Large-aperture Experiment to Detect the Dark Ages

Unique science: directly constrain 30 > z > 15 cosmology

Innovative technology and instrument development

Scalable large-N correlation and calibration

Array calibration for total power msrmnt

Effective, experienced team

Low risk

HI cosmo.

CASPER

LEDA

LWA

CDI: SciGPU

cuWARP

LEDA Prècis

- ATI development proposal
  - technology, instrumentation, technique, & training
- Field demonstration
  - deploy full-correlation back-end on LWA-1
  - add three outriggers within 1 km
    - noise switched front end
    - consider antenna design w/ improved impedance match
  - largest-N correlation system worldwide; O(10) kW, *O*(1) rack
- Breakthrough science
  - HI cosmology at very high redshift (z>15)
  - τ_{int} = *O*(weeks) *only!*
- Generalizable & scalable (e.g., PAPER, HERA)
- Cross-disciplinary applications (OCI, AGS)

LEDA Status

- 10 Nov 03 Proposed to NSF/ATI program
- 11 Apr 14 Reverse Site Visit @ NSF
  - LEDA, PAPER, MWA, Omniscope
  - Pending AST budget
- 11 May 01 SciGPU $ for FY11 demo
  - 32 or 64 antennas
  - spare parts / current generation
- Deployments pending support
  - LEDA64 from June 2012
  - LEDA512 from June 2013

LEDA Program Goals

- Meaningful observational constraints on HI absorption against the CMB near 60 MHz ($z \sim 20$)
  - Sky-averaged (DC) signature
  - Eye toward detection
- Place constraints on reionization initial conditions
- Demonstrate unique technical approaches
- Complement other HI experiments: $z < 10^{\pm}$
  - EDGES (DC), PAPER, MWA, LOFAR, GMRT (∡Pwr. Spect.)

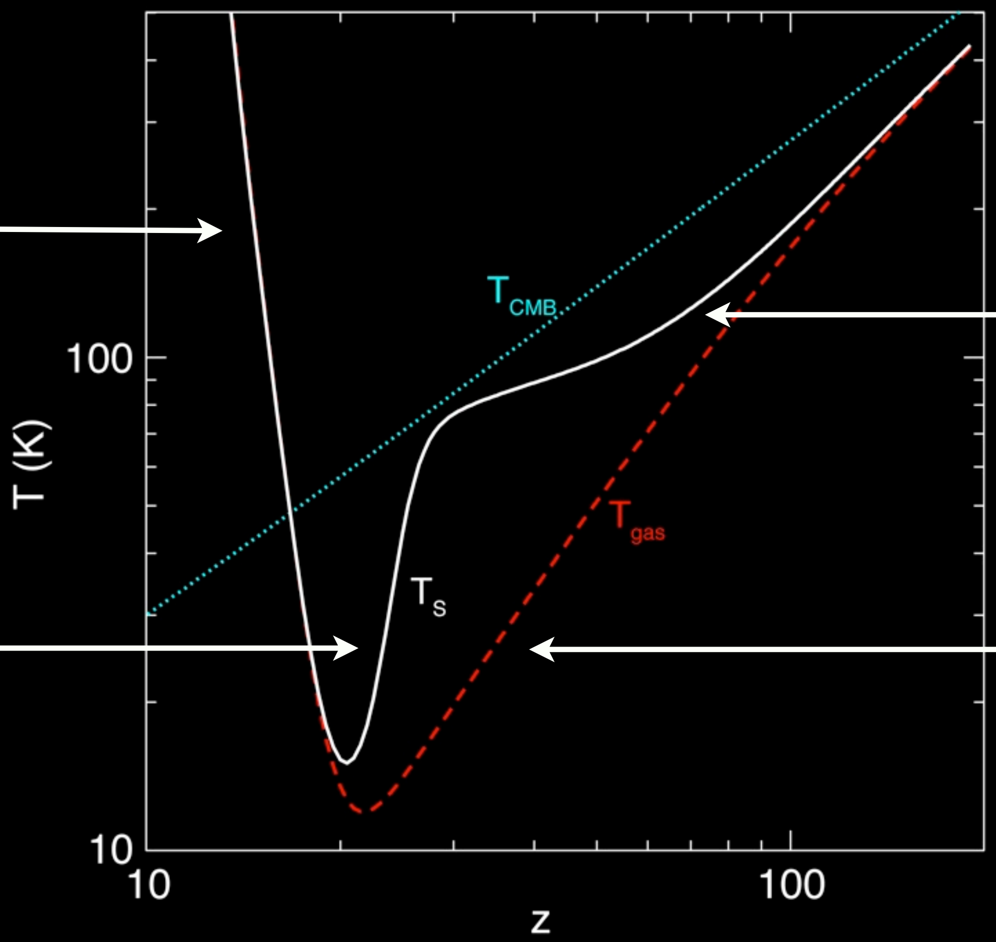
Science and Inference

The Physics of the 21cm Line

$$\delta T_{21} = 28\, x_H\, \Delta_b \frac{T_S - T_{\rm CMB}}{T_S} \left(\frac{1+z}{10}\right)^{1/2} \text{mK} \qquad T_{\rm S}^{-1} = \frac{T_{\rm CMB}^{-1} + x_c\, T_{\rm gas}^{-1} + x_\alpha\, T_{\rm rad}^{-1}}{1 + x_c + x_\alpha}$$

X-rays reheat

radiation from first stars recouples T_s and T_{gas}



Coupling of T_s and T_{gas} is lost

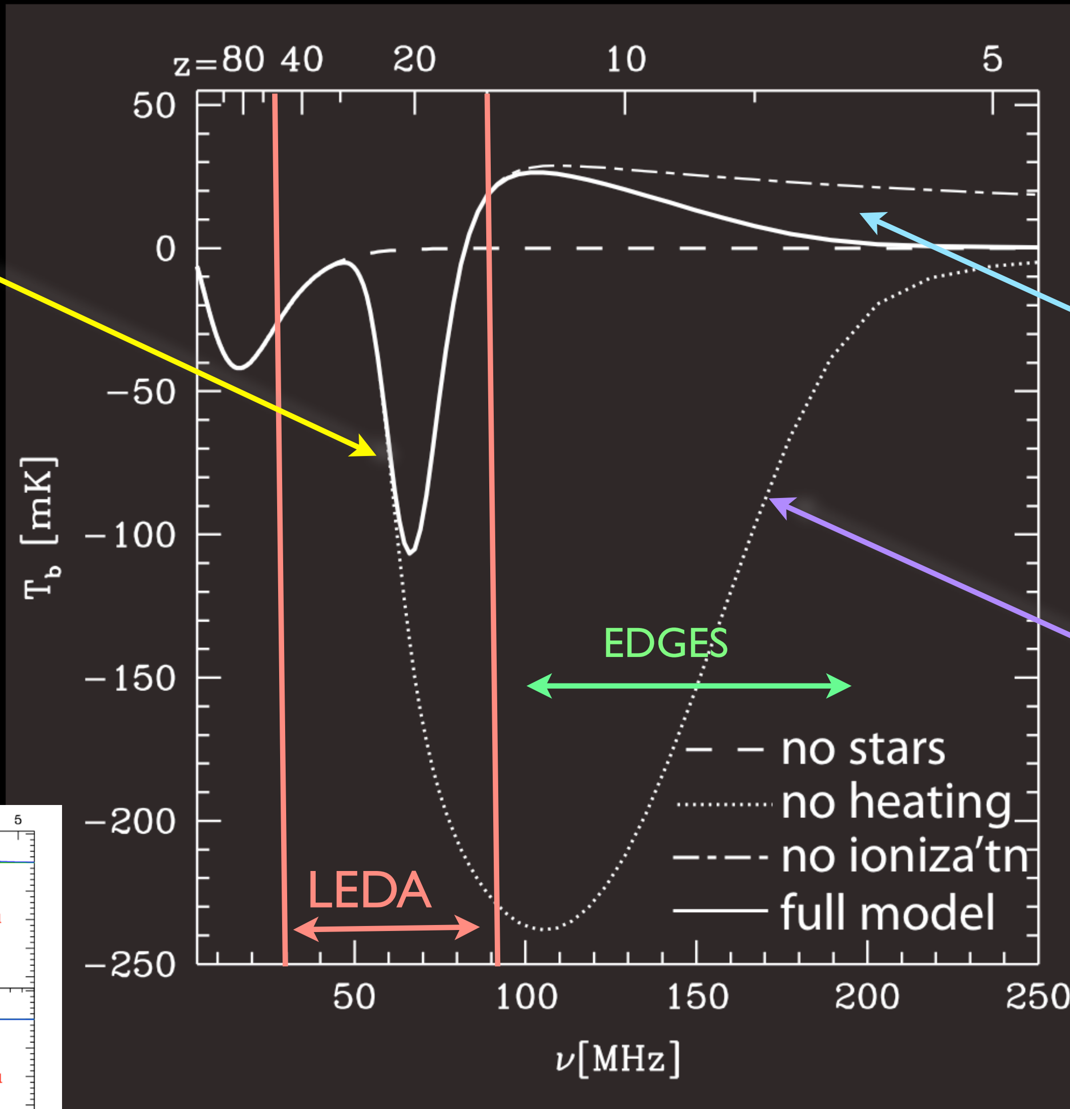
Gas cools adiabatically after recombination

LEDA Science

- Characteristics of HI trough are determined by thermal history at $15 < z < 1000$ and Lyα output
  - formation scenario of 1st stars and galaxies
    - compact pockets <1kpc in size, $\leq 10^8$ solar masses
  - exotic sources of heating: dark matter annihilations/decays, primordial black holes, strings, intergalactic shocks
- Trough is only means to detect IGM @ z>15 (till 2020+)
- Need > 0.1 km^2 to detect ∡pwr. spect. at z > 15
  - *BUT* LEDA may constrain the amplitude now
    - LEDA is a 1st step

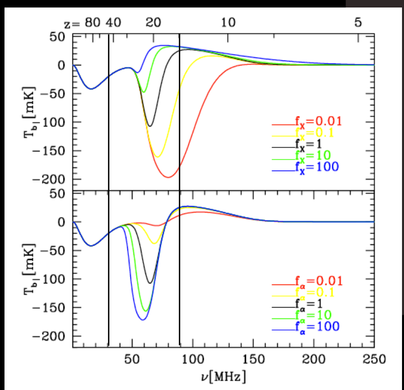
Inference

Lyman-α photon production (likely from stars) determines magnitude of decoupling from the dashed curve



Production of ionizing photons determines the difference between dash-dot and solid curves

Case where IGM not reheated prior to reionization. It takes just 10^{-3} eV per baryon to significantly change this curve.



Inference

• Maximum likelihood fit for sky plus parameterized model for signal;

-- minimal model has 3 physical parameters plus those for foreground/instrument

(1) efficiency for UV photon production

(2) efficiency of X-ray production

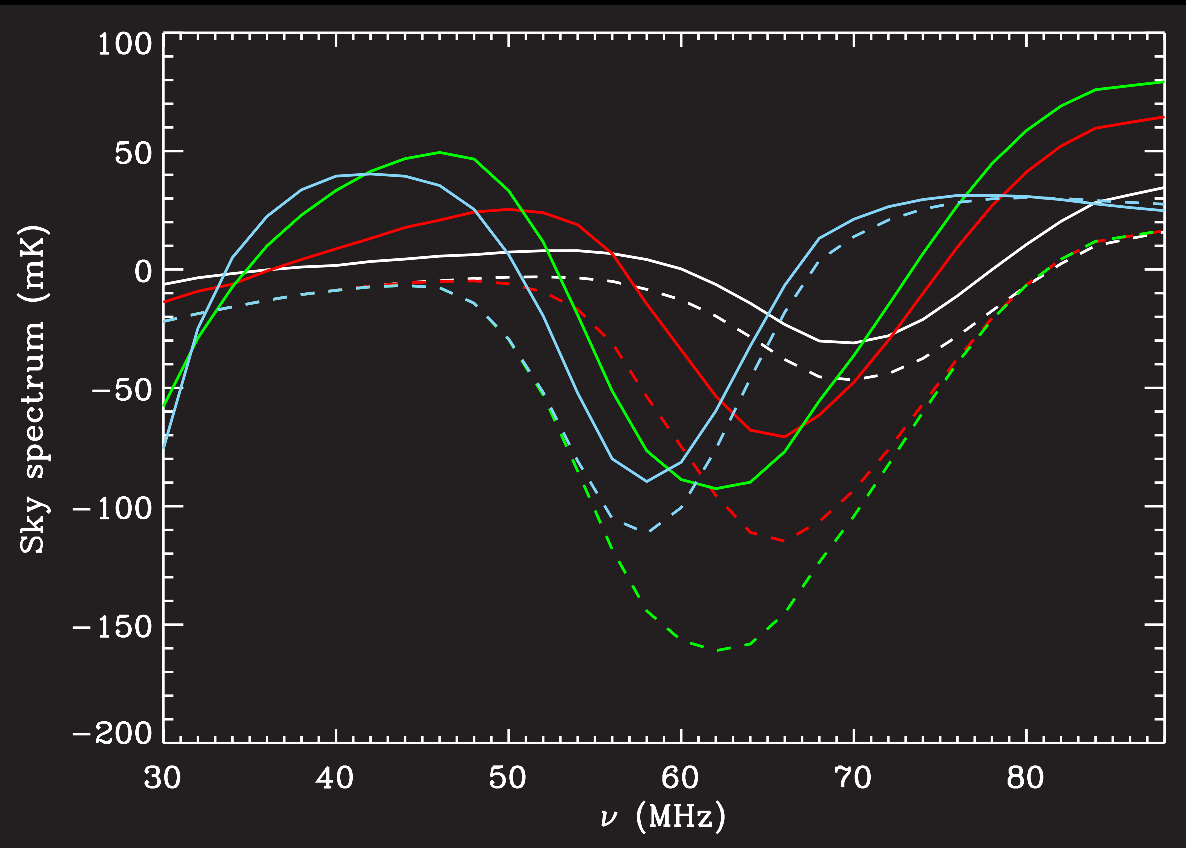
(3) the halo mass of the sources

-- full simulations of systematics will be used to gauge potential biases

-- Fisher Matrix analysis finds that a $\leq 5^{th}$ order polynomial for foregrounds still allows useful constraints on physical parameters

Data Analysis

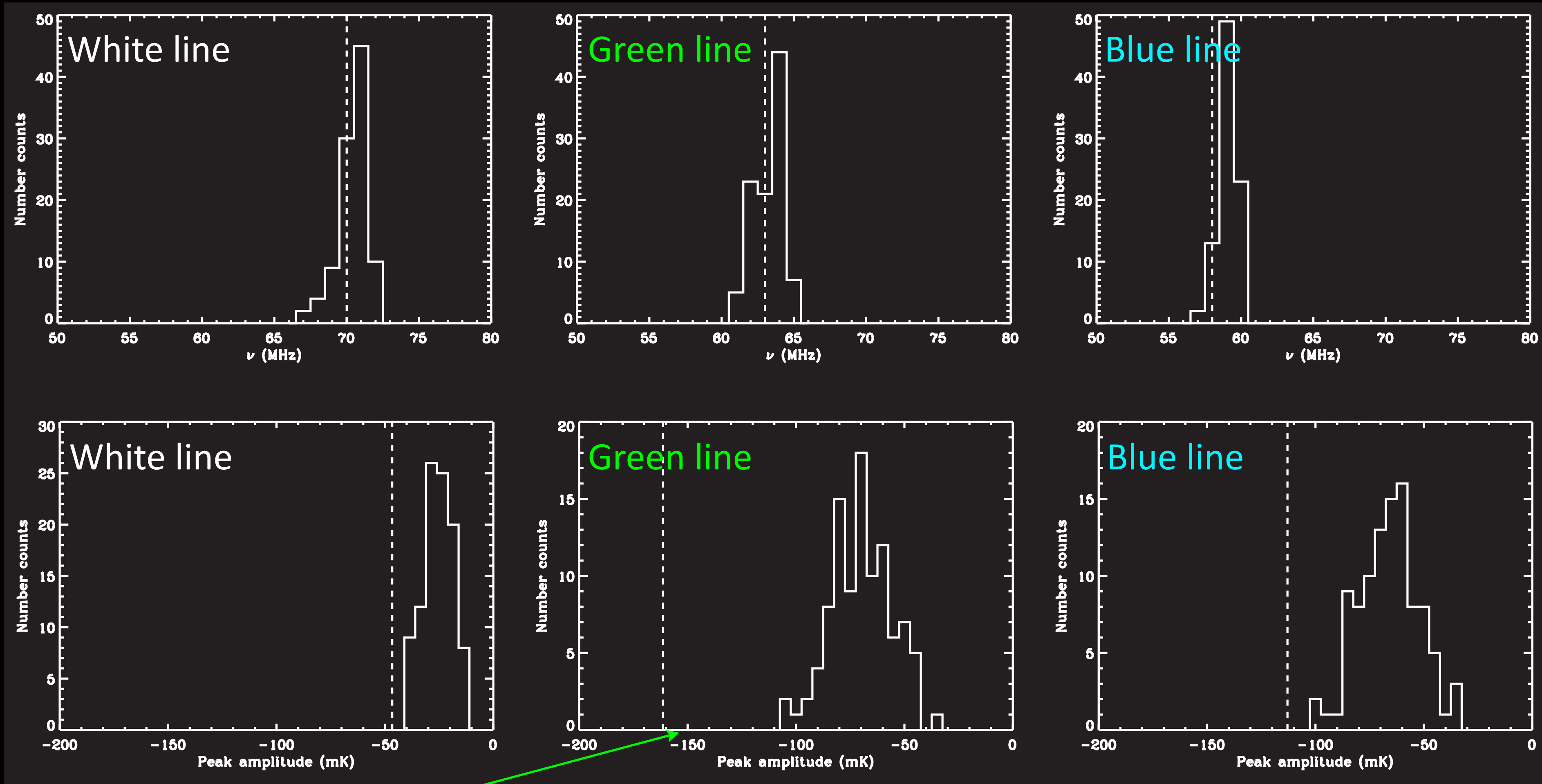
Recovery of Signal



White: F_{ESC}/10 Green: F_{α} x 10

- Sample approach no. 1
- Technique developed to assess readiness
- de Oliveira-Costa et al. (2008) foreground model at 30 & 88 MHz
- position-dependent spectral index estimates ($\alpha_{30\text{-}88}$)
- HI model (dashed line)
- Multiply by a frequency-dependent smooth antenna gain model
- Fit 3rd order polynomial
- Subtract polynomial from total-power data to obtain residual spectrum (solid line)

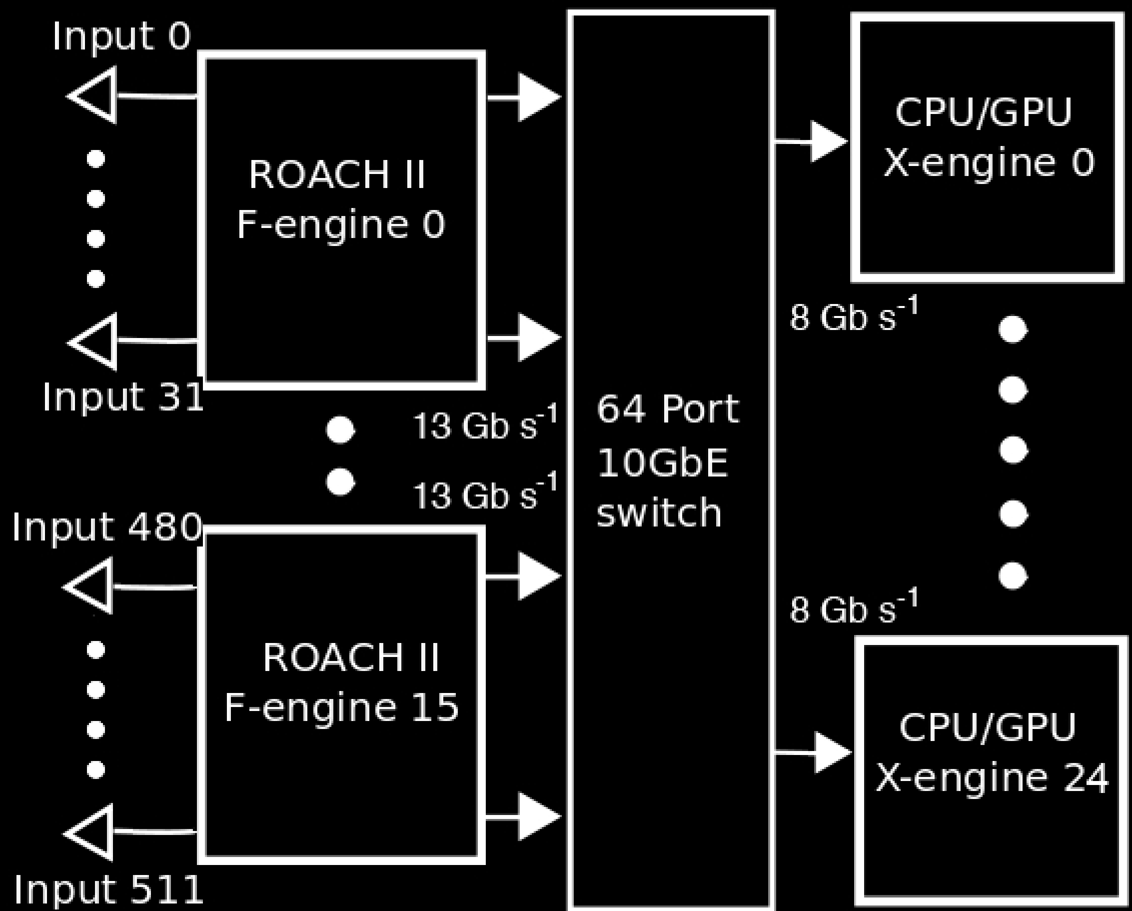
Recovering peak and amplitude position



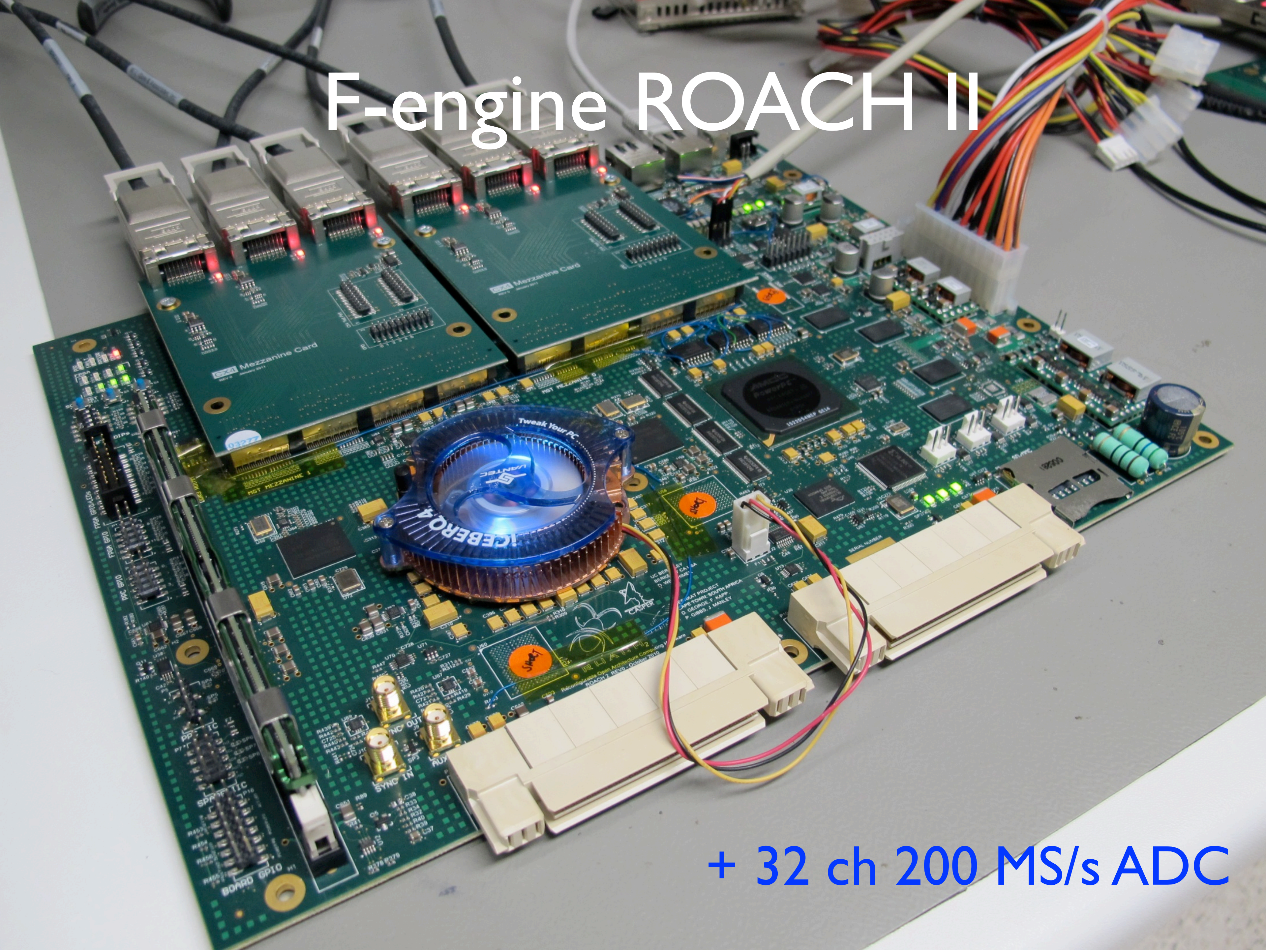
The amplitude bias can therefore be corrected in a statistical way. Peak and amplitude positions can be related directly to the production of UV photons and X-ray heating as a function of redshift

Technical Systems

Hybrid Correlator



F-engine ROACH II



+ 32 ch 200 MS/s ADC

X-engine

F-Engine → (SW) → X-Engine → Gate

Scalable in N_{ant} and BW

N_{ant}=256 x 2 pol.

B = 2 MHz

$N_{ant} \rightarrow O(10^3)$

Eff. ~ 80%

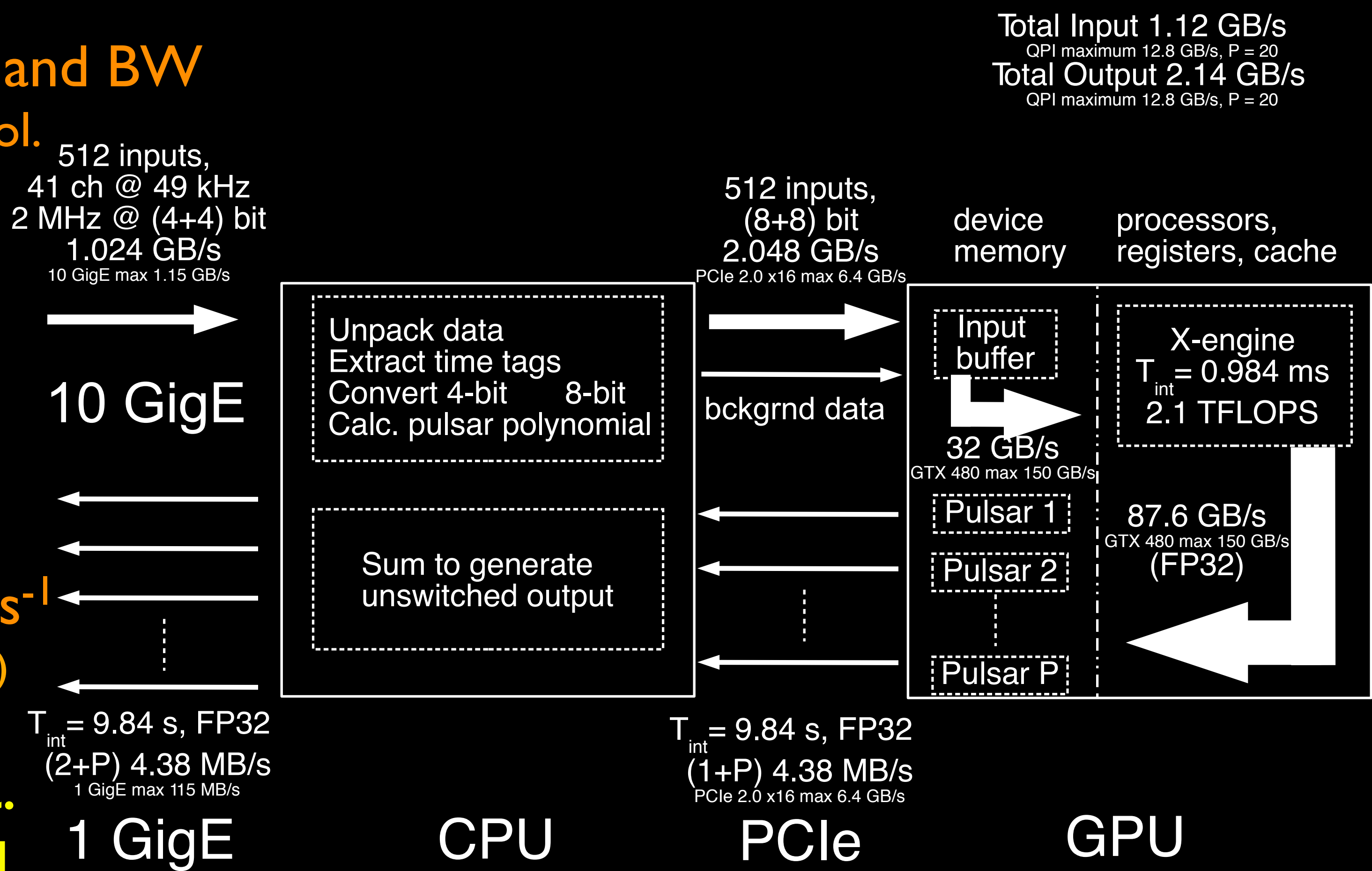
NIC→GPU

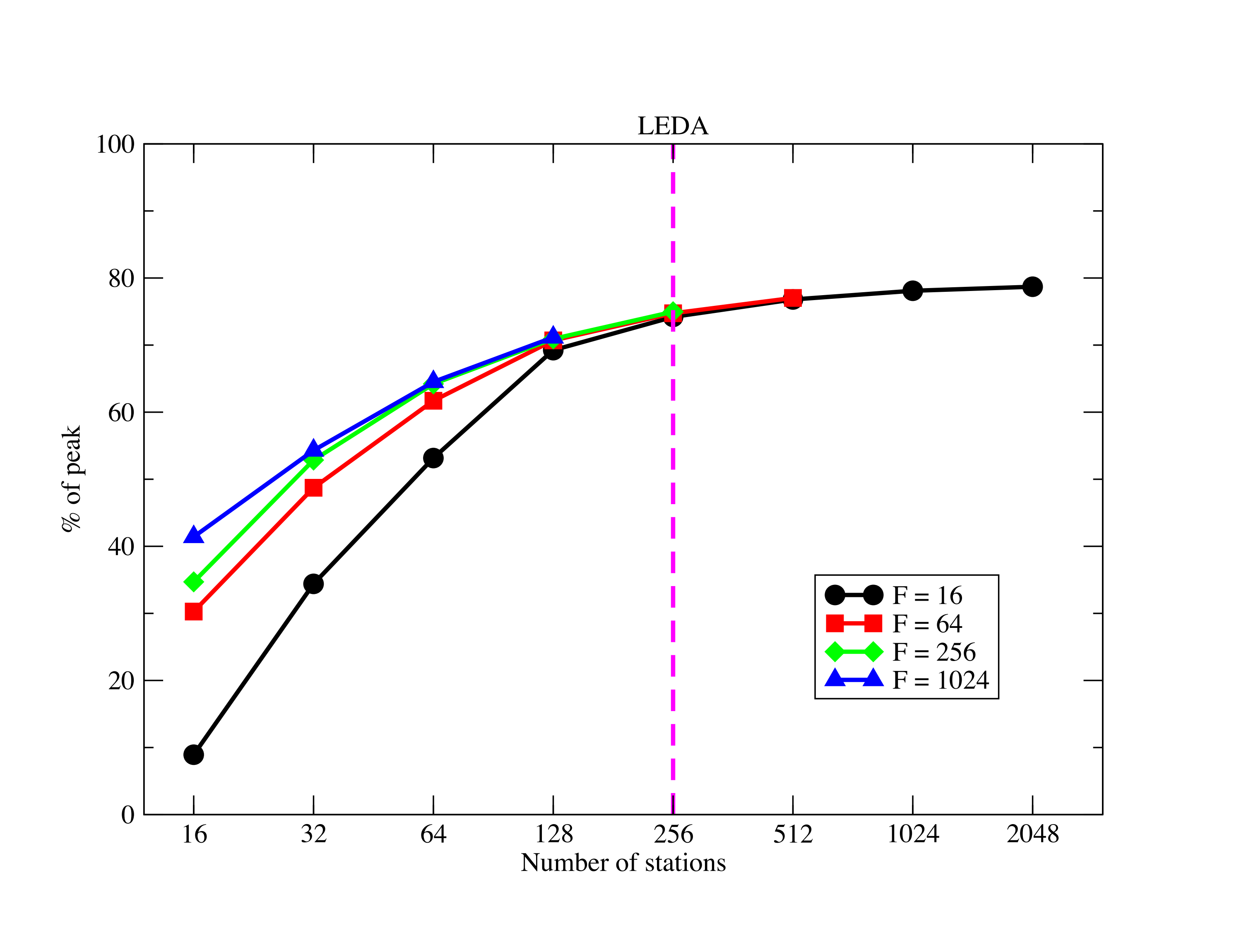
demo'd 9.2 Gb s^{-1}

(18.4 Gb s^{-1} padded)

X-eng. extant.

Benchmarked.



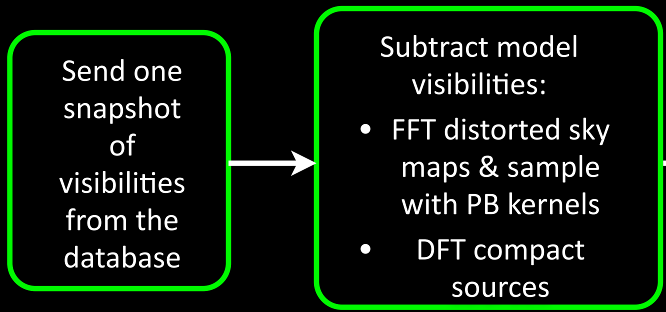


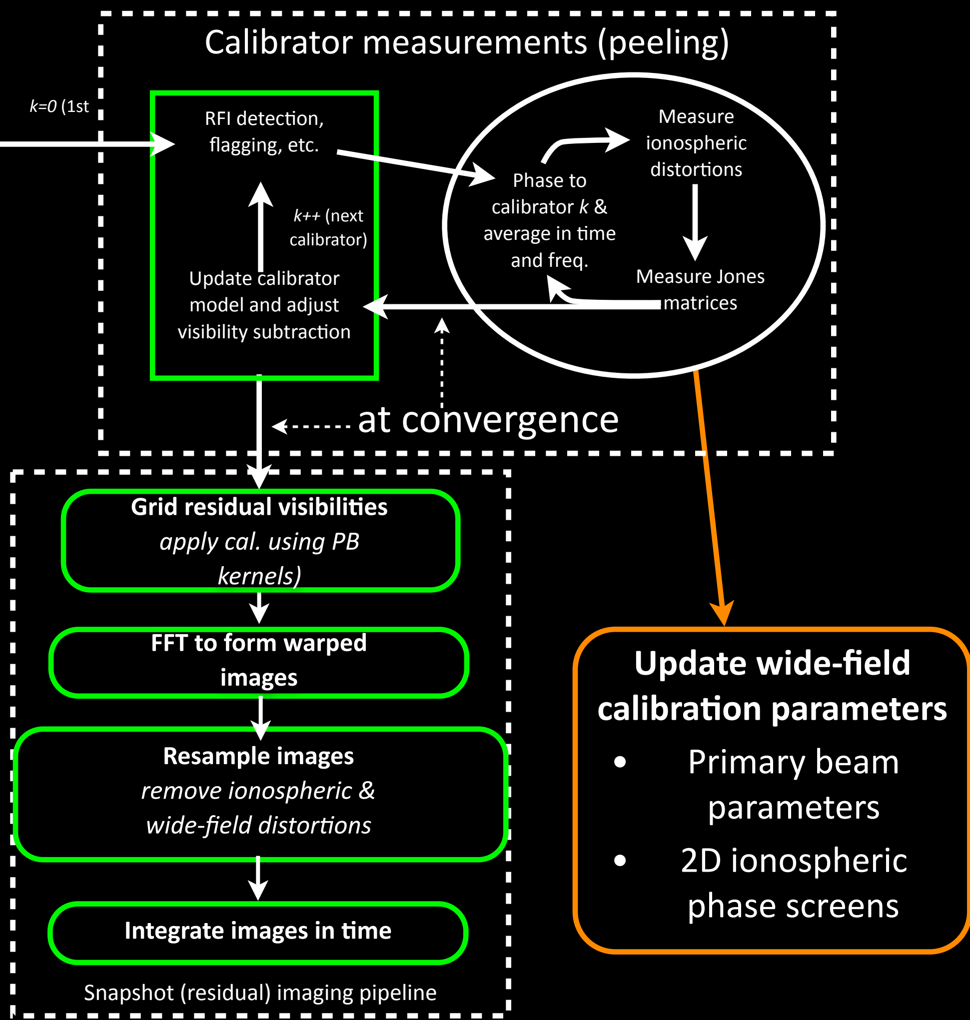
LEDA
100
80
60
40
20
0
% of peak
16
32
64
128
256
512
1024
2048
Number of stations
F = 16
F = 64
F = 256
F = 1024

Calibration System

CUDA Wide-field Array Processing

(cuWARP: after Mitchell et al. '08; Ord et al. '10)



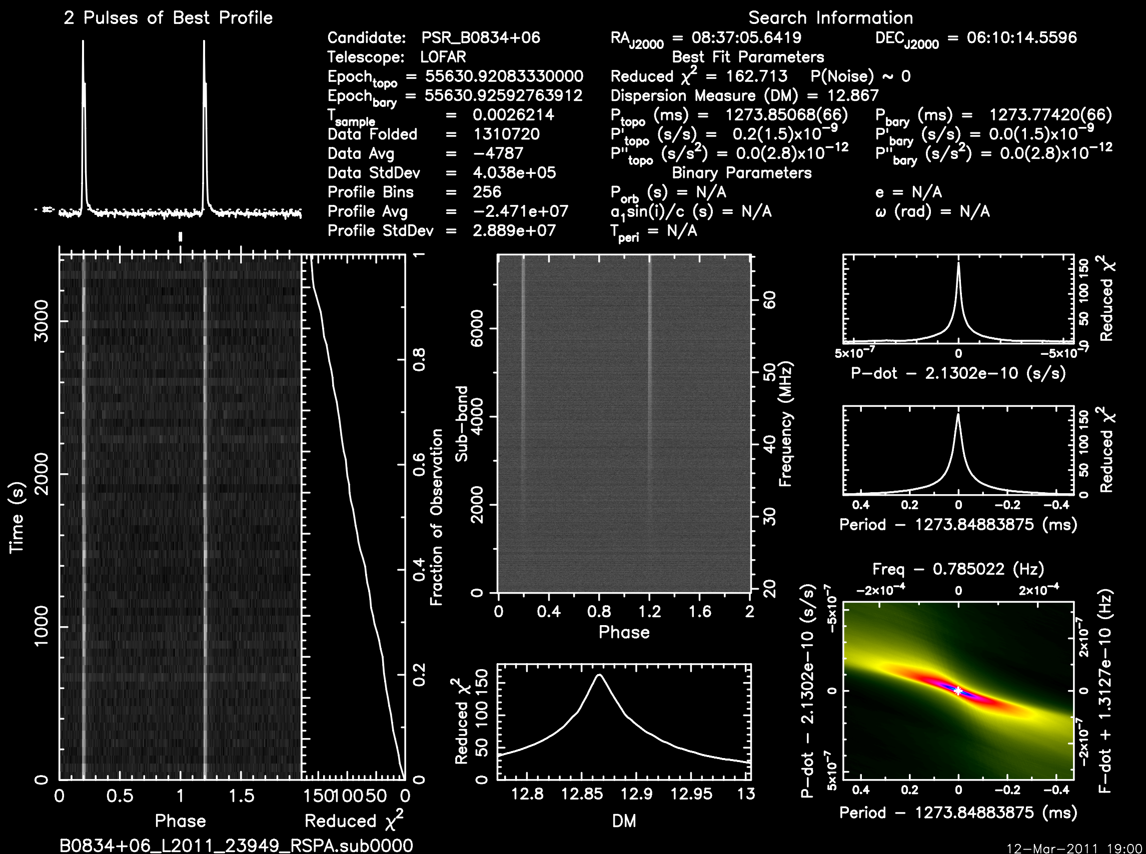


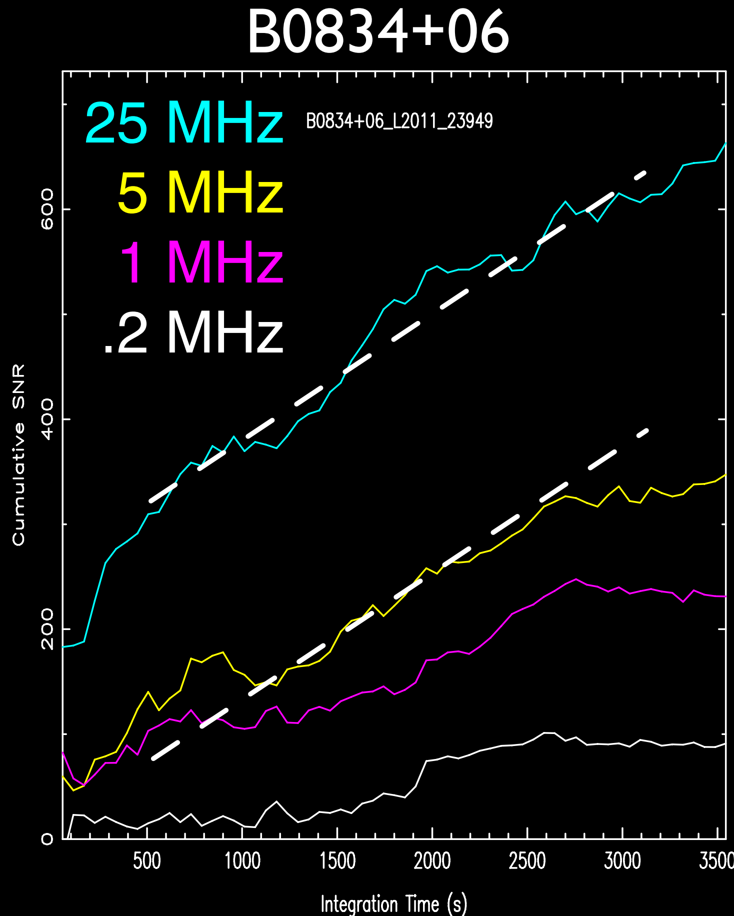
- Stream through the visibility dataset generating calibration models and residual sky maps.
- The residual maps, along with updated calibrator information, are used to update the sky model.
- "on" minus "off" pulsar and lunar visibilities go through the calibrator loop separately, but feed into the wide-field calibration process.
- The whole process is repeated, using the updated sky and calibration models, until the residual images have converged.

Pulsar Calibration

- Calibator obs. are limited by bright point & diffuse srcs.
  - e.g., sidelobe contamination, limits of peeling
- Visibility differences for pulsars (on-off) are unaffected
  - appear as point sources
  - require low duty cycle, DM, and scattering since ν < 90 MHz
- Pen et al. apply this to GMRT data; pulsar at field center
- generalize technique
  - track pulsars through antenna gain patterns
    - derive phase and polarization calibration corrections
    - average over scintils (ν,t) to obtain normalized amp corrxn

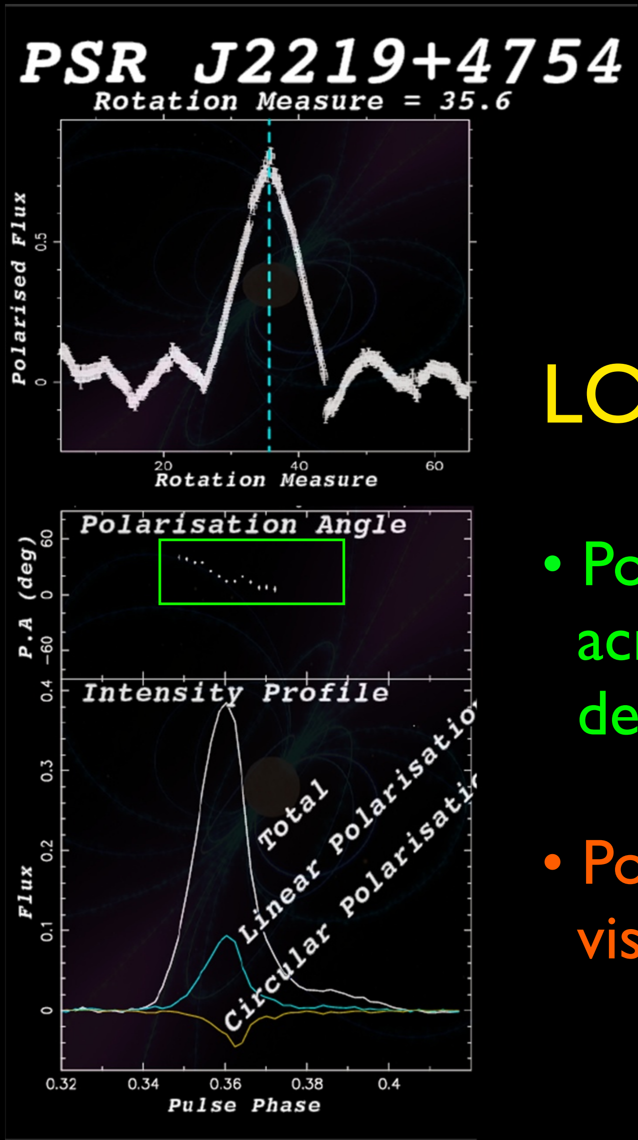
Pulsar Calibration





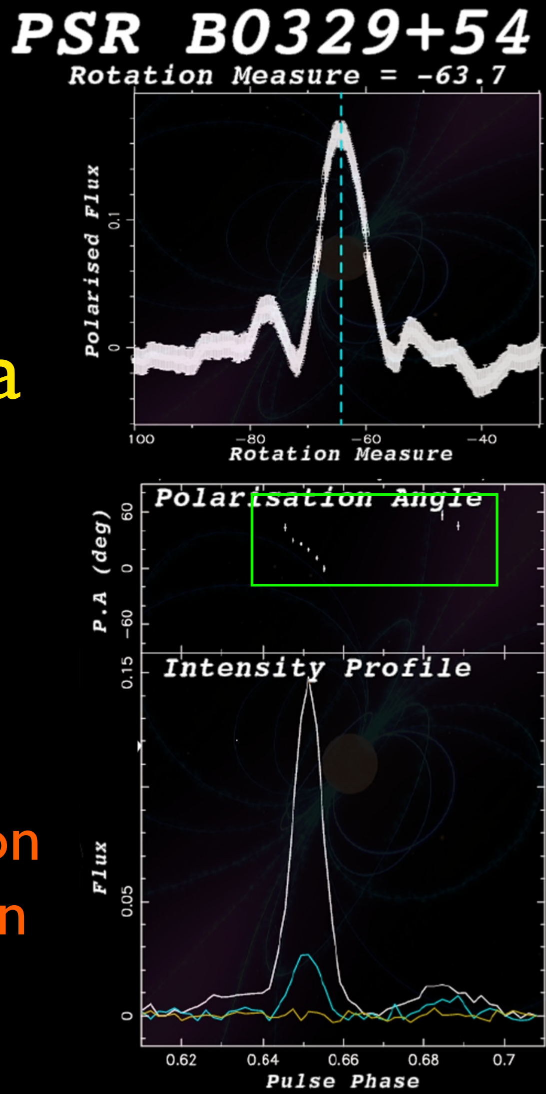
Jason Hessels and the LOFAR Pulsar Working Group

Pulsar Calibration

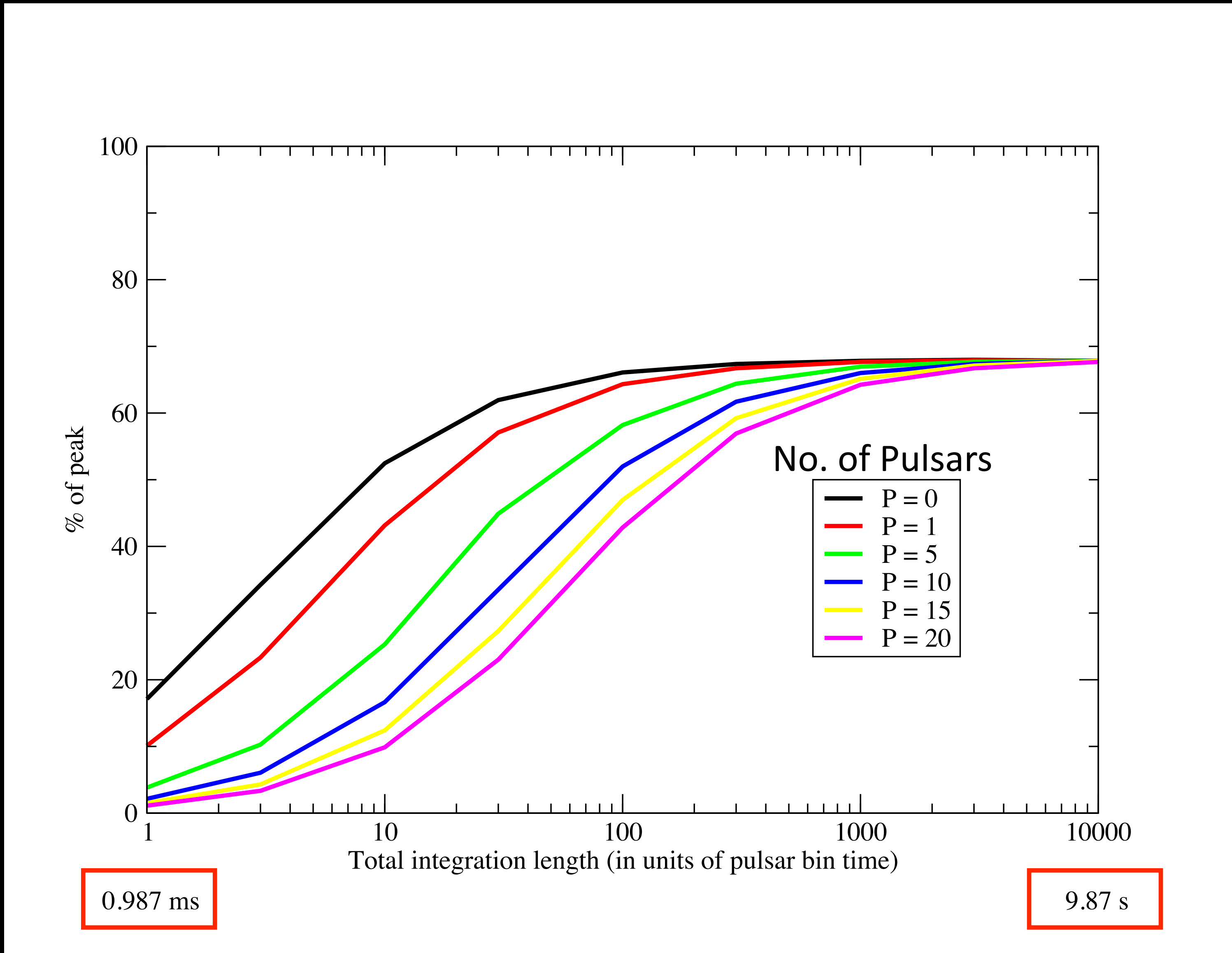


LOFAR LBA Data

- Polarization trace across pulse profile detected, 30-90 MHz
- Positive demonstration vis-a-vis LEDA cal. plan



LOFAR pulsar collaboration



100
80
60
40
20
0
% of peak
1
10
100
1000
10000
Total integration length (in units of pulsar bin time)
No. of Pulsars
P = 0
P = 1
P = 5
P = 10
P = 15
P = 20
0.987 ms
9.87 s

Risk Mitigation

Risk Reduction

Table 1 –Techniques in Mitigation of Systematics

- Compare / combine spectra from outriggers
- Rotate outriggers
- Use 4-point antennas for at least some outriggers
- Use sub-arrays to optimize spectra
- Vary signal paths to correlator
- Optimize ADCs w/r to noise temperature
- Refine antenna gain-pattern calibration
  - Vary calibration parameters: no. of cal. sources, accumulation time, etc
  - Track pulsar phase & polz variation on sky (on-off); vary sample of pulsars
  - Track normalized pulsar amplitudes (on-off) averaged over scintils, for 'stable' sub-sample
  - Explore use of lunar drift to generate on-off
- Correct for direction-dependent antenna gain in gridding step; boost dynamic range of sky model
- Toggle outrigger data on/off in sky model generation to test point source subtraction
- Vary criteria for excision of RFI, e.g., medians, kurtosis, etc

- Diversity in paths for suppression of systematics
- Since 10Nov03
  - tested prototype noise sw
  - X-engine optimized
    - pulsar gate prototype
  - pulsar characterization
    - LOFAR (Hessels et al.)
  - instrument simulator
  - strategy and tools for inferring model parameters

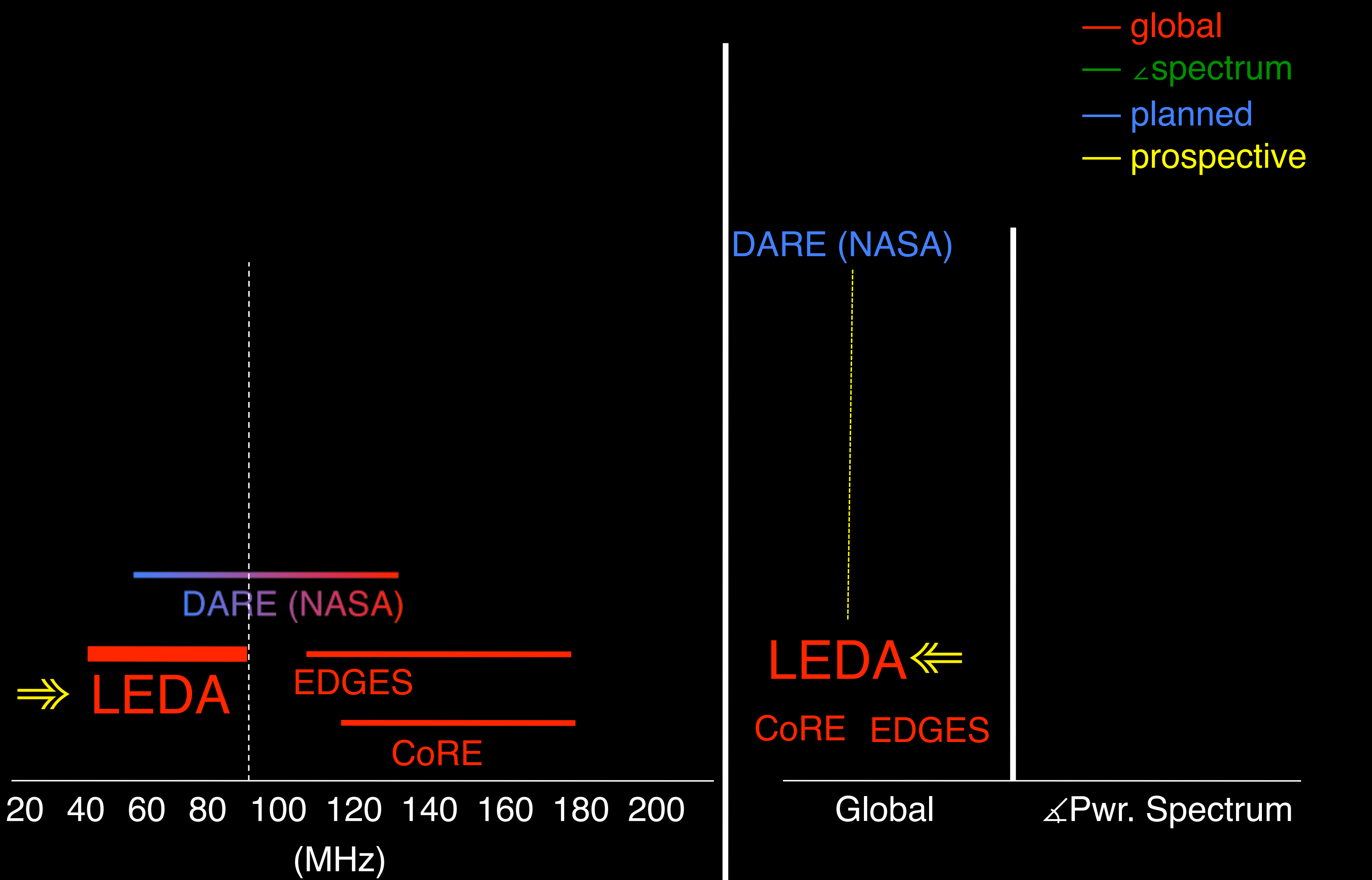
Wrap up –
Where does LEDA fit in?

High-*z* 21cm Experiments

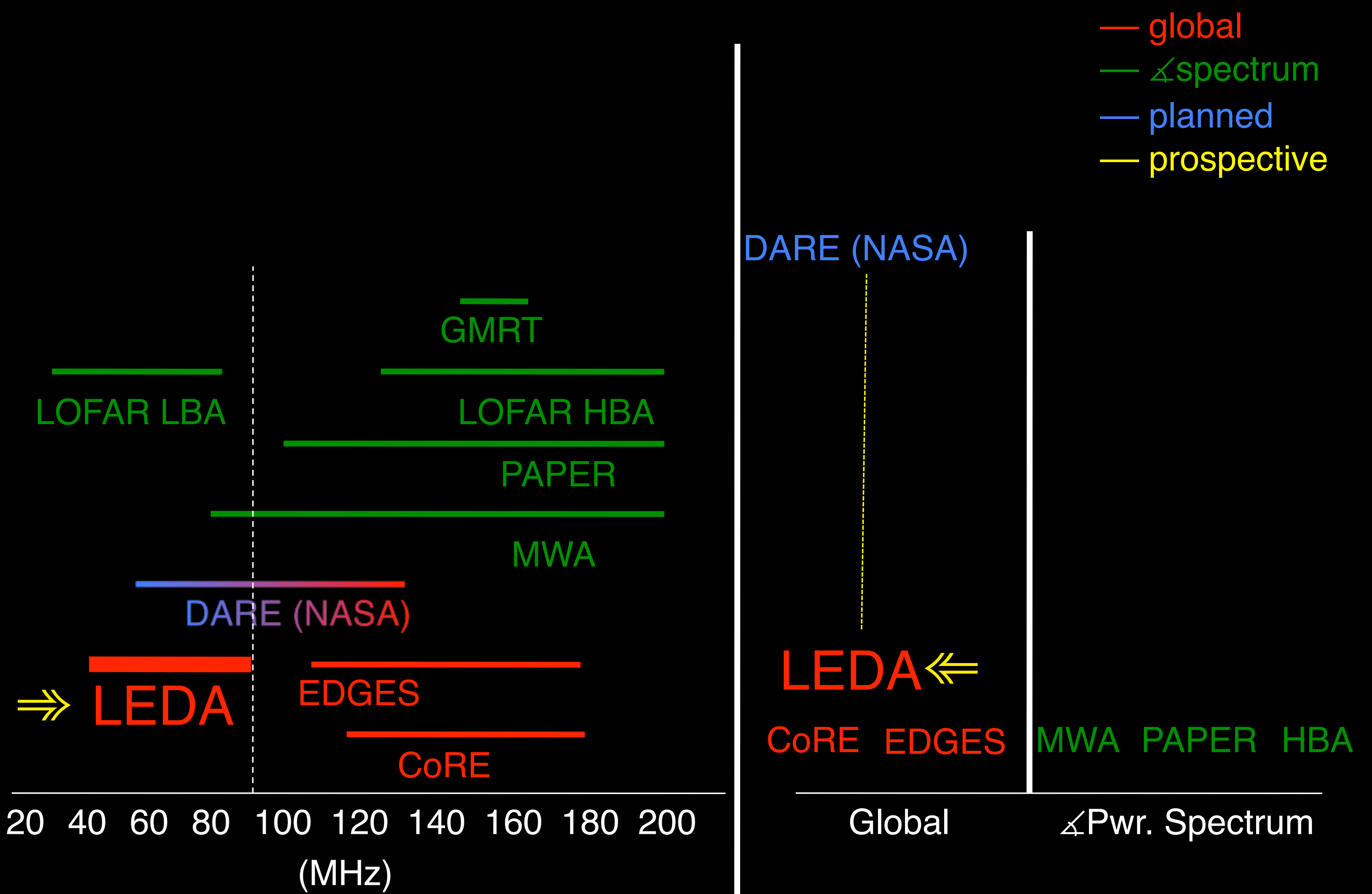
Experiment	Loc.	core array	lone	core Θ_{fringe} (°)	Science Band (MHz)	Status
GMRT	IN	14 dishes 1 km	–	0.1	144 – 150	operational
LOFAR	NL	50x 384 2 km	–	0.05	120 – 200	complete 01/11
MWA	WA	512x 16 1.5 km	–	0.08	80 – 200	5% prototype
PAPER	ZA	128 < 350 m	–	0.3 (reconfig)	100 – 200	32 elements
EDGES	WA	– –	1	–	100-170	operational
LEDA	NM	256 100 m	4(*)	2.7	38 – 88	risk reduction studies

* Outriggers at 300m separation

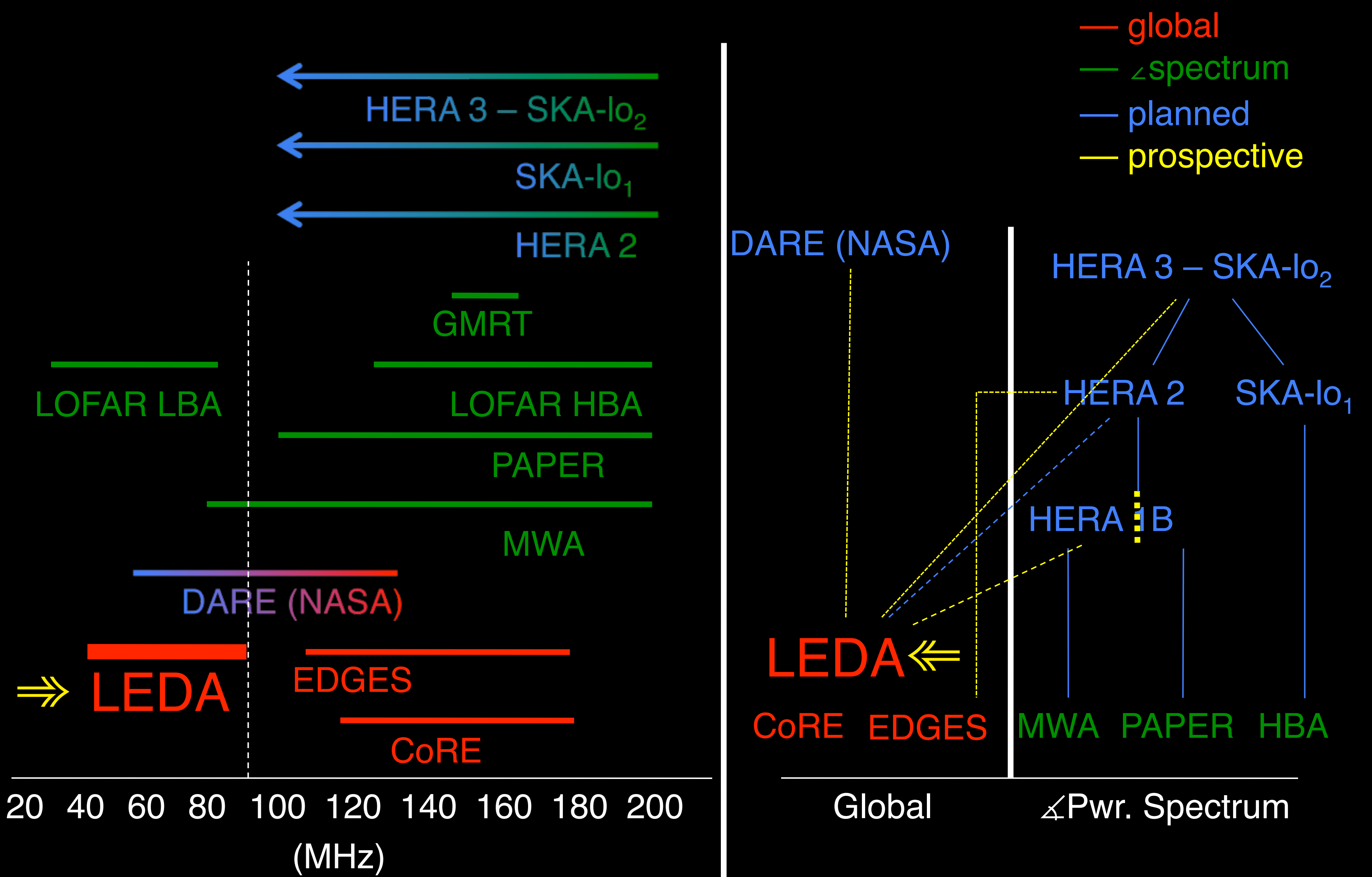
High-z 21cm Experiments



High-z 21cm Experiments



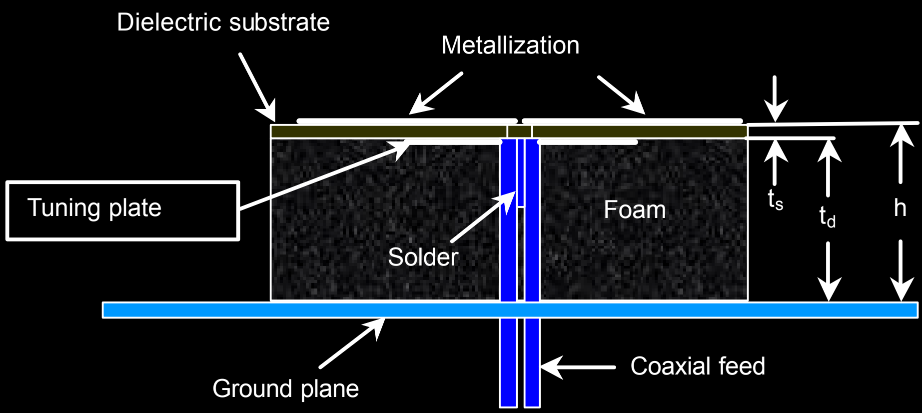
High-z 21cm Experiments

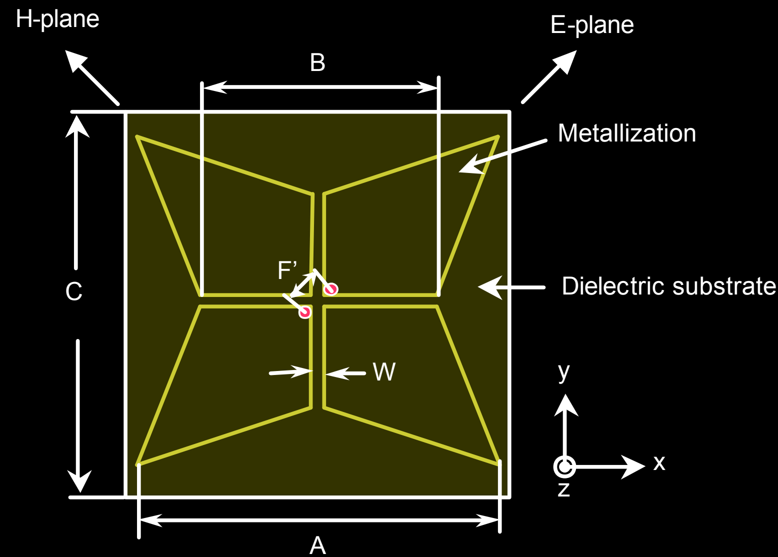


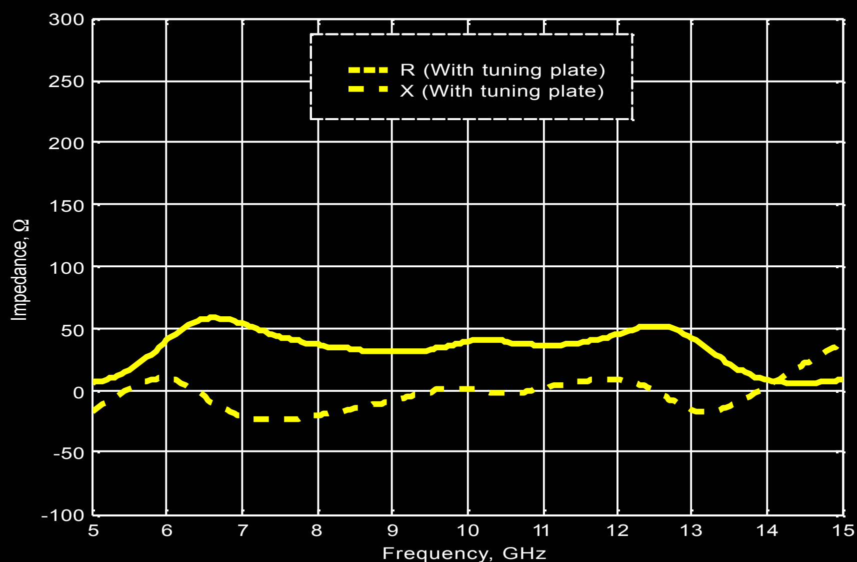
- end -

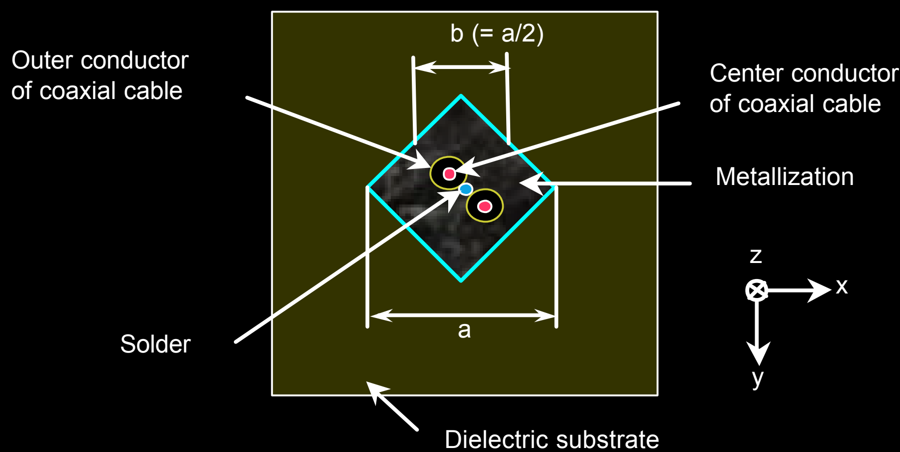
Modified FE

T.P. Antenna Contingency





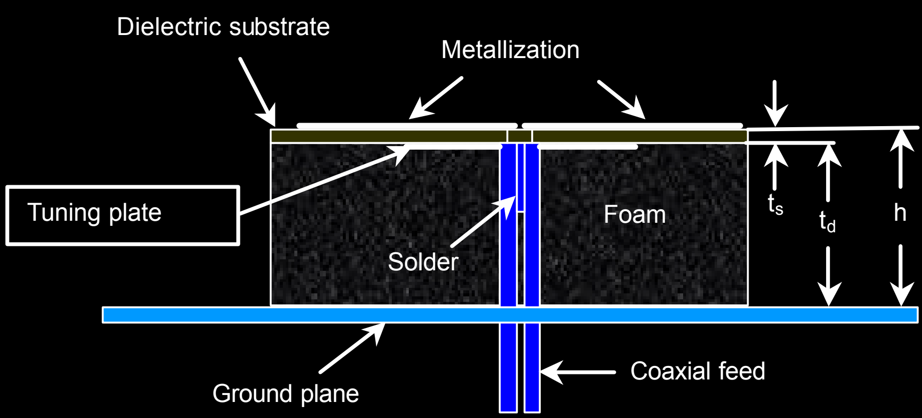


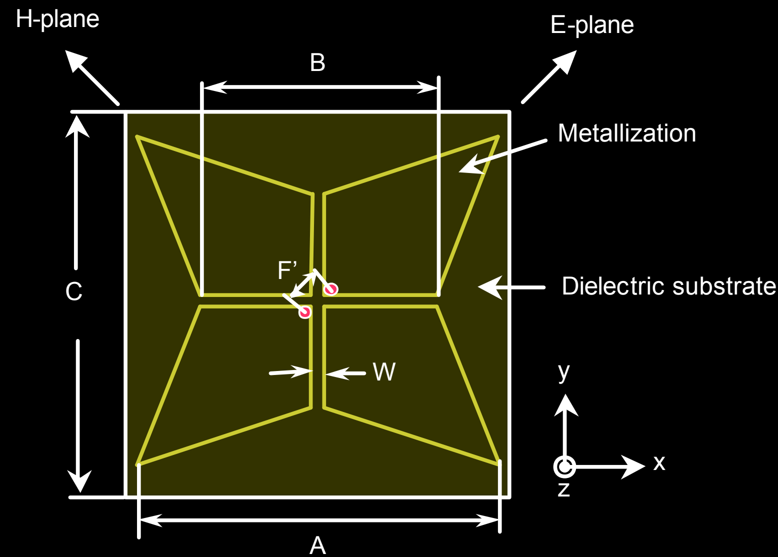


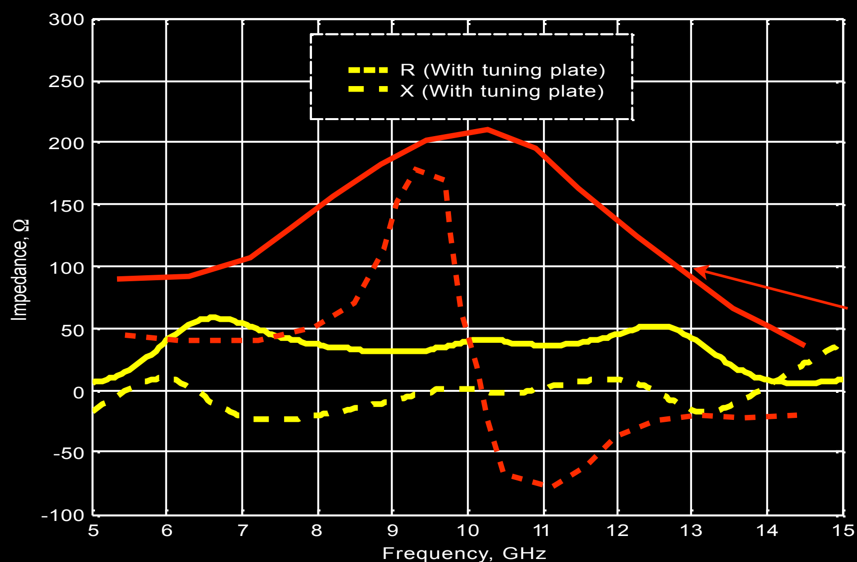
results for cm-wave scale model

adapted from Suh 2003

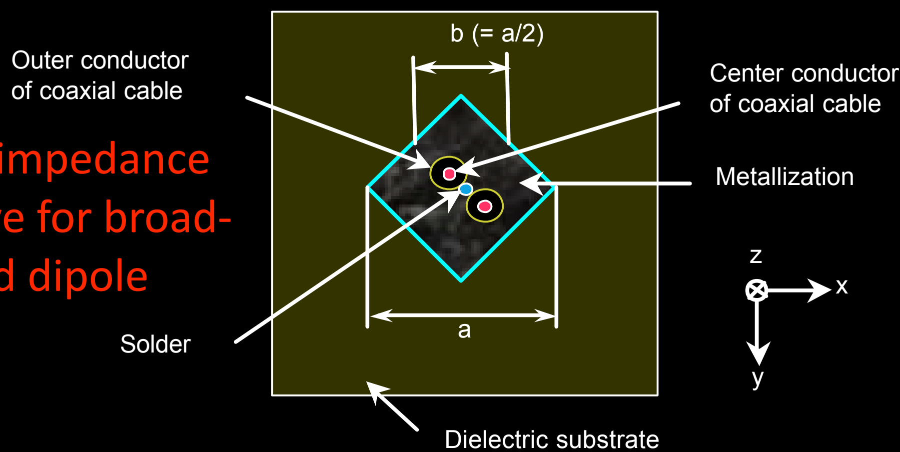
T.P. Antenna Contingency







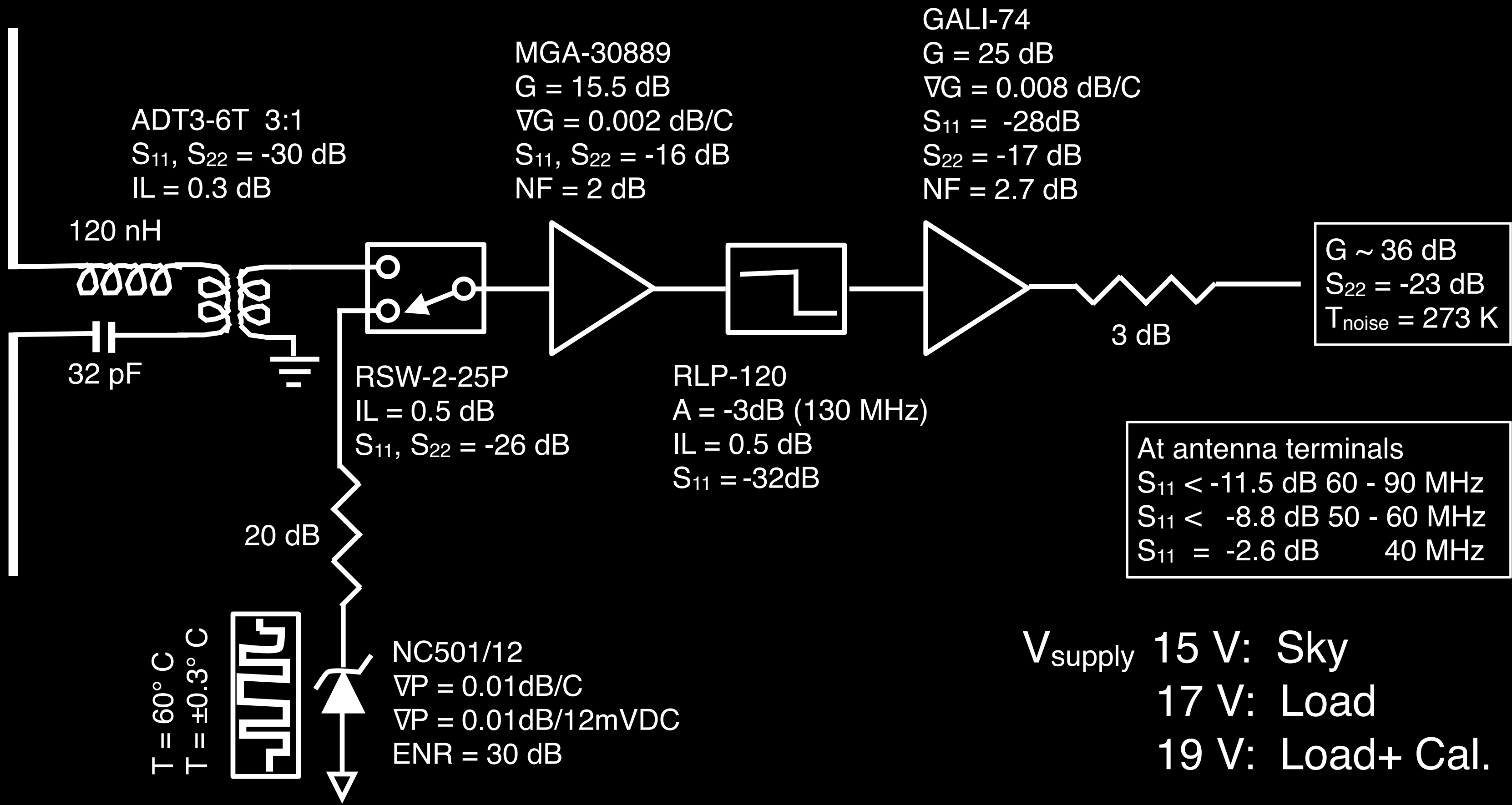
Toy impedance curve for broad-band dipole



results for cm-wave scale model

adapted from Suh 2003

Noise-switched Front-End



T_{Load} = 3000 (0.007%) K

EDGES LESSONS

Lessons from EDGES Expt.

- Complex environment
  - what is measured in the lab stays in the lab: $Z_{ant}(\nu)$, $G(\theta,\phi)$
  - need field-measured gain patterns & sky model
  - correction for ionospheric refraction of foregrounds, $f(\theta,\phi, \nu, t)$
- Multi-path reflection
  - surrounding structures, mountains, vegetation
- RFI is ever present
- Careful LNA & ADC engineering are important
  - high linearity, large bit depth, high clock stability
- Excellent broadband ant. match; VSWR modeling (?)

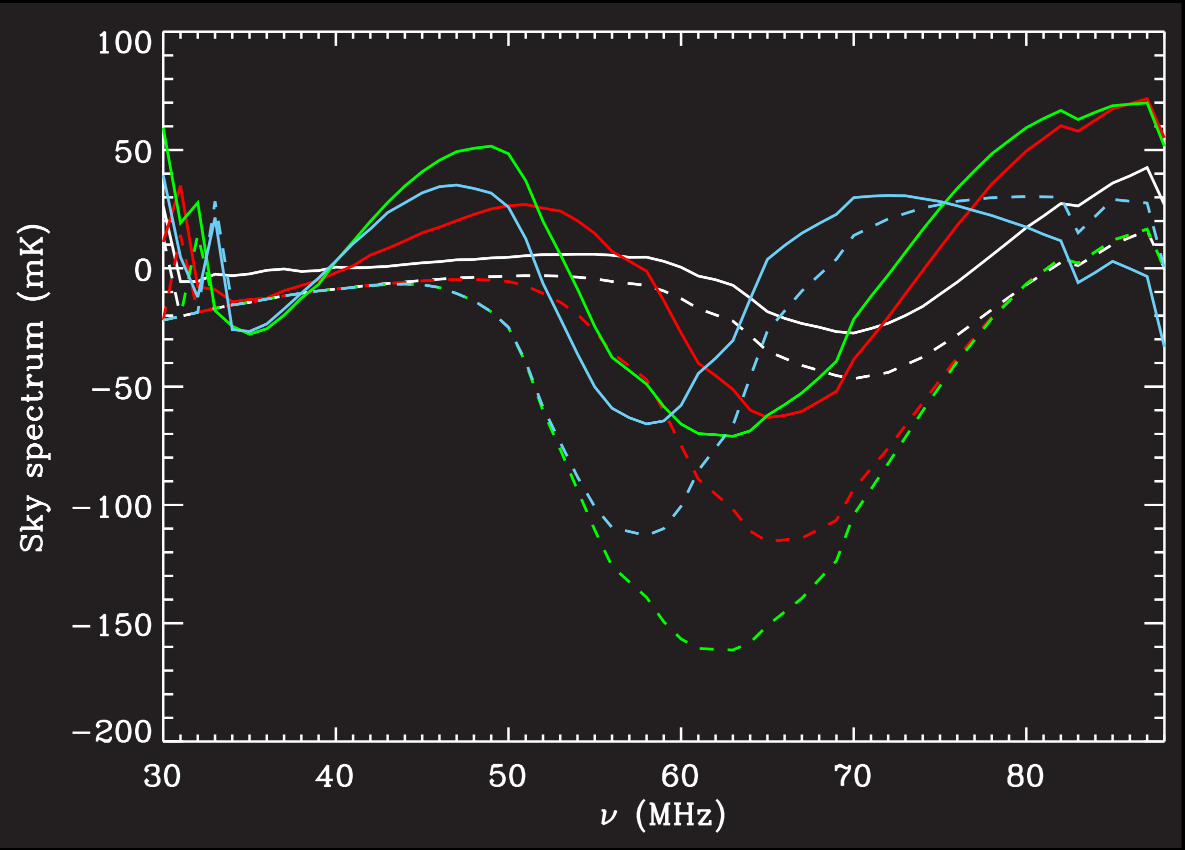
UNIQUENESS

LEDA

- Unique among HI cosmology instruments
  - LOFAR/LBA (15 < z < 46)
    - not intended for HI cosmology (HBA limit is $z \sim 11$)
    - no total-power & dipole gain cal. systems, optimizations
  - MWA ($z \lesssim 10$)
    - no total-power systems; problematic tile-gain patterns
  - PAPER ($z \lesssim 10$)
    - no total-power systems
  - EDGES ($z \lesssim 10$ but adaptable)
    - no opportunity to measure sky model or gain pattern

Data Analysis

Recovery of Signal

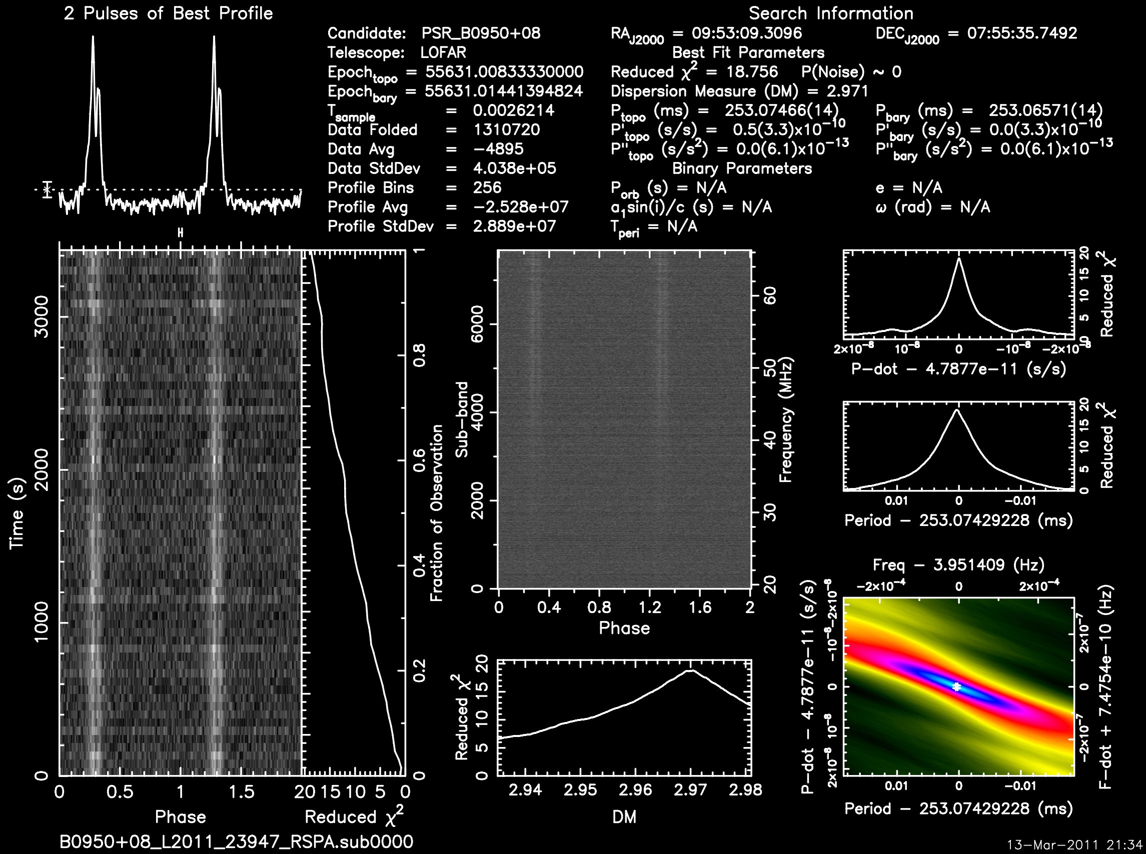


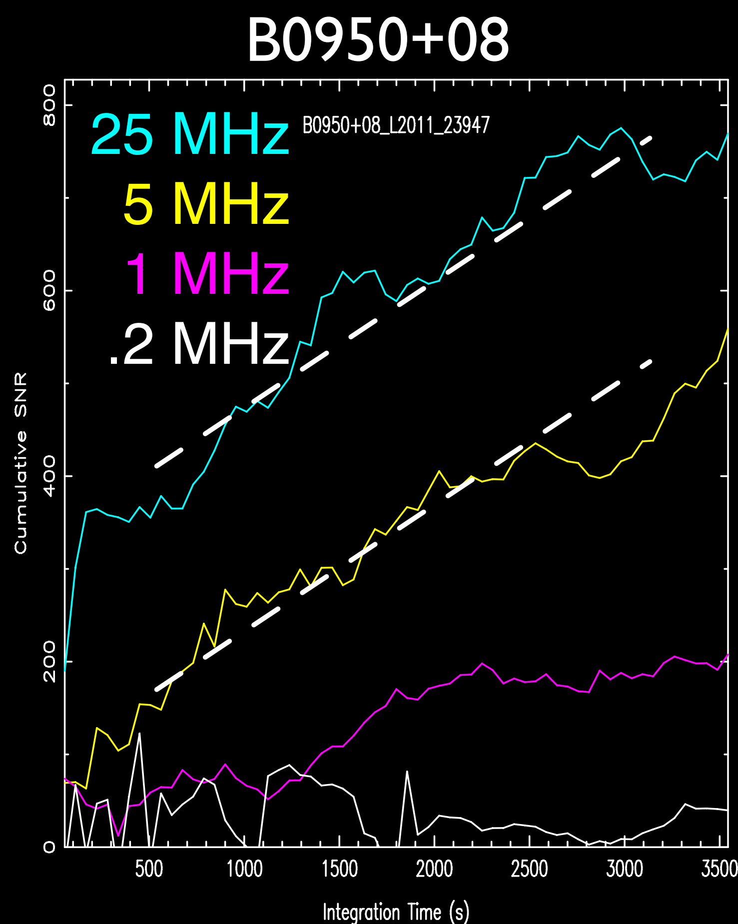
White: $F_{ESC}/10$ Green: $F_{\alpha} \times 10$

- Sample approach no. 2
- Technique developed to assess readiness
- de Oliveira-Costa et al. (2008) foreground model at 88 MHz
- extrapolate to 30-88 MHz of fit to 'dO-C' model over 100-200 MHz (Pritchard & Loeb 2009)
- HI model (dashed line)
- Multiply by a frequency-dependent smooth antenna gain model
- Fit 3rd order polynomial
- Subtract polynomial from total-power data to obtain residual spectrum (solid line)

Color	$F_\star$	F_X	F_{ESC}	N_{ION}	N_α
White	1	1	0.005	4000	9690
Red	1	1	0.05	4000	96900
Green	1	1	0.05	4000	969000
Blue	1	10	0.05	4000	96900

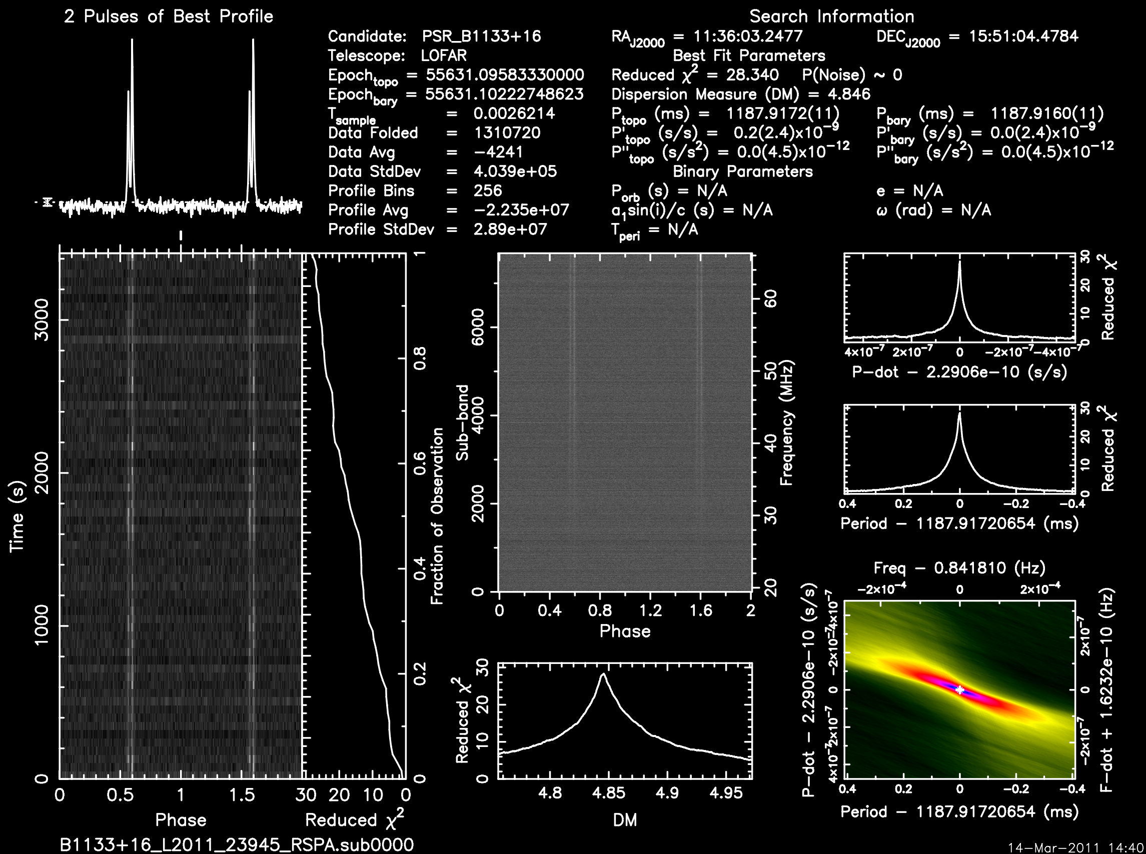
Pulsar Calibration



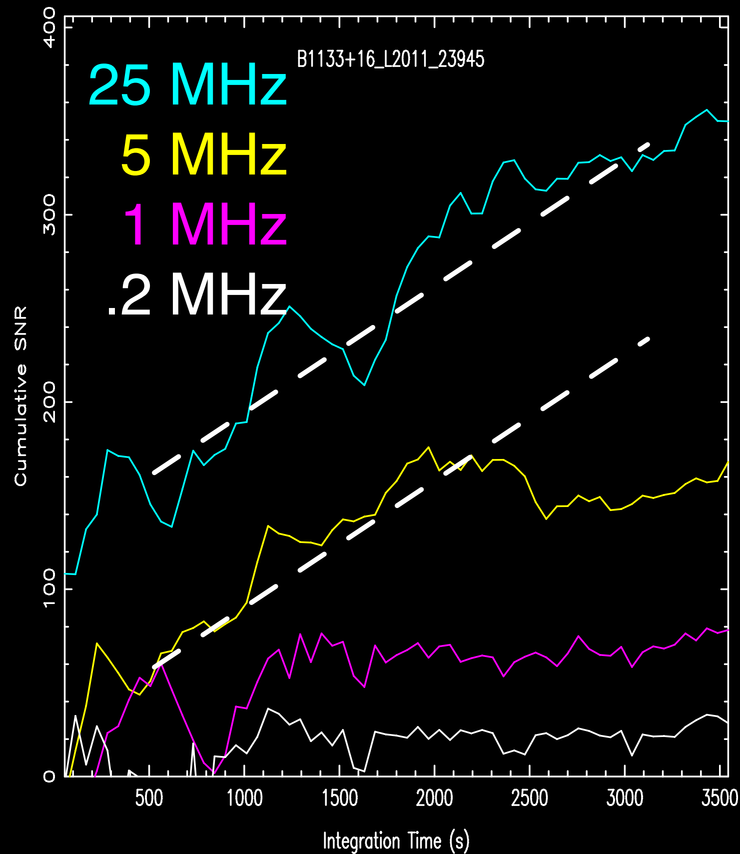


Jason Hessels and the LOFAR Pulsar Working Group

Pulsar Calibration



B1133+16



Jason Hessels and the LOFAR Pulsar Working Group

Pulsar Calibration

Table 1: A subset of the pulsar population, previously observed at this wavelength range, with sufficient signal to noise to aid mapping of the primary beam.

Pulsar	Period (ms)	DM $pc cm^{-3}$	Width t_i (ms)	t_{sc}^{1} (ms)	δ_t (s)	t_{DM}^{2} (ms)	δ_f^{3} (kHz)	flux[4] (Jy)	SNR[5] (peak)
B2303+30	1575.89	49.54	34.10	50.2	0.00	20.07	0.00	0.10	20
B1929+10	226.518	3.180	14.00	0.05	64.2	1.288	1.87	0.22	37
B2016+28	557.953	14.17	22.20	0.91	8.89	5.742	1.60	0.20	41
B0320+39	3032.07	26.01	74.70	5.33	0.00	10.54	0.00	0.16	43
B0818-13	1238.13	40.94	35.60	24.8	9.14	16.59	0.01	0.27	58
B1237+25	1382.45	9.240	60.60	0.32	22.0	3.744	8.60	0.44	89
B1642-03	387.690	35.73	8.000	15.3	3.09	14.48	1.20	0.72	118
B1749-28	562.558	50.37	15.00	53.5	25.6	20.41	0.01	0.96	119
B1133+16	1187.91	4.860	41.80	0.09	4.59	1.969	8.19	0.77	175
B1508+55	739.682	19.61	26.30	2.25	11.4	7.947	0.16	0.84	183
B0329+54	714.520	26.83	31.40	5.89	32.0	10.87	0.07	0.97	186
B2217+47	538.469	43.52	13.10	31.0	20.1	17.63	0.04	1.45	221
B0823+26	530.661	19.45	12.40	2.20	4.23	7.882	1.40	1.07	262
B0950+08	253.065	2.960	20.60	0.04	0.00	1.199	0.00	1.82	265
B0834+06	1273.77	12.89	33.90	0.71	10.1	5.223	2.50	1.58	412
B1919+21	1337.30	12.46	40.80	0.65	5.30	5.049	6.50	2.10	512

- Minimum set of 16 pulsars usable for calibration of ant. $\mathbb{C}$ gains, i.e., phs., pol.
- More pulsars via surveys
  - – LEDA, LOFAR

Pulsar Calibration

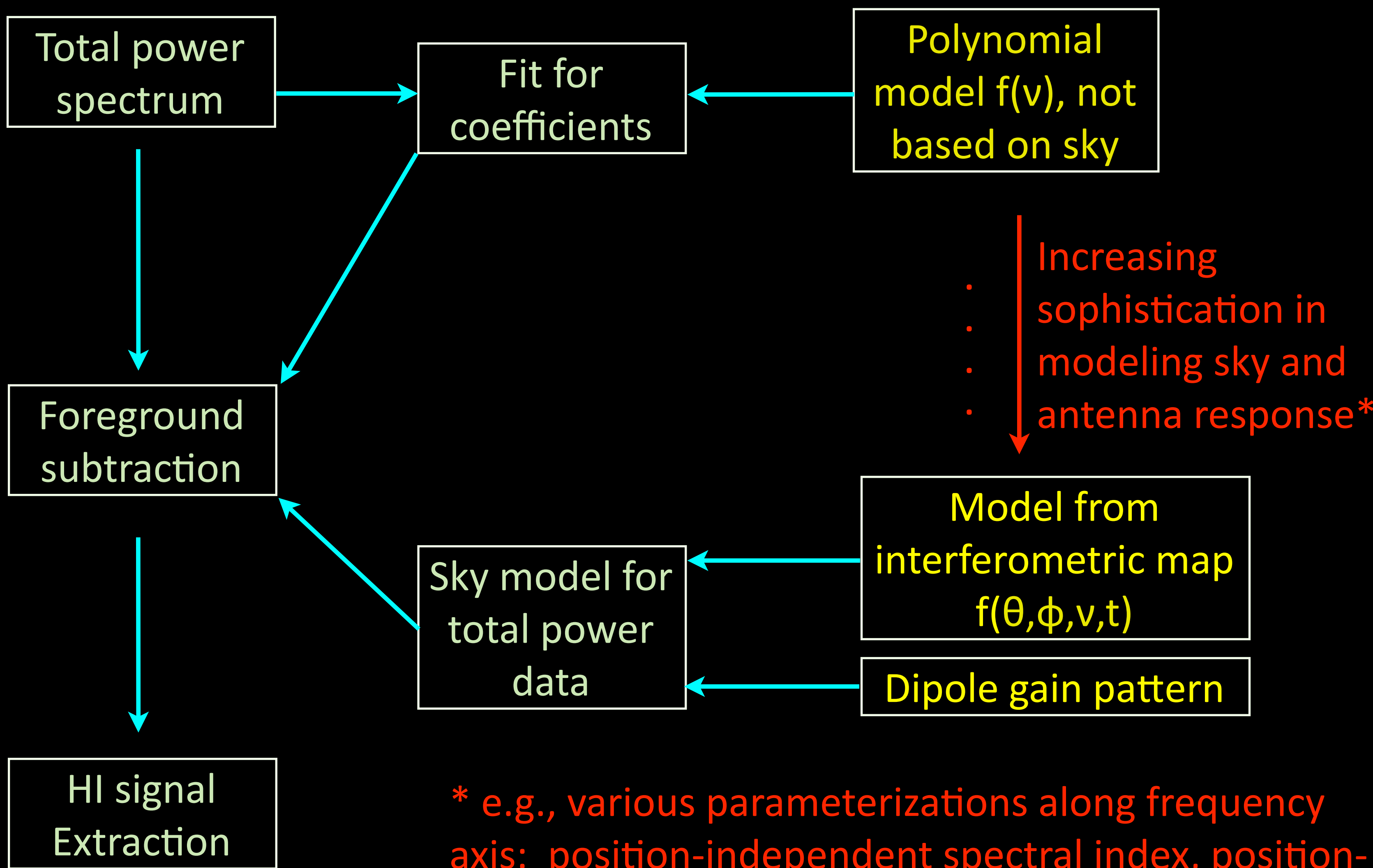
Table 2: The limitations to the Pulsar gate and integration time imposed by the Pulsar properties.

Pulsar	Width [1] (ms)	ON-PULSE (samples) [2]	OFF-PULSE (samples)	Rotations (per 600s)	Scintles [3] (600s x 250kHz)
B1929+10	14.046047	352	5662	2648	1243
B2016+28	22.347770	559	13948	1075	10533
B0320+39	74.960619	1875	75801	197	–
B0818-13	43.615703	1091	30953	484	986098
B1237+25	60.631764	1516	34561	434	792
B1642-03	17.729359	444	9692	1547	40322
B1749-28	55.792778	1395	14063	1066	430439
B1133+16	41.823661	1046	29697	505	3976
B1508+55	26.546491	664	18492	811	78887
B0329+54	32.117671	803	17863	839	63248
B2217+47	33.959270	849	13461	1114	182610
B0823+26	12.902882	323	13266	1130	25269
B0950+08	20.629151	516	6326	2370	–
B0834+06	33.984555	850	31844	471	5888
B1919+21	40.867160	1022	33432	448	4354

1 – Including propagation effects but not intrinsic pulse broadening
2 – Assuming 40 μ s sampling
3 – Approximate: Assuming 250kHz channels and 600 second time averaging

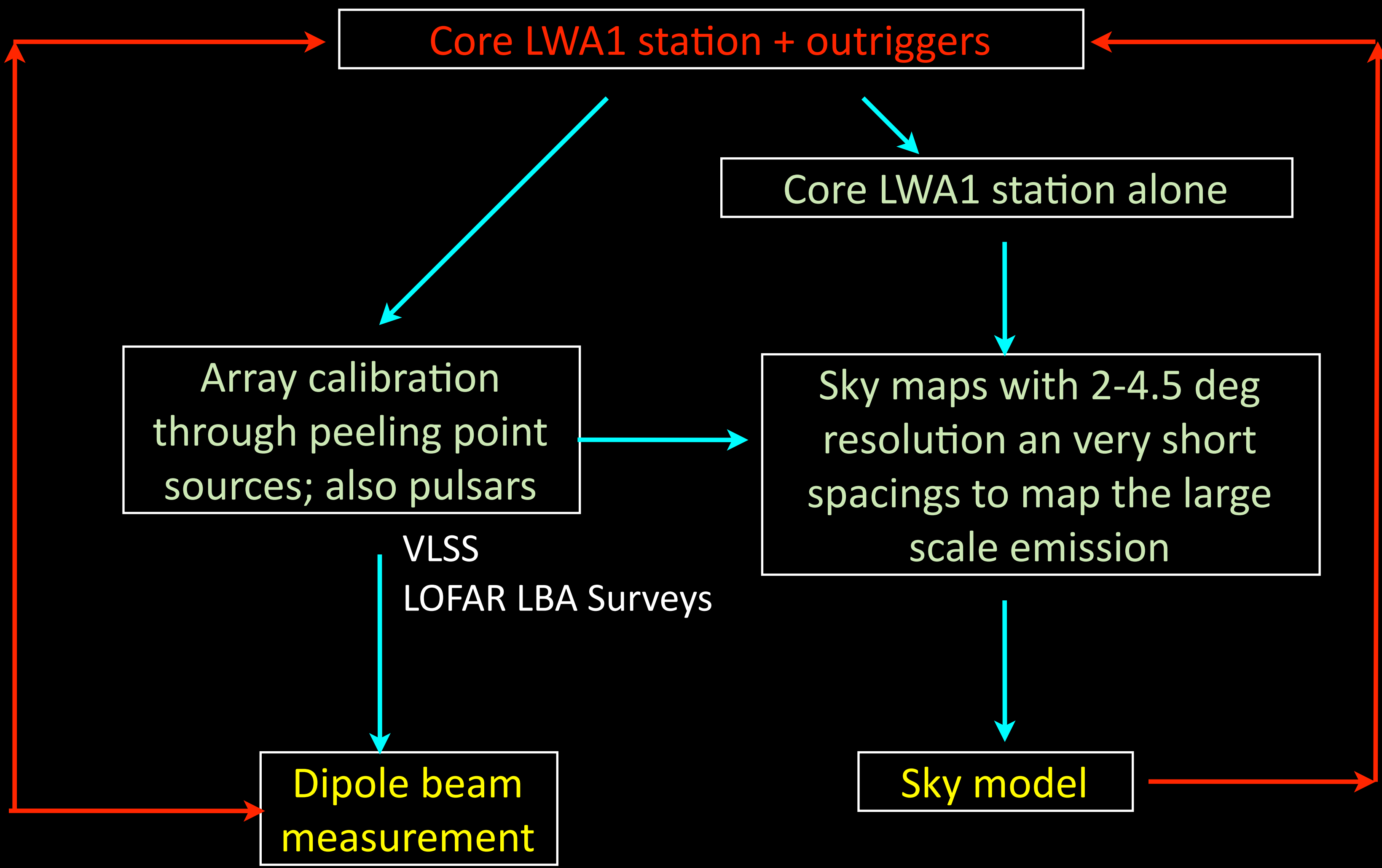
- Minimum set of 16 pulsars usable for calibration of ant. $\mathbb{C}$ gains
- A subset may enable cal. of rel. amplitude response
  - avg. in τ, ν

Data Analysis Flow



* e.g., various parameterizations along frequency axis: position-independent spectral index, position-dependent spectral index

Data Analysis Flow

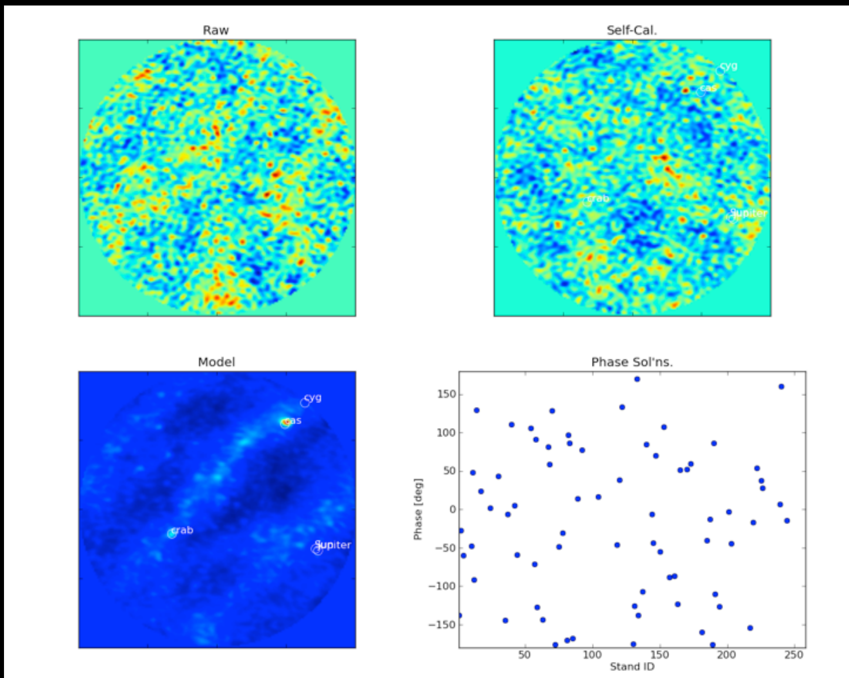


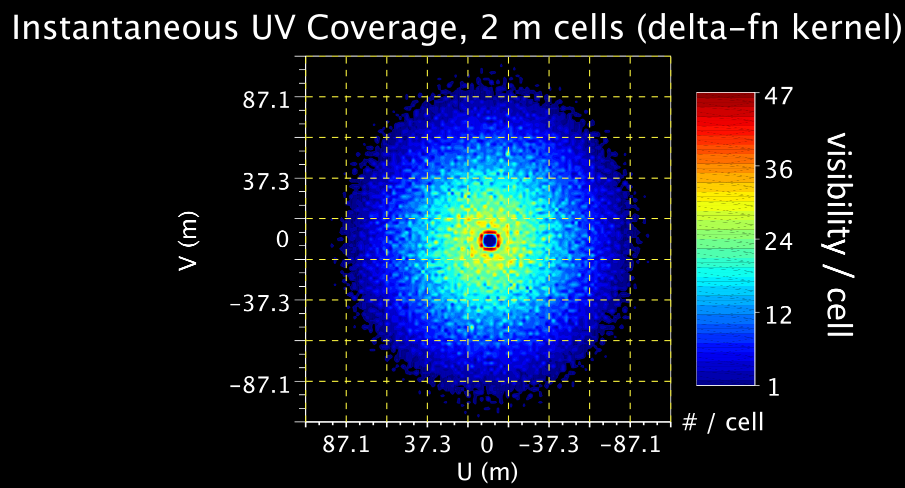
LWA

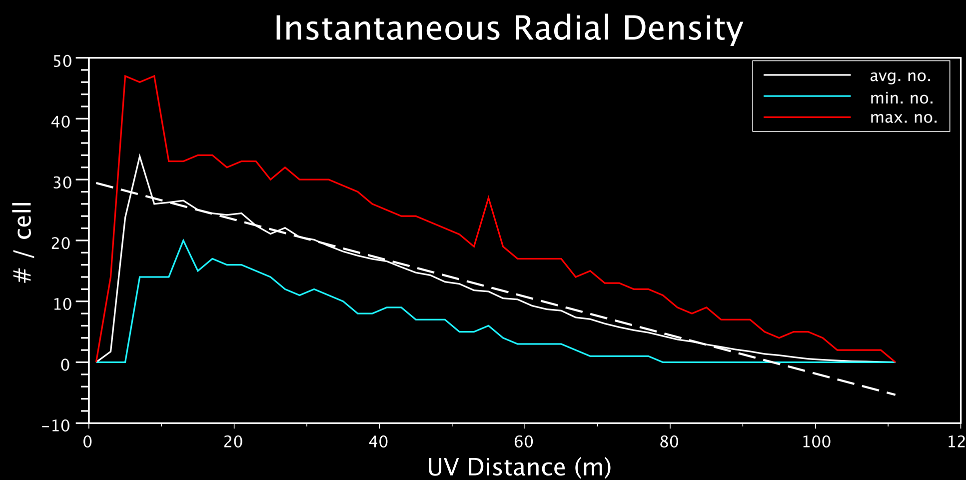
LWA-LEDA Logistics

- LEDA and LWA work together
  - half rack of available space in LWA1
  - 120 and 240 VAC available
    - 3 kW if running in parallel with LWA1
  - LWA Schedule is under UNM control
    - Can run LWA1/LEDA64 simultaneously
      - LEDA64 - manually recable LEDA inputs, small sensitivity loss for LWA1 during LEDA sessions
    - LEDA512 operates either
      - in existing LWA1 station (replaces DP)
      - in new LWA station (in parallel with DP)

LWA1 HOT OFF THE PRESS



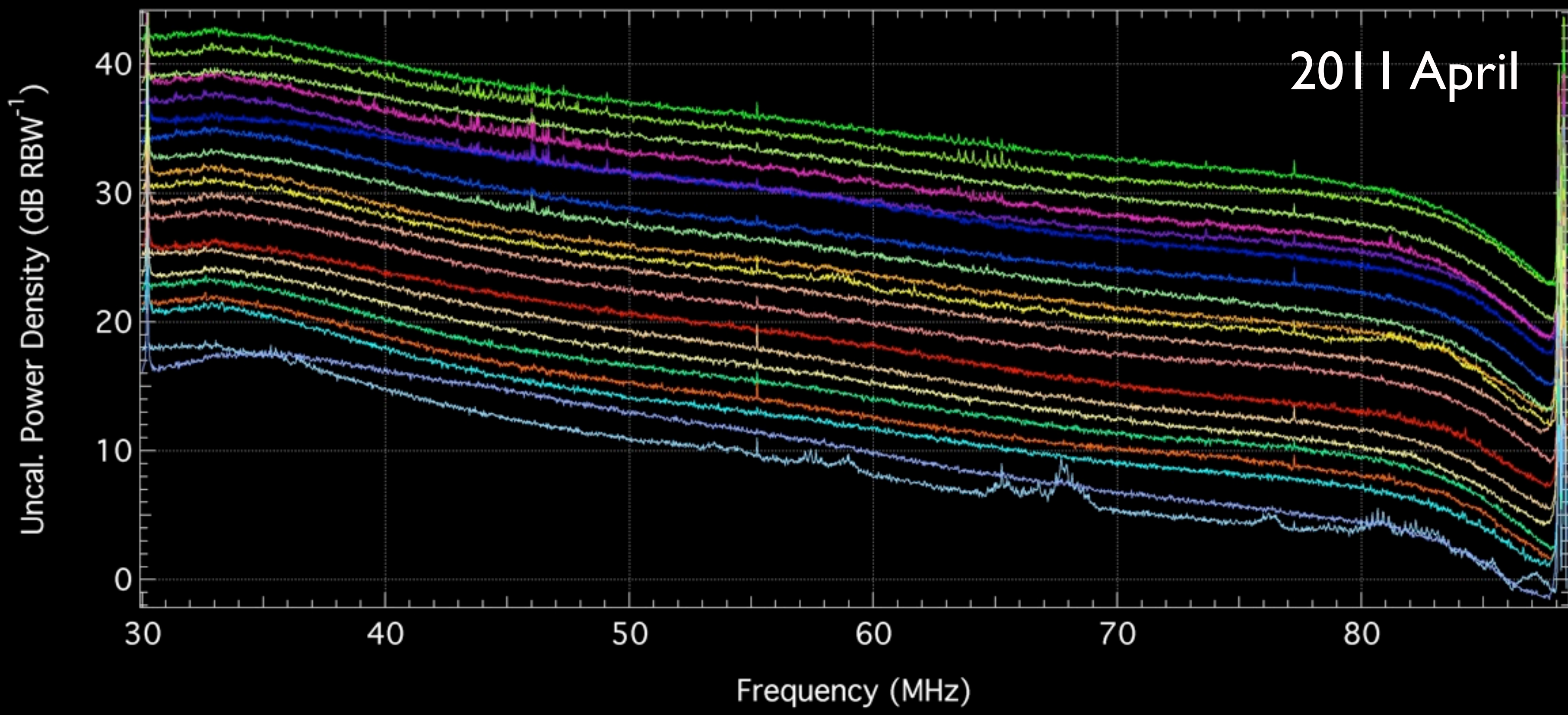




- 2011 April 8
- 256 antennas
- T_{int} = 42s
- B = 67 kHz
- 1 polarization

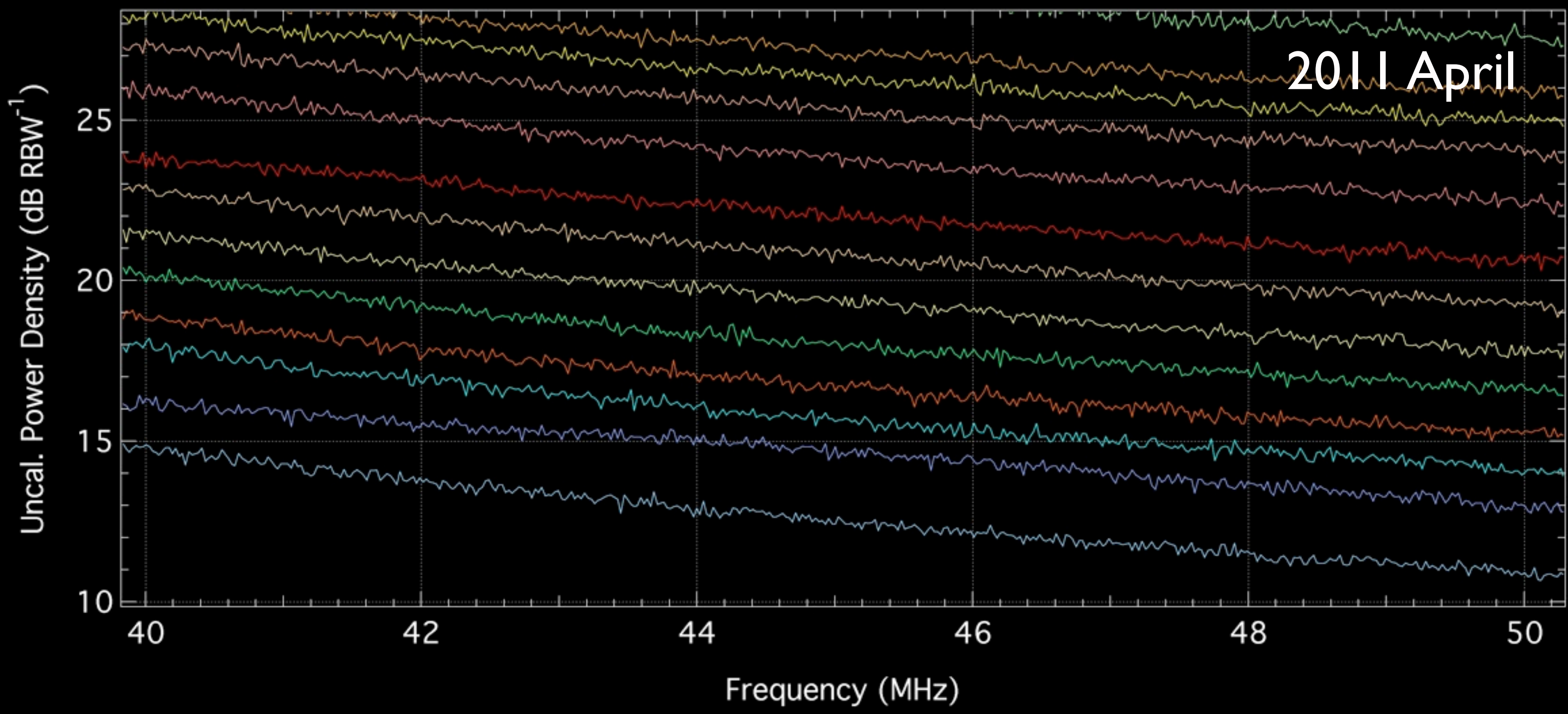
- Filled U,V coverage
- Outstanding snapshots
- Low systematics in images of diffuse foregrounds

Is the LEDA Band Clean? Yes.



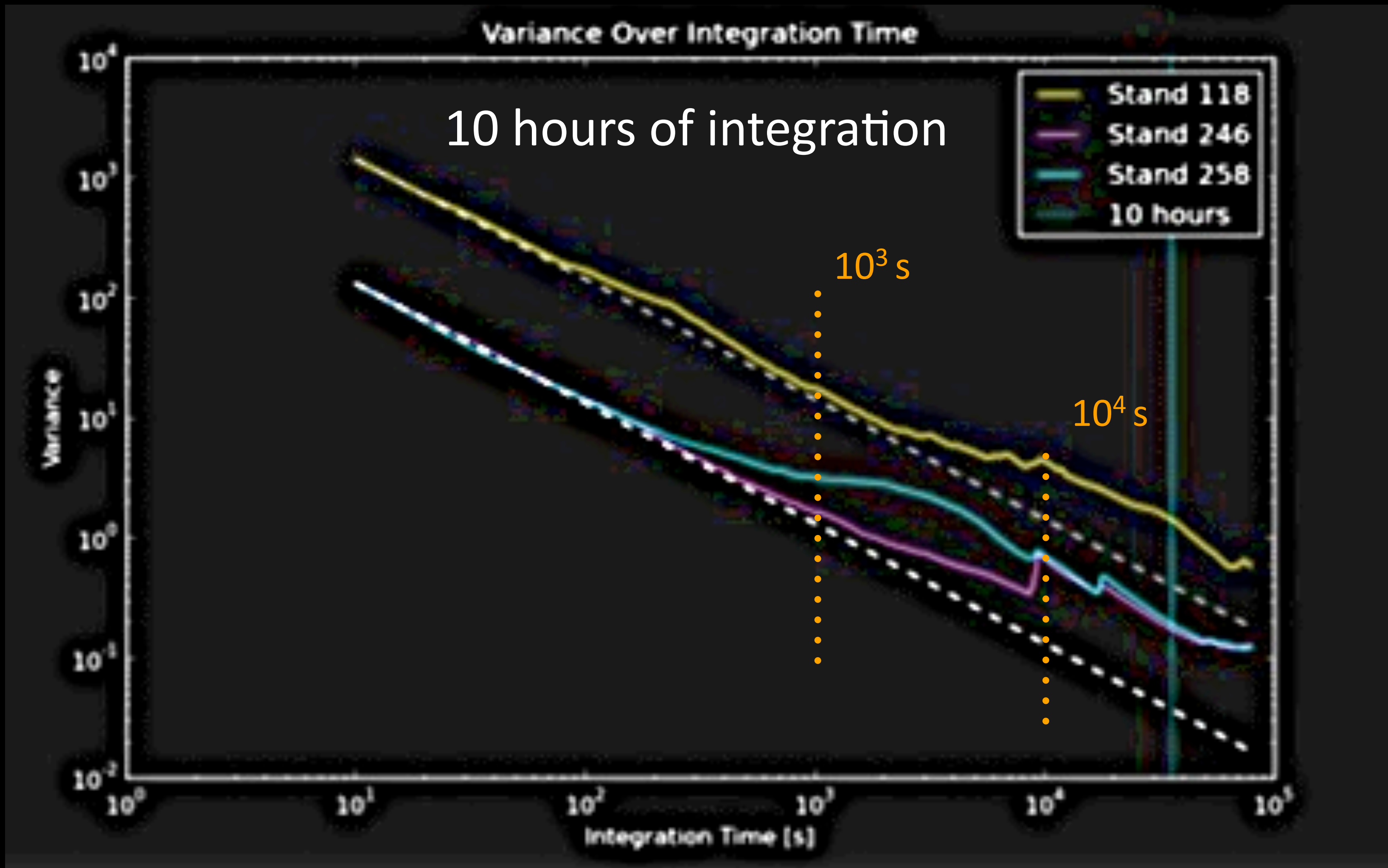
20 antennas; one pol. each; 23.926 kHz resolution; 61 ms

Is the LEDA Band Clean? Yes.

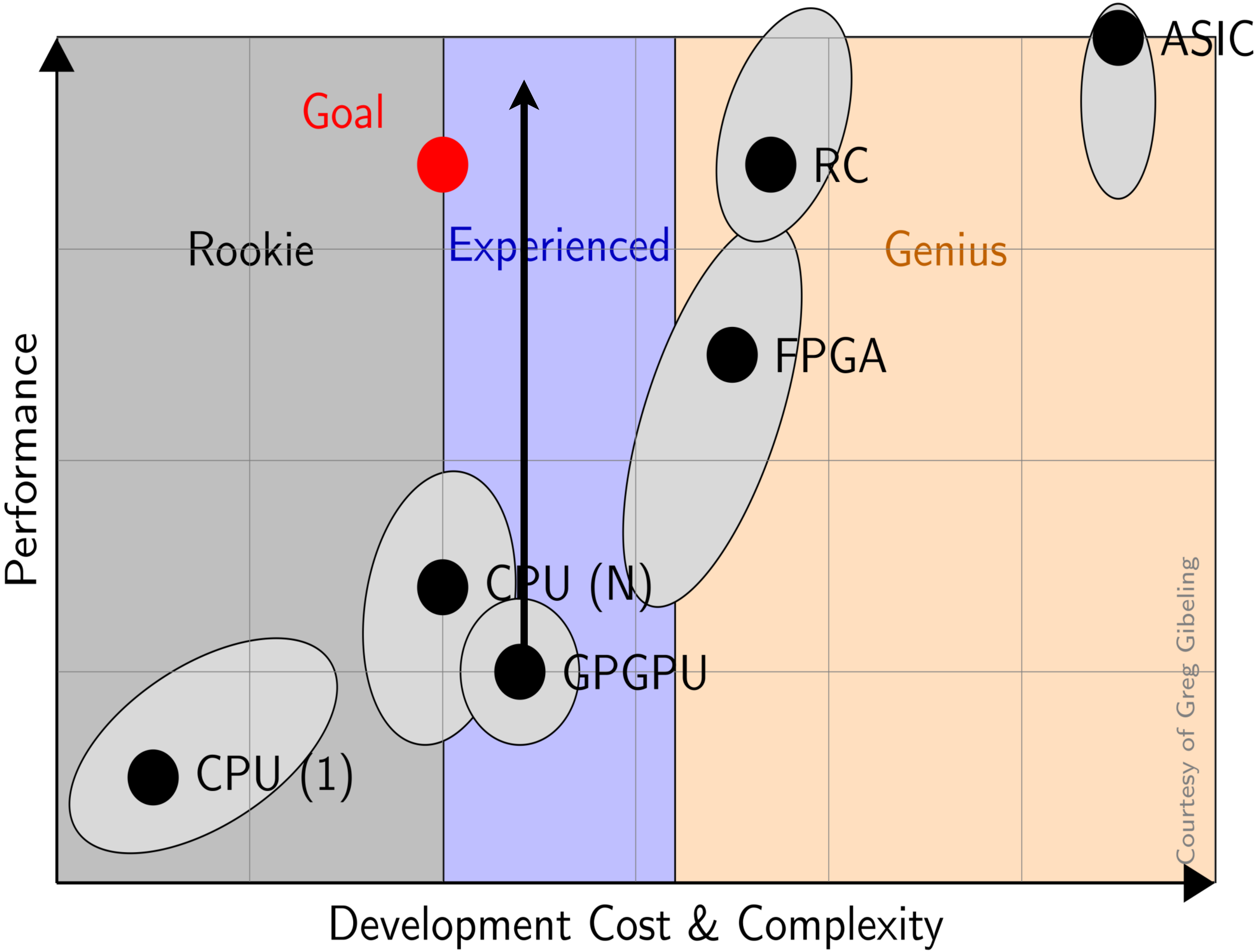


20 antennas; one pol. each; 23.926 kHz resolution

LWA1 Deep Integrations



Looking at three stands in a narrow bandwidth (~40 kHz)


ASIC
Goal
RC
Rookie
Experienced
Genius
FPGA
Performance
CPU (N)
GPGPU
CPU (1)
Courtesy of Greg Gibeling
Development Cost & Complexity

Noise-switched Front-End

- Outriggers equipped to measure total power
- Noise sw. required for band and temp. calib.

- Prototype designed & built at SAO
  - Differs from LWA FE design
    - Simpler; faster to design/build
    - Establishes engineering path
    - Difference in field not a problem
- Risk reduction measure
- Enables early evaluation of LWA antennas for T.P. measurement
  - 4-point antenna contingency