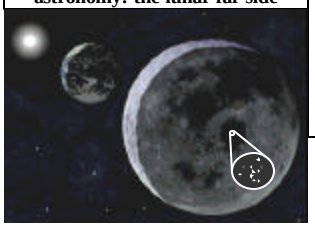
A Lunar Far Side Radio Array as the First Astronomical Observatory on the Moon

Yuki D. Takahashi

yuki@astro.gla.ac.uk
http://www.astro.gla.ac.uk/~yuki
Department of Physics & Astronomy
University of Glasgow, G12 8QQ, UK

A. Why a lunar radio array?

Reaching for the best for radio astronomy: the lunar far side



Even compared to a free-flyer in space:

- The one location permanently free from the significant natural and artificial interference from Earth.

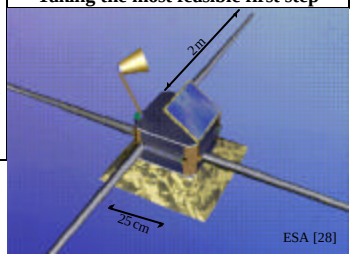
(This unique radio quietness will not likely last long once humans begin development around the Moon!)

- Also avoids Sun's dominating radiation during the lunar night (and study the Sun during the day).
- Stable platform for interferometry: no need to continuously monitor/control array positions.

A simple array of ~10 dipole antennas (like this one) is probably the most technologically feasible observatory to be placed and operated on the Moon.

- Radio antennas are much more robust than optics (against dust, temperature extremes, micrometeorites, ..).
- Deployment will be simple enough to do robotically (optical interferometer, for example, will likely require astronauts).
- Power and communication systems developed for this will be useful for any future missions to the Moon / Mars.

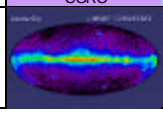
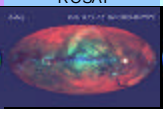
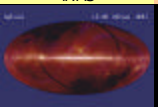
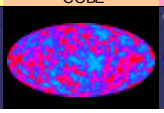
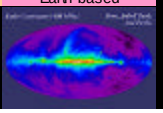
Taking the most feasible first step



ESA [28]

Discovering the new universe (by opening the new frequency window)

- The only unexplored part of the electromagnetic spectrum in astronomy.
- Violent phenomena involving energetic particles (Solar activity, cosmic rays, interstellar medium, millisecond pulsars).
- New objects & new phenomena never seen before at higher frequencies. • Completely unexpected discoveries.

	GAMMA RAY	X RAY	ULTRAVIOLET	VISIBLE	INFRARED	MICROWAVE	RADIO	VERY-LOW-FREQUENCY
wavelength (m)	10^{-15}~10^{-14}~10^{-13}~10^{-12}	10^{-11}~10^{-10}~10^{-9}	10^{-8}~10^{-7}	10^{-6}	10^{-5}~10^{-4}	10^{-3}~10^{-2}	10^{-1}~1	10^{1}~10^{2}~10^{3}~10^{4}
frequency (Hz)	10^{23}~10^{22}~10^{21}~10^{20}	10^{19}~10^{18}~10^{17}	10^{16}~10^{15}	10^{14}	10^{13}~10^{12}	10^{11}~10^{10}	10^{9}~10^{8}	10^{7}~10^{6}~10^{5}~10^{4}
observatory	CGRO	ROSAT	EUVE	HST	IRAS	COBE	Earth-based	Lunar Farside Array
View of the Universe								? Let's find out!

All images from http://www.gsfc.nasa.gov/ Image waiting to be disclosed.

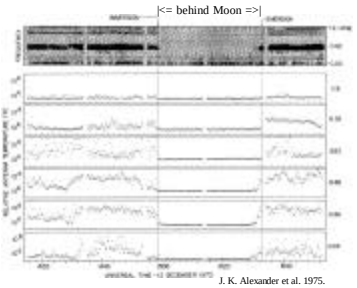
B. How to make it happen?

B.1. Must verify superior performance

We must confirm that such a radio array will perform as promised in the lunar environment.

- How might the lunar regolith scatter radio waves to disturb the observation?
- How much would the lunar "ionosphere" affect the observation?

The Moon's shielding effect was first demonstrated in the mid-1970s: When the Radio-Astronomy-Explorer-2 satellite was behind the Moon, its antenna temperatures dropped by a few orders of magnitude (see the data for various low frequencies =>). For high-sensitivity interferometric observations, however, we want to verify a much better attenuation on the lunar surface.



J. K. Alexander et al. 1975.

B.2. Must select candidate sites

- A crucial first step to further progress in mission design.
- Influences many elements including the communication architecture and the deployment method.
- Imperative for planning precursor missions to examine candidate sites.

- How far into the far side must the observatory be for the terrestrial interference to be sufficiently attenuated?

(The flux density of Earth's auroral kilometric radiation is up to 6 orders of magnitude higher than the galactic background level.)

C. Precursor studies for performance evaluation & site selection

C.1. Approach

Develop a code to simulate propagation of radio waves around the Moon to:

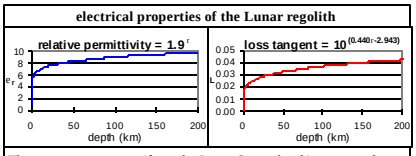
1. Simulate interferometric observations by an array on the lunar surface.
2. Study how well the Moon shields incident interference from Earth.

C.2. Simulation of radio wave propagation

On a uniform space-time grid, the scalar wave equation was solved using the finite difference method.

$$\nabla^2 E = \frac{1}{c^2}\left(\frac{s}{\varepsilon_0}\dot{E} + \varepsilon_r \ddot{E}\right)$$

electrical properties of the Lunar regolith

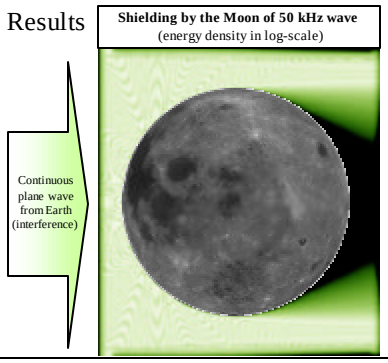


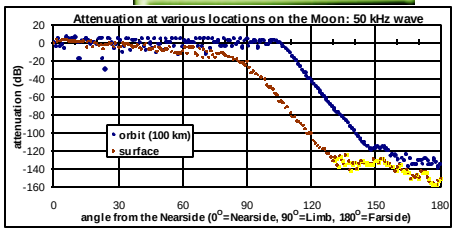
These approximations (from the Lunar Sourcebook) were used to place the Moon in the computational space. [$\sigma \approx \omega\varepsilon_0\varepsilon_r L_r$]

The lunar "ionosphere" and the local plasma were simulated by altering the effective permittivity according to the electron number density.

C.3. Results

Shielding by the Moon of 50 kHz wave
(energy density in log-scale)





C.4. Conclusions

- In the farthest 50° of the lunar surface, the interference will be attenuated by as much as 12~16 orders of magnitude, even for a very long wavelength of 6 km (frequency of 50 kHz).
- With this level of attenuation, the intensity of the terrestrial interference would be 6~10 orders of magnitude below the background level.
- At higher frequencies, the attenuation should only improve (less diffraction).
- An orbiter could estimate the level of terrestrial interference on the surface using the above comparison between the attenuation in orbit and on surface.
- The result for the orbit indicates that a lunar orbiting observatory will be able to take advantage of the shielding by the Moon only during a very small fraction of its orbit.

C.5. Further study

Even if the terrestrial interference is attenuated by 120 dB, an interferometer may pick it up if the noise is coherent. We are currently trying to determine the directivity and coherence of this attenuated interference on the far side of the Moon. We will simulate interferometric observations by an array on the lunar far side surface.

Past work to build upon:

Since the mid-1960s many people have worked toward radio astronomy from the Moon:

[1] Gorgolewski S. (1965) **The Advantages of a Lunar Radio Astronomy Observatory.** *Aeronautica Acta, New New Series 11*, No 2 126, 130-131.
[2] Gorgolewski S. (1966) **Lunar Radio Astronomy Observatory.** *Proceedings of the First Lunar International Laboratory (LIL) Symposium*,78-84.
[3] Douglas J. N. and Smith H. J. (1985) **A very low frequency radio astronomy observatory on the moon.** *Lunar Bases and space Activities of the 21st Century, LPI*, 301-306.
[4] Burns J. O. (1985) **A moon-earth radio interferometer** *. Lunar bases and space activities of the 21st century, LPI*, 293-300.
[5] Burns J. O., Asbell J. (1987) **Radio astronomy on the moon** *Radio Astronomy from Space, NRAO*, 29-39.
[6] Douglas J. N., Smith H. J. (1988) **A very low frequency radio astronomy observatory on the Moon.** *NASA, Future Astronomical Observatories on the Moon*, 113-118.
[7] Burns J. O. (1988) **MERI: An ultra-long-baseline Moon-Earth radio interferometer** *. NASA, Future Astronomical Observatories on the Moon*,97-104.
[8] Burns J. O. (1989) **A lunar far-side very low frequency array: proceedings of a workshop.** *NASA, Office of Management, Scientific and Technical Information Division.*
[9] Burns J. O. (1990) **The Lunar Observer Radio Astronomy Experiment (LORAE).** *Low frequency astrophysics from space*, 19-28.
[10] Sith H. J. (1990) **Very low frequency radio astronomy from the moon.** *Low frequency astrophysics/Aerospace* ,29-33.
[11] Kuiper T. B. H. Jones D. L., Mahoney M. J., Preston R. A. (1990) **A simple low-cost array on the lunar near-side for the early lunar expeditions.** *Low frequency astrophysics from space*, 46-51.
[12] Basart J. P., Burns J. O. (1990) **A very low frequency array for the lunar far-side** *. Low frequency astrophysics from space*, 52-56.
[13] Kuiper T. B. H. Jones D. L., Mahoney M. J., Preston R. A. (1990) **A lunar low-frequency radio array.** *Astrophysics from the moon, ASP*, 522-527.
[14] Dulk N. (1990) **VLF radio astronomy from the moon - Probing astrophysical plasmas** *. Astrophysics/Interstellar mean, ASP*, 515-521.
[15] Chan K. M., Johnson S. W., Yuan Z. (1990) **Foundation design for a radio telescope on the moon.** *ECOS 1*, 707-716.
[16] Algal F., Gerstle W. H., Johnson S. W. (1990) **Computer-aided-structural design of a lunar radio telescope.** *ECOS 1* 697-706.
[17] Basart J. P., Burns J. O. (1990) **Optical design of a lunar far-side very low frequency array.** *ECOS1,1077-1091.*
[18] Burns J. O. (1991) **Aperture synthesis imaging from the moon.** *Radio interferometry: Theory, techniques, and applications*, 420-427.
[19] Lauderdale P. B., Choi D. U., Doran R. J., Edelsohn C. R., Gurley J. C., Hagen F. A., Su C. W., Tillman M. L., Wanogren C. R. (1991) **Astronomical lunar low frequency array.** *IAF, 34C*, 42nd, 5.
[20] Doran R. J., Gurley M. A., Choi D. U., Edelsohn C. R., Gurley J. C., Hagen F. A., Lauderdale P. B., Su C. W., Tillman M. L., Wanogren C. R. (1992) **Engineering Design of an Unmanned Lunar Radio Observatory** *. Robotic telescopes in the 1990s, ASP Conf. Ser.* 34,347-365.
[21] Lauderdale P. B., Gurley M. A., Choi D. U., Doran R. J., Edelsohn C. R., Gurley J. C., Hagen F. A., Su C. W., Tillman M. L., Wanogren C. R. (1992) **Telerobotically Deployed Lunar-Farside VLF Observatory** *. Robotic telescopes in the 1990s, ASP Conf. Ser.* 34, 335-346.
[22] Dulk N. (1992) **Very low frequency radio astronomy from lunar orbit.** *ECOS2*,1925-1934.
[23] Marsh K. A., Mahoney M. J., Kuiper T. B. H., Jones D. L. (1992) **Concept for a lunar array for very low frequency radio astronomy** *. ECOS2*,1935-1940.
[24] International Space University (1993) **International Lunar Farside Observatory and Science Station.** 1993 ISU Design Project, W. W. Mendell.
[25] Lecacheux A. (1994) **Solar system, low frequency radio astronomy from the Moon.** *. AdSpR, 14*, 4, 197-201.
[26] Bougeret J.-L. (1996) **Very Low Frequency Radio Astronomy** *. AdSpR, 18*, 11,35-41.
[27] Woan G. (1996) **Design considerations for a Moon-based radio telescope operating at frequencies below 10MHz.** *Lunge Antennas in Radio Astronomy, ESA workshop WPP-110*,28-29.
[28] Bely P. Y.,Lasrance R. J., Volonte S., Ambrosini R. R., Ardenne A., Barrow C. H., Bougeret J. L., Marcaide J. M., Woan G. (1997) **Very Low Frequency Array on the Lunar Far Side.** *ESA report SCI(97)2*, European Space Agency.
[29] Jones D. L., and Weiler K. W. (1997) **Low Frequency Radio Astronomy from the Moon** *Astronomy from the Moon, IAU, JD.*
[30] Heidmann J. (1998) **SETI from the Moon: Avoiding Radio Pollution for Future Radioastronomy** *Astronomy from the Moon, IAU, JD.*
[31] Woan G. (1999) **A Very Low Frequency Radio Telescope on the Far Side of the Moon** *Measuring the Size of Things in the Universe: IBRT Interferometry and Heavy Ion Physics, CRIS '98*,347.
[32] Heidmann J. (2000) **A Proteine Radio Window on the Universe: Just One Lunar Crater, but Opened at all Frequencies** *. AdSpR, 26, 2*, 343-346.
[33] Maccone C. (2000) **Exploitation of A Tether from Earth Visible Location to Far Side for Lunar SETI.** *AdSpR, 26, 2*,359-370.
[34] Heidmann J. (2000) **Sharing the Moon by Thirds: An Extended SAHA Crater Proposal.** *AdSpR, 26, 2*,371-375.
[35] Heidmann J. (2000) **A proposal for a radio frequency interference-free dedicated lunar far side crater for high sensitivity radioastronomy: programmatic issues.** *Acta Astronautica 46*, 10-12 725-728.
[36] Heidmann J. (2000) **Recent progress on the lunar farside crater Saha proposal** *Acta Astronautica 46, 10-12* 661-665.
[37] Weiler K. W. (2000) **The Promise of Long Wavelength Radio Astronomy** *Radio Astronomy at Long Wavelengths, GMS, 119*, 243-255.
[38] Kuiper T. B. H. and Jones D. (2000) **Lunar Surface Arrays** *. Radio Astronomy at Long Wavelengths, GMS, 119*, 351-357.
[39] Woan G. (2000) **Capabilities and limitations of long wavelength observations from space** *. Radio Astronomy at Long Wavelengths, GMS, 119*, 267-276.
[40] Gorgolewski S. (2002) **Future space VLBI on lunar orbits and in the radio shadow on the far side of the Moon.** *NYMU.*
[41] Gorgolewski S. (2002) **Highest sensitivity radio astronomy and SETI from the far side of the Moon (including Crater SAHA).** *NYMU.*
[42] Maccone C. (2002) **RadioMoon: a space mission around the Moon to detect "ET-Free" and bioastronomical signals.** *NYMU.*
[43] Takahashi Y. (2002) **Radio astronomy from the Lunar far side: precursor studies of radio wave propagation around the Moon.** *NYME.*

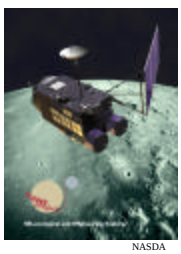
D. Let's begin proposing now!

Precursors (international missions):

1. Lunar orbiter
   - *Low-frequency radio receiver & transmitter* [noise level]
   - *Radar sounder* (0.3~30 MHz) [subsurface reflections]
   - *Imager/altimeter* (vertical resolution < 0.5 m, horizontal resolution < 10 m) [topology for antenna placement]
   - *Ionospheric survey* [electron density above lunar surface]
   - *Magnetometer* [low field desired]
2. Two-element orbiting interferometer
   - Inflatable phased-array antenna.
   - To assess radio & plasma waves in the lunar environment.
   - Radio spectrograph with large bandwidth.
3. Near side lander
   - Deploy 2-element interferometer on surface.
   - Active sounding to probe local subsurface.
4. Robotic array deployment
   - 10-element array over an area of ~20km.

SELENE ?

- *Lunar Radar Sounder (4-6MHz)*
  - Terrestrial noise behind the Moon.
  - Permittivity & conductivity profiles and subsurface reflections at candidate sites.
- *Terrain Camera & Laser Altimeter*
  - Would higher resolution be possible at candidate sites?
- *Radio Science*
  - Electron density profile throughout the lunar day & night and the transition.
- *Lunar Magnetometer*
  - Magnetic survey of candidate sites.



NASDA

SELENE is capable of making many measurements directly relevant to the future of astronomy from the Moon.

Thanks:
I would like to thank Dr Graham Woan for being a very approachable advisor. Thanks also to the Fulbright Foreign Scholarship Board.