LOFAR sensitivity aspects

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LOFAR sensitivity: a multi-faceted issue (1)

1) First, it depends on the application:

- Stokes I imaging (with CS, RS and/or IS baselines)
- Polarization imaging (Q,U → RM synthesis, or Stokes V)
- Timedomain work (UHECR, pulsars, transients (1s-1h)…)
- Spectral line work : → differential noise on kHz (e.g. recomb lines) or MHz (e.g. EoR) scales
- and,of course, whether you work in LBA or HBA

2) Secondly, there is thermal noise and noise achieved in practice:

Some issues here are:

- what is the background sky noise: i.e. are you observing in or above the Galactic plane ?
- how many stations are well-calibrated, and how are they weighted in the imager ?

For imaging we have also noise contributions due to:

- classical confusion noise (very relevant when using LOFAR core only !)
- PSF-sidelobe noise due to unsubtracted or 'uncleaned' sources (100+ needed)
- calibration residuals (A-team, ionospheric non-isoplanaticity, …)

LOFAR sensitivity: a multi-faceted issue (2)

3) For imaging applications the available processing resources (on CEPI or CEPII) will dictate how deep your image can go. This will hopefully evolve over the next 1-2 years, if only because the software will improve. If you have access to your own processing cluster, and staff to operate and maintain it !, the achievable sensitivity can approach thermal noise levels as shown by the EoR group.

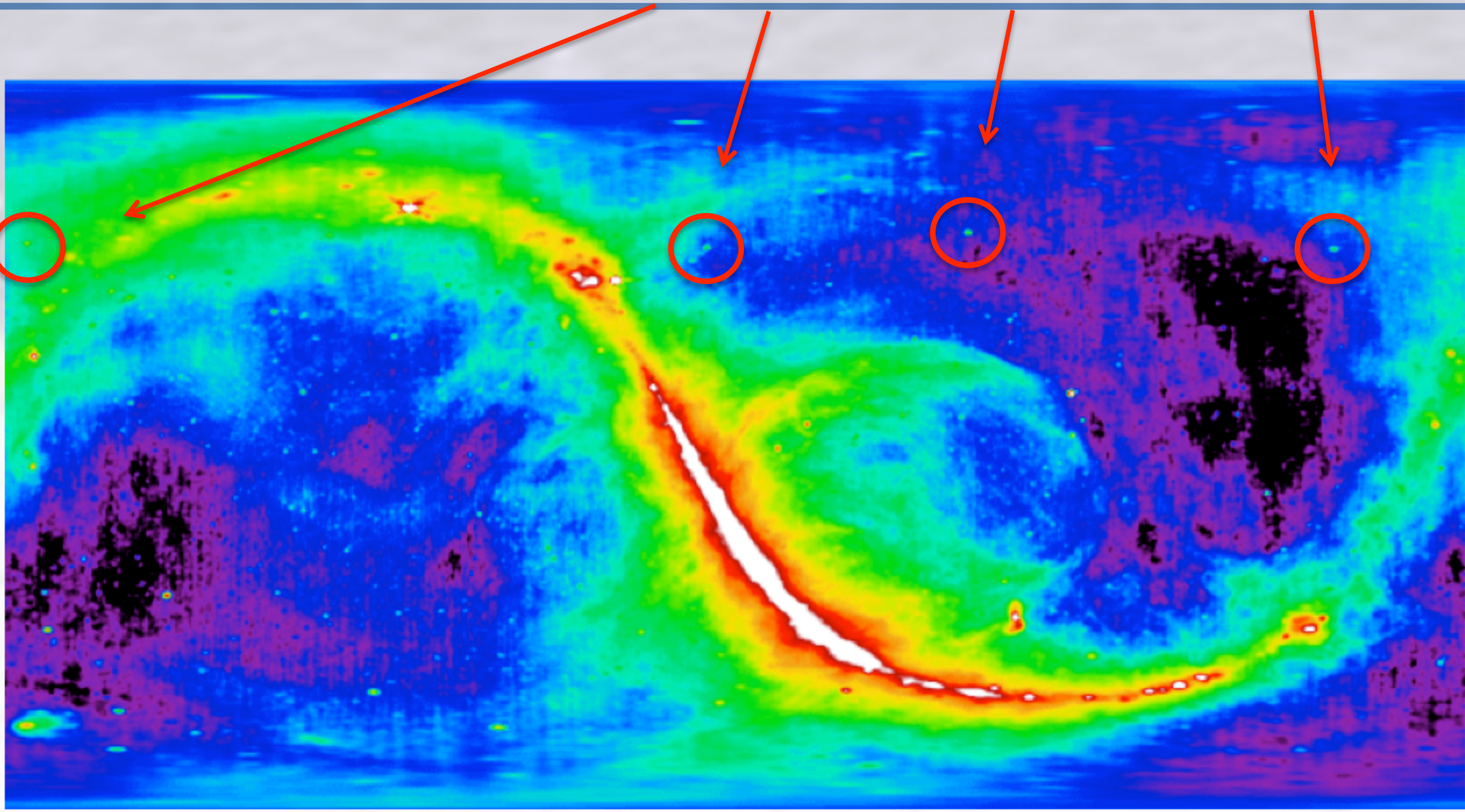
4) The pipeline(s) used and the type of processing used/required (e.g. BBS, demixing, SAGEcal, …) have a major effect on achievable noise levels.

5) And, finally, there is a flux scale issue (~10-20%? accurate, the least of our worries)

I will now show some graphs that may help you to turn these qualitative statements into practical numbers that you may want to use in your proposals or help you guide in the process to match your science to the expected LOFAR sensitivity evolution in the years ahead.

However, note that by the time you will write your Regular Proposal, following the call of May 2012, the numbers I am about to give may already have changed (for the better).

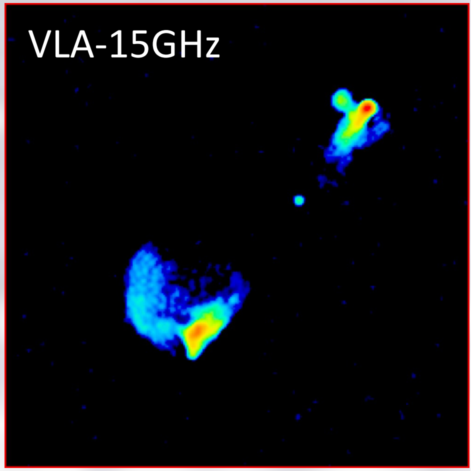
Galactic locations of 3C147, 3C380, 3C295 and 3C196



Haslam et al, 1981

3C295 as a flux and SEFD calibrator

RA= 14h 12m Dec = +52^o 12'! → < 1^o from zenith in Exloo !



5" double

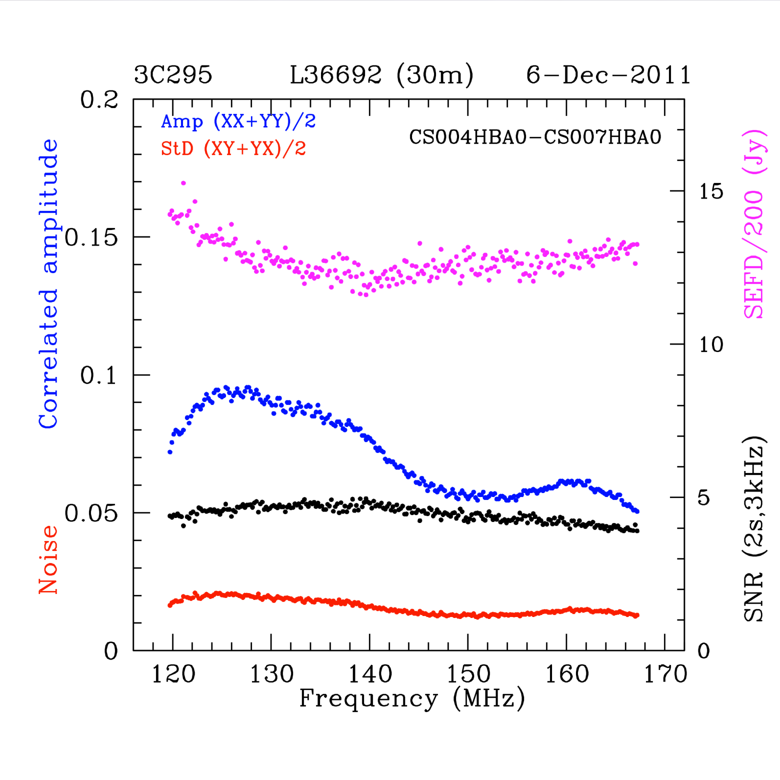
Adopted flux density in the LBA and HBA bands is a 4^o fit made by Anna Scaife (as part of MSSS flux scale preparation)

$\log(S) = 1.99 - 0.582 \log(\nu) - 0.298 \log^2(\nu) + 0.583 \log^3(\nu) - 0.363 \log^4(\nu)$
where ν = (frequency/150 MHz)

Predicted flux at 150 MHz: 97.8 Jy
Predicted flux at 60 MHz: 134.4 Jy

For the HBA-low (RCU mode 5) I have used observation L36692 on 6 Dec 2011
For the LBA-inner (RCU mode 3) I have used observation L44550 on 1 Feb 2012

SEFD in the HBA for CS and RS

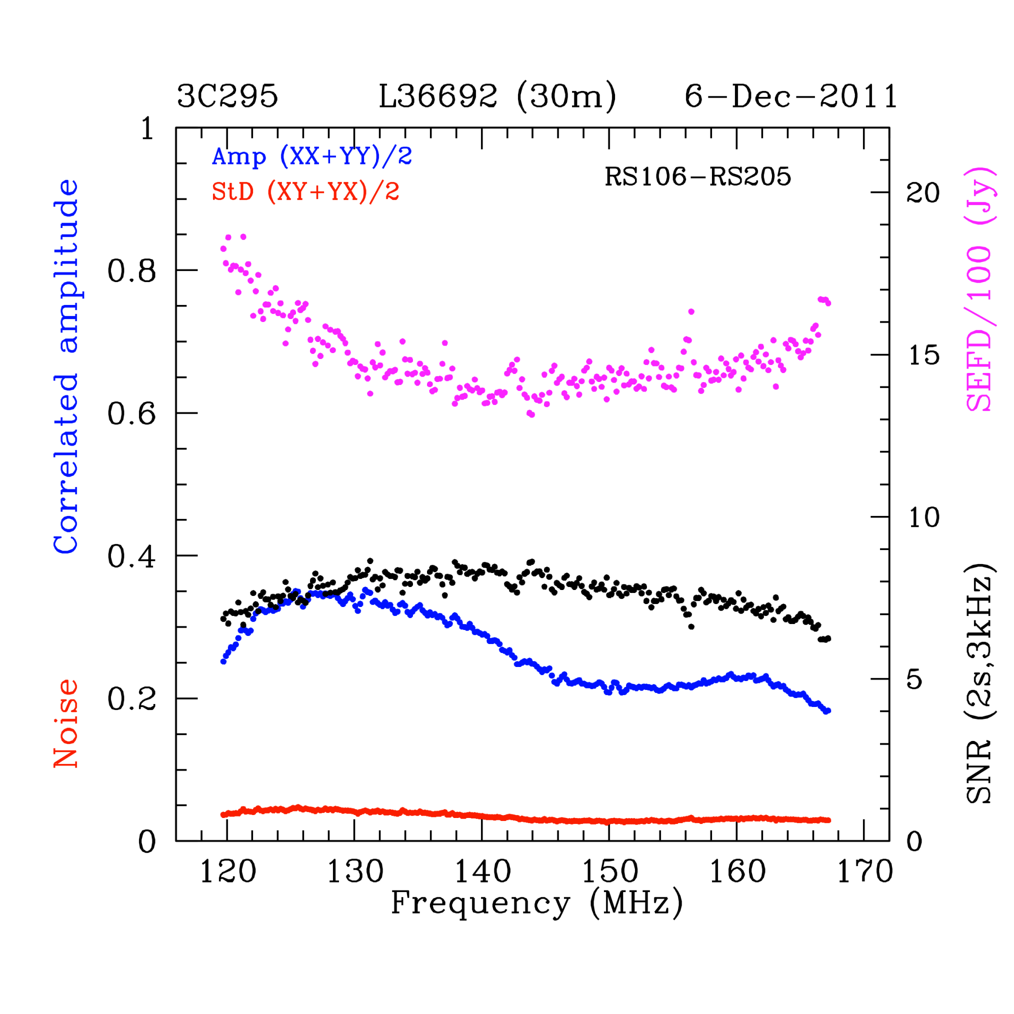


Noise and Correlation amplitude for visibility → SNR and SEFD derived

For good core stations (130-170 MHz) : SEFD ~ 2500 Jy

NB: I use SEFD = σ(Jy) * SQRT(2 Δν . Δτ) for 1 pol !

and for NL Remote Stations

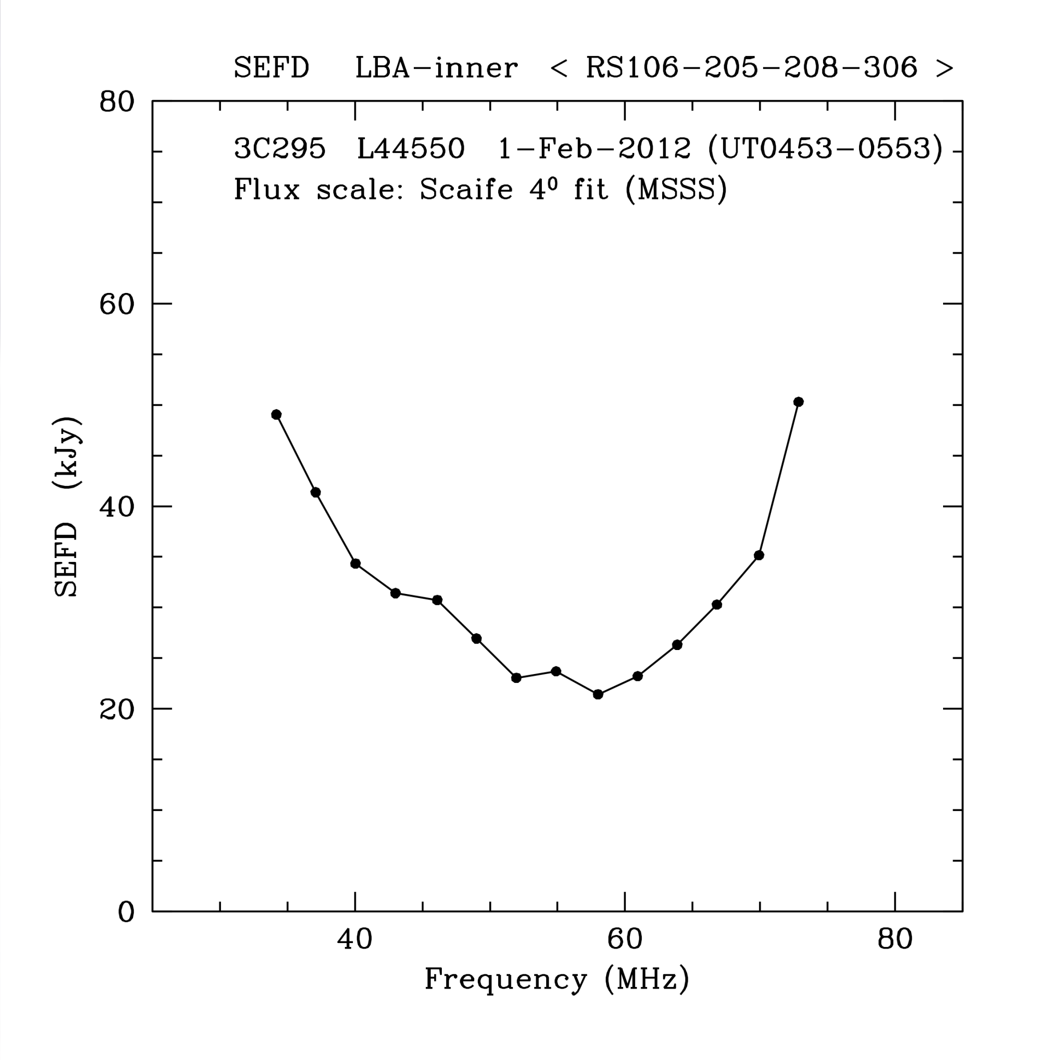


1400 Jy

Currently RS306 is much poorer.

RS307,406,503,508 &509 are not yet up to specs.

SEFD for LBA-inner for NL Remote Stations



LBA-inner in the Galactic halo in the 40-70 MHz range

SEFD ~ 20 – 30 kJy

To compute the effect of a rising Galactic background on the SEFD

SEFD = 2760 T_{sys}(K)/Aeff (m^2)

See also Wijnholds and van Capellen (IEEE- TransAAP, 59, 1981, 2011)

Sky brightness in Kelvin in LOFAR LBA and HBA bands

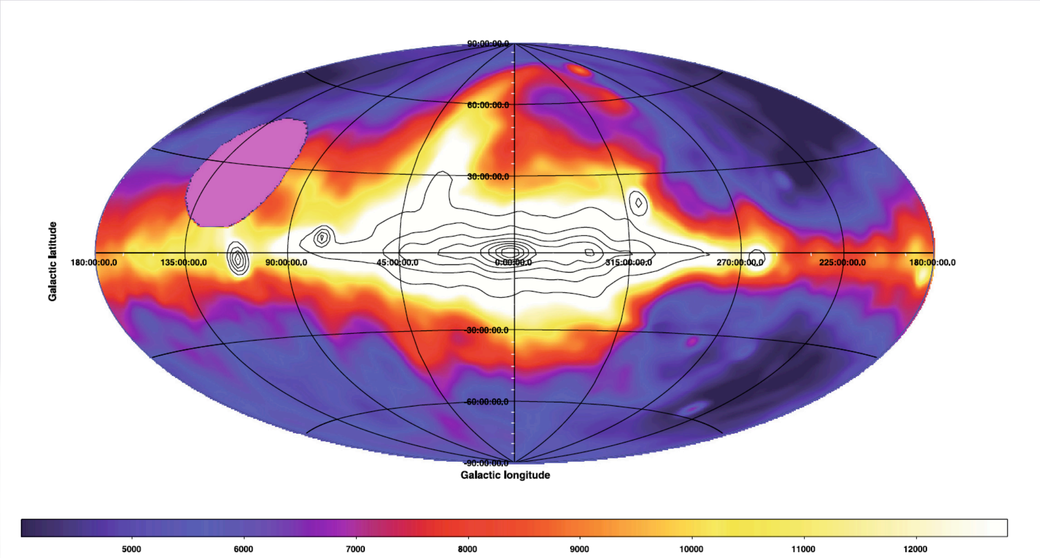
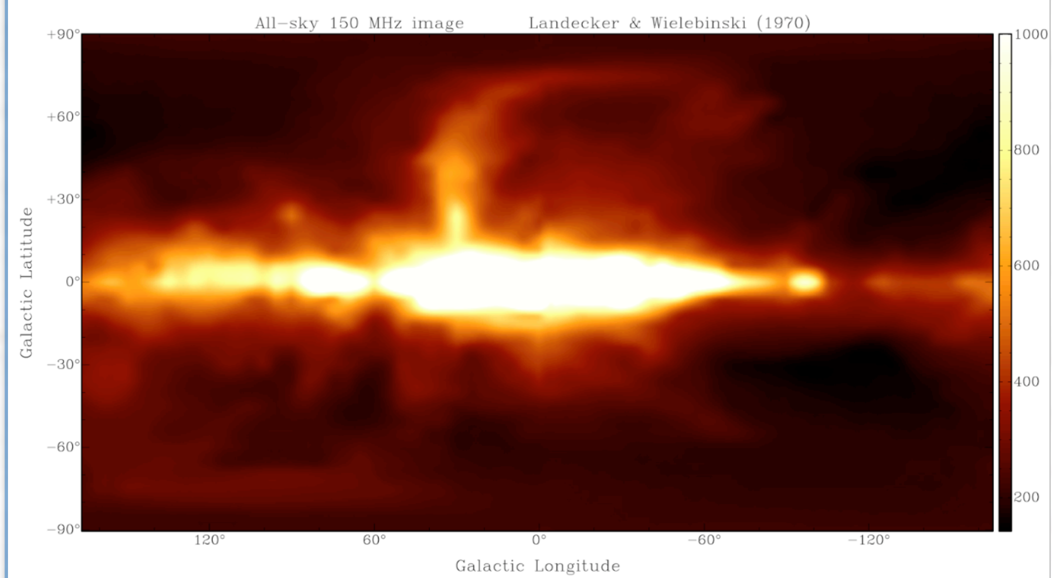


Fig. 1. Hammer-Aitoff projection of the 45 MHz full sky map. Eight contours are drawn between 15 000 and 60 000 K. The map does not cover the $\delta > +65°$ zone.



Guzman etal,
(A&A, 525, 138, 2011)

45 MHz

150 MHz

Landecker & Wielebinski
(AusJPA, 16, 1, 1970)

Additional comments

No practical SEFD values exist as yet for IS.
They should, in theory, be twice as good as those of NL Remote Stations

There is a still a wide range of SEFD values for Dutch CS and RS, especially in the HBA. So even if BBS or SAGEcal calibrates these different station gains there varying noise effects the final image noise.

The variations between stations seem to be smaller for the LBA.

Theoretical image sensitivity

The image noise that LOFAR can reach in theory is given by

$$\text{noise} \sim c \quad \text{SEFD} / (\text{SQRT}\ (4.B.t.N_{ifrs})$$

- where B is the effective (unflagged) bandwidth (usually ~ 180 kHz * N subbands)
- t the integration time in seconds
- N_{ifrs} the number of interferometers (assumed equally noisy!)
- c is a constant (~ 1.5) that includes losses due to the type of weighting scheme used (e.g. natural, Briggs,..) and the spatial tapering.

Another important consideration in this calculation is that not all interferometers have the same sensitivity: e.g. CS-CS, CS-RS and RS-RS. We will soon experiment with spatial tapering of the RS to estimate the effects this has on standard imaging.

Using 15x2CS and 7 RS in Spring/Summer of 2011 the EoR group has reached a subband noise level for high-resolution (~8" PSF) imaging of about 2 mJy in the 3C196 and NCP fields after 6h around 140 MHz. This is also what one computes from the above if one effectively assumes only 7x30 = 210 CS-RS interferometers (1.5 *2000Jy/ SQRT(4.180000. 210.21600) = 1.7 mJy).

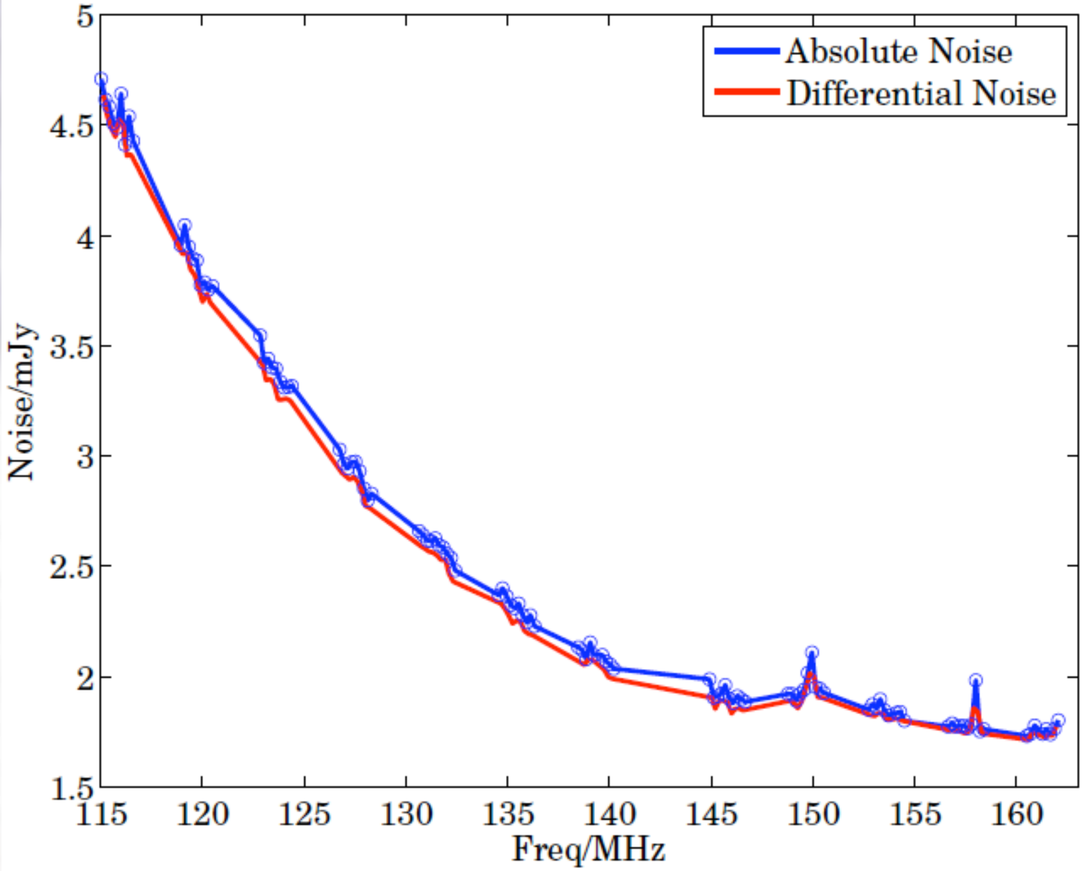
Thermal noise levels after 6h in the NCP field !

244 contiguous subbands of 0.18 MHz (not all are shown)

Absolute noise = Image noise

Differential noise =

(Image i – Image (i+1))/ √2



Differential and absolute noise

Practical image sensitivity

The good news:

Sometime this spring/summer we should have 24x2 CS and 10 RS and hopefully all with the same SEFD. This should yield an improvement of about a factor 2.5-3 in the thermal noise as well as the practical noise that can be expected

And this may also be the noise that can be expected in polarization and spectral line work or in applications in the (fast) timedomain.

The bad news: (see numbers on the web)

The standard imaging pipeline now can deliver a subband noise in the HBA band of about 6 mJy using 18x2 CS and 9 RS. This is still about 3-4x higher than thermal !!

In the LBA the practical noise number is about 80 mJy per subband in 6h.
Also note that the senstivity for N subbands does not really go down as SQRT(N)

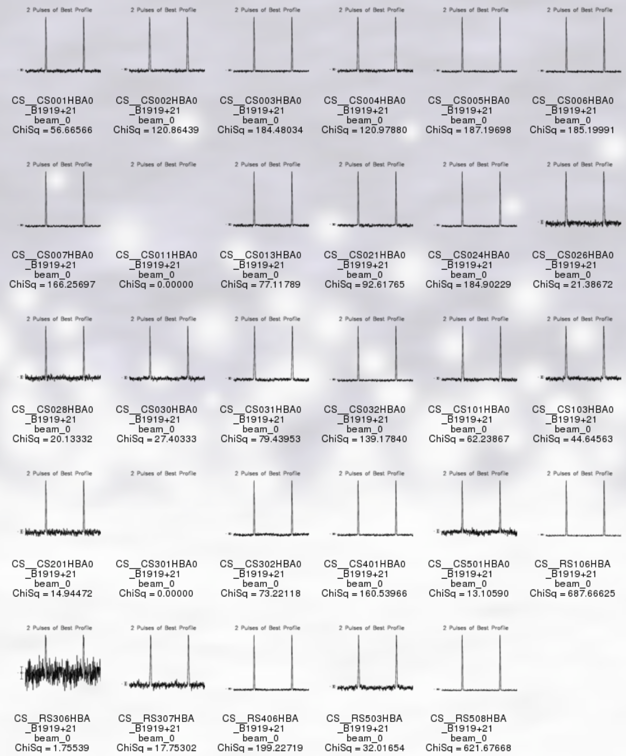
Work ahead of us:

Derive SEFD values for:

HBA RCU mode 6 185 - 215 MHz
HBA RCU mode 7 210 – 250 MHz
LBA-outer

This will only be done once:

- the origin of relative SEFD variations is solved
- new cal tables have been generated, if necessary



Integration of various absolute and relative sensitivity measurement techniques. (holography, interferometry, pulsar observations (fly's eye mode)).
An update of the LOFAR sensitivity note (Nijboer etal) is in preparation (available in March/April ?).