial interference.

The VLFRO was envisioned as a 15 × 30 km array operating between 300 kHz and 30 MHz.

Four years later NASA, the University of New Mexico, and BDM Corporation sponsored a workshop to define the science goals and preliminary specifications for a Very Low Frequency Array (VLFA) on the Lunar Far-Side. The strawman design was an initial 17 km circle, with the array growing with time to a 1000 km diameter [*Basart and Burns*, 1989].

In 1989, at the request of NASA's Astrophysics Division, JPL conducted a study of possible lunar astrophysics experiments which could be conducted at a Lunar Outpost to be established as part of the Lunar/Mars Human Exploration Initiative. One of the concepts studied was a 70 × 35 km T-shaped Lunar Low Frequency Imaging Array (LLFIA) [*Kuiper et al.*, 1989], also known as the Lunar Near Side Array (LNSA).

These various concepts [*Smith*, 1990; *Kuiper et al.*, 1990b; *Basart and Burns*, 1990] came together in 1990 at workshops held in Crystal City [*Kassim and Weiler*, 1990] and Annapolis [*Mumma and Smith*, 1990].

In the mid-90's, ESA also conducted a study of a lunar low frequency array [*Bély et al.*, 1997; *Woan*, these proceedings], also called the Very Low Frequency Array. (We will designate it VLFA-2 here.)

Although there was little technical interaction between the studies, the concepts were all quite similar. In this paper we review the concepts, identify design choices that need to be made, and technical challenges to be overcome.

2. CONCEPT COMPARISON

Table 1 summarizes the specifications for the four VLF array concepts. The considerations which led to the various choices are discussed below.

Table 1

2.1. Frequency Coverage and Array Size

The lower end of the frequency range is constrained to be > 20 kHz by the local interplanetary plasma frequency, and probably $\gtrsim 90$ kHz by the lunar ionosphere [*Douglas and Smith*, 1985]. On the day-side, the plasma frequency of the lunar ionosphere is estimated to be about 500 kHz [*Woan*, these proceedings], which would prevent observations much below 1 MHz.

Scattering and scintillation in the interplanetary and interstellar media broaden the apparent angular size of sources as roughly the square of the wavelength. Extrapolations from existing data are a bit uncertain, but interstellar scintillation should produce an apparent source size of $0.3^\circ - 2^\circ$ at 1 MHz, depending on Galactic latitude. Interplanetary scintillation should give a somewhat larger size, depending on solar elongation and solar cycle phase. Based on this consideration, Fig. 1 shows that an array size of ~ 100 km gives as much resolution as can be used frequencies < 3 MHz, where Earth-based observations are absolutely ruled out.

Fig. 1

The upper end is softly constrained by the possibility of doing high resolution observations from Earth which, while very challenging, have not really been tried with enough determination to establish where the practical frequency limit is. If 30 MHz is that limit, then potentially arcsecond resolution is obtainable, justifying an array size which approaches the lunar radius (1738 km) [*Basart and Burns*, 1990].

2.2. Antenna Elements

All the array concepts used short dipoles. In Table 1 the specified length is that of one dipole arm, or half the total length. All the dipoles are very short ($\ll \lambda$) at most operating wavelengths. Such dipoles have essentially all-sky coverage.

The main advantage of short dipoles over more optimally designed elements is that they are compact and simple to deploy.

2.3. Location

As seen in Fig. 2 the lunar near-side is exposed to a very harsh interference environment [*Alexander et al.*, 1975]. However, one person's interference is another person's research. The Earth's AKR could be one of the main research goals of an initial array on the Lunar Near Side. The experience obtained early in a renewed lunar exploration program will be very valuable for an eventual, much larger array on the Far Side.

Fig. 2

The crater Tsiolkovsky (Fig. 3), photographed during two Apollo missions[1], located at 128.5° E 20.5° S, provides a smooth surface 113 km across [*Taylor*, 1989]. The entire crater floor is visible from the central peak, providing an ideal location for the central station[2].

Fig. 3

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[1] http://images.jsc.nasa.gov/images/pao/AS8/10074968.htm
http://images.jsc.nasa.gov/images/pao/AS8/10074971.htm
http://images.jsc.nasa.gov/images/pao/AS13/10075509.htm

[2] The images made by Clemetine are available at

2.4. Receivers

The receivers should be fully tunable. This is important because the VLF domain is qualitatively very different from the frequencies studied by most radio astronomers. At cm and mm wavelengths, astronomers generally study static or slowly varying spectra, or time series at one or a few frequencies. The decametric through kilometric wavelength domain however is replete with richly complex dynamic events. Coherent emissions abound, because the scale of relevant structures is often smaller than the wavelength. Receivers will need to be able to record dynamic spectra as a matter of routine. (However, temporal variations from sources at interstellar distances and beyond due to multipathing [*Woan*, these proceedings].)

The requisite receiver electronics exists on VLSI chips. Shortwave radios with the necessary sensitivity, tunablity, and bandwidth are available as hand-held consumer items, with most of the mass being in the speaker, batteries, switches, and display. Likewise, VLSI consumer electronics exists for digitizing the data in, for example, digital audio tape recorders.

2.5. I.F. Data Handling

All the studies concluded that radio communication links would suffice to handle the digital data streams, though optic fiber was mentioned as an alternative for the VLFRO [*Douglas and Smith*, 1985], and photodiode lasers with small telescopes for the VLFA [*Basart and Burns*, 1990]. The demand on the link depended on what was assumed for the instantaneous bandwidth. The VLFA was envisioned as having up to 5 MHz bandwidth for up to 361 elements, which, allowing for guard bands, would put the communication bands into the GHz range. The VLFRO and LNSA concepts, because they assumed narrower bandwidths, could be accomodated with VHF links. All array

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http://www.nrl.navy.mil/clementine/clib/

concepts require a signal from the central site to which to lock the local oscillators at each element, and additionally signals to control the receivers.

Because of the curvature of the Moon, an antenna on top of a 3-m mast has a line-of-sight to a similar antenna up to 12 km away [*Kuiper et al.*, 1990a] (see Fig. 4). Barring a central antenna at great height (e.g. Crater Tsiolkovsky) or a physical link (e.g. optic fiber), most elements in the array will need to serve as relays for antennas farther out. Conceivably the telecommunications transceivers will be more complex than the observing receivers, though not more complex that cellular modems.

Fig. 4

If signals are to be relayed, then the system must provide for redundancy, so that the loss of a single element will not disconnect all the elements farther out along that arm. This means that two or more elements must be visible from any element except the last one in an arm.

An array on the far-side will also need a relay satellite. The VLFA-2 concept uses a satellite in a halo L2 orbit to connect the central station (on the central peak of crater Tsiolkovsky) with the Earth.

Another concept that should be studied, especially for a far-side array, is the possibility of having the "central station" on a satellite in an elliptical orbit chosen to be able to have the array in view for a large fraction of its orbit, and also have periodic links to Earth of long enough duration to download the correlated data (see below).

2.6. Data Processing and Delivery

The various concepts have quite a range of data processing requirements, as illustrated by Table 2.

Table 2

The concept with the least demanding data processing requirement (LNSA – within range of an upper end workstation) proposes to return the raw data to Earth. This is because the combination of being on the lunar nearside, plus the modest total data bandwidth, allows all the data to be returned and stored for both quick-look processing and later re-processing.

The upper end of the data processing requirements may be considered one of the "engineering challenges", which we consider next.

3. Engineering Challenges

The lunar low-frequency array concept is mature enough for a detailed engineering design study. At the Albuquerque workshop, Stewart Johnson summarized the engineering challenges for the VLFRO [*Johnson*, 1989].

3.1. Environment

Most of the environmental factors – vacuum, radiation, UV degradation, micrometeor impacts – are common to all operations in space and should not present any special challenges.

3.1.1. Temperature Variation. Temperature variation constitutes a serious engineering challenge. During the lunar night, the temperature of the lunar surface drops to ~ 100 K. During the lunar day, the lunar surface temperature rises to ~ 380 K. Experience with Mars Pathfinder and planning for future Mars mission has driven home the difficulty of coping with extreme temperature variations. Electronics are perhaps the least susceptible. Silicon-based chips can easily operate over the 100-380 K temperature range. The very challenging problems are mechanical and chemical. Chemical batteries operate in a typical range of ±40°C (230-310 K). Without special techniques, solder joints and epoxy bonds will crack when subjected to such extreme temperature cycling. Studying a Mars sample return mission, it was decided that it would be simpler to store the sample container in Mars orbit than on the surface of Mars.

One possible solution is to bury the electronics package in the lunar regolith. At a depth of 10 cm, the diurnal temperature variation is < 35 K [*Keihm et al.*, 1973].

Another potential solution to this problem is the "V-groove radiator". Fig. 5

Fig. 5

illustrates the concept, but the details of the design need to be tailored to the application.

In the LNSA concept [*Kuiper et al.*, 1990a], the station power subsystem (solar cells and battery) constituted 90% of the station mass. Providing heating and cooling to regulate the temperature of a package on the surface will further increase the size of the batteries and solar cells. Alternately, burial makes the deployment more complex. Finally, the rated life of lithium batteries is 80 cycles, or $\sim$ 7 years. Some consideration should therefore be given to the possibility of a simple and less expensive exploratory array operating without batteries, in the day-time only. The drawbacks are that the lunar ionosphere probably limits observations to > 1 MHz, and that the solar radio noise would always be present. In any case, the array should be designed to operate in this way after the batteries fail. Sensitive observations could still be done during solar minima.

3.1.2. Dust. Dust may also presents an engineering challenge. Dust adhering to reflective surfaces can increase solar energy absorption by a factor of two or three. Dust on solar panels degrading their performance may also merit further study. Experience with recent operations on Mars suggests that dust is less of a problem than first feared, although this experience may not be relevant to the airless Moon.

The solution to this problem may be as simple as waiting for the dust to settle before opening the solar panels.

3.2. Deployment

The main challenge is to find a cost-effective method of deploying the antenna elements. All the concepts assumed that the deployment vehicle would bear some family resemblance to the Apollo LRV, though operated autonomously or remotely. It would have to contend with craters and boulders, but in view of the experience with the Apollo LRV and the Mars Rover, this should present no insurmountable obstacles.

In view of the success of the Mars Pathfinder mission, some consideration should be given in future studies to having self-deploying antenna elements, using Mars Rover technology to move the elements to their assigned locations. This would be particularly attractive to dilute arrays with small numbers of elements, which could reconfigure to optimize UV coverage for particular needs or to fill in UV coverage. The next Mars rover is being designed to travel up to 10 km or more from the base station. Crucial navigation decisions will still be made by controllers on Earth, but it will have enough intelligence to negotiate simpler obstacles without help. Similar technology could be used for self-deploying array stations. One challenge to be addressed would be position determination. One possible solution would be to use VLBI techniques to solve for the baselines as the stations move out from the central site.

Deployment by impact does not yet seem to be practical yet. The current Mars microprobe design, presumably close to the state-of-the-art for battery-powered impactors, is supposed to survive an impact velocity of 600-700 km/h or $\sim$ 0.2 km/s. Free- fall onto the moon from infinity gives an impact velocity of almost 2.5 km/s. The difference is a factor of $\sim$ 200 in kinetic energy. Thus, current technology appears to be unable to provide a survivable hard lander for a low frequency array. (Smart artillery shells have electronics which survive much higher accelerations. However, they do not have deployable antennas.)

4. Conclusion

Lunar low frequency astronomy is an ideal candidate for lunar based science. A modest telescope could be deployed near a temporary or permanent lunar base early in a revived lunar exploration program. The telescope could be designed to grow by adding additional elements during successive missions to that base. (A prototype telescope could even be tested by deploying elements in a remote terrestrial region, such as the Antarctic polar plateau.) Eventually, as human presence on the Moon expands, an array could be started and expanded on the far side of the Moon.

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References

Alexander, J. K., Kaiser, M. L., Novaco, J. C., Grena, F. R., and Weber, R. R., Scientific instrumentation of the radio-astronomy-explorer-2 satellite, *Astr. & Astroph.*, *40*, 365, 1975.

Basart, J. P. and Burns, J. O., Lunar far-side very low frequency array, in Burns, J. O., Duric, N., Johnson, S., and Taylor, G. J., editors, *A Lunar Far-Side Very Low Frequency Array*, NASA Conference Publication 3039, 1989.

Basart, J. P. and Burns, J. O., A very low frequency array for the lunar far-side, in Kassim, N. E. and Weiler, K. W., editors, *Low Frequency Astrophysics from Space*, in Lecture Notes in Physics 362, Springer-Verlag, Berlin, pp. 52–56, 1990.

Bély, P. Y., Laurance, R. J., Volonte, S., Ambrosini, R. R., Ardenne, A. v., Barrow, C. H., Bougeret, J. L., Marcaide, J. M., Woan, G., Very low frequency array on the lunar far side, ESA report SCI(97)2, European Space Agency, 1997.

Douglas, J. N. and Smith, H. J., A very low frequency radio astronomy observatory on the moon, in Mendell, W. W., editor, *Lunar bases and space activities of the 21st century*, National Aeronautics and Space Admininstration, Lunar and Planetary Institute, Houston, pp. 301–306, 1985.

Johnson, S. W., Engineering for a lunar far-side very low frequency array, in Burns, J. O., Duric, N., Johnson, S., and Taylor, G. J., editors, *A Lunar Far-Side Very Low Frequency Array*, in Conference Publication 3039, NASA, 1989.

Kassim, N. E. and Weiler, K. W., editors, *Low Frequency Astrophysics from Space*, Lecture Notes in Physics 362, Springer-Verlag, Berlin, 1990.

Keihm, S. J., Peters, K., and Langseth, M. G., Apollo 15 measurement of lunar surface brightness temperatures: thermal conductivity of the upper $1\frac{1}{2}$ meters of regolith, *Earth & Plan. Sci. Let.*, *19*, 337, 1973.

Kuiper, T., Jones, D., Mahoney, M., and Preston, R., Lunar low frequency imaging array, Technical Report JPL D-6703, Rev. A, Vol. 2, Sec. 5C, Jet Propulsion Laboratory, Pasadena, California, 1989.

Kuiper, T. B. H., Jones, D. L., Mahoney, M. J., and Preston, R. L., Lunar low-frequency radio array, in Mumma, M. J. and Smith, H. J., editors, *Astrophysics from the moon*, in AIP Conference Proceedings 207, American Institute of Physics, New York, pp. 522–527, 1990a.

Kuiper, T. B. H., Jones, D. L., Mahoney, M. J., and Preston, R. L., A simple low-cost array on the lunar near-side for the early lunar expeditions, in Kassim, N. E. and Weiler, K. W., editors, *Low Frequency Astrophysics from Space*, in Lecture Notes in Physics 362, Springer-Verlag, Berlin, pp. 46–51, 1990b.

Mumma, M. J. and Smith, H. J., editors, *Astrophysics from the moon*, AIP Conference Proceedings 207, American Institute of Physics, New York, 1990.

Smith, H. J., Very low frequency radio astronomy from the moon, in Kassim, N. E. and Weiler, K. W., editors, *Low Frequency Astrophysics from Space*, in Lecture Notes in Physics 362, Springer-Verlag, Berlin, pp. 29–33, 1990.

Taylor, G. J., Site selection criteria, in Burns, J. O., Duric, N., Johnson, S., and Taylor, G. J., editors, *A Lunar Far-Side Very Low Frequency Array* in NASA.Conference Publication 3039, 1989.

Woan, G. Capabilities and limitations of long wavelength observations from space, these proceedings.

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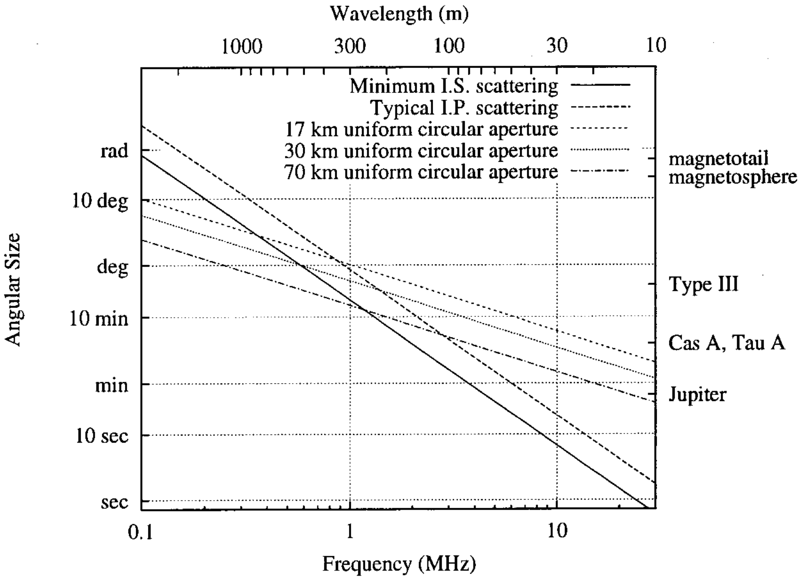

Figure 1. The achievable angular resolution is constrained by plasma inhomogenities which cause interplanetary and interstellar scattering.

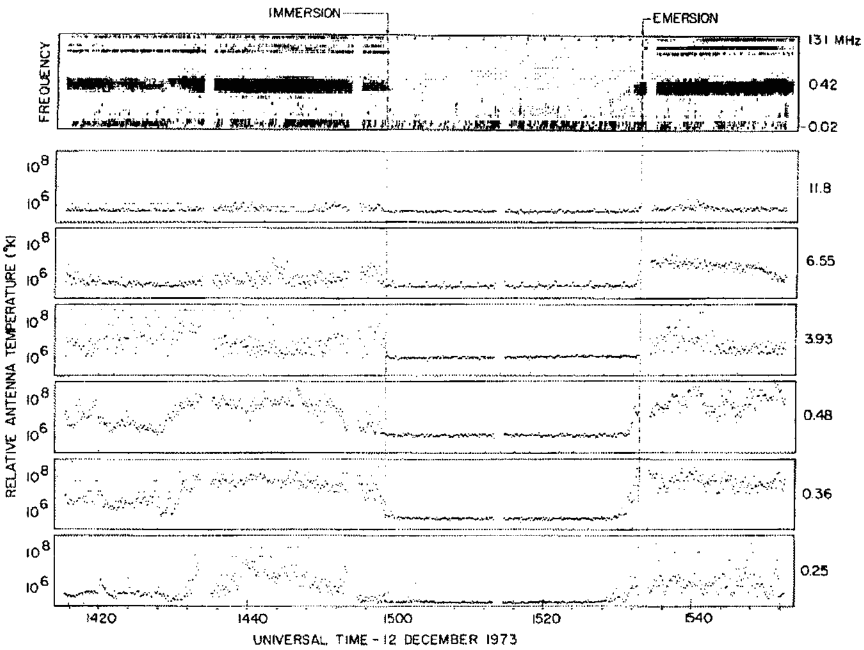

Figure 2. Example of noise levels observed by RAE-2 as it passed behind the Moon. Noise from the Earth was as much as 40 dB above that from the Galactic background.

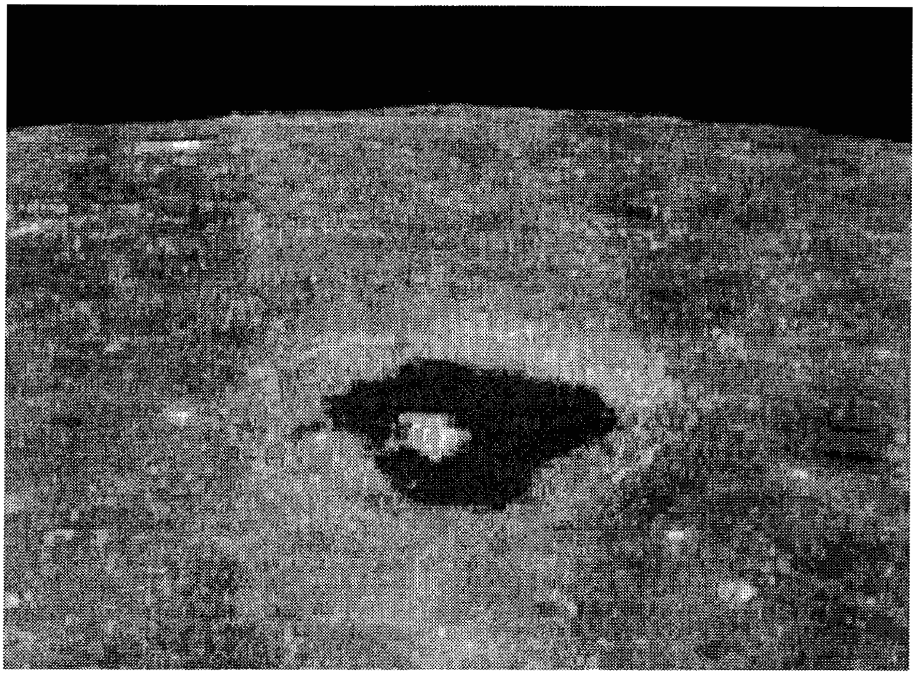

Figure 3. Tsiolkovsky is centered near 129 degrees east longitude and 21 degrees south latitude. The flat floor of Tsiolkovsky is much darker than the surrounding lunar surface. The dark material is about 125 kilometers. The central peak, which stands as an "island" within the dark material, is about 40 kilometers long.

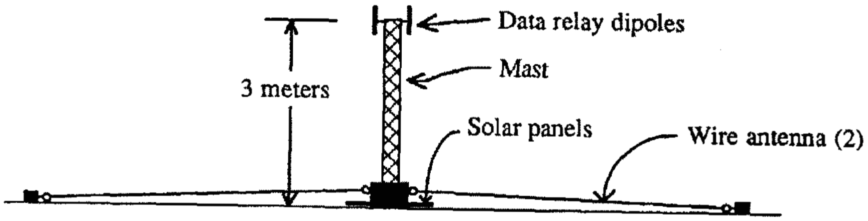

Figure 4. Schematic of a sinle LNSA station, showing the extended communications mast.

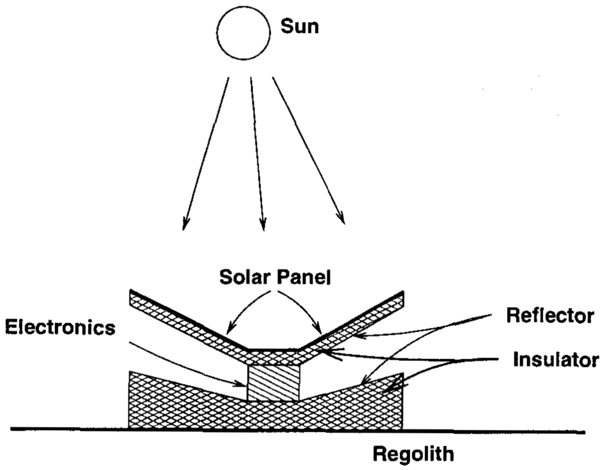

Figure 5. The V-groove radiator is designed so that the electronics package only "sees" cold sky.

Table 1. Comparison of Specifications

Concept	VLFRO	VLFA	LNSA	VLFA-2
Authors	Douglas & Smith	Bassart & Burns	Kuiper et al.	Bély et al.
Frequency (MHz)	0.3-30	1,3,10,30	0.15-30	0.5-30
Aperture (km)	15 × 30	17 → 1000	35 × 70	40
Configuration	T → filled	non-uniform circle	T	spiral-Y
Location	far-side preferred	far-side	near-side	far-side
Antenna type	short dipole	short dipole	crossed dipoles	crossed dipoles
No. of Antennae	300 → 10,000	169 → 361	19	300
Dipole length (m)		1	5	4
Receiver		superheterodyne	superhet.	superhet.
Bandwidth (kHz)	1 kHz	≤ 5 MHz	≤ 22 kHz	100 kHz
Data format	digital	digital	digital	digital
Data transmission	radio or optic fiber	radio or optical	radio	radio
Deployment	manned rover	rover	rover	rover
Correlation	on Moon	on Moon	on Earth	on Moon

Table 2. Data Processing Requirements

Array Concept	Num. of Elements	Num. of Baselines	Bandw. (kHz)	Operations/sec (Mflops)
VLFRO	300 →10,000	$4.5 \times 10^4 \rightarrow 5 \times 10^7$	1	$90 \rightarrow 10^5$
VLFA	169 → 361	$(1.4 \rightarrow 6.5)\times 10^4$	5000	$(1.4 \rightarrow 6.5) \times 10^5$
LNSA	19	171	2 × 22	15
VLFA-2	300	44850	100	3.6×10^4