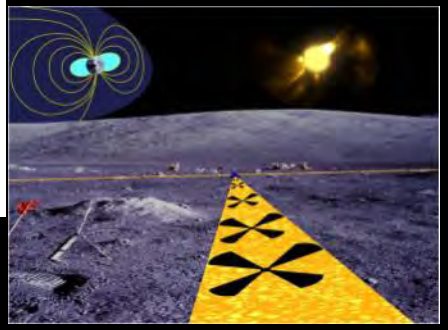
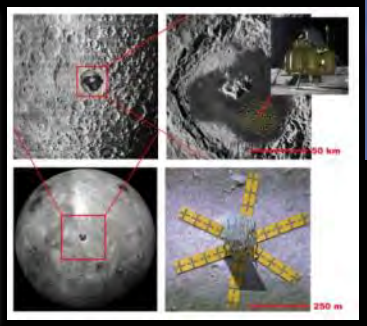
ROLSS - Launch 201X?



DARE - Launch 201X?

DALI - Launch 202X?

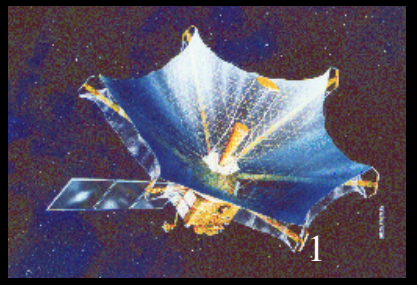


40 Years of Planning for Radio Astronomy from Space and the Moon

Kurt W. Weiler
Computational Physics, Inc. (CPI)
T. Joseph W. Lazio
JPL
Namir E. Kassim
Naval Research Laboratory

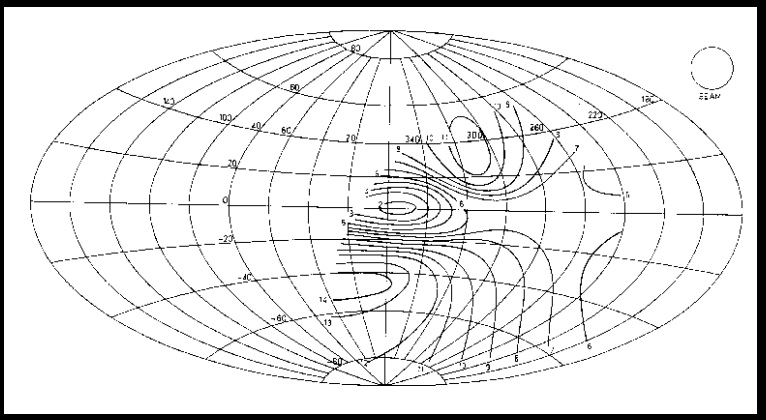
RAE-1/A - Launch JUL1968

RAE-2/B - Launch JUN 1973

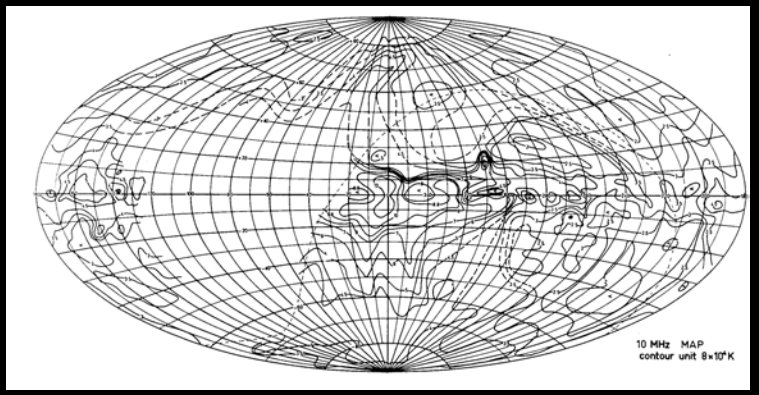


VSOP/HALCA - Launch FEB1997

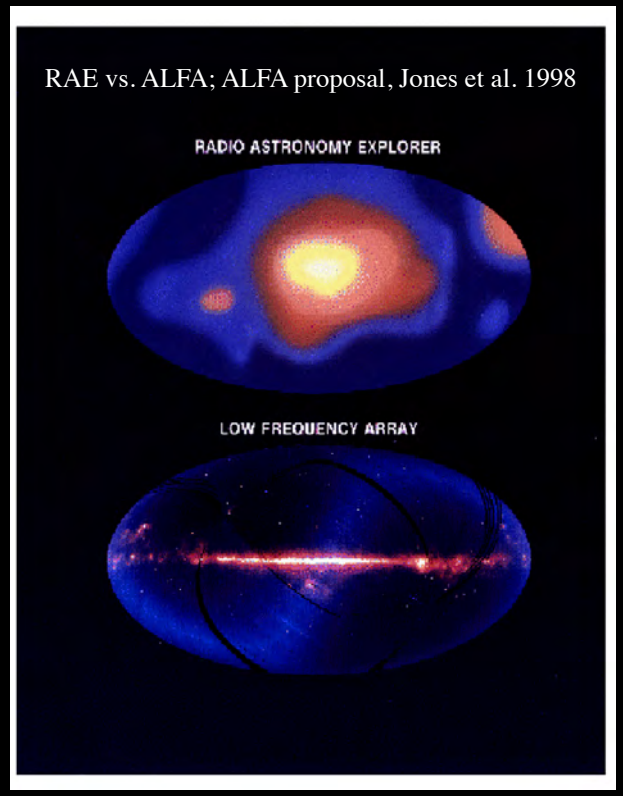
Current Status for Low Frequency Astrophysics <20 MHz

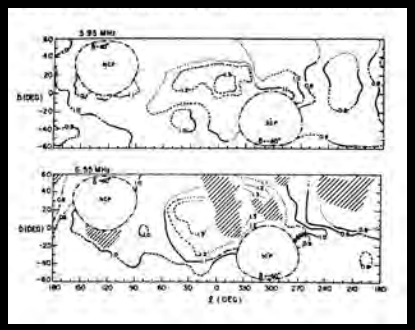


1.6 MHz; Ellis & Mendillo 1987

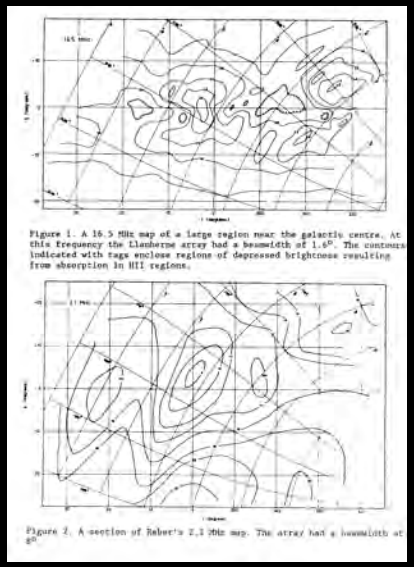


10 MHz; combined Caswell 1976 and Hamilton & Haynes 1968



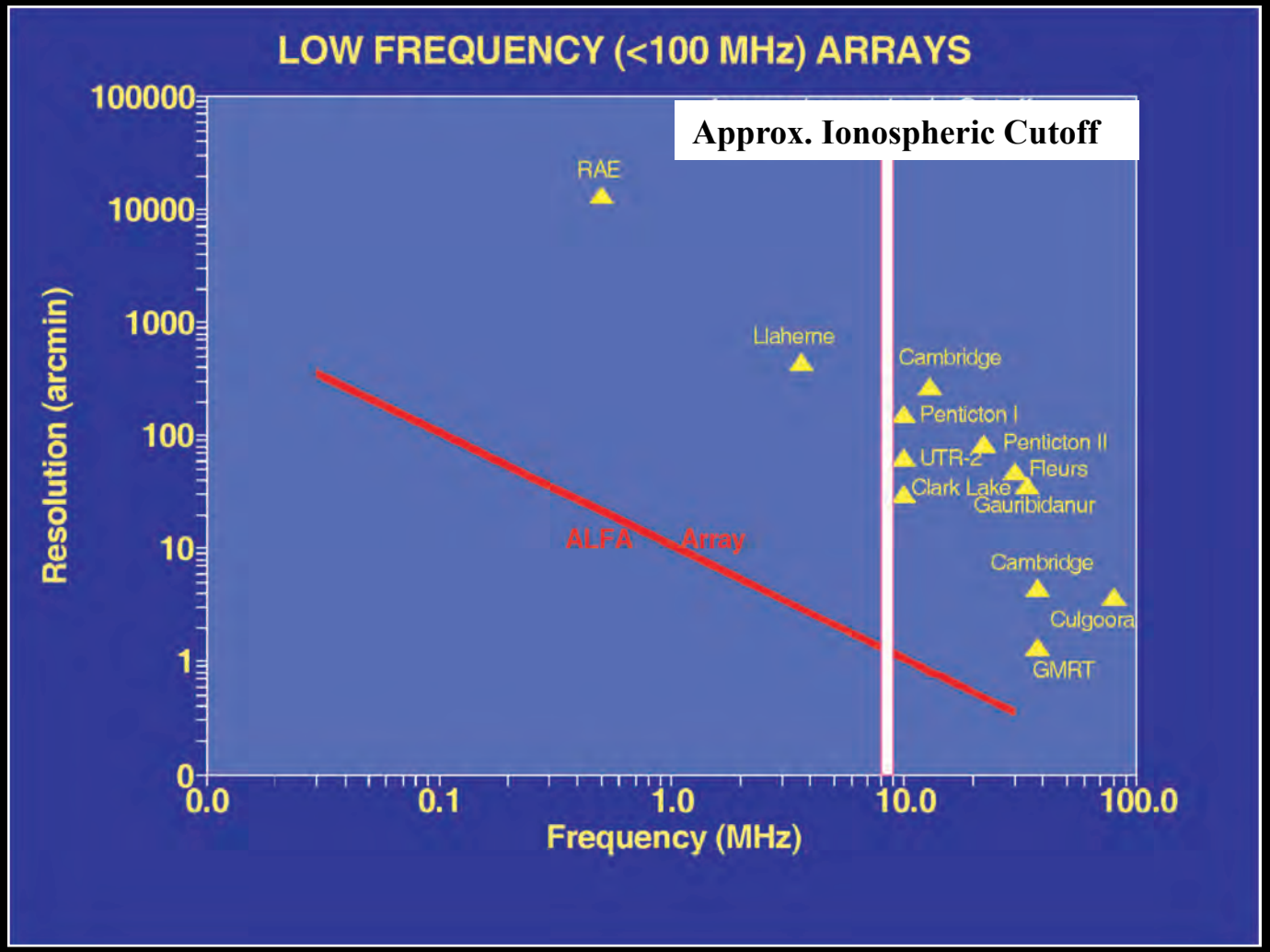


3.9 MHz (top) & 6.6 MHz (bot.); RAE, Alexander & Novaco 1974



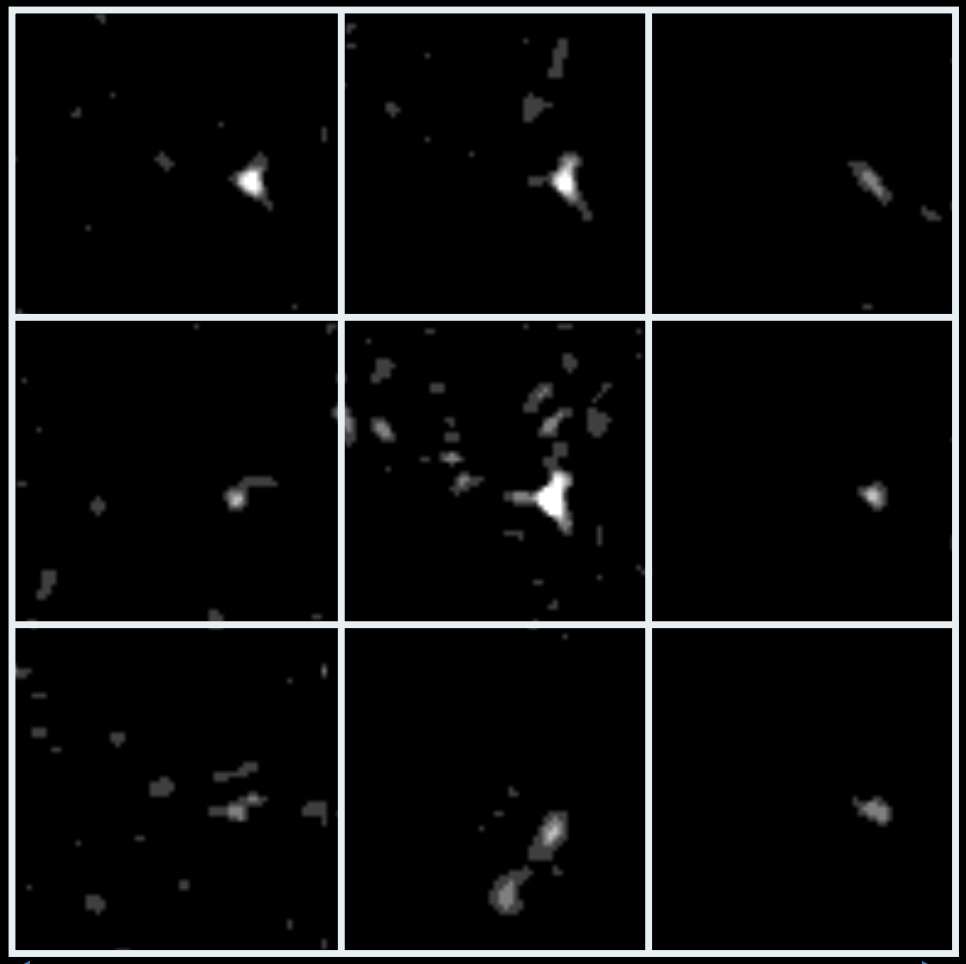
16.5 MHz; Llanherne Array, Cane 1975

The Need for Going to Space
(The Ionospheric Limit)



Historical perspective

Ionosphere limited aperture size of LW telescopes



~ 10° 74 MHz Field of View

- The ionosphere limited the maximum baseline of interferometers below 100 MHz to ***≤ ~5 km***.
- As main-stream radio astronomy went to high resolution and sensitivity (e.g. VLA), LW radio astronomy was left behind.
- Other problems: RFI, **3D** imaging – computational tedium only recently manageable

The Problem for Going to Space

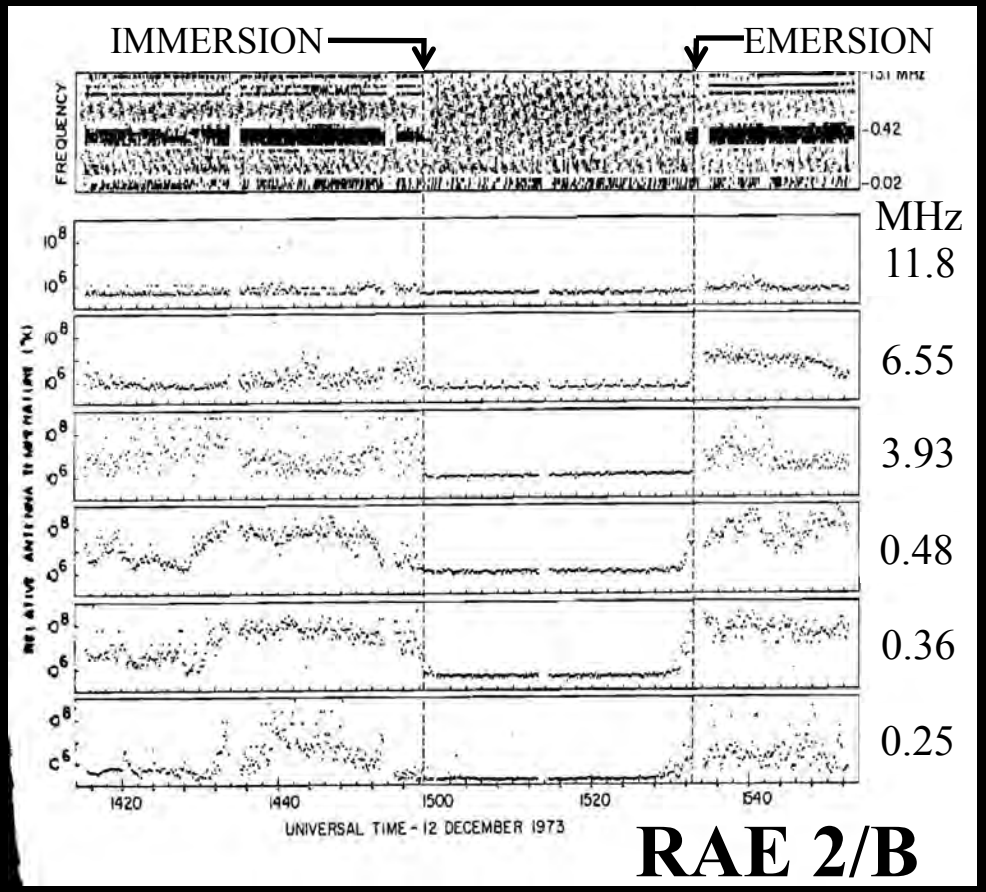
(Size, Weight, Power, Bandwidth, Baseline stability)

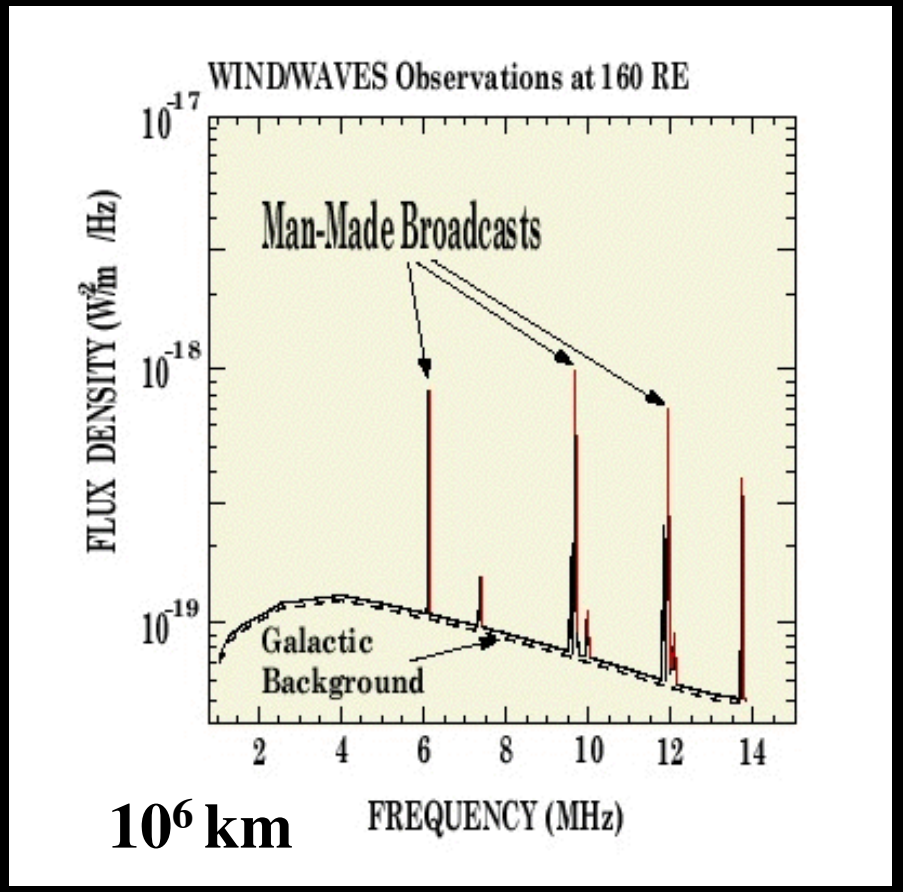
- **Robert C. Byrd Telescope (GBT)**
  - Single dish
  - 100m diameter; 7300 tons
  - Active surface
  - Parabola to 1/10 λ
  - 200 MHz – 50 GHz

- **Very Large Array (VLA)**
  - 27 antenna interferometer
  - 25 m diam; 230 tons each
  - 30 km largest extent
  - Baselines to fraction λ
  - 74 MHz – 45 GHz

The Need for Going to the Back-side of the Moon

(Radio Frequency Interference - RFI)

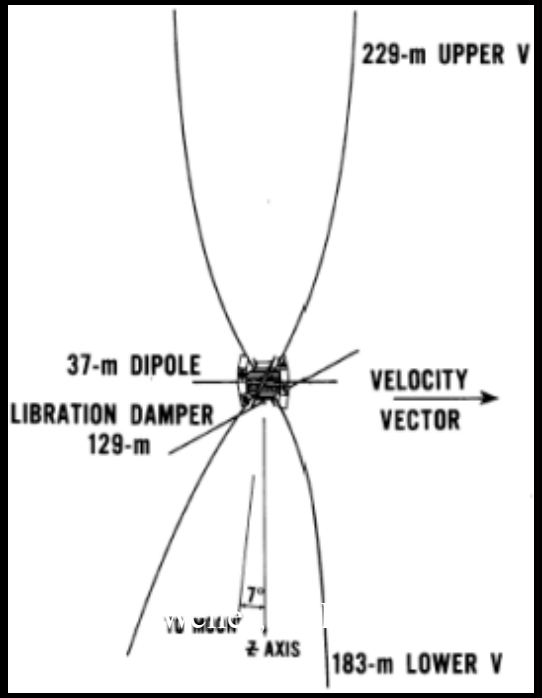




The Early Years
Radio Astronomer Explorers 1/A & 2/B (General Specifications)

- **RAE 1/A (Explorer 38) launched 04 July 1968**
  - 190 kg; Delta launch
  - Four 230 m long wires, one V-antenna up and one down
    - ✓ 25 kHz to 13.1 MHz
    - ✓ Perigee 5,835 km; Apogee 5,861 km; Incl. 121 deg
- **RAE 2/B (Explorer 49) launched 10 June 1973**
  - 328 kg; Delta launch
  - 229 m V away from Moon; 183 m V towards Moon; 37 m dipole parallel Moon
    - ✓ 25 kHz to 13.1 MHz
    - ✓ Lunar Orbit

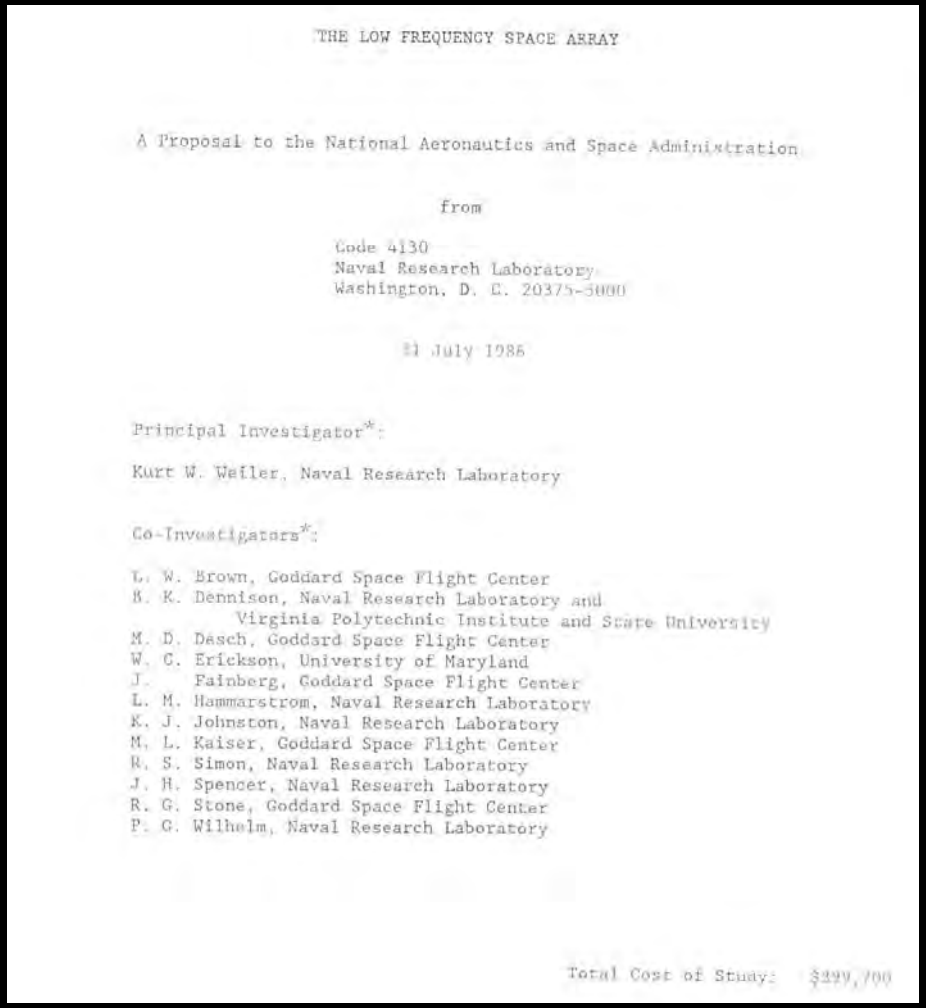
RAE-1/A



RAE-2/B

Renewed Interest in Radio Astronomy from Space (Interferometric Arrays)

- **The Low Frequency Space Array**
  - Submitted 31 July 1986
- **PI: Kurt W. Weiler (NRL)**
  - Co-Is
    - ✓ L.W. Brown (GSFC)
    - ✓ B.K. Dennison (VPI&SU)
    - ✓ M.D. Desch (GSFC)
    - ✓ W.C. Erickson (UMD)
    - ✓ J. Fainberg (GSFC)
    - ✓ L.M. Hammarstrom (NRL)
    - ✓ K.J. Johnston (NRL)
    - ✓ M.L. Kaiser (GSFC)
    - ✓ R.S. Simon (NRL)
    - ✓ J.H. Spencer (NRL)
    - ✓ R.G. Stone (GSFC)
    - ✓ P.G. Wilhelm (NRL)



THE LOW FREQUENCY SPACE ARRAY

A Proposal to the National Aeronautics and Space Administration

from

Code 4130
Naval Research Laboratory
Washington, D. C. 20375-5000

31 July 1986

Principal Investigator*:

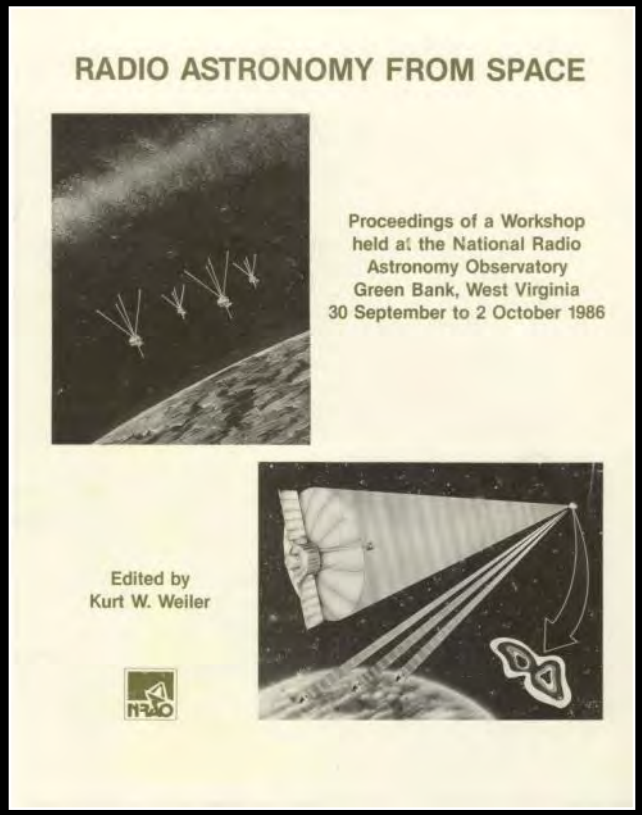
Kurt W. Weiler, Naval Research Laboratory

Co-Investigators*:

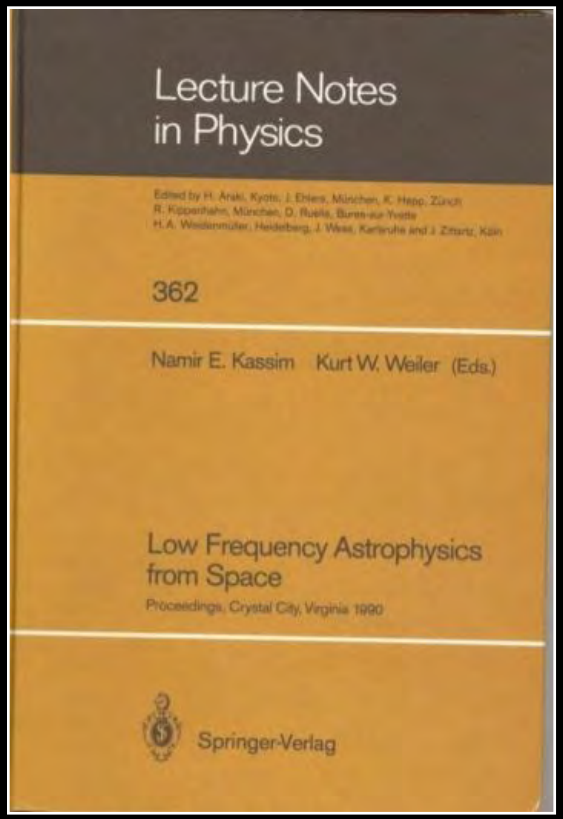
L. W. Brown, Goddard Space Flight Center
B. K. Dennison, Naval Research Laboratory and
Virginia Polytechnic Institute and State University
M. D. Desch, Goddard Space Flight Center
W. C. Erickson, University of Maryland
J. Fainberg, Goddard Space Flight Center
L. M. Hammarstrom, Naval Research Laboratory
K. J. Johnston, Naval Research Laboratory
M. L. Kaiser, Goddard Space Flight Center
R. S. Simon, Naval Research Laboratory
J. H. Spencer, Naval Research Laboratory
R. G. Stone, Goddard Space Flight Center
P. G. Wilhelm, Naval Research Laboratory

Total Cost of Study: $499,700

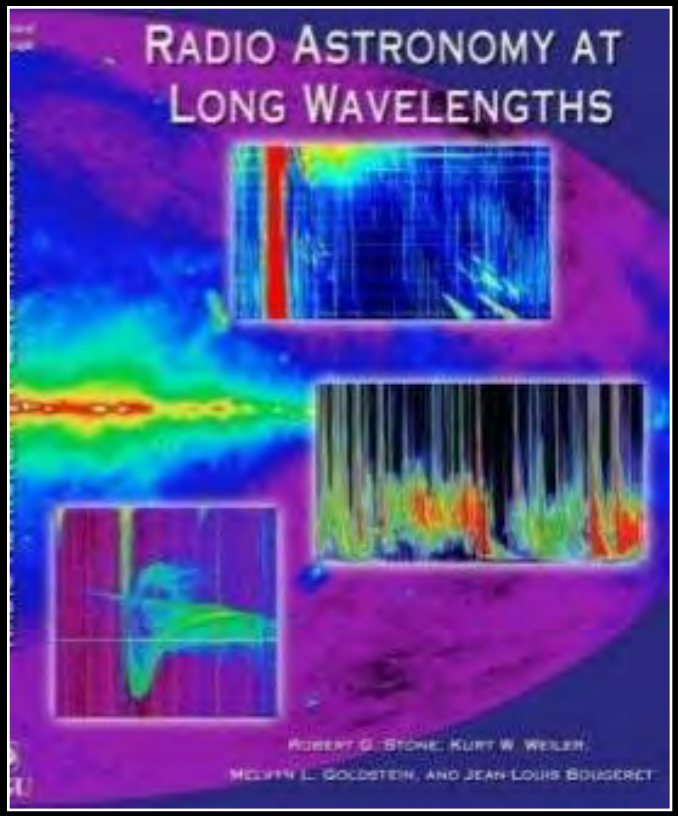
Generating Renewed Interest
(NRL Led Meetings and Books)



1986

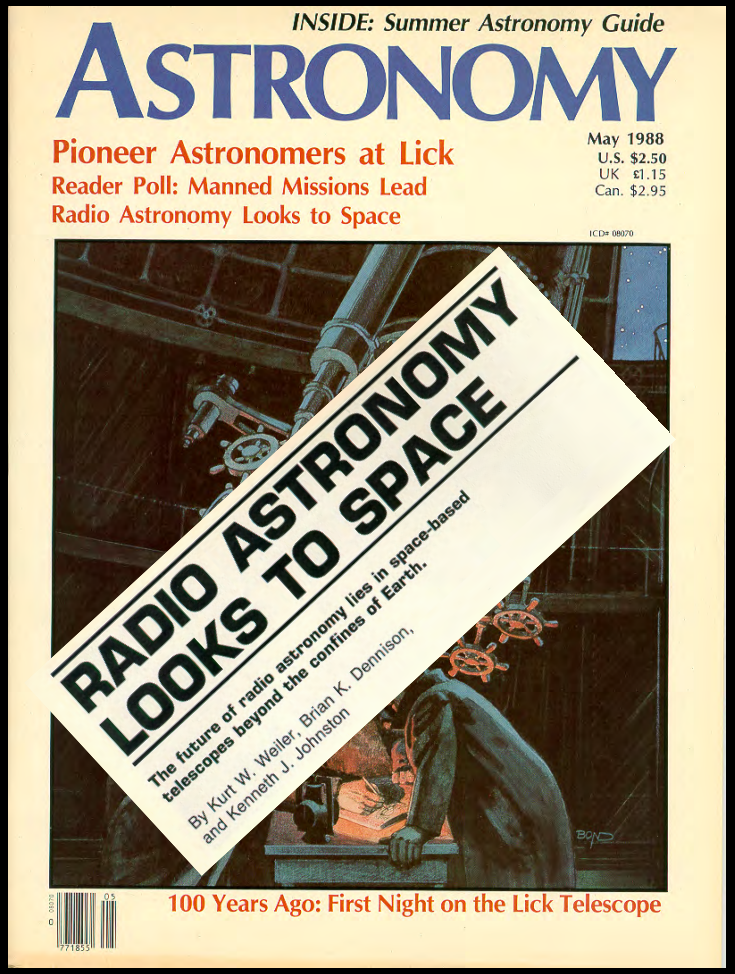


1990



1998

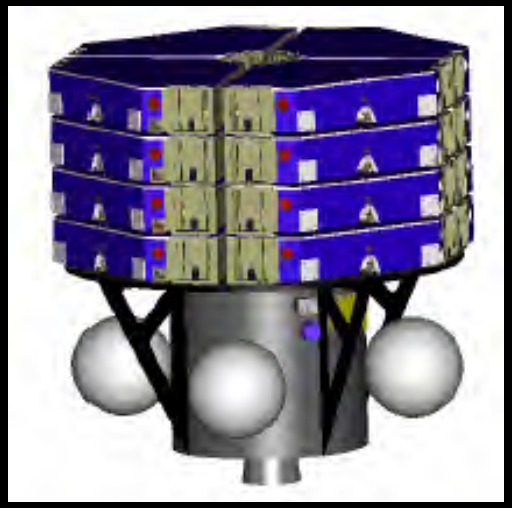
Generating Renewed Interest (NRL Led Popular Articles)



RA-in-Space/Moon Concepts

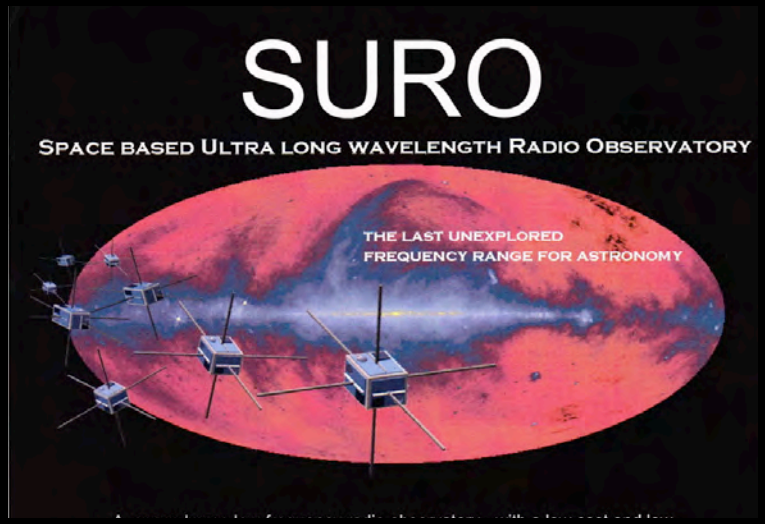
ACRONYM	Name	Location	Description	Era
ALFA	Astronomical Low Frequency Array	L2	Synthesis array of spacecraft	1996, 1998
ALLFA	Astronomical Lunar Low Frequency Array	Lunar surface	Synthesis array of dipoles	1991
ASTRO-E	Astro-E/Suzaku	High earth orbit	Single dish	2005-lost on launch
AstroArray	Astrophysical Array	Deep space	Synthesis array of dishes	1987
Chandrayaan-2 (GEMS)	Geophysical Monitoring Station	Lunar surface	Piggyback radio receiver on GEMS	2011
DALI	Dark Ages Lunar Interferometer	Lunar farside	Large array of stations	2025
DARE	Dark Ages Radio Explorer	Lunar orbit	Single spacecraft	2011
FIELD	Field-test of an Ionosphere Experiment for Lunar Deployment	Lunar nearside	Study lunar ionosphere	2011
HERA	HI Epoch of Reionization Arrays	Earth surface	Use data from existing and planned arrays	Now & into future
LAPS	Lunar Array Precursor Station	Lunar nearside	Study lunar ionosphere	2011
LARC	Lunar Array for Radio Cosmology	Lunar farside	Large array of stations	2025
LFSA	Low Frequency Space Array	LEO	Synthesis array of spacecraft	NASA,
LIRA	Lunar Imaging Radio Array	Lunar nearside	MERIT for solar work	2005
LNSA	Lunar Near Side Array	Lunar surface	Synthesis array of dipoles	1990
LORAE	Lunar Orbiting Radio Astronomy Experiment	Lunar orbit	2-element interferometer	1989
MERI	Moon-Earth Radio Interferometer	Lunar nearside	Earth-to-Moon interferometer	1990
MERIT	Moon-based Epoch of Reionization Imaging Telescope	Lunar farside	Synthesis array of dipoles	2005
MMAMA	Moon/Mars Analog Mission Activities	Lunar nearside	Technology development for solar arrays	2011
OHFRIM	Orbiting Low Frequency Radio Interference Monitor	LEO	Single spacecraft w/ dipoles	1990
ORAJES	Observateur Radio de l'activite Aurorale et des magnetospheres de Jupiter Et Saturne	Earth orbit >5 Re	Single satellite (I think)	1993
RadioAstron	Radio Astronomy satellite	High earth orbit	Single dish	2014?
RAE A & B	Radio Astronomy Explorer	High Earth orbit/Lunar orbit	Single spacecraft/up-down Vs	~1970
ROLSS	Radio Observatory for Lunar Sortie Science	Lunar nearside	Synthesis array of dipoles	2015-2018
SALSA	Synthesis Array for Lunar Submillimeter Astronomy	Lunar surface	Array of 4.5m dishes	1990
SIRA	Solar Imaging Radio Array	L2	Synthesis array of spacecraft	1998, current
SSMF	Space Station Millimeter Facility	Space Station	Multiple element array on Space Station	1988
SURO/DARIS	Space-based Ultra-long wavelength Radio Observatory/low-frequency distributed aperture array for radio astronomy in space	L2, L4, Moon	Synthesis array of spacecraft	ESA, 2010
VLFA	Very Low Frequency Array	Lunar surface	300 dipoles + central station; rover deployed	1993
VLO	Very Lowfrequency Lunar Observatory	Lunar surface	Dozen dipoles; rover deployed	
VSOP/HALCA	VLBI Space Observatory Program/Highly Adv. Lab. for Comm. and Astro	High earth orbit	Single dish	1997

Concepts for Radio Astronomy from Space



ALFA

LFSA



SURO

Low Frequency Space Array (LFSA)

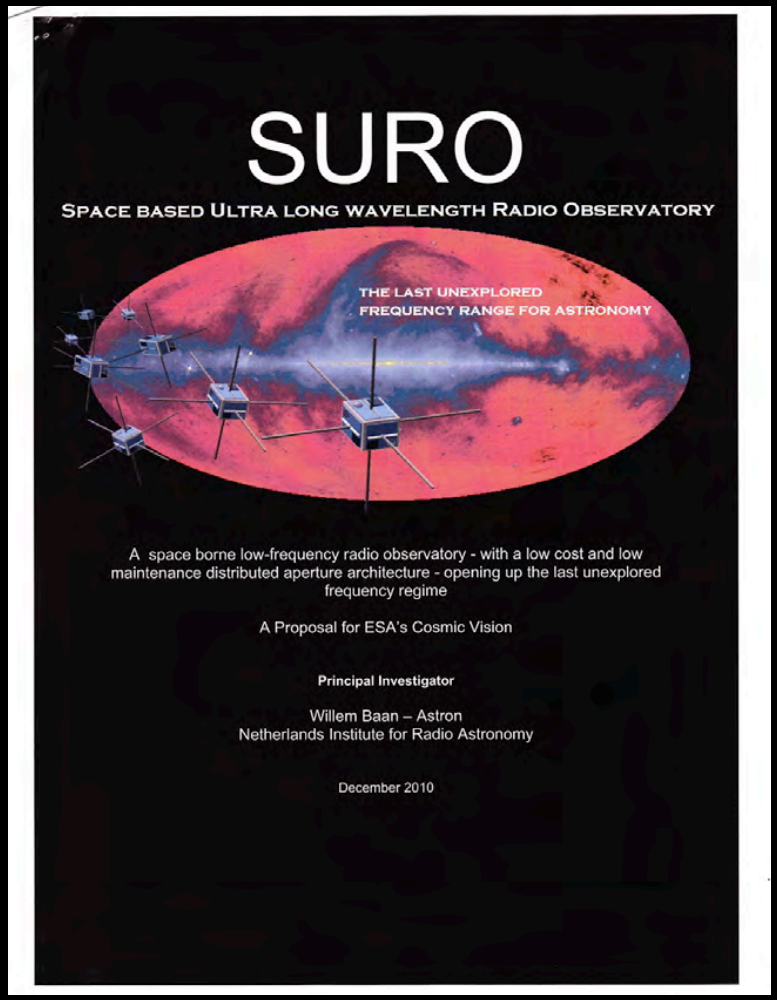
- **Single deployment bus**
  - 4 free-flying antennas (array elements)
  - Circular orbit at inclination 30 – 60 deg
  - Semi-major axis 10,000 – 12,000 km
  - Frequencies1.5, 4.4, 13.1, & 26.3 MHz
  - 50 kHz bandwidth

Simpler Concepts (LFSA-2)

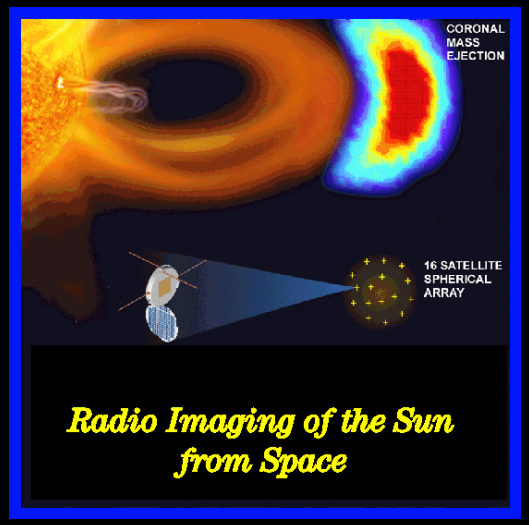
- **System Parameters**
  - 4-8 identical elements
  - Large circular orbit - >20,000 radius
  - 3 mutually orthogonal dipole antennas
  - Freqs. – 1.5, 4.4, 13.4, 25.6 MHz
  - Direct full BW transmission to ground
  - Changing array spacings
    - ✓ 1 year
    - ✓ < 1 km
    - ✓ >300 km

SURO (Space-based Ultra-longwavelength Radio Observatory

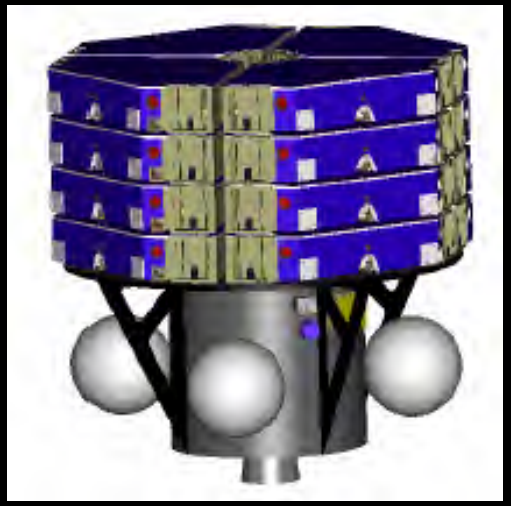
SURO System Engineering Solutions		
Function	**Base-line**	**Alternative**
Orbit	Sun dynamic orbit (4-10 million km)	Sun/Earth L2 Lissajous (1.5 million km)
Launch	Soyuz direct escape	Dnepr/Vega/Rocket direct escape
Mission Duration	10 years	3 years
Science	Frequency range: 300 kHz – 30 MHz; Frequency band: 10 MHz Sensitivity: 65 mJy per year; Resolution 5 arcmin at 5MHz:	
Constellation control	Separation 5 – 100 km; Ranging accuracy: <50mm at 30 km; Relative orientation ±1° (from multi-lateral metrology)	
	Chemical and cold gas propulsion and reaction wheels; 2.4 GHz inter-satellite linking (ISL).	Electrical propulsion and passive attitude control: 1 GHZ inter-satellite linking (ISL).
Spacecraft	Mother wet mass: 881kg Daughter wet mass: 100 kg Launch wet mass: 1784 kg	Mother wet mass: 320 kg Daughter wet mass: 10 kg Launch wet mass: 400 kg
Ground Station	35 metre antenna	15-35 metre antenna
Cost at completion to ESA	M€312	M€118

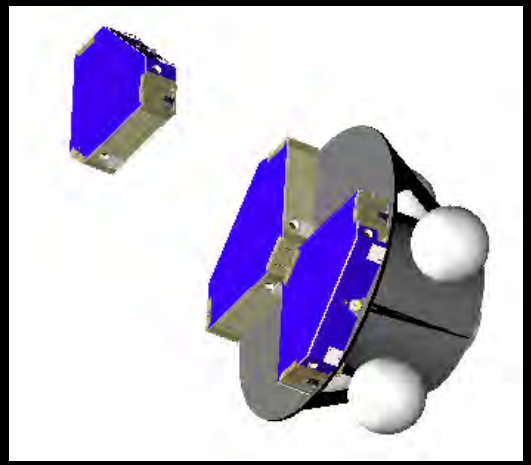


Detailed Design (led by JPL)
(Astronomical Low Freq. Array – ALFA)
(Solar Imaging Radio Array – SIRA)

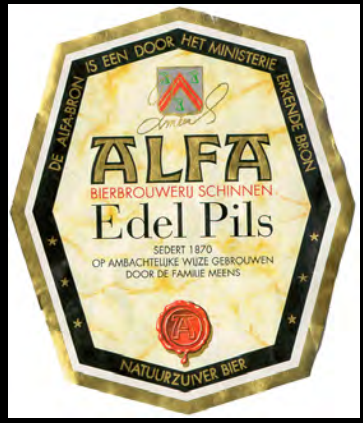


- **No. of satellites 12 -16**
- **Pointing control 2°**
- **Downlink SNR 0 dB**
- **Data rate (kb/s) 256**
- **Instrument power 7 W**
- **Instrument mass 2 kg**
- **Radiation (kRad) 7.6**
- **Propellant (kg) 0.31**
- **Reliability (sats/yr) 12/1**





JPL CubeSat 10JUL2012



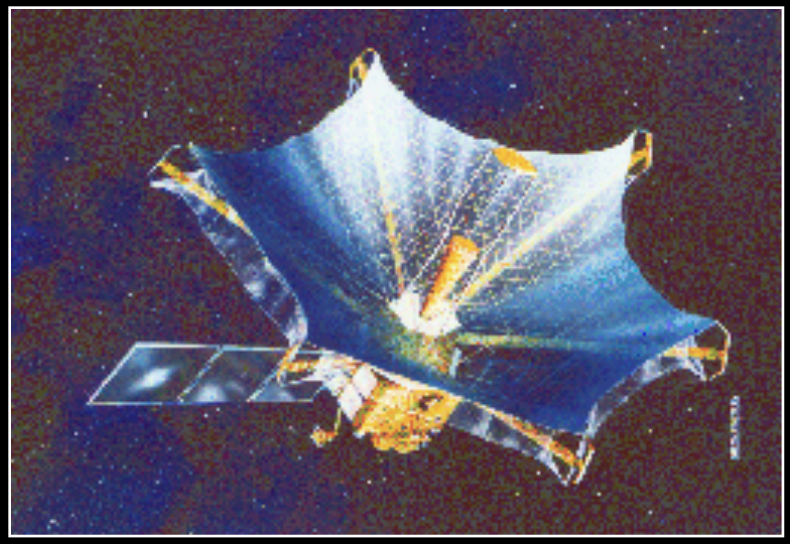
Kurt W. Weiler, CPI

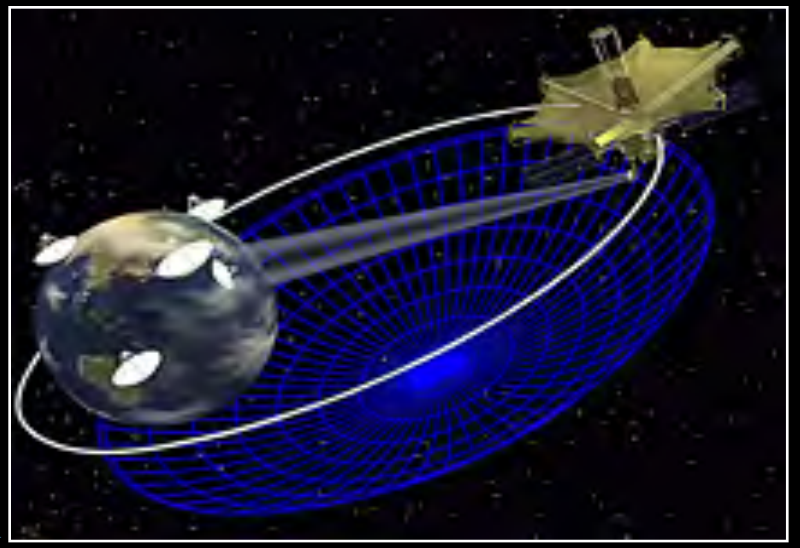
PI & Lead Organization

ALFA – Jones et al. 1998, JPL

SIRA – MacDowall et al. 1998, GSFC

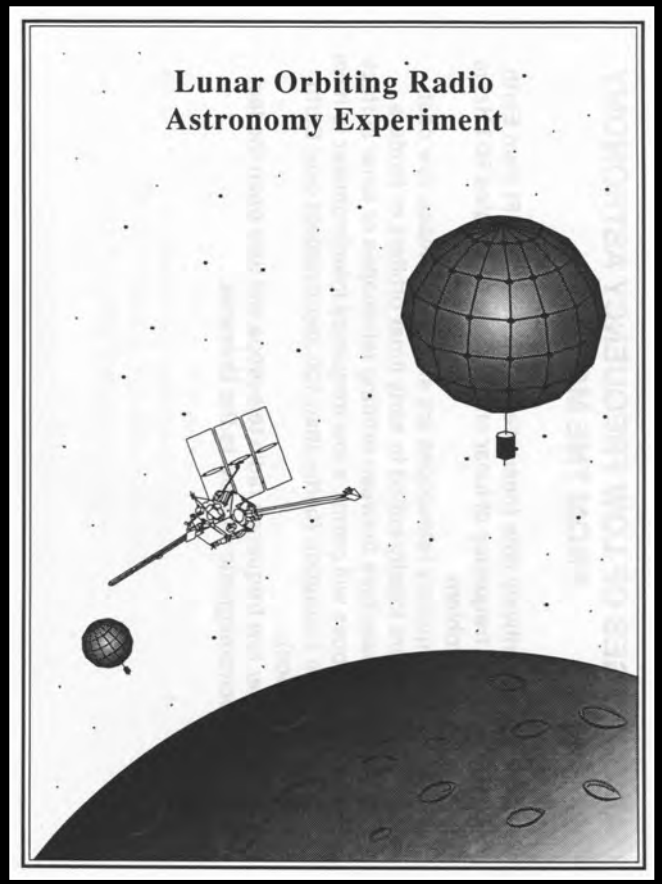
VLBI Space Observatory Program (VSOP)
Highly Adv. Lab. for Comm. and Astro. (HALCA)

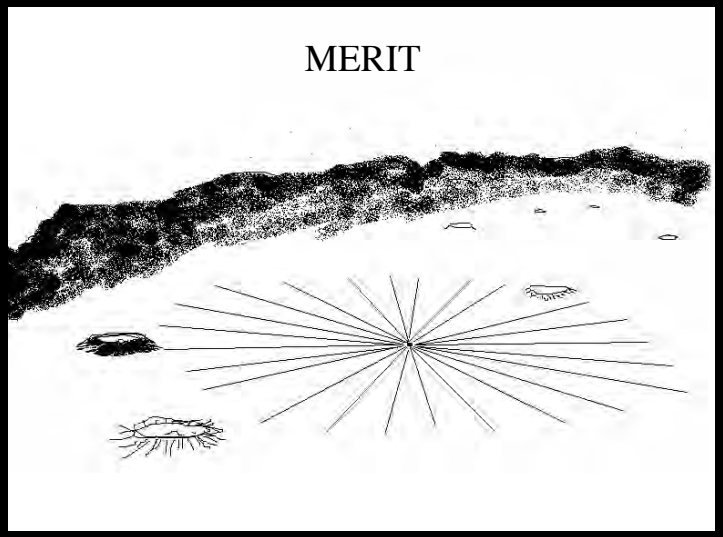


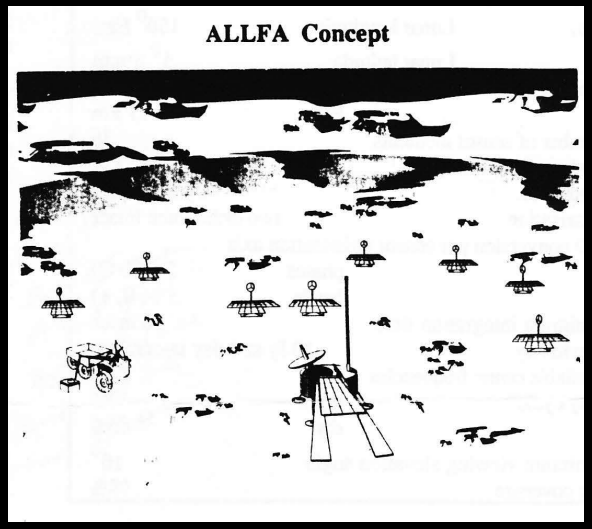


- **Japanese - MUSES-B**
  - Collab. with NRAO/others for ground stations
- **Space-to-ground VLBI**
- **Launched 12 Feb. 1997 (M-V rocket)**
- **8m diameter**
- **815 kg**
- **Apogee 21,000km; perigee 560km**
- **Freqs. 1.6, 5, 22 GHz**
- **VSOP-2 planned for 2012 launch**

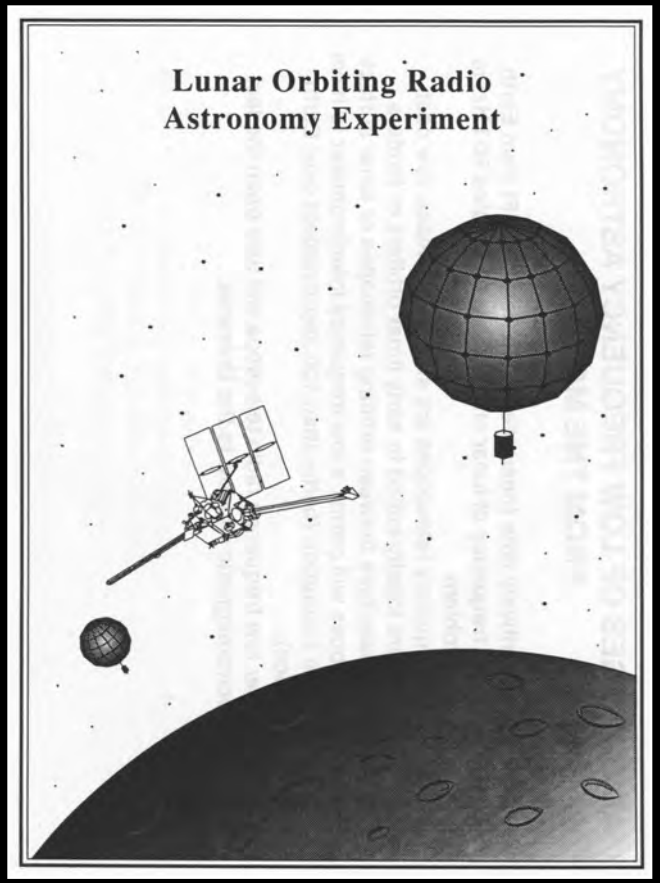
Concepts for Radio Astronomy from the Moon







Lunar Orbiting Radio Astronomy Experiment (LORAE) Lunar Near-Side Array (LNSA)



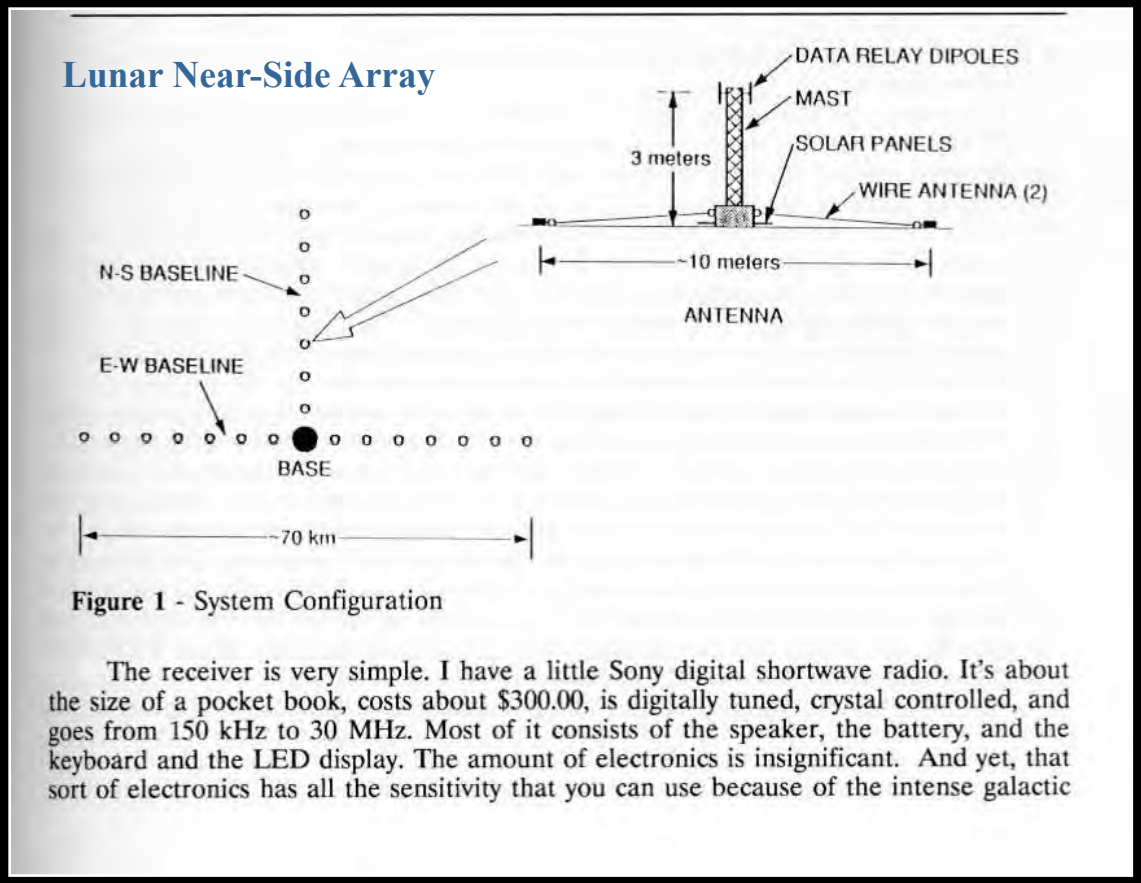


Figure 1 - System Configuration

The receiver is very simple. I have a little Sony digital shortwave radio. It's about the size of a pocket book, costs about $300.00, is digitally tuned, crystal controlled, and goes from 150 kHz to 30 MHz. Most of it consists of the speaker, the battery, and the keyboard and the LED display. The amount of electronics is insignificant. And yet, that sort of electronics has all the sensitivity that you can use because of the intense galactic

LORAE
Burns - UCO

1990-1998

LNSA
Kuiper-Jones - JPL

Moon-based Epoch of Reionization Imaging Telescope (MERIT)

MERIT Concept

- Deployment on lunar surface
- Array of ~20,000 short dipoles
- Multi-arm radial configuration
- Each arm is a thin kapton sheet, unrolled from hub by a rover
- Antennas & feed lines on sheet
- Maximum baselines ~10 km
- Aperture synthesis imaging
- Angular resolution 1' at 100 MHz
- Frequency range 6 – 250 MHz
- HI redshift range z ~ 5 – 250
- Frequency range for solar observations 0.05 – 50 MHz
- Spectral dynamic range > 10^6, spectral resolution 0.01 – 1 MHz
- All electronics located at central hub, powered by small RTG
- EoR/astrophysics observations at night, solar observations during day
- Daily science data rate ~1 TB (assuming real-time cross-correlation)

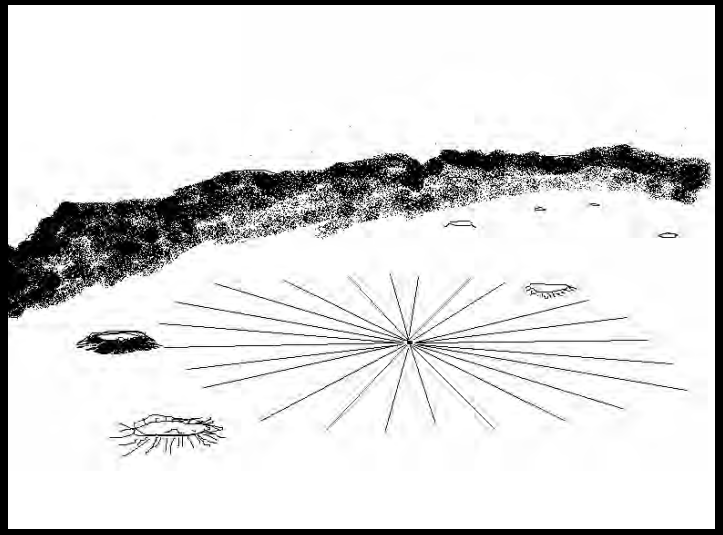
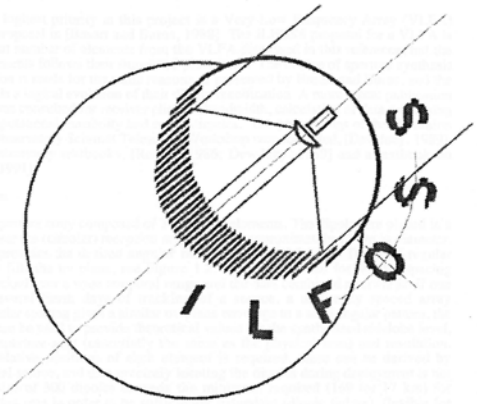


Figure 5. Sketch of the MERIT array on the lunar surface. The radial spoke configuration allows easy deployment and a good distribution of baseline lengths in the array. No active elements or power distribution is required on the spokes; signals follow low-loss transmission lines to the central hub (lander) where receivers and the cross-correlator are located. Power and heating will be provided by a small RTG.

Very Low Frequency Array (VLFA – ESA)

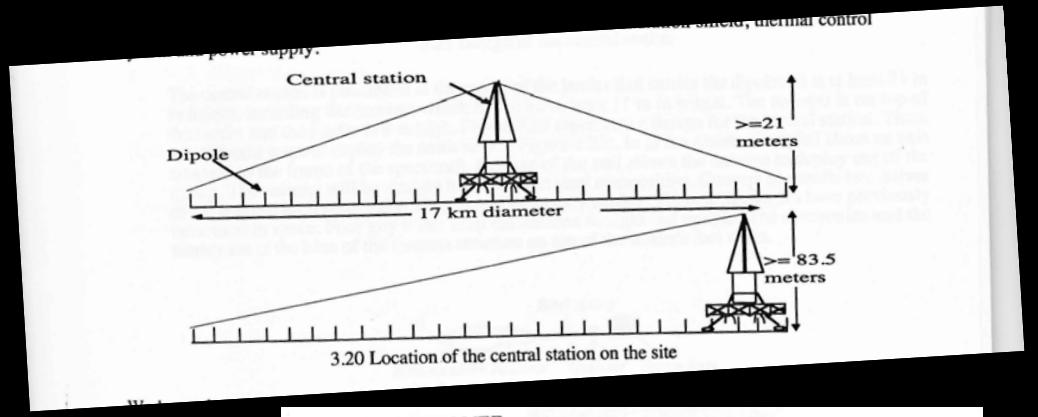
INTERNATIONAL
LUNAR FARSIDE OBSERVATORY & SCIENCE STATION

EXTRACT FROM



PROJECT REPORT
1993

VLFA



3.20 Location of the central station on the site

300 element dipole array on lunar surface

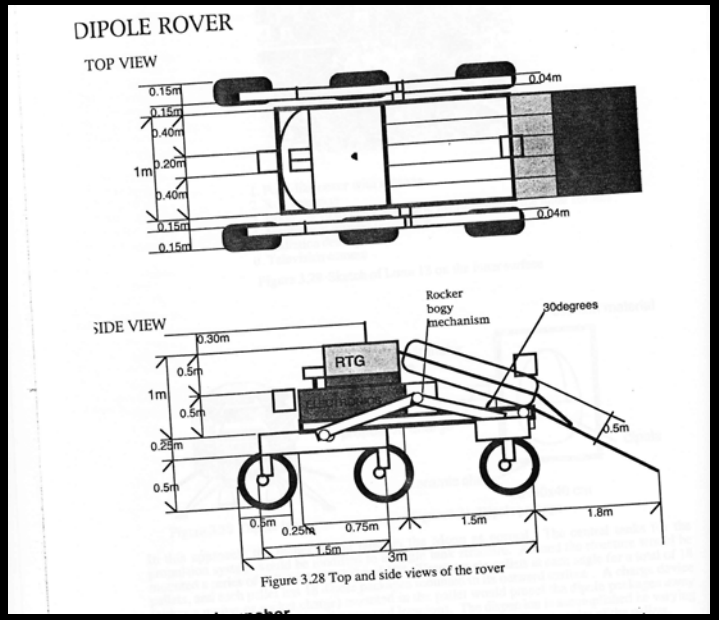


Figure 3.28 Top and side views of the rover

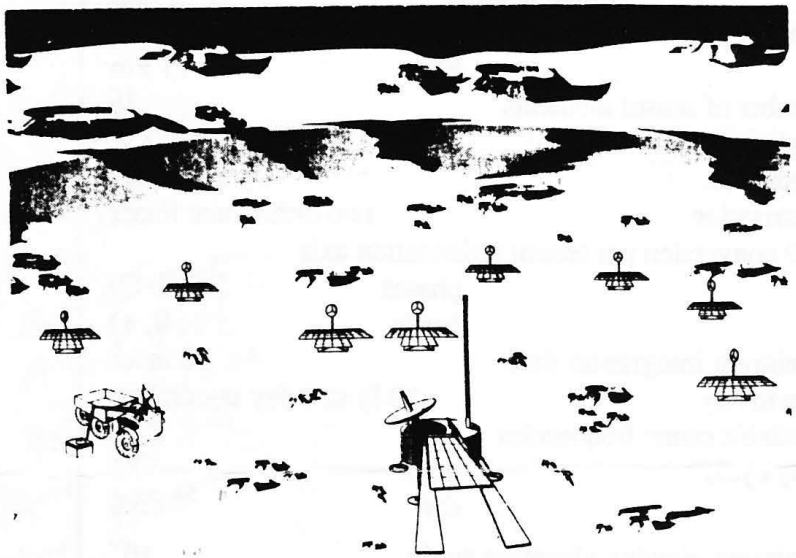
Astronomical Lunar Low Frequency Array (ALLFA)

Telerobotically Deployed Lunar Farside Very Low Frequency Radio Observatory

Introduction

The Astronomical Lunar Low Frequency Array (ALLFA) is a radio observatory placed robotically on the farside of the Moon. Frequencies below 30 MHz cannot be effectively observed from Earth (including from Earth orbiting satellites) due to absorption from the Earth's ionosphere and interference from man made radio broadcasts. The farside of the Moon is shielded from this interference, thus enabling sensitive observations across this frequency range. Robotic emplacement presents many engineering challenges whose solutions have applications to future space exploration missions. Particularly relevant to SEI are the telerobotic rover, capable of deploying the observatory across a large expanse with little autonomy, a lunar lander, capable of soft landing on the surface of the Moon with minimal a-priori knowledge of the surface terrain, and a relay satellite, in orbit about the lunar libration point L2 to provide continuous communications between the Earth and the lunar farside.

ALLFA Concept



BUT!

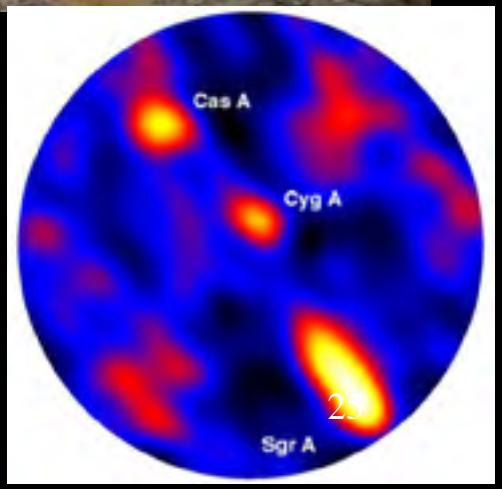
Ground-based work has to first show need

Ground-based EoR Work

Telescope/ Experiment	Date	Location
CORE	On-going	Australia
EDGES	On-going	(I) Haystack, MA (II) TBD
VLA-EOR	2005	New Mexico
GMRT	On-going	India
21CMA/PAST	Suspended	China
PAPER	Construction	(I) Green Bank, WV (II) Australia
LOFAR	Construction	The Netherlands
MWA	Construction	Australia
LWA	Construction	New Mexico
SKA	Design & Development	South Africa & Australia

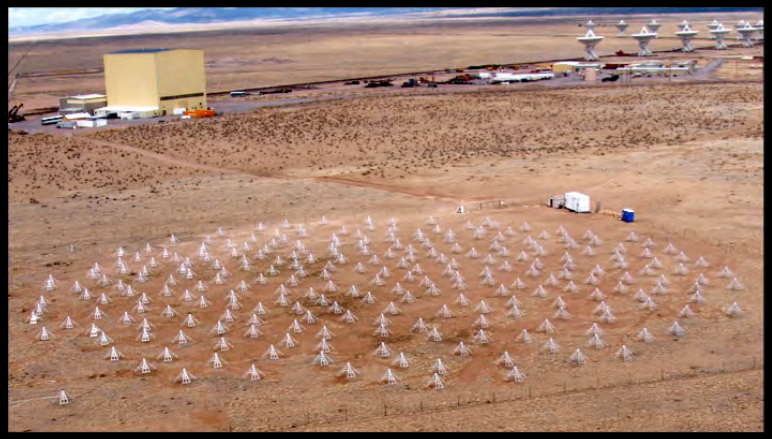
Long Wavelength Demonstrator Array (LWDA)

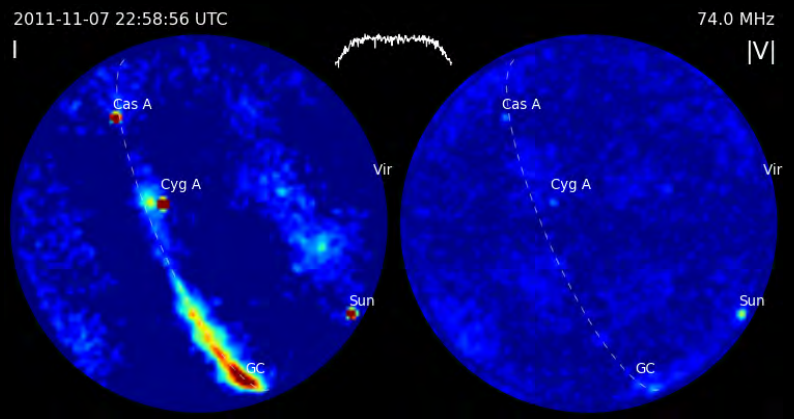
- Aim is to explore high-resolution, long-wavelength sky for first time …
- *But*, frequency range well-matched to Dark Ages exploration as well
  - 20–80 MHz
  - $z \sim 15–70$
- Located in a reasonably radio-quiet place on the planet: New Mexico, centered on VLA site



LWA-1

http://www.phys.unm.edu/~lwa/lwatv.html



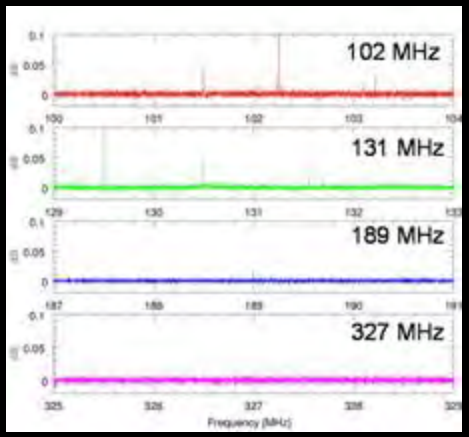


Low Frequency Array (LOFAR)

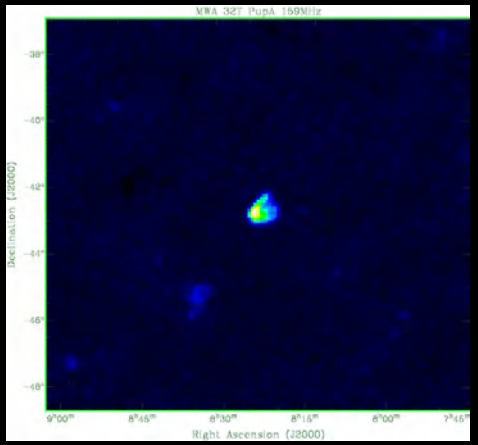
LBA Near Exloo

Central terp + HBA near Tautenberg

Murchison Widefield Array
MWA

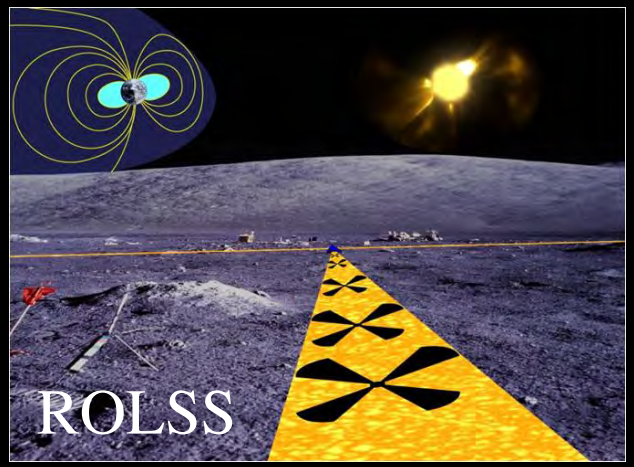


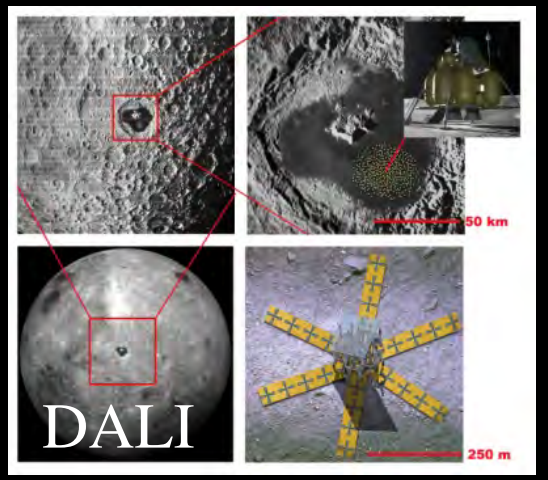
Interference levels

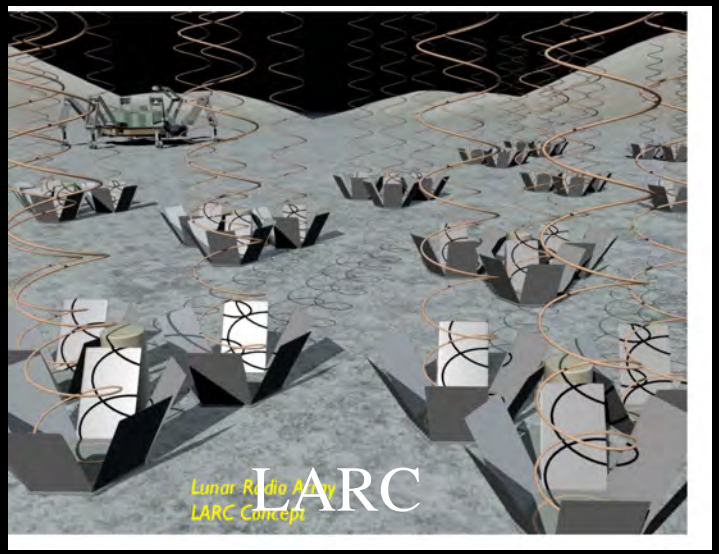


Puppis A

New Lunar Surface Concepts

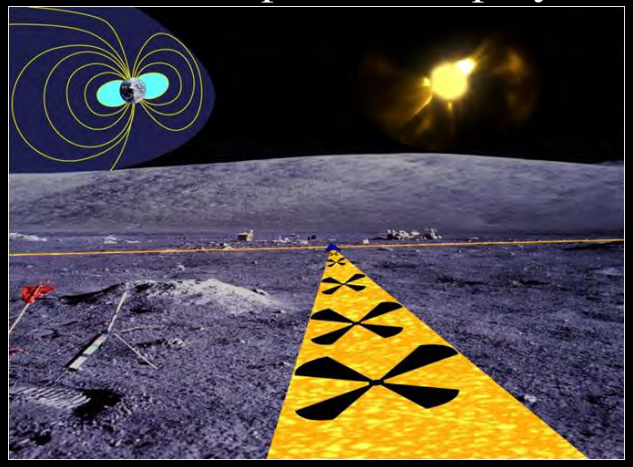






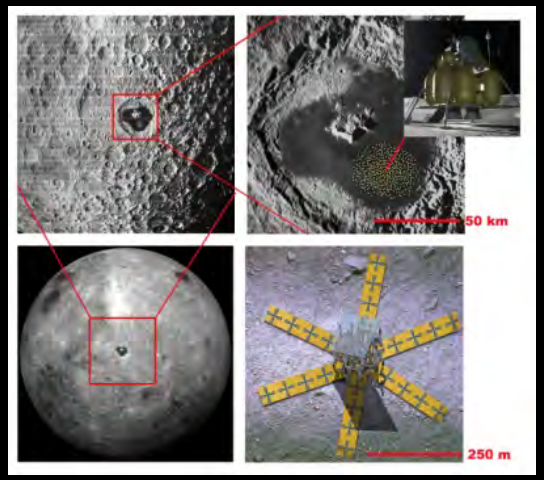
Radio Obs. for Lunar Sortie Sci.-- ROLSS
Dark Ages Lunar Interferometer – DALI

- **Lunar Sortie Science Opportunity (LSSO)**
  - Low frequency (1-10 MHz) interferometer
  - Deployed by astronauts
  - Key Science – solar particle acceleration
  - Key Technology - large number of antennas deposited on polyimide film



JPL CubeSat 10JUL2012

- **Antennas grouped in "stations"**
  - Antennas on polyimide film
  - On-going work characterizes properties
- **1000 stations of 100 antennas each**
- **Stations deployed by rovers**
  - Rover unroll poly film; then becomes receiver/transmission "hub"
  - Stations acquire/store data during night
  - Stations transmit for correl. on during day
- **Relay satellite downlink to Earth**



Kurt W. Weiler, CPI

Lunar Array for Radio Cosmology (LARC)

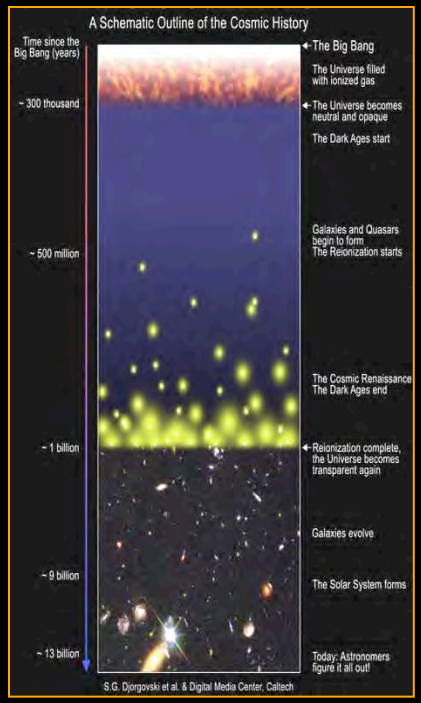
LARC Concept

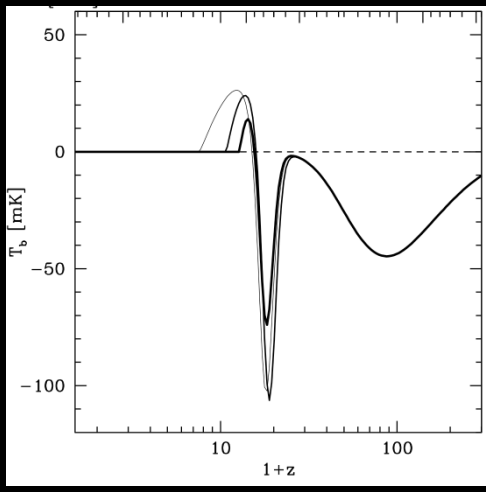
- Push for the best capability for cosmology
- ~ 10,000 antenna elements – make them autonomous
- Direct digital conversion at each antenna element
- Optical communication to transmit data to correlator – *see poster b J. Villasenor*
- Very large correlator – power consumption not an issue, but complexity may be (new algorithms area a development area)
- Transmission of data to Earth
- Robotic deployment using ATHLETEs
- Operate during lunar night, storing data for correlation during day

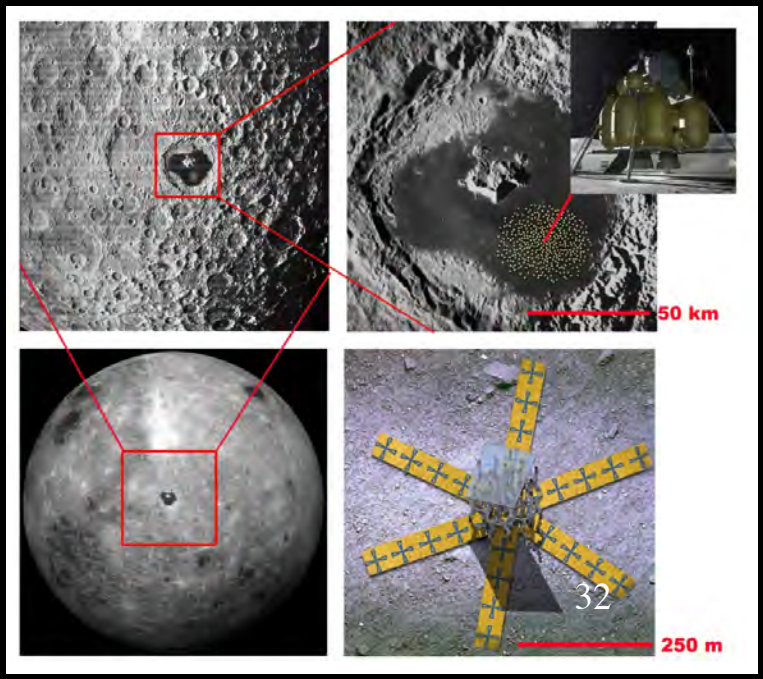
Technology development is part of LUNAR program
Plan submitted to astrophysics decadal survey

Why the Moon's Far Side?

- Sun
  - Only nighttime observations sufficient
- Radio frequency interference
  - No place on Earth dark at these frequencies
- Ionosphere
  - Significant effects already seen at 74 MHz ($z \sim 20$)







JPL CubeSat 10JUL2012

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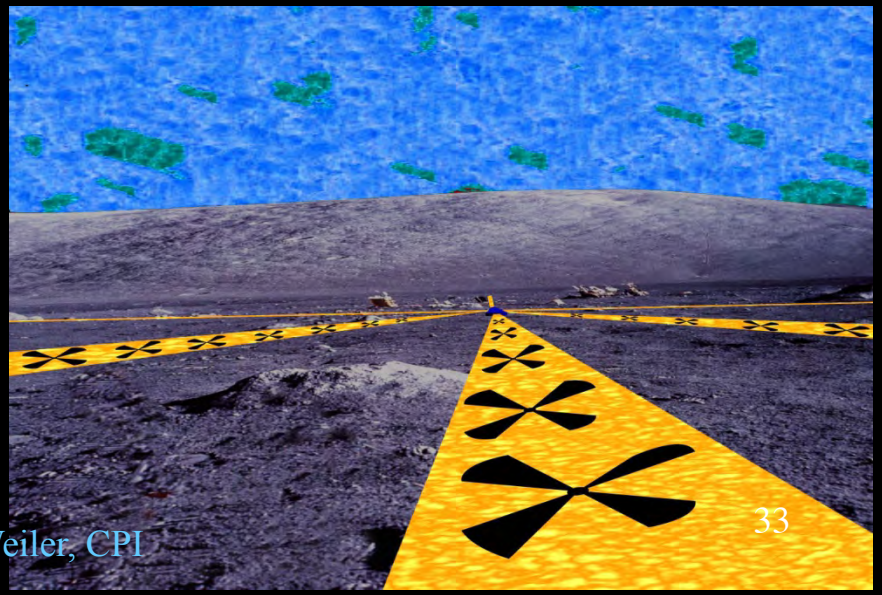
DALI/ROLSS Antennas

- Electrically short dipoles deposited on polyimide film.
- Polyimide film has long history of spacecraft applications.
- On-going work to test polyimide film in lunar conditions and electrical properties
  - NRL
  - NASA/GSFC
  - U. Colorado

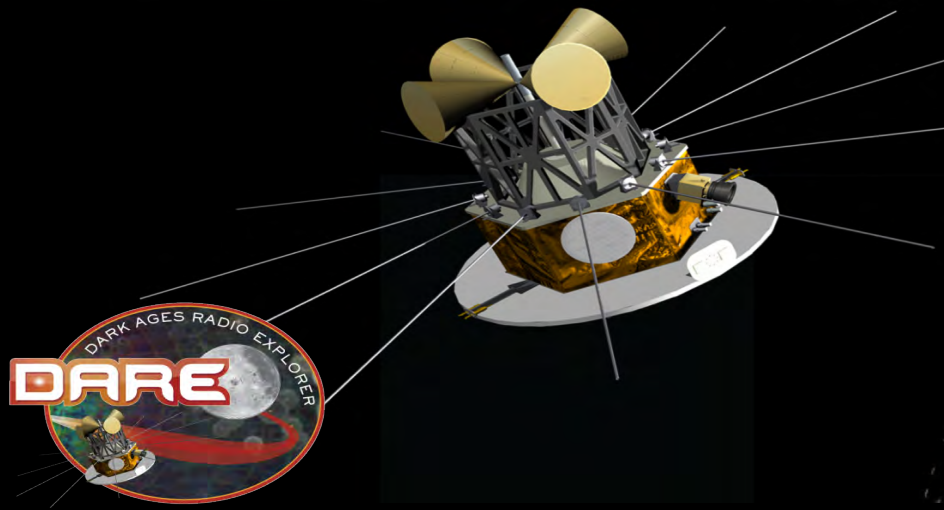
Polyimide film field tests



The Newest Proposal

DARE

DARK AGES RADIO EXPLORER



Jack Burns
University of Colorado Boulder
and
NASA Lunar Science Institute

Lessons from 40 years

- RA from space & Moon lacks/lacked a "killer ap"
- Astrophysics –
  - Technical limitations
    - Low resolution
    - Low sensitivity.
  - Need to go to space
    - Ground-based work will have to show a dire need to go to lower frequencies
- Solar – Building support within the solar community
- BUT! I remain optimistic
  - EoR/Dark Ages may be the "killer ap"
  - z >~ 100 REQUIRES going to space/Moon
  - NLSI/LUNAR provides a focal point and is doing great work
  - Burns/Jones/Lazio are giving dynamic leadership
- What is lacking is political support

FINISH