VLA and VLASS Overview

Anna D. Kapinska (NRAO)

VLA interferometer

Located in New Mexico, on the San Agustin Plains,
at 6970 ft (2120m) altitude.

→ 28 antennas: 27 observing at any time, 1 for maintenance
→ arranged in Y-shape
→ each antenna of 25m diameter
→ 4 configurations allowing for range of angular resolutions
→ observing north of –40°

Originally constructed in 1973-1980,
upgraded in 2003-2012

Angular resolution

Depends on frequency (0.074-45 GHz) and VLA configuration

Configurations: **A** (largest) ← **B** ← **C** ← **D** (smallest)

Configuration	A	B	C	D
B_{max} (km[1])	36.4	11.1	3.4	1.03
B_{min} (km[1])	0.68	0.21	0.035[5]	0.035
Band	**Synthesized Beamwidth θ_{HPBW}**(arcsec)[1,2,3]			
74 MHz (4)	24	80	260	850 14 arcmin
350 MHz (P)	5.6	18.5	60	200
1.5 GHz (L)	1.3	4.3	14	46
3.0 GHz (S)	0.65	2.1	7.0	23
6.0 GHz (C)	0.33	1.0	3.5	12
10 GHz (X)	0.20	0.60	2.1	7.2
15 GHz (Ku)	0.13	0.42	1.4	4.6
22 GHz (K)	0.089	0.28	0.95	3.1
33 GHz (Ka)	0.059	0.19	0.63	2.1
45 GHz (Q)	0.043 43 mas	0.14	0.47	1.5

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Reconfiguration:

approx. every 4 months

Call for proposals:

2x year – 1st Feb & 1st Aug

Largest angular scale (LAS) & Field of View (FoV)

LAS: Depends on frequency and VLA configuration

LAS is the largest angular scale the interferometer is sensitive to. Source features more extended than that will be "*resolved out*".

FoV: Depends on frequency and individual antenna size

This will be more than LAS, FoV is the amount of sky the antennas "see" with a single pointing (→ primary beam)

Largest angular scale (LAS) & Field of View (FoV)

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1.5 GHz (L)	36	120	970	970
3.0 GHz (S)	18	58	490	490
6.0 GHz (C)	8.9	29	240	240
10 GHz (X)	5.3	17	145	145
15 GHz (Ku)	3.6	12	97	97
22 GHz (K)	2.4	7.9	66	66
33 GHz (Ka)	1.6	5.3	44	44
45 GHz (Q)	1.2	3.9	32	32

5.5 deg

1.2 arcsec

Largest angular scale (LAS) & Field of View (FoV)

LAS: Depends on frequency and VLA configuration

FoV: Depends on frequency and antenna size

approx. formulas:

$$\theta_{PB} = 50/\nu_{GHz}$$

$$\theta_{PB} = 42/\nu_{GHz}$$

$$\Theta = f \frac{\lambda}{D_{ant}}$$

11.3 deg → 28 arcmin → 4.2 arcmin → **56 arcsec**

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1.2 arcsec

Frequency specifications

Ten frequency bands from 50 MHz to 50 GHz

- 8 cryogenic bands, with Cassegrain subreflector, covering 1–50 GHz (L to Q bands)
- 2 uncooled, prime-focus bands, covering 50–450 MHz (4 and P bands)

VlA can observe up to 8 GHz instantaneous bandwidth (wide-band)

- Two set of samplers: 8-bit ($\Delta\nu$=2 GHz) and 3-bit ($\Delta\nu$=8 GHz)

& in full polarisation (circular and linear depending on band).

Observing modes

- Continuum (Stokes I)
- Polarimetry (Stokes Q,U,V)
- Spectral lines
- Sub-arrays [each sub-array can perform completely independent observing program simultaneously]
- Mosaicking [multiple pointings and phase centres]
- On-the-fly mapping (OTF) [“scanning mode”]
- Solar system objects
- Using VLA as a VLBI station
- Pulsar observing

WIDAR Correlator

WIDAR=Wideband **I**nterferometric **D**igital **AR**chitecture

The correlator's basic features (not all implemented yet):

- **64 independent full-polarization subbands**. Each can be tuned to its own frequency, with own bandwidth (128 MHz to 31.25 kHz) and spectral resolution (from 2 MHz to 0.5 kHz)
- **100 msec dump times** with up to 16,384 channels and full polarization (faster if spectral resolution, bandwidth, or number of antennas is decreased)
- **Up to 8 sub-arrays**. Maximum implemented to date is 3.
- **Phased array** capability with full bandwidth (pulsar and VLBI)
- **Special pulsar modes:** 2 banks of 1000 time bins, and 200 μsec time resolution (all spectral channels), or 15 μsec (64 channels/spw).

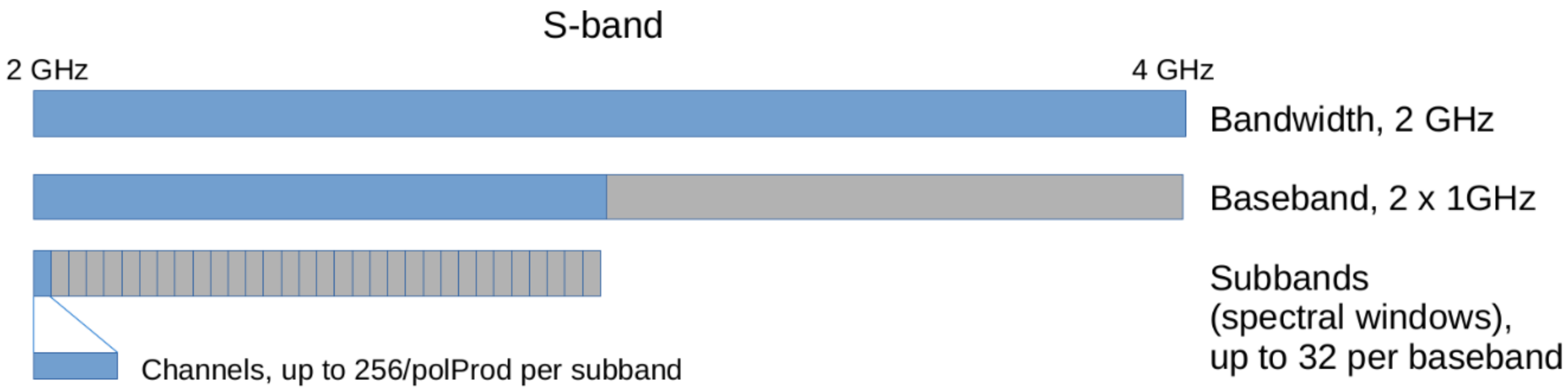
General Observing (GO)

Standard observing set ups available to anyone:

- up to 8GHz bandwidth (depending on band)
- 3-bit and 8-bit modes, can use combination of these
- up to 3 sub-arrays in 8-bit mode

- spectral set-up:
  - 1 or 2 GHz basebands (can have independent set-ups)
  - 1 baseband can be made of up to 32 independently tunable subbands
  - subband (spectral window) widths: max 128 MHz, min 31.25 kHz
  - single Baseline Board Pair (BlBP; one per subband is default) can handle 256 spectral points divided over polarisation products, i.e.:
    - 256 spectral channels in single polarisation
    - 128 spectral channels in dual
    - 64 spectral channels in full

General Observing (GO) - cont.



This gives up to 16,384 spectral channels.

If more is needed, there are options: (1) recirculation, (2) baseline board stacking, or using (1) and (2) simultaneously

<u>Observing modes in GO</u>: continuum, polarisation, spectroscopy, solar observing, OTF mosaicking (P,L,S,C bands), P band continuum and spectrocopy, 3 simultaneous subarrays, mix of 3-bit and 8-bit modes

Shared Risk & Resident Shared Risk Observing (SRO & RSRO)

Shared risk capabilities are beyond those offered for general observing, but underwent initial development or planning by the NRAO staff, and are available for those that would like to push the VLA and VLBA capabilities to new limits.

Shared risk observations are no guaranteed to succeed, and as per policy the Observatory does not have obligation to make up for inadequate observations (shared risk).

Resident share risk are even less developed endeavours, and require the proposer(s) to be present at NRAO as a visitor for some time to help developing the capability (pushing the boundaries!).

<u>Examples:</u> 3-bit subarrays for VLA, multi-mode subarrays for VLA, real time correlation for VLBA, rapid response of VLBA, improved troposphere model for VLBA, etc.

→ more on offered capabilities for the next VLA/VLBA proposal call (2024A) later today

Post observations: software

https://casa.nrao.edu/

NRAO data reduction software, CASA

- Designed to handle wide-band upgraded-VLA and ALMA data
- Based on C++ reduction tools, with iPython interface for easy data manipulation

CASA
Common Astronomy Software Applications

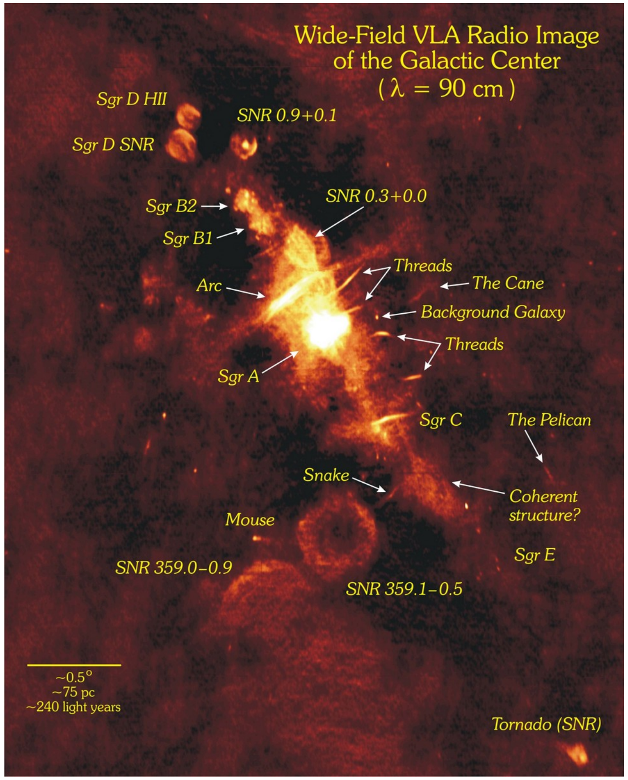
Developed by international consortium composed of:

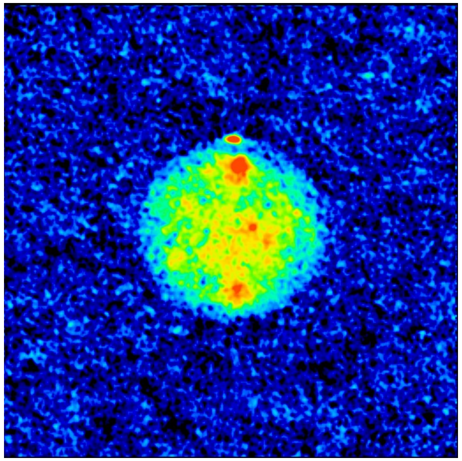
→ ***Talk on Tuesday pm:***
CASA Data manual processing (VLA, VLBA) & VLA Pipeline processing

VLA Science

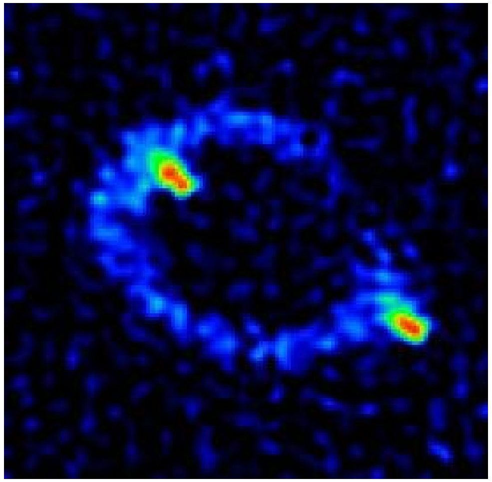
VLA is the most versatile, widely-used radio telescope in the world. It can map large-scale structure of gas and molecular clouds, pinpoint ejections of plasma from supermassive black holes, and find ice on solar system planets.

Galactic Center, Kassim+, 1986.



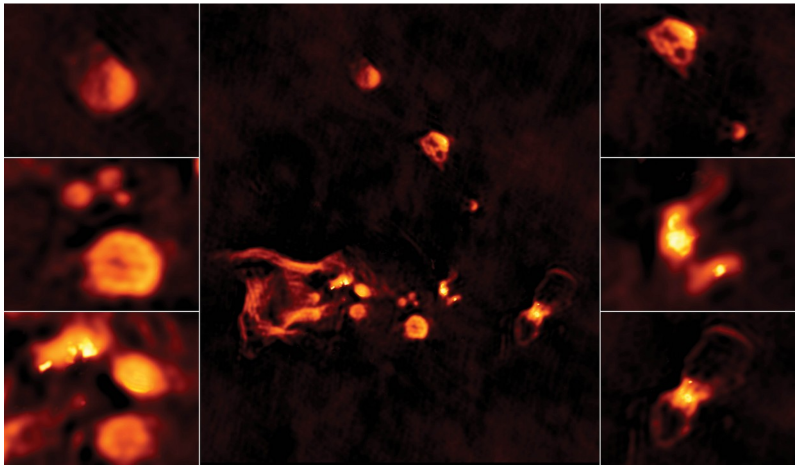


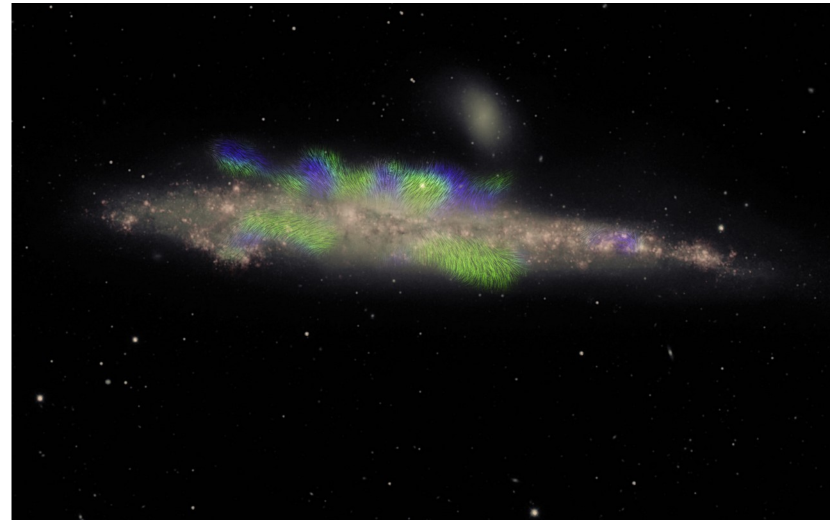
Discovery of ice on Mercury through a radar experiment in 1991 using NASA JPL/DSN 70-m antenna in Goldstone, CA, as the transmitter, and VLA as the receiver.



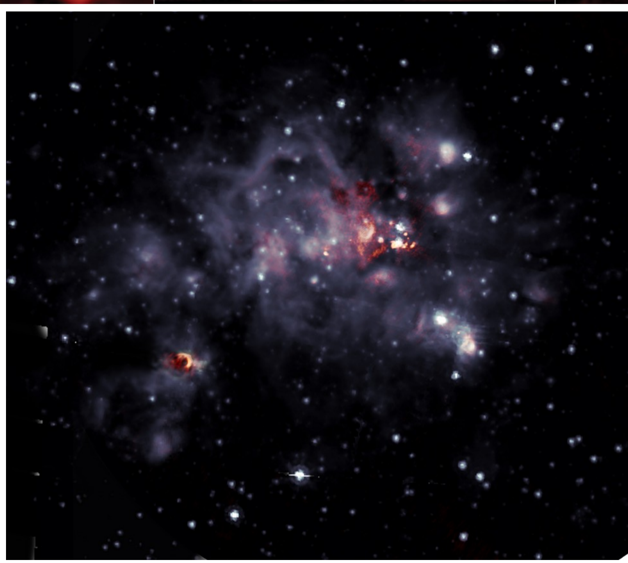
First Einstein ring discovered with VLA (by Hewitt+, in 1987): lensed quasar MG1131+0456.

VLA Science





NGC4631, CHANGES survey. Composite of optical and radio, with magnetic structures (filaments) extending into galactic halo (blue pointing away, green towards us). Credit: English+



Radio (orange) and infrared composite image of giant molecular cloud W49A (left), and zoom in onto its HII regions (left top). Credit: DePree+

VLA Sky Survey (VLASS)

Most recent, ongoing NRAO VLA survey. Started in 2017.

Slides contribution: Claire Chandler (NRAO).

VLA Sky Survey (VLASS)

High angular resolution, all-sky* radio survey

- ***All-sky** (33,885 deg^2 above declination –40°)
- Frequency: **3 GHz** (2–4 GHz) → “S-band”
- 64 x 2-MHz channels per spectral window, 16 spectral windows
- **Stokes I wideband** and **Stokes IQU cubes**
- High angular resolution: **2.5’’** (VLA B/BnA-configurations)

- Synoptic and **multi-epoch**: 3 all-sky epochs separated by 32 months
- Observing time: 920 hours per configuration cycle x 6 cycles
  → (13% of VLA science time)
- Full survey observing period: 7 years (Sep 2017 – Oct 2024)

Area (deg^2)	Resolution (robust)	RMS goal (μJy/bm) epoch/full	Density (deg^{-2})	Total Detections
33,885 ($\delta > -40°$)	2.5”	120 /69	~290	9,700,000

VLA Sky Survey (VLASS): Science Goals

- Be reference radio sky at high angular resolution for multi-wavelength studies
- AGN feedback, flares, BH merger events; synergies with surveys at other wavelengths (resolution is key!)
- Transient astrophysics
  → VLASS is expected to open new parameter space for finding dusty/unbeamed GRBs, SNe, compact object mergers, and other transients
- Perform Faraday tomography of the magnetic sky
  → Studies of magnetic fields throughout the universe: hot gas in galaxy clusters, magnetic fields within other galaxies, magnetic field in the Milky Way
- Extreme pulsars, cool stars with active coronae, planetary nebulae, HII regions

VLA Sky Survey (VLASS)

Product	Timescale for production	Notes
Raw visibility data	Immediate	In standard archive
Calibrated data (initial)	1-2 weeks	From standard archive
Quick Look Images	Few weeks	Stokes I wide-band continuum only
Single Epoch Images	Delayed, started	Stokes I wide-band continuum and tapered
Single Epoch Images	In design stage	Stokes IQU cubes
Single Epoch Catalogs	w/Single Epoch Images	By product
Cumulative Images	In design stage	Stokes I wide-band continuum and tapered
Cumulative Images	In design stage	Stokes IQU cubes
Cumulative Catalogs	w/Cumulative Images	By product

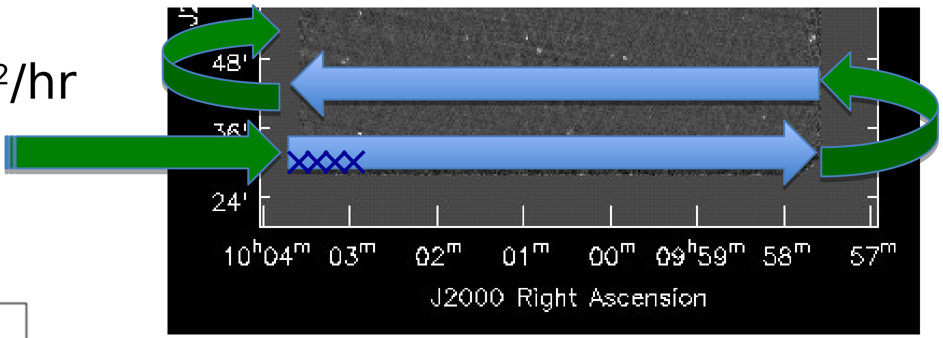
VLASS Processing:

→ Uses CASA ALMA/VLA data calibration pipeline with special VLASS “recipe”

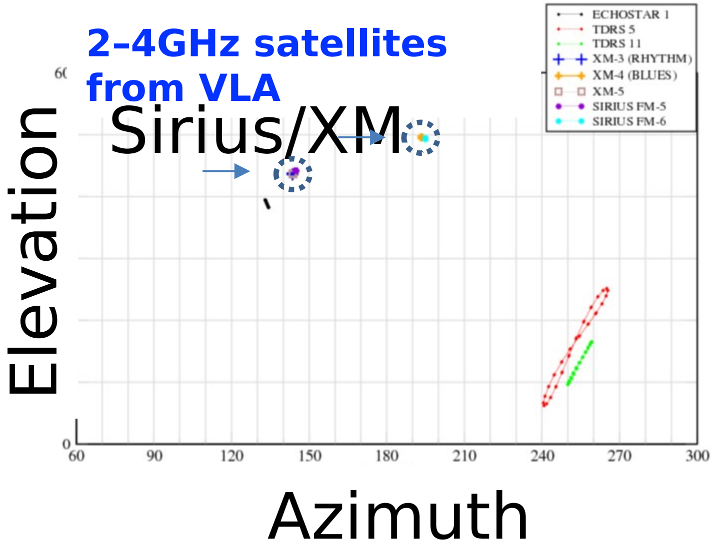
→ New imaging pipeline developed

VLASS – Technical aspects

- Multi-epoch sky coverage enabled by On-The-Fly (OTF) mosaicking
  - Scan telescopes across sky while taking array data
    - Very efficient for short dwell times
  - Scan rate 3.3’/s, row sep 7.2’
  - VLASS survey speed: ~20 deg^2/hr
  - Equivalent time-on-source: 5s

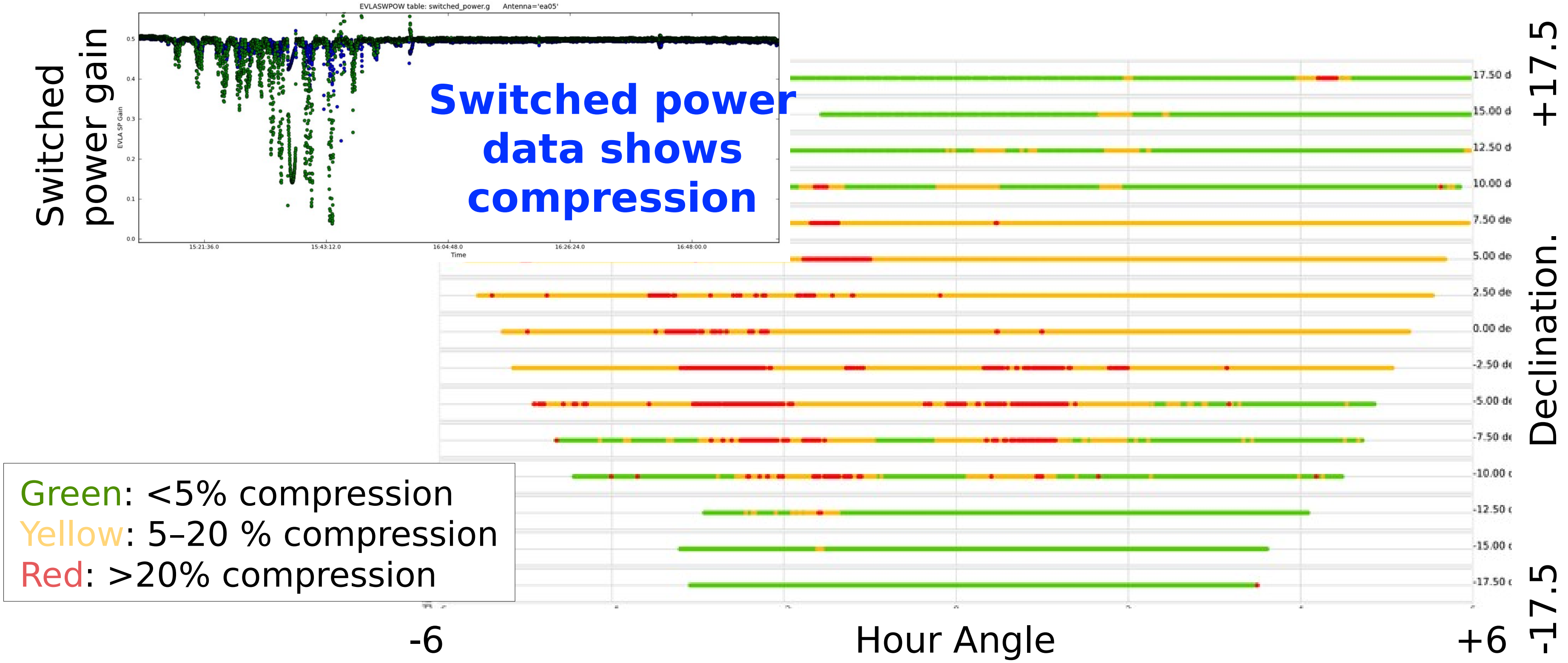


- RFI

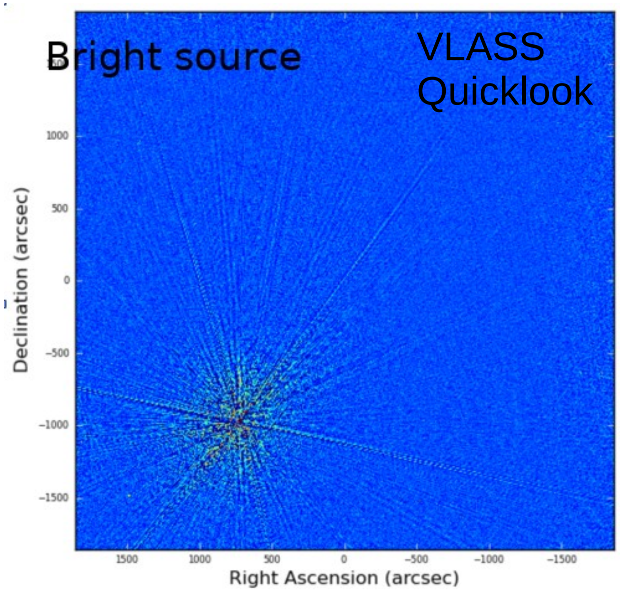


VLASS – Technical aspects

- Compression (identified in pilot data)
  - Affects entire baseband, not just spws containing RFI
  - Problem for much larger fraction of sky than originally thought
  - Special algorithm developed that can correct for moderate compression



VLASS – Technical aspects



Mosaic imaging algorithms

- Quicklook imaging: ‘mosaic’ gridder
  - Uses fit to azimuthally averaged PB
  - Issues with bright sources outside primary beam that are not subtracted in major cycle
- Single Epoch imaging: ‘awproject’ gridder
  - Uses 2D PB derived from ray tracing
  - Required further development

→ Both algorithms have issues with use of single PSF in minor cycle

Single Epoch Images

→ best science ready quality
→ will use self-calibration for better decovolution of bright sources
→ pipelines under final testing

VLASS – Technical aspects

Single Epoch Images (wideband)

→ current definition:

0.6 arcsec resolution (11520x11520 pixel =1x1 deg.)

noise <170 microJy/bm

mtmfs will generate multiple image products:

– Stokes I (Taylor term 1 and 2 images),
– RMS images
– source catalog

Single Epoch Images (cubes)

→ current definition:

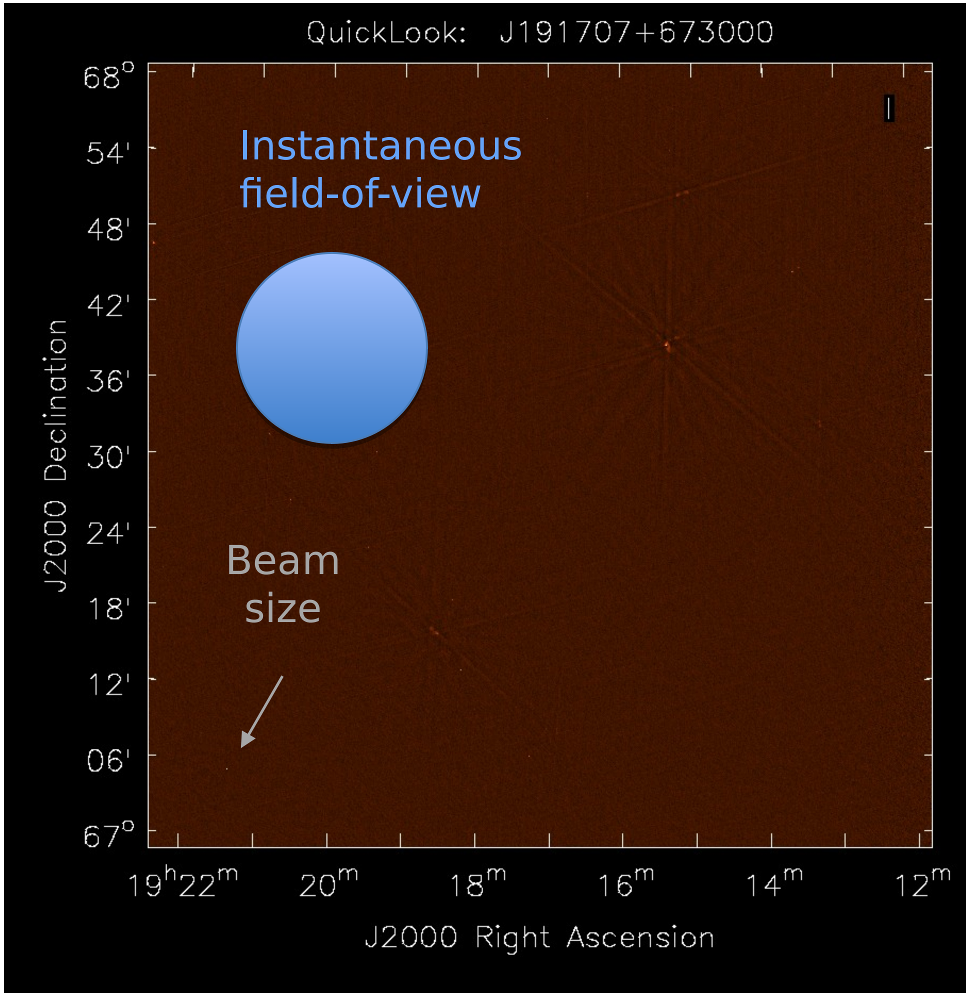
0.6 arcsec resolution (11520x11520 pixel =1x1 deg.)

noise <670 microJy/bm for 128MHz cube

mosaic gridder will generate multiple image products:

– Stokes IQU for each 128MHz spectral window
– corresponding RMS images

VLASS Quicklook images



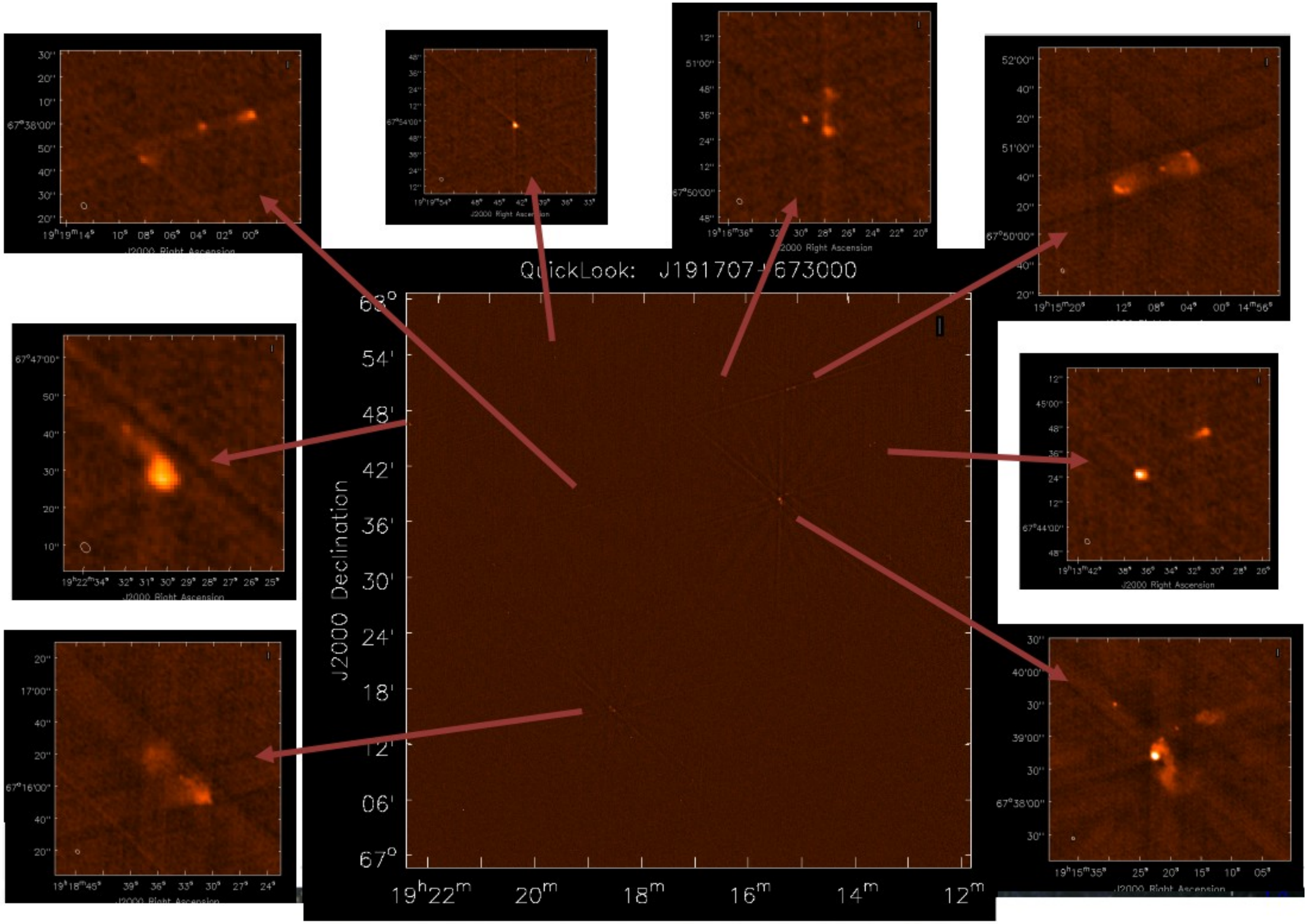
Quicklook images:

1°x1° subimage (full 2°x2°)
1” pixel size (13Mpix)

416 phase-centers (2x0.45s T_{int})
~10GB visibility data
multi -term, multi-frequency image

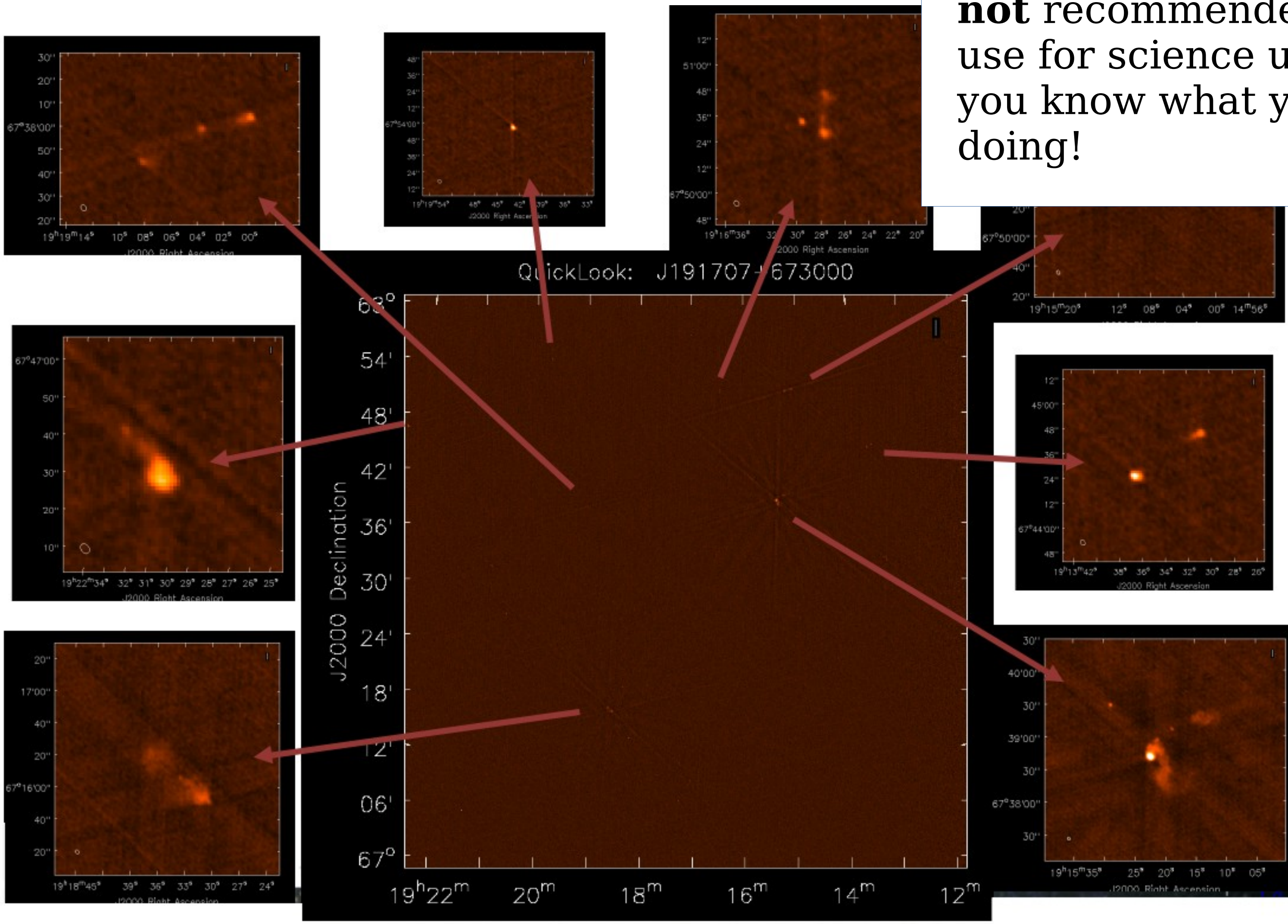
goal: $\boldsymbol{\sigma}_I$ = 120**μ**Jy/beam

VLASS Quicklook images

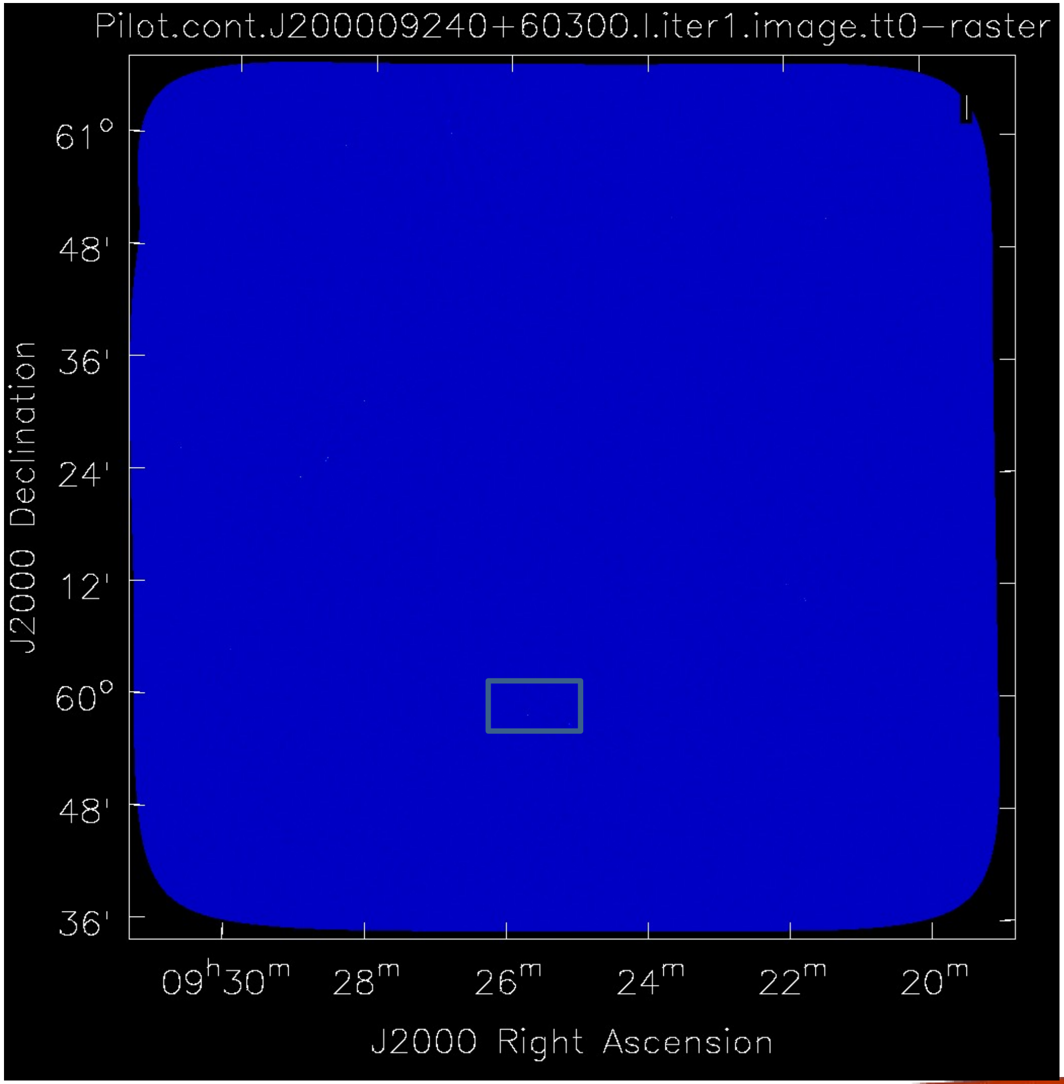


VLASS Quicklook images

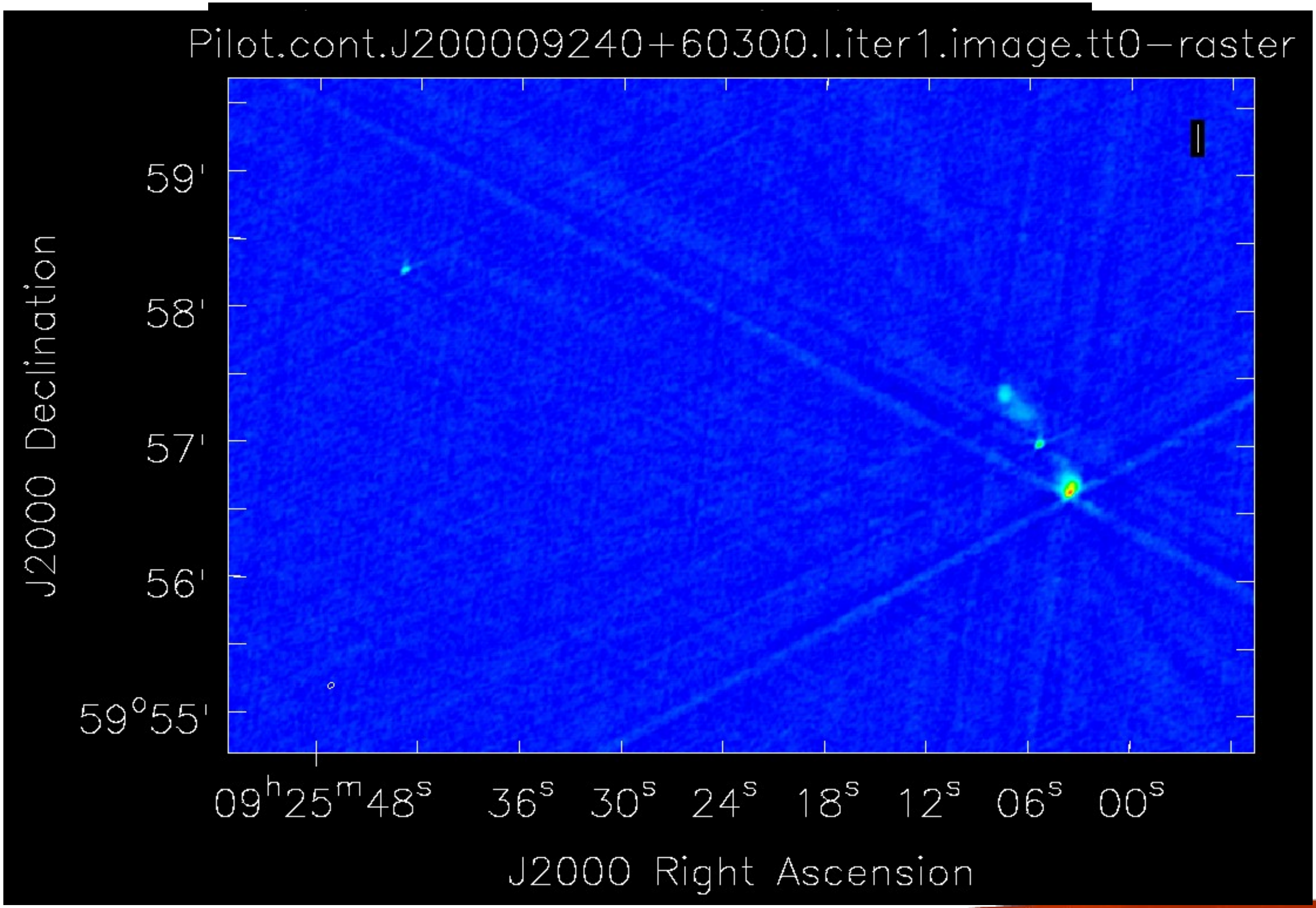
Not science ready – **not** recommended to use for science unless you know what you are doing!



VLASS Single Epoch Wideband images



VLASS Single Epoch Wideband images



VLASS – Enhanced Data Products
Community driven

Canadian Initiative for Radio Astronomy Data Analysis (**CIRADA**) funded by the Canada Foundation for Innovation, covers various projects (VLASS, CHIME, ASKAP), total value ~CAD$9.4M, PI Bryan Gaensler (U. Toronto)

For VLASS CIRADA delivers:

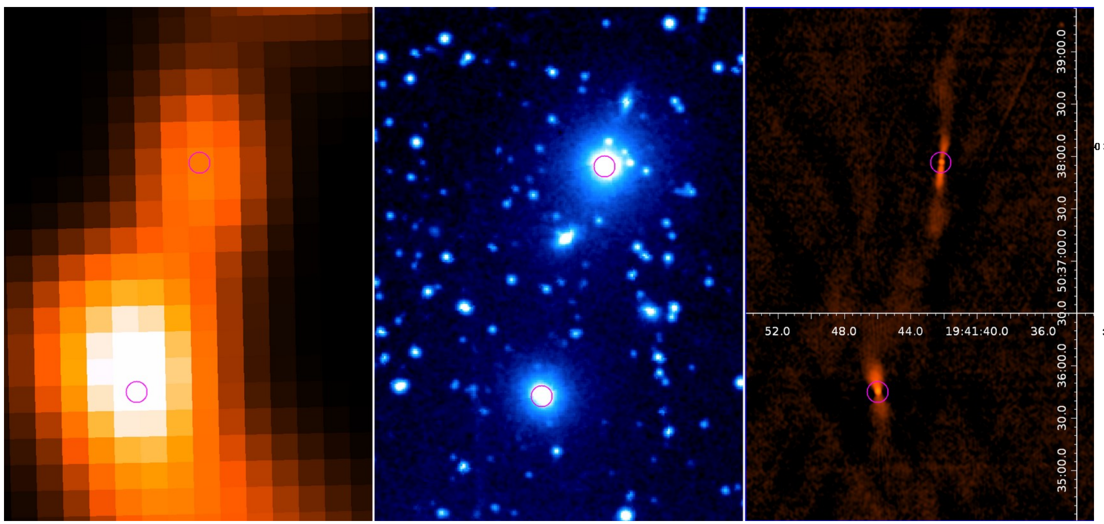
- Source catalogs, including radio polarimetry and multi-wavelength matches
- Cubes of Faraday depth for bright sources
- Transient identification, quality assurance, and announcements based on QL images and *realfast*
- Accessible archive of above products

Shea Brown (U. Iowa) also working on machine learning algorithms for source classification: https://bablai.com/vlass/

VLASS – Enhanced Data Products
Polarization

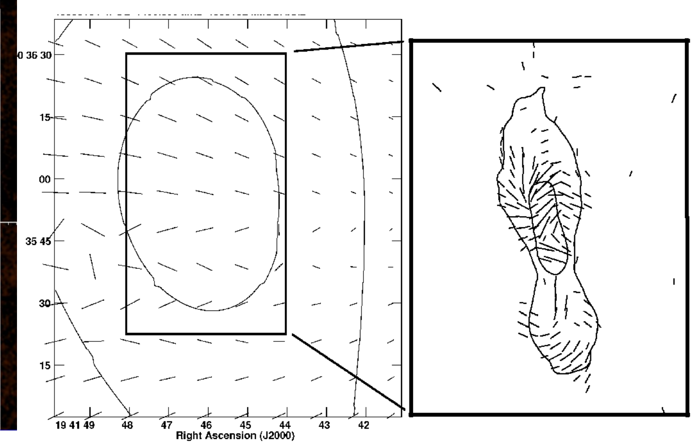
Polarization calibration and imaging under development (NRAO), but polarimetric data products for some objects good, demonstrated below on radio source 3C402

NVSS DSS VLASS



Polarization of 3C402S (courtesy Larry Rudnick, U. Minnesota):

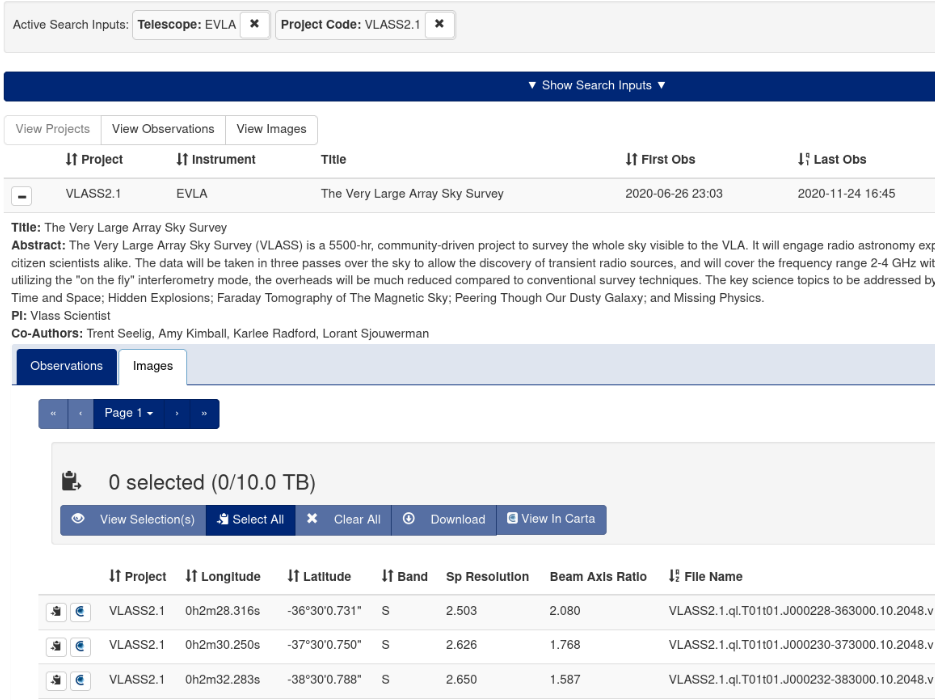
NVSS VLASS



VLASS Data Access

Visibility data, calibrations, images and flags are available through the new NRAO archive (NRAO AAT):

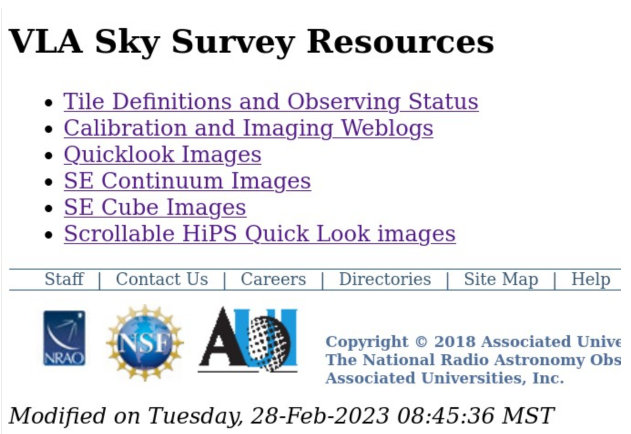
http://data.nrao.edu/



Quick Look Images are also available from:

https://archive-new.nrao.edu/vlass/

Including: tile definitions, pipeline weblogs, HiPS images, and first Single Epoch and Cube images!



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