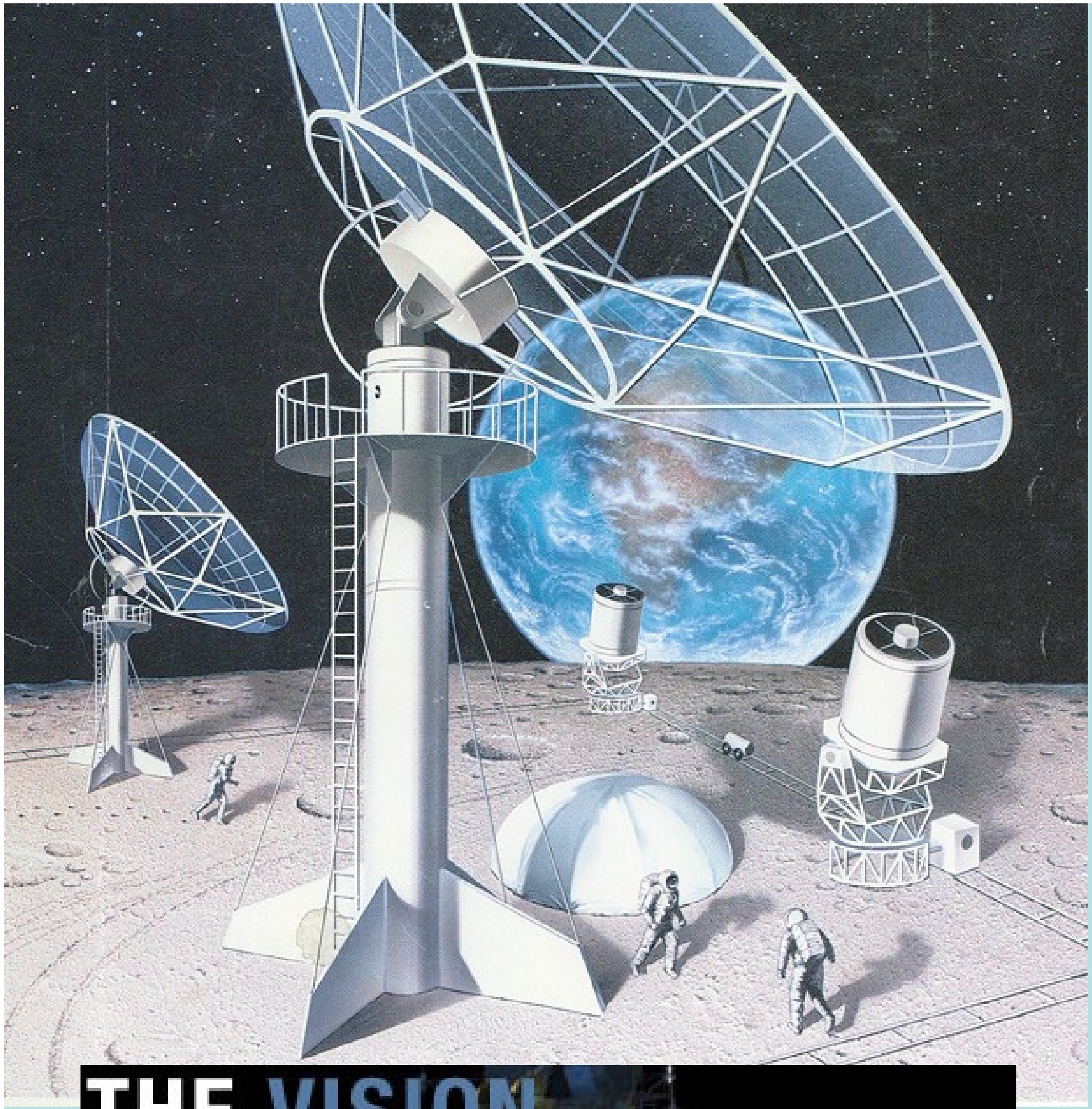
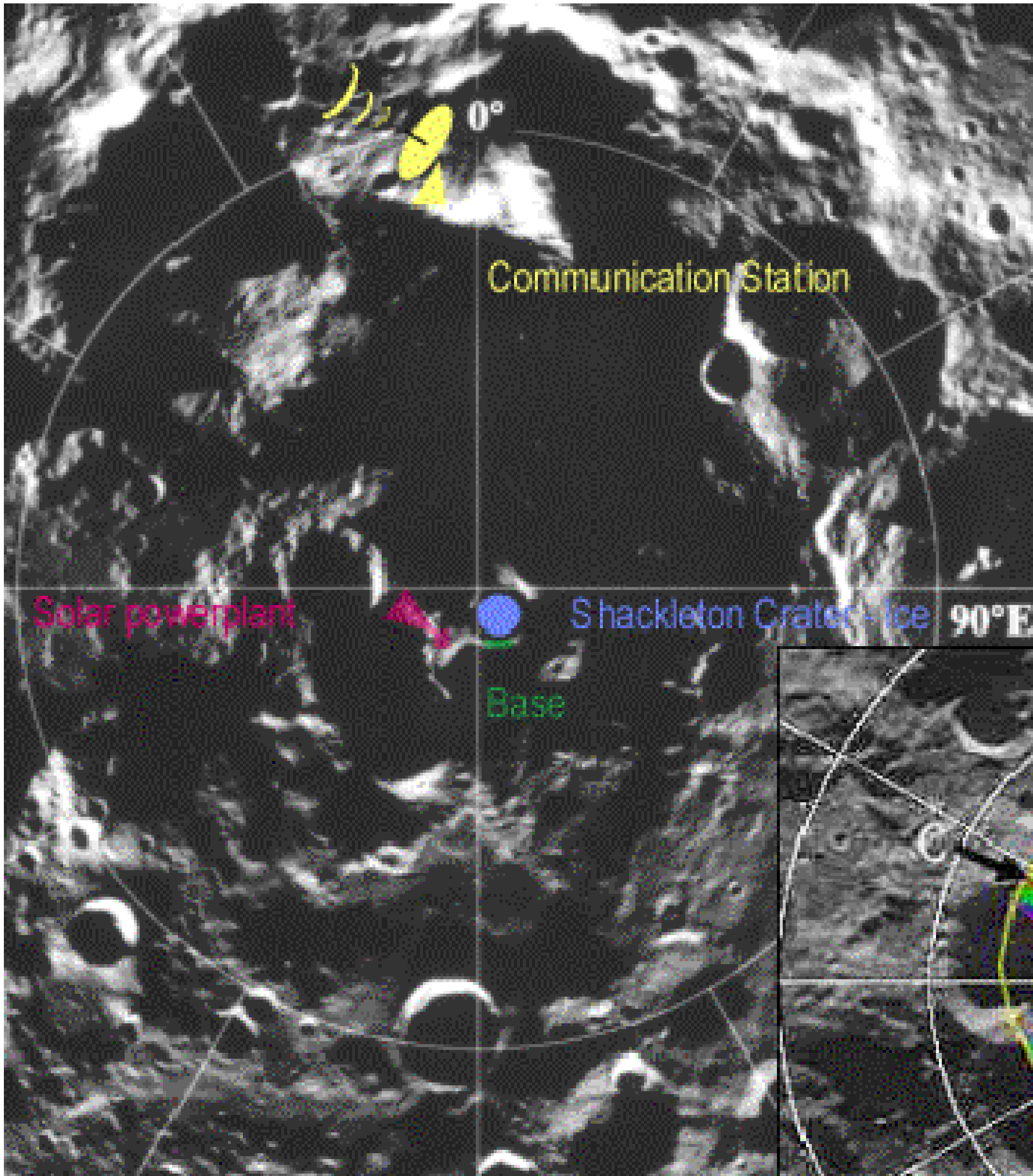


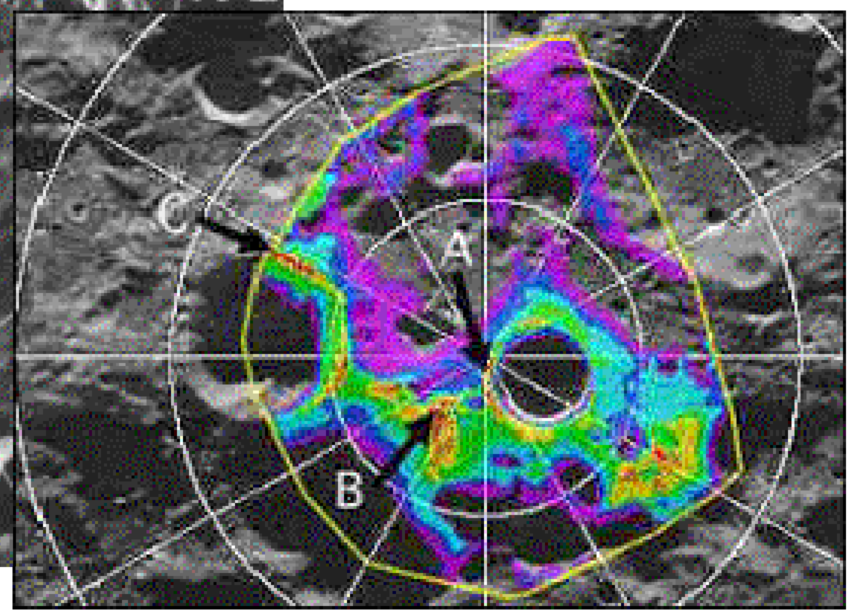
ASTRONOMY FROM THE MOON

Jack Burns
Center for Astrophysics and Space Science
University of Colorado

Ball Aerospace – Aug. 17, 2006

Possible Site for a Lunar Base – Shackleton Crater





plenty of sunlight for power production
- rim receives sunlight 80% of time
- 2 other sites within 10 km collectively receiving sunlight 98% of time

close to ice resources in the permanent shadowed crater

high ground for siting communication antenna
- 120 km from 6000m high Mount Malpert which has constant view of earth

loose regolith on crater rim is useful for covering base

Potential Advantages of the Lunar Surface for Telescopes

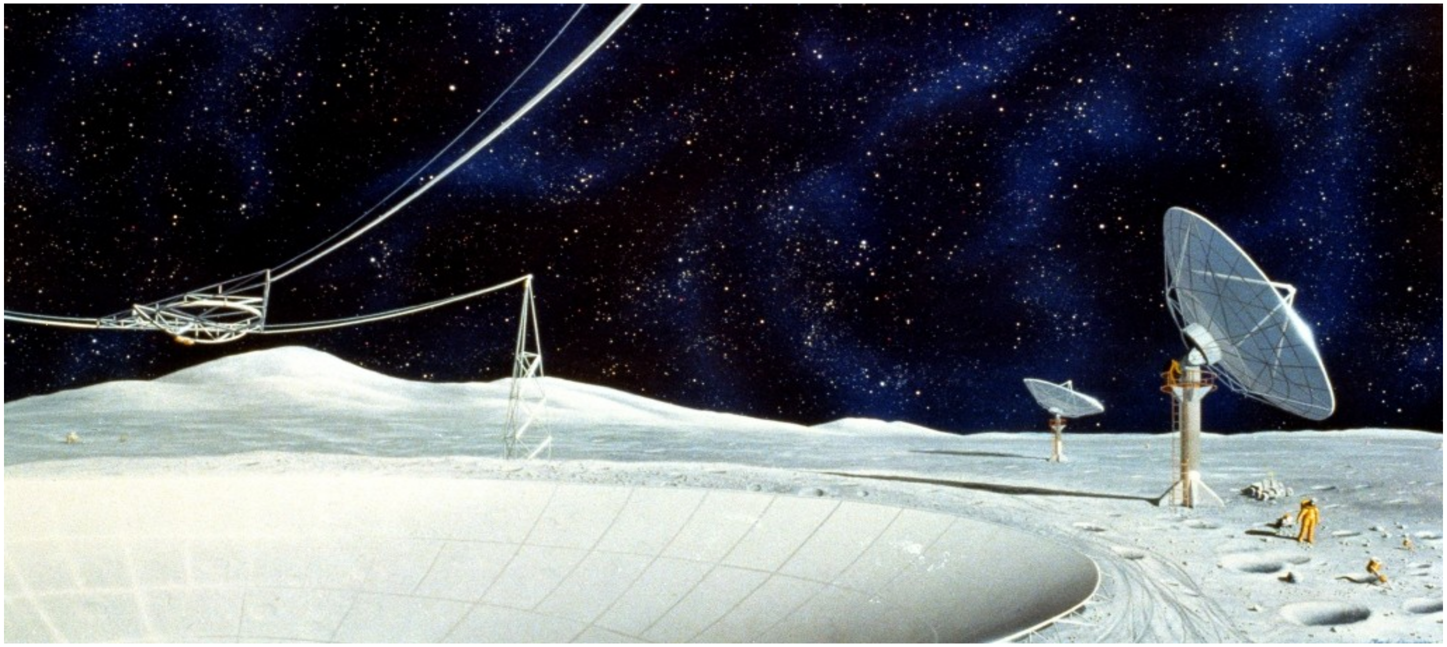
following Smith (1990) in *Observatories in Earth Orbit & Beyond*
(# = unique to the Moon versus Earth-Sun Libration Point)

- *Ultra-hard vacuum* (about 10^5 cm^{-3}). Accessible at all wavelengths.
- *Large, solid, stable surface (#).* Minimal tectonic activity (10^{-8} of Earth). "Huge vacuum optical bench" for large interferometric arrays.
- *Cosmic ray protection* for humans who service telescopes & detectors (#). A few meters of regolith provide nearly complete protection from radiation.
- *Dark & Cold Sky (partial #).* With good passive shielding, telescopes in Shackleton crater may achieve temperatures of 7 K (Lester et al. 2003).
- *Rotation.* Access to entire sky at mid-latitudes. Facilitates lunar-rotation aperture synthesis for interferometers. Long integration times.

Potential Advantages of the Lunar Surface for Telescopes

(continued)

- *Proximity to Earth.* Easy access for servicing telescopes with Earth-Moon transportation infrastructure.
- *The Lunar Farside (#).* Shielding from terrestrial interference, AKR, & solar flares. Free from atmospheric absorption & distortion.
- *Raw materials (#).* Potential water, fuel for nuclear power generators (He^3), and building materials.
- *Landforms (#).* Use craters for large-collecting area apertures. But maria terrain is subdued & easy to navigate (Lowman, 2006).
- *Access to people & infrastructure.* Telescope support for deployment, repair, & upgrades. Lowers technology risk & possibly the cost.

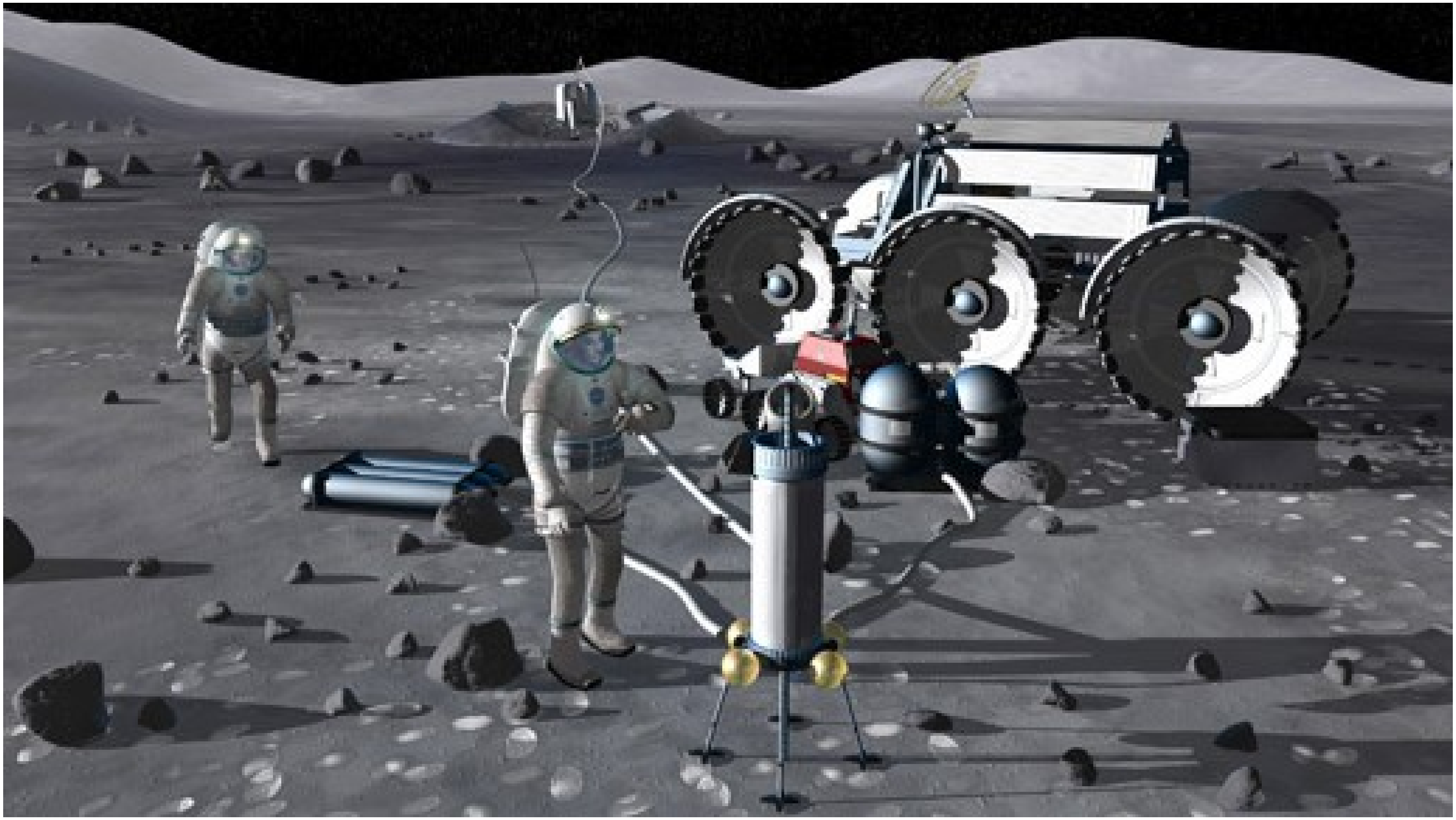


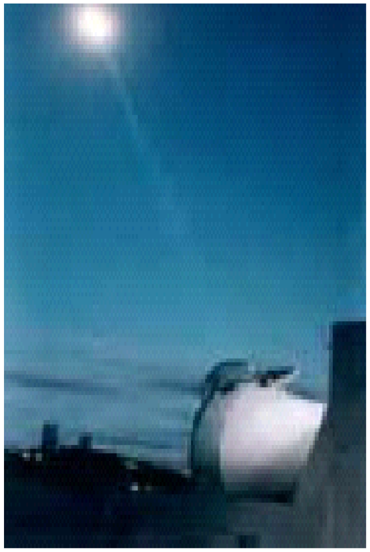
Concerns with the Moon's Surface
following Lester, Yorke, & Mather, 2003 in *Space Policy*

- *Dirt & Dust* kicked up by lunar activities threaten contact bearings & optical surfaces. Electrostatic charging leads to "static cling". Although laser retroreflectors show little degradation after 30 yrs.
- *Solid surface* may not be ideal for telescopes. Free-space is very stable place to put a telescope or array.
- *Gravity* presents loading problems with structural deformations. Telescopes must be stiffer and, thus, more costly & technologically challenging for large apertures. Exception is liquid mirror, transit telescope (R. Angel).
- *Ultra-cold crater* may be a challenge for both astronauts & equipment to function over long periods. Solar power not available. Sky coverage limited at Shackleton.
- *People pollute.* May stir up dust near telescopes. Mining may grow the atmosphere & increase optical depth. Communication satellites may destroy radio-quiet environment of farside.

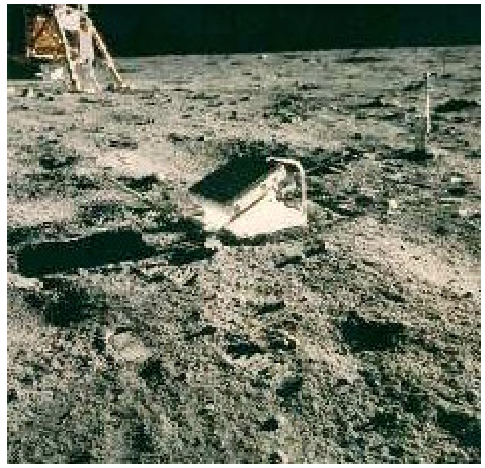
Harrison Schmitt at Apollo 17 site.
Note dust clinging to space suit.

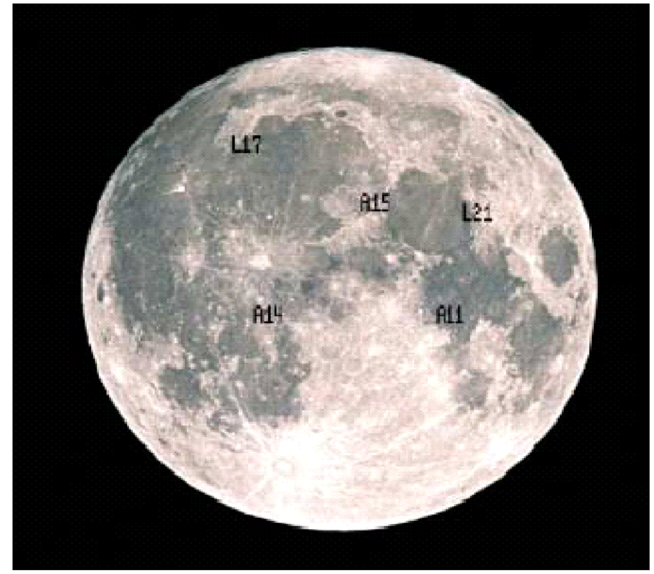
Examples of Previous Concepts for Lunar Telescopes





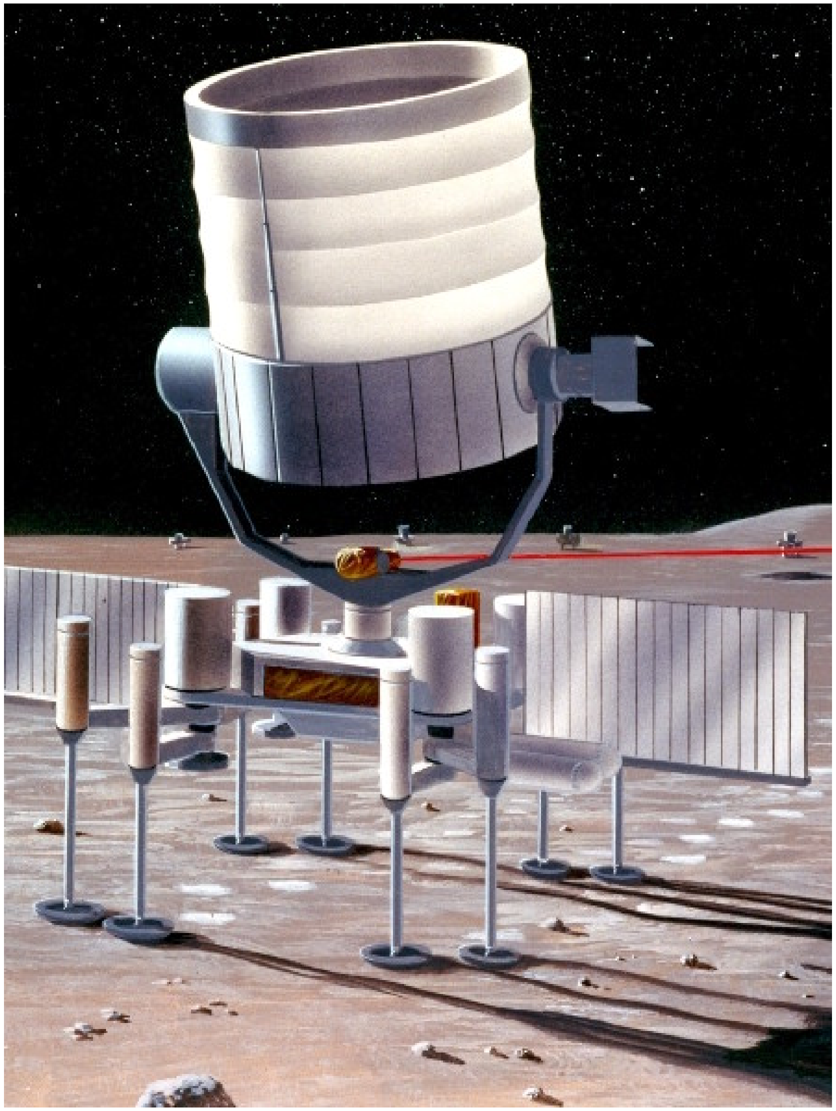
Lunar Laser Ranging





- Currently 5 passive, laser retroreflectors at Apollo 11, 14, 15 sites.
- Improve current situation with more extensive network together with an earth-pointing laser beacon to improve guiding from Earth telescopes (Faller, 1990 in *Physics & Astrophysics from a Lunar Base*).
- Add microwave & optical transponders => improve ranging accuracy by 100x (Bender et al. 1990 in *Astrophysics from the Moon*).
- *Possible science*:
  - New constraints on small fluid lunar core from improved measures of lunar libration & tidal displacements.
  - Improved limits on time variation of G & G.R. constraints (factors of 10-100).

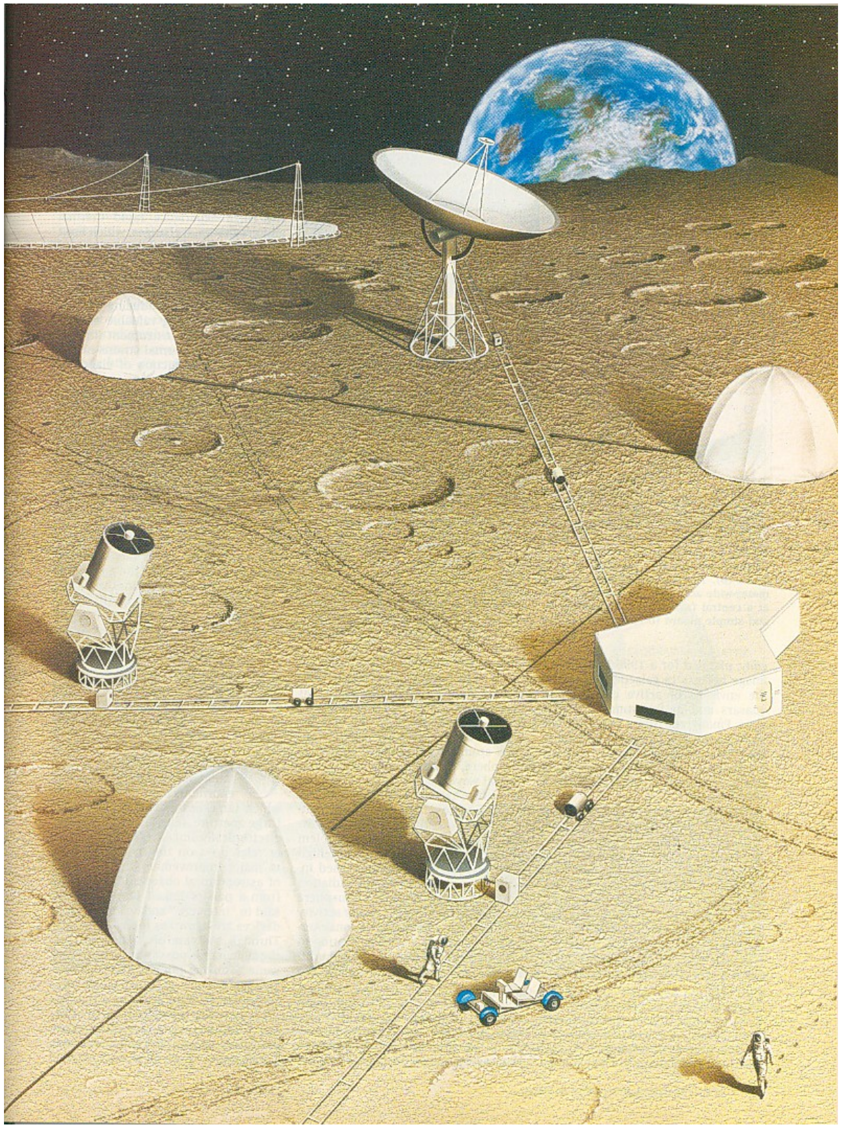
Shackleton Crater Ultra-Cold Telescopes



- “Naked” cathode array at far-IR wavelengths (Lester, 1990 in *Future Astronomical Observatories on the Moon*).
- Submillimeter/far-IR long (km) baseline interferometer, taking advantage of stable baseline, natural cyrogenic environment, & sky transparency (Ho, 1990 & Mahoney, 1990 in *Astrophysics from the Moon*).
- *Possible science*:
  - Imaging proto-planetary disks around solar-mass stars.
  - Collimation of jets/outflows in protostellar objects.
  - Imaging ultra-luminous, distant galaxies in formation.

Lunar Optical Interferometer

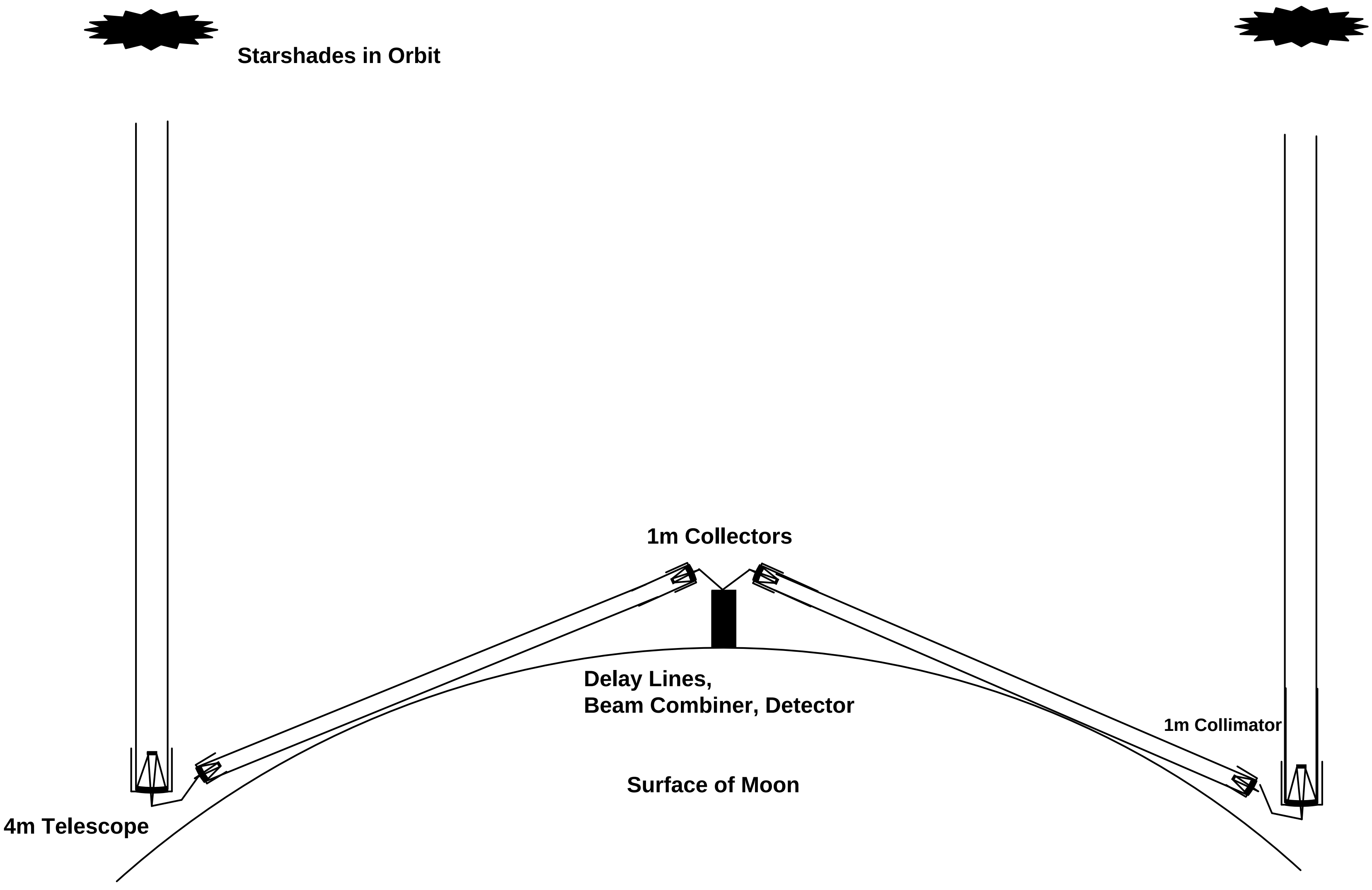
following Burns, Johnson, & Duric (1990) in *A Lunar Optical-uv-IR Synthesis Array*



- Long-baseline array of 43, 1.5-m aperture telescopes distributed in concentric rings ranging from 0.5 to 10 km.
- Microarcsecond imaging and 0.1 microarcsec astrometry.
- *Possible science*:
  - Imaging Earth-like extra-solar planets (see concept by Cash, 2006).
  - Imaging central engine regions in AGNs.
  - Proper-motion studies of galaxies & quasars to determine isotropy of Hubble expansion.

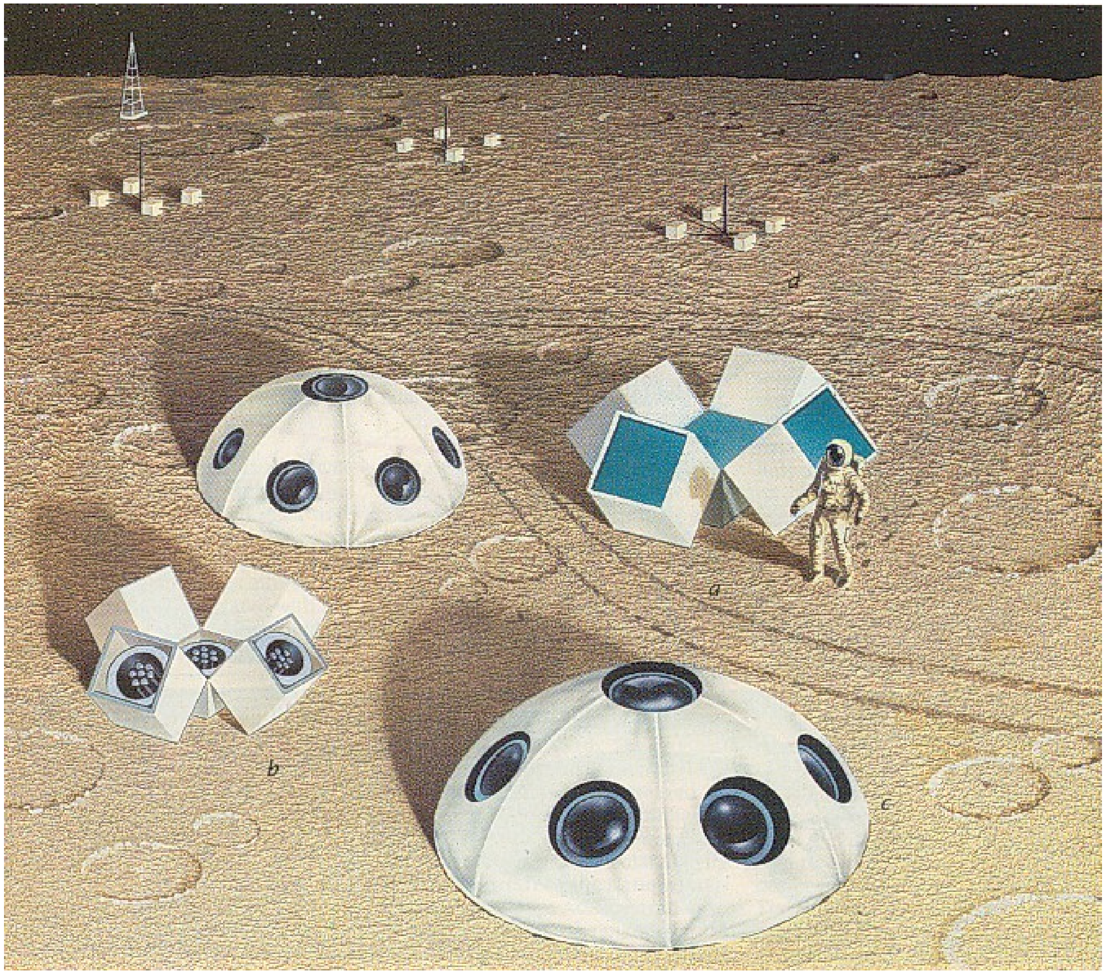
Extra-solar Planet Imaging using a Lunar Optical Interferometer with Star Shades

concept by W. Cash (2006)



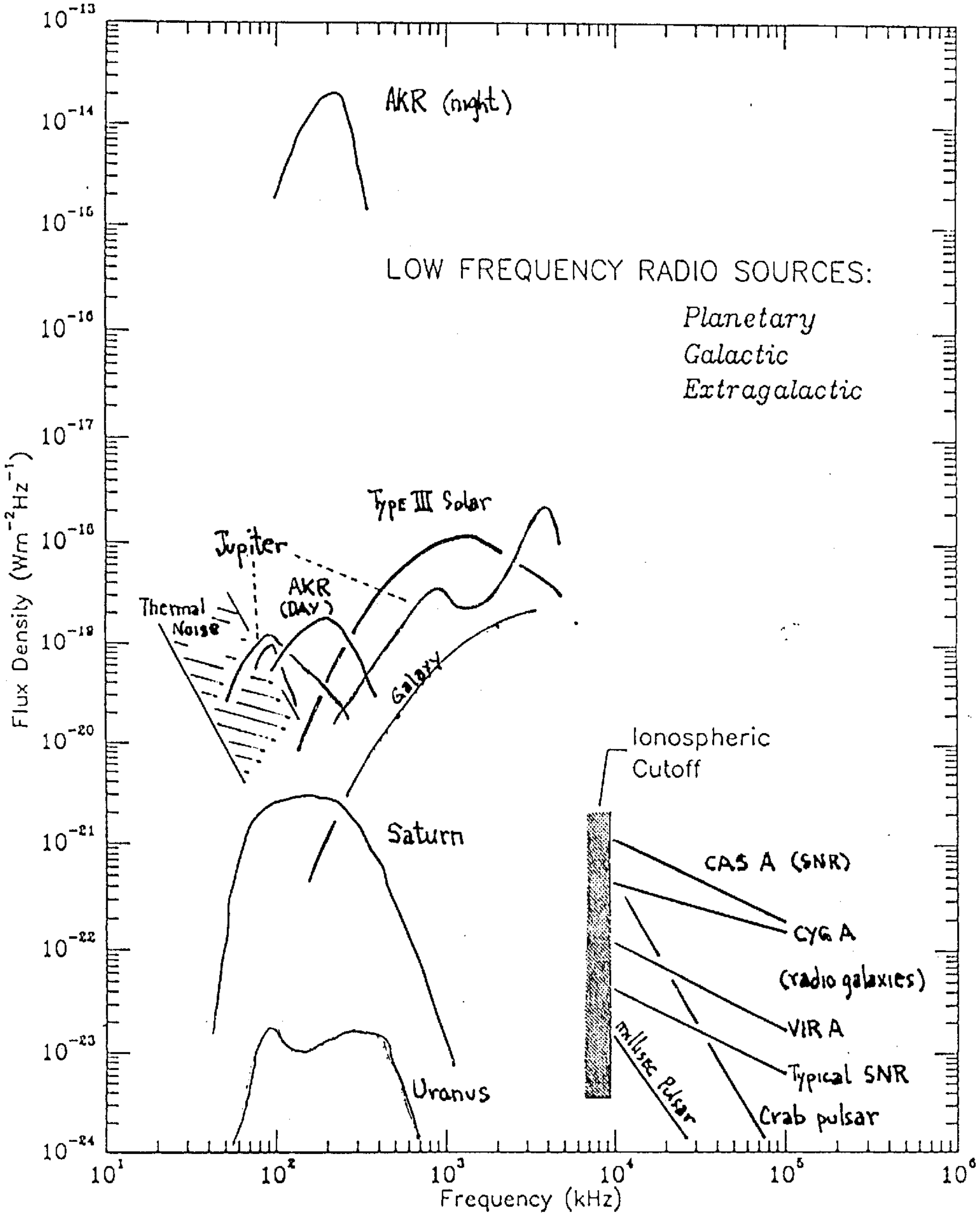
Long-Baseline X-ray Interferometer

concept by C. Martin (1990) in *Astrophysics from the Moon*



- 9-element array of 2.4-m diameter apertures.
- Baseline is 2-4 km.
- Angular resolution is <0.1 microarcsec at E < 1 keV.
- *Possible science*:
  - Imaging accretion disks around 10^8 solar mass black holes in AGNs at 100 Mpc.
  - Imaging active star coronae.

A Lunar Farside Low Frequency Array



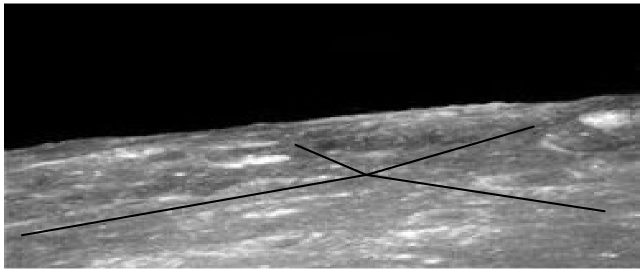
The very low frequency environment in space:

- >1 MHz interference is from Earth ionospheric breakthrough.
- <1 MHz interference comes from Earth's auroral kilometric radiation (AKR) peaking at 200 kHz.
- Cyclotron radiation from magnetospheres of all the planets at 100's of KHz.
- Type III solar bursts.
- Milky Way becomes opaque at <2 MHz.

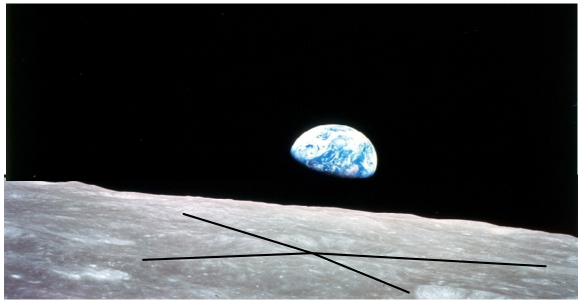
Lunar Farside Radio Astronomy Observatory
following concepts by Kassim, Jones, MacDowall *et al.* (2006)

- Array of ~20,000 short dipoles.
- Multi-arm radial configuration.
- Each arm is a thin kapton sheet, unrolled from hub by a rover (D. Jones *et al.,* JPL).
- Antennas & feed lines on sheet.
- Maximum baselines ~10 km.
- Aperture synthesis imaging.
- Angular resolution 1' at 100 MHz.
- Frequency range 0.1–250 MHz.
- All electronics located at central hub, powered by small RTG
- Astrophysics observations at night, solar observations during day.
- Daily science data rate ~1 TB (assuming real-time cross-correlation)

Rover tracks on Moon. Robotic rovers are ideal means to deploy telescope elements in a radial line from central facility.



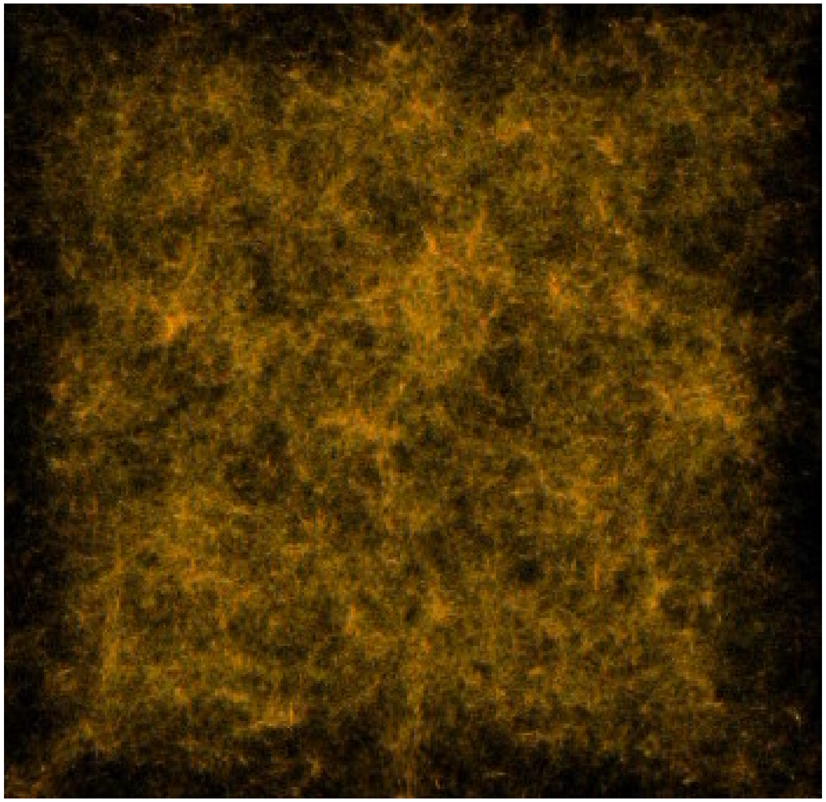
Lunar far side site: Maximum terrestrial interference shielding, but needs data relay.



Lunar limb site: Some interference shielding, direct data downlink possible.

Possible Science with a Lunar LF Farside Array

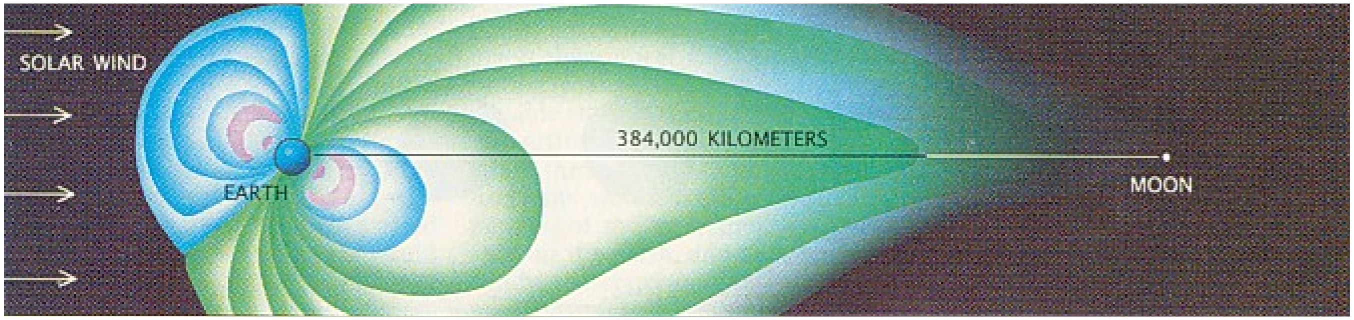
Baryons in z=10 universe from simulations
(courtesy E. Hallman, U. Colorado)

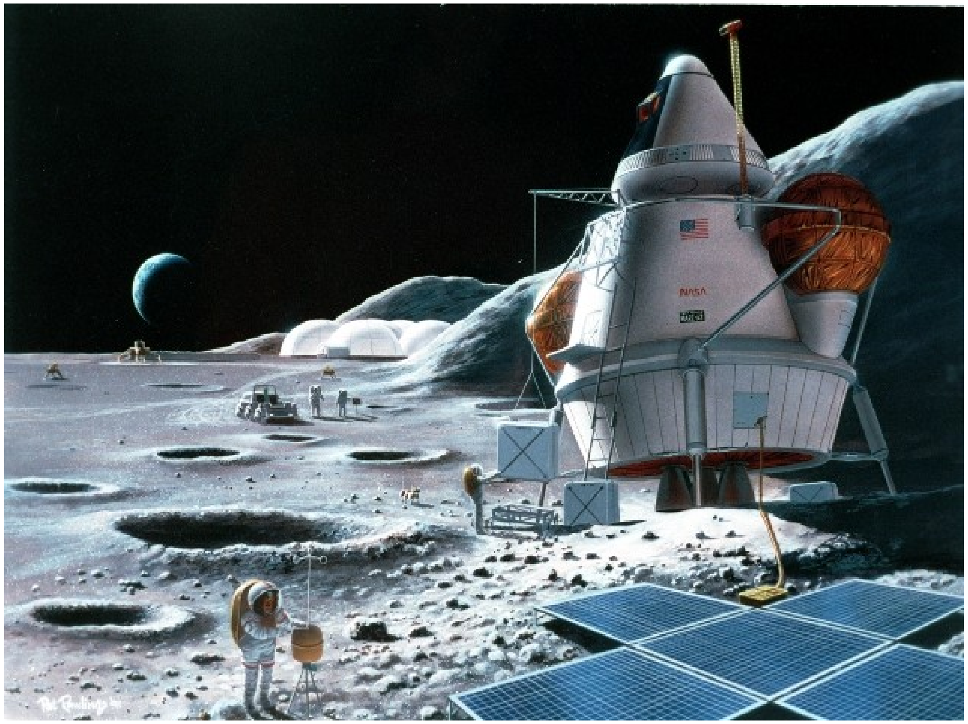


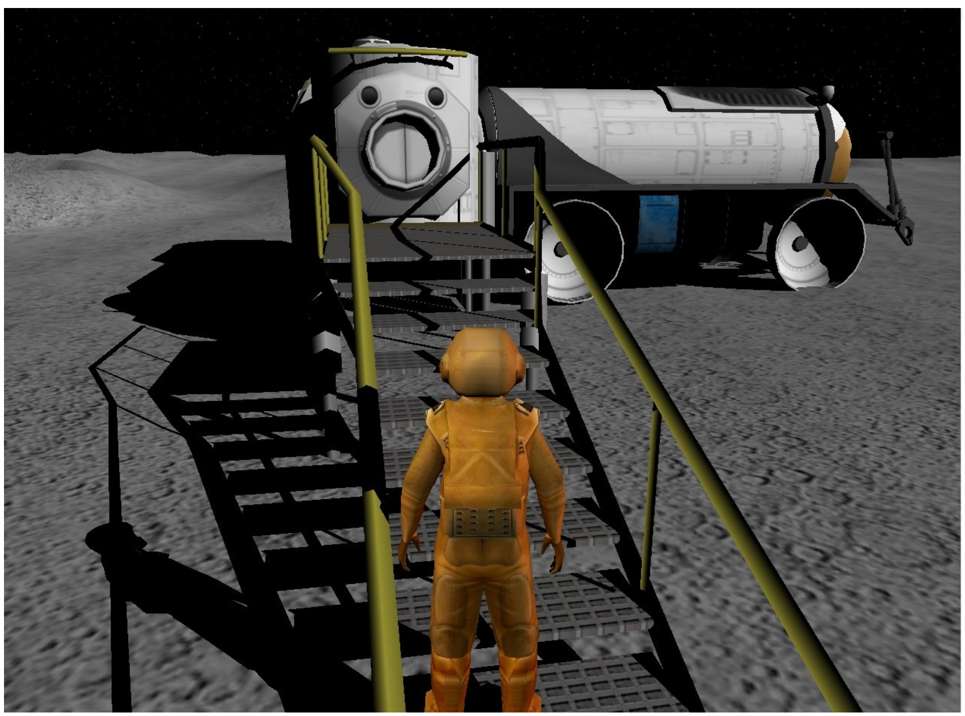
- Image cyclotron maser emission associated with solar system planets.

- Search for electron cyclotron emission from extra-solar planets below 1 MHz.

- Observe epoch for formation of the first sources of ionizing radiation from redshifted HI in emission and absorption (z = 5-250 accessible with array).







Some Thoughts in Summation

- Trade studies are needed to further examine Earth-Sun libration vs. lunar surface, especially for interferometers where lunar potential appears greatest.
- More data required on lunar surface conditions – dust, thermal environment.
- Need baseline data on current lunar environment, especially at frequencies < 100 MHz to monitor as human presence on Moon develops.
- Trade study needed of LF array on Earth vs. Moon. What dynamic range is required to see epoch of reionization & can that be achieved on Earth?