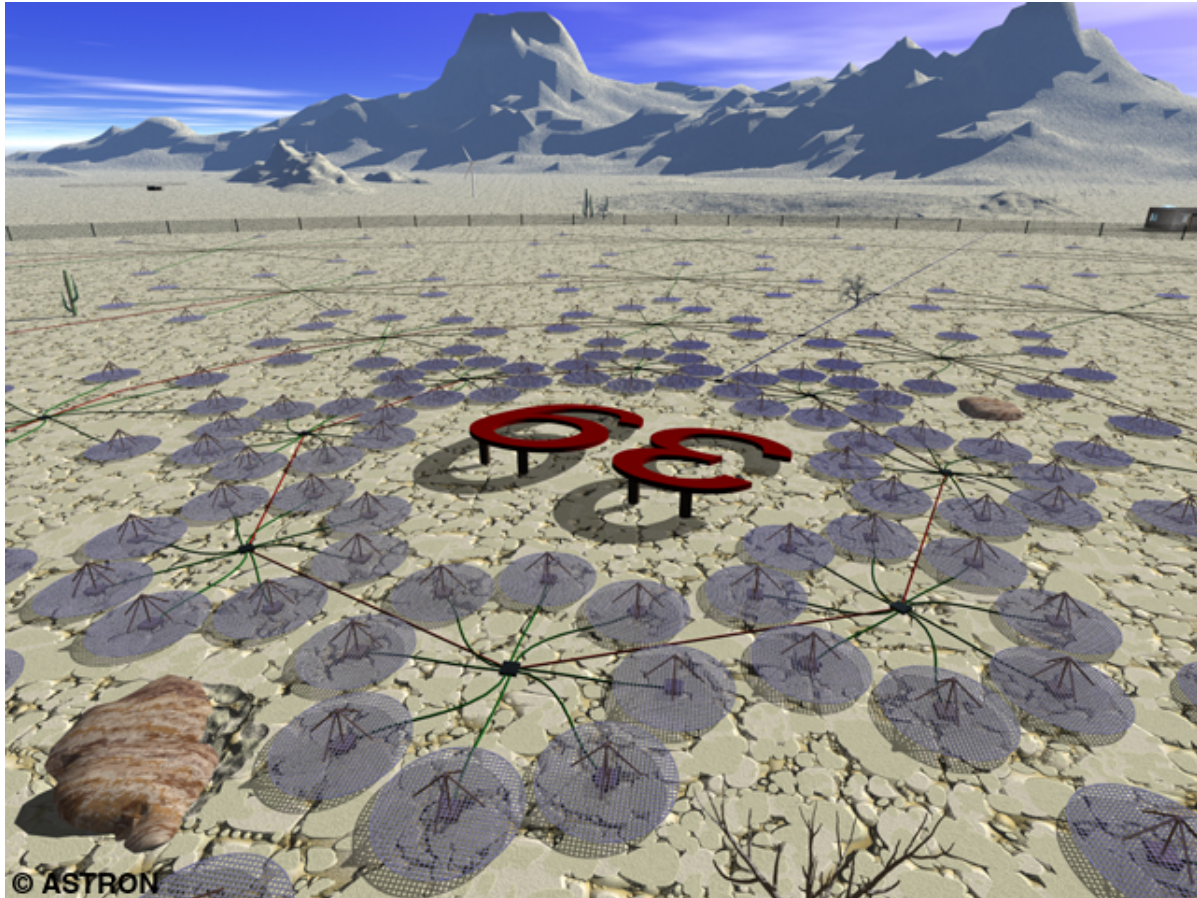


LOFAR

A LOw Frequency radio ARray

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Netherlands **F**oundation for **R**esearch in **A**stronomy



LOFAR BASICS

- 10 MHz to 250 MHz (excluding FM band)
 - Lower limit set by ionosphere
 - Upper limit set by cost, science needs
- Imaging instrument, interferometric aperture synthesis
- Extreme agility, flexibility (no moving parts)
 - Quasi-omnidirectional dipole antenna elements
 - Early digitization preserves all-sky information
 - Complete sky and frequency agility, digital beamforming
 - Sophisticated RFI mitigation techniques
 - Multibeaming, simultaneous multifrequency
- New regime of resolution, sensitivity
 - Can now meet computational challenges of calibration and imaging
 - High resolution circumvents confusion limits of the past

Schedule: 2001-2003 Development
2003-2005 Construction
2005-? Operation

THE ANTENNA ELEMENT

Figure 7. Impression of single polarisation LOFAR antenna element

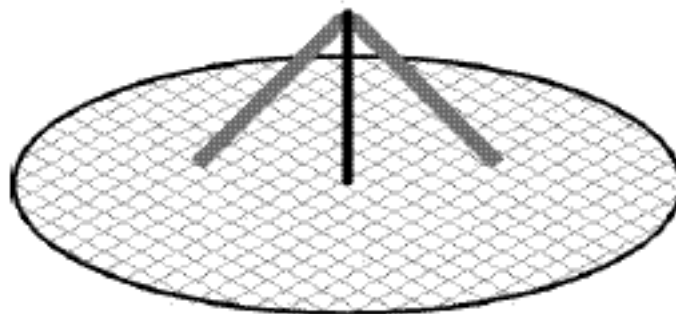


Figure 8. E-plane (linear scale)

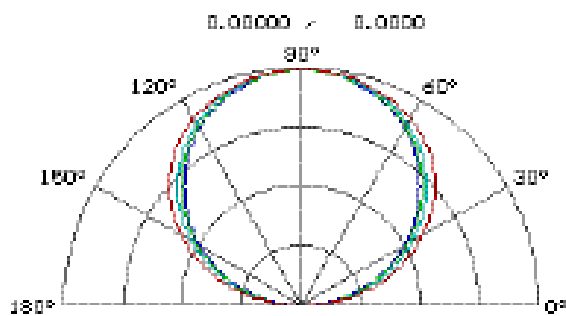
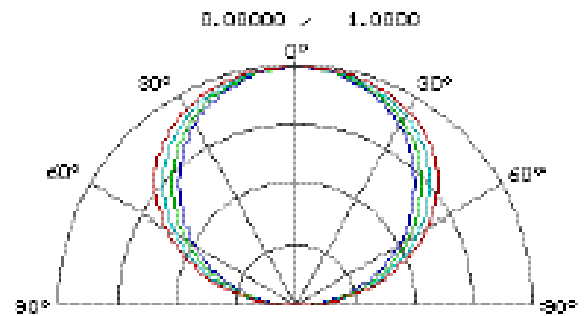


Figure 9. H-plane (linear scale)

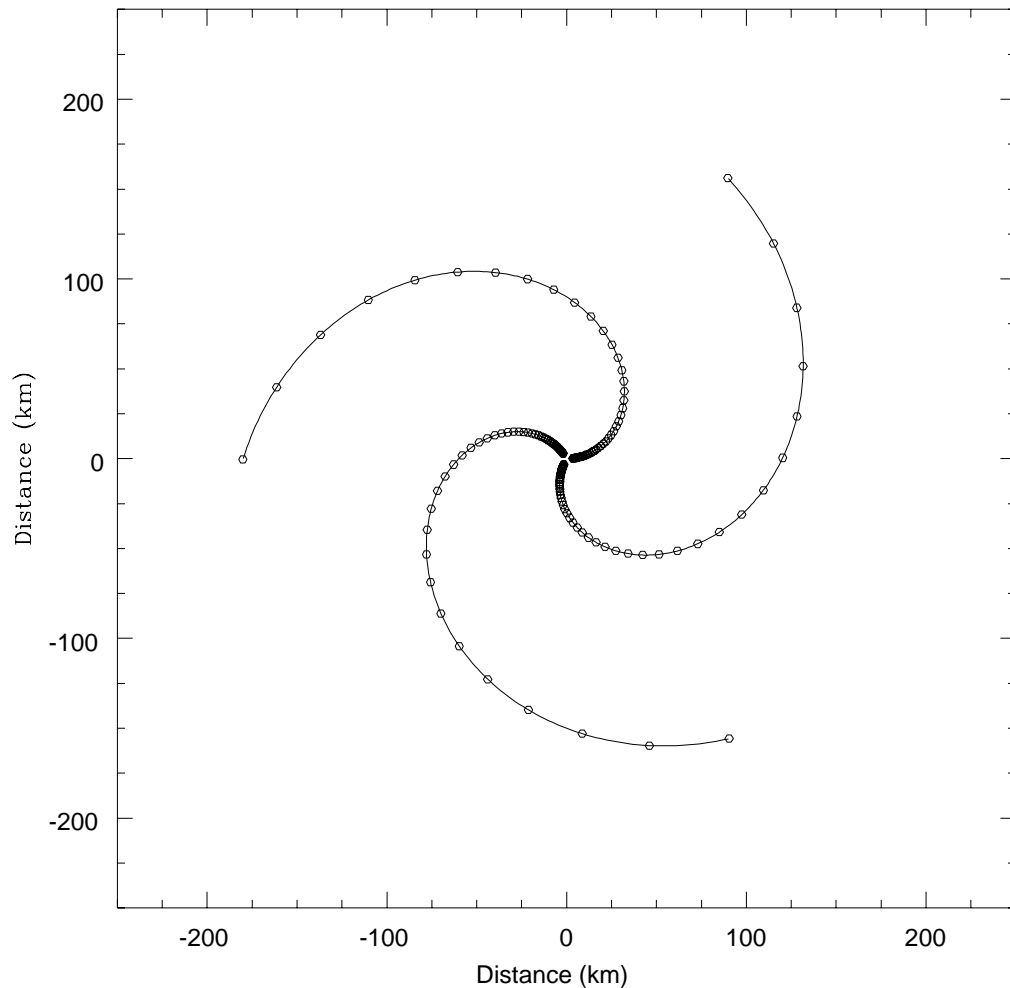


Beam patterns for frequencies of 10 MHz, 100 MHz, 150 MHz, and 200 MHz (Tan and Rohner 1999, SPIE Proceedings Astronomical Telescopes and Instrumentation 2000, Radio Telescopes, Volume 4015).

HIERARCHICAL BEAM FORMATION AND SYNTHESIS MAPPING: BASELINE DESIGN

- 9 receptors (crossed-dipoles) form a *cluster*
- 9 clusters form a *station*
- There will be a total of 13,365 receptors in up to 165 stations
- Each station is treated as a phased array and forms one or more beams on the sky; signal from each beam is sent to central processor
- Station diameter is 150 m, giving a station beam of about one degree at 100 MHz
- Within the station beams, correlation and synthesis imaging techniques give an image with resolution λ/B , B = maximum baseline.
- B = 400 km, giving resolution in images of 1.5" at 100 MHz
- For inner 2 km of array (25% of dipoles), all dipole signals brought to central processor. Imaging without beam forming (i.e., imaging of entire dipole field of view) for these signals may be possible
- Example data rate from remote station: 8 beams * 2 polarizations * 4 MHz * 2 * 4 bits = 64 Mbyte/s

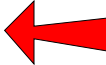
A POSSIBLE CONFIGURATION OF STATIONS



Standard imaging: after delay compensation, correlation, and integration, each baseline (station pair) gives us a measurement of one component of the two-dimensional spatial Fourier transform. Inversion of the Fourier transform yields an image.

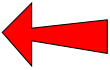
Other processing techniques may be implemented; for example, for transient searches and pulsar studies.

PRIMARY SCIENTIFIC DRIVERS

- The High-Redshift Universe
- The Epoch of Reionization
- Cosmic Rays
- The Bursting and Transient Universe 
- Solar Terrestrial Relationships

The Bursting and Transient Universe

For the **first time** radio astronomers will be able to use a large telescope to survey a large fraction of the sky for bursting and transient sources. For the **first time** the ability to recognize and eliminate radio frequency interference will be an integral part of the design of the telescope. For the **first time** rapid electronic pointing of a large radio telescope will allow prompt (within seconds) sensitive observation of sources identified with other instruments. This makes possible:

- An unbiased wide-field survey of the sky for transients
 - Great discovery potential
- Targeted surveys of hosts
 - Giant pulses from pulsars
 - Bursts from Jupiter-like planets around other stars
 - Radio supernovae
 - Flare stars
- Triggered events
 - Gamma-ray bursts - afterglows
 - Microquasars (associated with X-ray transients)
 - Radio supernovae
 - Gamma-ray bursts - prompt emission (not known to exist, but may)
 - Radio bursts from LIGO events (not known to exist, but may) 

Burst Detection Considerations

Baseline design - flux density sensitivity in 10 seconds of integration ($\nu = 100$ MHz):

$$S_{10\sigma} \sim 3 \times 10^{-28} \text{ Watt/Hz m}^2$$

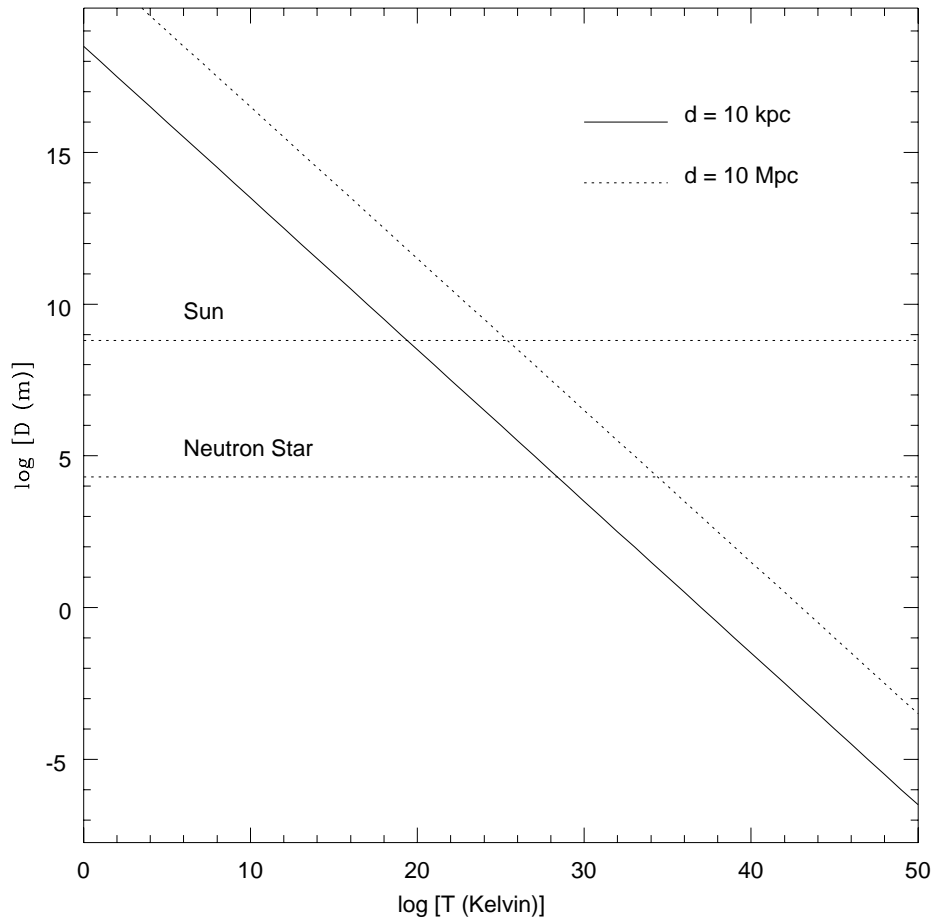
Relationship to brightness temperature, T , and source diameter, D :

$$S = \frac{2kT}{\lambda^2} \left(\frac{D}{d}\right)^2$$

where d is the source distance.

For $\nu = 100$ MHz

$$D = \left(\frac{d}{10 \text{ kpc}}\right) 3.0 \times 10^{18} T^{-1/2}$$



Burst Detection Considerations (con.)

For 10-second burst, brightness temperatures of $\sim 10^{30}$ K or more are needed. Some possible mechanisms:

- Electron-cyclotron maser
- Plasma radiation
- Curvature radiation
- Cyclotron-Cerenkov radiation

Existence Proof: giant pulses in the Crab pulsar (Lundgren et al. 1995, ApJ, 453, 433):

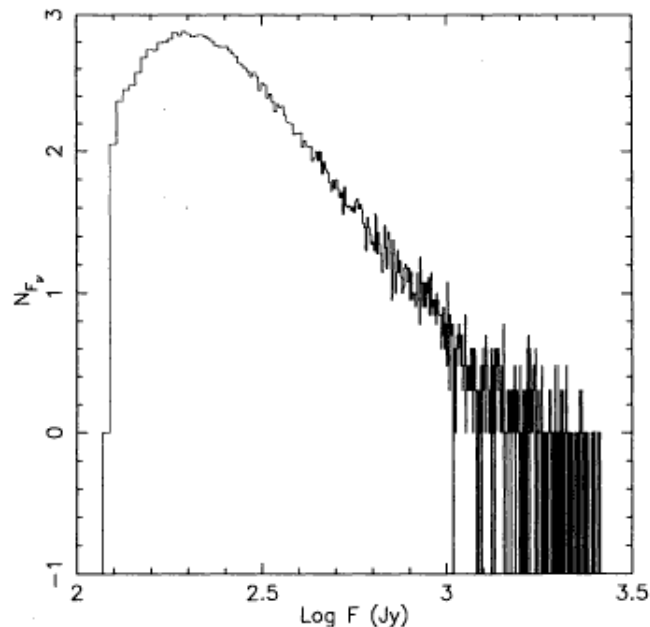


FIG. 4.—Distribution of giant-pulse flux densities is displayed in a log-log plot. The average flux density of 2 Jy is off the scale of the plot. Each bin contains the total number of pulses observed within the corresponding 5 Jy flux-density range.

The brightest of these individual 1.5-msec pulses imply a brightness temperature of $10^{30}/f$ K, where f is the fraction of the surface of the neutron star covered by the source.

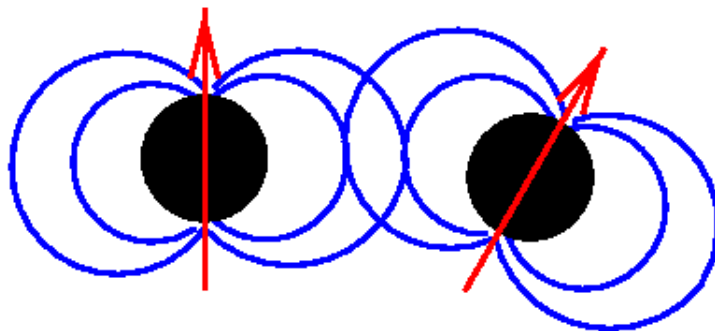
Inspiral Detection Considerations

Model of Hansen and Lyutikov (2000):

NS-NS binary is modeled as a conducting sphere (one neutron star) moving through an external magnetic field (due to other neutron star). For an observing frequency of 400 MHz they find:

$$S \approx 2.1 \text{ mJy} \frac{\epsilon}{0.1} \left(\frac{d}{100 \text{ Mpc}} \right)^{-2} B_{15}^{2/3} a_7^{-5/2}$$

where ϵ is the efficiency of conversion of particle energy to radio emission, d is the distance, B_{15} is the magnetic field in units of 10^{15} G , and a_7 is the semi-major axis in units of 10^7 cm . For pulsars, values of $\epsilon = 0.1$ have been inferred.



Integrating for the duration of an inspiral event may make this detectable. For example, integrating for ten minutes at 100 MHz would make give a 10σ detection for $d \leq 44 \text{ Mpc}$ (but VERY UNCERTAIN).

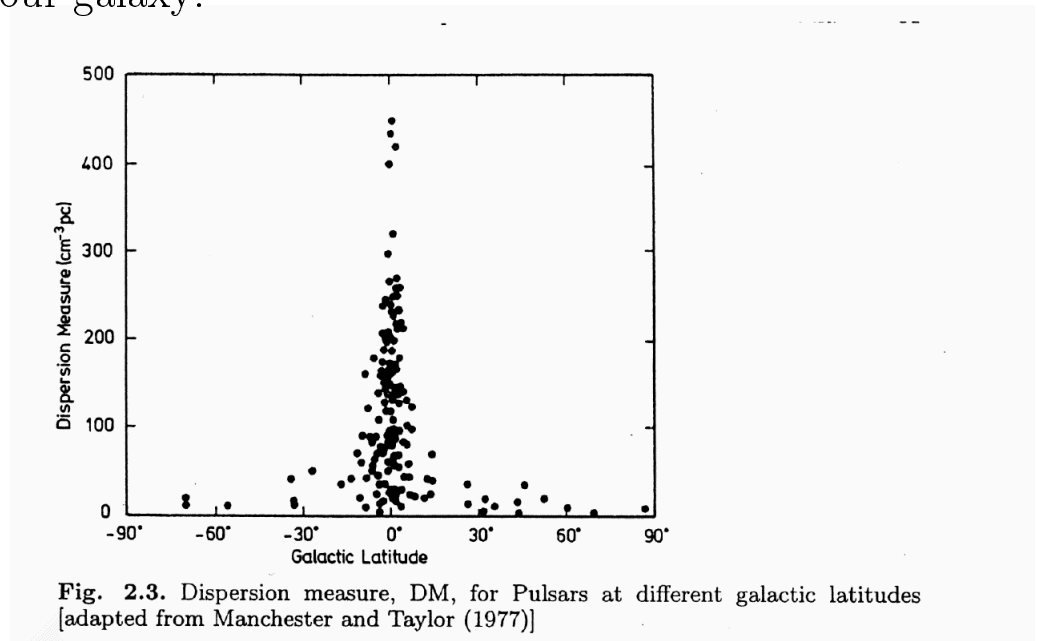
THE PLASMA DELAY

$$\Delta\tau = \frac{e^2}{2\pi cm_e} \left(\frac{1}{\nu_1^2} - \frac{1}{\nu_2^2} \right) \int_0^d n_e(\ell) d\ell$$

It is convenient to define the “dispersion measure,” DM:

$$\text{DM} = \int_0^d \left(\frac{n_e}{\text{cm}^{-3}} \right) d \left(\frac{\ell}{\text{pc}} \right)$$

Dispersion in our galaxy:



For $\text{DM} = 30 \text{ cm}^{-3} \text{ pc}$ and 10 MHz, plasma delay is **~ 1200 seconds**

- Radio emission may very well occur *before* (at the source) the gravitational wave emission.
- LOFAR may be able to buffer data and form beam after delay (but this is expensive).
- Differential delay across 4 MHz band centered at 10 MHz is ~ 1000 seconds.

POSSIBLE CONNECTIONS TO LIGO

- Comparison of LOFAR and LIGO records of transients
 - Bursts, chirped periodic signals, other?
 - Coincidence would strengthen case for astronomical event
 - Probably will be limited by computation costs/capabilities
- LOFAR observations triggered by LIGO
 - Would allow the full sensitivity of the LOFAR array (i.e., *all* the dipoles forming the beam)
 - Would allow a more thorough search of the data taken at the time of the event
 - Would provide a template waveform for the LOFAR search
- LIGO searches triggered by LOFAR?
 - Maybe - we need to see what we find