Making Diagnostic Interferometry Possible: The Need for Data Processing on Spacecraft of the Next Millenium.

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Abstract

There is a growing understanding that missions involving multiple spacecraft are becoming critical for the advance of Space Science. Yet multispacecraft missions present serious technical challenges, space-to-ground communication is a critical bottleneck. Space Science missions probe a rich and complicated environment; current instrumentation is capable of producing more information than we can downlink to Earth. When increases in instrument information productivity, the number of spacecraft, and the number of space missions are multiplied to obtain the future demand on communication resources, we see a problem. Current methods of information extraction from spacecraft sensor data will not scale for the multispacecraft systems that are necessary for the advance of Space Science. Still, important, raw sensor data *must* be transmitted to Earth for analysis.

A possible solution to these competing needs is to carefully select what data is transmitted to Earth. For many missions, this has meant reducing the mission scope, limiting sensor capability, and limiting the time during which data is taken. However, these circumstances render many worthwhile missions infeasible, particularly those using interferometry to examine the Space Environment. With sufficient on-board computational and memory resources, data can be manipulated in place onboard the spacecraft, with some reductions, results, or synopses of the data being transmitted to Earth. In this work, we examine the data processing needs of an exceptionally demanding application, an orbiting *Radio Interferometric Array*, that is being developed for the *REE Flight Processor*.

The *REE Flight Processor* is a spaceworthy scalable parallel computer being developed by NASA's High Performance Computing and Communication Program's Remote Exploration and Experimentation (REE) Project. The REE Project seeks to capitalize on commercial supercomputing technology to create an economical, robust, fault-tolerant processor with exceptionally small mass and power requirements. We will explore the implications of this new technology for such fundamentally important diagnostic tools as wave interferometry.

Low Frequency Radio: A New Window 1

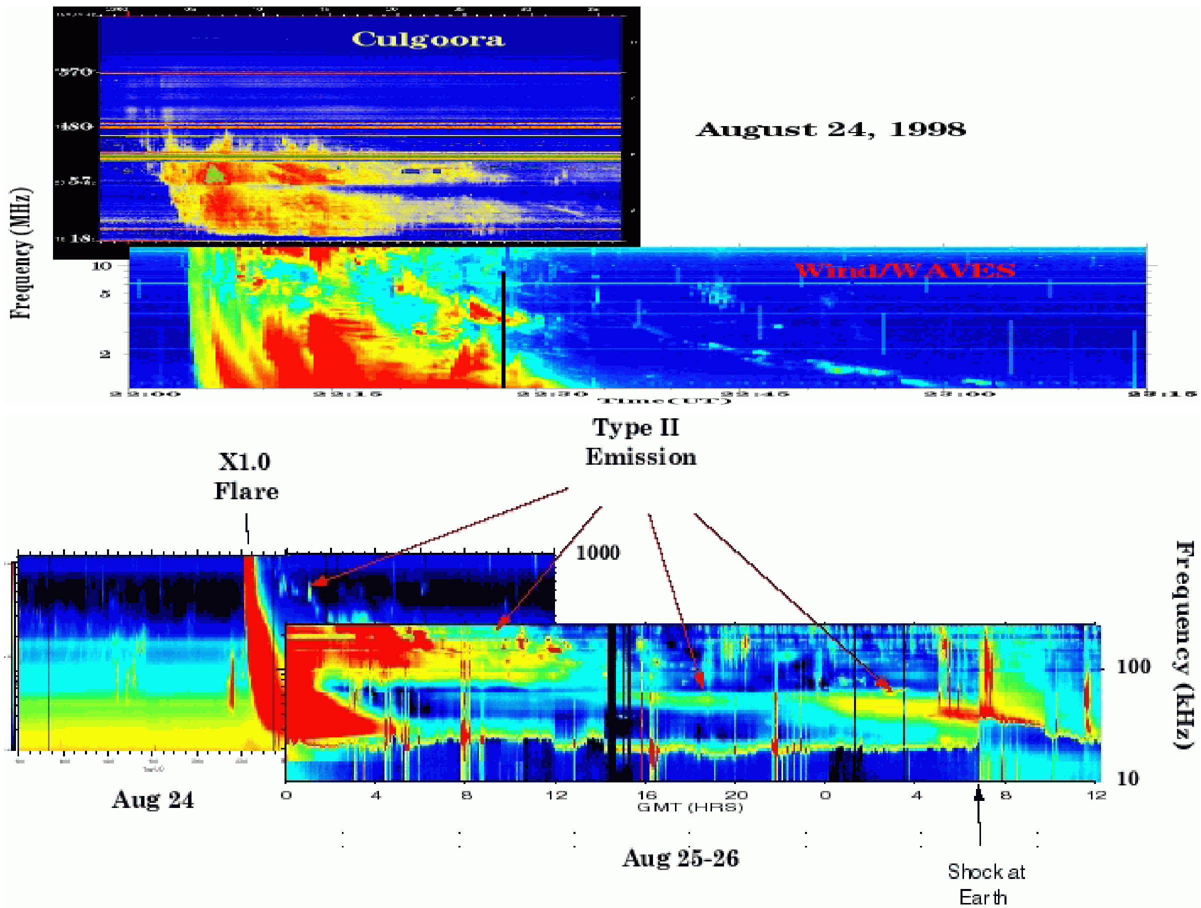
The Earth's ionosphere makes impossible ground based radio imaging at frequencies below 30 MHz. However, many Solar-Terrestrial phenomena have been detected with the WIND/WAVES instrument.

- Solar bursts and particle streams
- Solar wind structure
- Coronal Mass Ejections
- Interplanetary shocks & clouds
- Magnetospheric and auroral dynamics

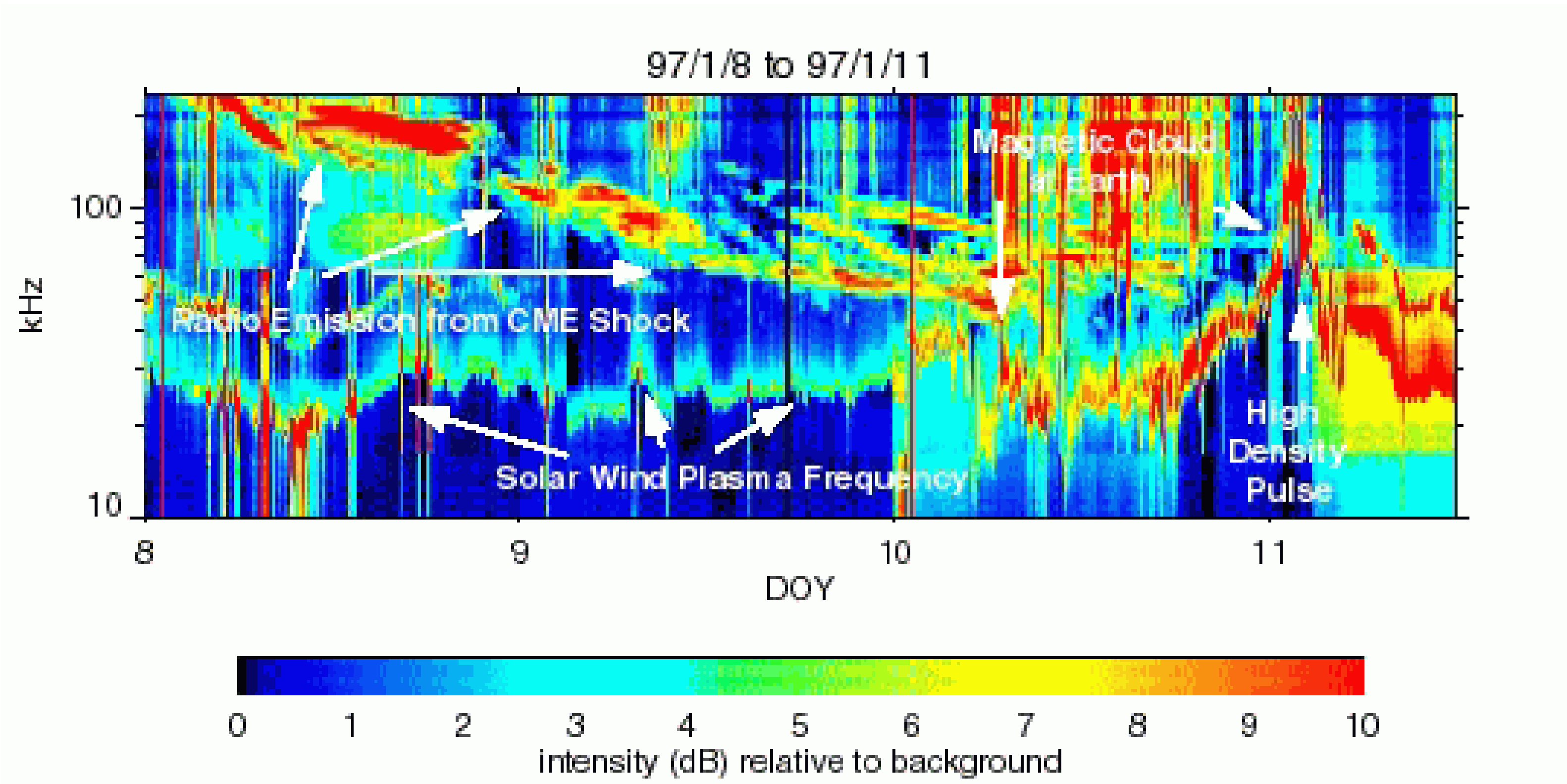
No imaging capability exists at these low frequencies, even though these low frequencies are intrinsically tied to the fundamental plasma physics that governs these phenomena's behavior.

Low Frequency Radio: A New Window 2

Visible from Earth. Visible from Space.



An Information Rich Environment



WIND/WAVES Observations of the Solar-Terrestrial Environment.

A Conceptual Model

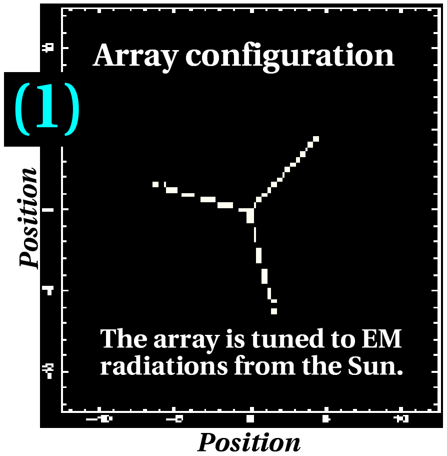
As part of NASA's Remote Exploration and Experimentation (REE) Program and the Solar-Terrestrial Probe Line, we have developed a computer model to examine the algorithmic and computational requirements of low frequency radio observatories. In this work we concentrate on the *Solar Imaging Radio Array*. A related concept is the *Astronomical Low Frequency Array*.

Our current models are simple, and do not as yet include many important effects, e.g. noise, doppler drift, non-planarity, etc.

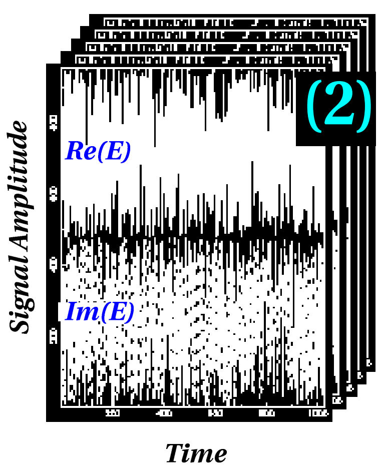
REE Solar Terrestrial Probe Science Application

Solar Imaging Radio Array/ALFA

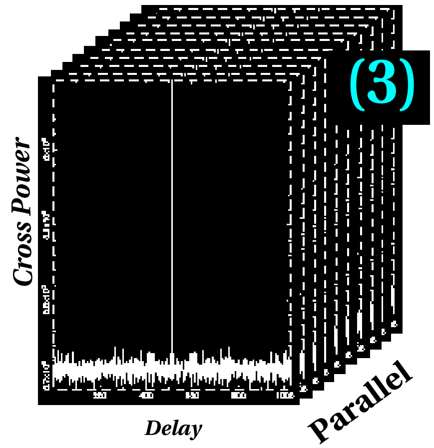
The numbers 1–5 correspond to the flow of the data through the system.



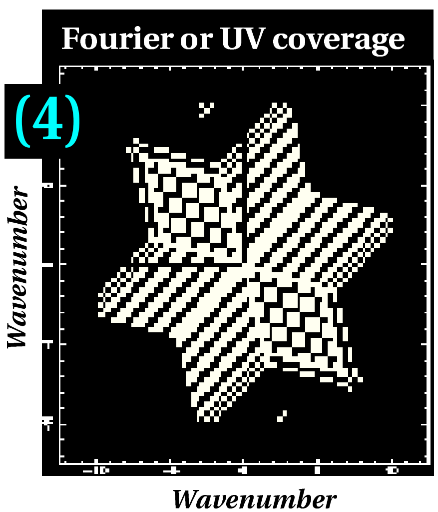
The signals have the main frequency removed and are then sampled.

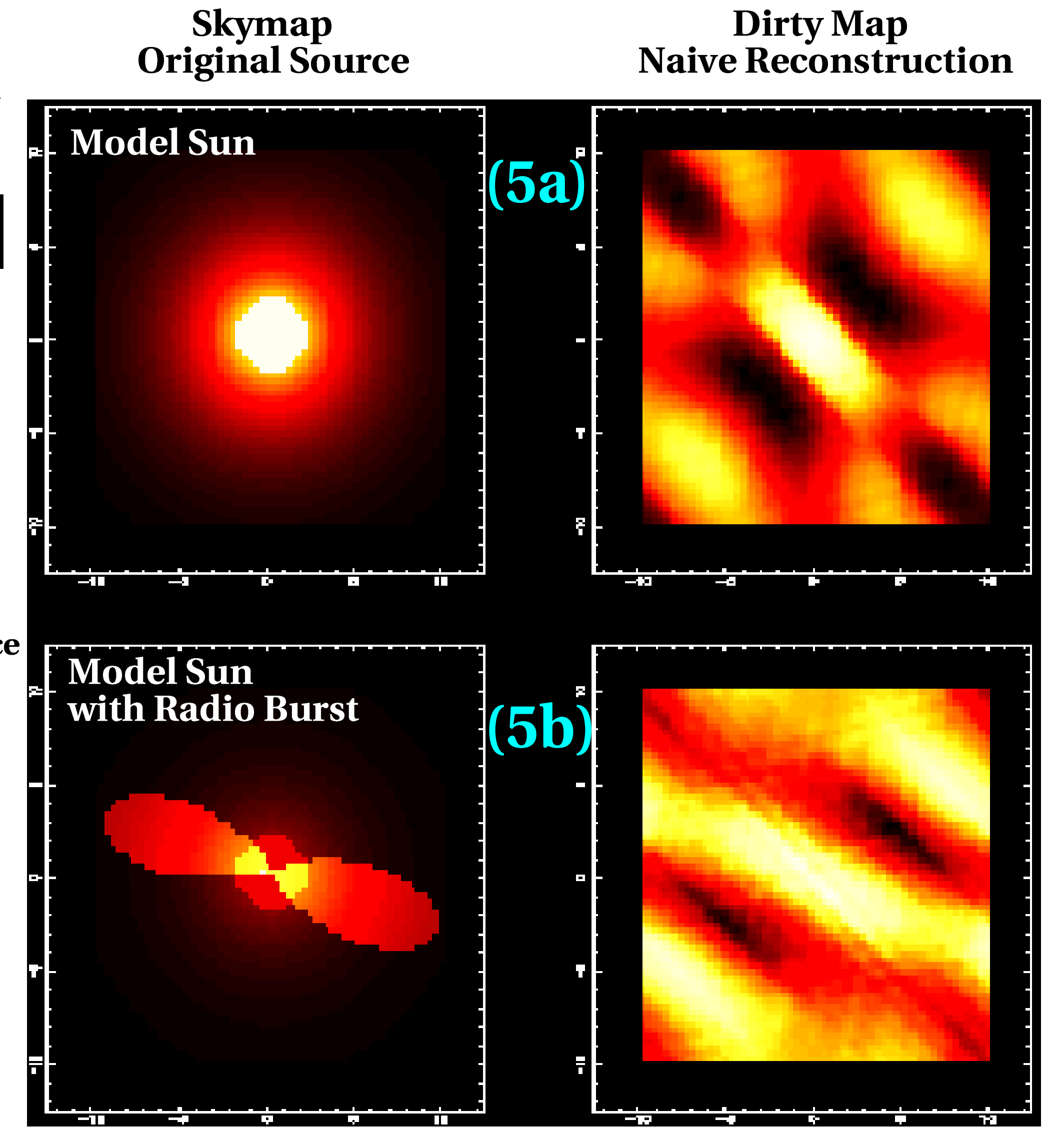


Cross–Correlating the downsampled signals yields points in Fourier Space, and a lot more information.



Good coverage of Fourier Space (spatial frequencies) yields better reconstructions and *enables* real–time imaging.

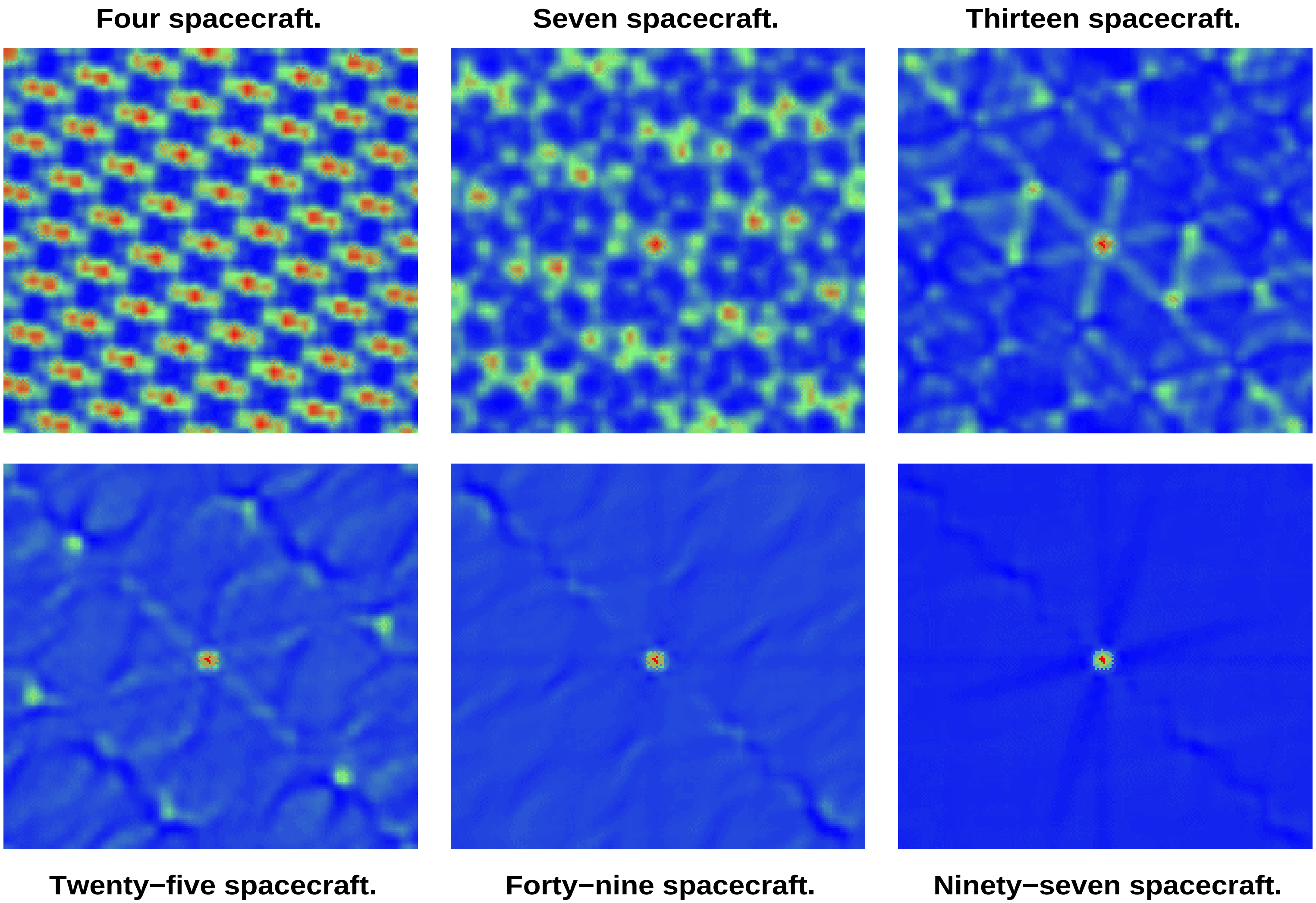




These data are from a working parallel application that models the first steps in synthesizing an image from radio array measurements. This simulation was for 46 spacecraft. The 'Dirty Map' is the starting point for further deconvolutions, e.g. CLEAN or Maximum Entropy.

MLR 980902

REE Enables Real Time Interferometric Imaging
Solar Imaging Radio Array



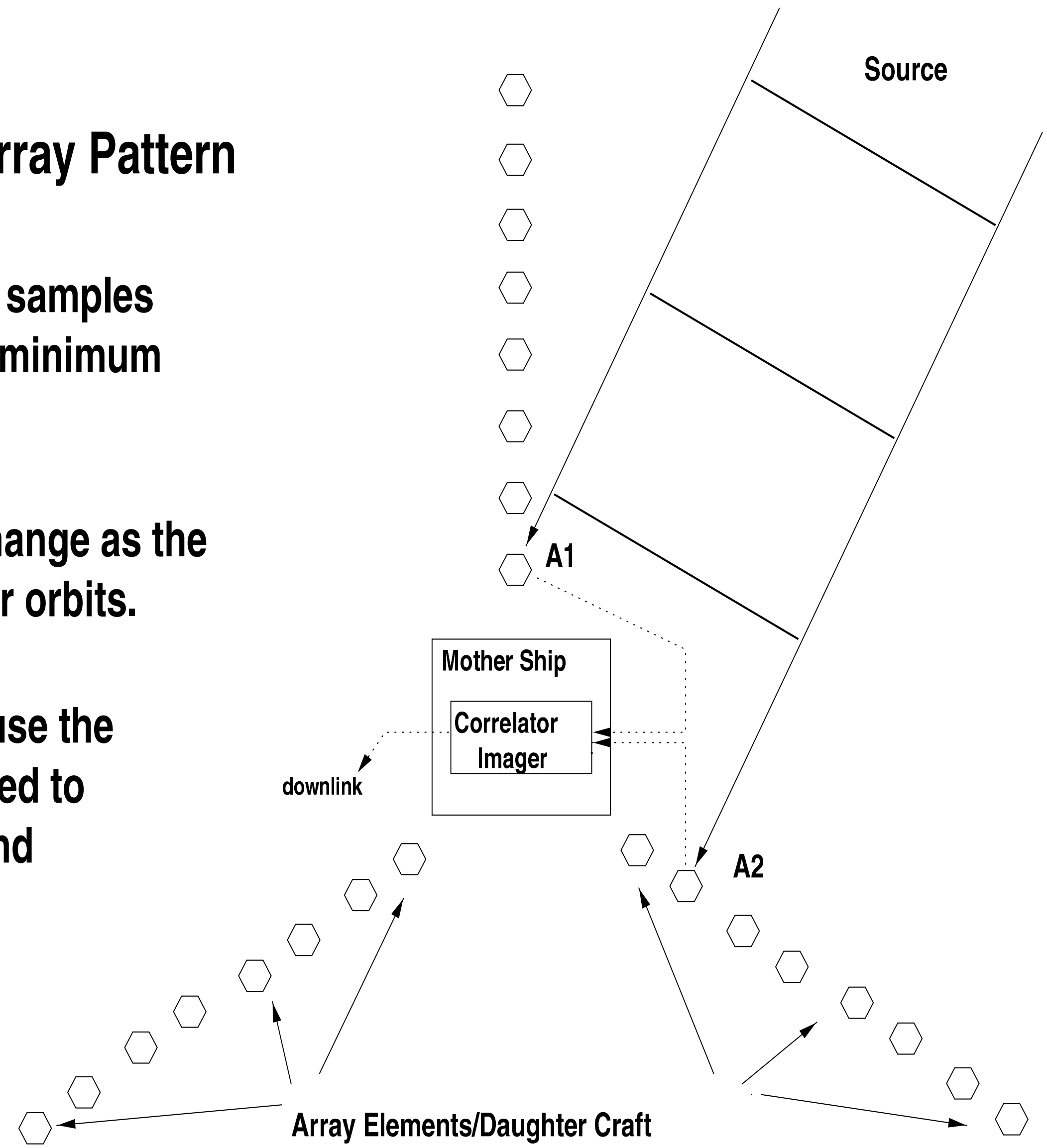
Above are the modeled snapshot responses of optimal interferometric arrays to a point source. As the number of spacecraft becomes larger, the waves are better sampled, and naive reconstructions of the sky become more accurate and interpretable. These images were made with the *REE/Solar−Terrestrial Probe Radio Astronomical Imaging* application running on the NASA/GSFC Cray T3E.

Example: Interferometer Array Pattern

An Array configured as a Y samples the wavevector space with minimum redundancy.

In space, the pattern will change as the spacecraft move about their orbits.

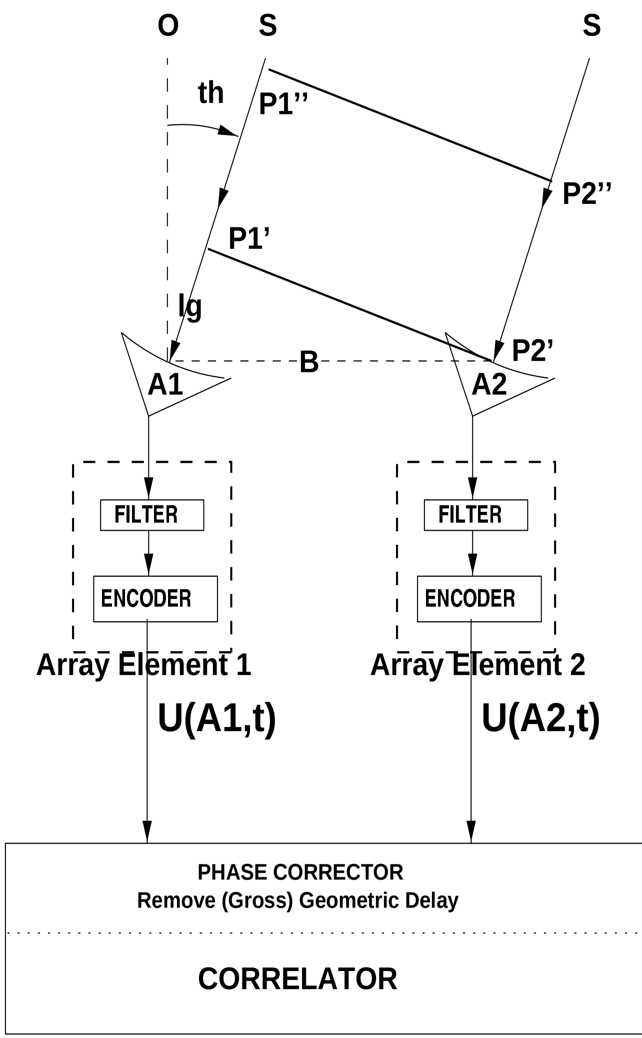
The Mother Ship could house the advanced computers needed to perform the correlations and imaging.



(Not to scale.)

Schematic Two Element Interferometer

After Wohlben, Mattes, and Krichbaum (1991)



A1: Receiver 1
A2: Receiver 2

B:=A1A2: Baseline
S: Source
O: Reference direction
th: Angle OA1S

P1'P2', P1''P2'': Surfaces of constant phase

lg:=Distance between A1 and P1'.
tg:=lg/wave phase speed:=geometric delay

FILTER downsamples the signals to lower frequencies.
ENCODER stamps data with timing and other calibration info.

U: Field measurement as a function of position and time
t: time

Cross Correlation as a function of 'small' lag, tau.

R(A1,A2,tau)

The R(A1,A2,0) are the Visibilities V(B), where B=A2-A1. The Visibility V(B) is the Spatial Fourier Transform of the Source's pattern on the sky.

Interferometry for Low Frequency Radio Imaging

Interferometry is this process of combining waves or signals together to obtain an interference pattern; this pattern is a severe constraint on the properties of the waves.

The fundamental analysis is the cross-correlation R of signals U obtained with instruments at points A separated by geometric *baselines*. From the cross-correlation R the *visibilities* $V(A_1, A_2)$ can be found.

$$R(A_1, A_2, \tau) = \lim_{T\to\infty} \int_{-T}^{T} dt\, U(A_1, t) U^*(A_2, t + \tau) \tag{1}$$

The phase delay is τ.

Interferometry, cont'd.

If the waves of interest do not suffer strong phase changes along the path between a distant source and one's detector, then one can write:

$$\tau = \tau_{\text{geometric}} - \tau_{\text{instrument}} = \mathbf{B} \cdot \mathbf{s} - \tau_{\text{instrument}}, \qquad (2)$$

where $c^{-1}\mathbf{B} \cdot \mathbf{s}$ is the projection of the directed baseline onto the direction to the source. c is the speed of the wave, for example, the speed of light. The instrumental lag is a combination of wanted and unwanted parts: $\tau_{\text{instrument}}$ is adjusted to cancel the geometric phase.

Sensor data production rate

- $N_{\mathrm{s/c}} = 16$ spacecraft;
- $N_{\mathrm{base}} = N_{\mathrm{s/c}} \left(N_{\mathrm{s/c}} - 1\right) = 120$ baselines;
- $N_{\mathrm{detectors}} = 2$ per spacecraft;
- N_{bits}: the number of bits per sample;
- $R_d = 125\, N_{\mathrm{bits}}\, \mathrm{kb\, s^{-1}}$ data sampling rate per detector.
- $R_d\, N_{\mathrm{detectors}} = 250\, N_{\mathrm{bits}}\, \mathrm{kb\, s^{-1}} = 22\, \mathrm{Gb\, day^{-1}}$ per spacecraft.

The science data rate for a small array is $\sim 360\, N_{\mathrm{bits}}\, \mathrm{Gb\, day.^{-1}}$
Assuming maximum array availability.

A CD-ROM holds about 4 Gb.

Communication demands

Assuming continuous operation of the Radio Interferometric Array, consider what happens if we wish to downlink all of the data from the radio receivers for processing on the ground.

Sixteen spacecraft at the L1 point between the Earth and the Sun creating a total of $\sim 360\,N_{\rm bits}\,{\rm Gb\,day}^{-1}$ place great demands on the communication infrastructure.

- *DSN:* $40\,N_{\rm bits}$ *hours per day of X-band downlink at* $2.5\,{\rm Mb\,s.}^{-1}$
- *For* $N_{\rm s/c} \approx 100$, *communication demands increase about 6-fold.*

Higher bandwidth communication, optical, K-band, may help, but have their drawbacks: mass, power, technological readiness...

Moving Some Computations Into Space

A possible way to circumvent the communications bottleneck is to keep more of the data in space, and analyze it there.

A fundamental step for the RIA is the *cross-correlation*, $R(\mathrm{A}_1, \mathrm{A}_2, \tau)$, of the signals from different array elements (A_1, A_2).

For low frequency radio, there are strong reasons for performing the cross-corrleation using *Fast Fourier Transform* (FFT) techniques. Then, the FFTs set the computation requirements.

MOP/s and GigaOP/s Enable These Calculations

For the sixteen spacecraft mission:

- $N = \left(\frac{\tau_d}{1\,\mathrm{s}}\right)$ 125 ksamples;
- Computations $\sim 32 \times N$-long 1D-FFTs per second;
- $\sim 32 \times 6\, N \log_2 N$ Operations per second;
- $\sim$ 400 MOP/s (Million Operations per second).

For the $\sim$ 100 spacecraft mission:

- $\sim$ 2400 MOP/s (Million Operations per second).

Assumed are one second ($\tau_d = 1$ s) data gathering intervals. The operation rate and algorithms required depend on the fidelity, N_{bits}, of the samples. Depending on the details of the signal sampling chosen, N_{bits} could be between 1 and 32 bits.

How to get GigaOP/s Computing In Space?

Better single processor performance creates new possibilities for onboard data processing. Compare LINPACK performance and power usage (MFL=MFLOP, FL=Floating Point, OP=Operations, W=WATT).[a]

- Intel P6 1995, 38(200) MFLOPS: 1(5) MFL/W
  - Commodity item
- IBM RAD 6k 1997, $\sim$ 20(27) MOPS: $\sim$ 2.0(2.5) MOPS/W
  - Radiation hardened, *Mars Pathfinder, Deep Space 1*
- DEC 21264 1998, $\sim$ 400(1800) MFLOPS: $\sim$ 6(27) MFL/W

[a] Some characteristics of RAD 6k and 21264 are estimated from POWER2 and 21164a respectively.

Rad-soft vs. Rad-hard performance.

Commercial Off The Shelf (COTS) processors are vastly faster than their Radiation Hardened counterparts.

- The Rad-hard RAD6000[a] runs at ~25 MHz, 22 MOPs, 10 W.[b]
- The Non-rad-hard PowerPC 750[c]: 400 MHz, 733 MOPs, 8 W.

The exceptional performance of COTS processors makes their use in space quite attractive.

- Their susceptibility to radiation effects must be accounted for.
- Hardware and software strategies to achieve fault tolerance are being pursued by REE.

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[a] IBM

[b] Power numbers here do not include support systems.

[c] IBM & Motorola

The REE Flight Processor

NASA/HPCC/REE is developing high performance computers for space flight.

Performance Goals.

- REE processor 1999, $>$ 720 MOPS, 24 Watts: $>$ 30 MOPS/W
- REE processor 2002, $>$ 6 GOPS, 20 Watts: $>$ 300 MOPS/W

To achieve these goals the REE processor uses:

- Multiple high performance COTS processors;
- Scalable networking architecture;
- COTS computing environment (e.g. Beowulf, MPI, POSIX);
- Various levels of fault tolerant operation;
- Lightweight "middleware" layer for Fault Detection, Mitigation.

Summary: REE/STP Radio Imaging Application

- Space based radiowave interferometry suffers a severe communication bottleneck.
- High fidelity or cadence image synthesis requires high performance communication or computation.
- To explore these issues, we have developed a model space based radio interferometer. The model runs on the GSFC SGI/Cray T3E Massively Parallel Processor, and will soon be tested on the REE Flight Processor Testbed.
- To make state-of-the-art computing available on orbit, the REE Flight Processor takes advantage of:

  COTS processor performance,

  Parallel computers' intrinsic redundancy, and the

  Known structure of our (numerical) algorithms.

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