Next Generation Radio Telescopes: From LOFAR to the SKA

2nd School on Multi-wavelength Astronomy

01 July 2010

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ASTRON / LOFAR / UvA

Next Generation Radio Telescopes: From LOFAR to the SKA

Overview of LOFAR

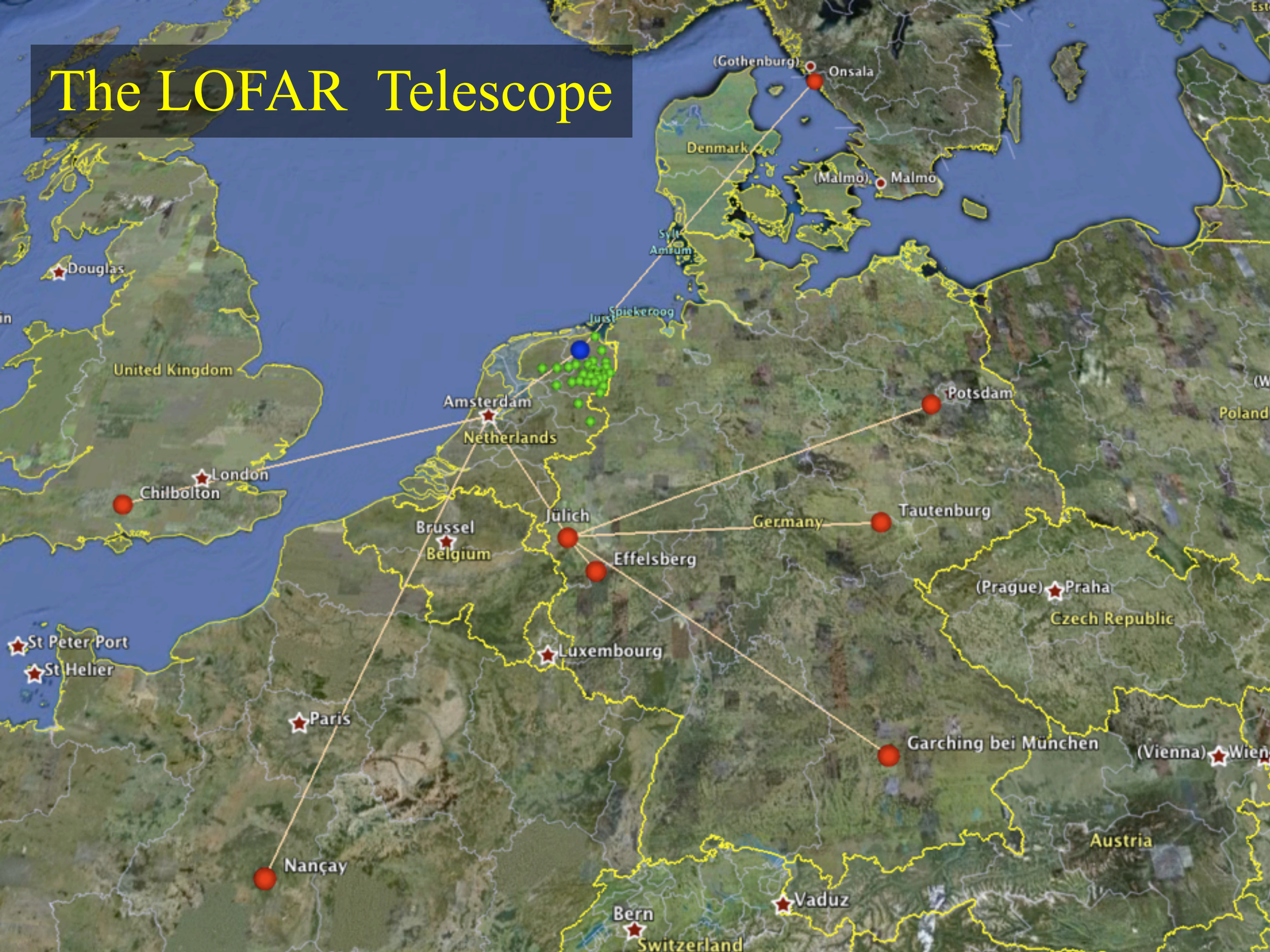
New Technologies for Radio Astronomy

Data and Processing Challenges

Science Pipelines

SKA and its Pathfinders

The LOFAR Telescope

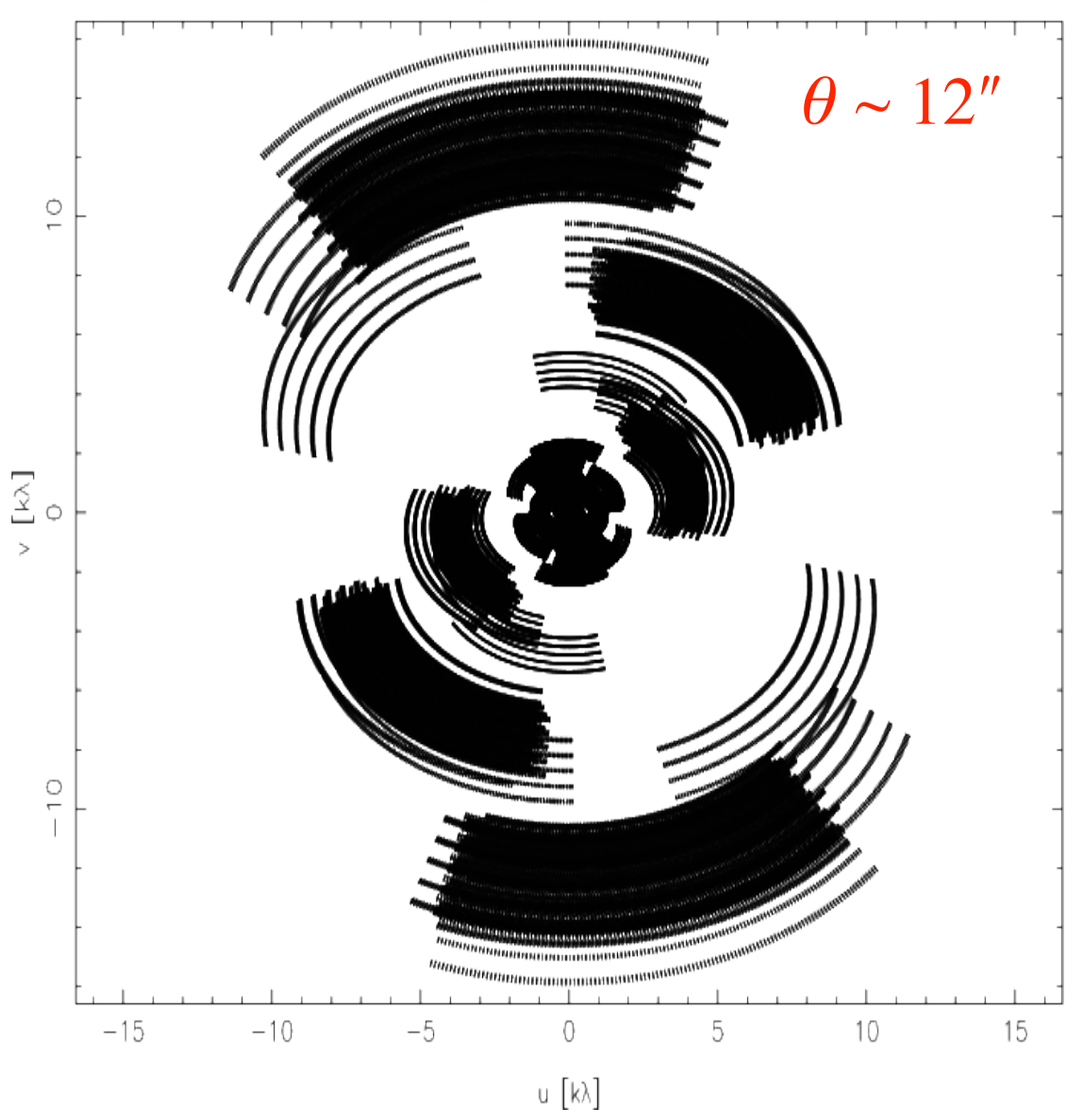


LOFAR Superterp

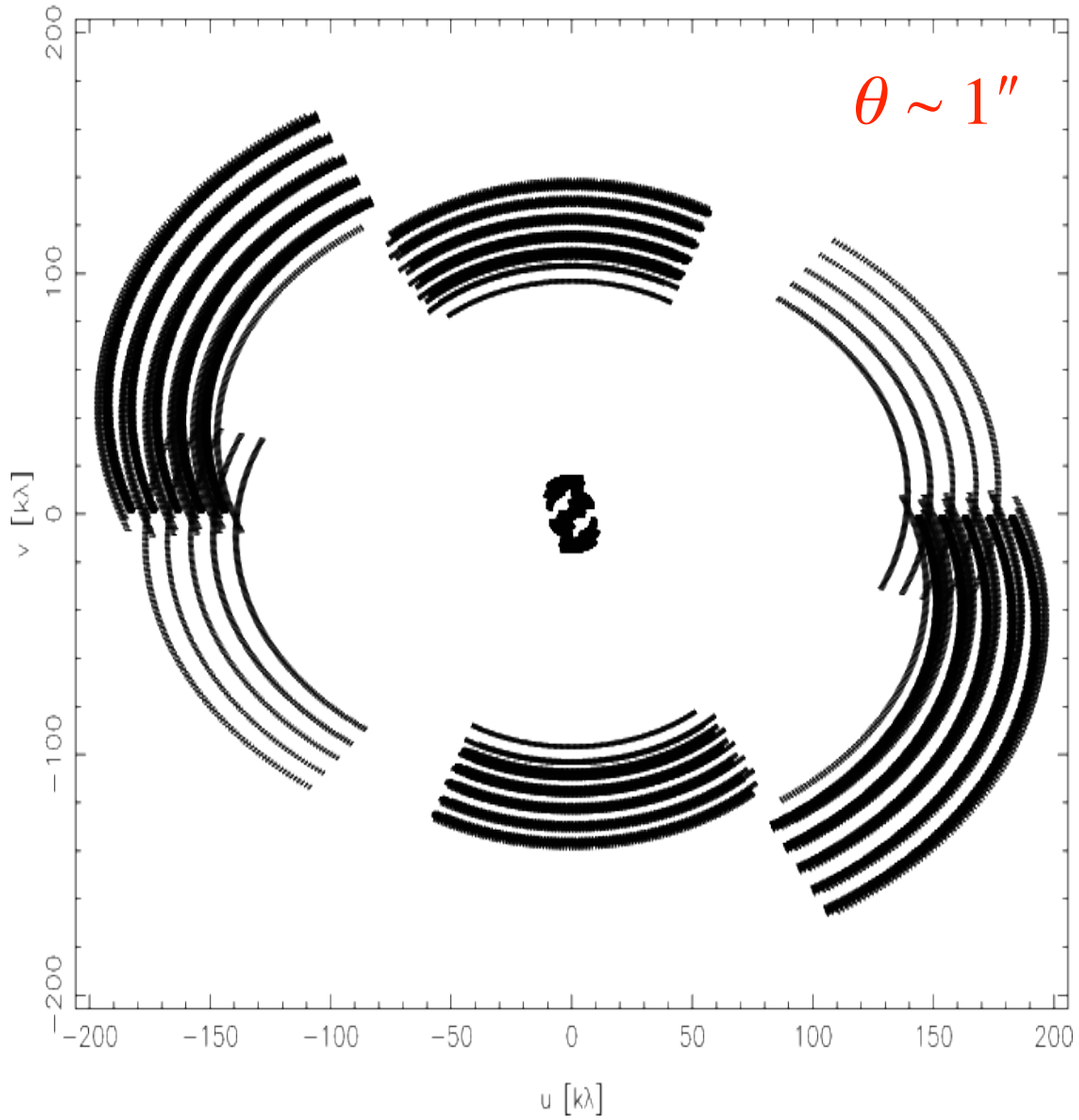
June 2010

Current *uv*-plane coverage

NL-only baselines



NL+International baselines



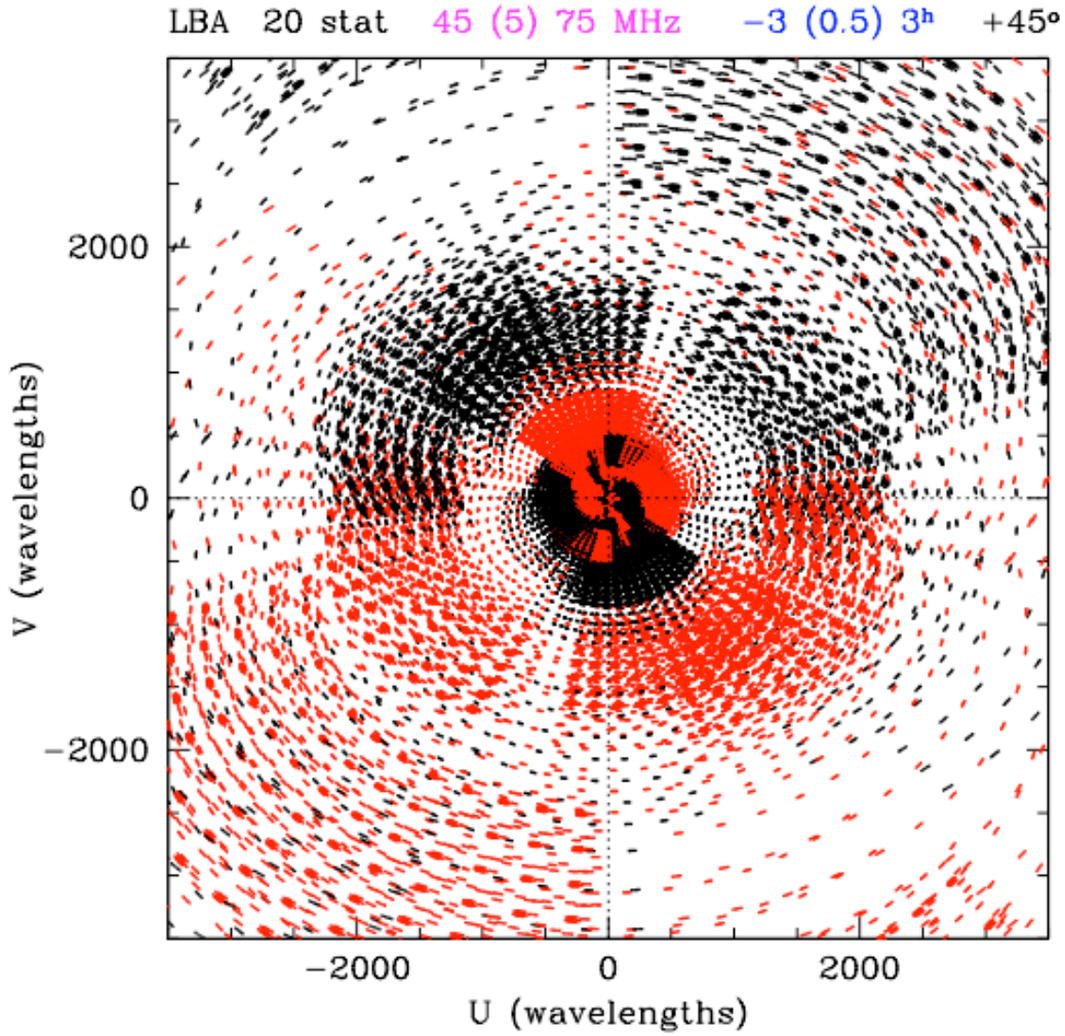
Dec=+47 deg 120-155 MHz

Freq. (MHz)	λ (m)	Resolution L = 2 km (arcsec)	Resolution L = 10 km (arcsec)	Resolution L = 80 km (arcsec)
15	20.0	1650	330	41.3
30	10.0	825	165	20.6
45	6.67	550	110	13.8
60	5.00	413	82.5	10.3
75	4.00	330	66.0	8.25
120	2.50	206	41.3	5.16
150	2.00	165	33.0	4.13
180	1.67	138	27.5	3.44
210	1.43	118	23.6	2.95
240	1.25	103	20.6	2.58

Freq. (MHz)	λ (m)	ΔS_{13+7} (mJy)	ΔS_{13+7} Tapered (mJy)	ΔS_{18+18} (mJy)	ΔS_{25+25} (mJy)
15	20.0	201		110	79
30	10.0	37		20	15
45	6.67	20		11	7.8
60	5.00	13		7.2	5.2
75	4.00	21		12	8.4
120	2.50	0.74	0.89	0.41	0.29
150	2.00	0.58	0.71	0.32	0.23
180	1.67	0.67	0.81	0.37	0.26
210	1.43	0.76	0.91	0.42	0.30
240	1.25	0.84	1.0	0.46	0.33

System Performance

(NL-only baselines)



Effelsberg

Nancay

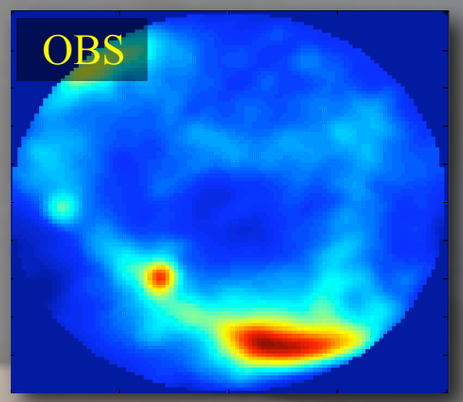
Garching

Chilbolton

Tautenburg

Potsdam

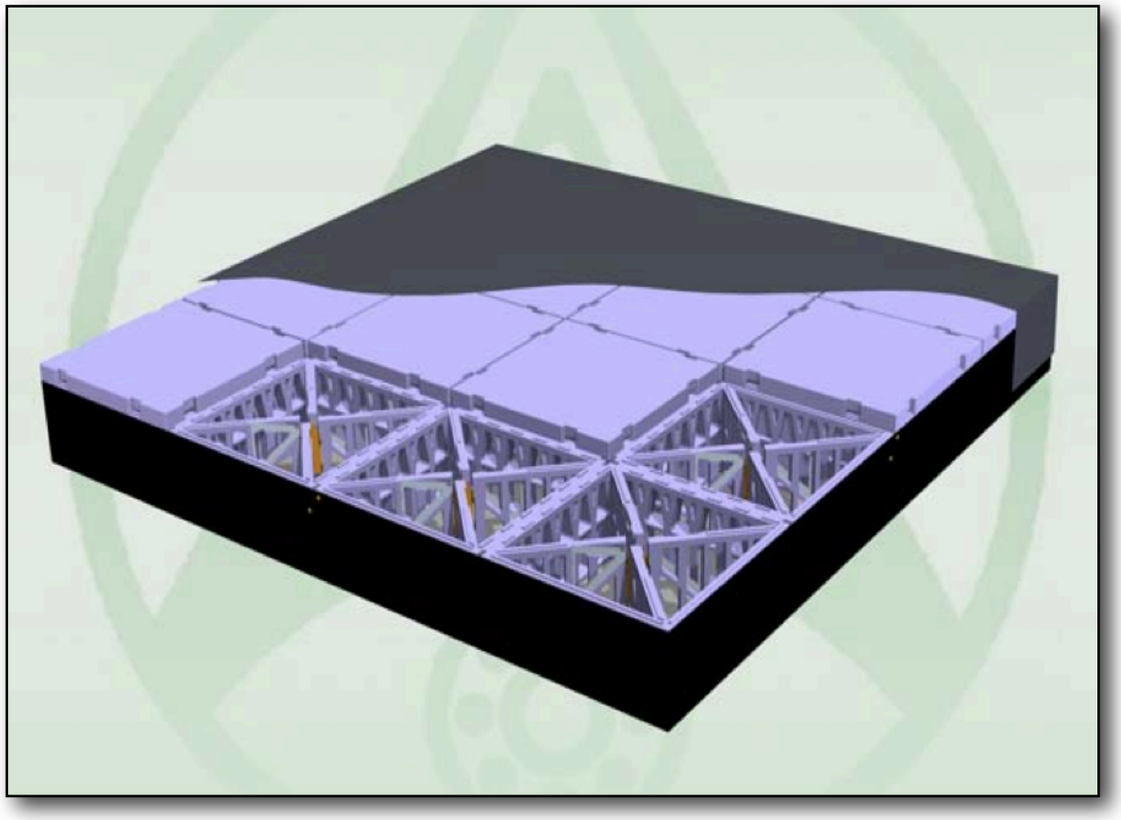
Station/Item	Cabinet	LBA	HBA	Fibre	CEP connection	Validated
CS302						
RS307						
RS503						
RS106						
RS208						
CS030						
CS401						
CS021						
CS032						
RS306						
CS301						
CS501						
RS509						
CS103						
CS001						
CS002						
CS003						
CS004						
CS005						
CS006						
CS007						
CS024						
CS201						
CS101						
CS026						
RS205						
CS017						
RS104						
RS210						
RS310						
RS404						
RS406						
RS407						
RS409						
RS410						
RS508						
Effelsberg						
Tautenburg						
Garching						
Potsdam						
Juelich						
Nancay						
Onsala						
Chilbolton						
Totals	32	30	27	29	29	22



LOFAR Antennas

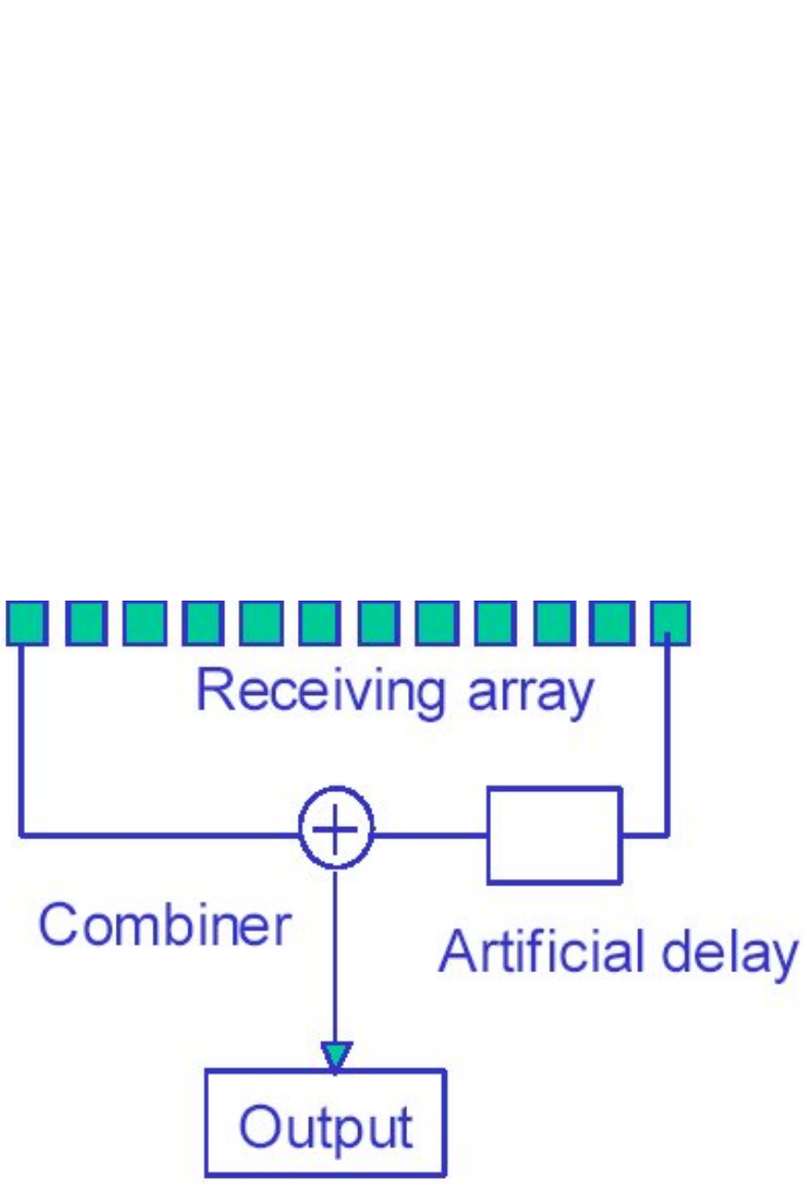
Low band antenna: 30 – 80 MHz
48/96 antennas per station

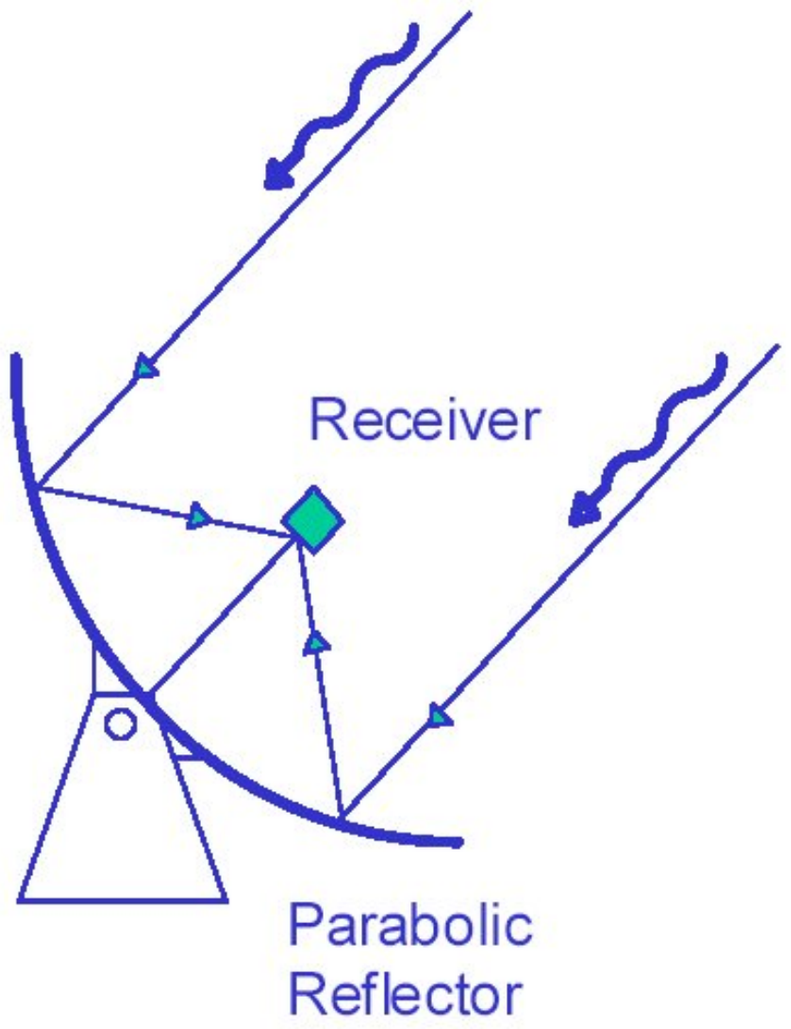
High band tiles:120 – 240 MHz
96 tiles/station, 4x4 antennas/tile



- 36 NL + 8 EU stations of dipoles
- Replace big dishes by many cheap dipoles
- No moving parts: electronic beam steering
- Flexible digital beam forming

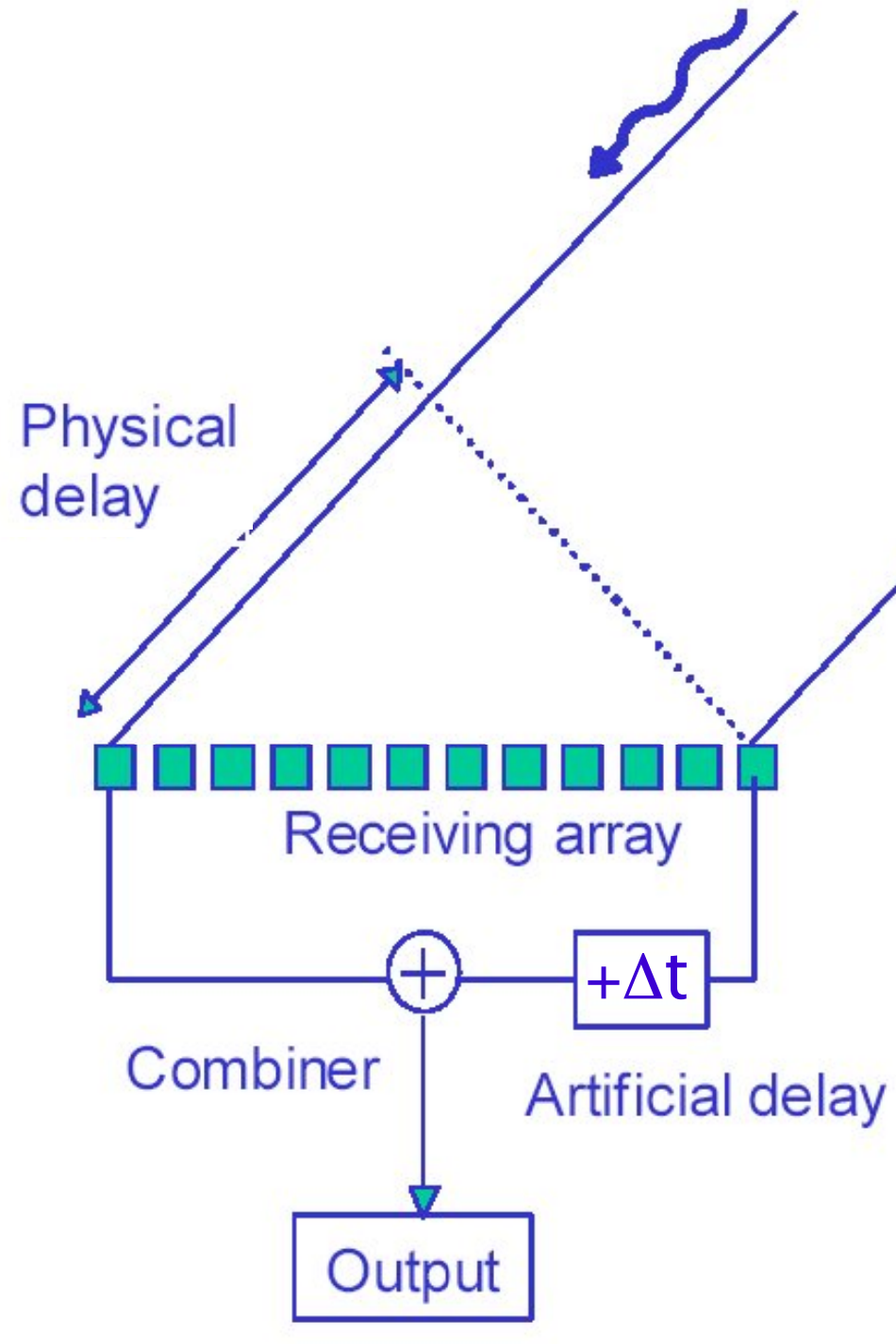
Phased Array Detectors

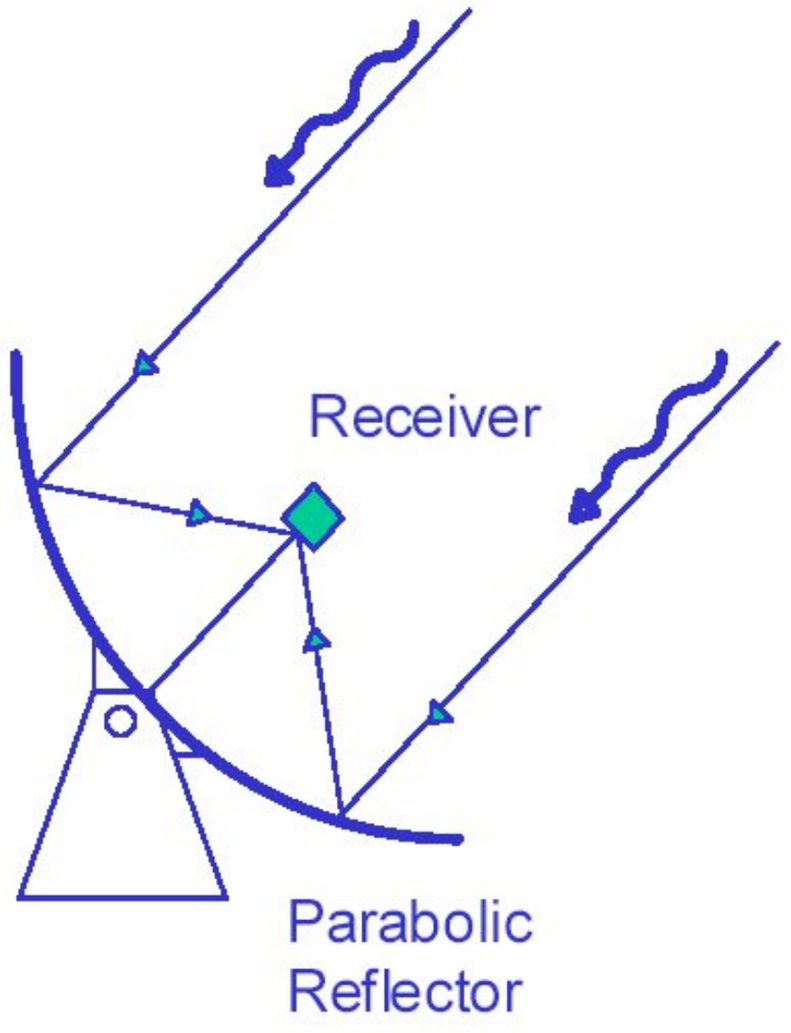




Electronic beam steering

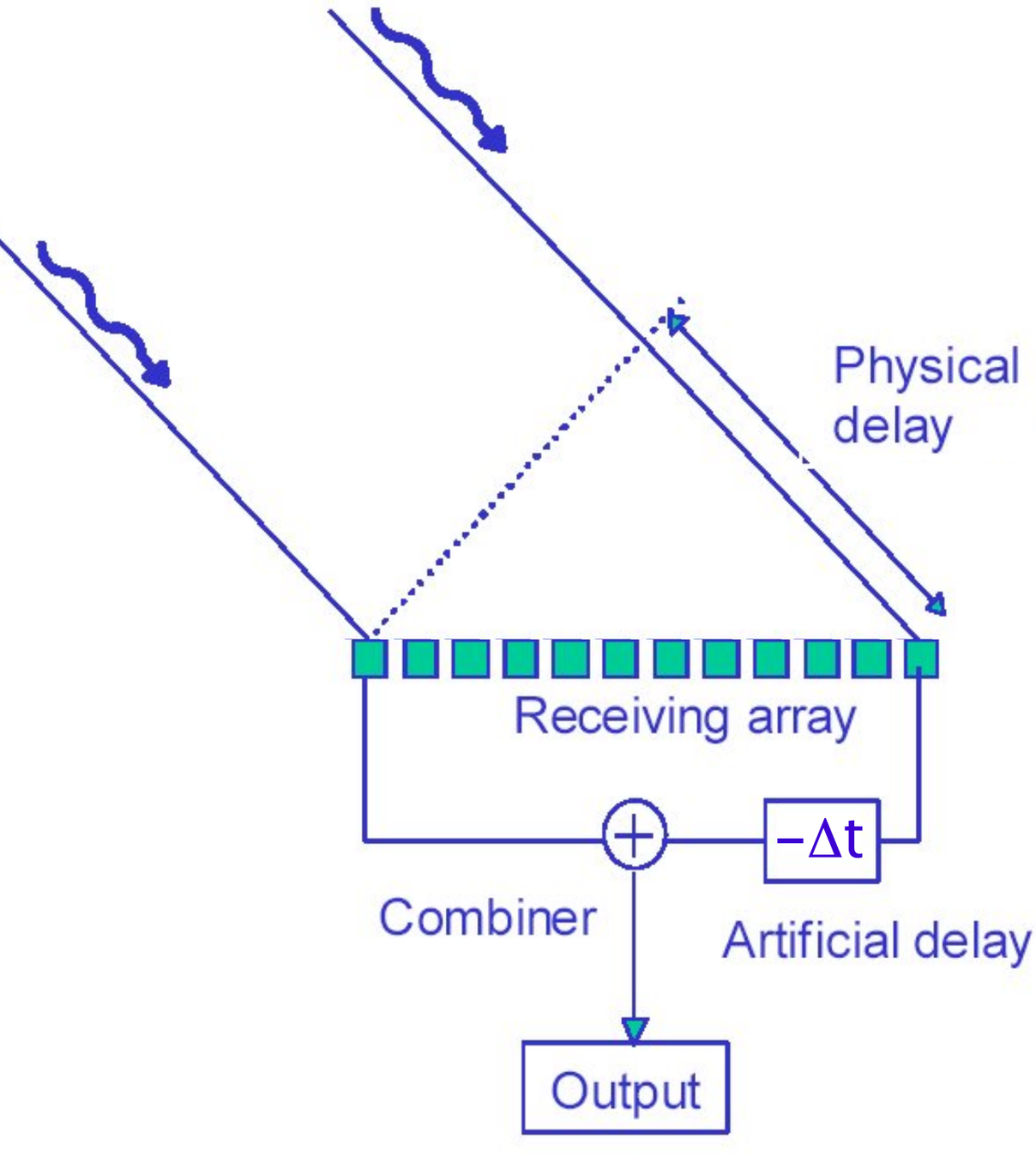
Phased Array Detectors

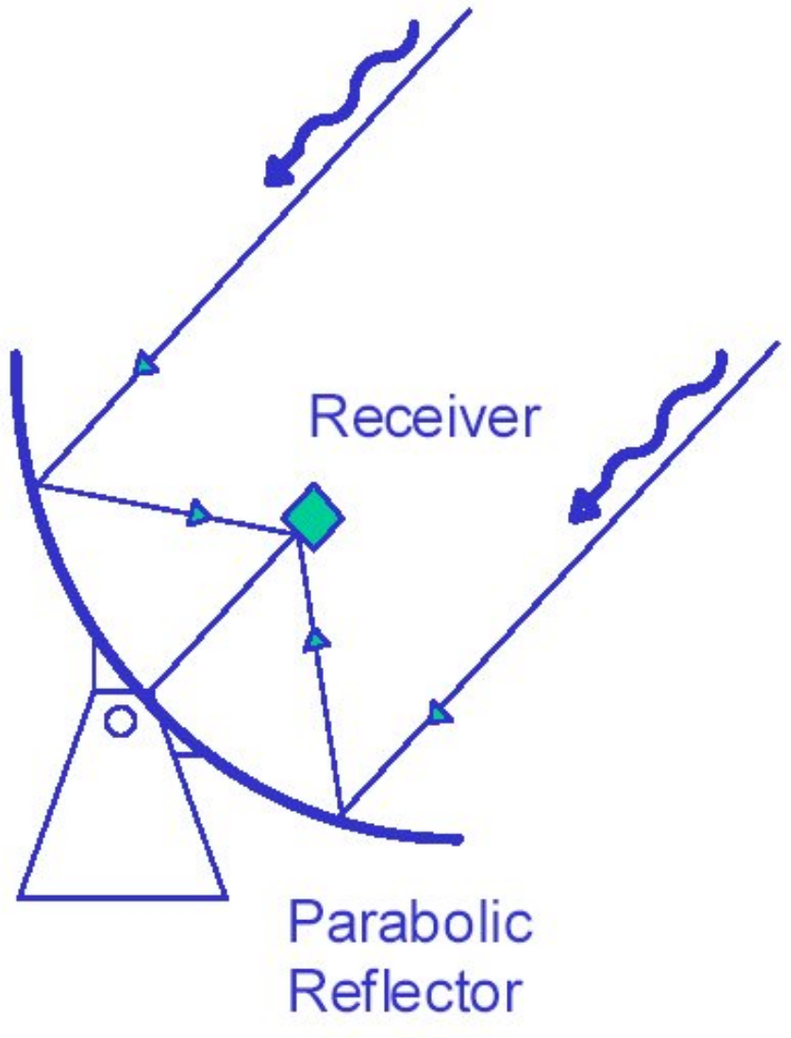




Electronic beam steering

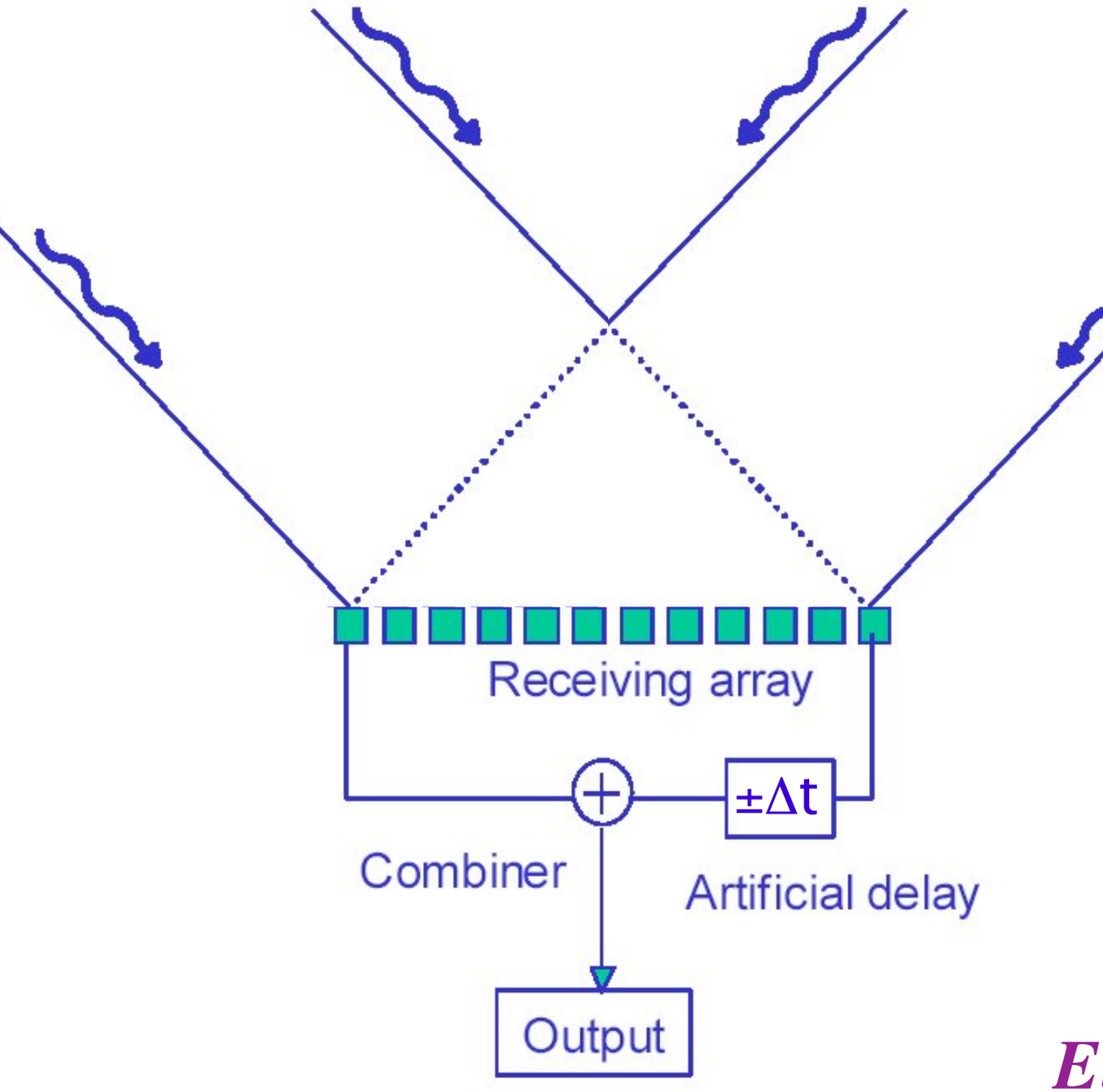
Phased Array Detectors

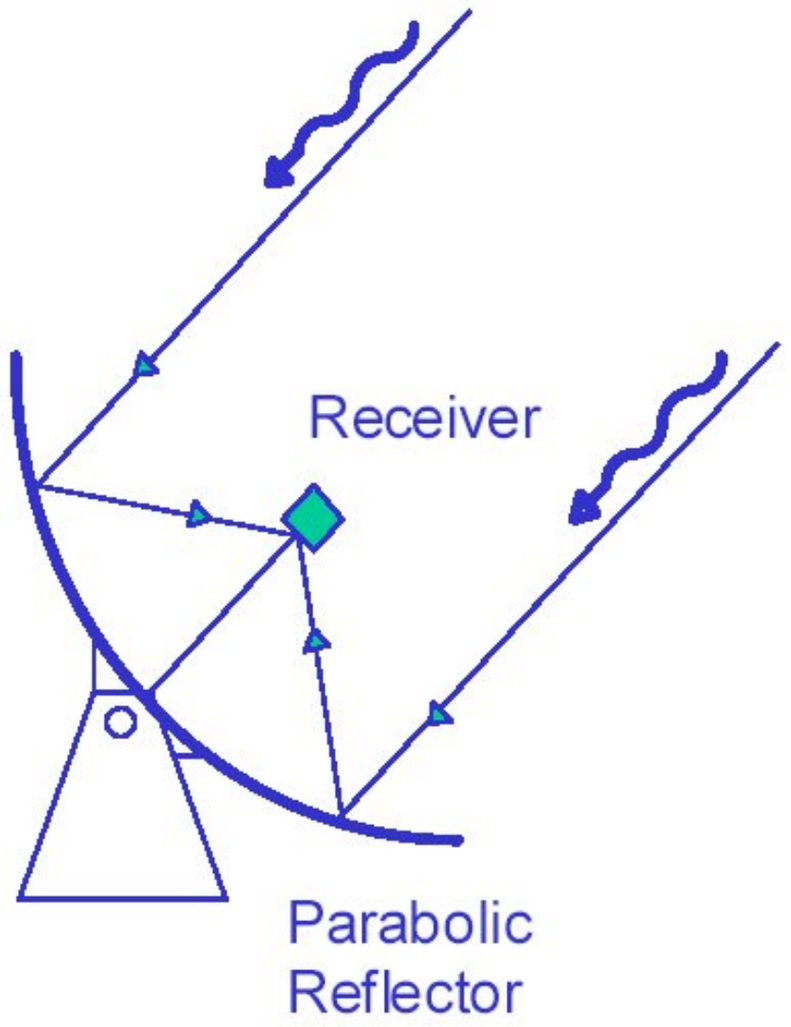




Electronic beam steering

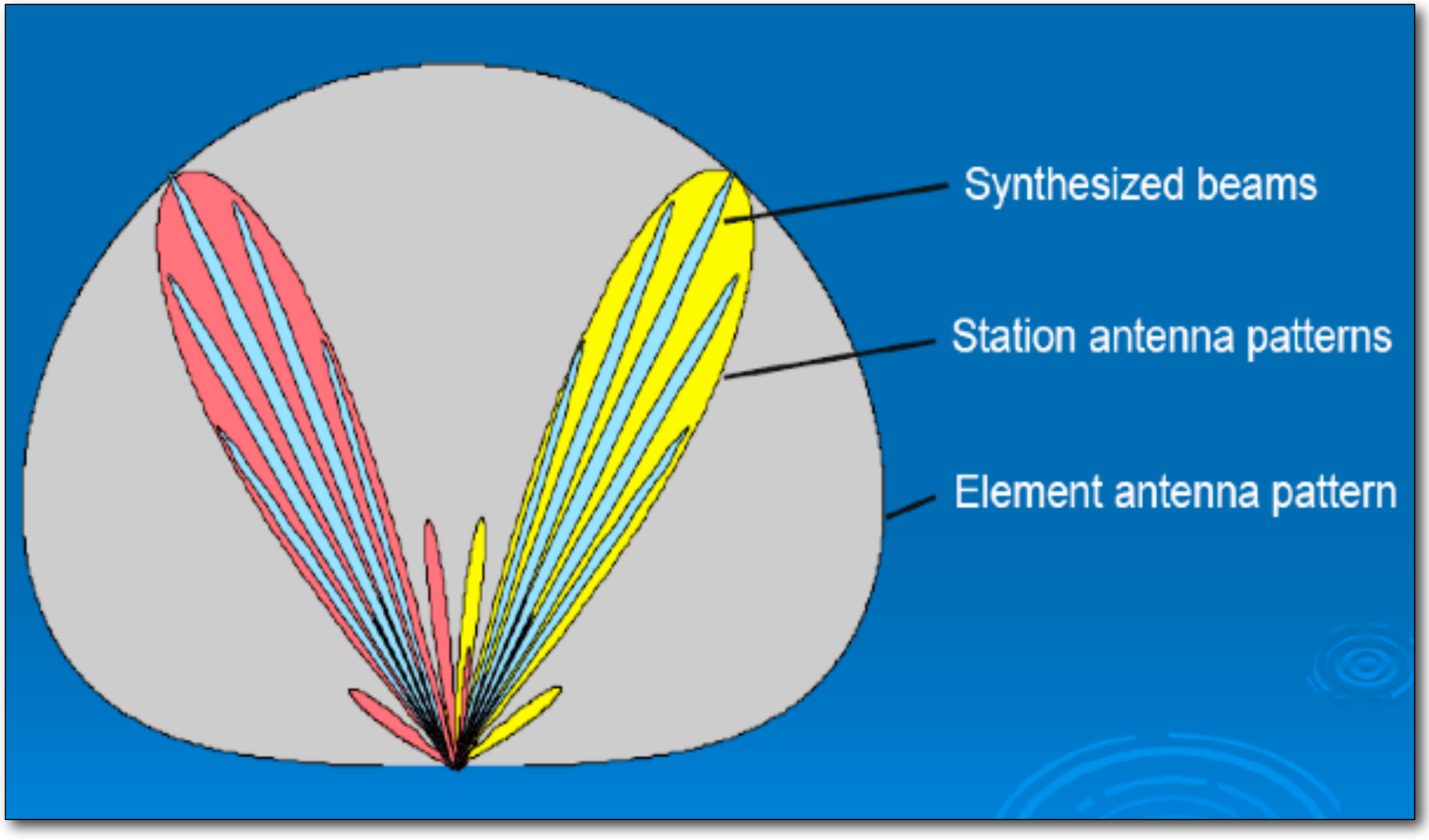
Phased Array Detectors





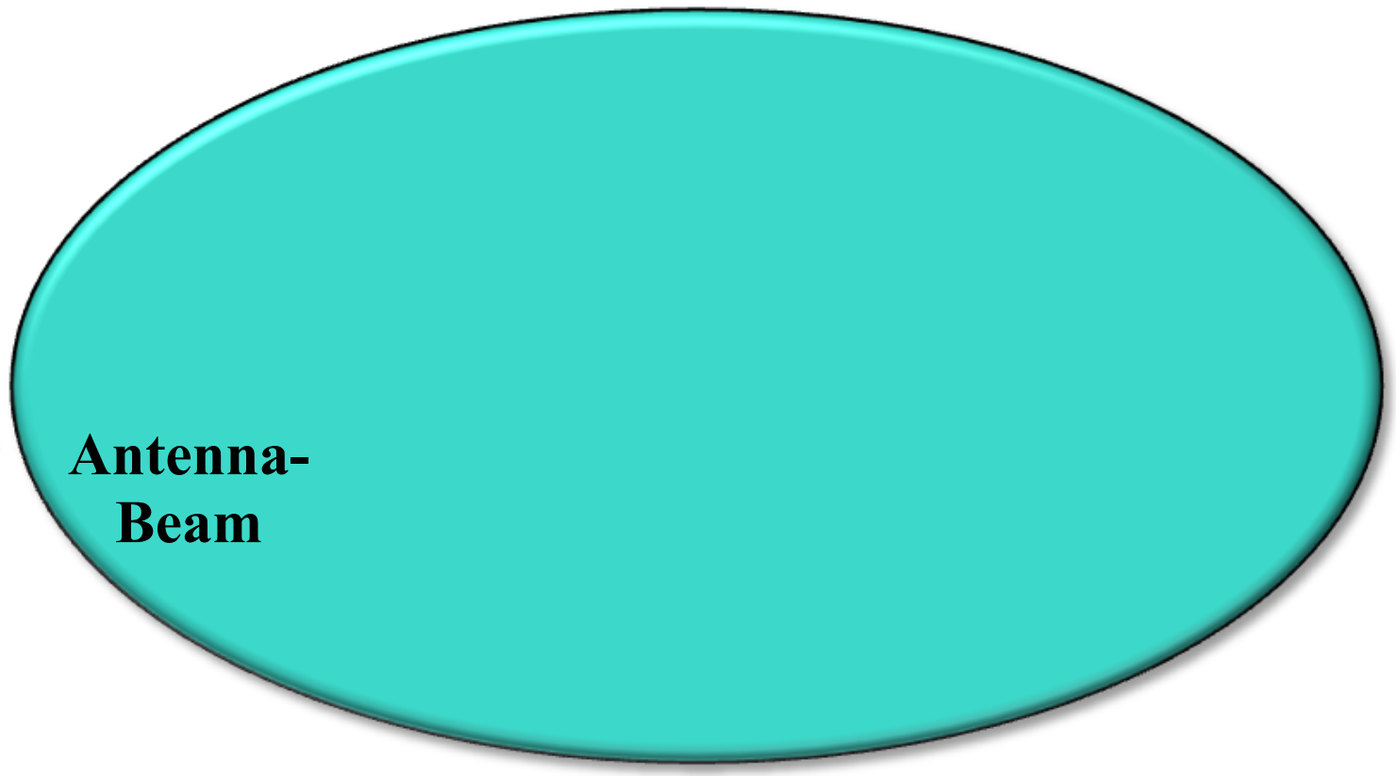
Electronic beam steering

Digital Beam-Forming



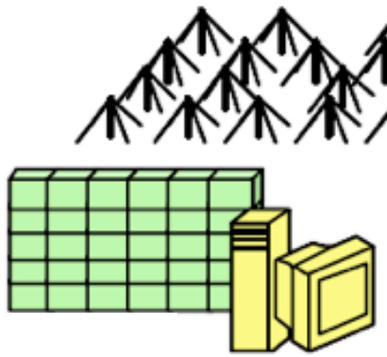
Digital Beam-Forming

Dipole



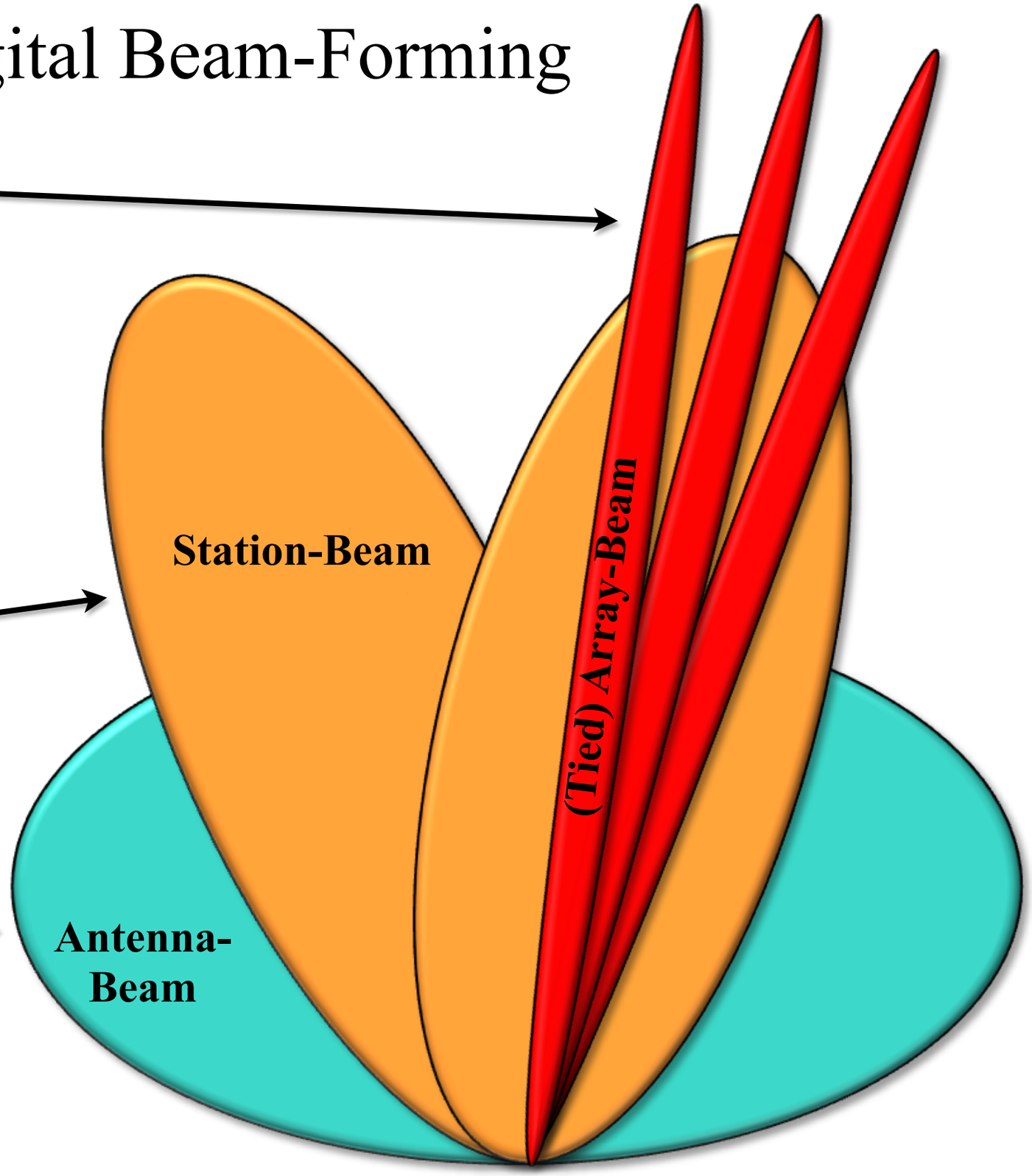
Digital Beam-Forming

Array



Station

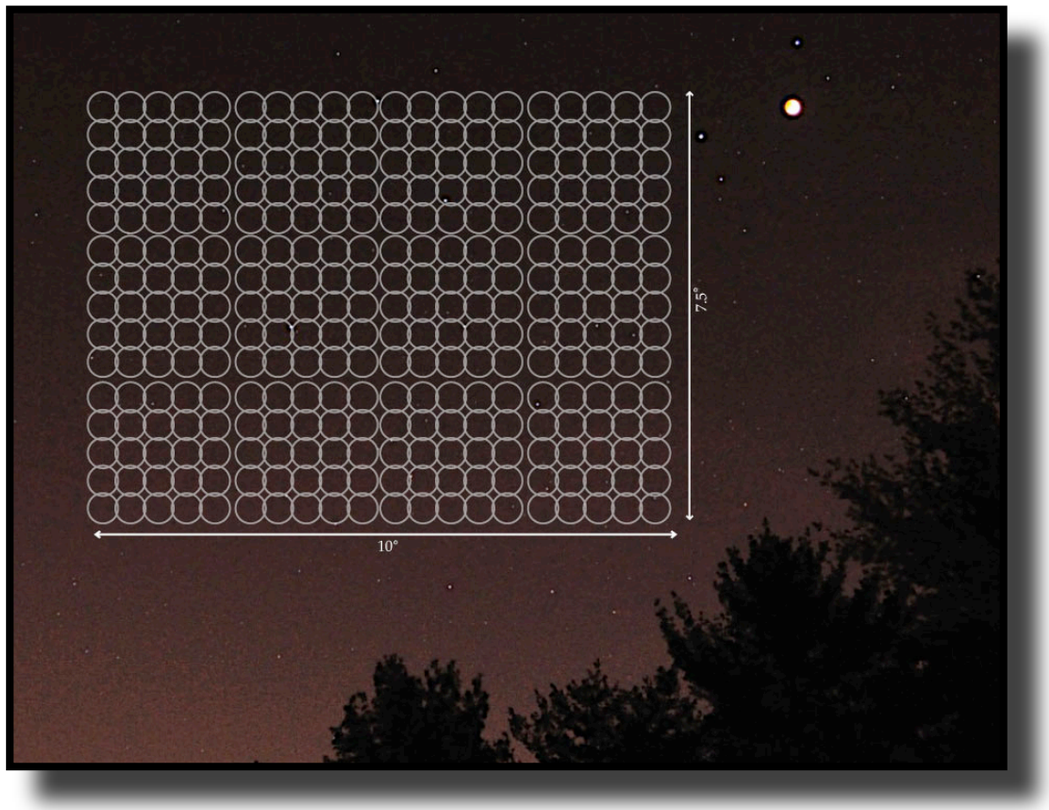
Dipole



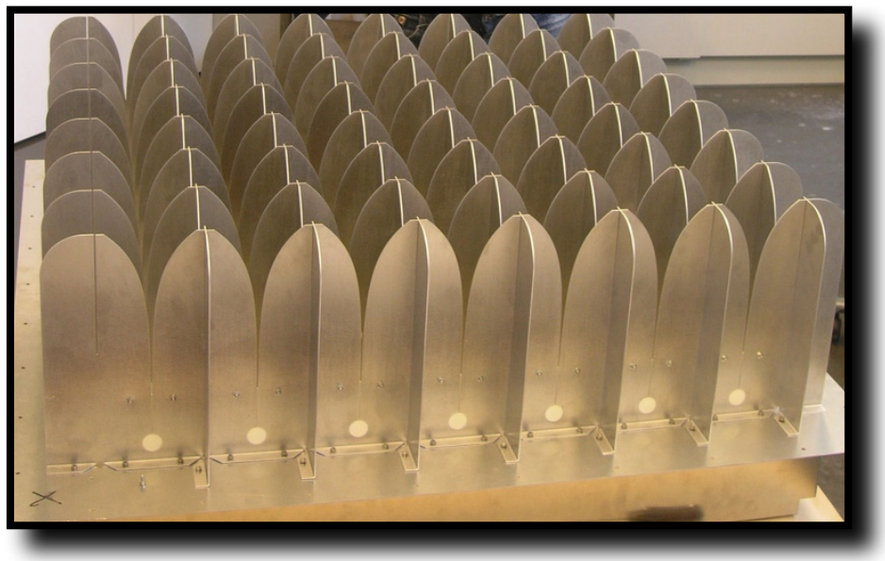
Parallel observations
Fast re-configuration
Rapid response

Phased Array Feeds

- Replace single-pixel detector with array of detectors and turn single dish into a camera.
- Survey speed increases by factor 20-40. Can do in a day what now takes a month!

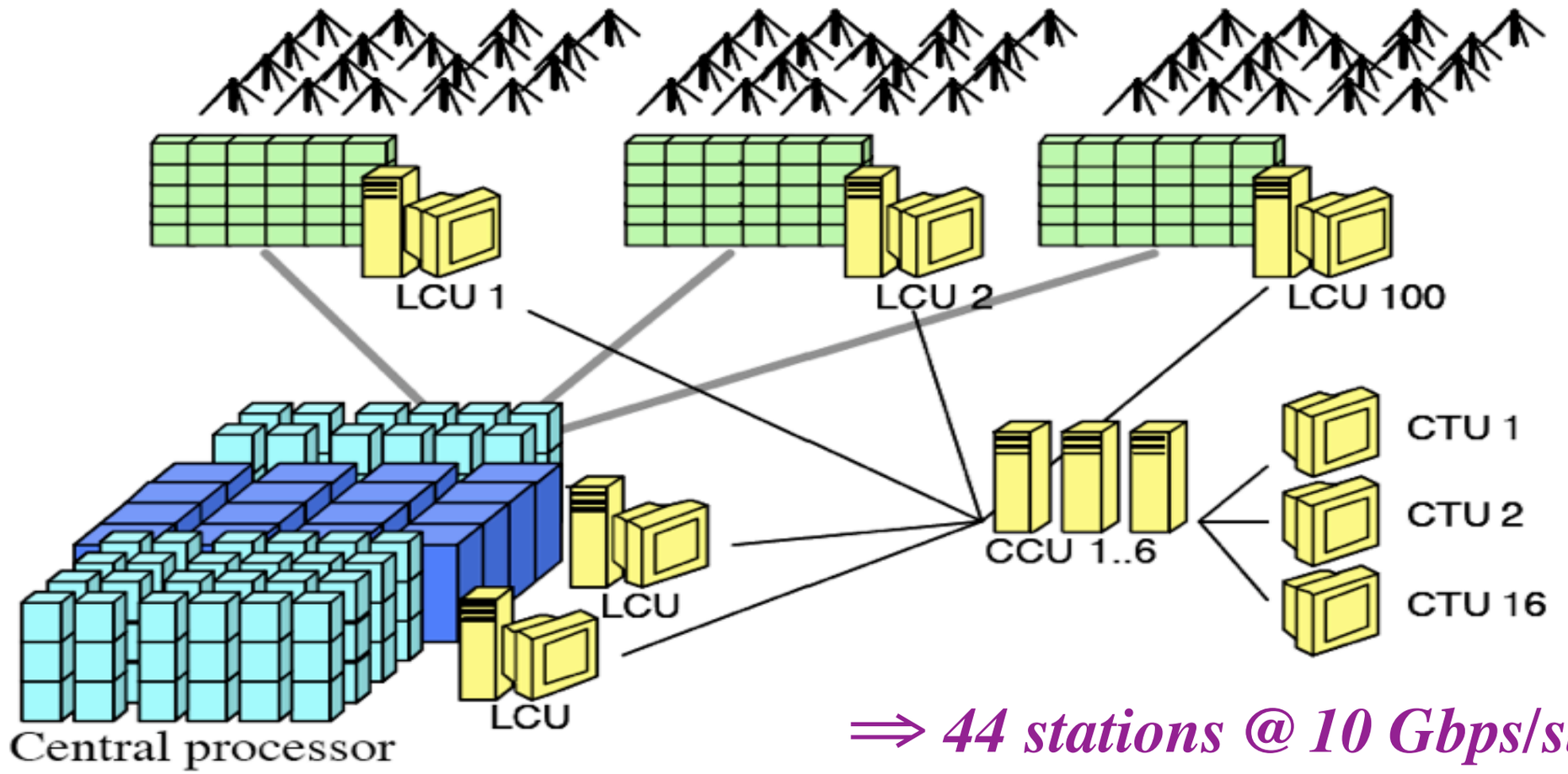


Apertif system on WSRT



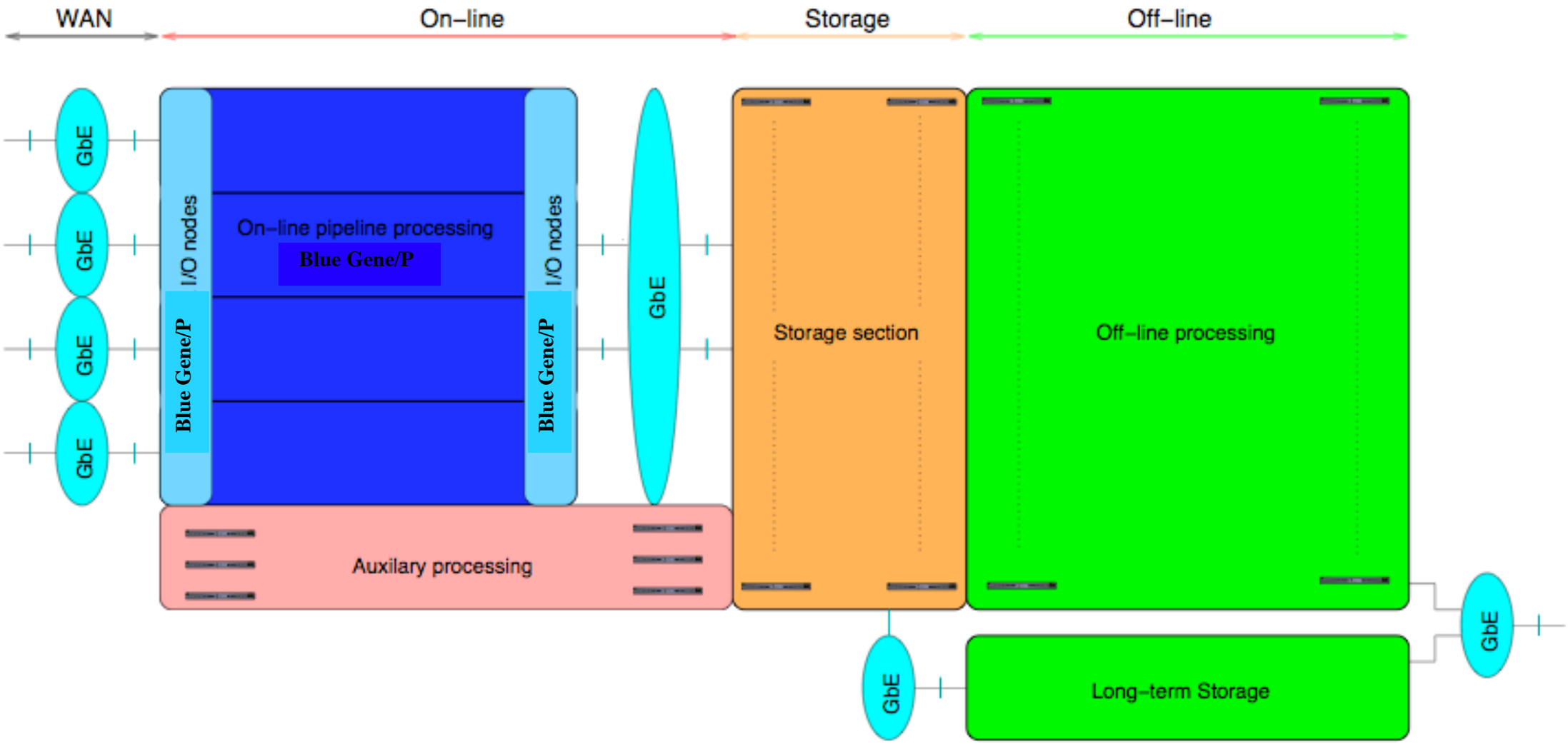
LOFAR Data Flow

- Station level processing *Amplification, digitization, filtering, beam-forming, transient ram buffers (TBB)*
  - Central processing *Delay compensation, correlation, calibration, science pipelines (BG/P, storage, offline cluster)*



⇒ 44 stations @ 10 Gbps/station

Central Processing



- BG/P *Data reception, transpose, correlation, beam-forming, de-dispersion, 45 TFLOPS*
  - Storage system *Short term storage of data, ~2 PByte, >100Gbps I/O*
    - Offline cluster *Pipelines, data products, off-line analysis, ~25 TFLOPS*


IBM
Blue Gene/P

Remote Operation

LOFAR Science Drivers

Key Science Projects

Epoch of Reionization

Transients and Pulsars

High Energy Cosmic Rays

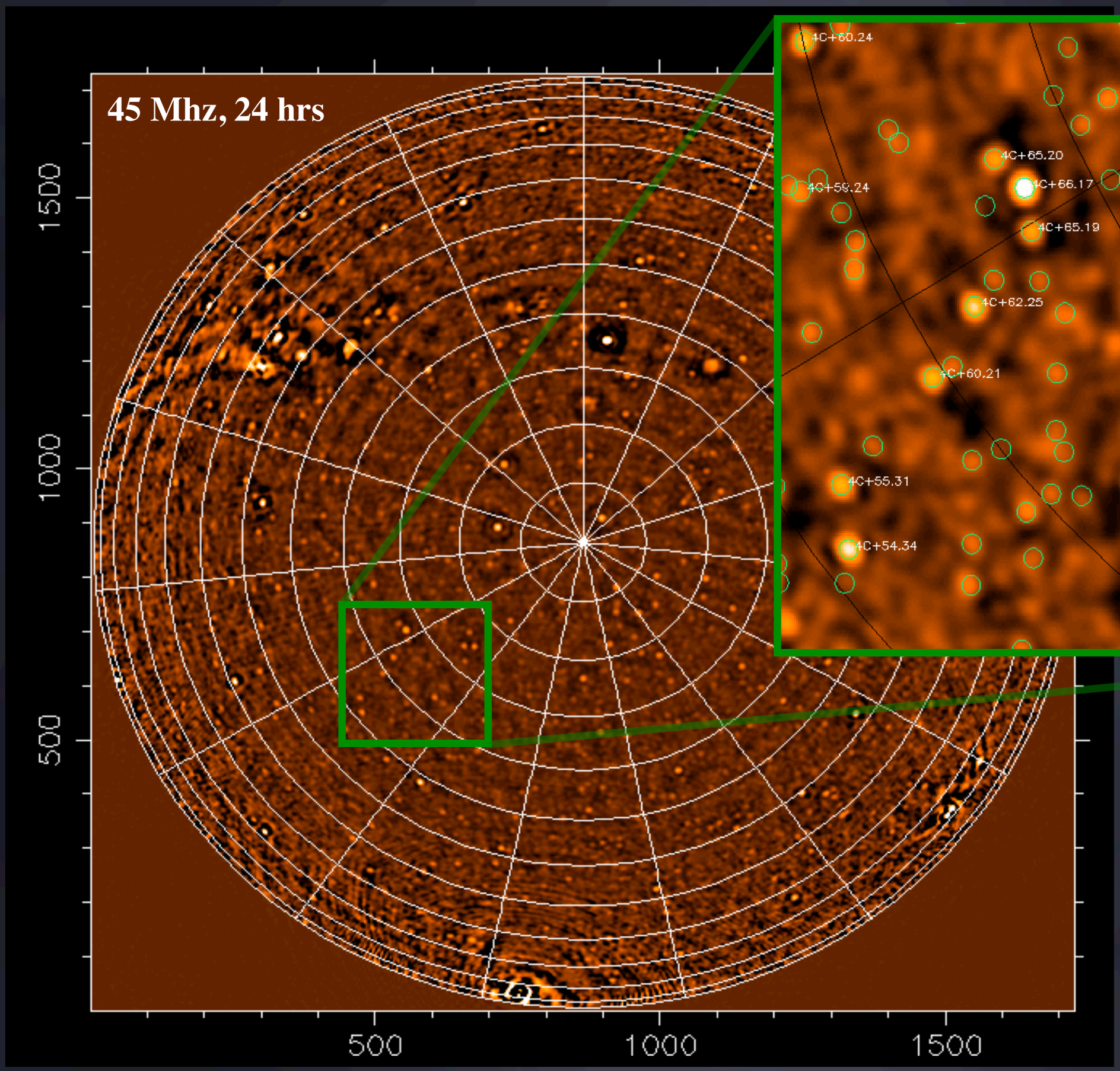
Surveys and the Distant Universe

Cosmic Magnetism

Solar Physics and Space Weather

⇒ International membership from all partner countries

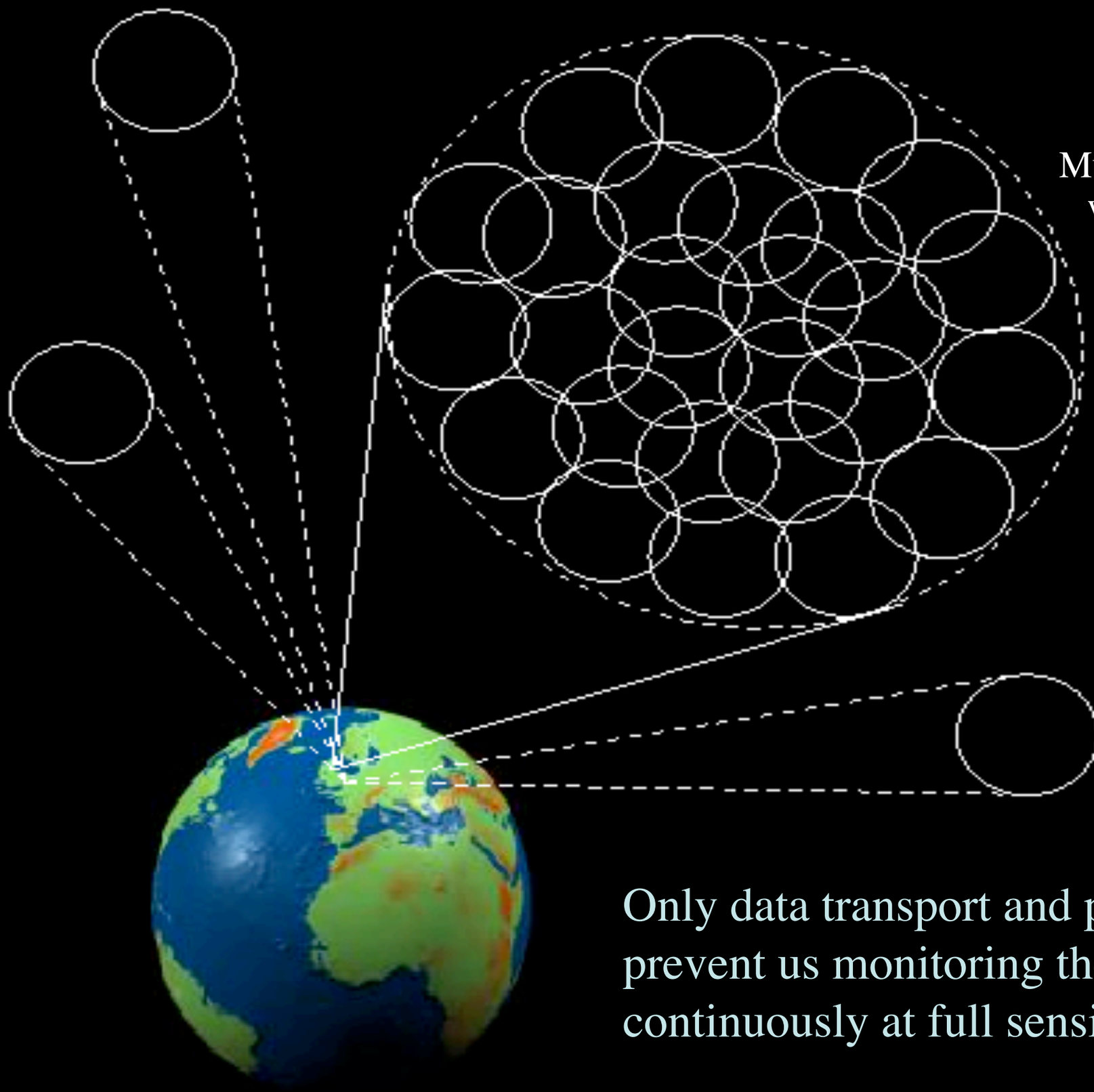
Contribute development and commissioning resources



All-sky Surveys with LOFAR

50+ supernova remnants,
100's of clusters z< 0.6,
Protoclusters at z~2,
Many z>2 radio galaxies,
Halos, relics, etc...

Radio Sky Monitor: Multiple station beams tile out a significant fraction of the sky and detect transients sources on timescales down to 1 second



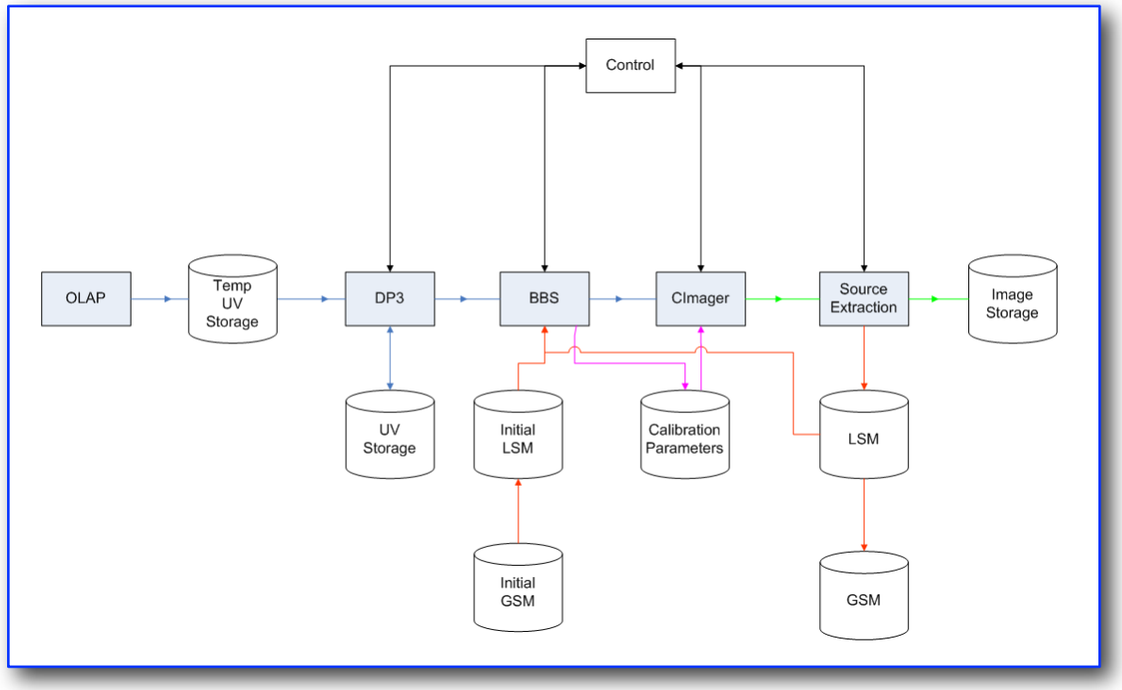
Multiple beams used to watch for new transients

Single beam(s) monitor known sources

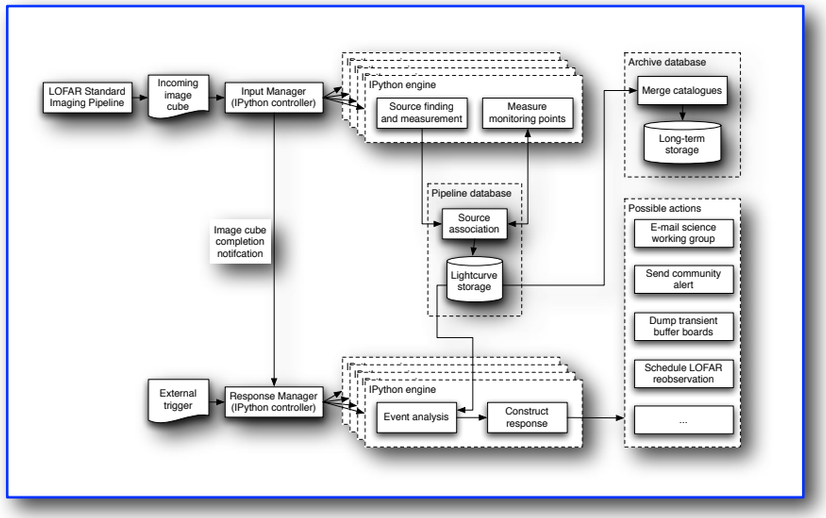
Only data transport and processing power prevent us monitoring the entire visible sky continuously at full sensitivity and resolution!

Science Pipelines

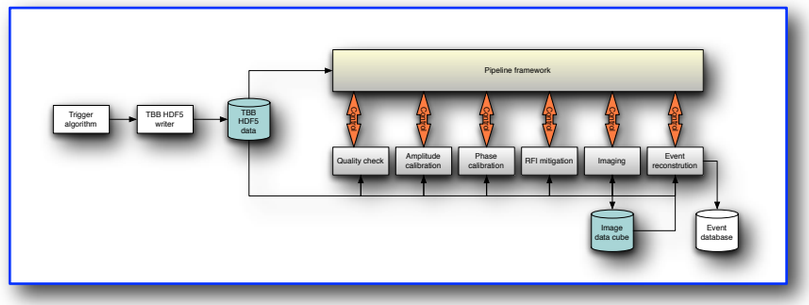
Standard Imaging



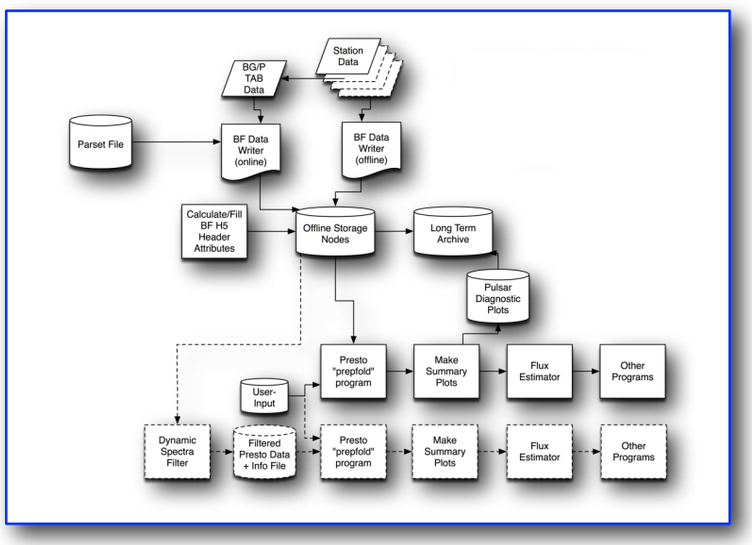
Transient Detection



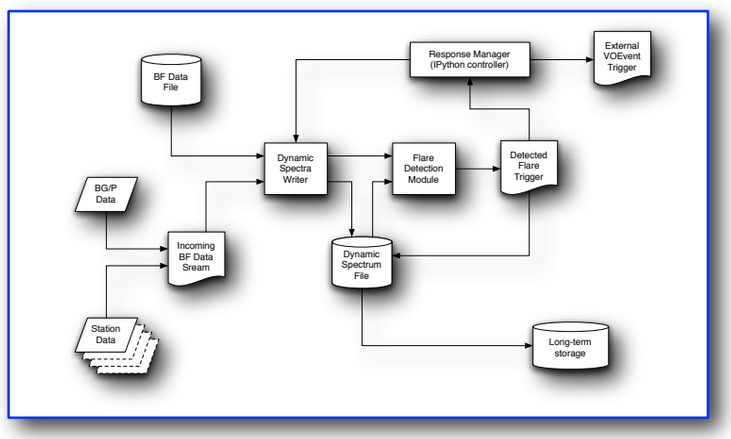
VHECR



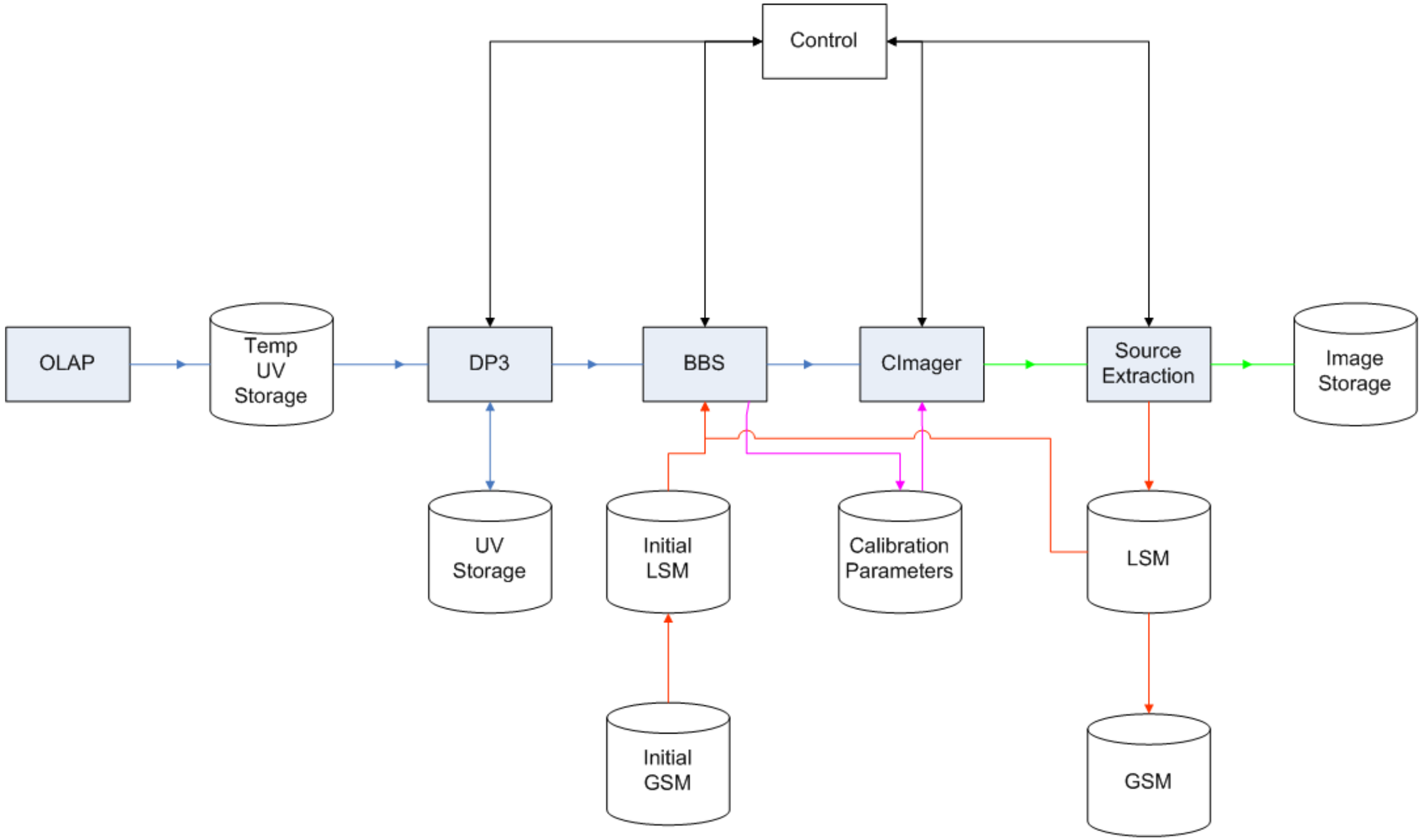
Known Pulsars



Dynamic Spectra



Standard Imaging Pipeline



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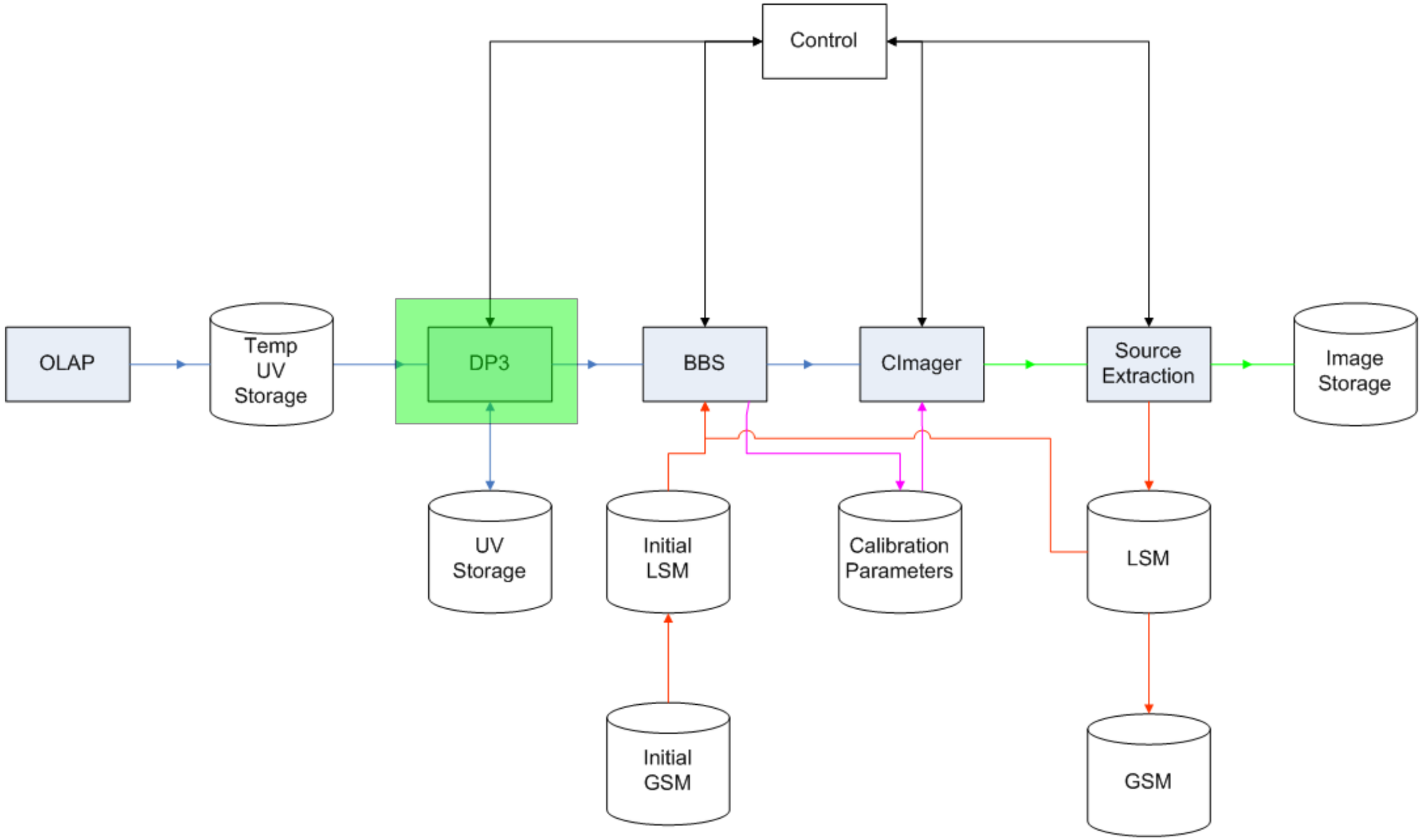
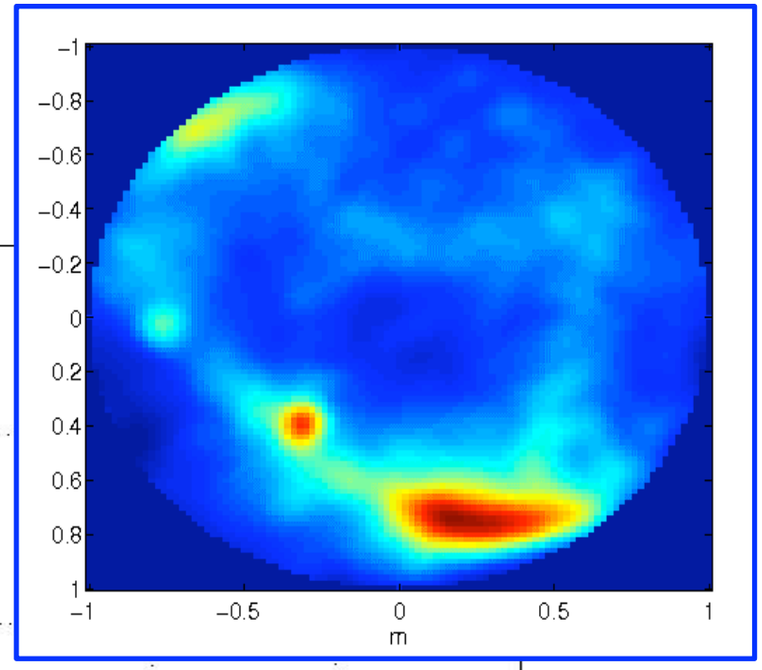
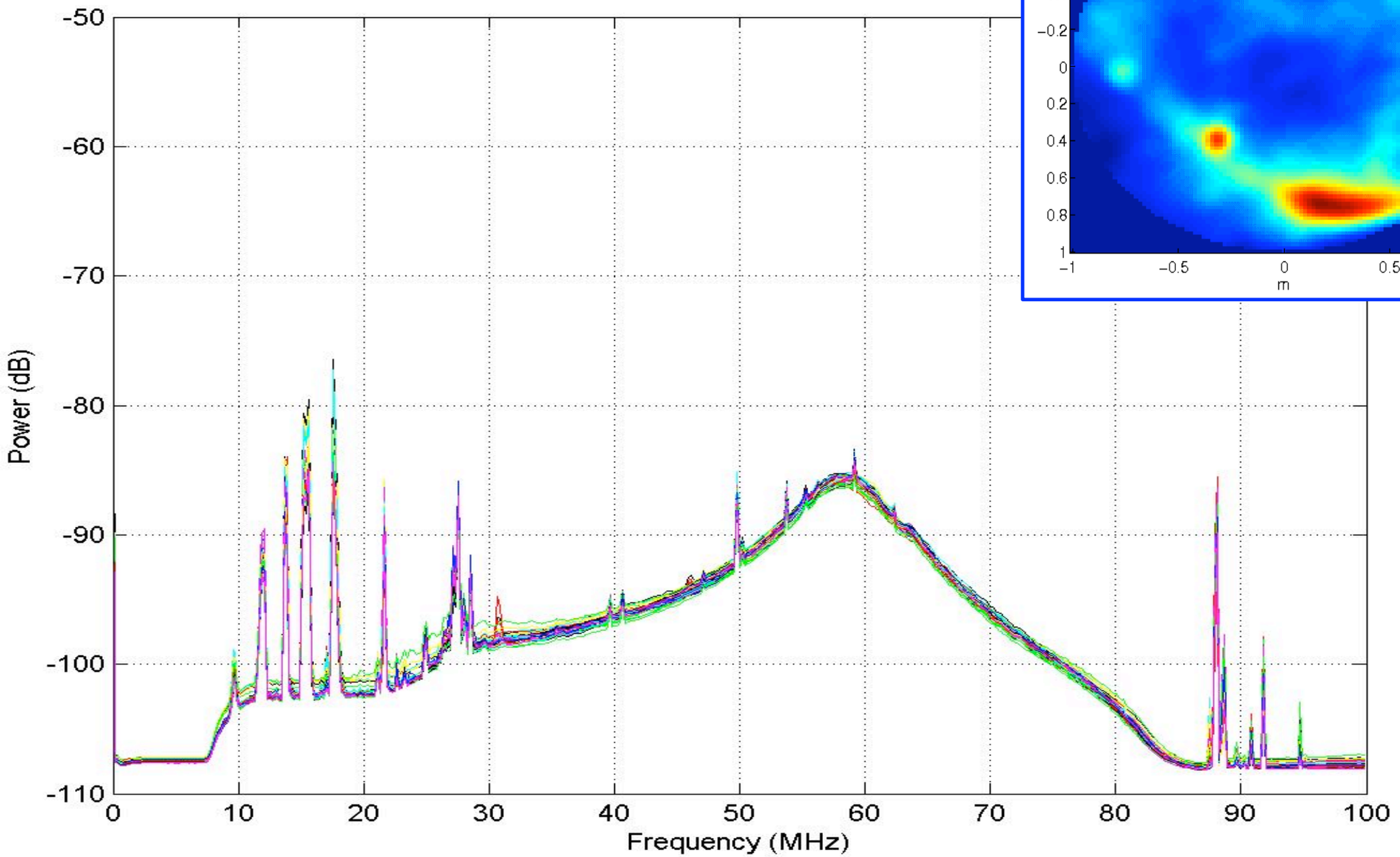
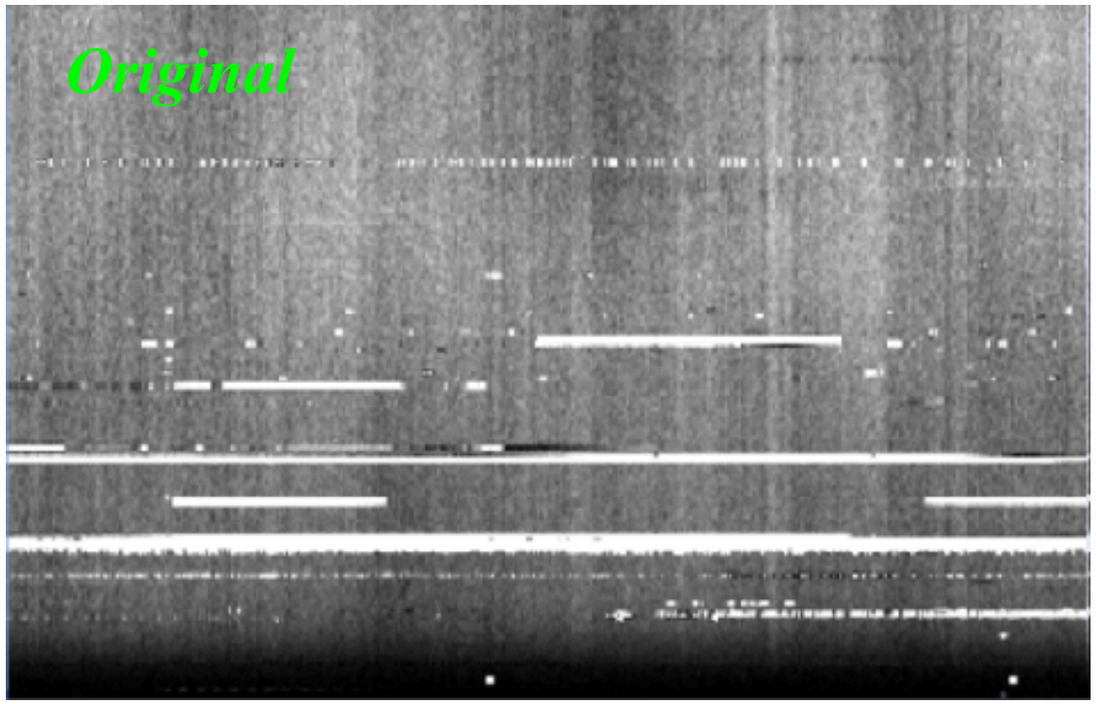


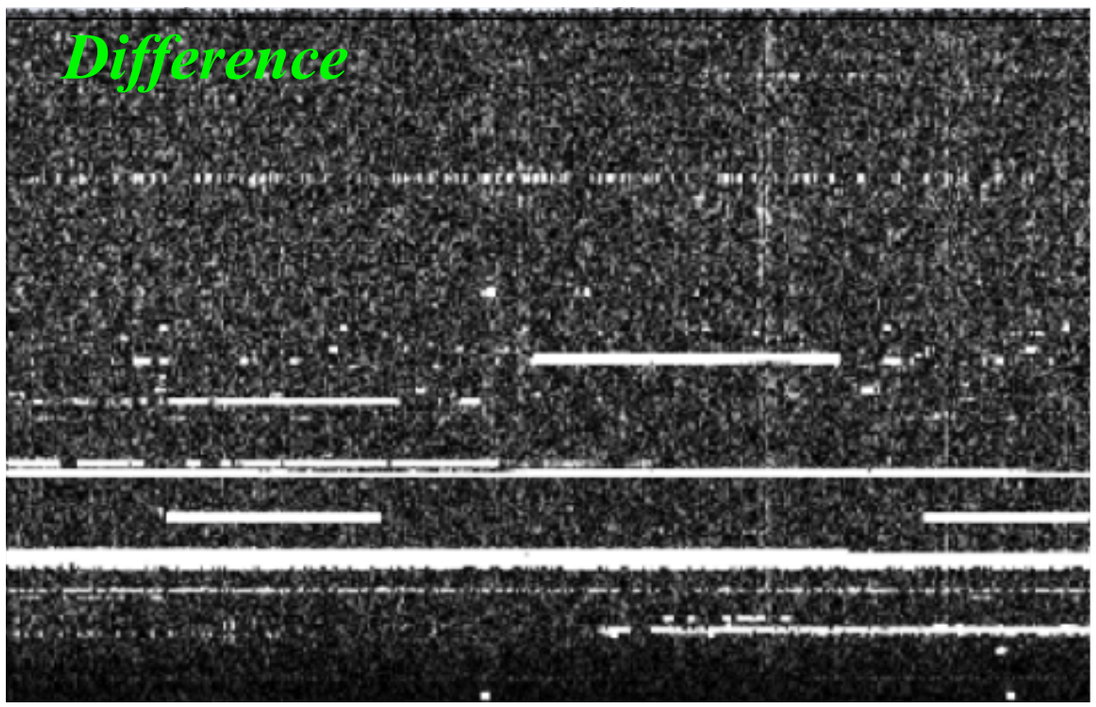
Local RFI Environment

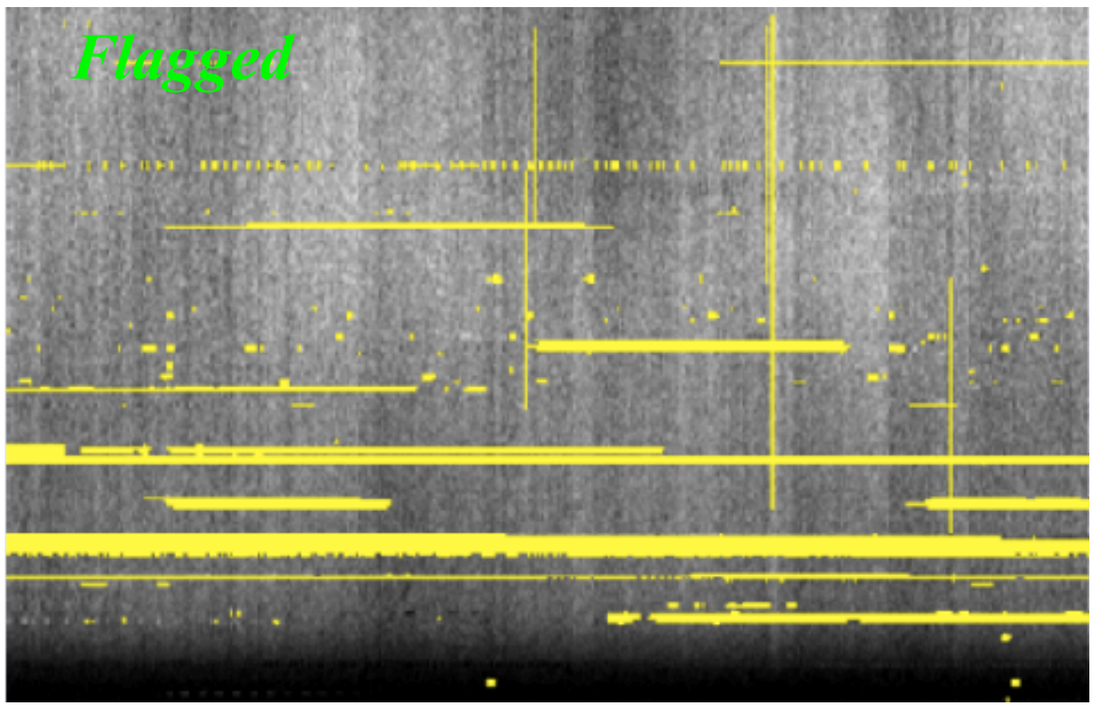




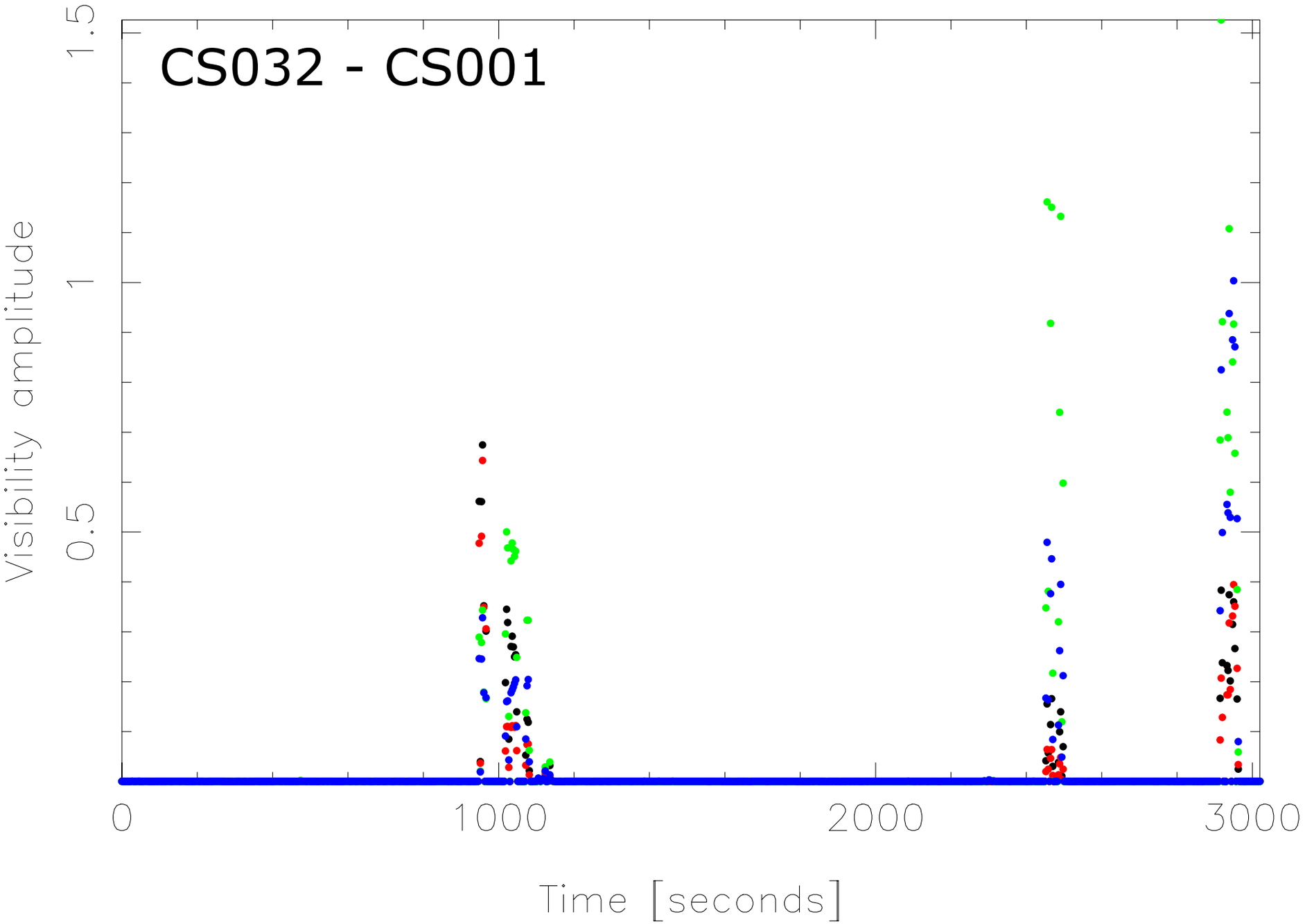
Automated RFI Flagging



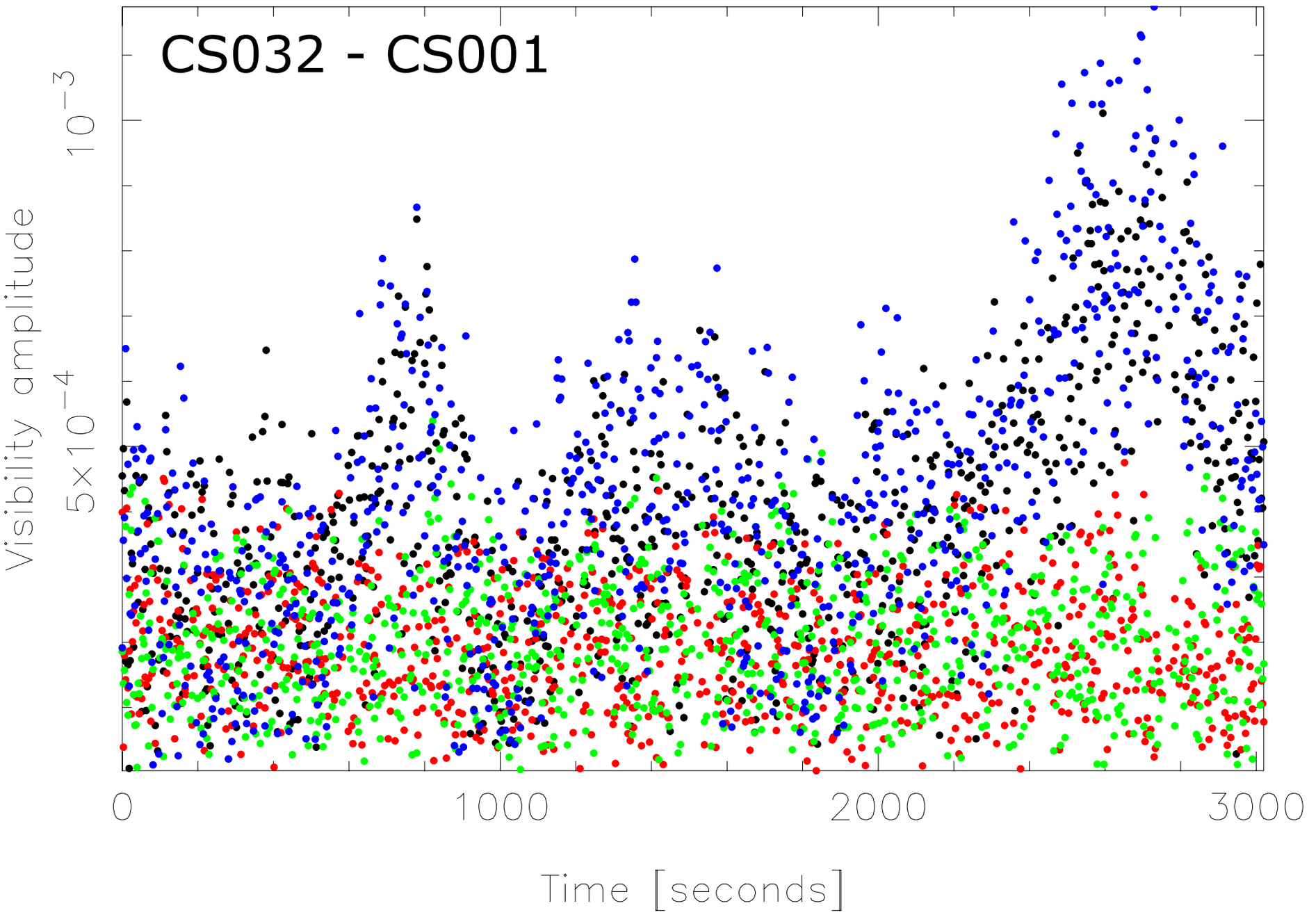




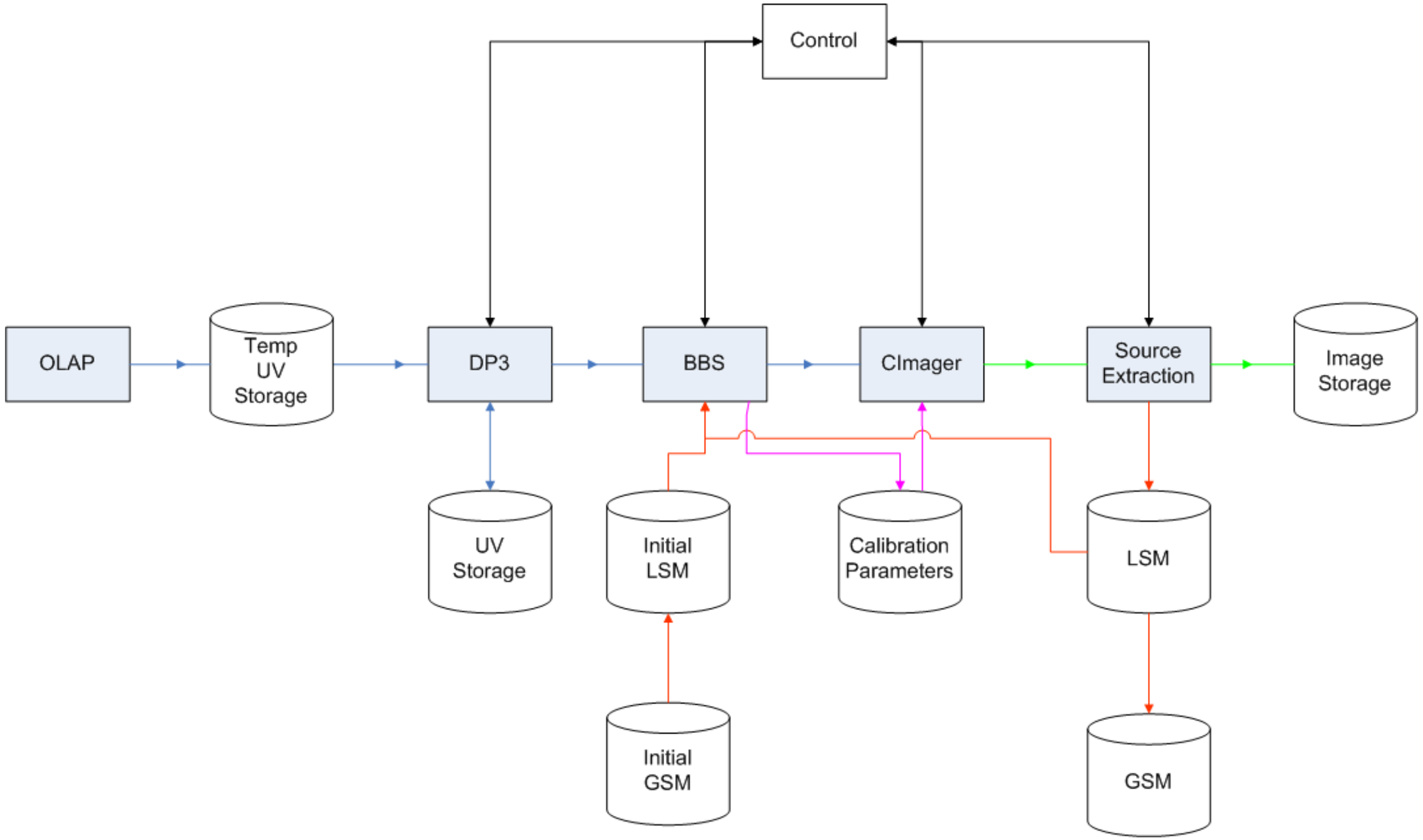
Automated RFI Flagging



Automated RFI Flagging



Standard Imaging Pipeline



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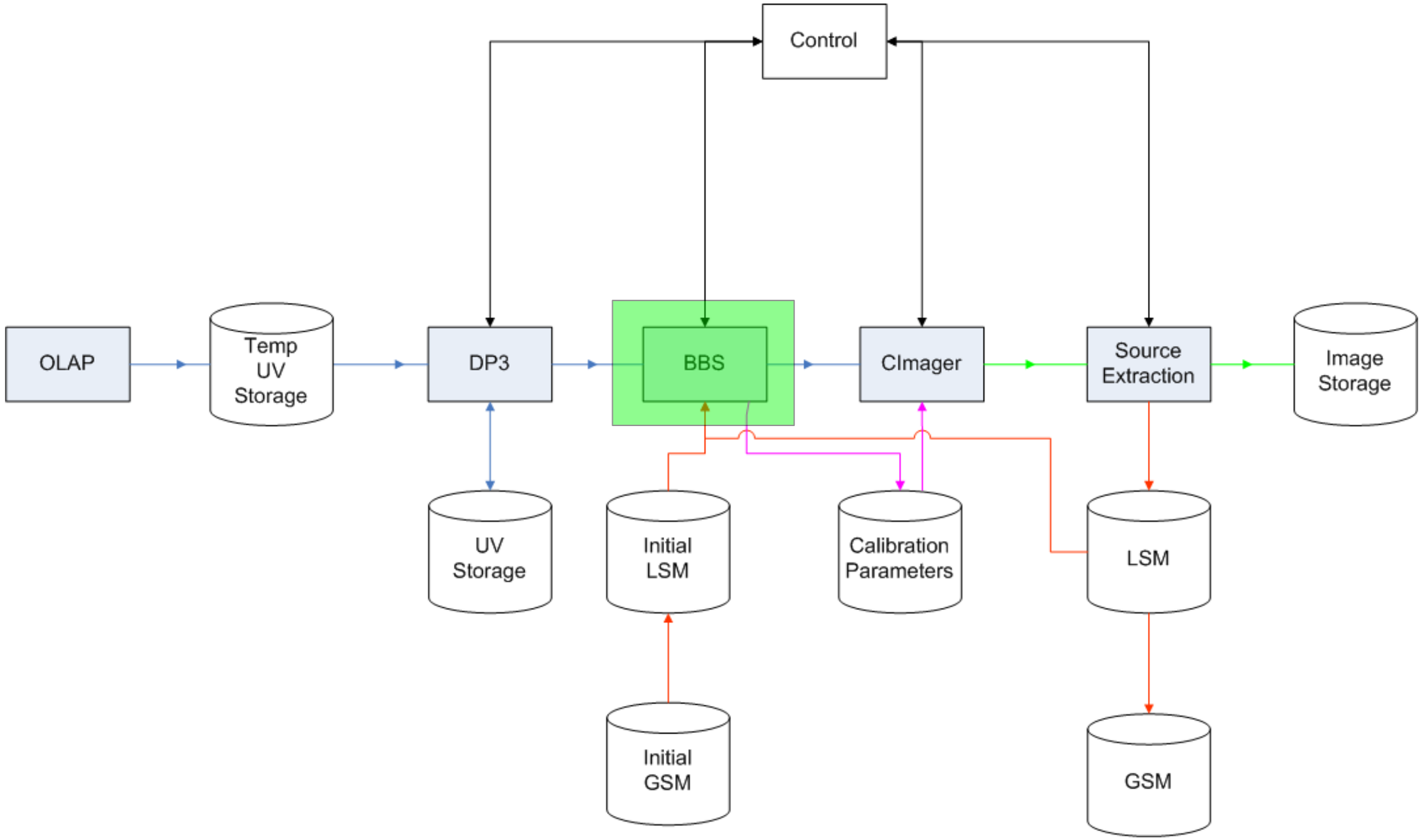
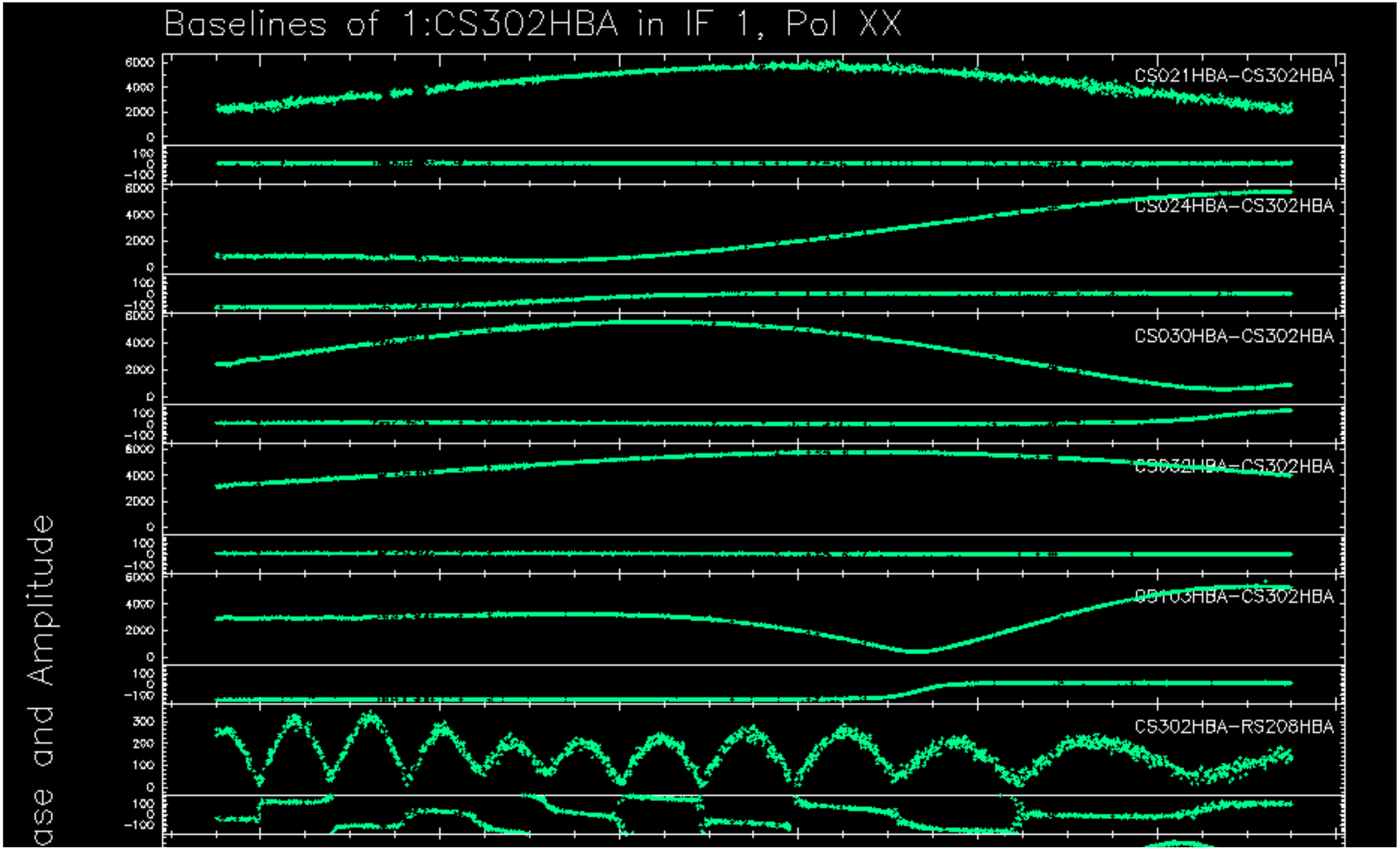
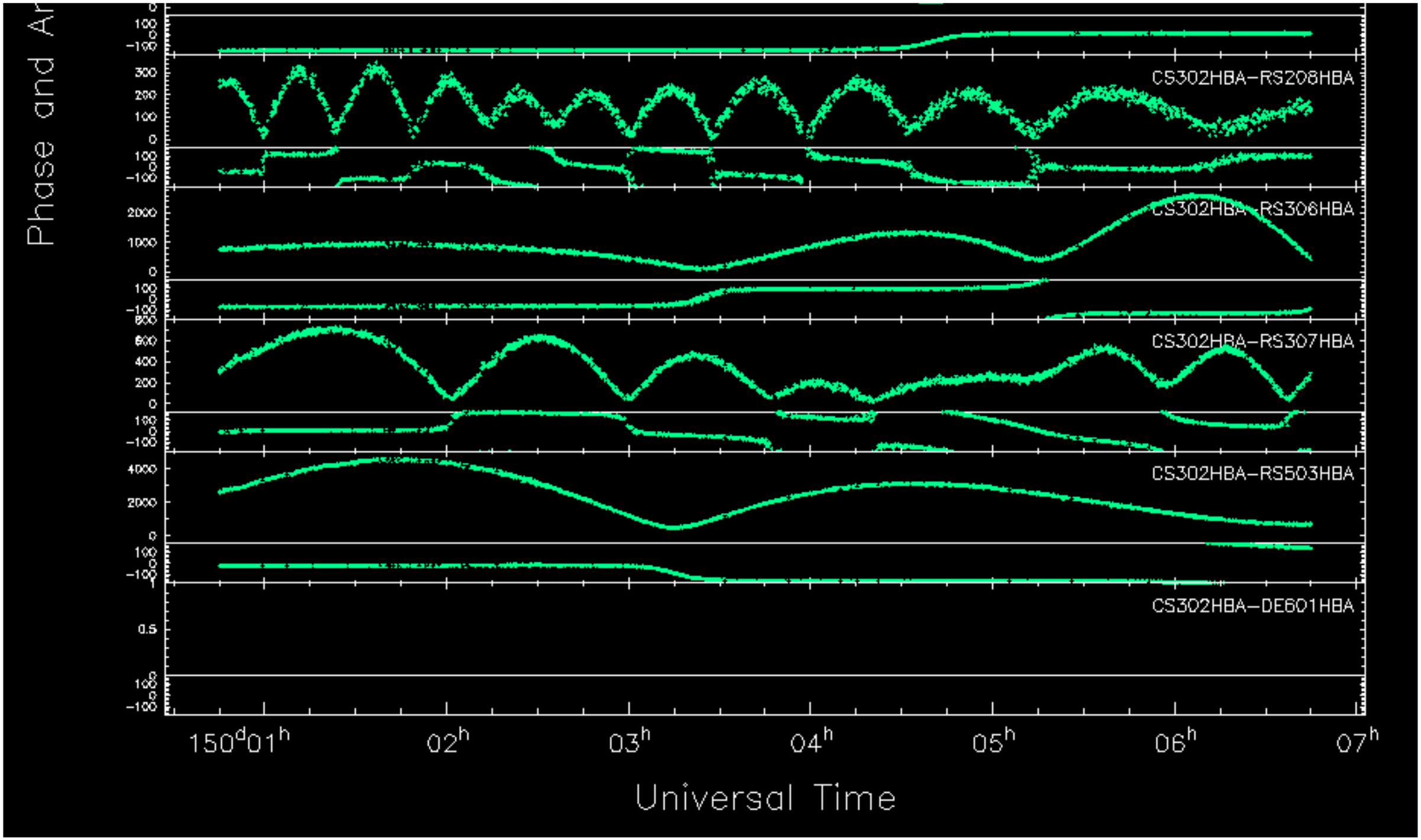


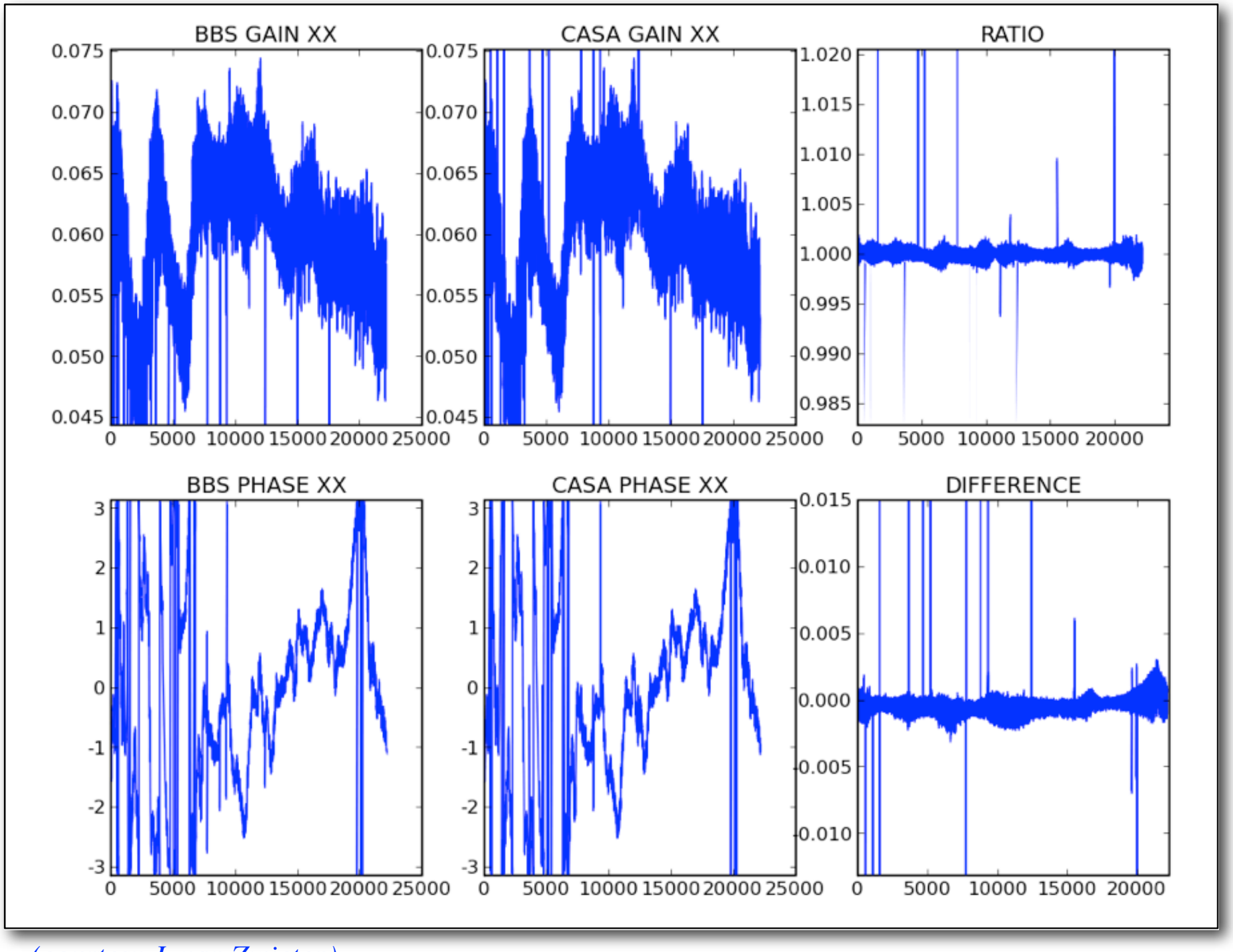
Data Quality



Data Quality



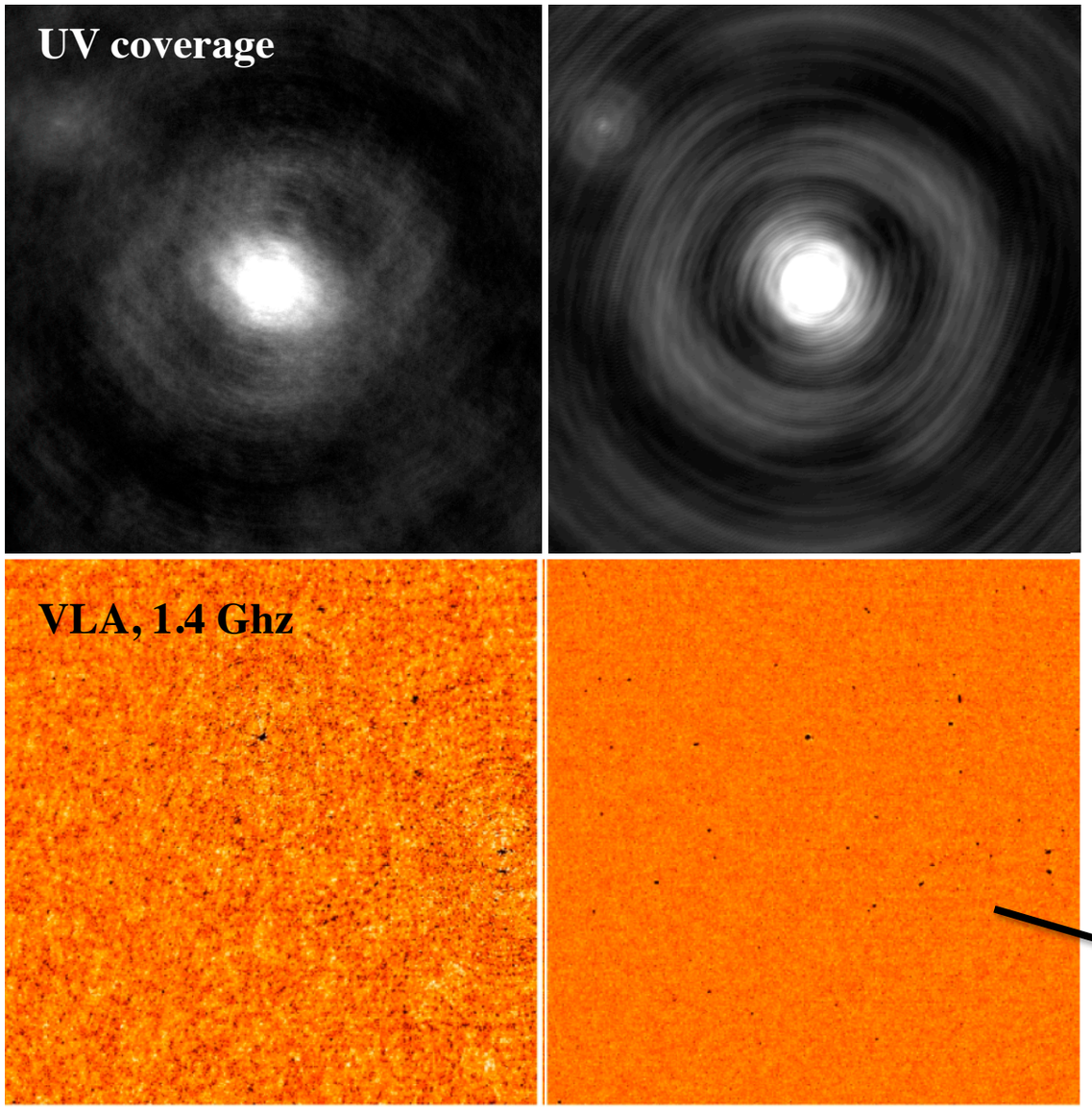
Calibration Testing



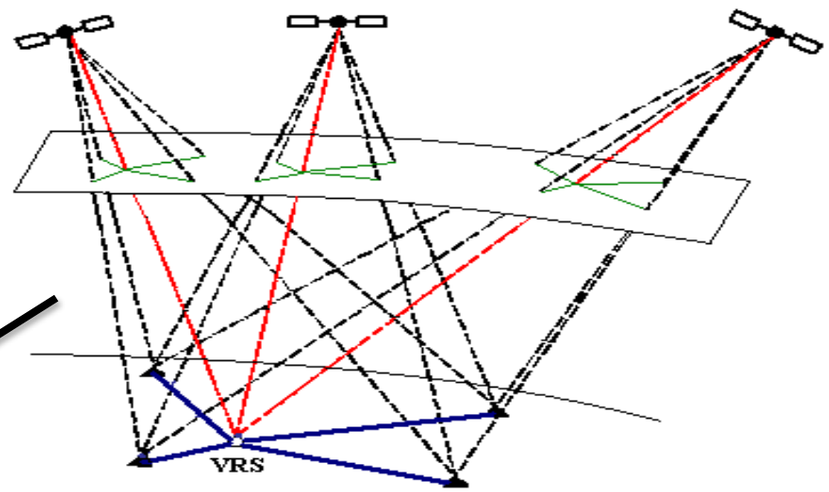
(courtesy J. van Zwieten)

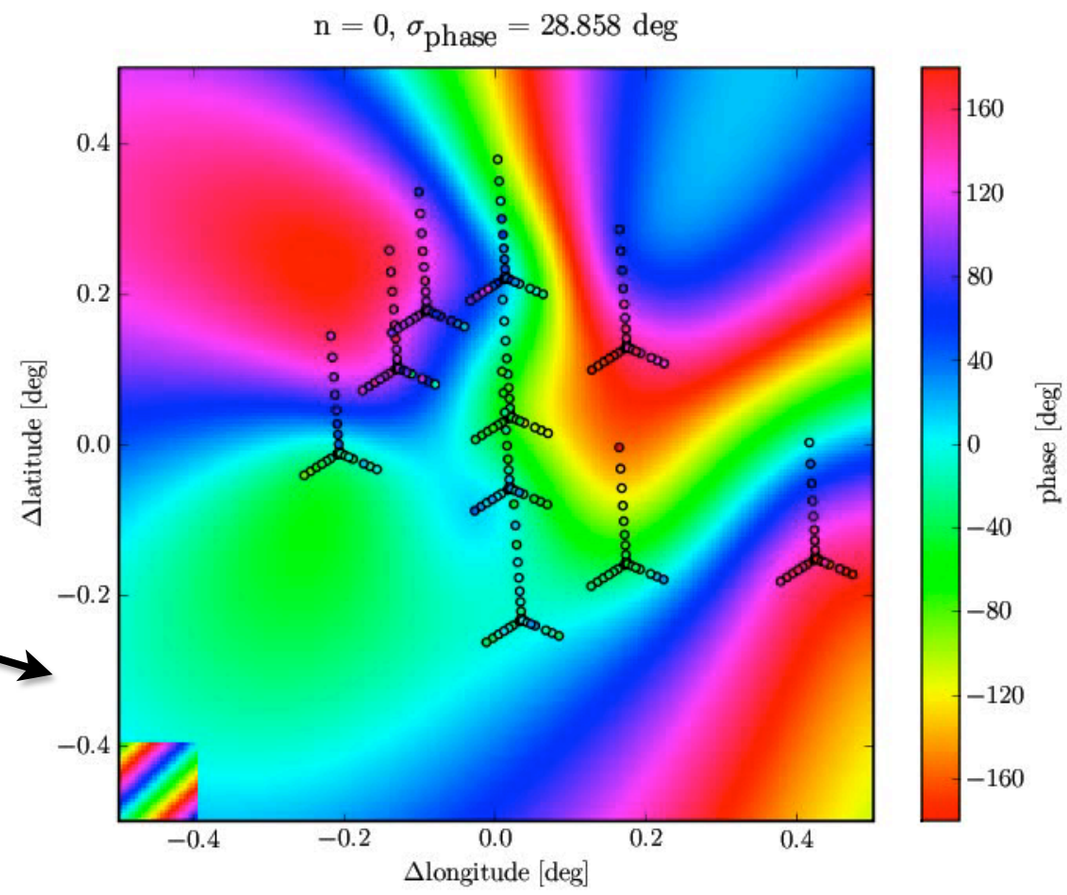
Ionosphere Correction

Uncorrected | Corrected

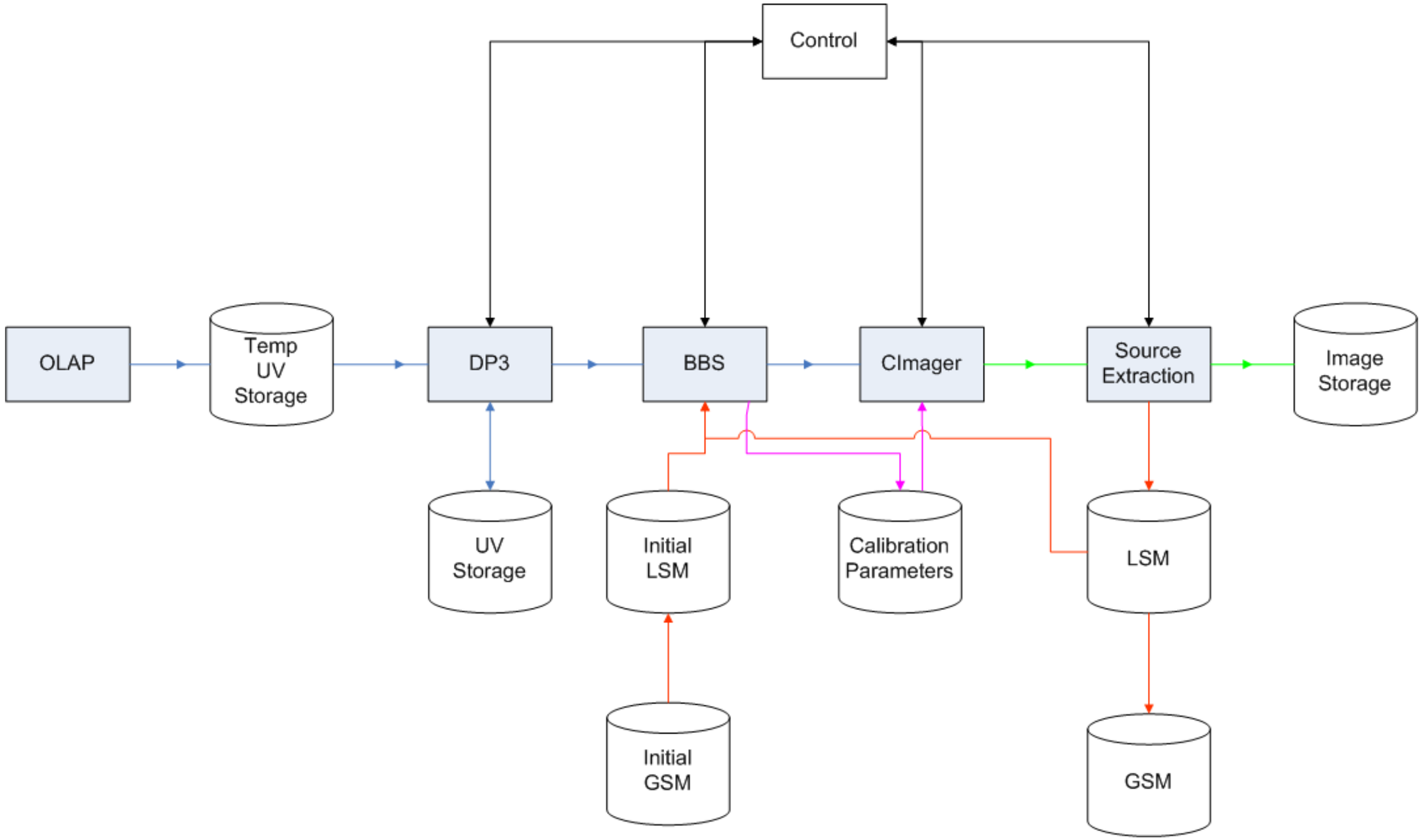


(courtesy H. Intema)

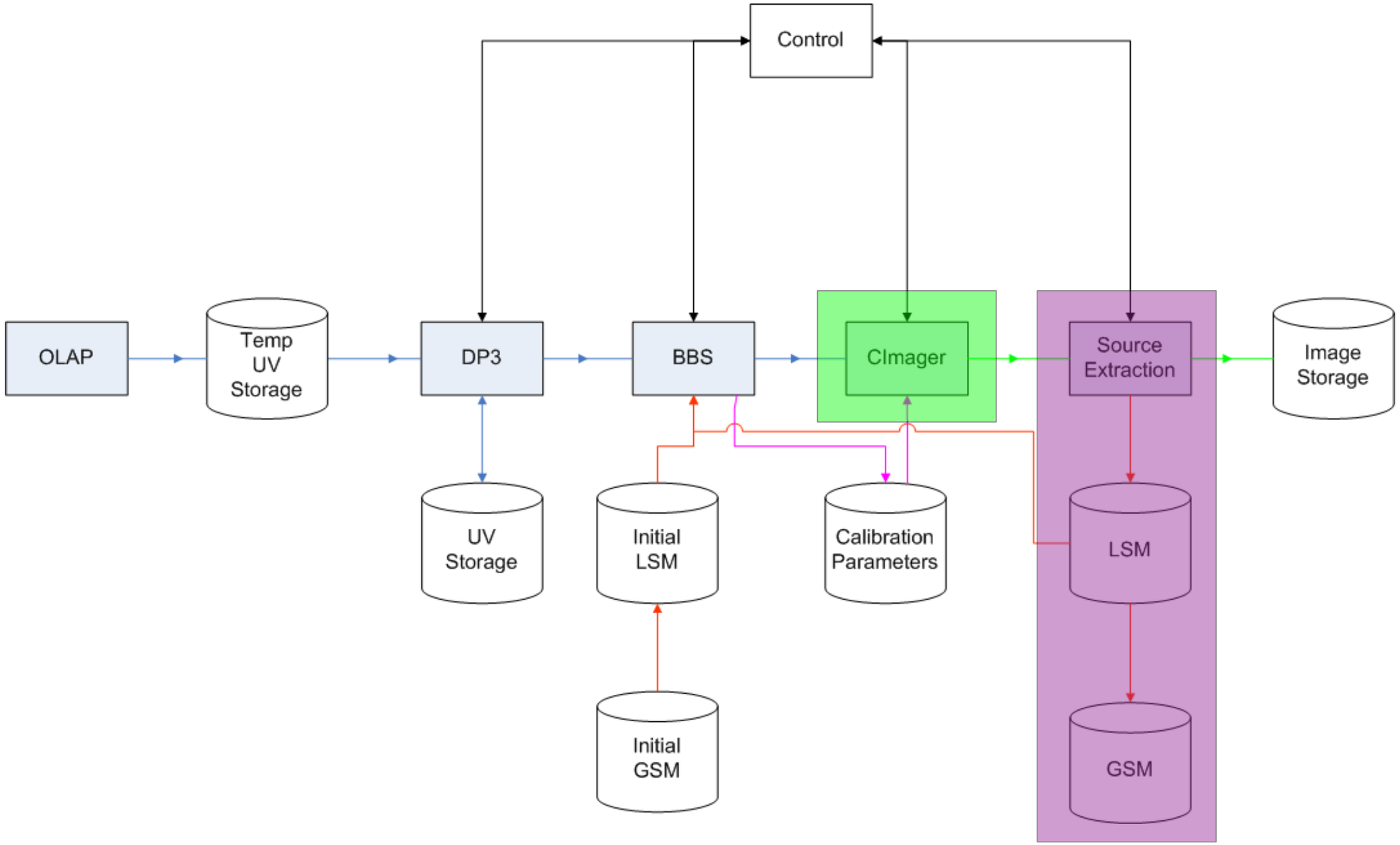


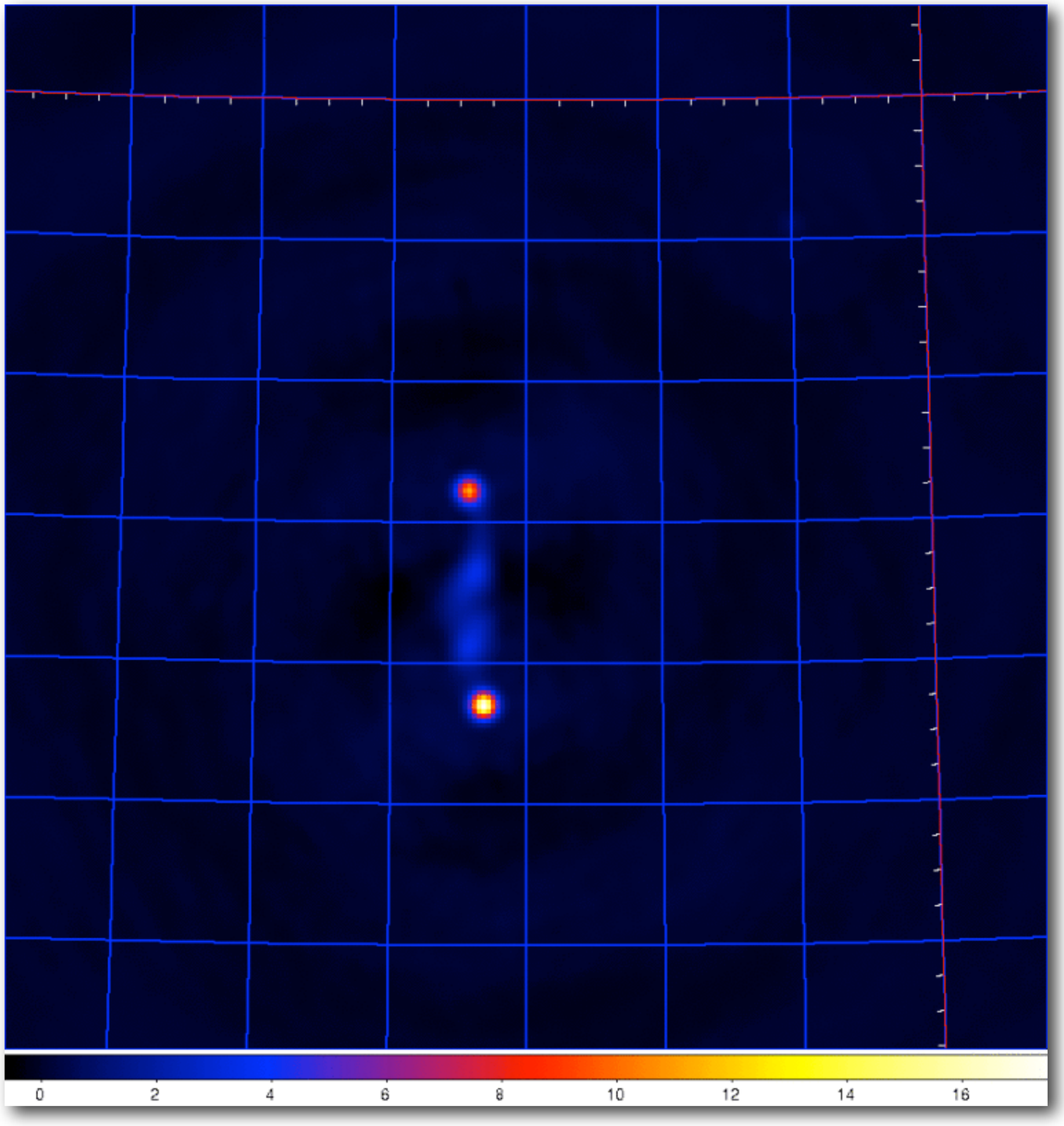


Standard Imaging Pipeline



Standard Imaging Pipeline



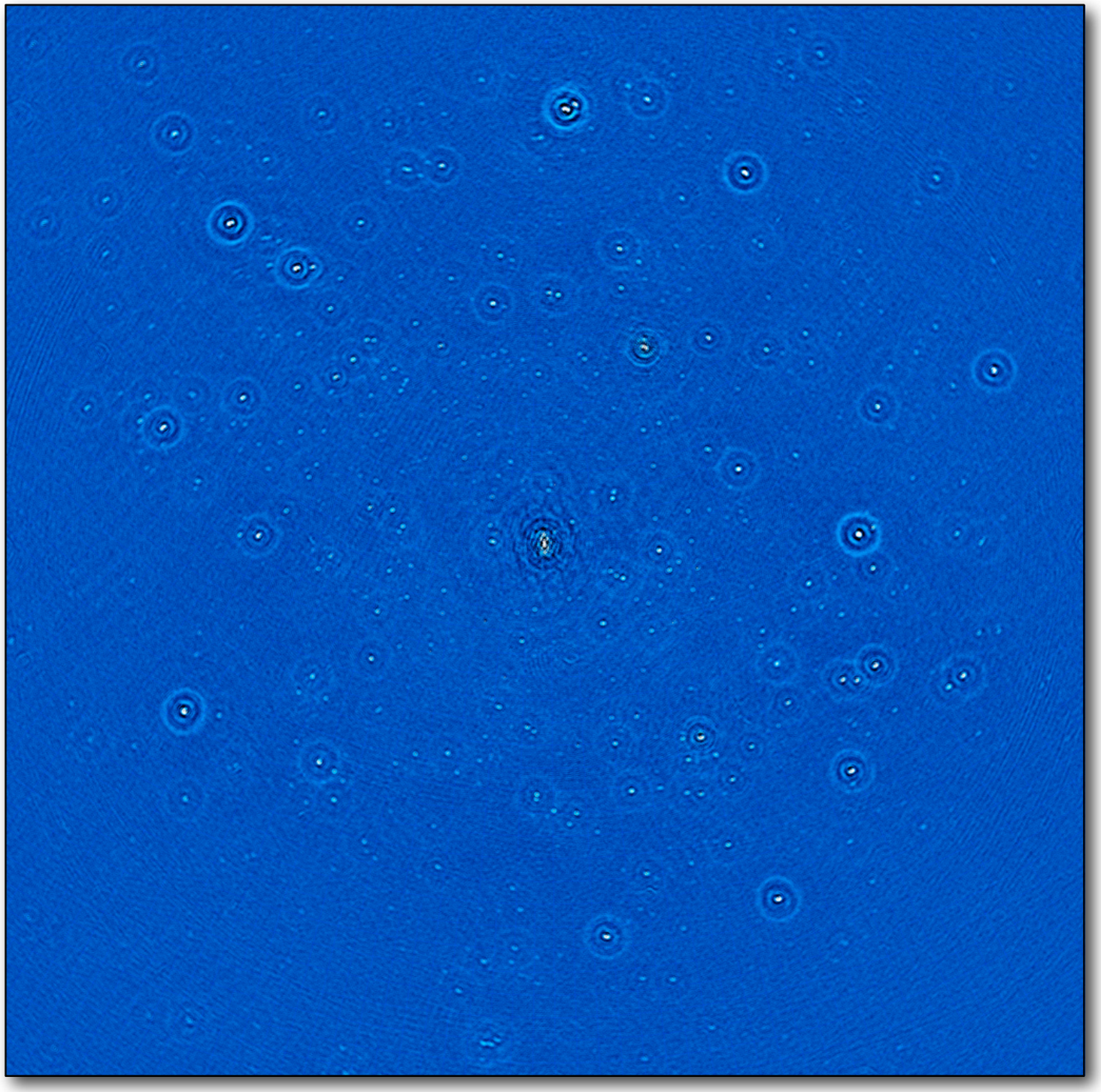


(courtesy S. Yatawatta)

3C 61.1
Wide-field imaging

HBA 115-185 MHz
8(x2)+ 4 stations
8 deg x 8 deg field
4 arcsec pixels
~5.18x10^7 pixels
10 arcsec PSF

10 Jy peak
1 mJy noise



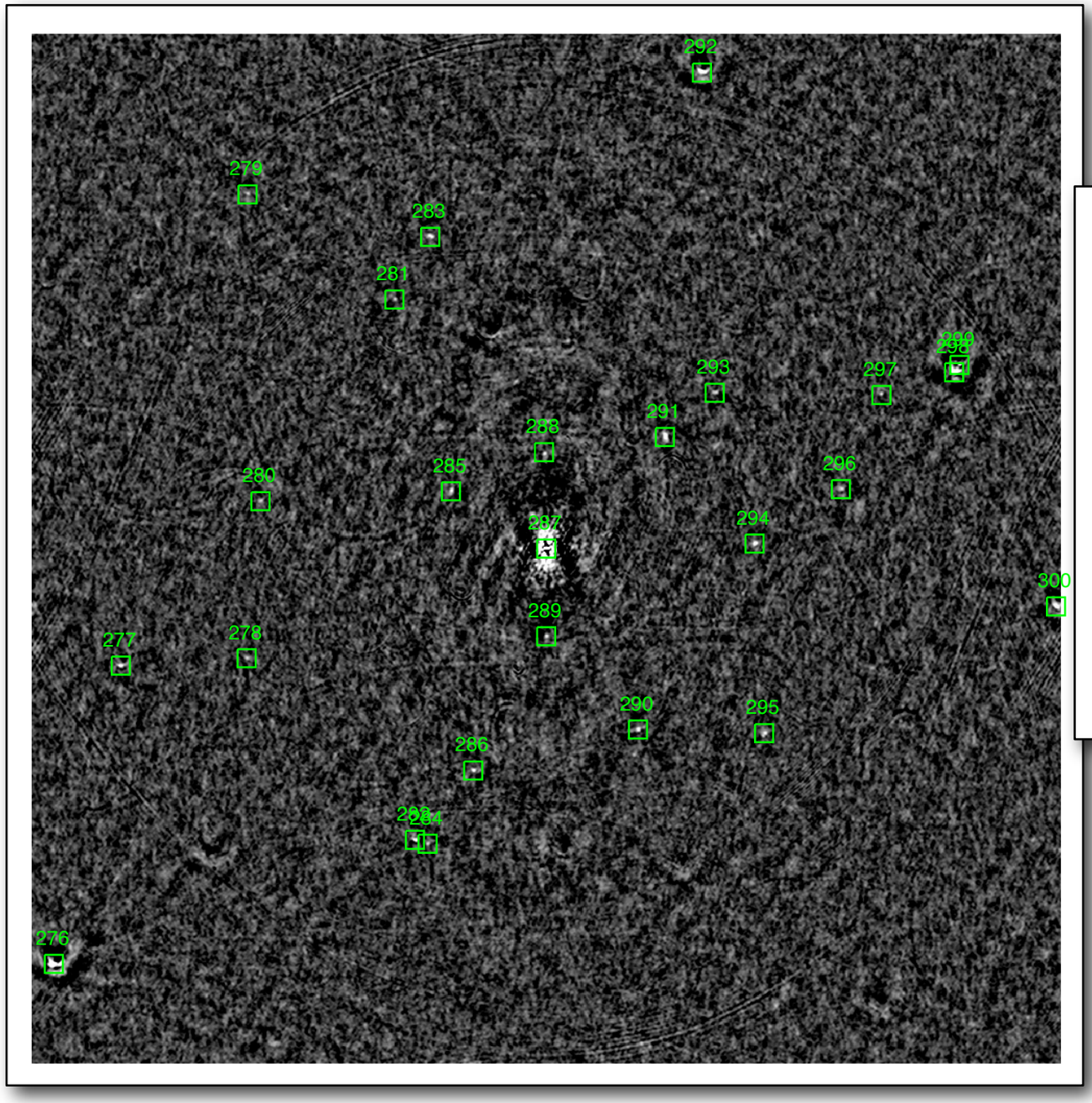
(courtesy S. Yatawatta)

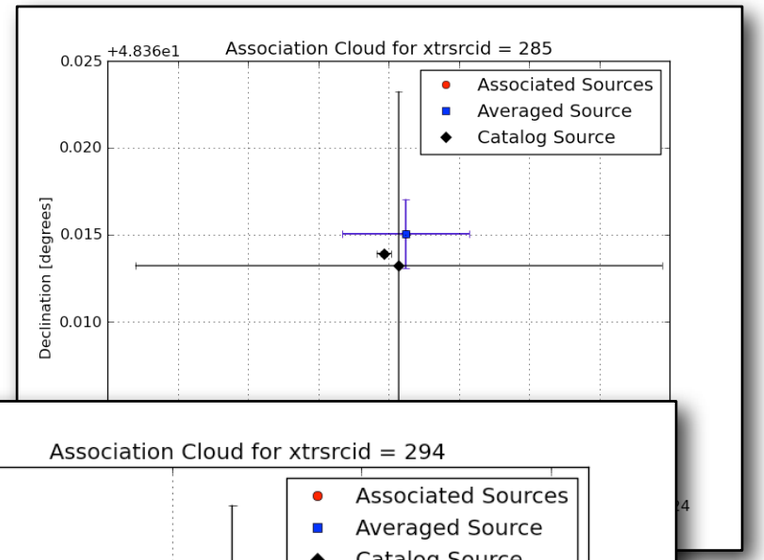
3C 61.1
Wide-field imaging

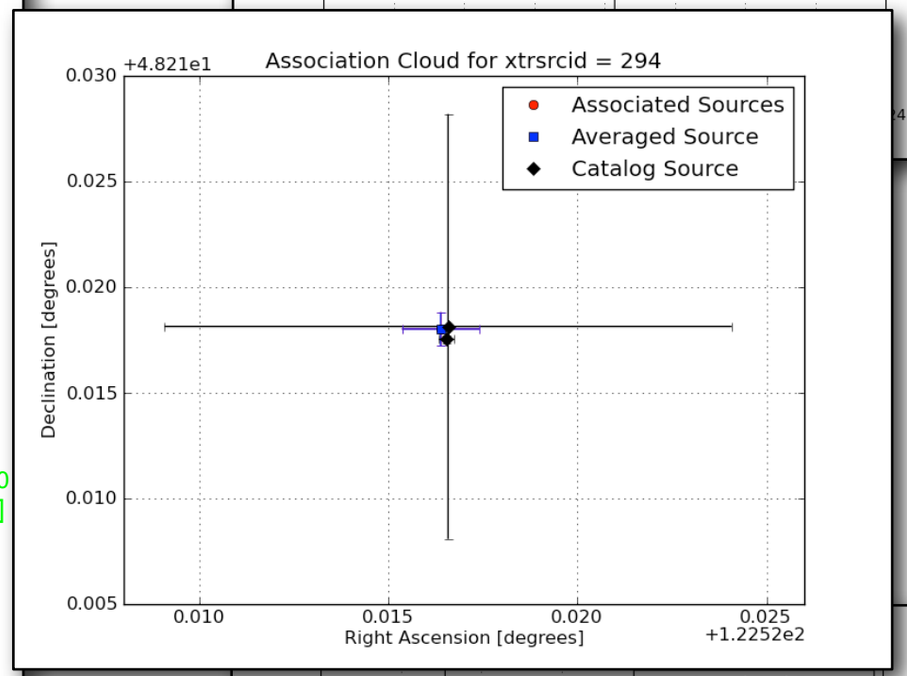
HBA 115-185 MHz
8(x2)+ 4 stations
8 deg x 8 deg field
4 arcsec pixels
~5.18x10^7 pixels
10 arcsec PSF

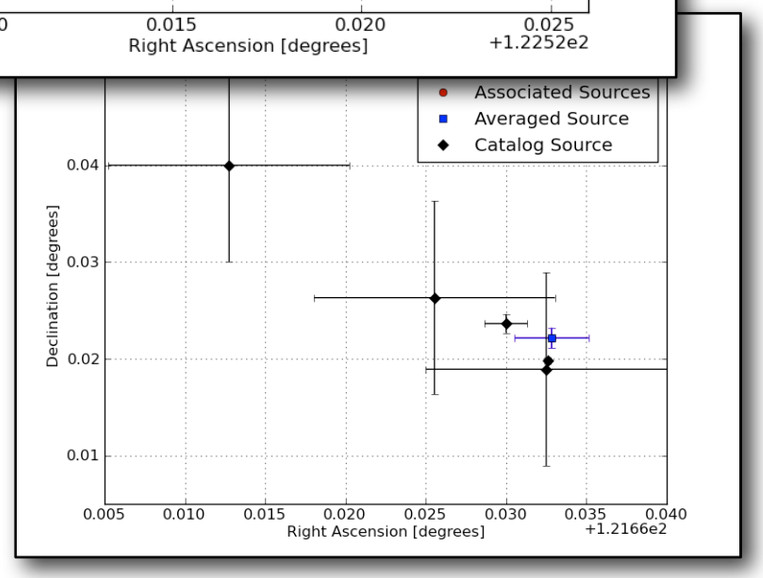
10 Jy peak
1 mJy noise

GSM and Source Finding

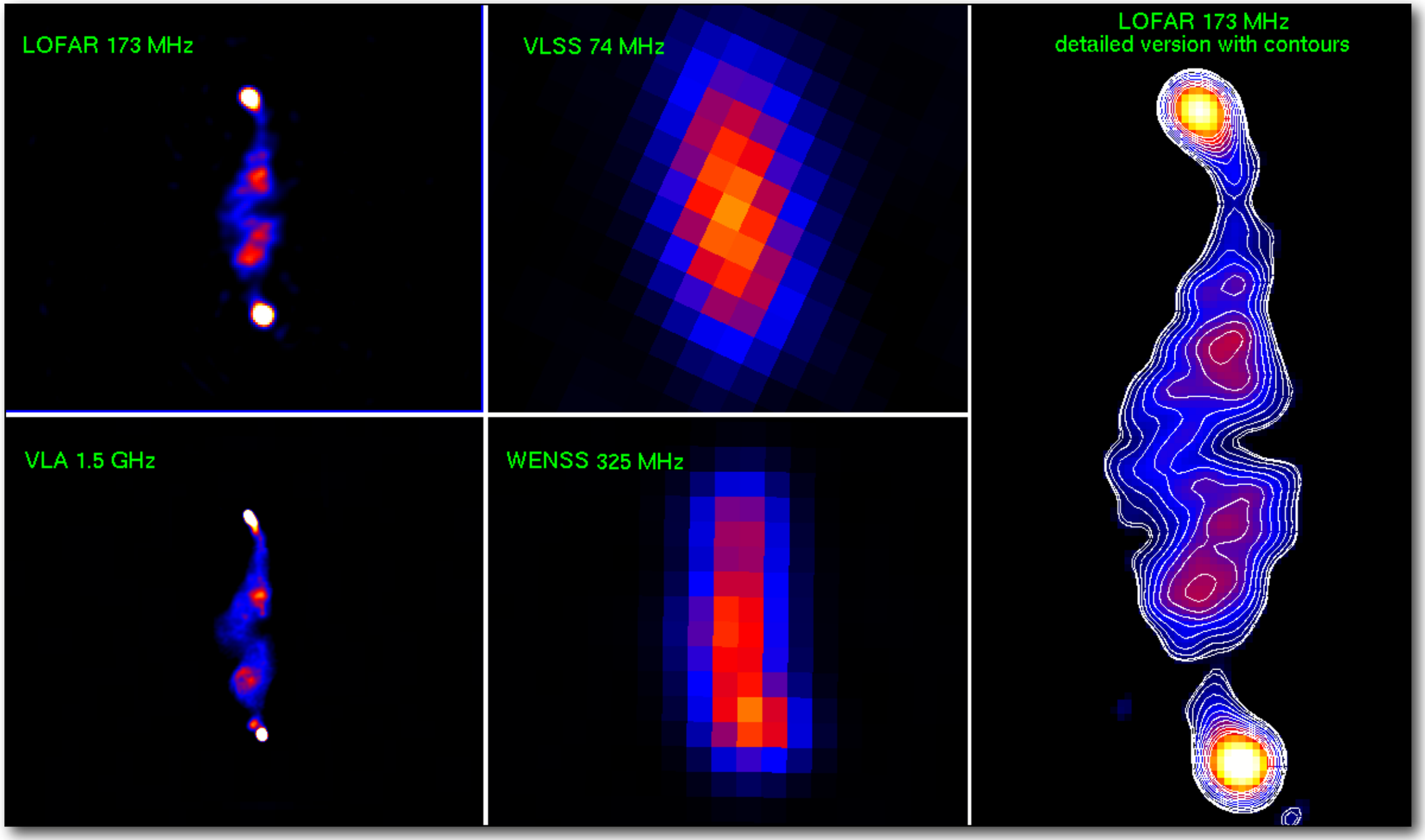








(courtesy B. Scheers, N. Mohan, J. Swinbank)



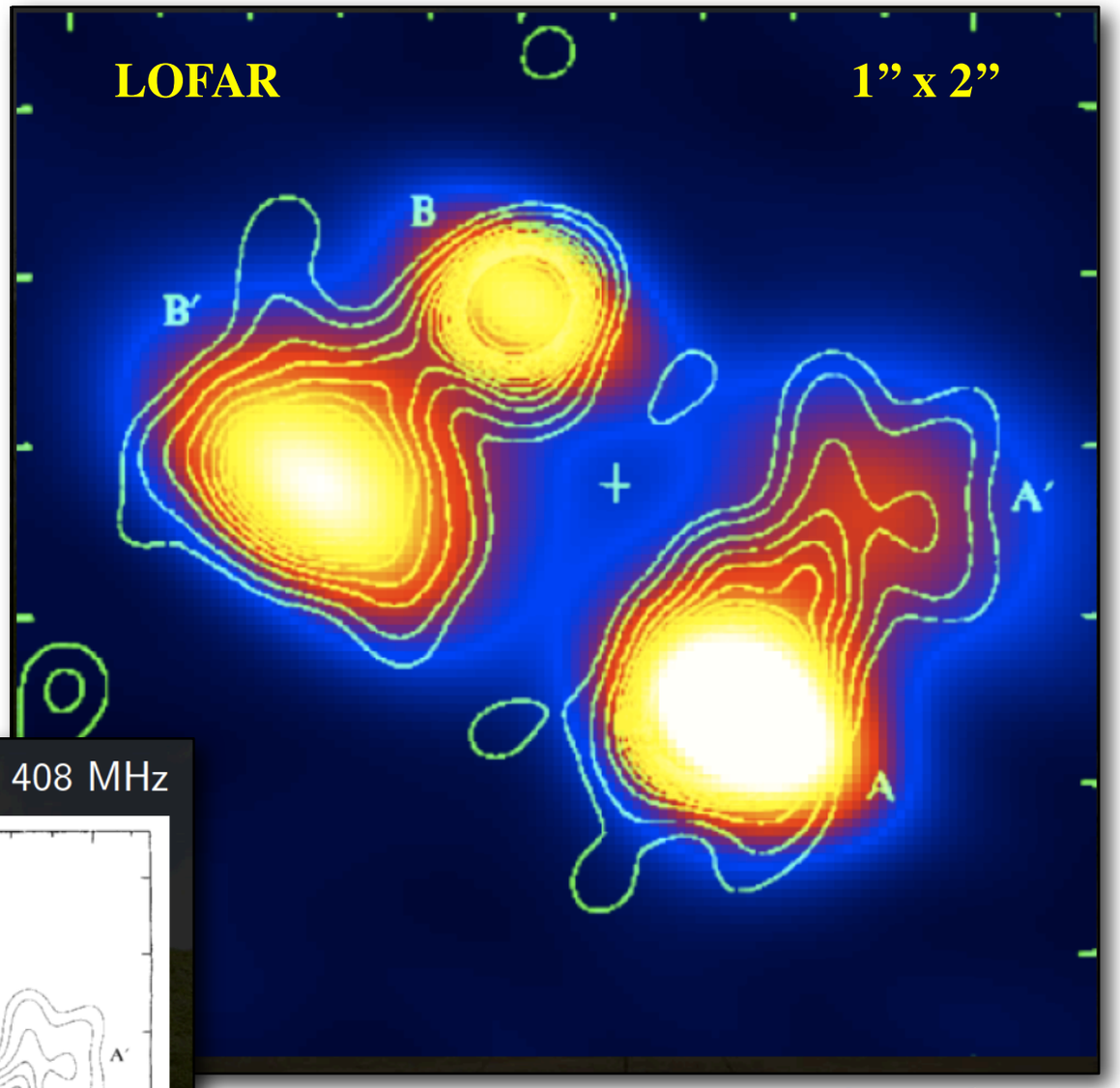
(courtesy R. van Weeren)

3C 61.1, 60 hr, 20 HBA stations (16 split core + 4 remote)
1 sub-band, 9.7 by 9.4 arcsec resolution

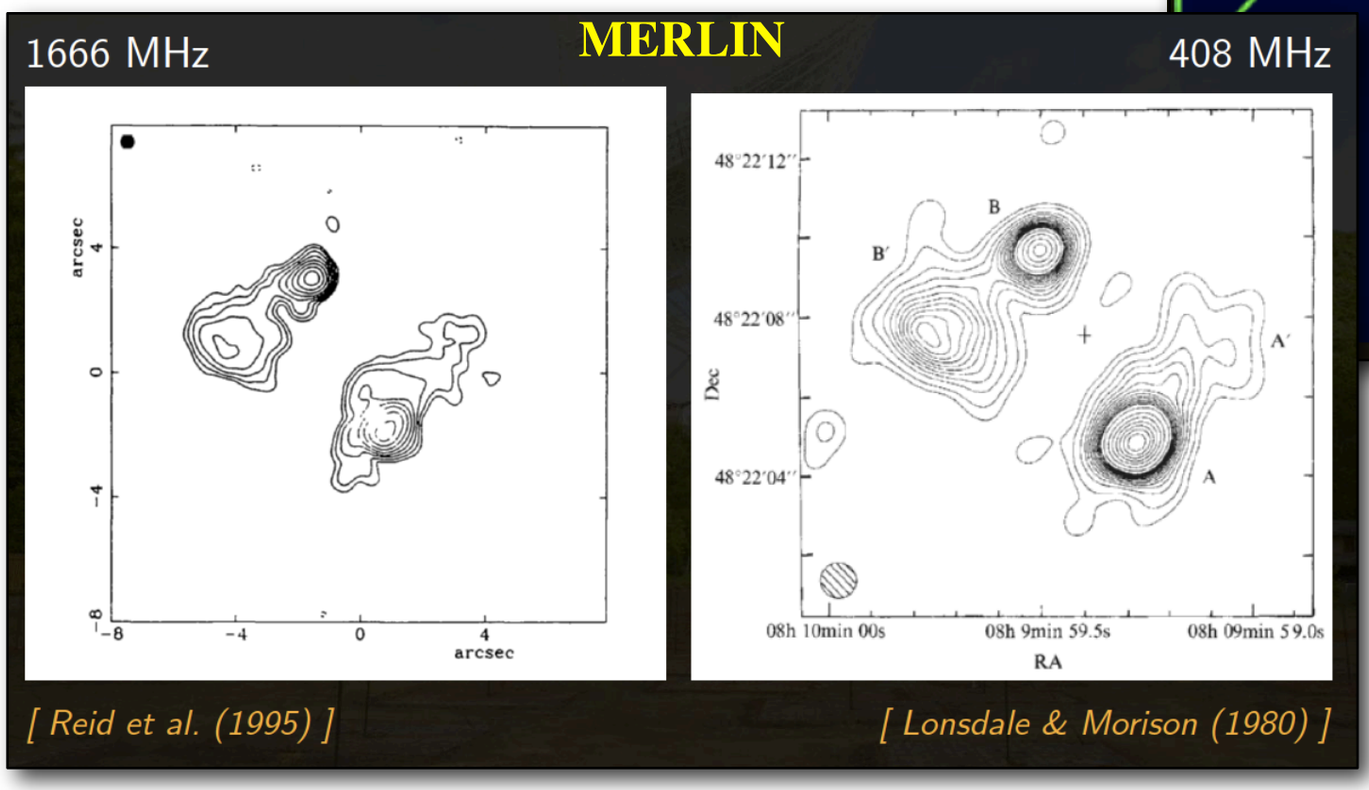
3C196 (~140 Jy)

Morphology at 50 MHz consistent with structure in 408 MHz Merlin maps

Highest resolution image at 50 MHz to date!

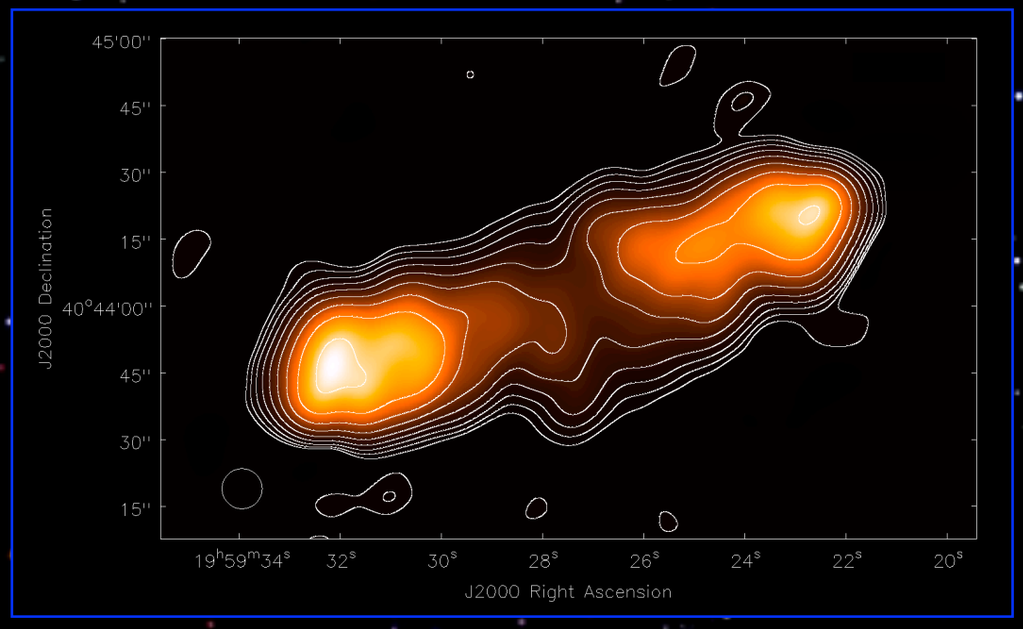


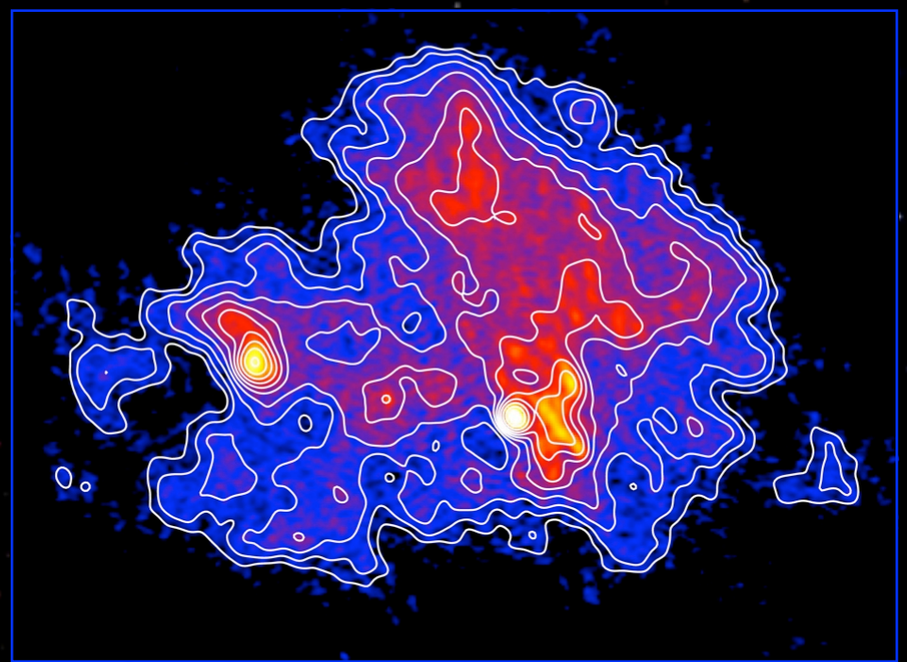
(courtesy: O. Wucknitz)

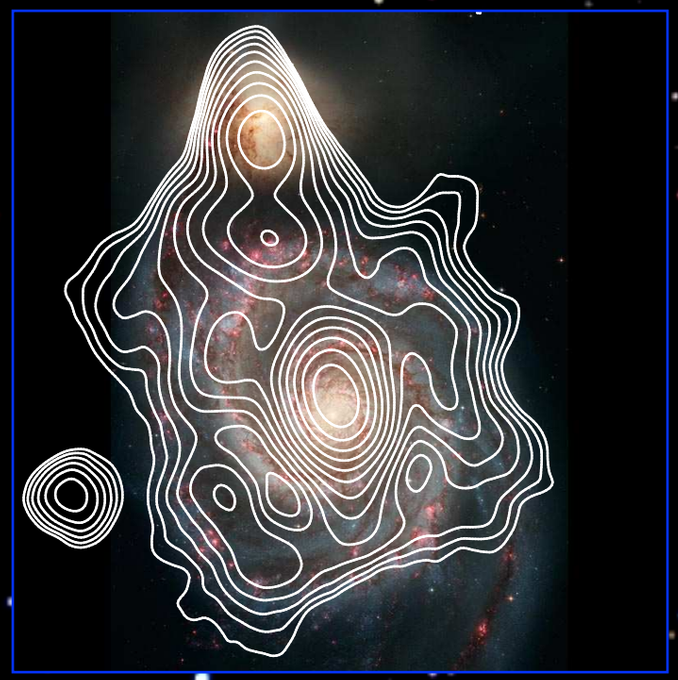


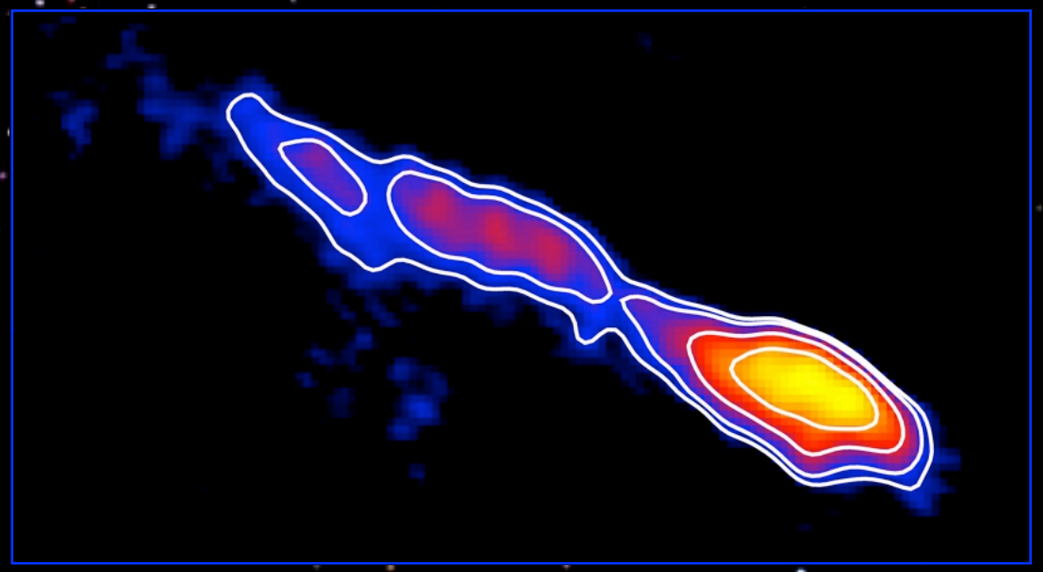
- LBA, 31 subbands, 44–59 MHz
- 6 hr on 12/13 Feb 2010
- 5 NL + 3 DE stations (Effelsberg, Unterweilenbach, Tautenburg)

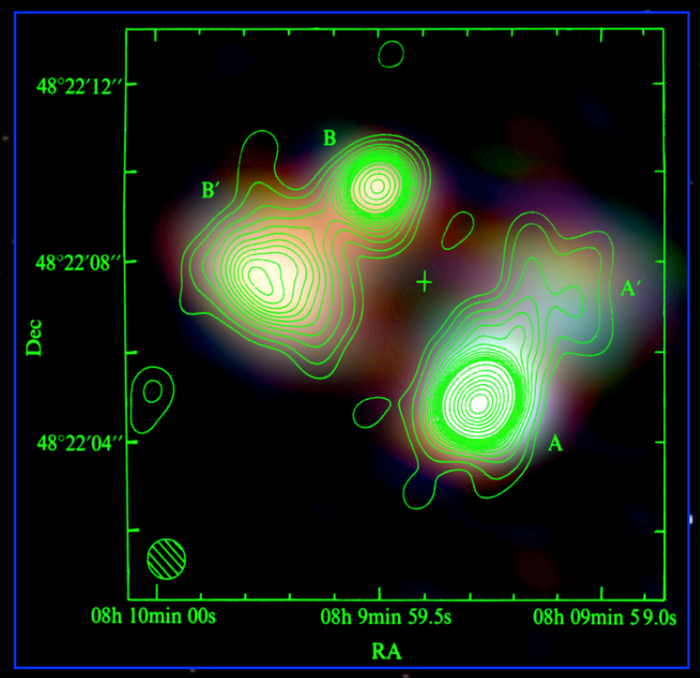
Some Recent Results











Hierarchy: MWA

[4x4]x24x28

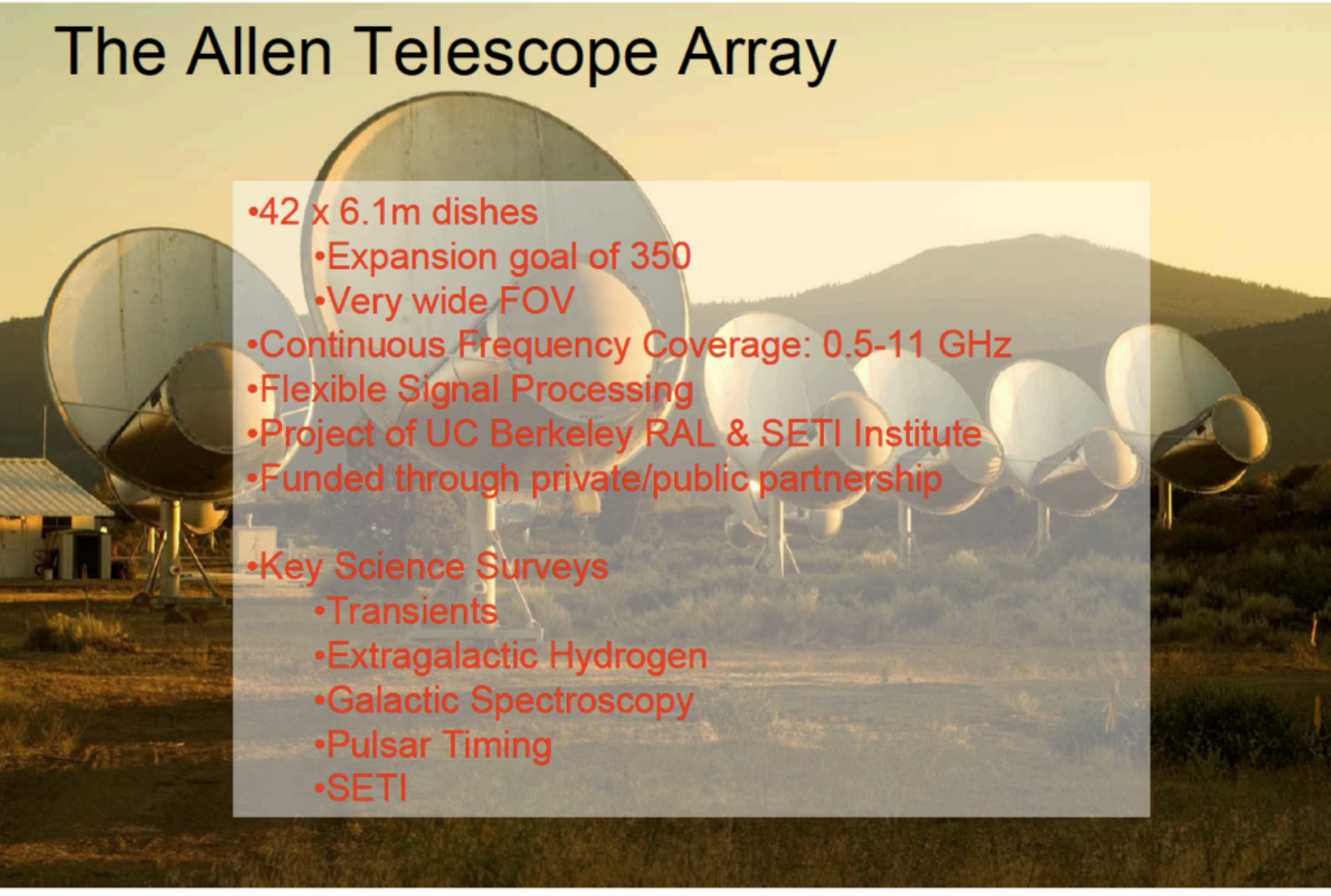
[4x4]x512

5% prototype

400m

The Allen Telescope Array

The Allen Telescope Array



- 42 x 6.1m dishes
  - Expansion goal of 350
  - Very wide FOV
- Continuous Frequency Coverage: 0.5-11 GHz
- Flexible Signal Processing
- Project of UC Berkeley RAL & SETI Institute
- Funded through private/public partnership

- Key Science Surveys
  - Transients
  - Extragalactic Hydrogen
  - Galactic Spectroscopy
  - Pulsar Timing
  - SETI

MeerKAT & Infrastructure

High Level Specifications

Parameter	KAT-7	MeerKAT
F_{low}	1.2 GHz	580 MHz
F_{high}	1.95 GHz	15 GHz
A_e/T_{sys}	16 m^2/K	200 m^2/K
DR_{imag}	30 dB	50 dB
DR_{spec}	30 dB	50 dB
Xpol	-20 dB	-25 dB
BW	256 MHz	~4 × ~256 MHz
N_{chan}	4 096	32 768 per band
Max baseline	200 m	8 km (60 km)

The Australian SKA Pathfinder

ASKAP Design Goals

High-dynamic range, wide field-of-view imaging

Number of dishes	36 (3-axis)
Dish diameter	12 m
Max baseline	6km
Resolution	30″
Sensitivity	65 m^2/K
Speed	$1.3x10^5$ $m^4/K^2 \cdot deg^2$
Observing frequency	700 – 1800 MHz
Field of View	30 deg^2
Processed Bandwidth	300 MHz
Channels	16k
Phased Array	188 elements

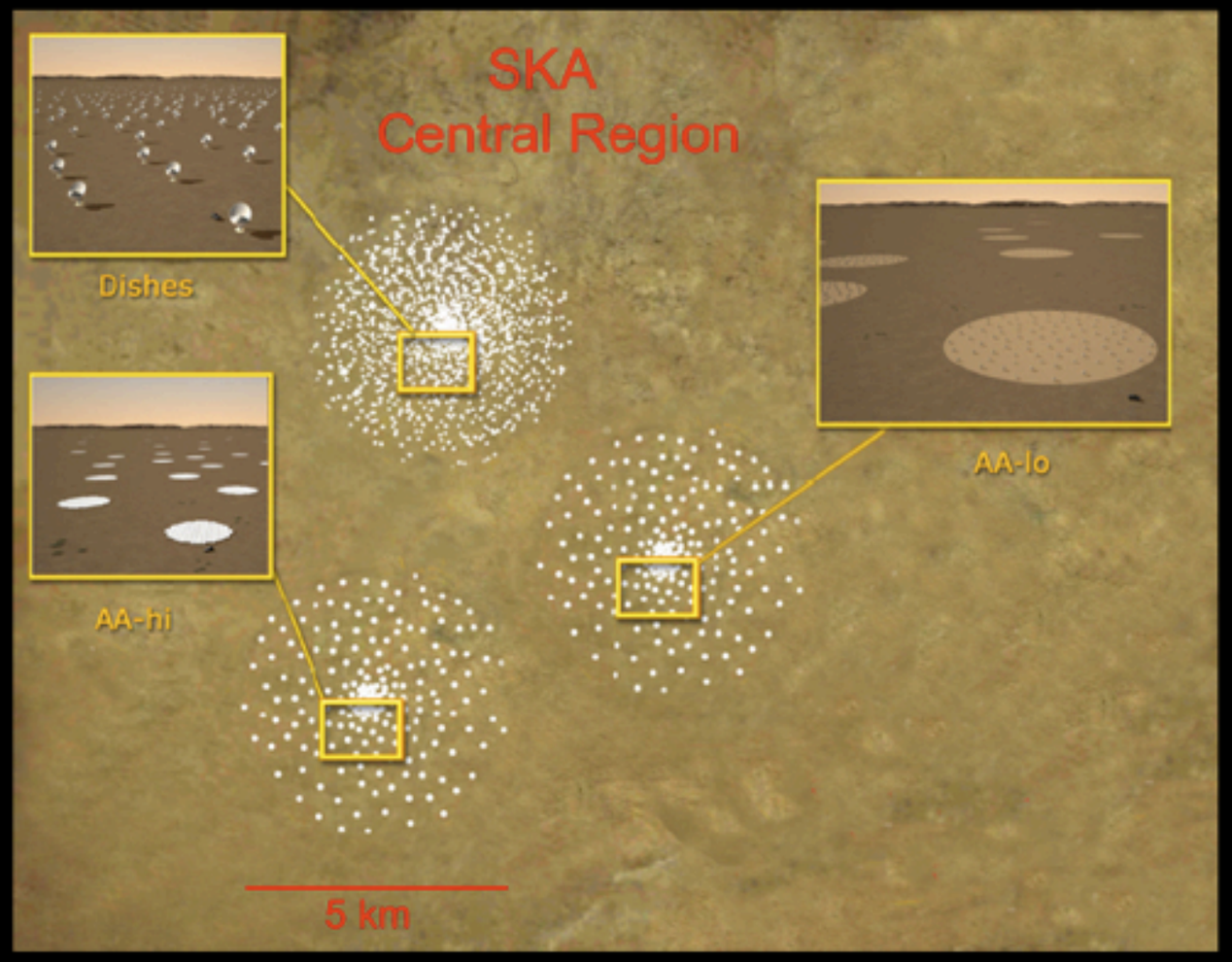
Murchison Radio Observatory (MRO)

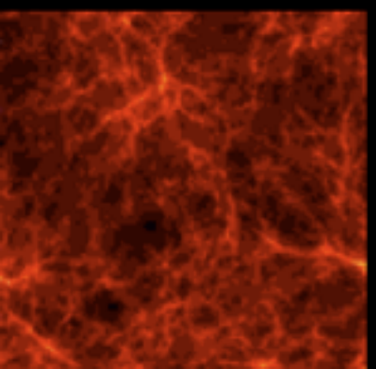
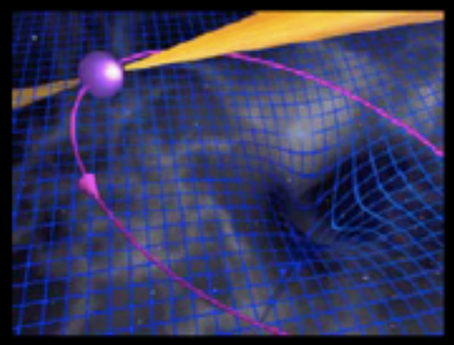
projects (MWA, EDGES, +)

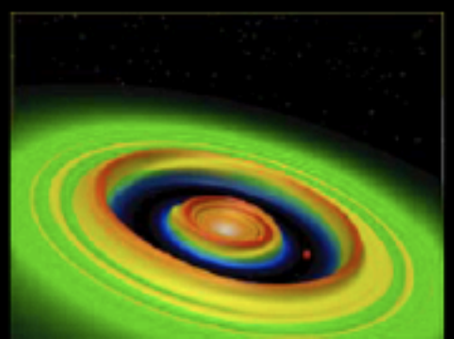
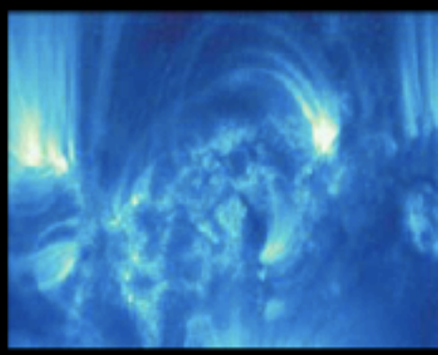
Square Kilometer Array
The Global Radio Wavelength Observatory

- Originally: "Hydrogen telescope"
  Detect H I emission from Milky Way-like galaxy at $z \sim 1$

- SKA science much broader
  ⇒ Multi-wavelength, multi-messenger
- On-going technical development
- International involvement




Swinburne Astronomy Productions

The SKA needs YOU!

The End