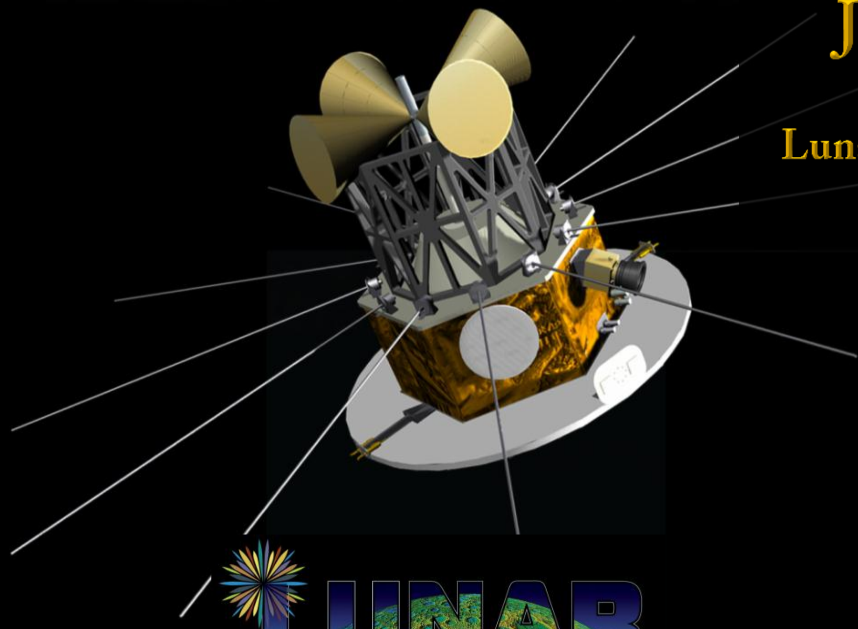
DARE

DARK AGES RADIO EXPLORER



Jack Burns for the DARE Team

University of Colorado Boulder,
Lunar University Network for Astrophysics Research,
& NASA Lunar Science Institute

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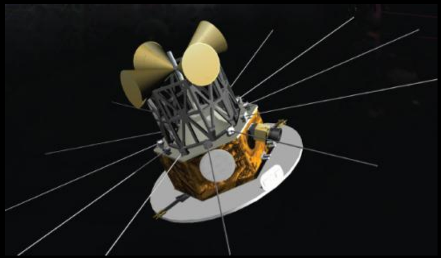

DARE PROJECT TEAM

Principal Investigator:
Jack Burns, U. Colorado

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Project Manager:
Daniel Andrews, ARC

Deputy Project Manager:
Jill Bauman, ARC

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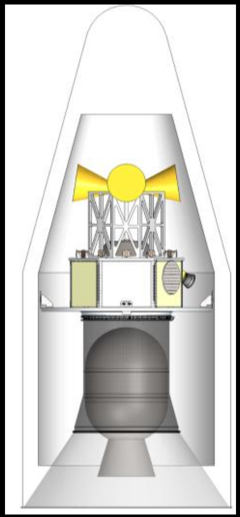
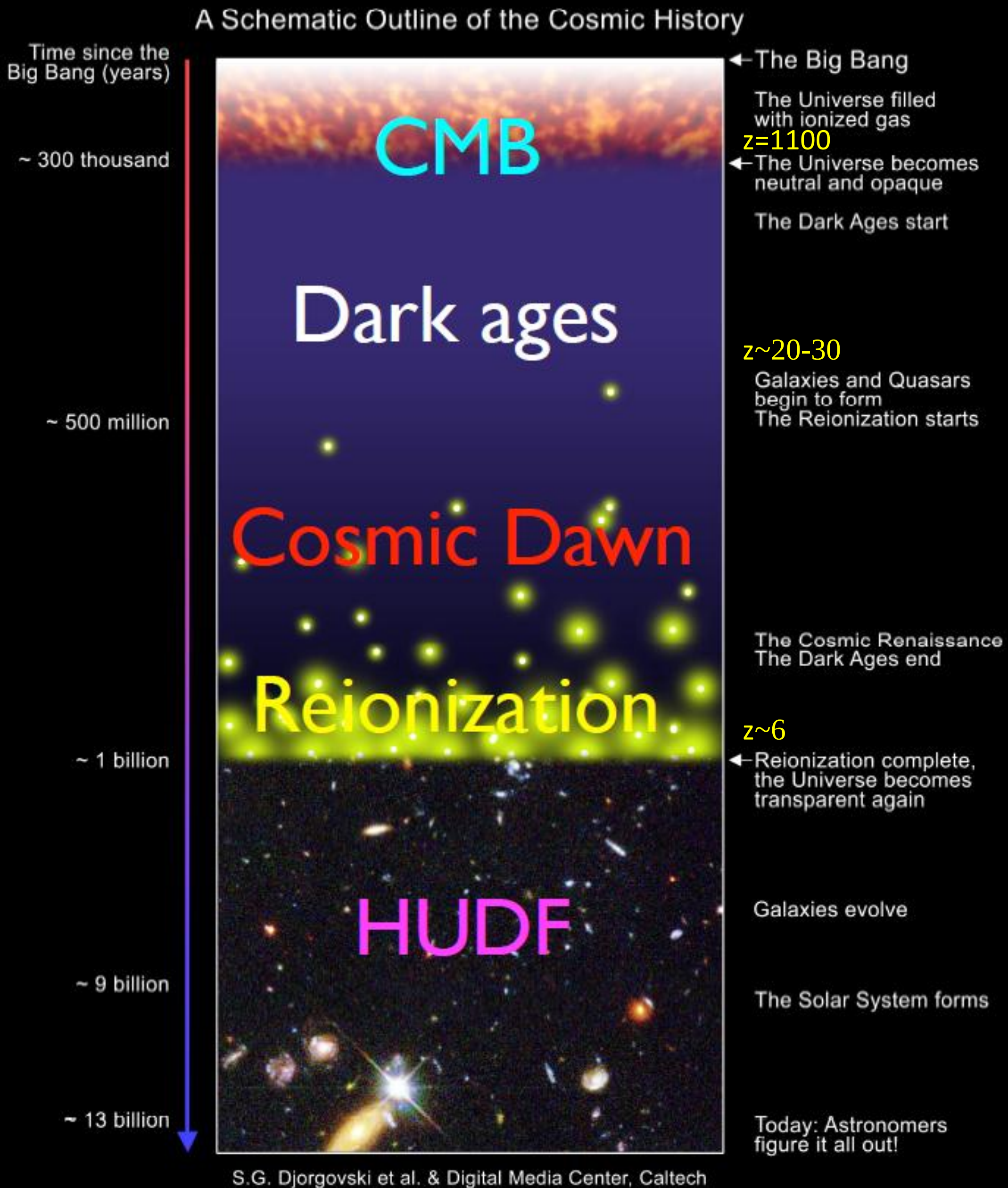
Christopher Carilli, Natl. Radio Astronomy Obsv.
Steven Furlanetto, UCLA
Geraint Harker & Abhi Datta, U. Colorado
Abraham Loeb, Harvard University
Jonathan Pritchard, Harvard-Smithsonian Center for Astrophysics

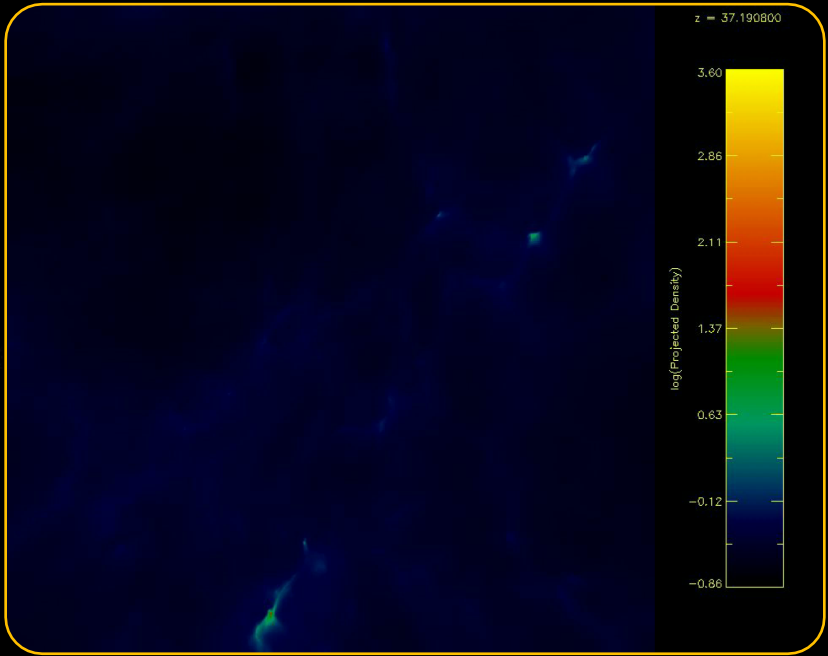
PARTNERSHIPS



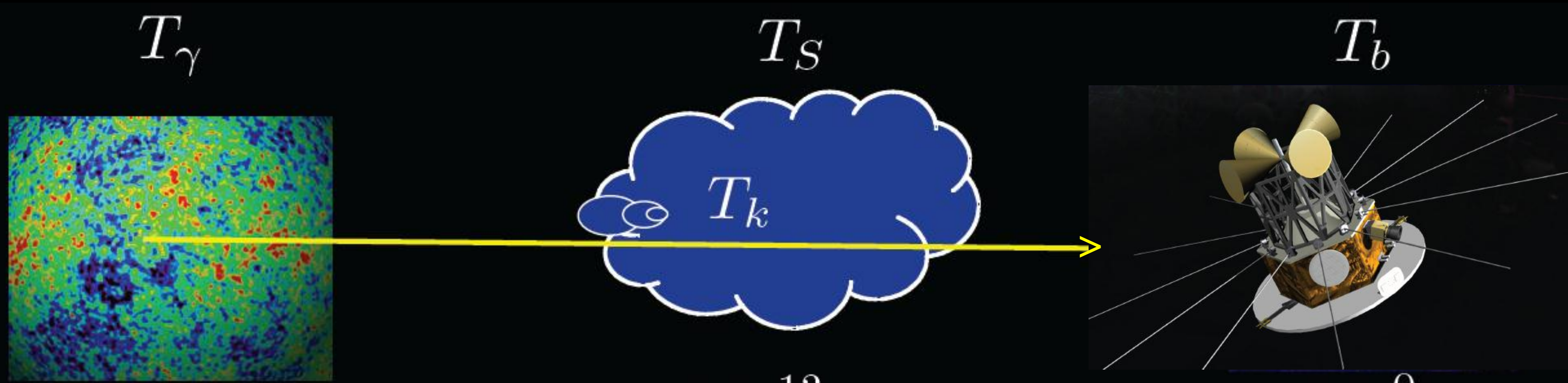
The First Billion Years



The First Stars
John Wise, Georgia Tech



The 21-cm Line in Cosmology



$z = 13$, $\nu = 1.4\,\mathrm{GHz}$

$z = 0$, $\nu = 100\,\mathrm{MHz}$

CMB acts as back light

Neutral gas imprints signal

Redshifted signal detected

neutral fraction — baryon density — spin temperature — peculiar velocities

brightness temperature ($P = kT_b \Delta\nu$)

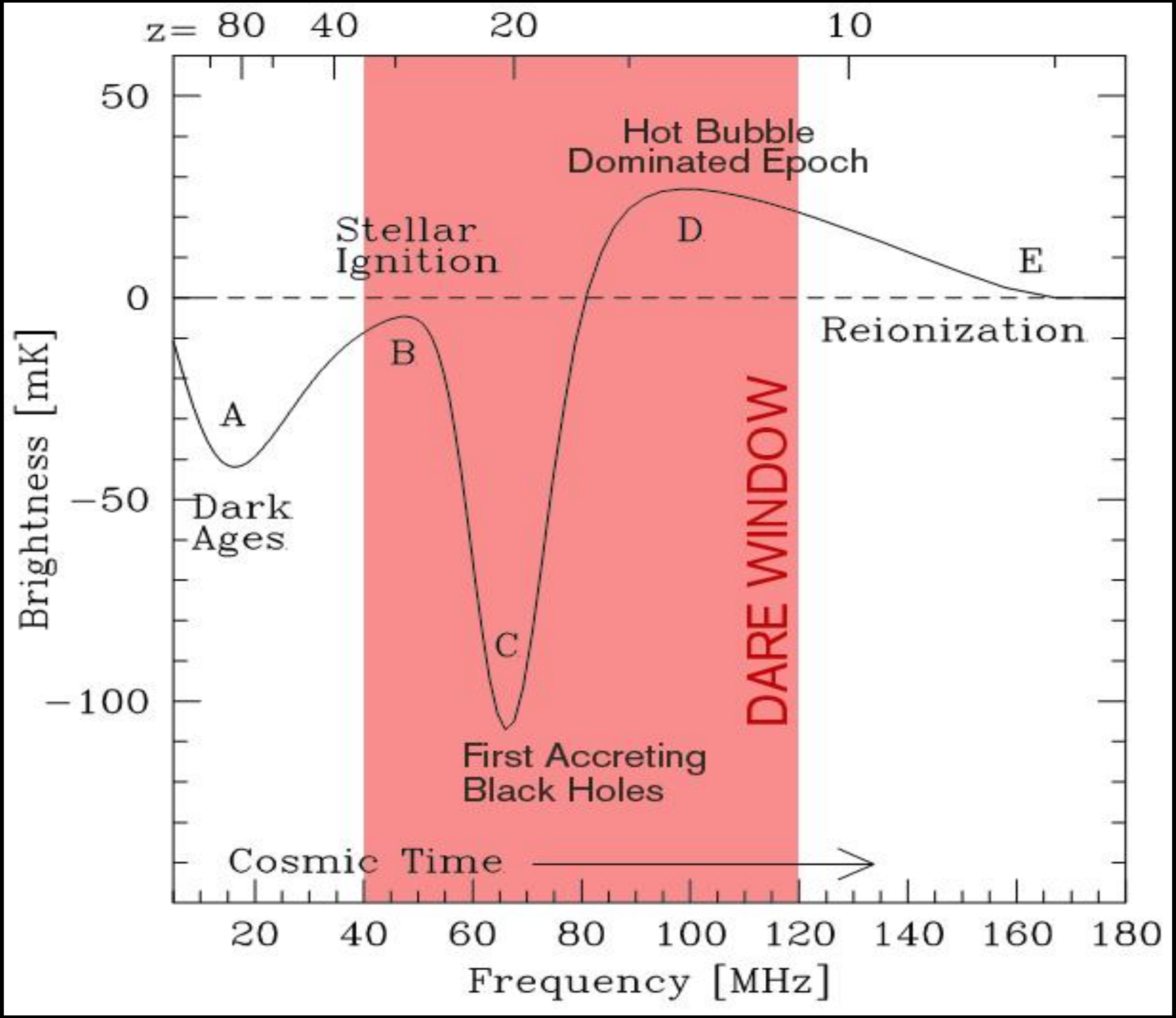
$$T_b = 27 x_{\rm HI} (1+\delta_b) \left(\frac{T_S - T_\gamma}{T_S}\right) \left(\frac{1+z}{10}\right)^{1/2} \left[\frac{\partial_r v_r}{(1+z)H(z)}\right]^{-1} \mathrm{mK}$$

spin temperature set by different mechanisms:

- Radiative transitions (CMB)
- Collisions
- Wouthysen-Field effect

Courtesy of J. Pritchard

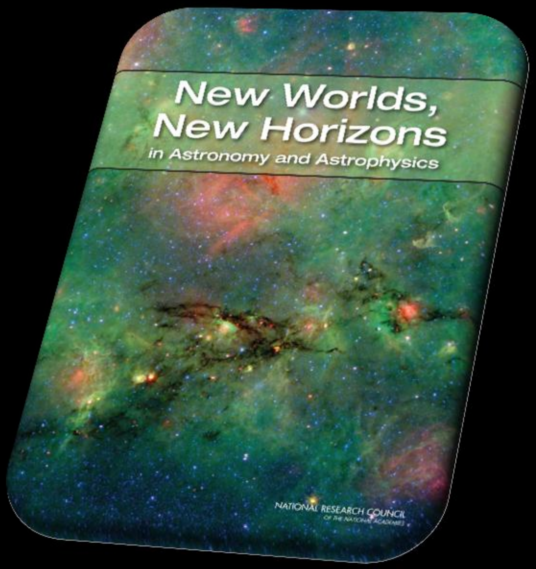
DARE will focus on determining or constraining *Turning Points* B, C, D



Adapted from Pritchard & Loeb, 2010, *Phys. Rev. D,* 82, 023006

Astro 2010 identifies Cosmic Dawn as a top science objective: Searching for the First Stars, Galaxies & Black Holes

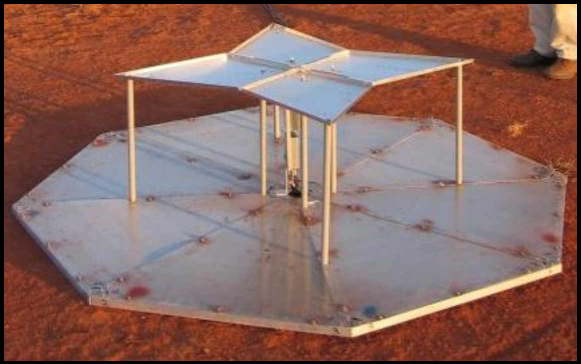
"A great mystery now confronts us: When and how did the first galaxies form out of cold clumps of hydrogen gas and start to shine—when was our cosmic dawn? Observations and calculations suggest that this phenomenon occurred when the universe was roughly half a billion years old, when light from the first stars was able to ionize the hydrogen gas in the universe from atoms into electrons and protons—a period known as the epoch of reionization… Astronomers must now search the sky for these infant galaxies and find out how they behaved and interacted with their surroundings." **=> *This is DARE's science!***

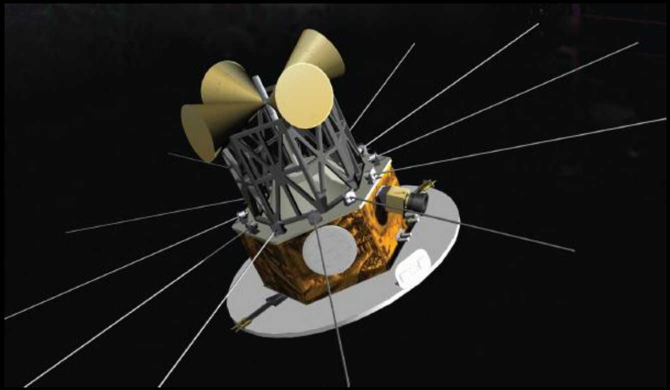


"What were the first objects to light up the Universe and when did they do?" We can uniquely address this mystery with DARE in lunar orbit (sky-averaged 21-cm spectrum) .

Lessons from EDGES

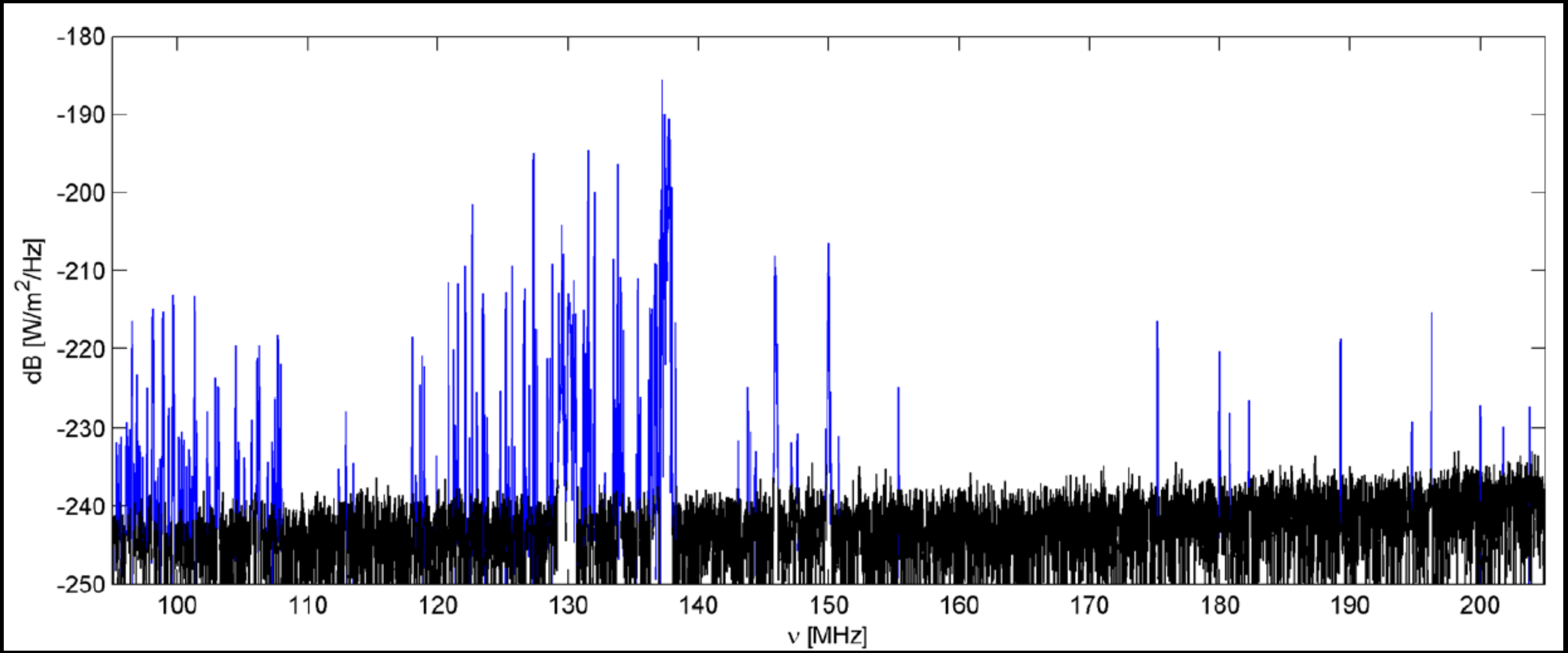
- $10^{9\text{-}10}$ dynamic range difficult because of RFI =>A/D converters need high bit-depths & be highly linear. Susceptible to internal clock stability errors & digital noise.
- Multipath reflections=> complex spectral interference.
- Complex environment makes transferring instrument response function from lab impossible.
- Ionosphere adds significant noise at <80 MHz.





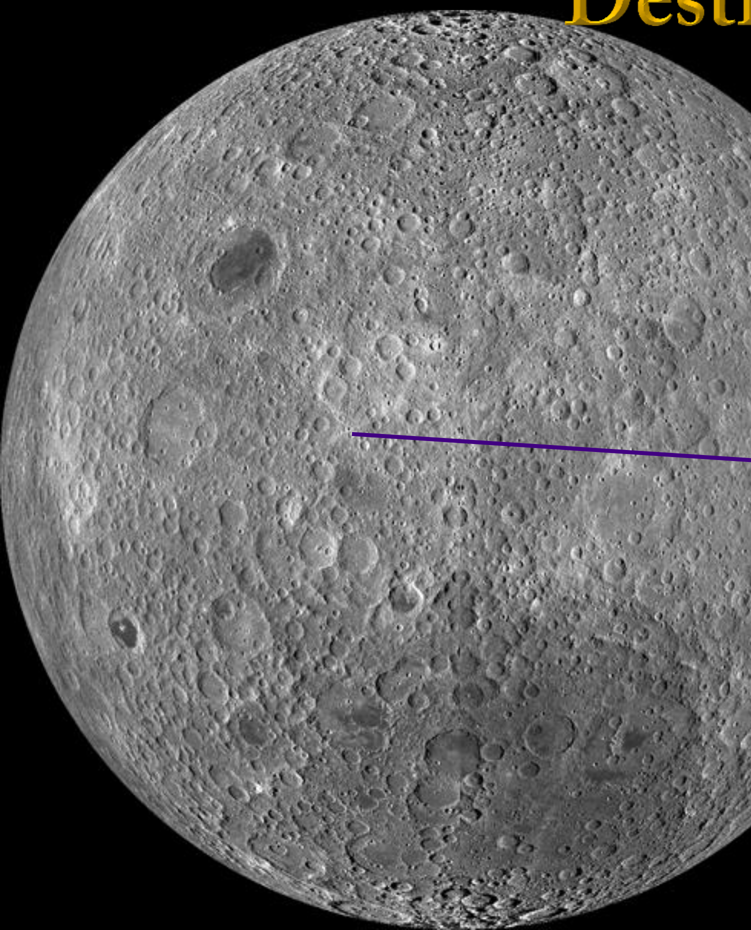
Analogous to why COBE went to space!

Radio Frequency Interference in Western Australia



Lunar Advantage: No Interference!

Destination: Moon



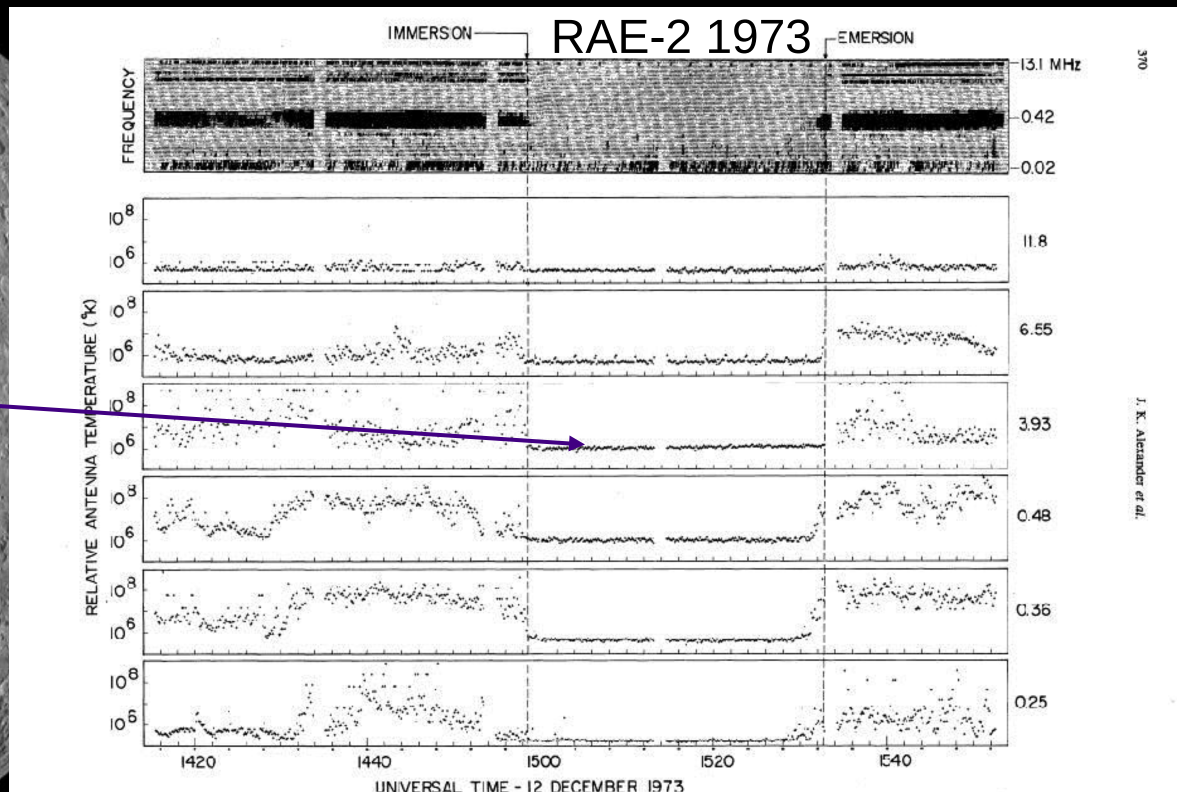
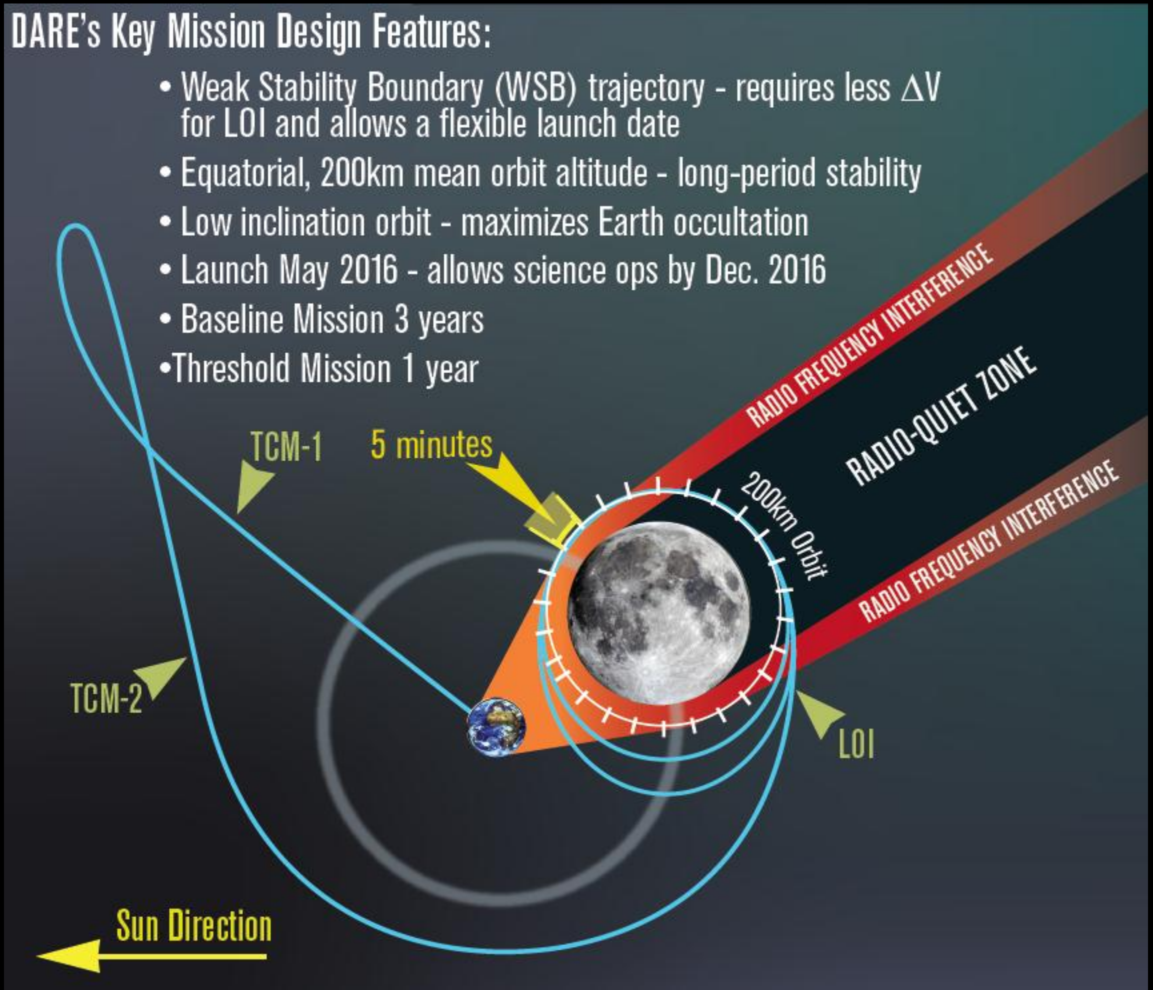


Fig. 5. Example of a lunar occultation of the Earth as observed with the upper-V burst receiver. The top frame is a computer-generated dynamic spectrum; the other plots display intensity vs. time variations at frequencies where terrestrial noise levels are often observed. The 80-s data gaps which occur every 20 m are at times when in-flight calibrations occur. The short noise pulses observed every 144 s at the highest frequencies during the occultation period are due to weak interference from the Ryle-Vonberg receiver local oscillator on occasions when both that receiver and the burst receiver are tuned to the same frequency

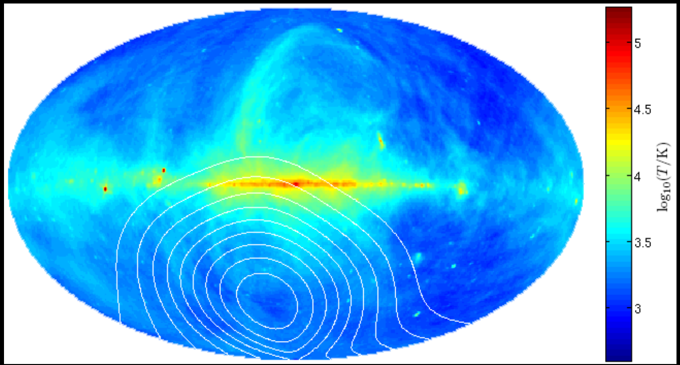
DARE's Biggest Challenge: *Foregrounds*

Highest foreground (RFI) eliminated by being above lunar farside!

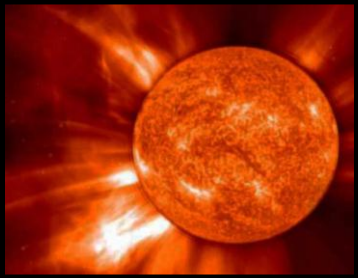


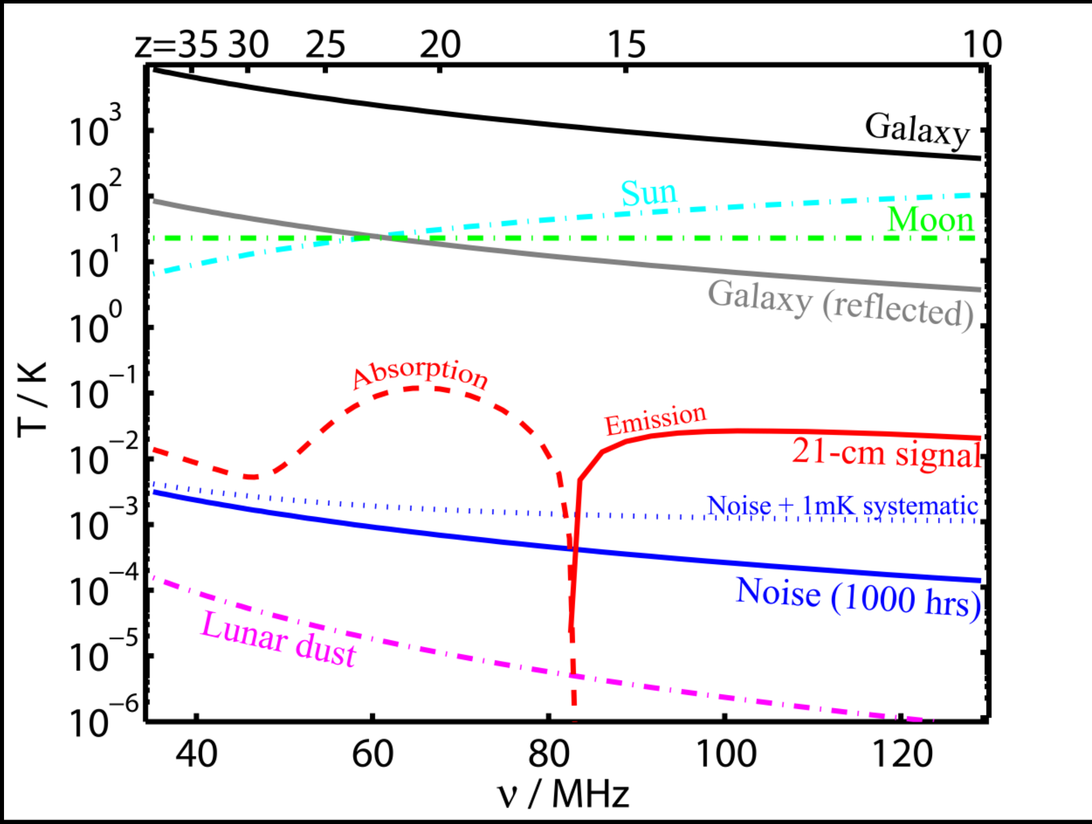
DARE's Biggest Challenge: *Foregrounds*

1) Milky Way synchrotron emission + "sea" of extragalactic sources.

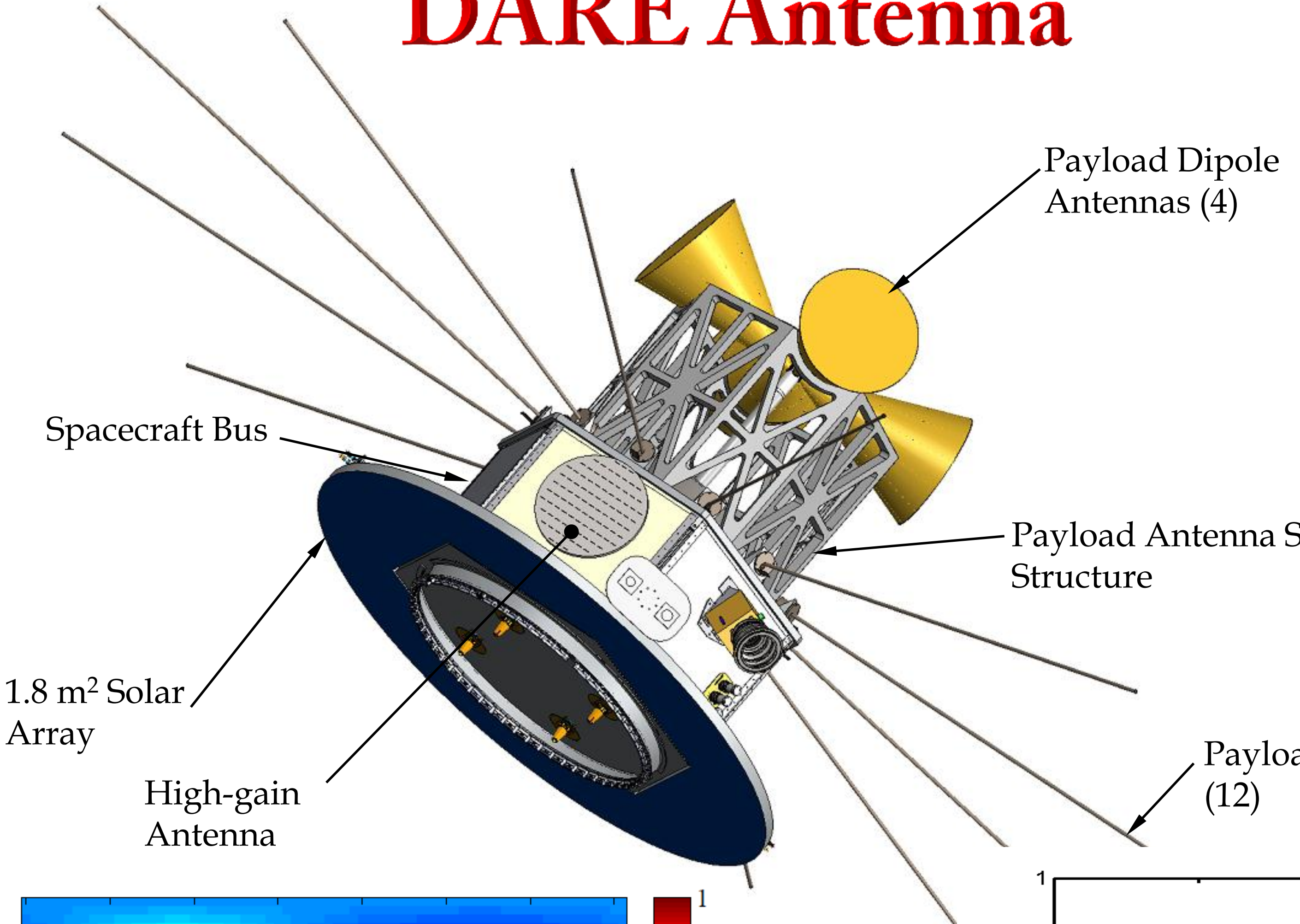


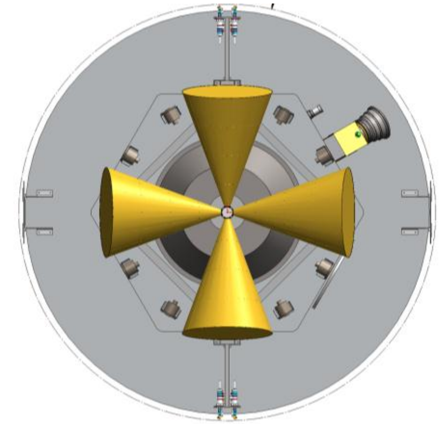
2) Solar system objects: Sun, Jupiter, Moon

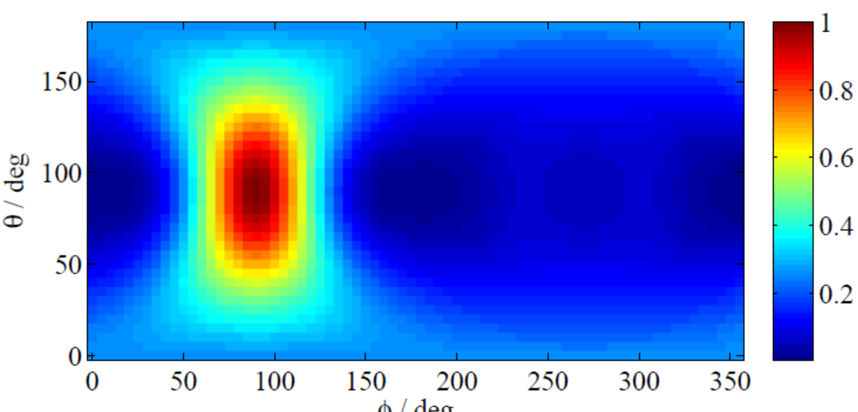


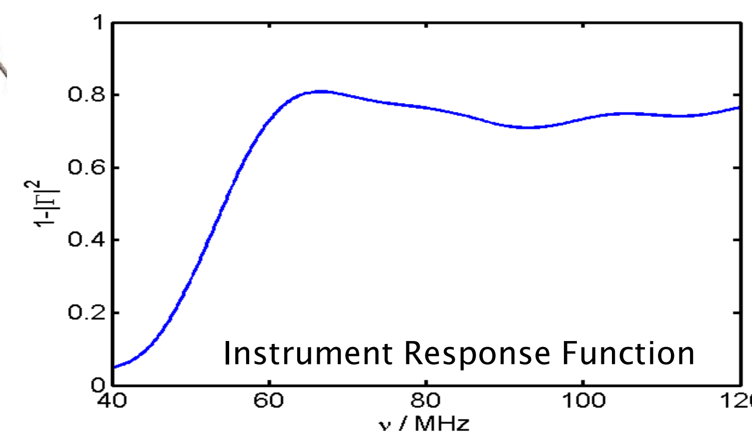


DARE Antenna









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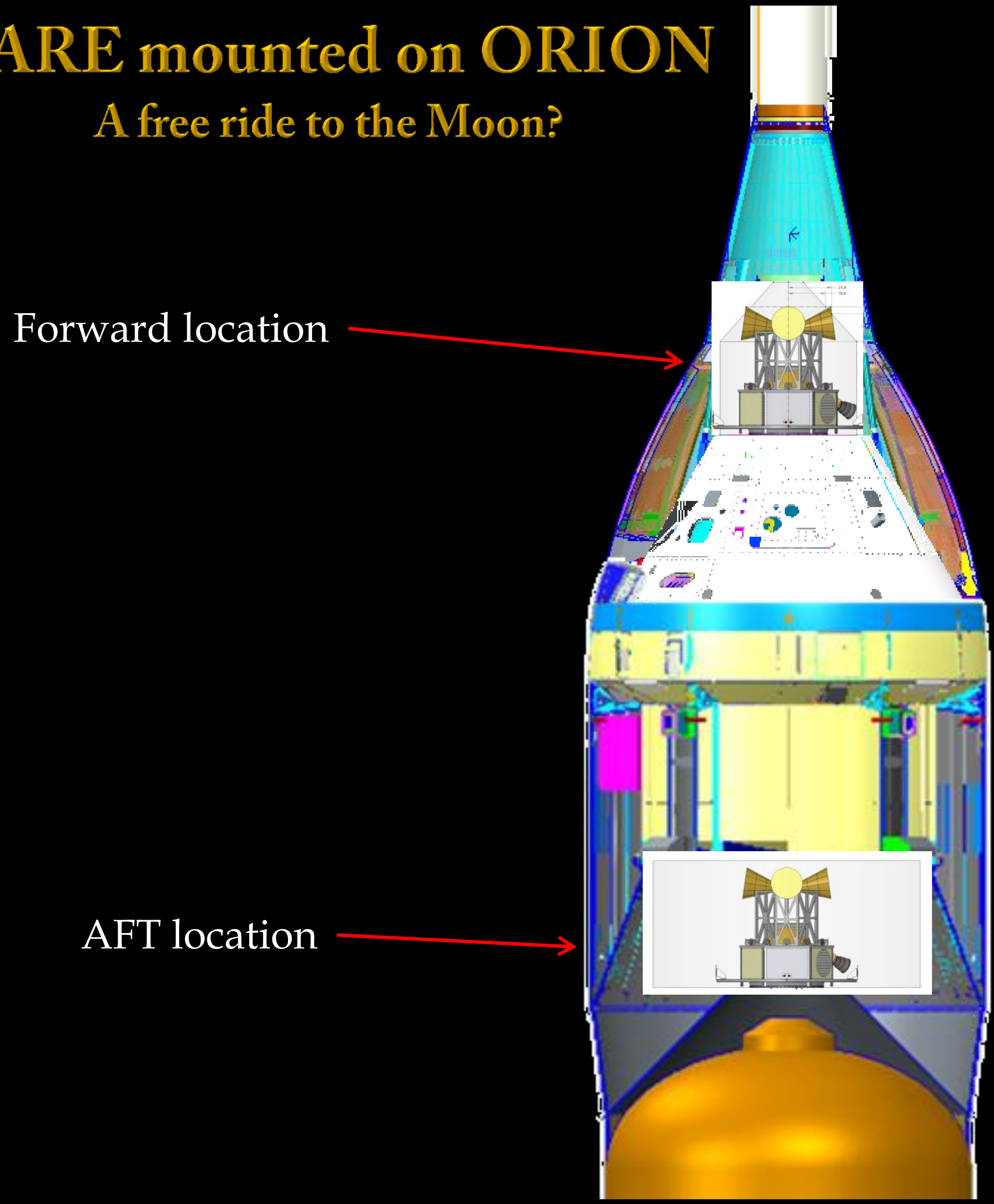
DARE mounted on ORION

A free ride to the Moon?



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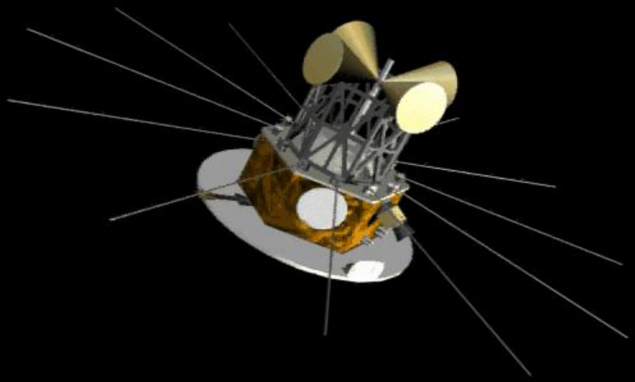
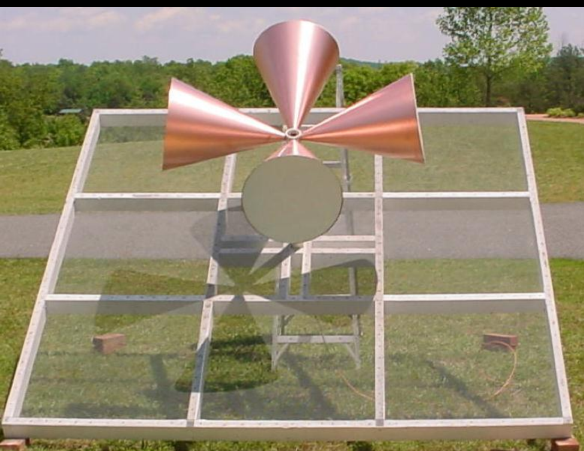
DARE Status & Timeline

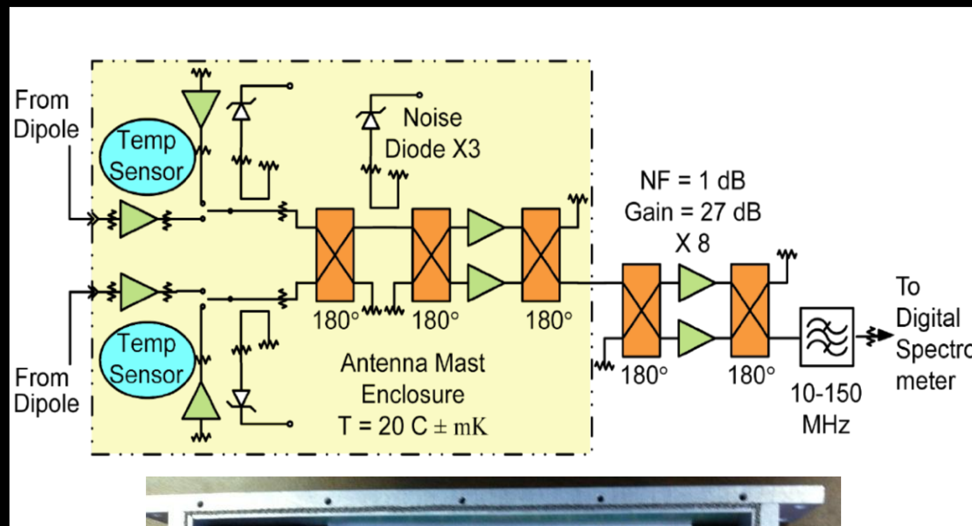
- DARE was proposed as a Explorer Mission in February, 2011.
- Mission was not accepted for Phase A study– but very high referee ratings.
- DARE Engineering prototype has been developed (NRAO and JPL).
- Instrument Verification Program includes the initial field tests in Green Bank, WV (Feb-Mar, 2012) as well as the DARE-ground experiment in Western Australia (Mar, 2012 onwards).
- Results from these experiments will be critical in re-proposing DARE for a SMEX mission in late 2013.



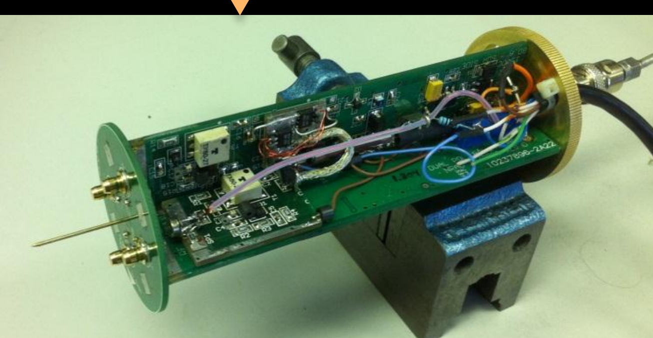
DARE Engineering Prototype: Components

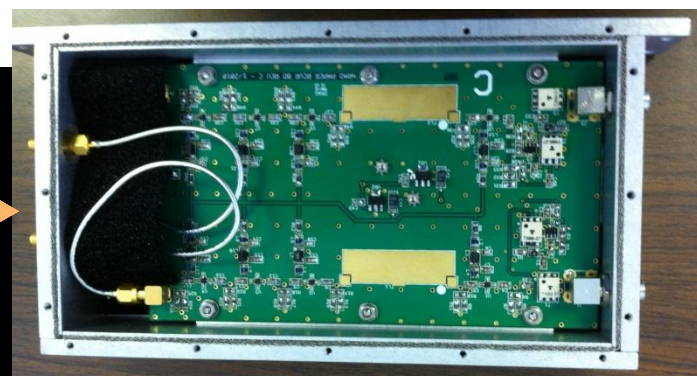
- DARE will operate at low radio frequencies between 40-120 MHz
- Components of all three subsystems (antenna, receiver and spectrometer) are at TRL ≥ 6
- Instrument Verification Program underway to have the integrated instrument at TRL 6





Antenna + BALUN (NRAO)



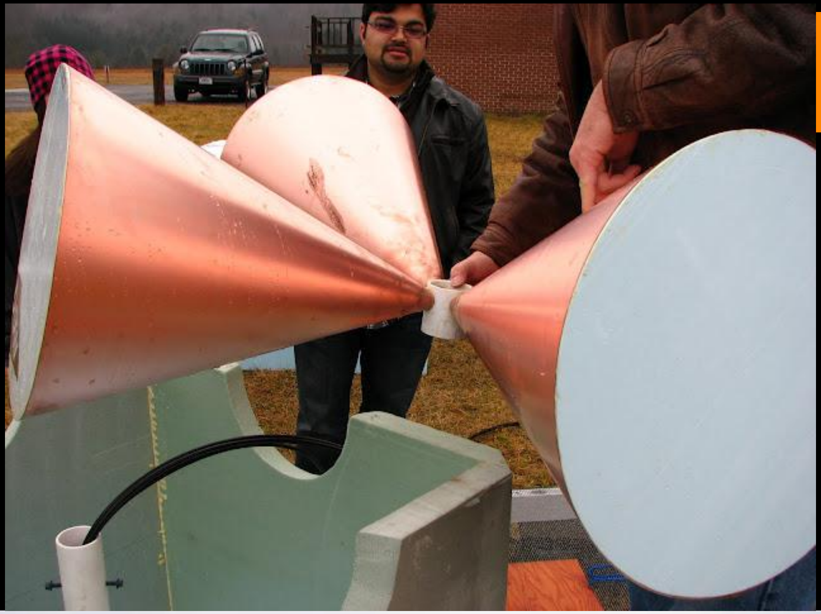


Front End Receiver (NRAO)

Digital Spectrometer (JPL)

Green Bank field tests

- DARE Engineering prototype was deployed at the NRAO site in Green Bank, WV.
- Recorded data for about 2 weeks.
- Initial field tests validated the performance of three stages of DARE instrument: antenna, front-end and digital spectrometer.



Initial Calibration

- $P_{OFF} = g(T_{Load} + T_{Rcvr})\,(1 + n_0)$
- $P_{ON} = g(\,T_{Ant} + T_{Rcvr})(1 + n_1)$

- Equating these two we get :

$$T_{Ant} = \frac{P_{ON}}{P_{OFF}}\,(T_{Load} + T_{Rcvr}) - T_{Rcvr}$$

- To the first order of approximations :

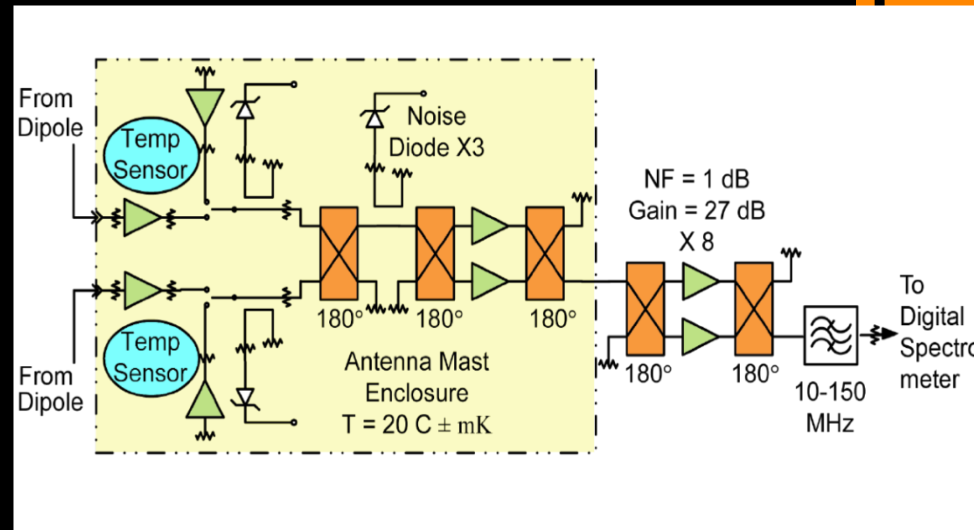
$$T_{sky} \sim {}^{T_{Ant}}/_{(1-\Gamma^2\,)}$$

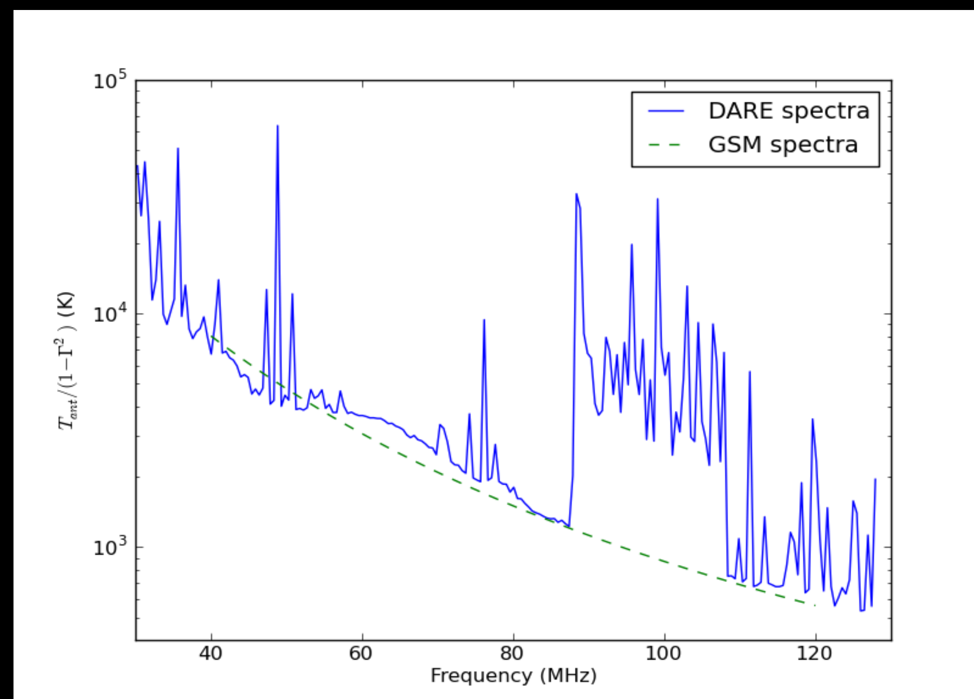
where Γ is the Reflection coefficient.

Calibrated spectra shows effects of :

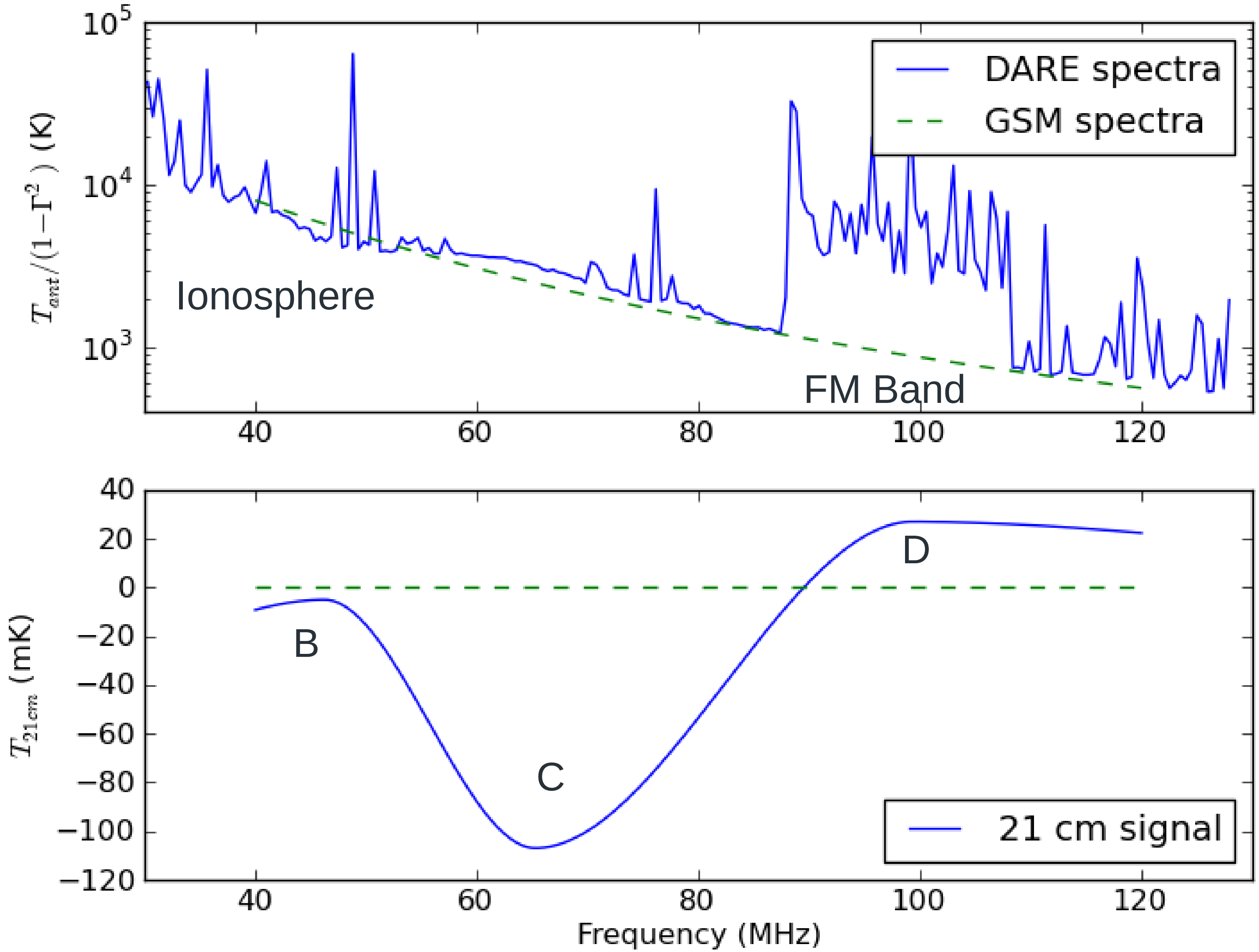
1) Radio Frequency Interference (RFI)
2) Earth's Ionosphere

These are two major challenges for ground based observations at these frequencies.





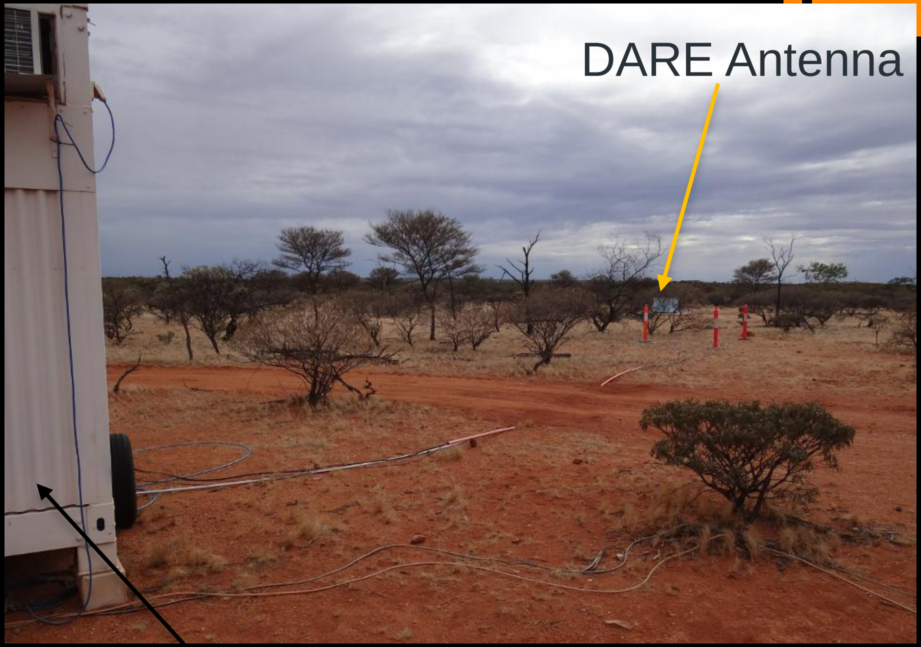
First Results



Galactic synchrotron spectral index ~ 2.7

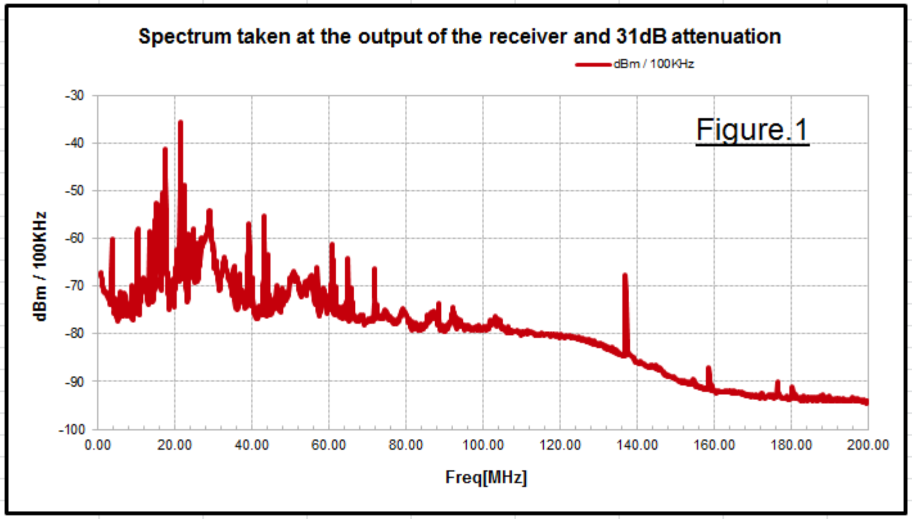
DARE-ground experiment in Western Australia

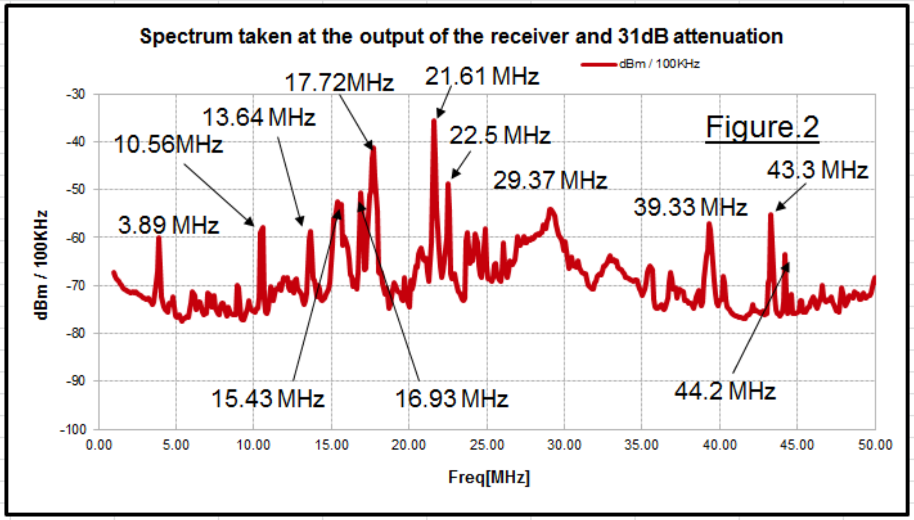
DARE Engineering prototype was deployed on March 21, 2012 at Murchison Radio Observatory (MRO).

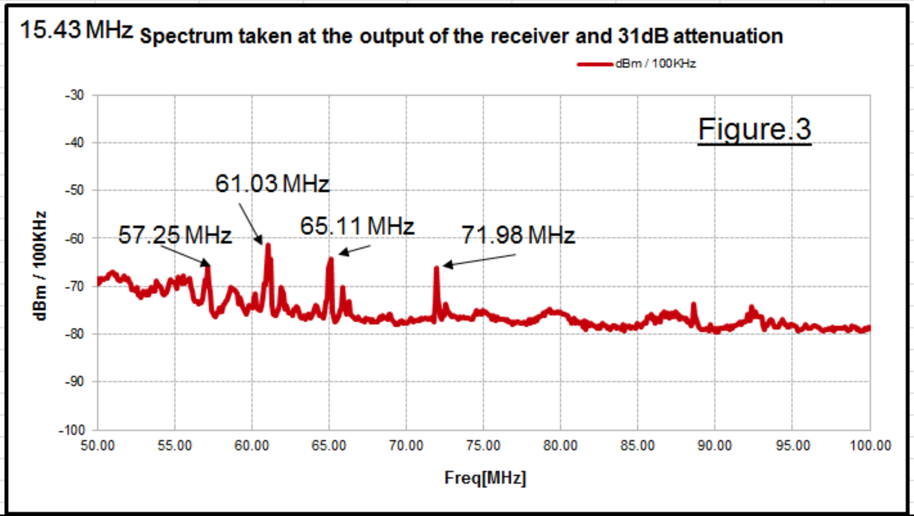


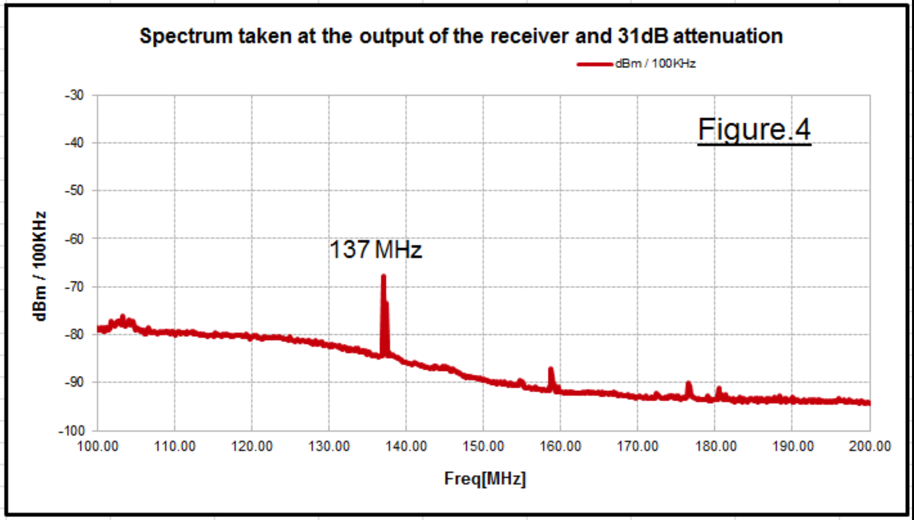
EDGS/DARE Instruments HUT

RFI environment at another Radio-Quiet Zone



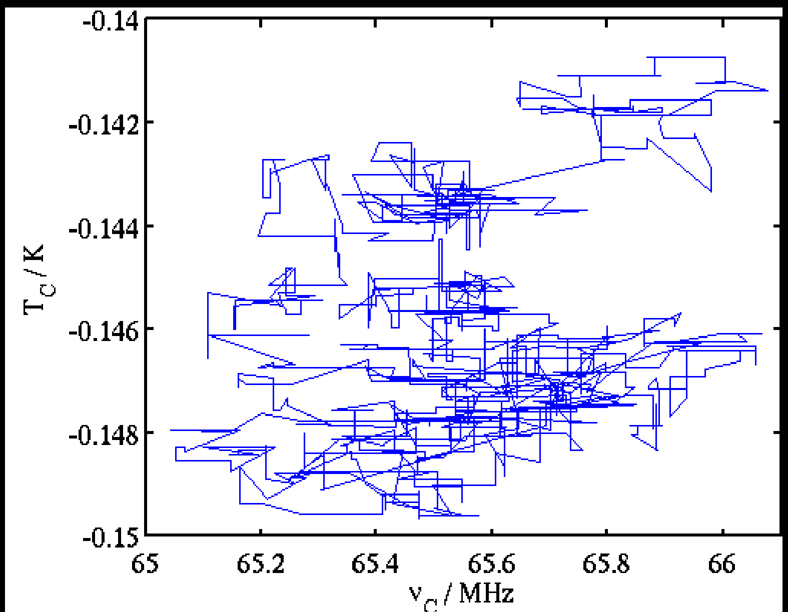


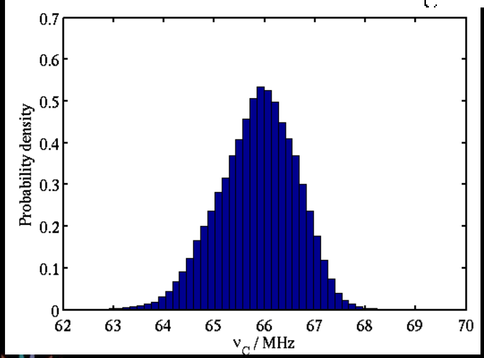




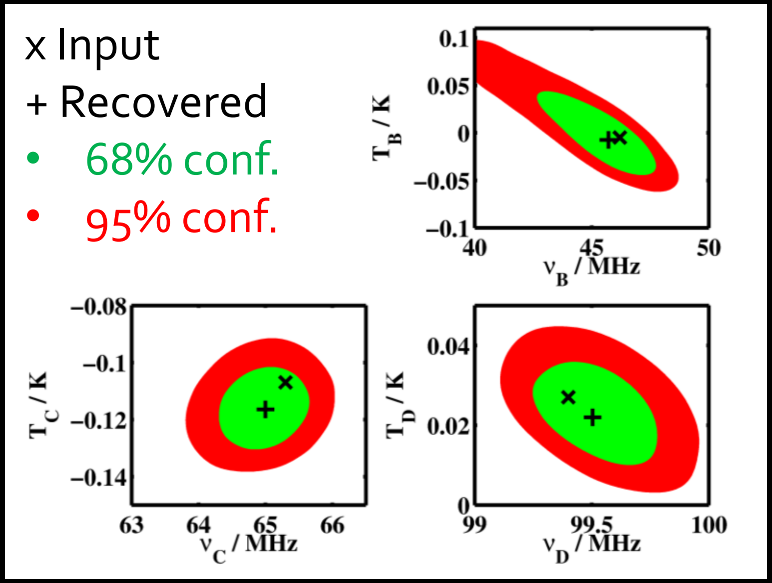
Strong RFI (@ 20 MHz) caused saturation of the receiver. Modified receiver has been installed.

MCMC approach to signal extraction for fiducial DARE mission

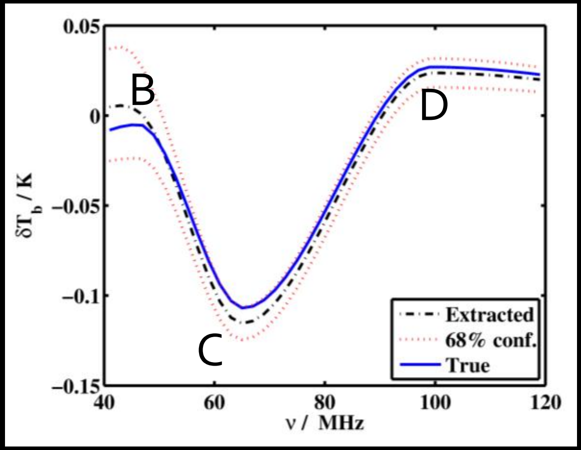




Random walk through parameter space
→ unbiased, random samples of the posterior probability distribution



Positions of turning points B, C and D



Shape of 21-cm signal

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For details see Harker et al. (2012), MNRAS, 419, 1070

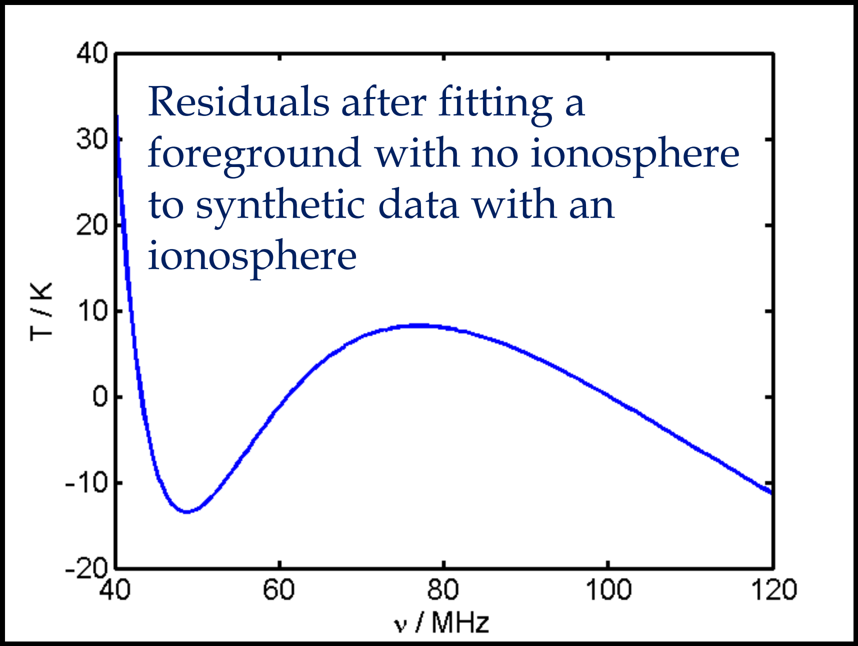
Modeling Earth's Ionosphere

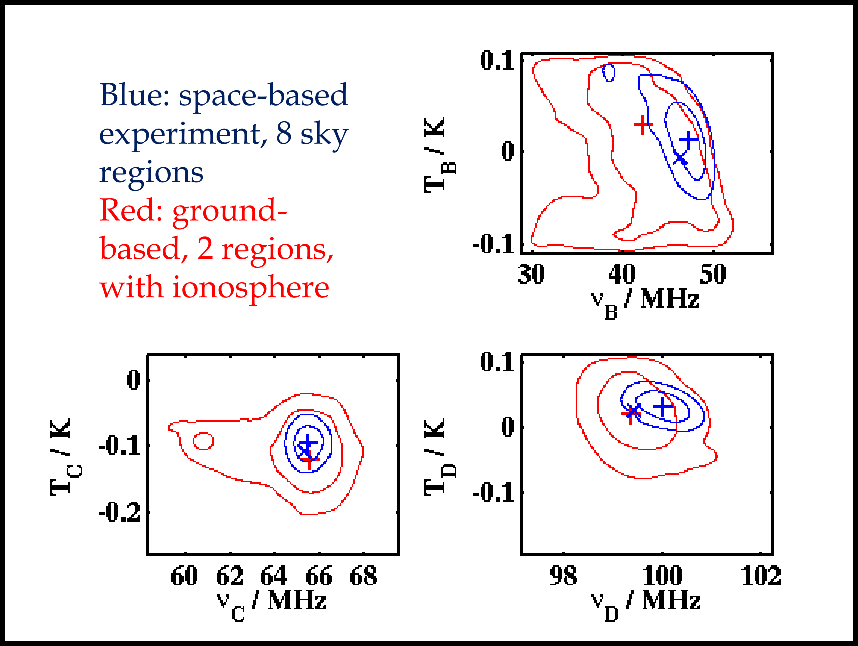
ionosphere produces a contribution to the spectrum scaling as (frequency)$^{-2}$

$$T_{with} = T_{without} - T_{without}(1-L)\left(\frac{\nu}{\nu_0}\right)^{-2} + T_{electrons}$$

Loss factor

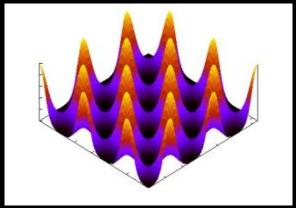
Electron temperature





Nested sampling

- We have adapted the likelihood computation used in the MCMC analysis to work with the public code MultiNest, which implements the ‘Nested Sampling’ algorithm for Bayesian inference.



Feroz, Hobson, Bridges, 2008/9

- Advantages
  - Flexible: works for complicated likelihood functions.
  - Allows us objectively to compare the evidence for different signal models given the data.
  - Well tested in applications in particle physics, cosmology (e.g. CMB) and lensing.
- Disadvantages
  - Not optimized for very high-dimensional parameter space.
  - Computationally intensive: has been compiled for, and is being tested on, the Janus supercomputing facility at the University of Colorado.

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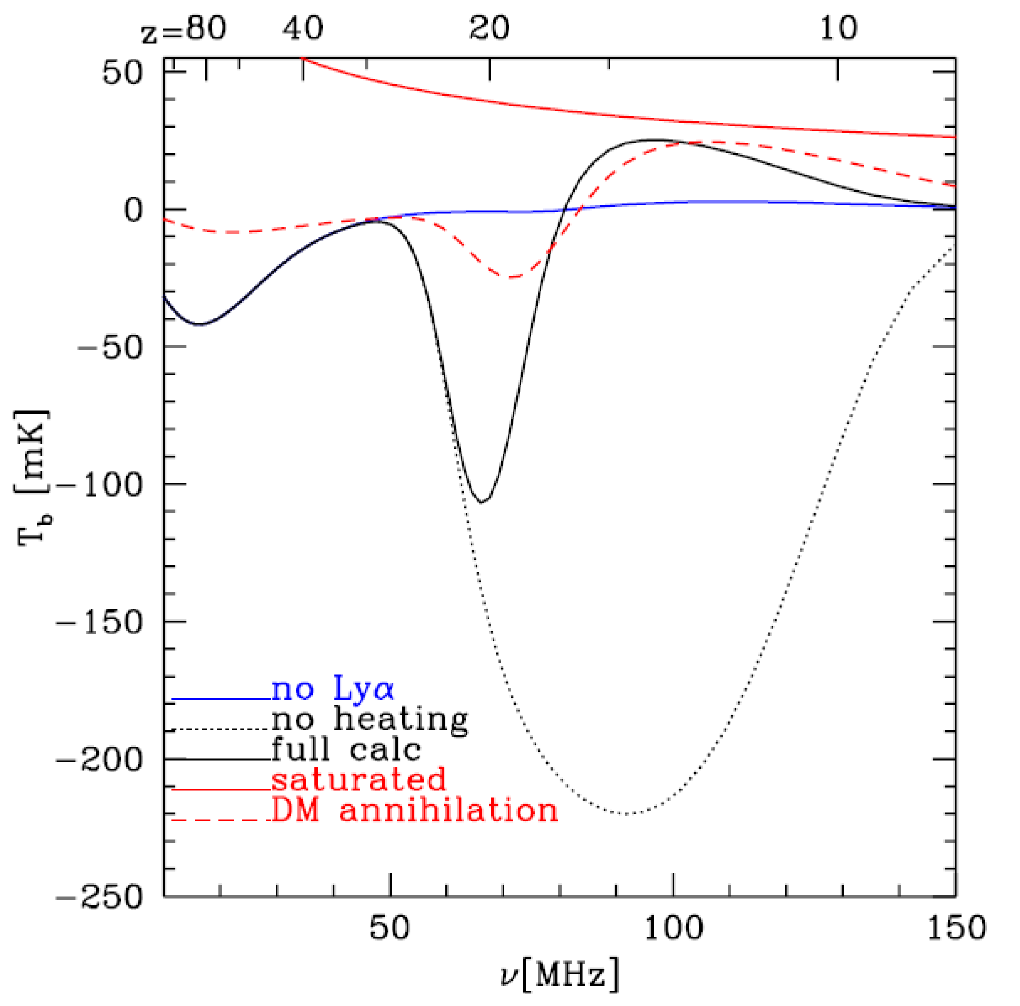
Future work: alternative signal models

- A wide range of values for the model parameters are allowed by current constraints.
- Alternative models (e.g. including decaying dark matter) may not be described very well by the turning points scheme.
- The nested sampling algorithm will allow us to test how well DARE can select between models with very different shapes.
- We are exploring alternative parametrizations.



Pritchard & Loeb (2010)

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Dark Ages Radio Explorer (DARE)

- DARE is designed to address:
  - When did the First Stars ignite?
  - When did the first accreting Black Holes turn on?
  - When did Reionization begin?
- DARE will accomplish this by:
  - Constructing first sky-averaged spectrum of redshifted 21-cm signal at $11<z<35$.
  - Flying spacecraft in lunar orbit & collecting data above lunar farside -- only proven radio-quiet zone in inner solar system.
  - Using biconical dipole antennas with smooth response function & Markov Chain Monte Carlo method to recover spectral *turning points* in the presence of bright foregrounds.
  - Using high heritage spacecraft bus (WISE) & technologies/techniques from EDGES.

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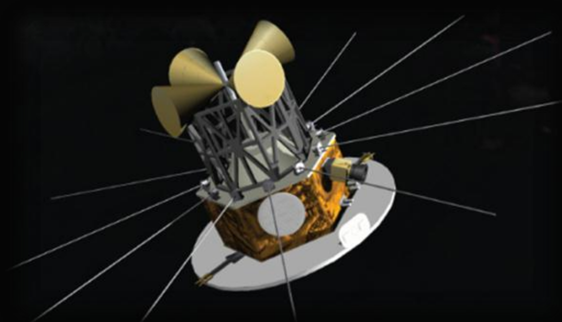

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See Burns *et al.*, 2012, *Advances in Space Research*, 49, 433.
http://lunar.colorado.edu/dare/