Image: B. Premkumar

OBSERVING WITH THE GIANT METREWAVE RADIO TELESCOPE

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Outline

- The upgraded Giant Metrewave Radio Telescope (uGMRT).
- Types of uGMRT science.
- Before the proposal: Basic questions.
  : The Exposure Time Calculator (ETC).
- Writing the proposal: The coversheet.
  : The science case.
  : The technical justification.
- Before the observations: Choosing calibrators.
  : Frequency settings.
  : Correlator issues.
  : Command files and source lists.
- During the observations: Monitoring the data.
- When things go south…

THE UPGRADED GMRT

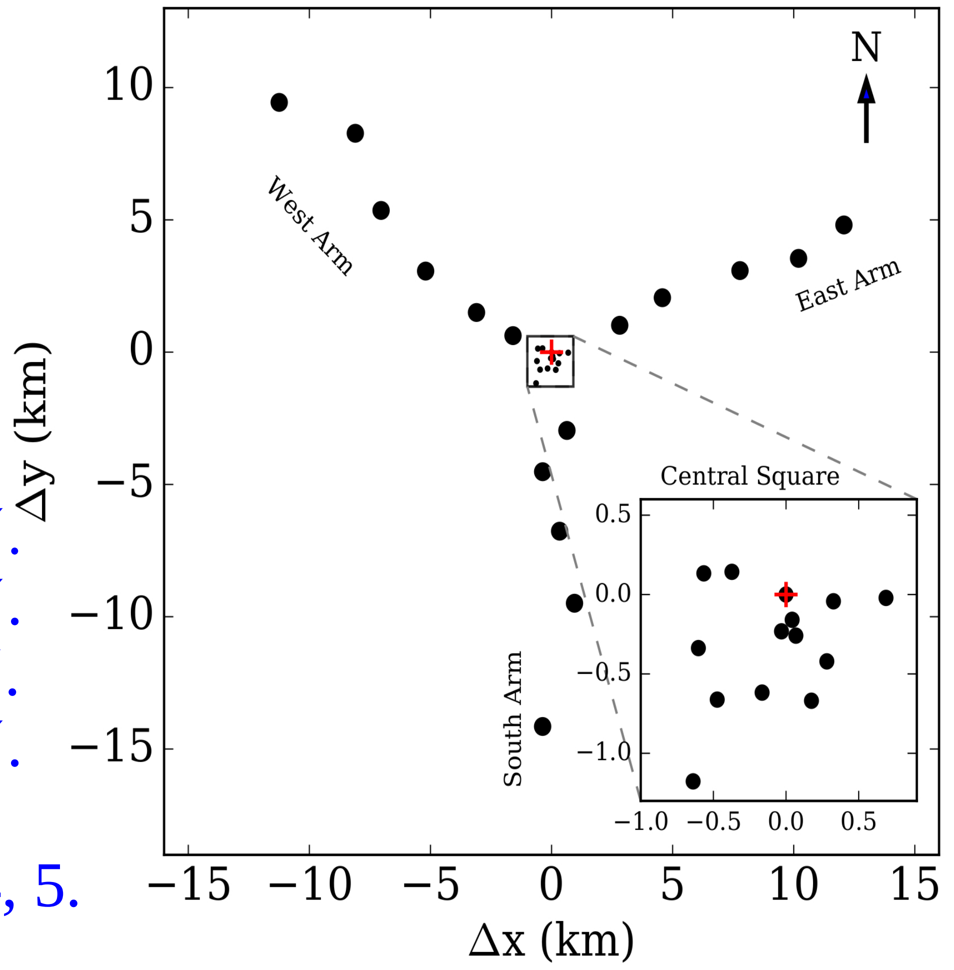
(Gupta et al. 2007, Curr. Sci.)

- 30 mesh antennas; 45m diameter.

- 14 dishes in a ~1 km central square.
  16 dishes along the arms of a “Y”.
  435 baselines: ~ 75 m – 25 km.

- Frequency bands, Resolution (full, C.Sq.)
  Band–2: 125 – 250 MHz: ~ 17´´, ~430´´.
  Band–3: 250 – 500 MHz: ~7.5´´, ~185´´.
  Band–4: 550 – 850 MHz: ~4.5´´, ~110´´.
  Band–5: 980 – 1500 MHz: ~2.5´´, ~ 62´´.

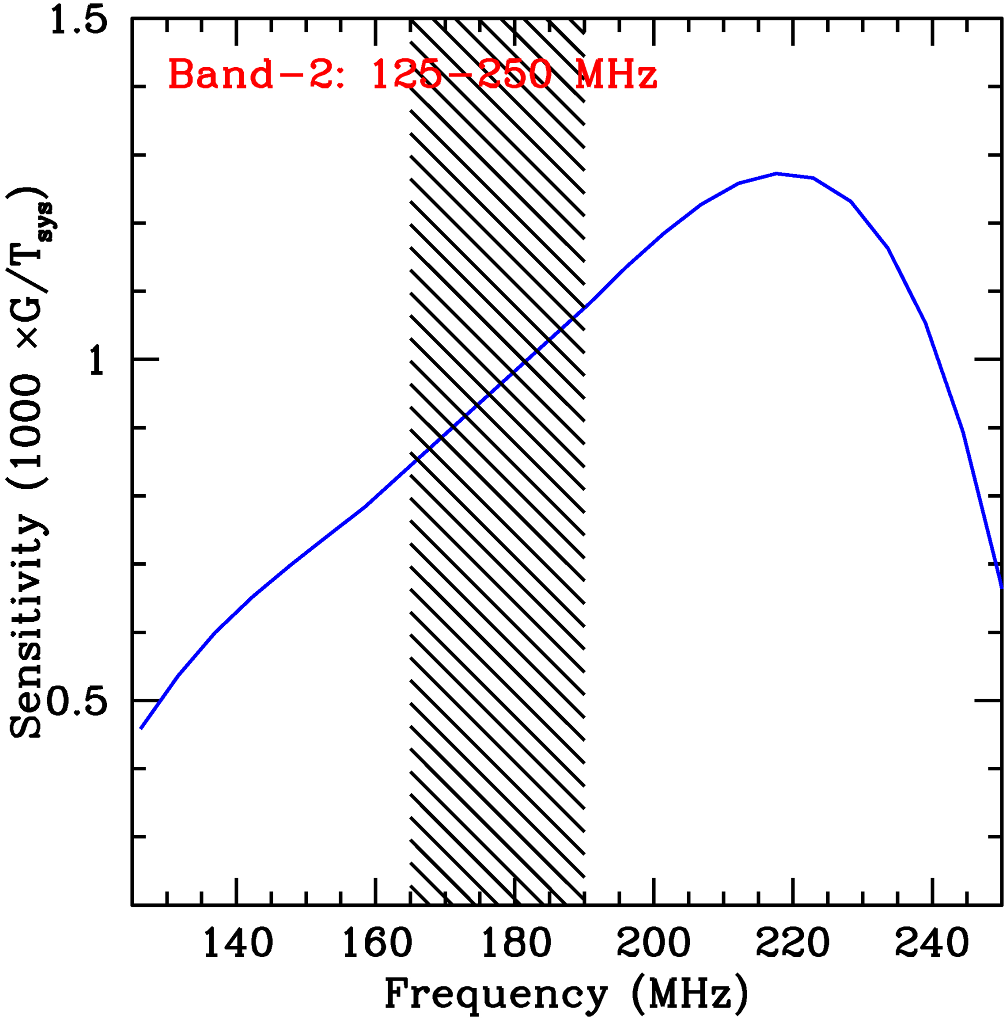
- ~ 100 MHz sub-bands within Bands 3, 4, 5.

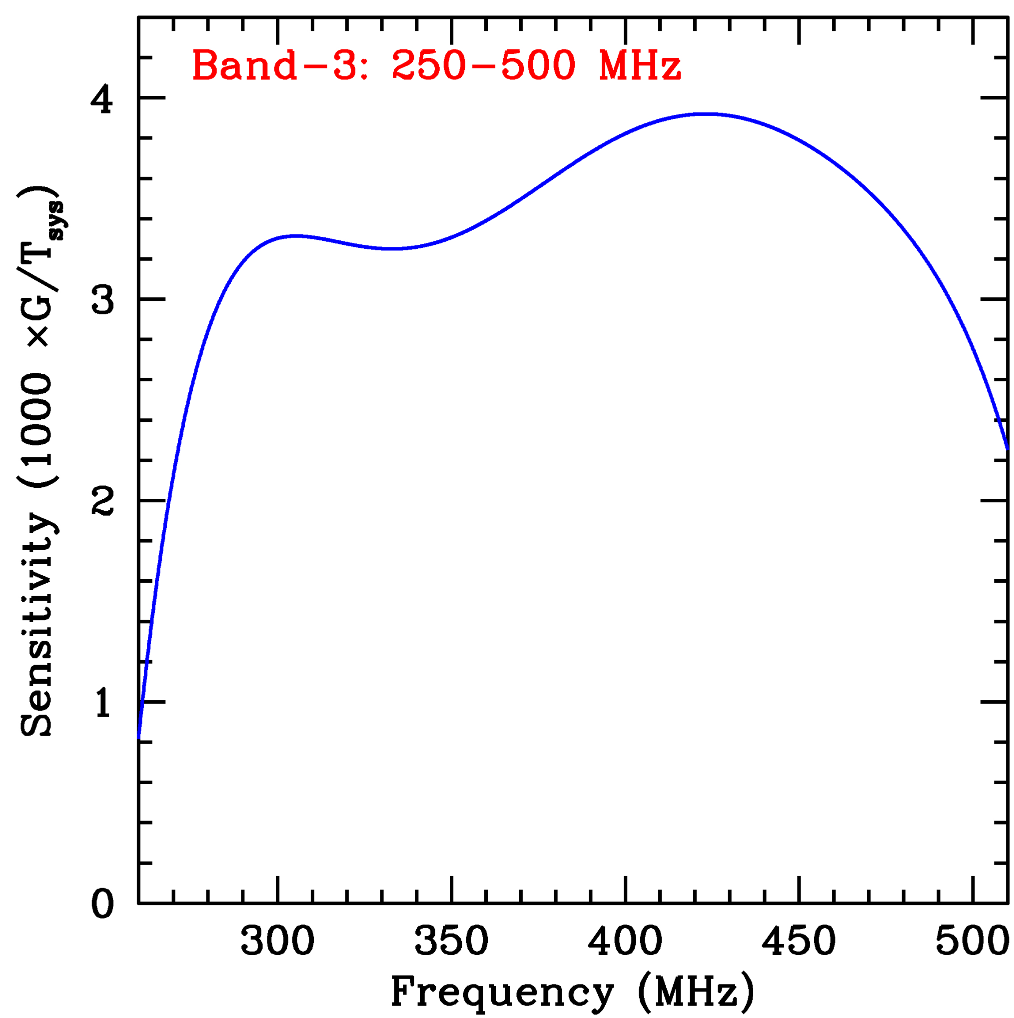


- Two correlators, independent data paths:
  GMRT Wideband Backend (GWB):
    Bandwidth = 0.39 – 400 MHz; 2048 – 16,384 channels;
  GMRT Software Backend (GSB):
    Bandwidth = 0.52 – 33.33 MHz (no 8.33 MHz!); 128 – 512 channels.

The uGMRT Receivers

(NK, in prep.)



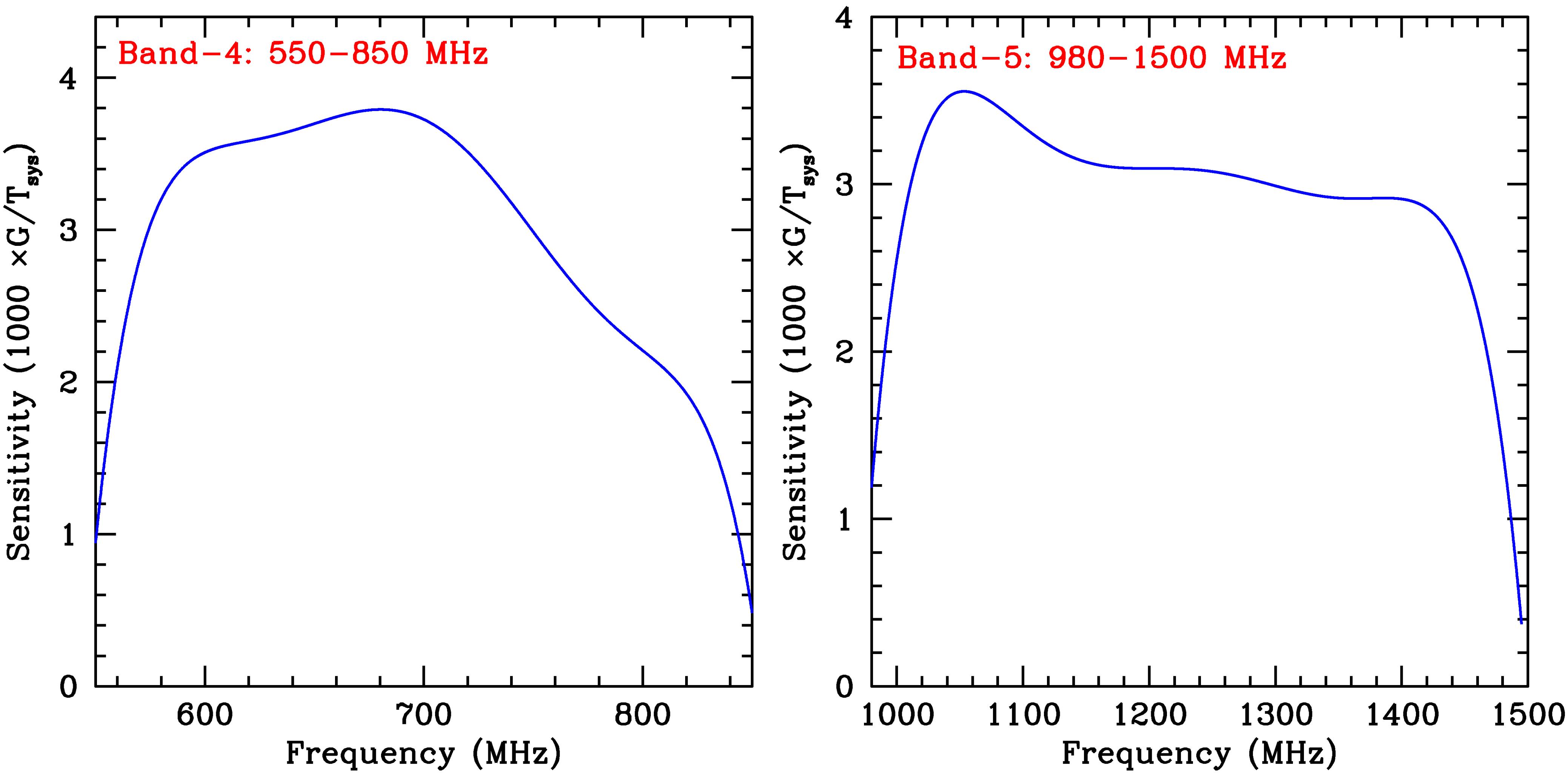


- “Band–2”: 125 – 250 MHz.
  Notch filter at ~ 165 – 185 MHz to zap a strong TV station.

- “Band–3”: 250 – 500 MHz. MUOS satellites at 360 – 380 MHz.
  RFI below 275 MHz. Digital TV (upto 11 PM): ~ 480 – 490 MHz.

The uGMRT Receivers

(NK, in prep.)



- "Band–4": 550 – 850 MHz. Remarkably clean band!
  Cut-off at ~ 850 MHz, to avoid cellular transmissions.

- "Band–5": 980 – 1500 MHz. Cut-off at ~ 980 MHz, to avoid GSM band.
  Lots of satellite RFI at ~ 1200 – 1300 MHz.

Types of uGMRT Science

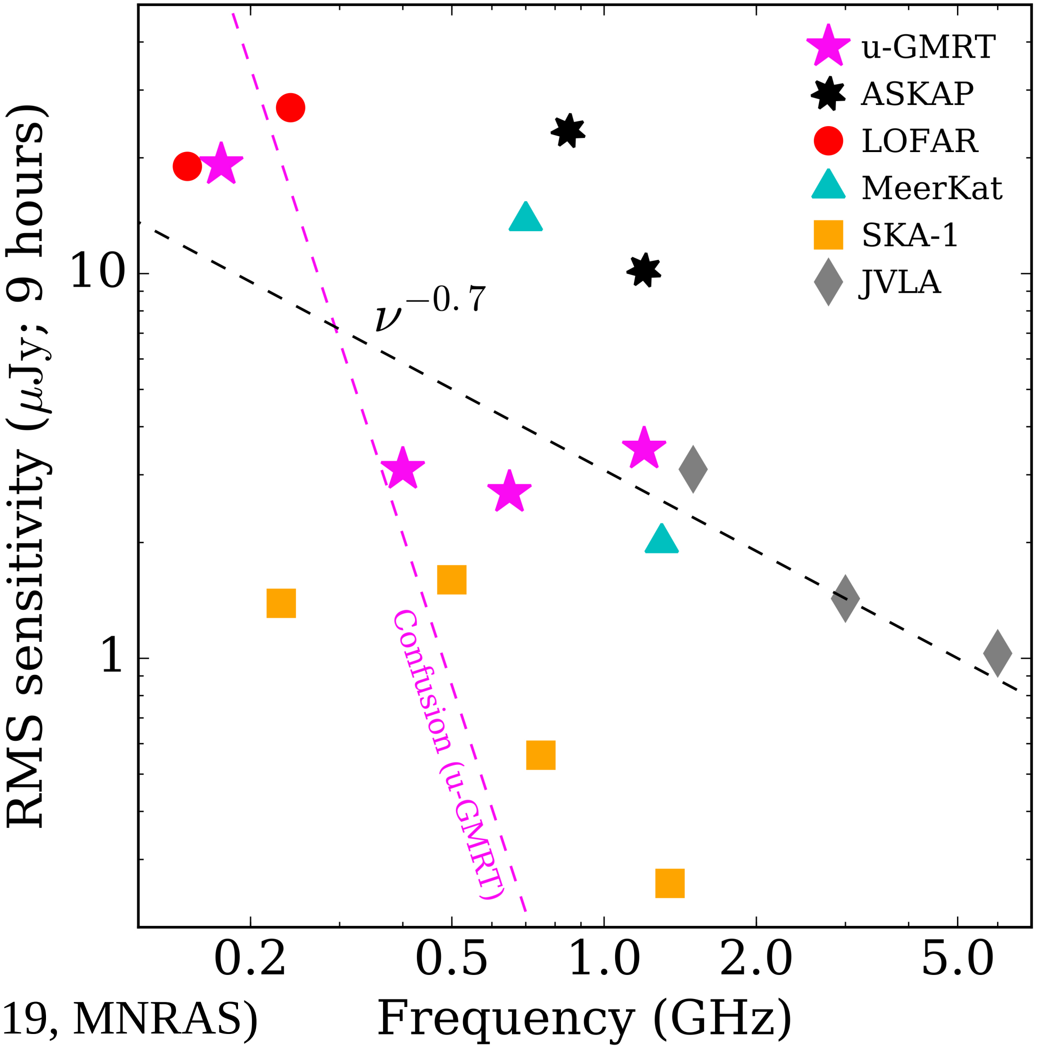
- Broadly, two kinds: Interferometry, Beamformer.

- Interferometry: Continuum, Spectral Line, Polarimetry.
  Beamformer : Time domain studies (e.g. Pulsars, Transients).

- Polarimetry with uGMRT is still a dark art: Contact NCRA folks!

- Today: Interferometry, line and continuum observations.

- Science examples?



(Patra et al. 2019, MNRAS)

Before the Proposal: Basic Questions

- What sensitivity do you need? Is your target a point source or extended?
- Continuum observations: Will you be limited by source confusion?
  (e.g. Condon et al. 2012, ApJ)
- Spectral line observations: Is there RFI at or near your line frequency?
- Dynamic range: Is there a very bright source in the field? Are there bright sources at or below the half-power point of the primary beam?
- Spectral dynamic range: Do you need very accurate bandpass calibration?
- Bandpass calibration: Does your calibrator also have a line in its band?
- Is your source in the Galactic Plane? Do you need extra time to measure the system temperature or for bandpass calibration?
- Do you need to mosaic, to cover a wide area?
- Do you need help? If you ask this question, the answer is yes!

The GMRT Exposure Time Calculator

http://www.ncra.tifr.res.in/etc

- Calculates the *theoretical* time needed to achieve a given RMS noise, or the *theoretical* RMS noise achievable in a given on-source time.

- Sensitivity estimates based on the measured GMRT sensitivity and the contribution of the sky background at the observing frequency.
(Haslam et al. 1982, A&AS)

- Allows the user to enter her/his estimate of a *Fudge Factor* to obtain the true on-source time needed to achieve a given RMS noise.

- Allows the user to enter his/her estimate of additional overheads, over the defaults (e.g. for bandpass calibration, polarization calibration, …)

- Estimates the confusion limit at the observing frequency.
(Condon et al. 2012, ApJ)

- Searches for bright sources within the field of view, and out to the first null, and provides warnings if the dynamic range is likely to be high.

- Estimates the angular resolution, assuming uniform weighting.

Writing the Proposal

(Highly opinionated!)

- Formally, four parts: The proposal coversheet.
  The science case.
  The technical justification.
  The ETC output.

- The coversheet: Write a coherent abstract! This does influence referees. If you're a Ph.D. student, write a good description of your thesis project, and why the proposed observations are important here.

- The science case: *Always* check spelling! Do *not* trust spell-checkers! Read the proposal out loud, and *listen* to the sound and the argument. Unless you write very well, use short sentences. Define all acronyms.

- The technical case: Should be self-contained, explaining (e.g.) the band, bandwidth, angular resolution, spectral resolution, velocity coverage, UV coverage, and sensitivity, and the required time. Should justify the assumed Fudge Factor and overheads (if different from the ETC). Should discuss issues like RFI and dynamic range, if relevant.

Before the Observations: The Calibrators

https://science.nrao.edu/facilities/vla/observing/callist
http://gmrt.ncra.tifr.res.in/~astrosupp/calib/vlacal.html (Santaji Katore)

- **Flux calibration:** One (or two!) of 3C48, 3C138, 3C147, 3C286, 3C295. Note: 3C295 is resolved by the GMRT's long baselines; be careful!

- **Phase calibration:** "Point" source within $\sim 10^\circ$ of the target; $S_\nu \gtrsim 1$ Jy.

```
0137+331   J2000  B 01h37m41.299431s 33d09'35.132990'' Aug01 3C48
0134+329   B1950  B 01h34m49.826400s 32d54'20.259000''
-----------------------------------------------------
BAND         A B C D    FLUX(Jy)    UVMIN(kL)  UVMAX(kL)
=====================================================
 90cm    P   S S S S      42.00
 20cm    L   X P P P      16.50                    40
  6cm    C   X S P P       5.48                    40
3.7cm    X   X X S P       3.25                    40
  2cm    U   X X S P       1.78                    40
1.3cm    K   X X X S       1.13                   100
0.7cm    Q   X X X S       0.64                   100
```

D ≡ 1 km
C ≡ 3.3 km
B ≡ 11 km
A ≡ 35 km.
GMRT ≡ B+ or A-!

Every ~45m at Bands 4 and 5, ~ 40m at Band–3, ~ 30m at Band–2.

- **Bandpass calibration:** Should not add to the RMS noise on the target!!!
  ⇨ S/N on the bandpass calibrator should be $\gg$ than S/N on the target.
  ⇨ $\Delta T_{BP} \gg \Delta T_{SOURCE} \times (S_{BP}/S_{SOURCE})^2$. Ideally, your phase calibrator!!!

FREQUENCY SETTINGS

- Continuum: Use GMRT defaults, unless there's a *very* good reason.

- Spectral lines: Must choose the local oscillators.
  Aliasing: Choose filters to filter out the "image response"!

- GWB: Single Local Oscillator ("GAB LO") sets the edge of the band.
  Upper sideband ($\nu_{LO} < \nu_{RF}$) ⇨ Observing band = ν_{LO} to (ν_{LO} + BW).
  Need to filter out image response at ν_{RF} to (ν_{RF} – BW).

- GSB: Band edge set by a combination of two oscillators (LO1, LO4).
  Upper sideband ($\nu_{LO1} < \nu_{RF}$) ⇨ Band = ($\nu_{LO1} + \nu_{LO4}$) to ($\nu_{LO1} + \nu_{LO4}$ + BW).
  Need to filter out image response at ($\nu_{LO1} - \nu_{LO4}$) to ($\nu_{LO1} - \nu_{LO4}$ - BW).

- Image response excluded via the front-end filters! For narrow bandwidths, front-end sub-bands (width ~ 100 MHz) used to exclude the image.
  Band–3: 250 – 500, 250 – 340, 300 – 400, 350 – 450, 400 – 500.
  Band–4: 550 – 850, 550 – 650, 635 – 735, 720 – 820, 800 – 900.
  Band–5: 980 – 1500, 1000 – 1120, 1110 – 1230, 1220 – 1340, 1330 – 1450.

FREQUENCY SETTINGS

- GSB settings: Can use "tune" to select the LO's. But one has to choose the front-end sub-band carefully, to filter the image response.

  http://gmrt.ncra.tifr.res.in/~astrosupp/tune/tune.html (Santaji Katore)

- GWB settings: For narrow-bandwidth observations, the DDC ("digital down-conversion") LO is used, to select the GWB band.

- E.g. Spectral line at 450 MHz, with a bandwidth of ~ 4 MHz:

  GSB: BW = 4.167 MHz. Band ~ 448.2 – 452.3 MHz.
  LO–1 = 520 MHz, IF BW = 18 MHz, LO–4 = 63.5 MHz,
  Digital sub-band = 1.

  GWB: BW = 3.125 MHz ⇨ Band ~ 448.4 – 451.6 MHz.
  GAB LO = 500 MHz, Sideband flag: 1 (LSB), ACQ BW = 100 MHz,
  DDC = 1, Decimation Factor = 32, DDC LO = 48.4 MHz.

- Note: If LO < 450 MHz ⇨ Aliasing with the full 250 – 500 MHz band! To avoid aliasing, one would have to use the 400 – 500 MHz sub-band.

Correlator Issues

- Do you need both correlators? Yes, only for multiple spectral lines!
  E.g. one could cover multiple narrow recombination lines or the four (redshifted) ground-state OH lines in a single run, by using the GWB in narrow-band mode to cover one frequency, and the GSB to cover a different frequency.

- GWB settings:
  Integration time: Typically, ~ 10 seconds (minimum time ~ 0.67 seconds).
  Number of channels = 2048 (could use more channels for data editing).
  ⇨ File size (FITS) ~ 60 GB, in a 10-hour observing run.

- GWB narrow-band modes: ~ 25% higher noise in the upper 25% of the band; especially relevant for narrow bandwidths, $\leqslant$ 12.5 MHz.

- Frequency-switching for bandpass calibration (e.g. for Galactic HI 21cm absorption): Use *in-band frequency-switching*!
  This implies a wider GWB bandwidth and so, more channels (i.e. larger file size), but improves the final sensitivity by sqrt(2)!

Command Files and Source Lists

- GMRT observations use “command files”, which are run by the operators to execute a set of commands to the antennas.

- Source names and co-ordinates should be listed in a text file, on the main GMRT control computers.

- Online command file and source list (and settings!) creator:

  http://www.ncra.tifr.res.in:8081/~secr-ops/cmd2/cmd.html

  (Santaji Katore)

  Show the resulting command files and settings to a regular user!

- Check rise/set times of all sources (target and calibrators)!

  http://www.ncra.tifr.res.in/~secr-ops/obs_setup/rst.html

  (Santaji Katore)

- Send all settings, command files, and source lists to the control room *at least 3 days (preferably, a week) before the observations*!

During the Observations

- *Don't* be an absentee astronomer! Data quality tends to improve if the astronomer is present for observations (or it feels that way!). You also learn about new modes, and solutions to problems. And, if there's a goof in the settings, you can fix it right away!

- Monitoring tools: http://gmrt.ncra.tifr.res.in/~astrosupp/mon/gmon.html

(Santaji Katore)

- Inspect the data while they're being taken! This can help in cases of RFI or malfunctioning antennas. Or if the flux density of the phase calibrator has dropped significantly (due to variability)…

- In the control room: Use "matmon", "bandmon", and "mon", to inspect the data as they're coming in.

- Use "*tax*" to inspect the correlator data from the LTA file.

(Sanjay Kudale, Sanjay Bhatnagar)

- Talk with the operators!!! And make notes during the observing run.

DON'T PANIC!

And always carry a towel.

(Douglas Adams)

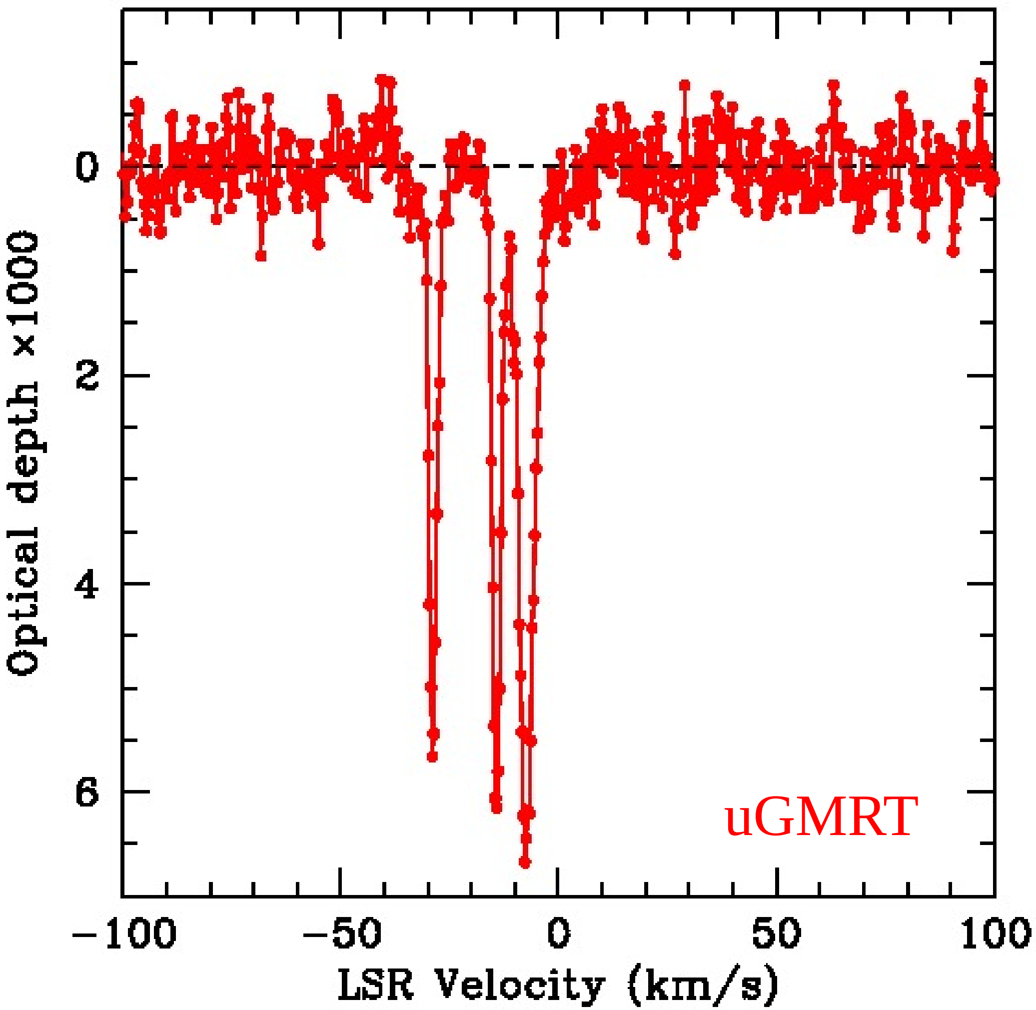
If you've goofed your settings horribly, don't worry; we've all done this.
Speak sadly to the operations folk and you may get the time again.
And, if not, at least you'll have a good story for your Nobel lecture.

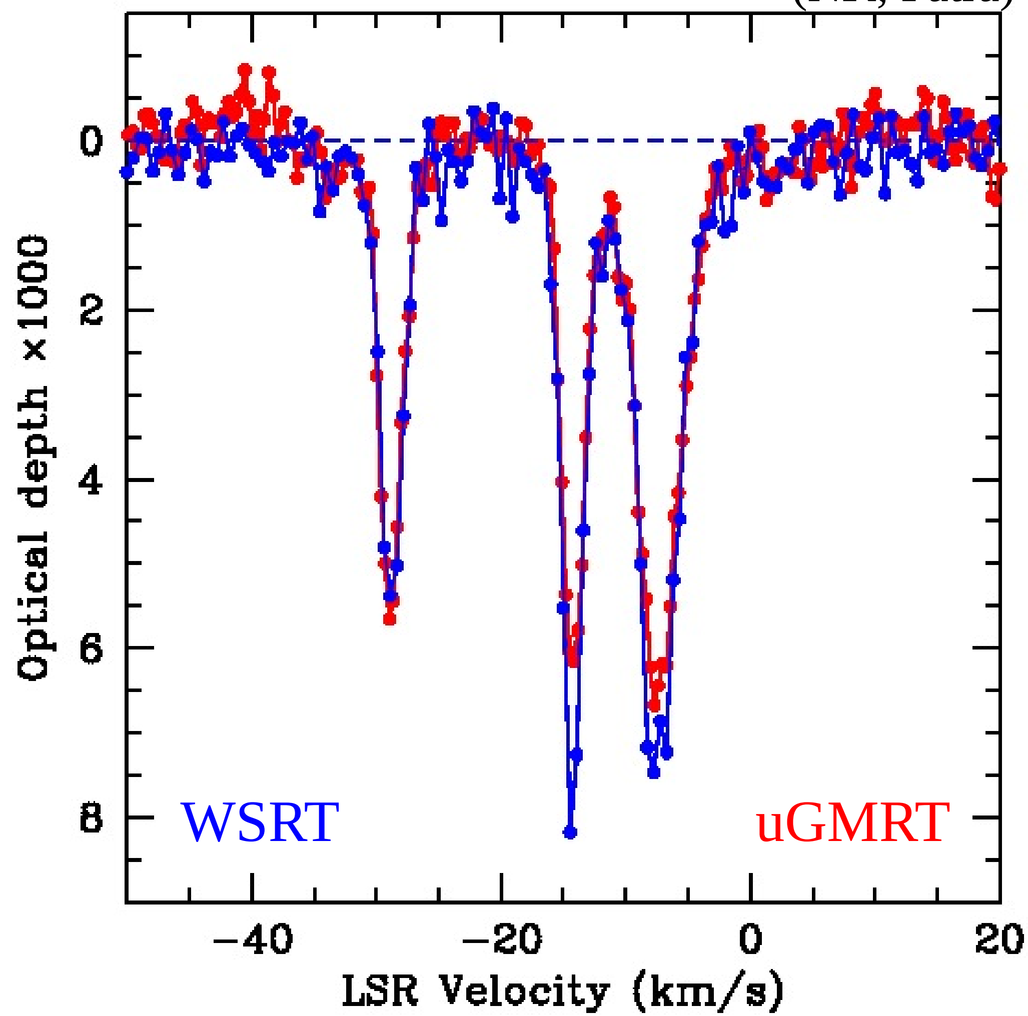
The GMRT Wideband Backend (GWB)

- Optical fibre system brings 50 – 2000 MHz RF band from antennas.
- Analog Backend system: Converts to 0 – 400 MHz baseband.
- "Hybrid correlator": Analog-to-digital conversion followed by packetization on FPGA's, and a CPU – GPU correlator. Dual Tesla K40 GPU's on each of sixteen T630 nodes.
- 100, 200 and 400 MHz input bandwidths; 2,048 – 16,384 channels. Narrow-band modes: 100 MHz – 0.39 MHz, in steps of 2. Pulsar and beamformer modes; full polarization.
- 8-bit correlator for bandwidths $\leqslant$ 200 MHz; 4-bit for 400 MHz.
- Online RFI mitigation tools now being developed on FPGA's. Plan to port to GPU's soon.
- Parallel signal path for the old GMRT Software Backend (GSB).

Spectral Lines: Frequency Switching

(NK, Patra)





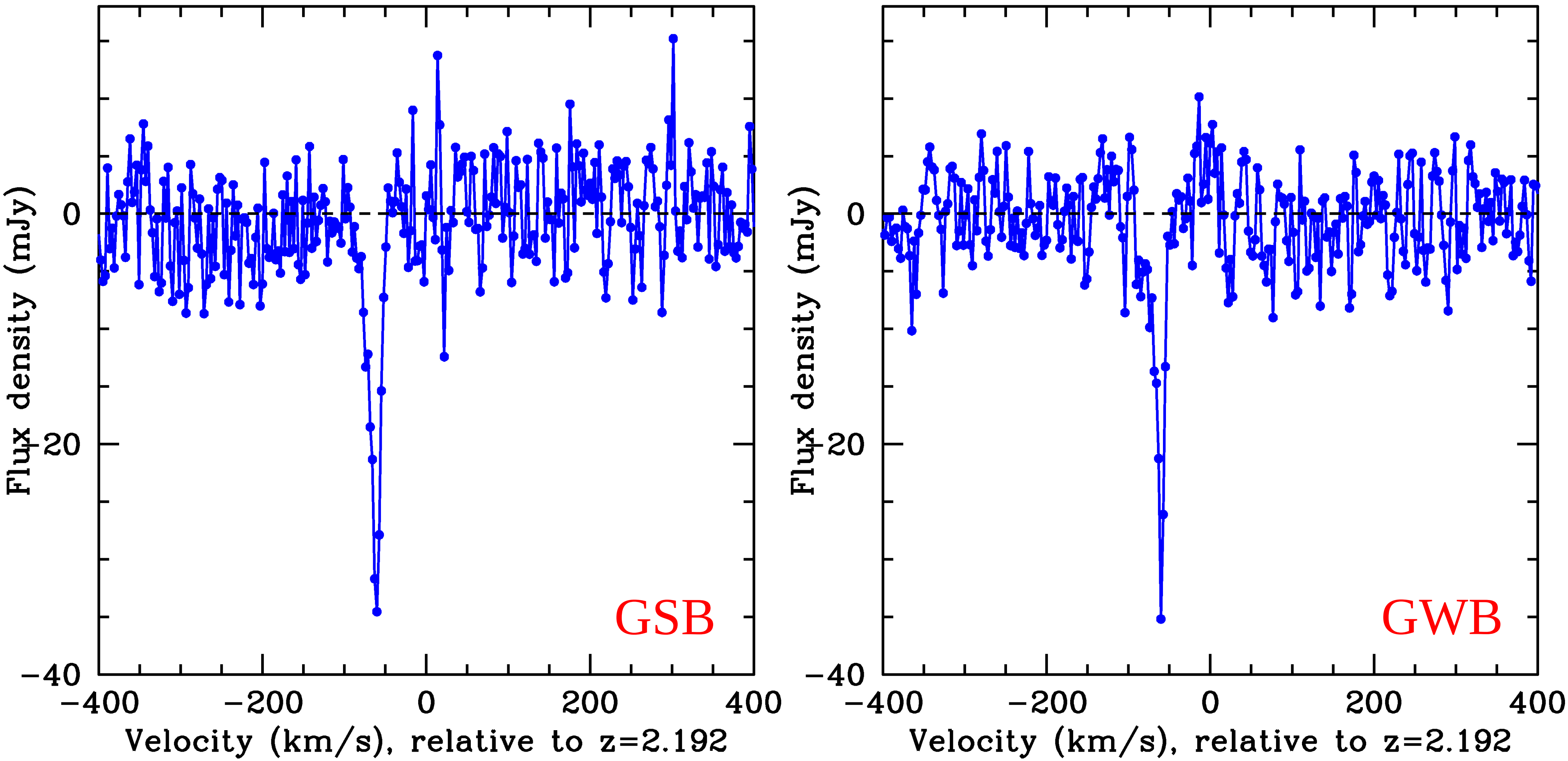
- First high-spectral resolution (0.3 km/s) uGMRT HI 21cm spectrum! Sensitivity in 5-hour observing run similar to that of the best-ever Galactic HI 21cm spectrum (using WSRT for ~ 24 hours!).

(Braun & NK 2005, A&A-Lett.)

- Clear changes in line profile: Small-scale structure in the cloud!

SPECTRAL LINES: ONLINE RFI MITIGATION

(Muley, Buch, NK)



- RFI spikes replaced by noise before correlation in the GWB data. No RFI mitigation in the *simultaneous* GSB data (daytime run).
- RMS noise in GWB spectrum 20% lower than in GSB spectrum.

The Upgraded GMRT

(Gupta et al. 2017, Curr. Sci.)

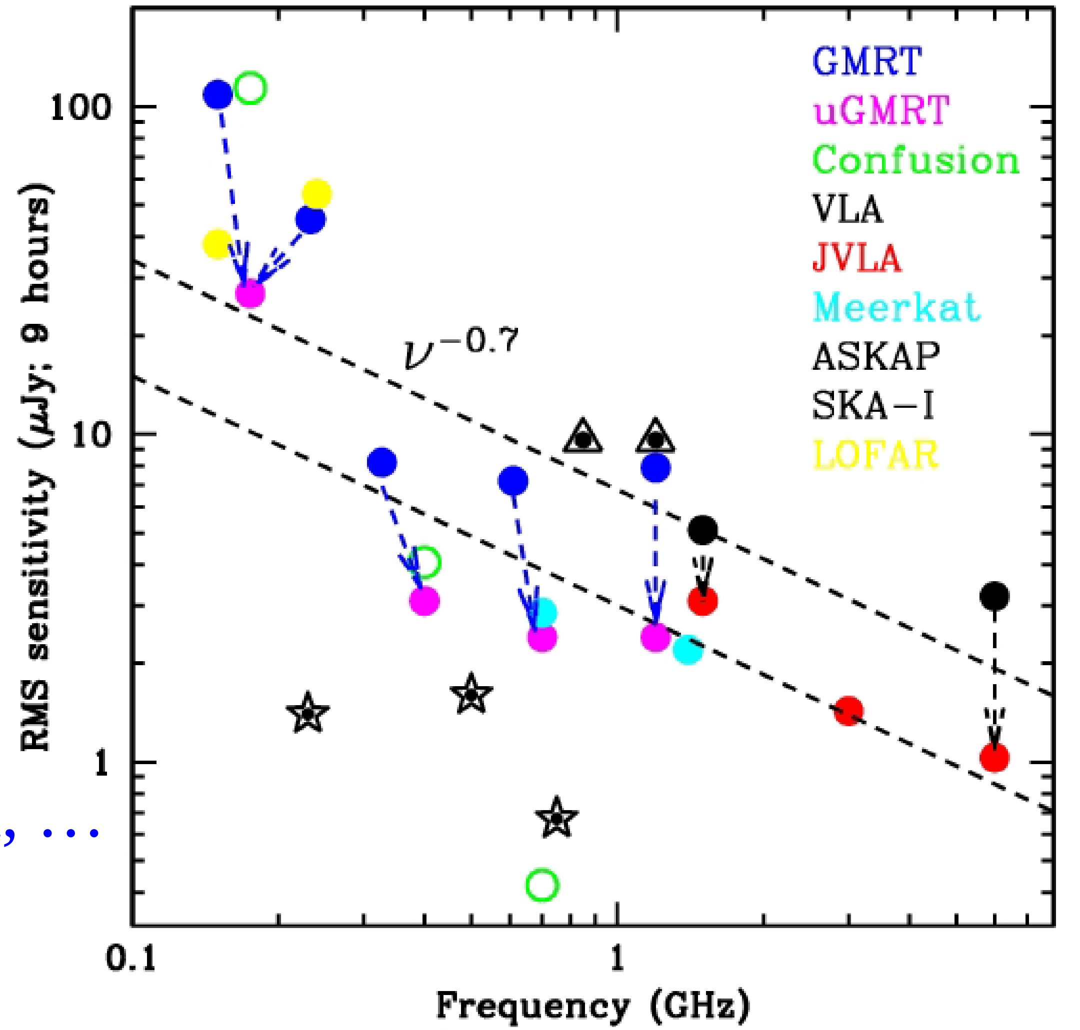
- Proposed ~ 2007; begun ~ 2010.

- New wide-band receivers:
  125 – 250 MHz; 250 – 500 MHz;
  550 – 850 MHz; 1.0 – 1.5 GHz.

- GMRT Wideband Backend:
  400 MHz BW, 16384 channels.

- New, cleaner signal path, new algorithms to excise RFI, new servo & antenna control system, …

- Continuum, pulsar sensitivity better by a factor of ~ 3!



- Uniform* frequency coverage ⇨ Great HI 21cm redshift coverage!

- Correlator, signal path, all receivers done: Observations under way!