KAIRA

Kilpisjärvi Atmospheric Imaging Receiver Array

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Sodankylä Geophysical Observatory, Finland

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Why KAIRA?

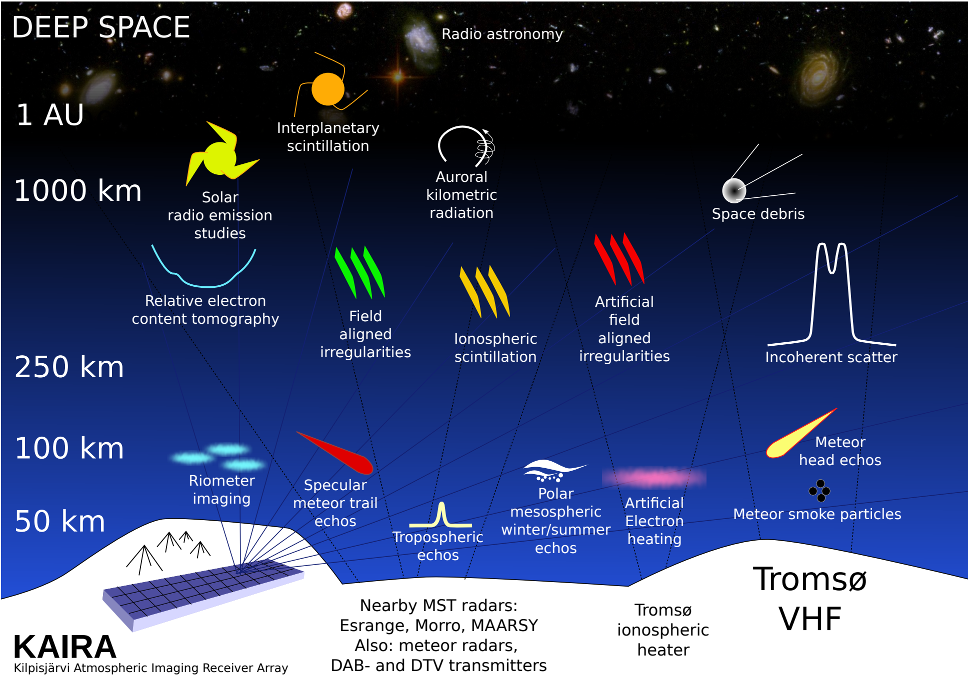
- Two years ago we wrote a proposal for a LOFAR remote station.
- The main goal was to try out the hardware as a EISCAT3D pathfinder.
- Since then, many more science goals have been attached to the project.

What is LOFAR?

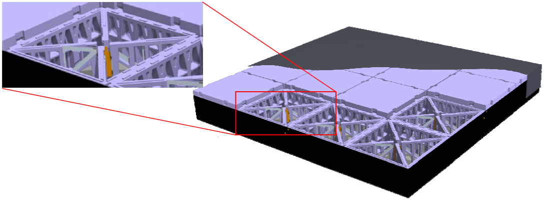
LEGO blocks for radio science

What is KAIRA?

- KAIRA is a dual array of wide band dipole VHF radio antennas
- A project of the Sodankylä Geophysical Observatory, principally funded by the University of Oulu in Finland.
- HBA: 30 $\times$ 50 m radio telescope for the 120-240 MHz
- LBA: 30 m diameter radio telescope for the 30-80 MHz
- Uses proven LOFAR antenna and digital signal-processing hardware. Black sheep of LOFAR.
- Primary purpose to receive EISCAT VHF transmissions
- Multiple uses in geophysical remote sensing and radio astronomy
- Prototype for EISCAT3D


DEEP SPACE
Radio astronomy
1 AU
Interplanetary scintillation
1000 km
Solar radio emission studies
Auroral kilometric radiation
Space debris
Relative electron content tomography
Field aligned irregularities
Ionospheric scintillation
Artificial field aligned irregularities
Incoherent scatter
250 km
100 km
Riometer imaging
Specular meteor trail echos
Polar mesospheric winter/summer echos
Artificial Electron heating
Meteor head echos
Meteor smoke particles
50 km
Tropospheric echos
Nearby MST radars: Esrange, Morro, MAARSY
Also: meteor radars, DAB- and DTV transmitters
Tromsø ionospheric heater
Tromsø VHF
KAIRA
Kilpisjärvi Atmospheric Imaging Receiver Array

LOFAR Antennas

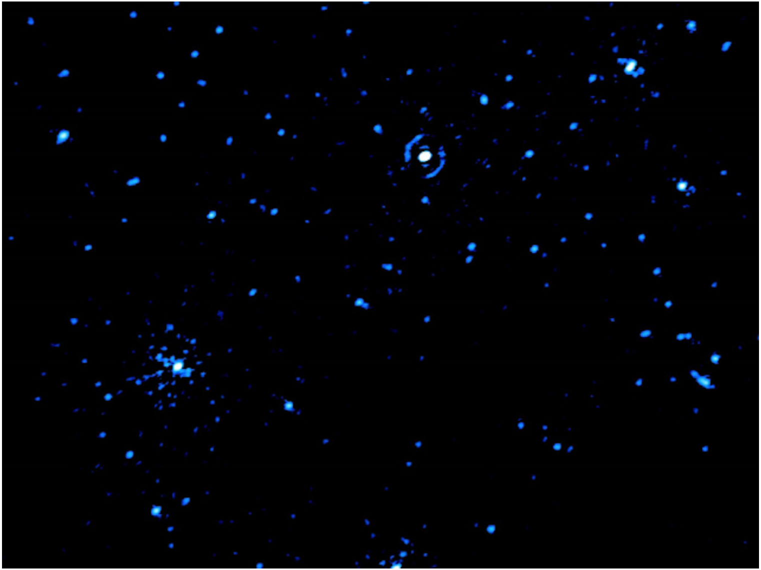


- Low Band Array 30 to 80 MHz.
- High Band Array 120 to 240 MHz.

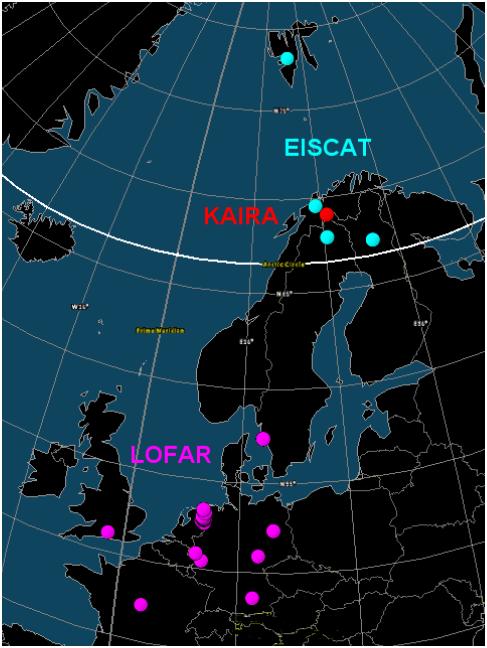
LOFAR Antennas

LOFAR Antennas

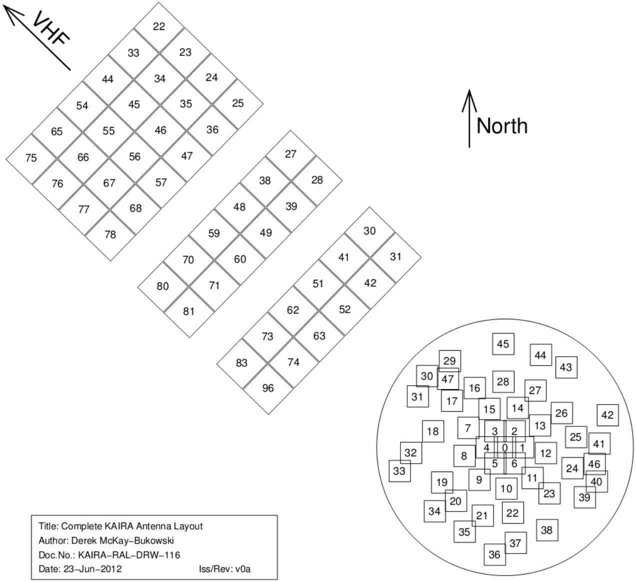
Interferometry



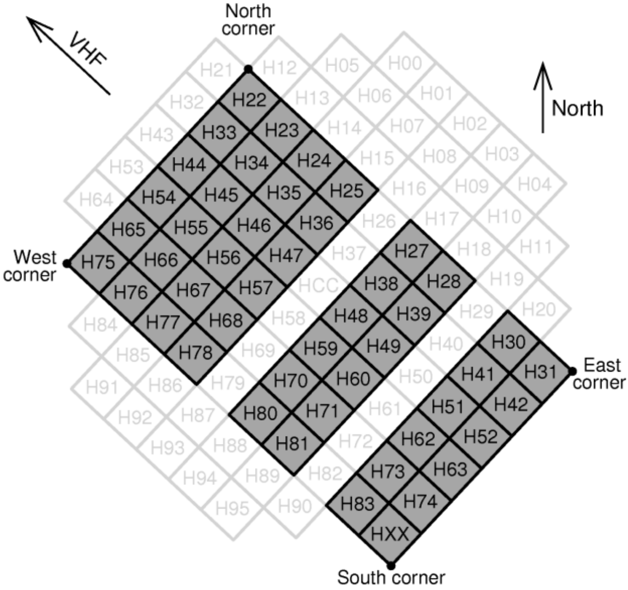
KAIRA Site layout



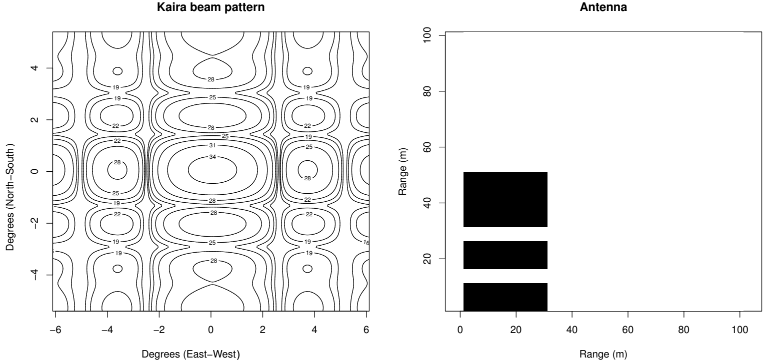
KAIRA Site layout



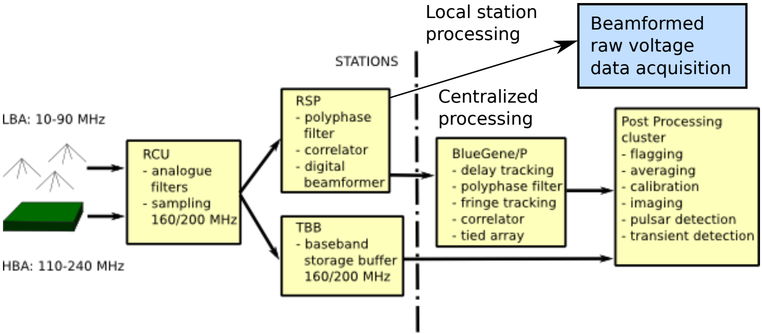
HBA Tile layout



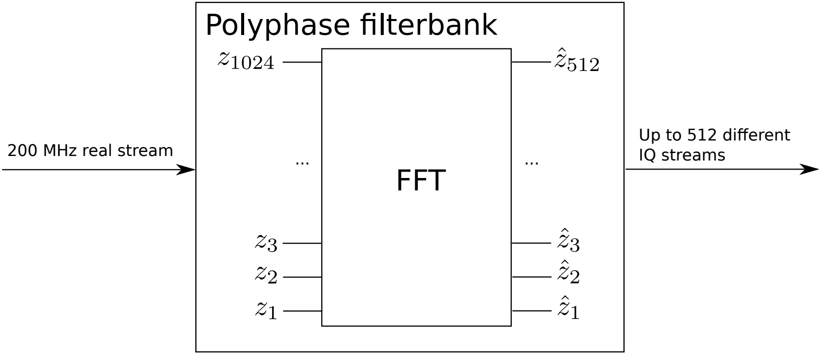
HBA Beam pattern



LOFAR Signal Processing



LOFAR Signal Processing



LOFAR Signal Processing

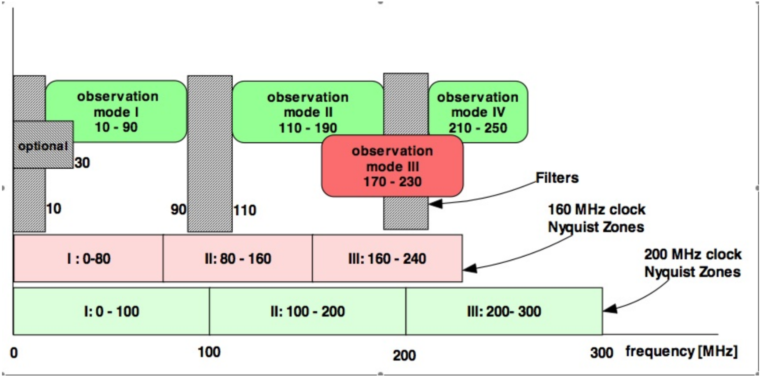
What is a digital downconverter?

$$z_t = \sum_{n=1}^{N_{\rm int}} x_{n+tN_{\rm int}} \exp(i\omega_c(n + tN_{\rm int})) \qquad (1)$$

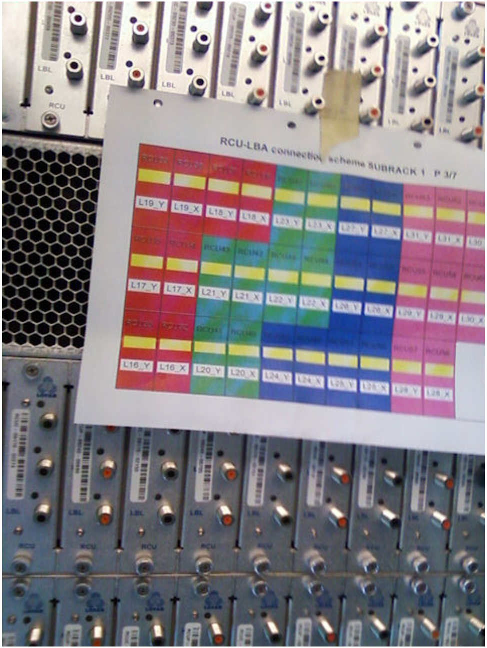
What does FFT do?

$$z_\omega = \sum_{n=1}^{N} x_n \exp(i\omega n) \qquad (2)$$

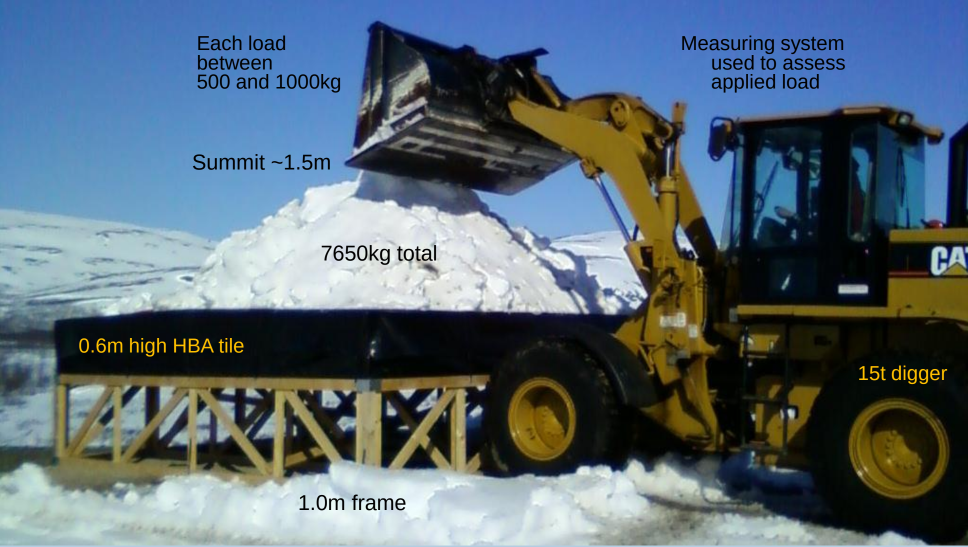
LOFAR Signal Processing



LOFAR Signal Processing



Snow testing



- Destructive testing
  - Snow impact, loading, lateral stresses, etc.

Snow testing continues...

Ilkka's visit to Astron

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Station Data Cookbook

Fast lag-profile inversion

- Lag-profile measurements are convolution measurements
- The transmission window in monostatic measurements prevents us from using frequency domain methods for deconvolution
- But bi-static observations have no transmission gaps and we can use FFT to dramatically speed up lag-profile inversion.

Lag-profile inversion

Consider the measurement equation for range and Doppler spread targets, but in this case using multiple different radar transmission envelopes indexed with c:

$$m_t^c = \sum_{r \in R} \epsilon_{t-r}^c \, \zeta_{r,t} + \xi_t. \tag{3}$$

If we now take conjugated self-products of these measurements with a lag τ. These can be organized as

$$m_t^c \overline{m_{t+\tau}^c} = \sum_{r \in R} \epsilon_{t-r}^c \overline{\epsilon_{t-r+\tau}^c} \, \sigma_r^\tau + \xi_t', \tag{4}$$

where $\sigma_r^\tau = \mathrm{E}\, \zeta_{r,t} \overline{\zeta_{r,t+\tau}}$, and ξ_t' is a zero-mean noise term, which is dominated by the receiver noise in the case of low signal to noise ratio measurements. In the case of high signal to noise ratio measurements, this will also have significant zero mean contributions from the incoherent scatter cross-products $\zeta_{r,t} \overline{\zeta_{r',t+\tau}}$, where $r \neq r'$.

Lag-profile inversion

In more concise form, the lag-product equations can be stated as

$$m_t^{c,\tau} = \sum_{r \in R} \epsilon_{t-r}^{c,\tau} \sigma_r^\tau + \xi_t', \tag{5}$$

which is equivalent to the measurement equation for coherent (stationary) range-spread radar targets. For each lag τ, the measurement equations are different, as the ambiguity functions $\epsilon_{t-r}^{c,\tau}$ depend on the lag (and also transmission envelope). The equation is linear, i.e., the relationship between the unknown σ_r^τ and the measurements $m_t^{c,\tau}$ can be represented in matrix

$$\mathbf{m}^{\mathbf{c},\boldsymbol{\tau}} = \mathbf{W}^{\mathbf{c},\boldsymbol{\tau}} \boldsymbol{\sigma}^{\boldsymbol{\tau}} + \boldsymbol{\xi}', \tag{6}$$

where the measurement vector $\mathbf{m}^{\mathbf{c},\boldsymbol{\tau}}$ spans over all time indices that contribute to the unknown $\boldsymbol{\sigma}^{\boldsymbol{\tau}}$.

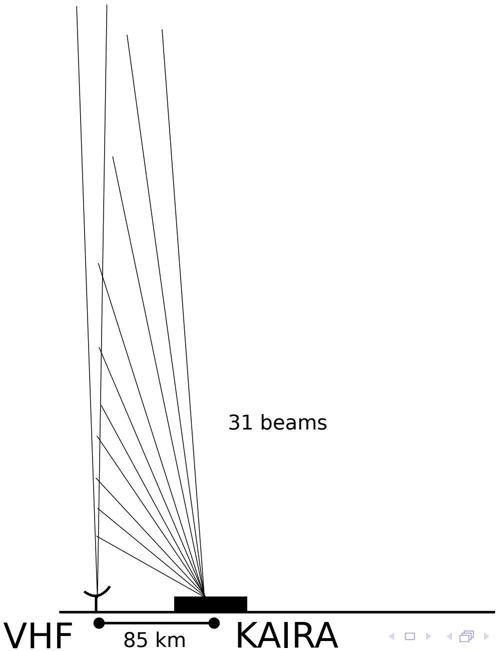
Fast lag-profile inversion

$$\mathbf{x_{ML}} = (\mathbf{A^H \Sigma^{-1} A})^{-1} \mathbf{A^H \Sigma^{-1} m} \tag{7}$$

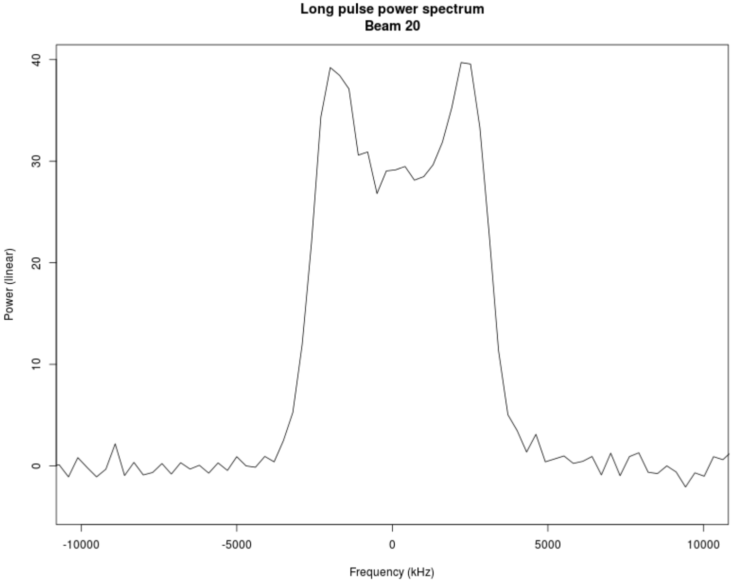
In frequency domain, the generalized linear least-squares for lag-profile inversion can be written as

$$\sigma_r^\tau = \mathcal{F}^{-1} \left\{ \frac{1}{\sum_{c=1}^{N_{\mathrm{codes}}} |\epsilon_c^\tau(\omega)|^2} \sum_{c=1}^{N_{\mathrm{codes}}} \overline{\epsilon_c^\tau}(\omega) m_c^\tau(\omega) \right\} \tag{8}$$

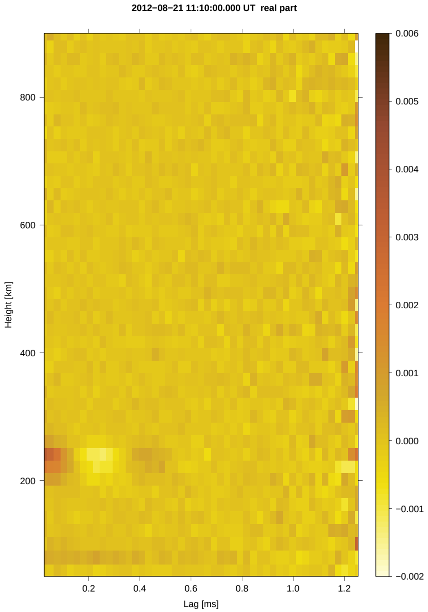
Bi-static configuration



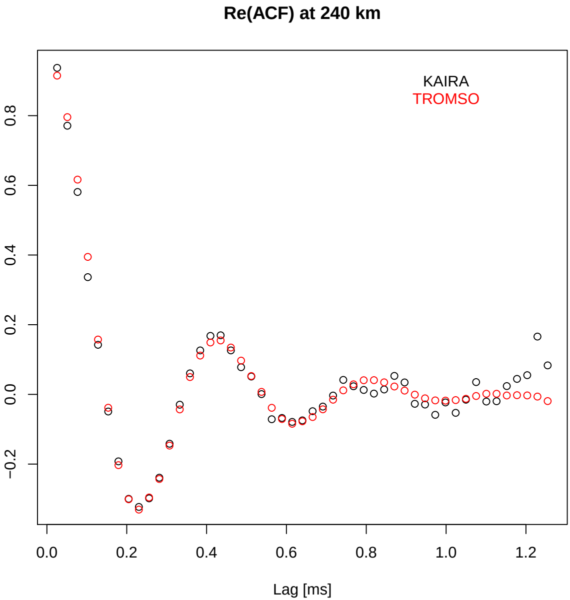
First radar light 17.8.2012



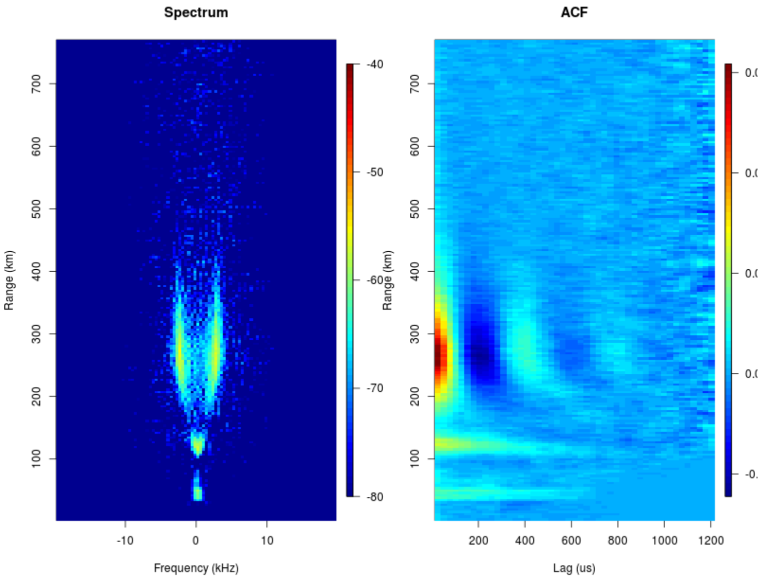
First coded pulse experiment 21.8.2012



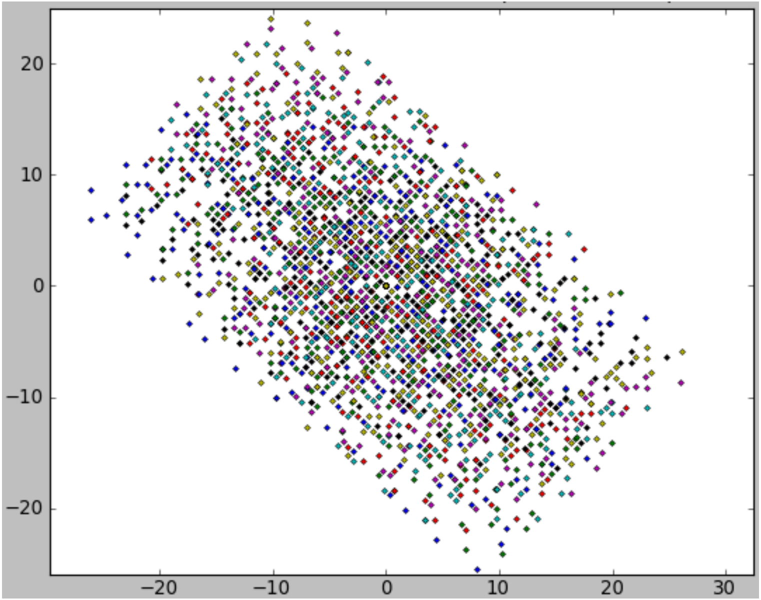
Comparison with Tromso



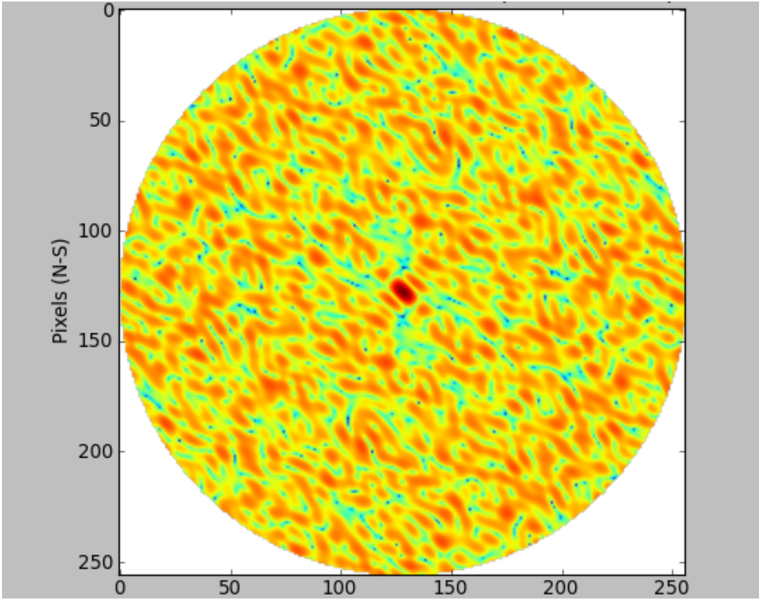
Fast LPI result from all beams



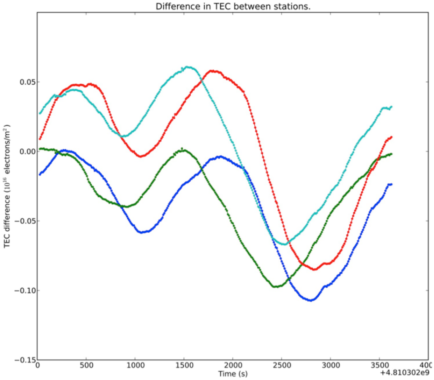
All-sky imaging

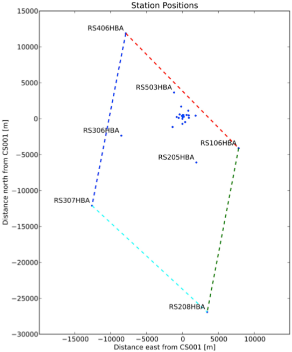


All-sky imaging

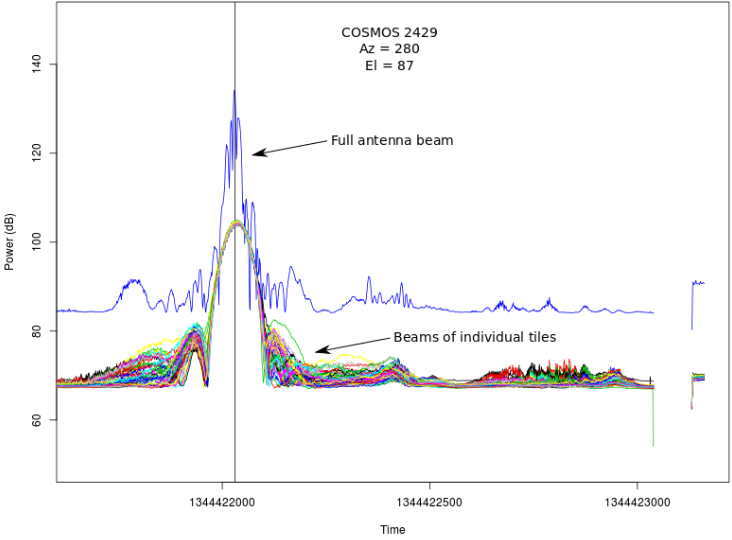


Relative total electron content

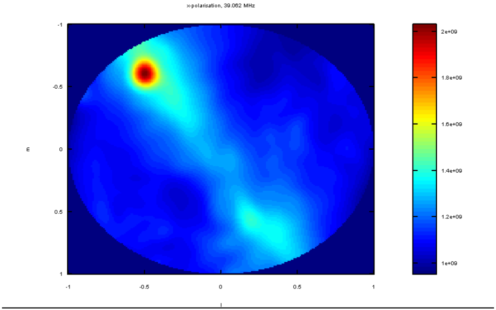




Beam shape using beacon satellites



Wideband Imaging Riometer



- All-sky imaging can be piggy-backed on all LOFAR stations operating with the LBA antenna. This is done by using the cross-correlated signals from all baselines that can be stored in parallel with other LOFAR operations.
- It is also possible to perform a dedicated riometer experiment with beams tracking radio sources in the sky.
- Wide frequency range (30-80 MHz)

Wideband Imaging Riometer

What can we do with this?

- More tolerant to interference
- Accurate quite-day curve by tracking radio sources
- Inverting electron density profile from multi-frequency riometer absorption[1]
- Inverting electron density and electron temperature from multi-frequency riometer absorption?

[1] Lavergnat, J., and J. J. Berthelier (1973), An iterative mathematical technique for deriving electron-density profiles from multifrequency riometer data, Radio Sci., 8(7),

What next?

- Do more VHF measurements
- Develope imaging riometer software
- Look at meteor head echos
- Look into IPS measurements

http://kaira.sgo.fi