EVLA Status and Prospects

Panoramic Radio Astronomy, 2-5 June 2009

Michael P. Rupen

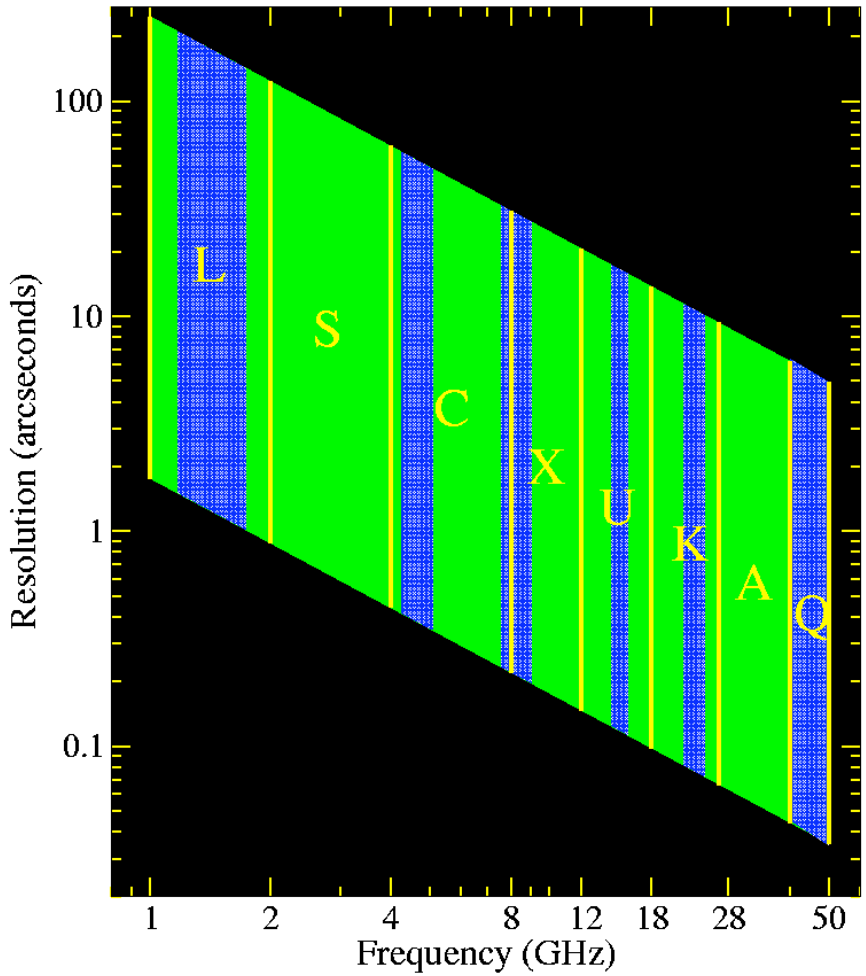
Project Scientist for EVLA's WIDAR Correlator

Atacama Large Millimeter/submillimeter Array
Expanded Very Large Array
Robert C. Byrd Green Bank Telescope
Very Long Baseline Array

NRAO

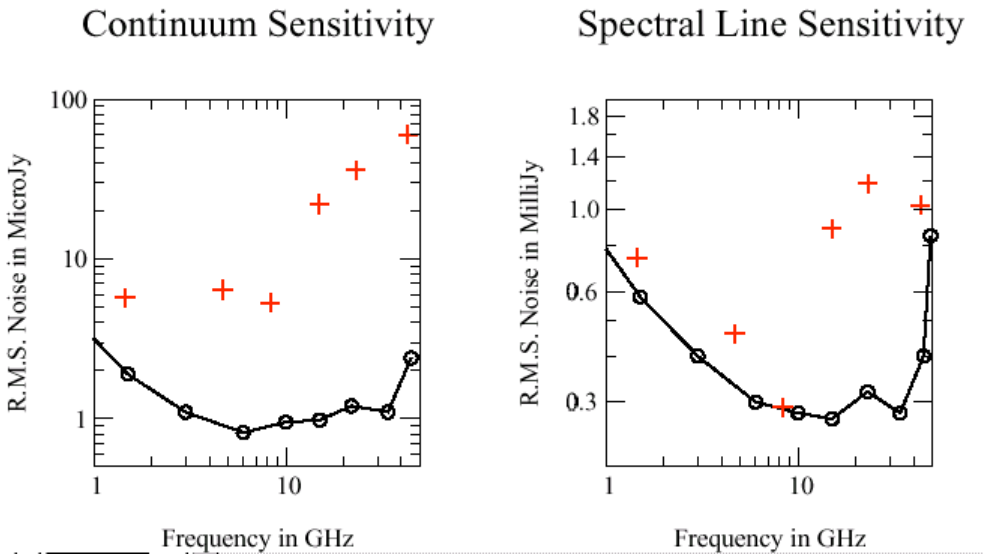
Basic capabilities

Main improvements



- Continuous frequency coverage, 1-50 GHz

Main improvements



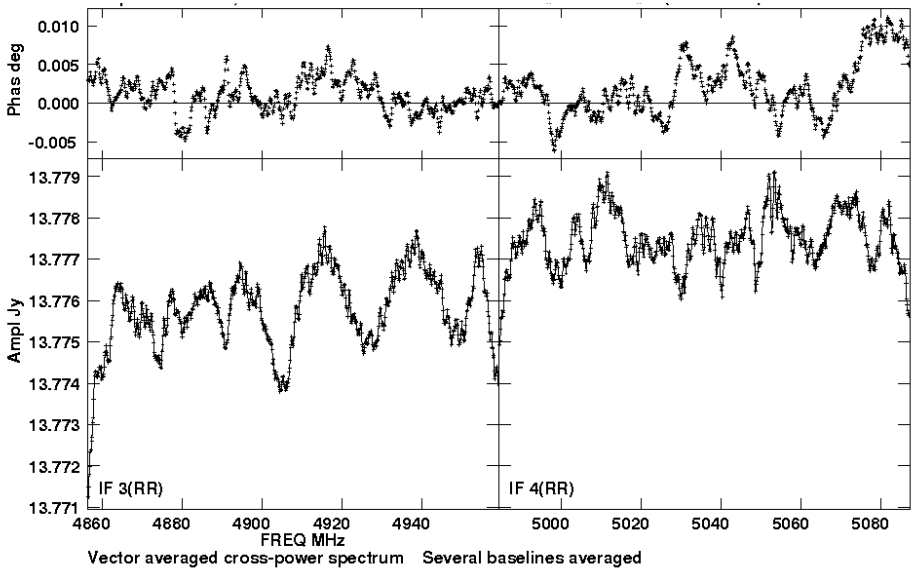
- **Continuous frequency coverage, 1-50 GHz**
- **Wide bandwidths (up to 2 x 8 GHz, 2:1 BWR)**
  - ✓Sensitivity, uv-coverage, spectral index, RM, …

1-σ, 12-hours

Red: Current VLA

Black: **EVLA Goals**

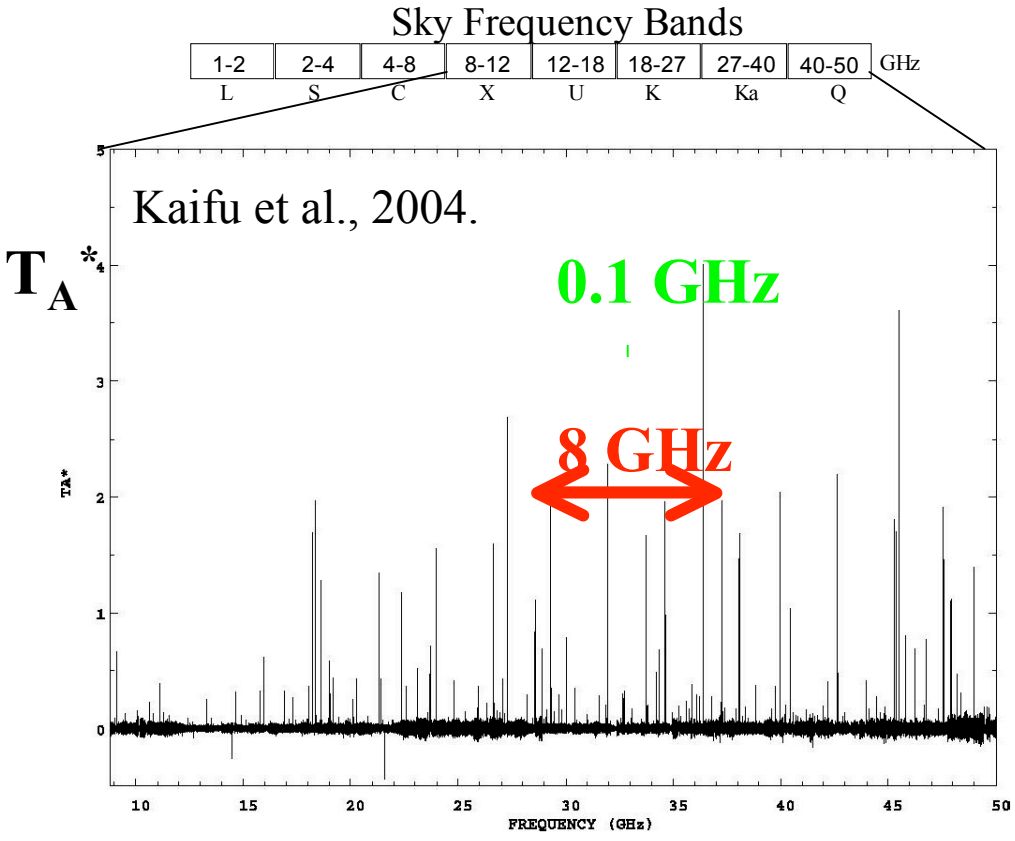
Main improvements



- Continuous frequency coverage, 1-50 GHz
- Wide bandwidths (up to 2 x 8 GHz, 2:1 BWR)
- Much more stable (digital)

- 3C84 @ 5 GHz
- ~10 hours
- WIDAR PTC

Main improvements



- **Continuous frequency coverage, 1-50 GHz**
- **Wide bandwidths (up to 2 x 8 GHz, 2:1 BWR)**
- **Much more stable**
- **WIDAR correlator**
  - ✓16,384 - 4 million channels
  - ✓64 independent 31 kHz-128 MHz subband pairs
  - ✓Time res'n as fine as ~10 microsec
  - ✓4- or 7-bit correlation
  - ✓RFI rejection
  - ✓2000 pulsar phase bins
  - ✓VLBI-ready (phased VLA/Y1)

Saving money

- **Same dishes**
  - Primary beam at 1.5 GHz:
    30 arcmin
  - Pointing as best of VLA dishes (rms= 6” blind, 3” referenced)
  - Same slew/switching rates as VLA
  - **Same collecting area**
- **Same configurations**
  - Switching to D-C-B-A, primarily for data rate & software reasons
  - Spatial resolution at 1.5 GHz:
    45, 15, 4, 1 arcseconds
  - E configuration?

Status & test results

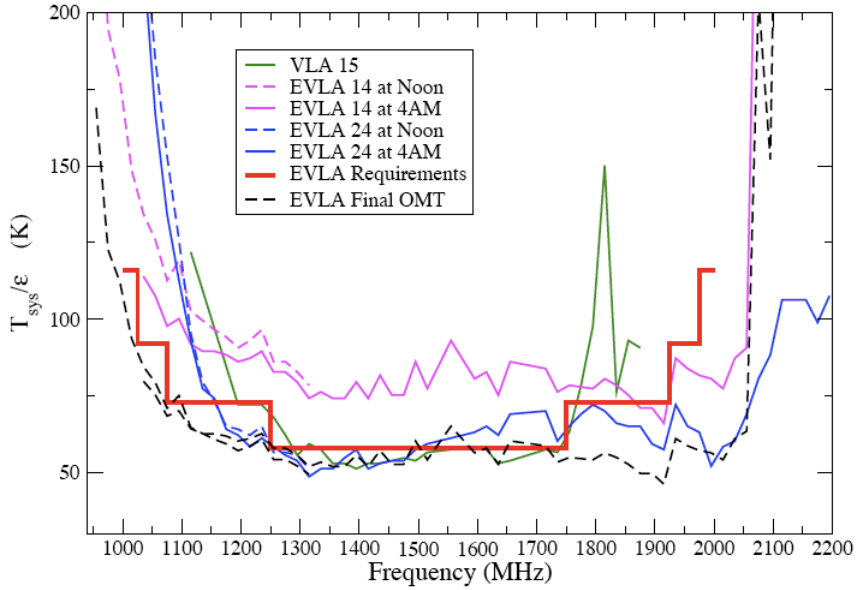
Current status

EVLA

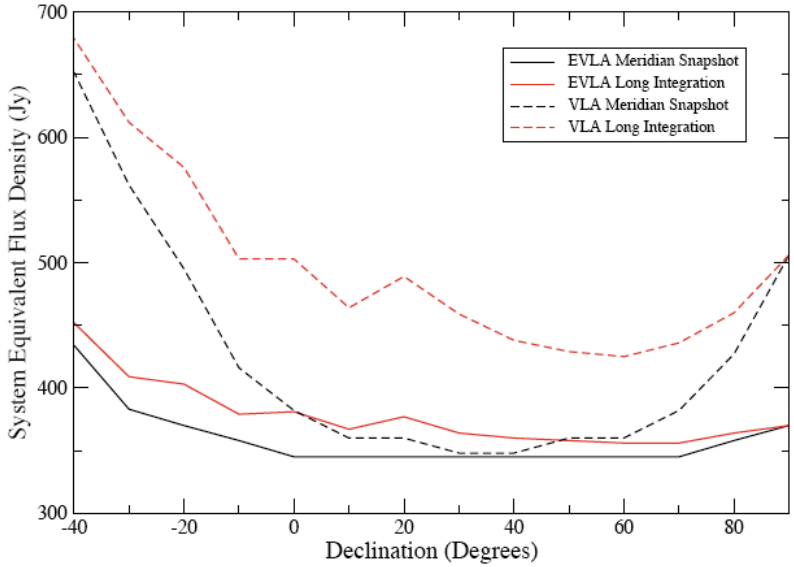
- All fiber laid
- **21 EVLA antennas** now in use -- account for >70% of ant-hours
- **All feed horns fabricated for L,** C, Ka; S and Ku underway
- 10 Ka-band, 2 S-band receivers deployed
  - Ku-band prototype under development
  - **50 MHz-1 GHz receiver** will be tested, thanks to NRL
- **OMTs meet specifications** (L, C, S); X-band design almost complete
  - **L-band prod'n begins 2009**
- LO/IF ahead of schedule
- 8-bit (1 GHz) samplers installed; first 3-bit (2 GHz) due in July
- Real-time **software on track** (migrated from Modcomps; Proposal, ObsPrep, Scheduler, Archive Tools; WIDAR systems integration)
- Post-processing software looking good (CASA; algorithms; cluster)
- WIDAR correlator
  - data cables & all racks installed
  - final hardware ordered
  - 10-station, 4 subband, single pol'n **WIDAR-0 fringing nicely** (March 6)

NRAO

1-2 GHz sensitivity



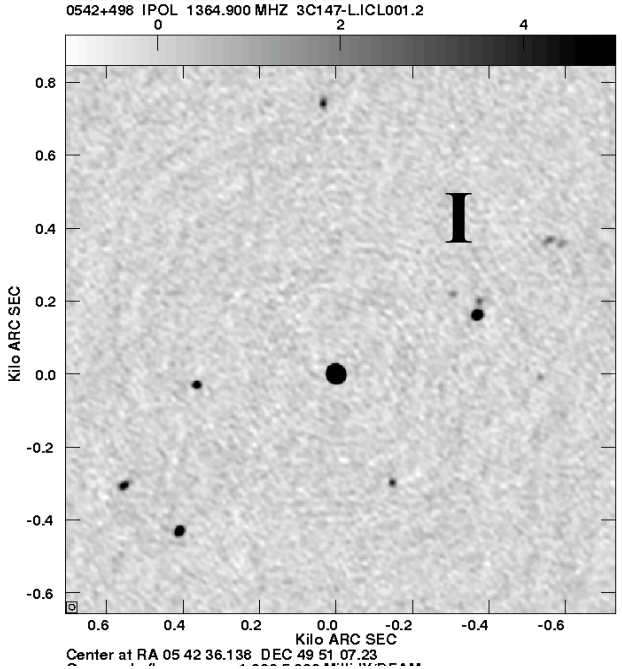
- Tuning: 940-2200 MHz
- Tsys/eff= 65-70 K
- Aeff/Tsys~ 200 m^2/K

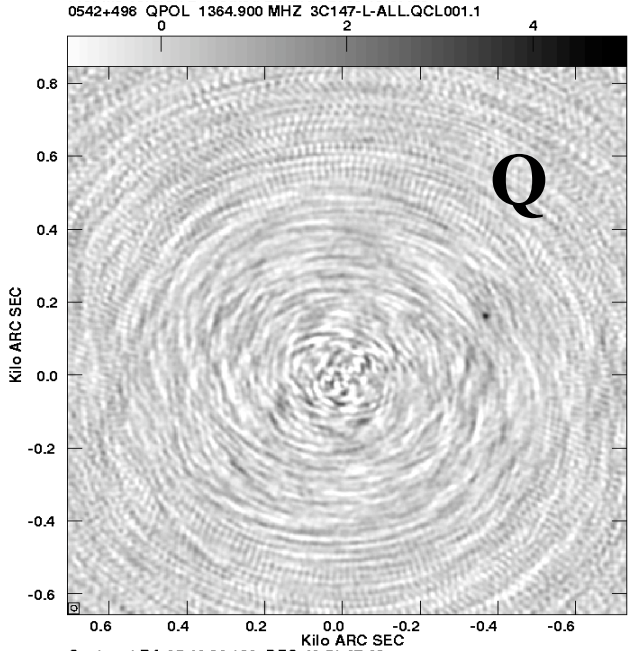


- Much flatter response with elevation
- Schedule:
- 8jul09: 2 30jul09: 3
- jan11: 15 may12: 25
- dec12: 28

Pol'n stability: L-Band (1485 MHz)

- 3C147 (unpolarized)
- 6 hours' *continuum* data with *interim L-band polarizers*
- Single pol'n solution





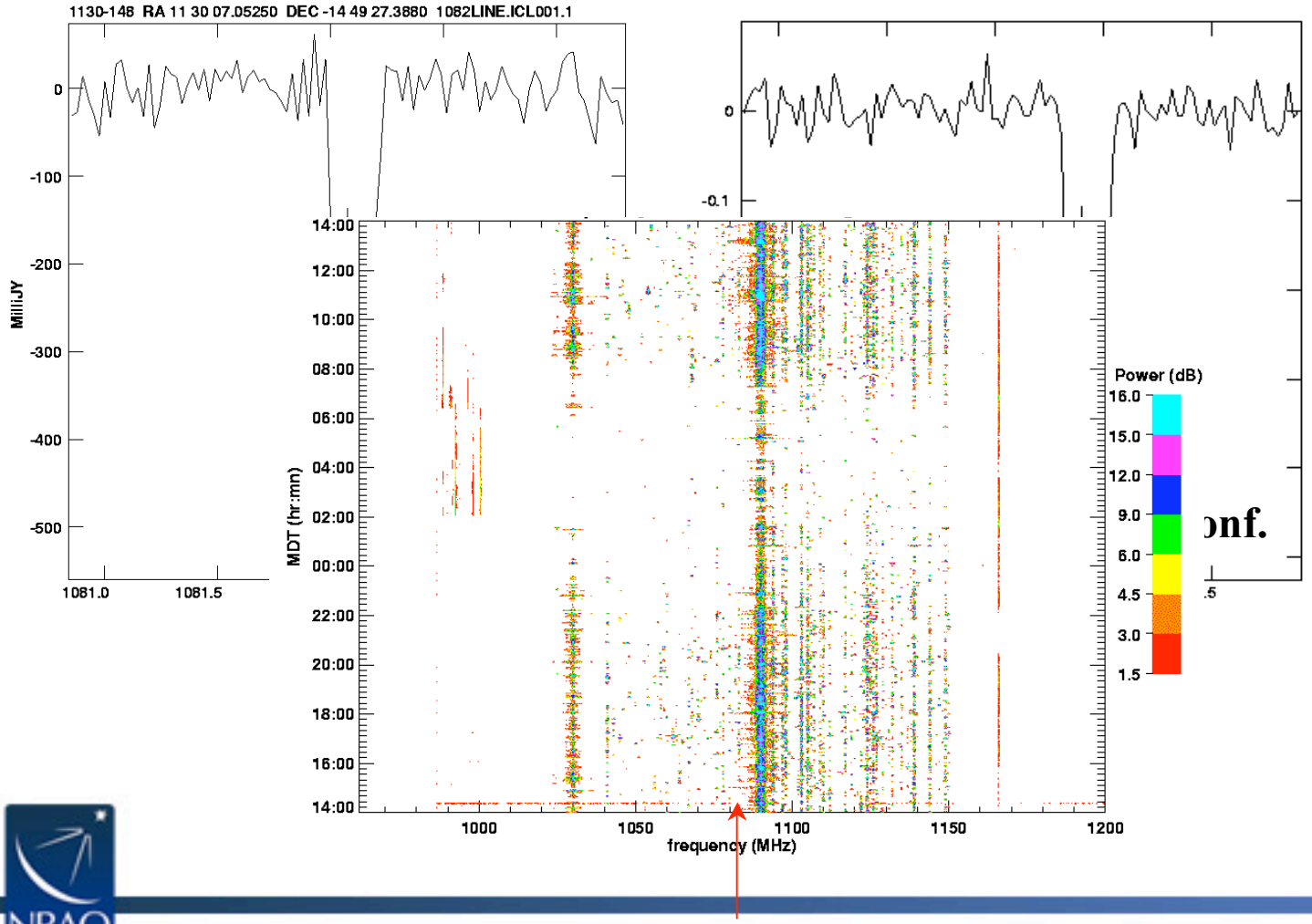
Peak = 21241 mJy, σ = 0.21 mJy

Max background object = 24 mJy

Peak = 4 mJy, σ = 0.8 mJy

Peak at 0.02% level – but not noise limited!

Observing near RFI: interim system

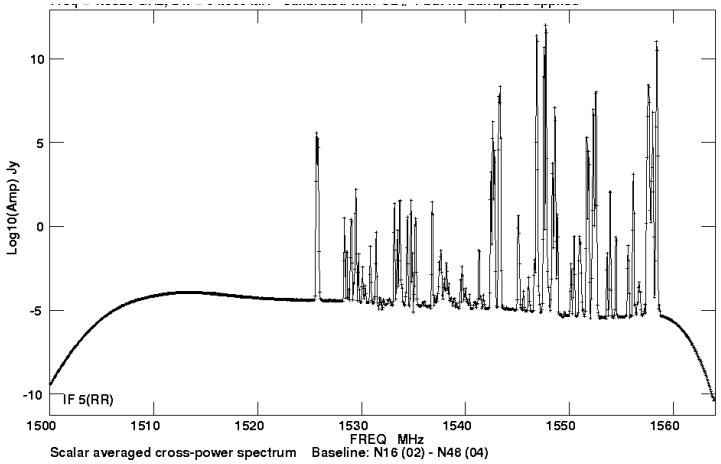


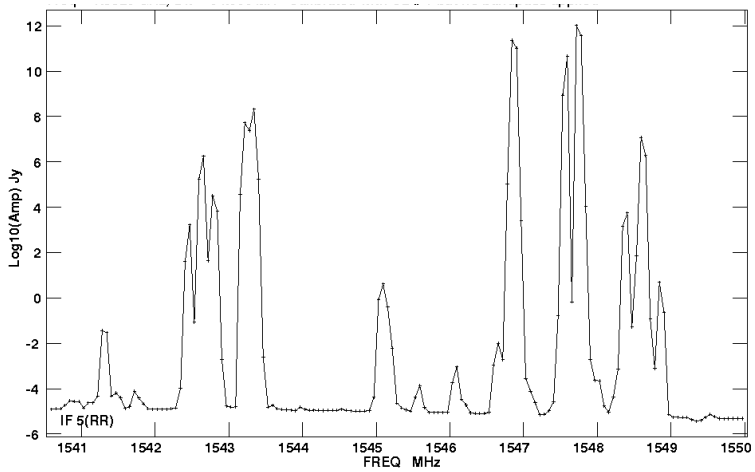
- PKS 1127-145
- Z=0.31
- 1082 MHz

Momjian 2008

RFI: correlator linearity

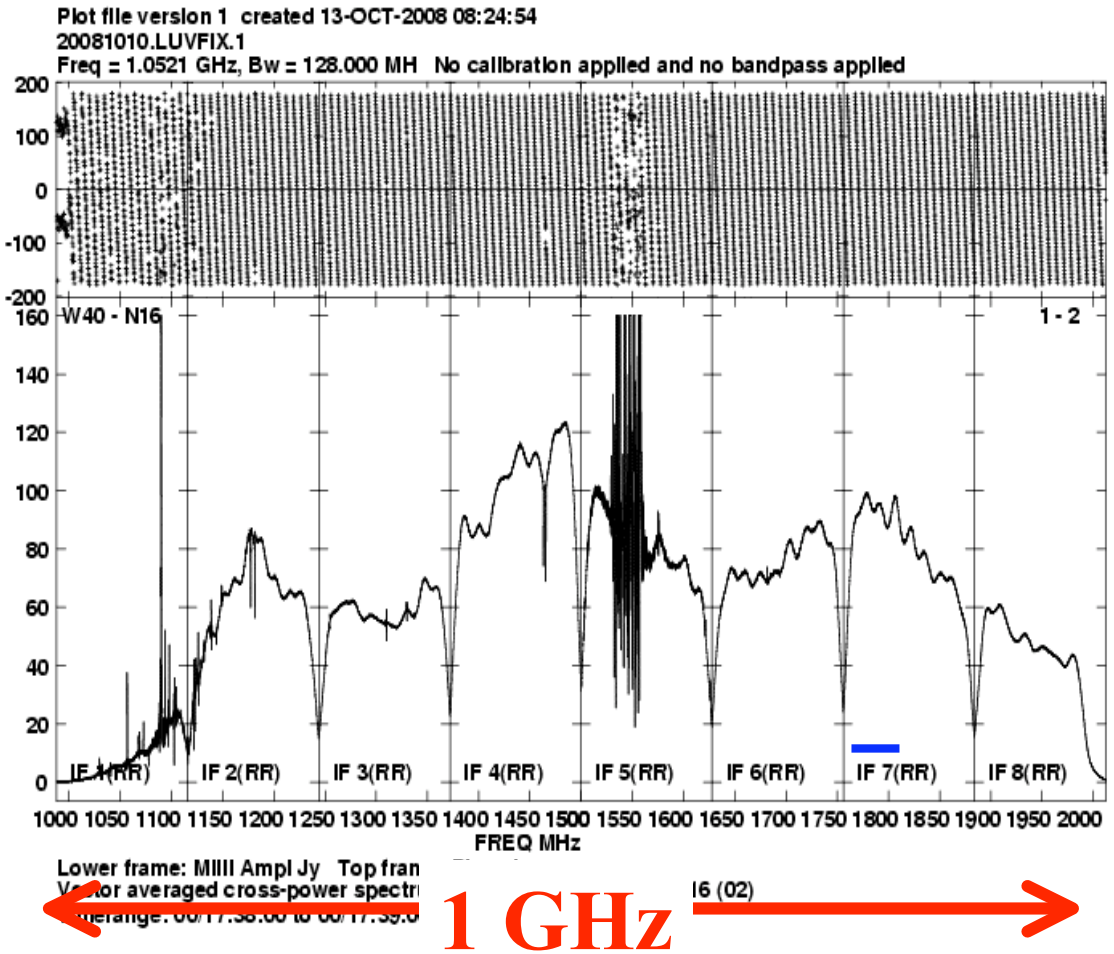
- WIDAR designed to provide more than 50 dB linearity.
- Early tests with the WIDAR PTC are very encouraging



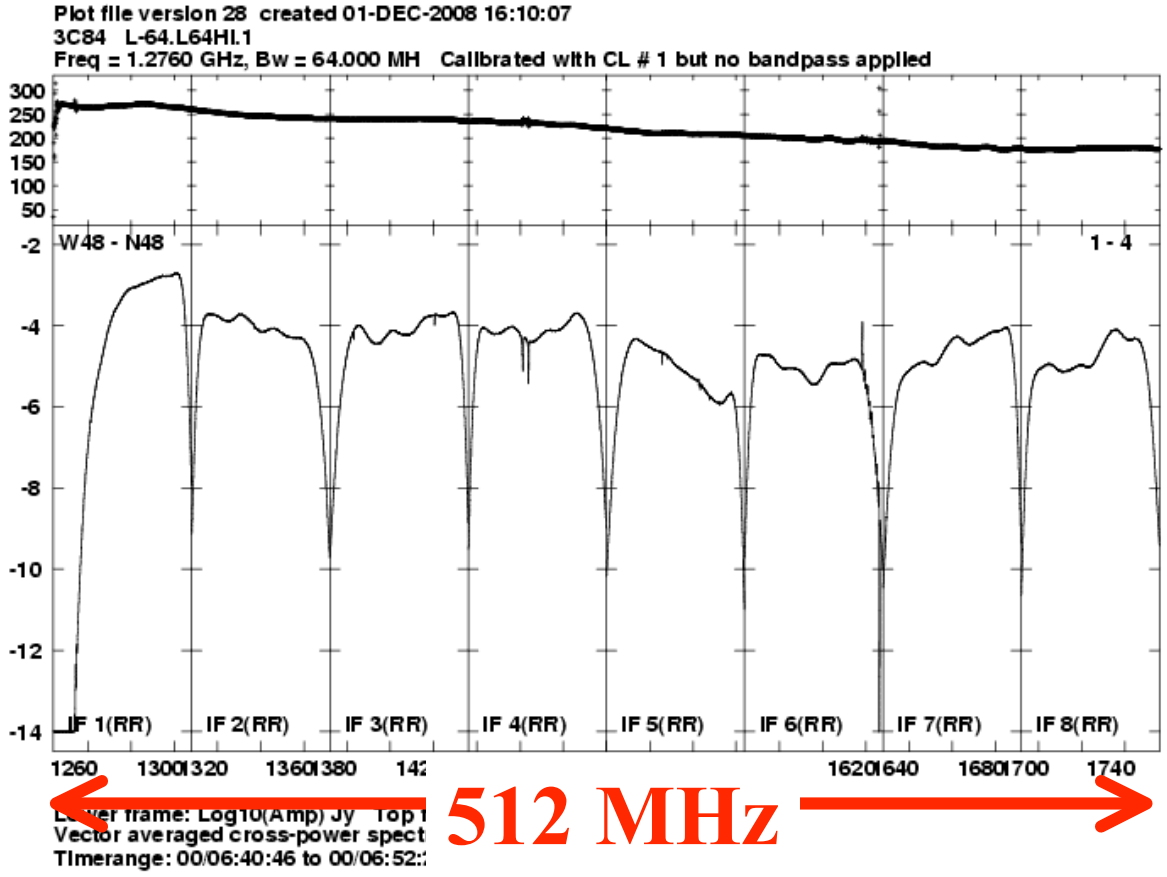


- Left: Scalar averaged spectrum of 3C84, showing INMARSAT
- Right: Closeup, showing astronomical signal between emissions.
- There is no sign of correlator saturation, at a level 40 dB below the peak signal strength.

1-2 GHz: continuum + RFI

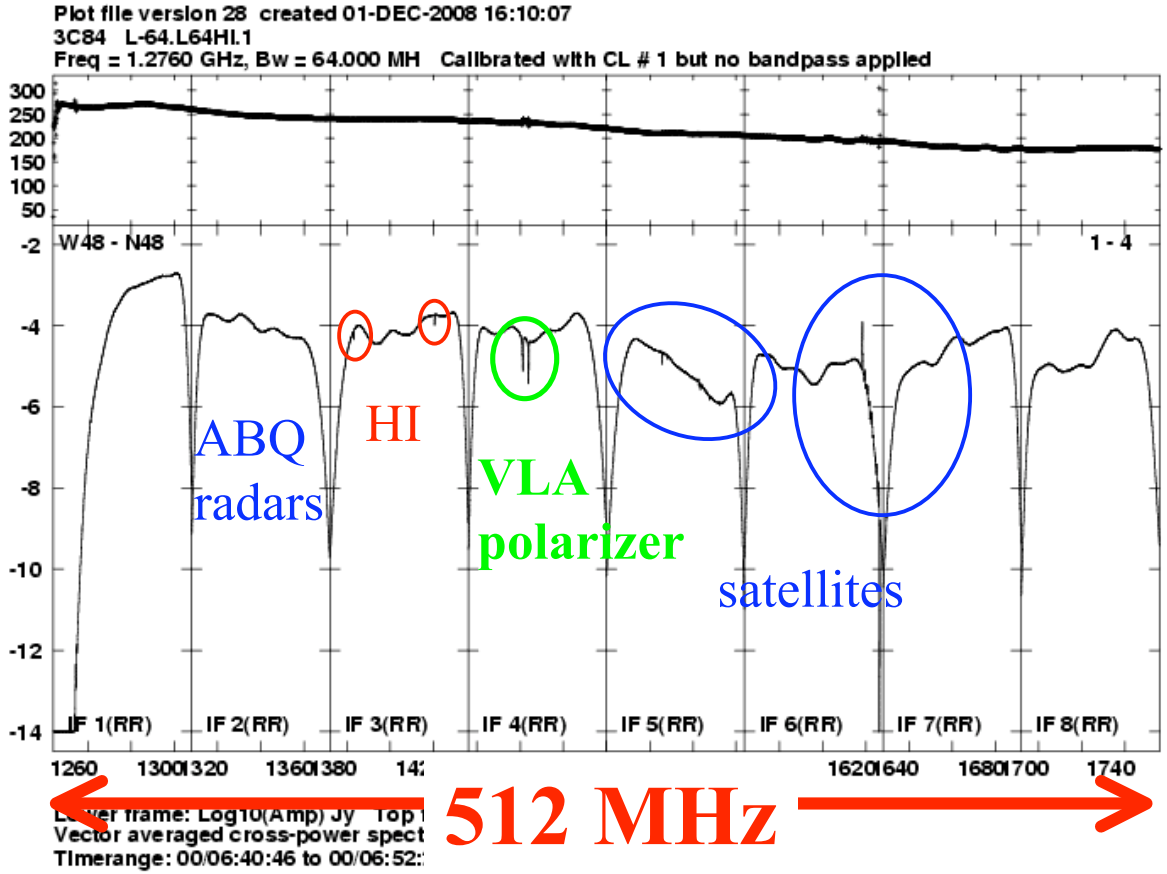


3C84 @ 1.5 GHz



- 1244-1756 MHz
- 8192 x **62.5 kHz** (13 km/s for local HI)

3C84 @ 1.5 GHz



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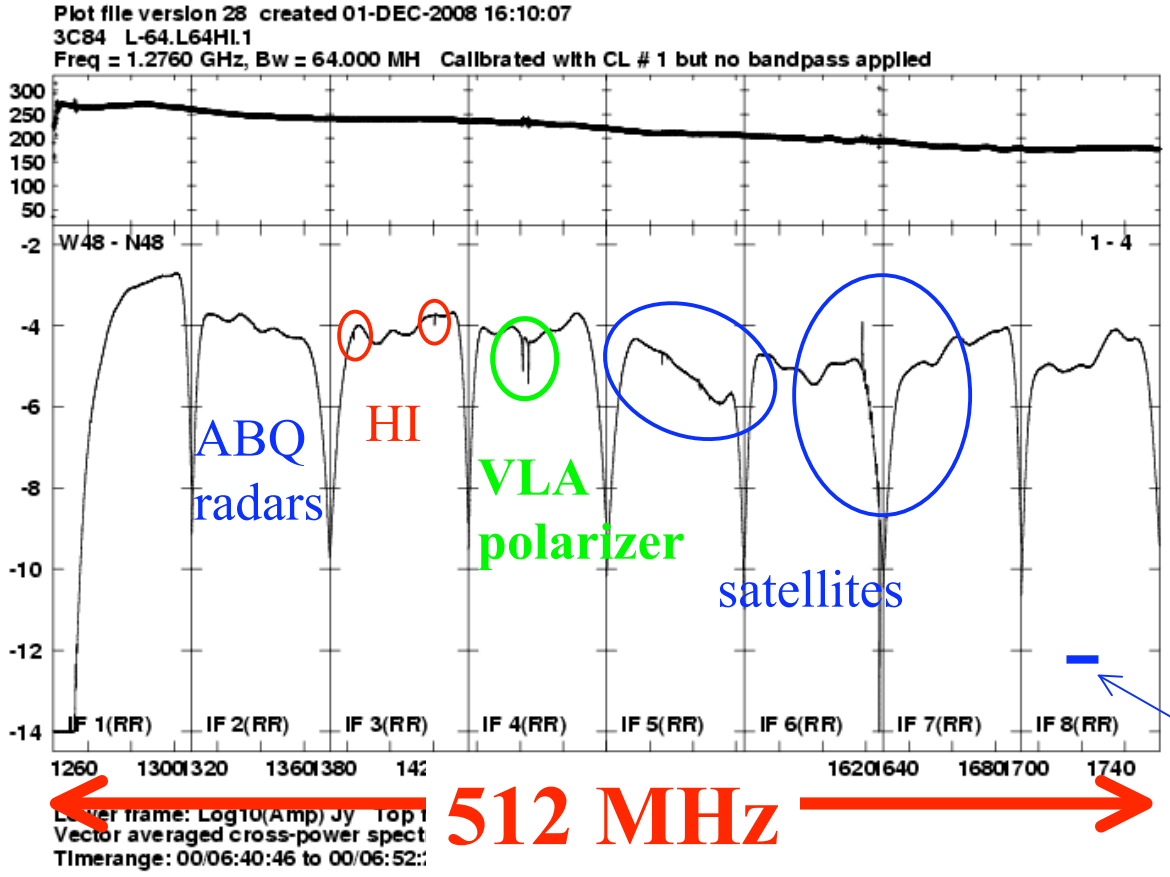
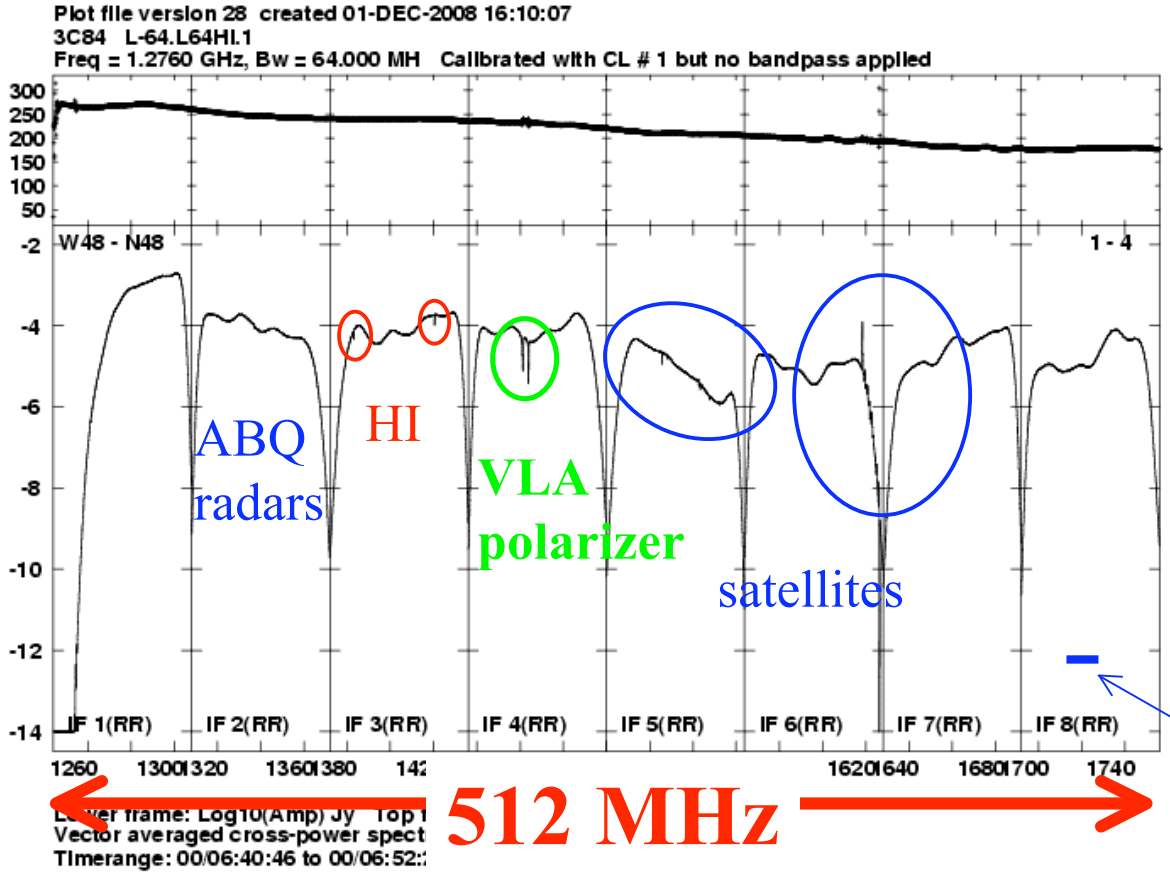


- 1244-1756 MHz
- 8192 x **62.5 kHz** (13 km/s for local HI)

Current VLA: 6.25 MHz @ 98 kHz

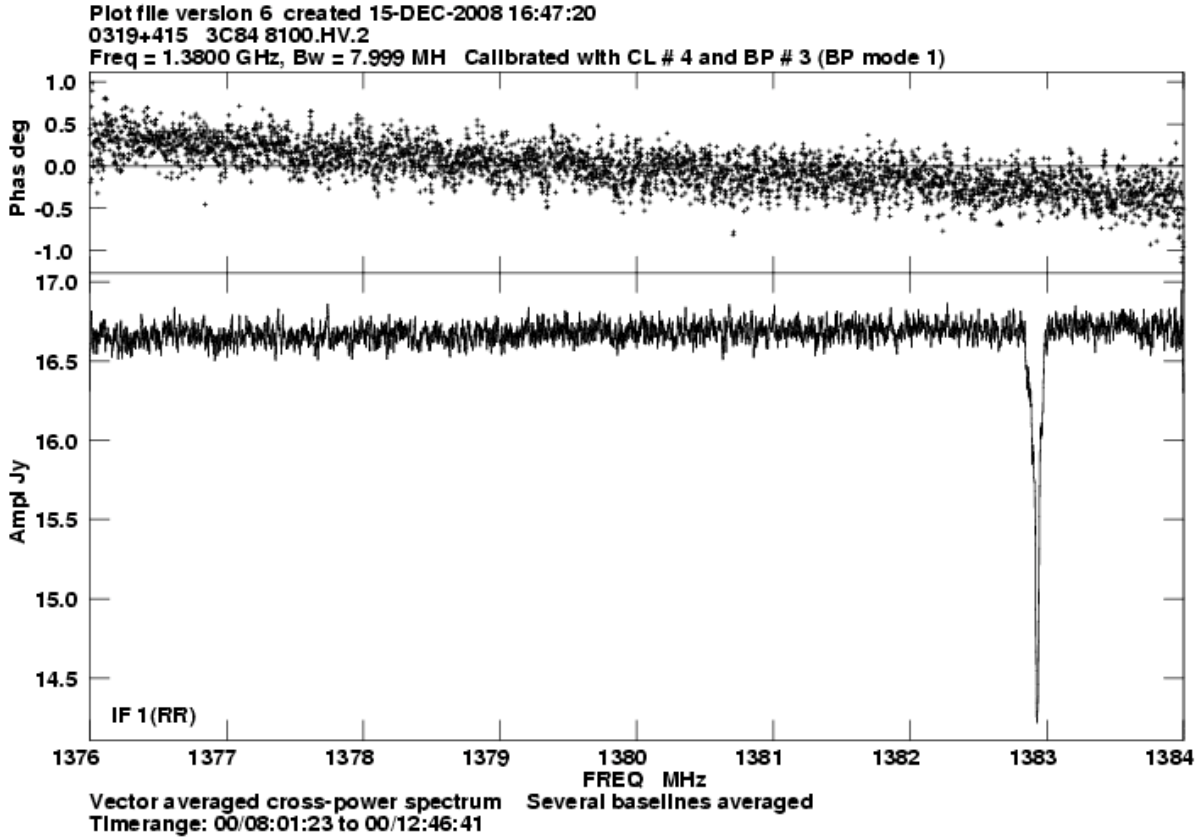
3C84 @ 1.5 GHz



- 1244-1756 MHz
- 8192 x **62.5 kHz** (13 km/s for local HI)
- Final EVLA:
  - **512 MHz (z=0-0.3)**
  - **@ 7.8 kHz (1.7 km/s)**

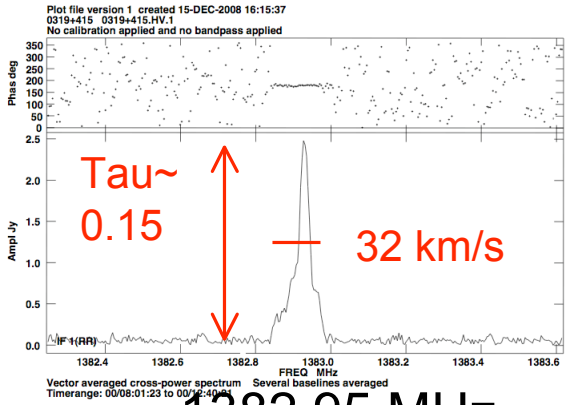
Current VLA: 6.25 MHz @ 98 kHz

3C84 @ 1.5 GHz

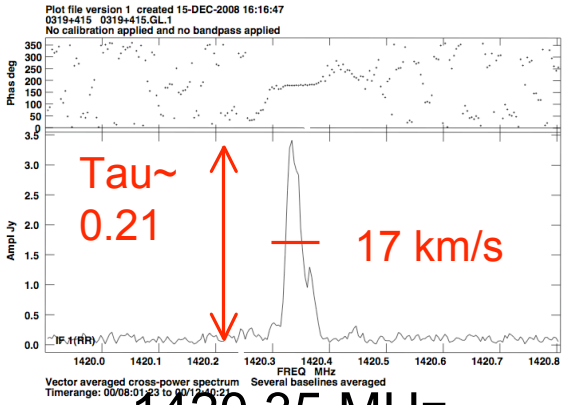


- 1376-1384 MHz (one 8 MHz subband)
- 4096 x 1.95 kHz (0.4 km/s)

3C84 @ 1.5 GHz

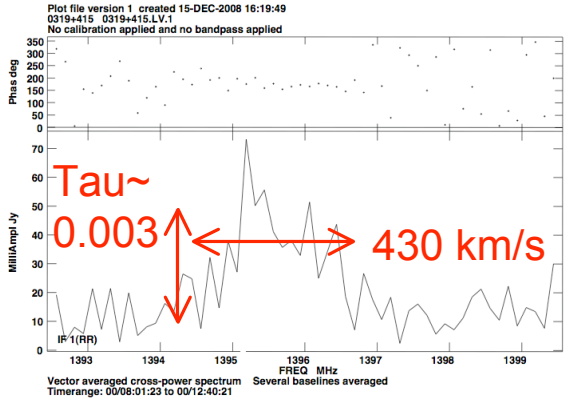


1382.95 MHz



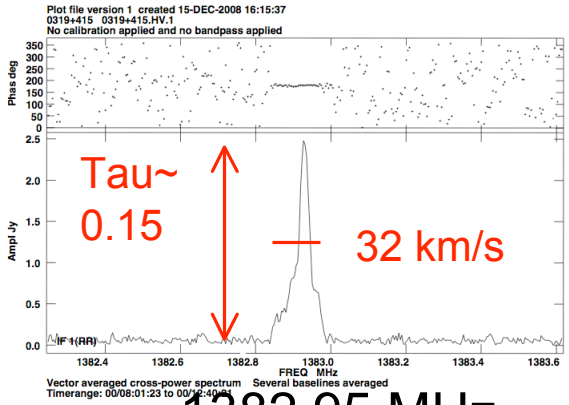
1420.35 MHz

- 8 x 8 MHz subbands
- 8 x 4096 channels
  - Avg'd x2 (3.9 kHz)
  - or x64 (470 kHz)
- Zoomed in here!

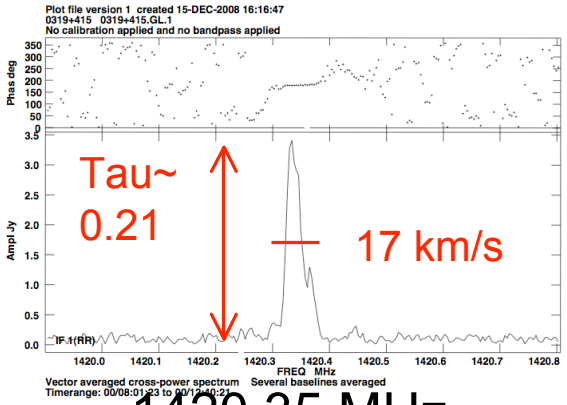


1395.5 MHz

3C84 @ 1.5 GHz



1382.95 MHz



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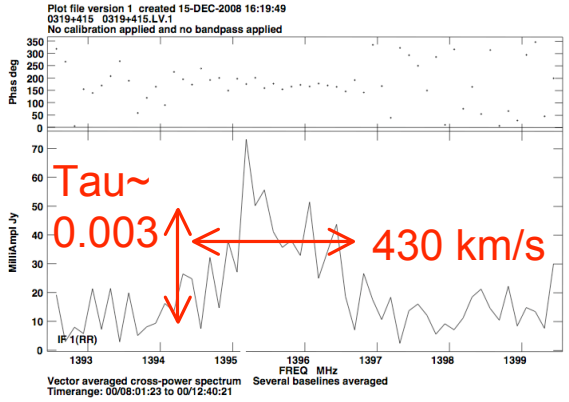
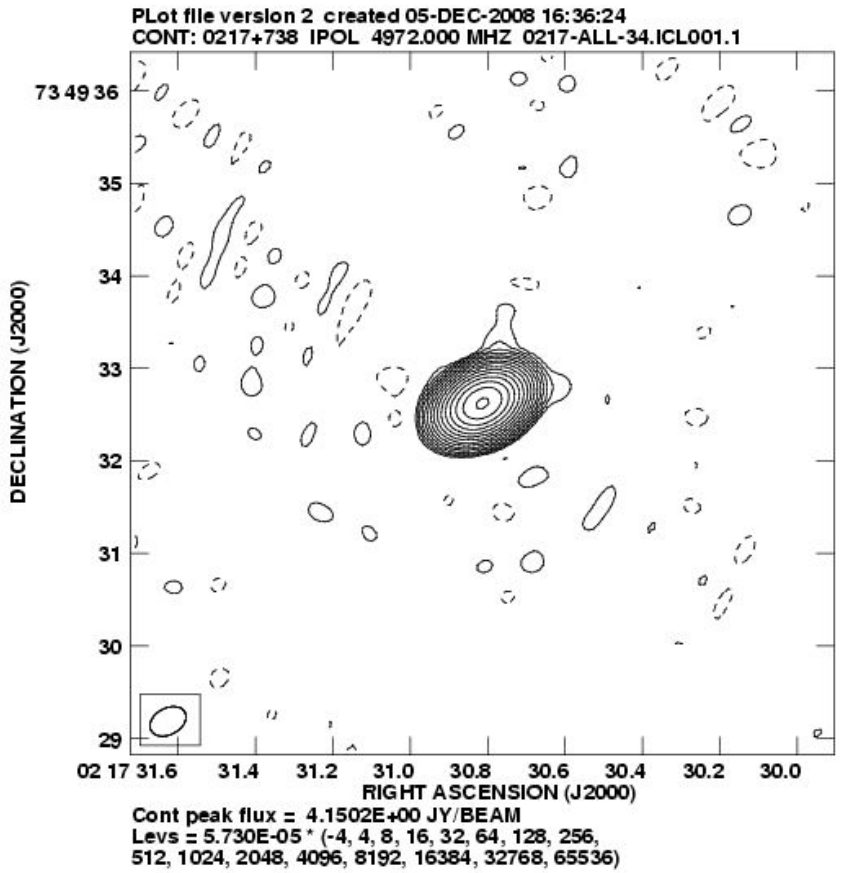


1395.5 MHz

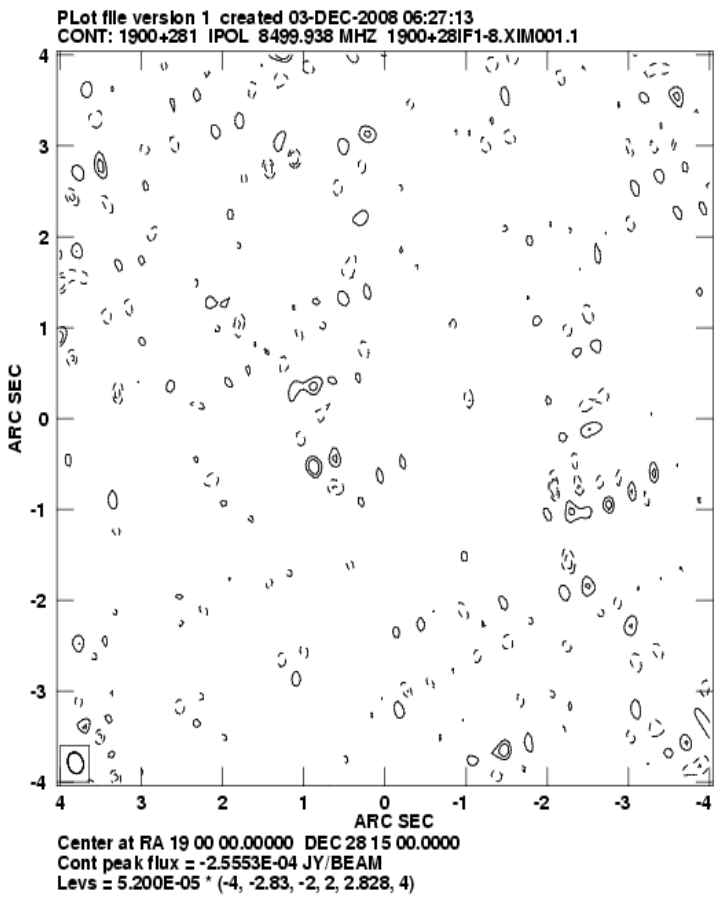
- 8 x 8 MHz subbands
- 8 x 4096 channels
  - Avg'd x2 (3.9 kHz)
  - or x64 (470 kHz)
- Zoomed in here!
- Full EVLA:
  - 64 **independently tunable** subband pairs
  - **Different bandwidth & resolution** for each subband pair

Image not limited by closure errors



- 0217+738
  - 4 Jy "dot"
  - 2hr10min on-source
- 4588-5612 MHz
- Self-cal'd image
- Peak:rms= 72,800:1

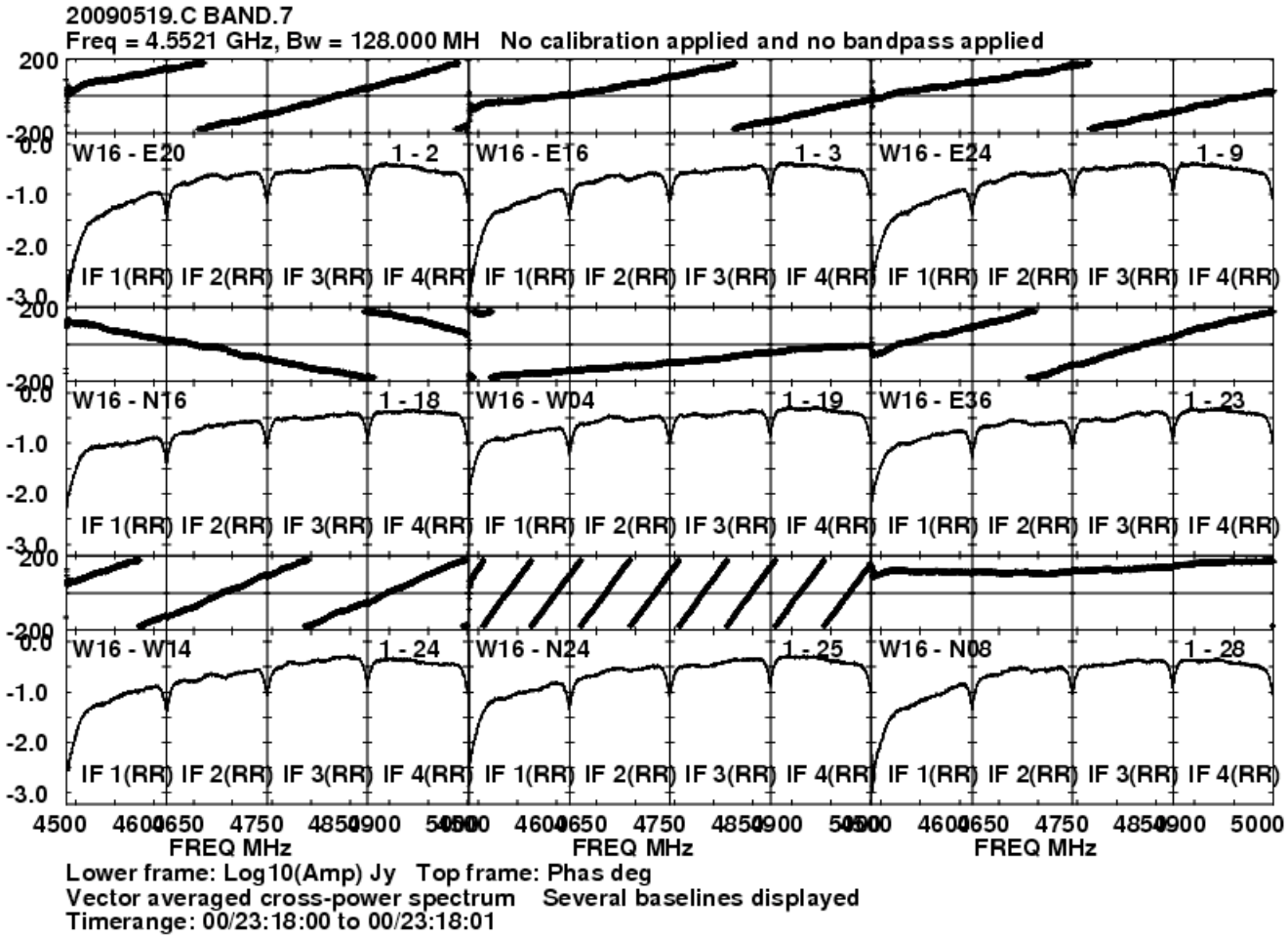
Deep image of a blank field



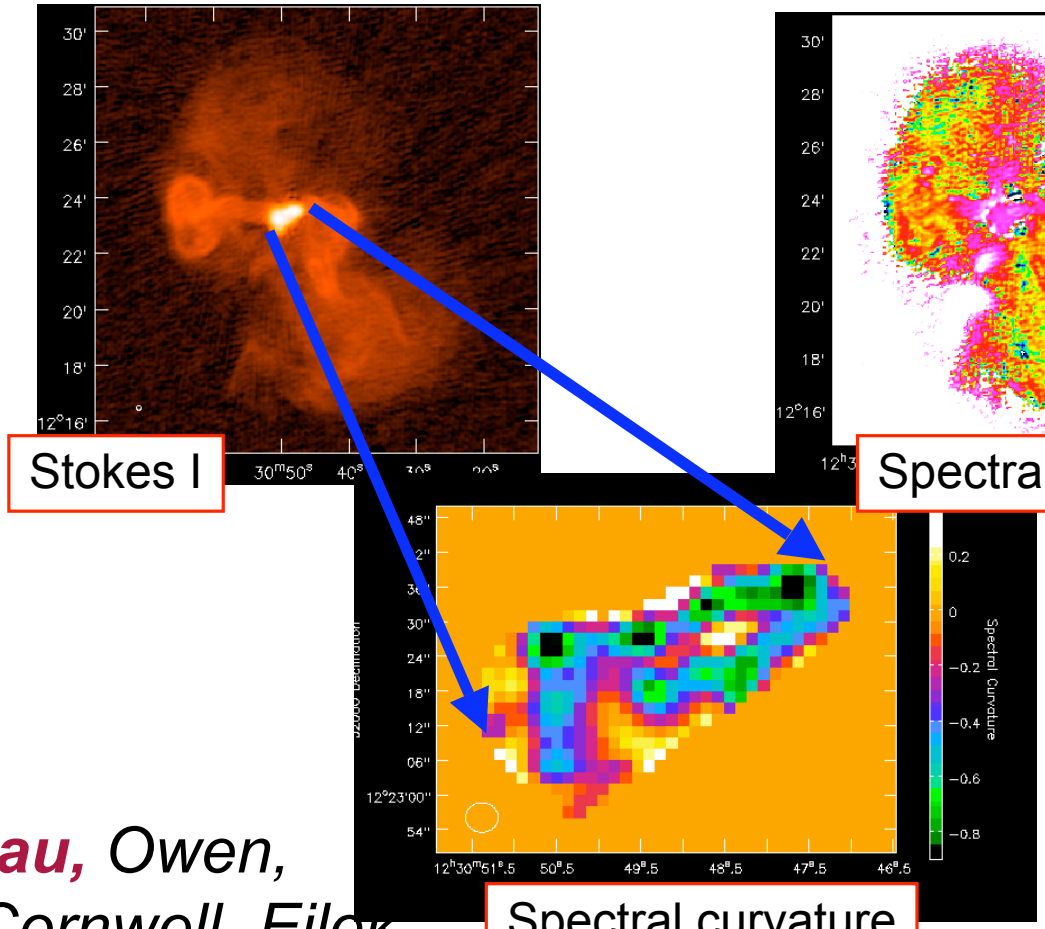
- J1900+2815
- 9012-7988 MHz
- 2.3 hours on-source
- Rms in 125 kHz: 2.84 mJy/beam
- Rms in 103 MHz (825 channels): 0.11 mJy/bm
- Rms in 825 MHz (825x8 channels): 0.052 mJy/bm

WIDAR-0 with 10 antennas

- 3C84, 512 MHz @ 5 GHz, RR



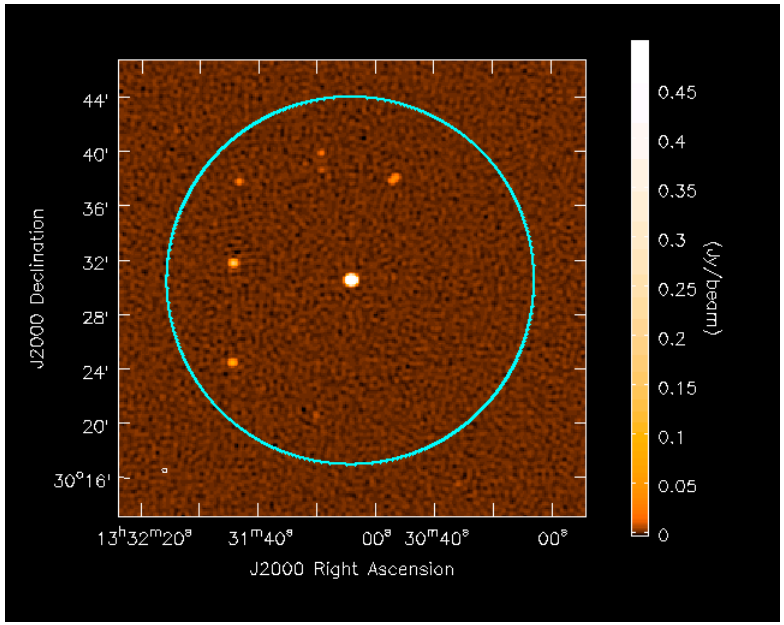
Deconvolution with 1.7:1 BWR



- M87 in C config.
- 1.18-1.86 GHz
- 10 3-min snapshots at each of 16 frequencies
- MS-MFS in CASA

Rau, *Owen, Cornwell, Eilek*

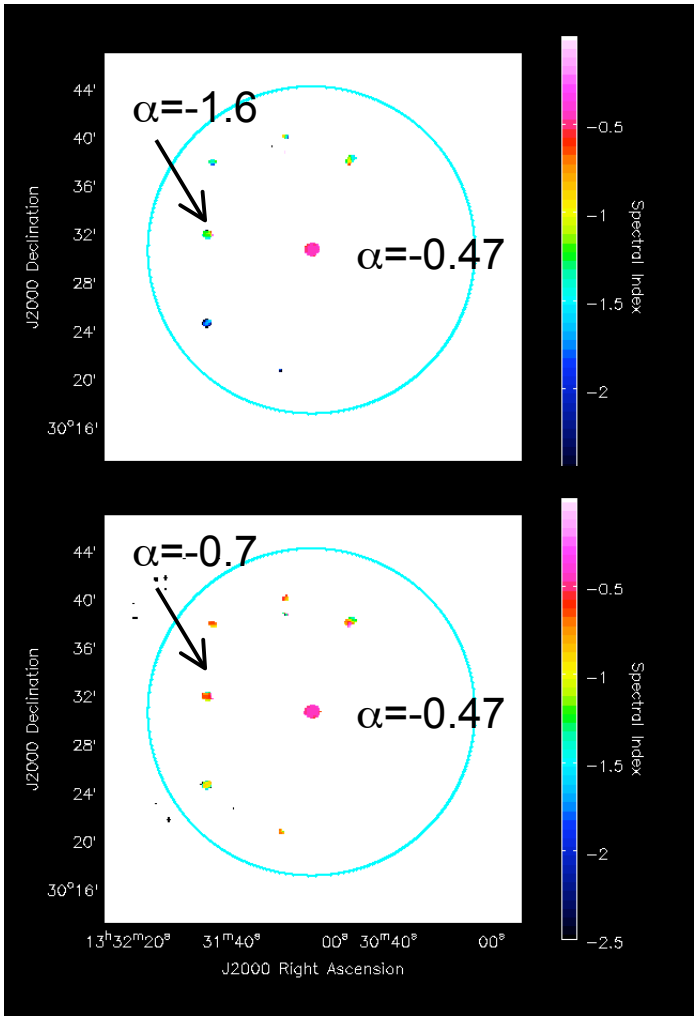
Primary beam correction with 1.5:1 BWR



3C286 field (1.2 GHz to 1.8 GHz)

Without PB correction

With PB correction



Rau, *Owen, Cornwell, Eilek*

Access to the EVLA

- Antennas in use all the time
- Receiver bands made available when >5
- WIDAR correlator in general use by March 2010
- Shared Risk Observing (Open or Resident) beginning T1 2010: http://www.aoc.nrao.edu/evla/astro/
  - First proposal call: 1 October 2009
  - Initial OSRO: 2 x 128 MHz, ramping up each configuration cycle
  - Initial RSRO: 2 x 1 GHz, ramping up each configuration

The role of the EVLA

The EVLA in context

- One of *many* new or hugely upgraded radio telescopes
  - ASKAP, MeerKAT, APERTIF, ...
- EVLA is *not* primarily a 1-2 GHz spectral line survey instrument
  - Main strength of VLA has always been flexibility: frequency coverage, spatial resolution, temporal resolution, etc.
  - Improvements are mainly related to continuum sensitivity and flexibility -- no new collecting area (though much better at low elevations)
  - Lots of competition for telescope time!
    - Stellar flares to high-z CO

The EVLA's role at 1-2 GHz

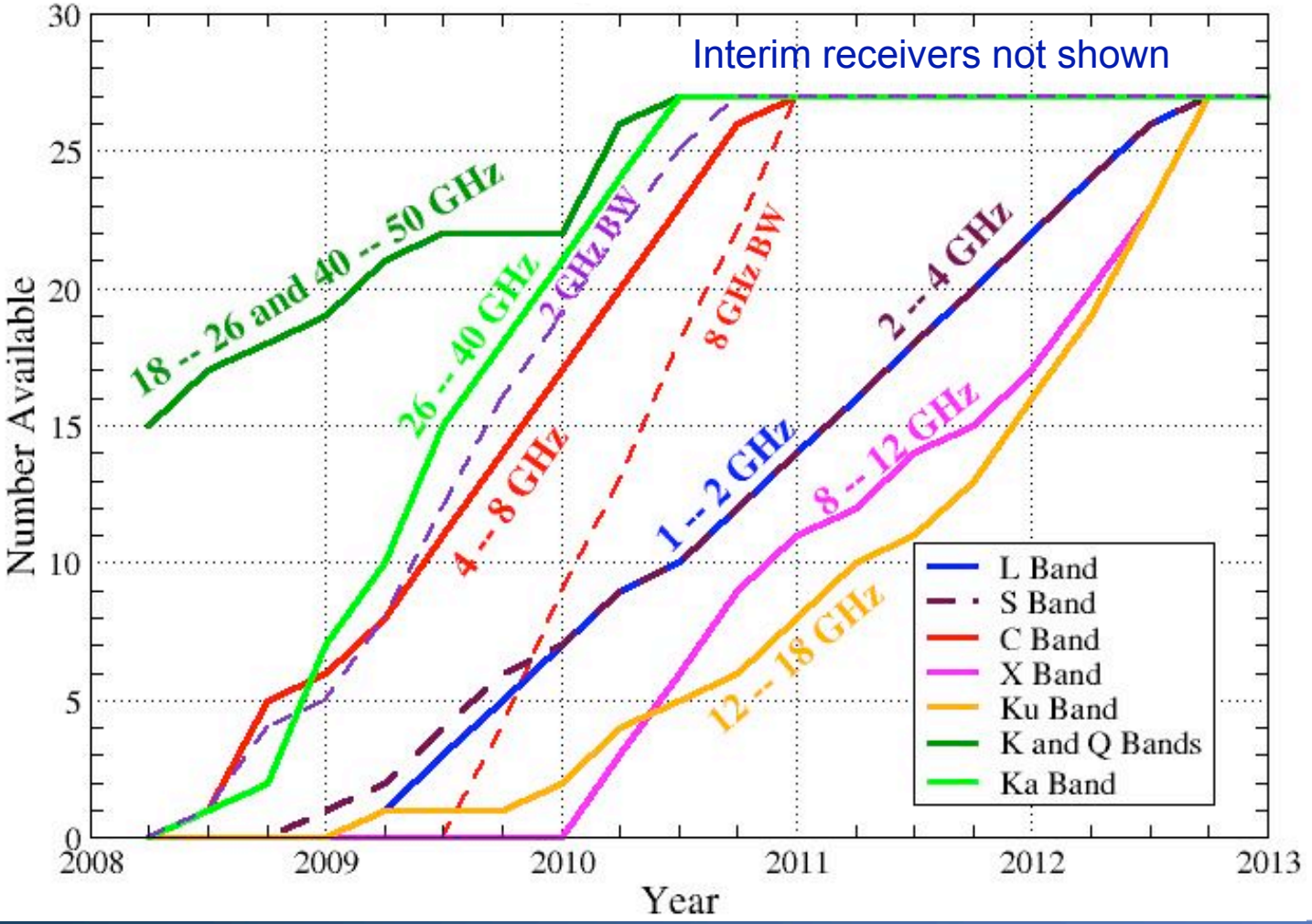
- Very deep integrations on single fields
  - High-z
  - Diffuse HI
  - N.b. needs LOTS of time, or special resolution, to compete
- Some piggy-back surveys (e.g., always observe Galactic & targeted HI, OH, RRLs)
  - mis-match between line & continuum sensitivities makes this unsuitable for surveys of more distant HI
- High-resolution, high-sensitivity follow-up studies
- Extensions to higher frequencies
  - Continuum
  - Redshifted molecular lines
  - etc. etc.
- High-sensitivity VLBI/pulsar element

Implications & questions

- Observatory arrangements or individual PIs?
- Any implications for EVLA operations?
  - standard correlator setups
  - preferred setups (maybe even data formats) to allow combining or auto-processing follow-up data
  - rapid response to triggers
  - will there be more or less HI at the EVLA?
  - ???
- Does the arrow go both ways?
  - Given EVLA data, should one go after a source with MeerKAT/APERTIF/???
- Role of E configuration

Tables & useful details

Schedule: Growth of New Capability



SEFD & sensitivity results

	Band (GHz)	SEFD/Jy		Sensitivity/1σ, 9hrs	
		Req'd	Actual#	Full BW μJy	1 km/s mJy
L	1 – 2	325	TBD	1.6	0.5
S	2 – 4	235	~280*	~1.0*	~0.6*
C	4 – 8	260	275	0.7	0.3
X	8 -- 12	300	TBD	0.8	0.3
Ku	12 -- 18	385	TBD	0.8	0.3
K	18 -- 26.5	650	420	0.75	0.25
Ka	26.5 -- 40	760	600	1.1	0.29
Q	40 -- 50	1570	1310	2.3	0.76

Blue = System tested
Red = Prototypes to be tested in 2009
* Preliminary result
\# Rough average over the band

SEFD= 5.62 Tsys/ε
$\sigma = SEFD/[\eta_c N_A \sqrt{(B\tau)}]$
$\eta_c = 0.91$ (4-bit)
$N_A = 27$

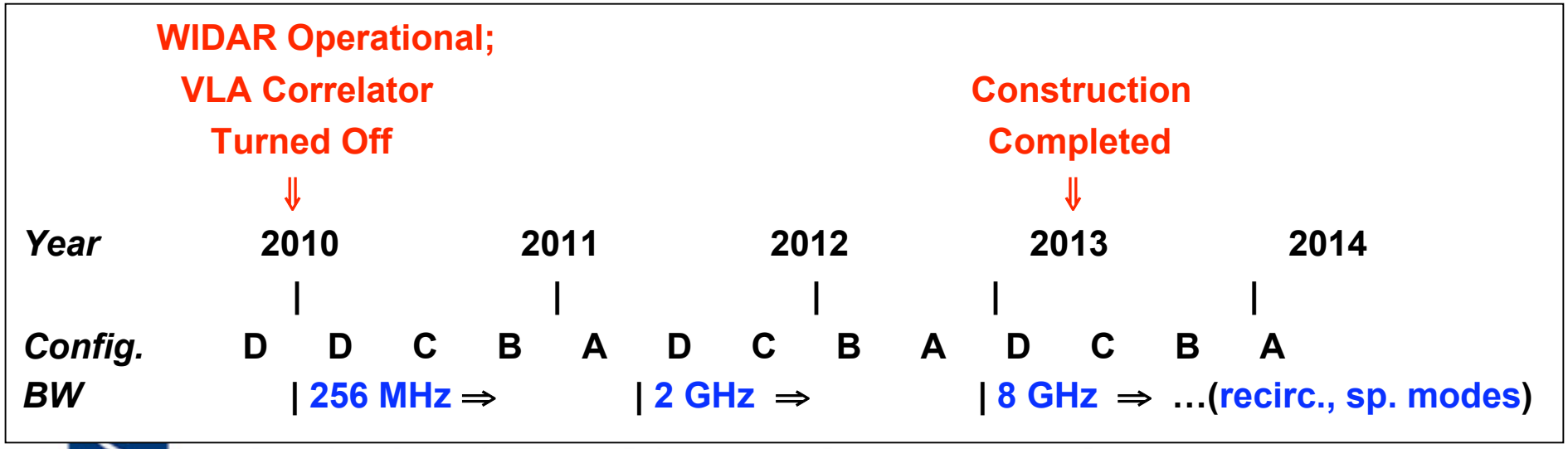
Efficiency and Tsys Results

	Band (GHz)	Tsys		Aperture Effic.	
		Req'd	Actual#	Req'd	Actual#
L	1 – 2	26	TBD	.45	0.40 – 0.45
S	2 – 4	26	24 – 28*	.62	~0.52*
C	4 – 8	26	24 -- 31	.56	.53 -- .61
X	8 -- 12	30	TBD	.56	TBD
Ku	12 -- 18	37	TBD	.54	TBD
K	18 -- 26.5	59	36 -- 42	.51	.57 -- .48
Ka	26.5 -- 40	53	40 -- 50	.39	.48 -- .36
Q	40 -- 50	74 -- 116	55 -- 100	.34	.37 -- .28

Blue = System tested and in place, or under installation.
Red = Prototypes to be tested in 2009
* Preliminary result
# Range over the band

Open Shared Risk Observing (OSRO)

- http://www.aoc.nrao.edu/evla/astro/osro.shtml
- T1 2010 (1oct09 proposal deadline):
  - New bands
  - 2x128/2^N MHz full pol'n 64 channels; or
  - 1x256/2^N MHz dual pol'n, 256 channels
  - 1 sec dumps



OSRO WIDAR modes (1)

- Continuum applications and spectro-polarimetry
  - Two independently-tunable sub-band pairs (IFs), full pol., each with bandwidth $128/2^n$ MHz (n=0,..,12), 64 channels

Sub-band BW (MHz)	Number of poln. products	Number of channels/poln product	Channel width (kHz)	Channel width (kms^{-1} at 1 GHz)	Total velocity coverage (kms^{-1} at 1 GHz)
128	4	64	2000	600/ν(GHz)	38,400/ν(GHz)
64	4	64	1000	300	19,200
32	4	64	500	150	9,600
16	4	64	250	75	4,800
8	4	64	125	37.5	2,400
4	4	64	62.5	19	1,200
2	4	64	31.25	9.4	600
1	4	64	15.625	4.7	300
0.5	4	64	7.813	2.3	150
0.25	4	64	3.906	1.2	75
0.125	4	64	1.953	0.59	37.5
0.0625	4	64	0.977	0.29	18.75
0.03125	4	64	0.488	0.15	9.375

OSRO WIDAR modes (2)

- Spectral line applications
  - One tunable sub-band pair (IF), dual polarization, with bandwidth $128/2^n$ MHz (n=0,..,12), 256 channels

Sub-band BW (MHz)	Number of poln. products	Number of channels/poln product	Channel width (kHz)	Channel width (kms^{-1} at 1 GHz)	Total velocity coverage (kms^{-1} at 1 GHz)
128	2	256	500	150/ν(GHz)	38,400/ν(GHz)
64	2	256	250	75	19,200
32	2	256	125	37.5	9,600
16	2	256	62.5	19	4,800
8	2	256	31.25	9.4	2,400
4	2	256	15.625	4.7	1,200
2	2	256	7.813	2.3	600
1	2	256	3.906	1.2	300
0.5	2	256	1.953	0.59	150
0.25	2	256	0.977	0.29	75
0.125	2	256	0.488	0.15	37.5
0.0625	2	256	0.244	0.073	18.75
0.03125	2	256	0.122	0.037	9.375

Resident Shared Risk Observing (RSRO)

- http://www.aoc.nrao.edu/evla/astro/rsro.shtml
- Experts in residence as temporary staff members in exchange for early access
  - up to 100 hrs/month
  - NRAO staff also have early access
- Scientific, technical, & budgetary review
- Regular proposal calls, starting 1 October 2009
- Rough schedule:
  - T1 2010: 2x1 GHz total BW, 0.1 sec dumps
  - T2 2010: 2x8 GHz total BW
  - T3 2010: Recirculation (lots more channels)
  - T1-T2 2011: Increased flexibility in correlator resource allocation
  - T3 2011-: Special modes (pulsars, speed dumps, …)

RSRO: T1 2010-T2 2011

Date	Array Config	Total bandwidth per pol'n	Number of subband pairs	Channels per sb pair (4 pp)	Comments
T1 2010	D	1 GHz	16	64	All sb identical 8-bit samplers
T2 2010	C	8 GHz	64	64	All sb identical 3-bit samplers
T3 2010	B	8 GHz	64	<= 16,384	All sb identical Add recirculation
T1 2011	A	8 GHz	64	<=16,384	Independent subbands
T2 2011	D	8 GHz	64	<= 16,384	Can trade subbands for channels

Potential Areas of RSRO Participation

- Development of correlator modes
  - General correlator resource allocation
  - Multiple spectral lines for Galactic and extragalactic applications
  - Solar observing
  - Planetary observing
  - Astrometry
  - Phased array and VLBI
  - Pulsars
- Development of observing and calibration strategies
  - Wideband calibration methods
  - High frequency calibration
  - Improved referenced pointing
  - Ionospheric calibration
  - Calibrator models
  - Polarimetry
  - Mosaicing
  - RFI excision
- Development of data reduction strategies and algorithms
  - Automated flagging
  - Wideband, wide-field imaging
  - High dynamic range imaging
  - Algorithm development
  - Algorithm implementation
  - Post-processing computing and networking optimization
  - On-the-fly imaging

RSRO requirements

- At least one expert from each participating group must be in residence in Socorro
  - must contribute effectively to commissioning
  - limited support for salaries or accommodation may be available
- Proposals will have three parts:
  1. Scientific justification, to be peer reviewed as part of NRAO's current time allocation process
  2. Technical section describing personnel and expertise to be involved in the residency, to be reviewed by NRAO staff
  3. Budget specifying the level and nature of any support requested from NRAO; proposals that do not require Observatory support will have a substantial advantage over those that request NRAO resources

RSRO details

- Time available:
  - Up to 25% of the time available for astronomy will go to RSRO programs (~100 hours/month)
- Residency:
  - Minimum of *one month* of resident commissioning effort required for every *20 hours* of time allocated, minimum residency of *3 months*
  - May take place before the observations, but observers must be present for observations
  - An EVLA commissioning staff collaborator will not satisfy the residency requirement
  - Graduate students will not (in general) satisfy the residency requirement
  - Resident personnel will work under NRAO management with well-defined deliverables

RSRO capabilities: per subband, no recirculation

- In the end WIDAR will provide 64 completely independent subband pairs (independent tuning, bandwidth, pol'n products, etc.)

Sub-band BW (MHz)	Number of poln. products	Number of channels/poln product	Channel width (kHz)	Channel width (kms^{-1} at 1 GHz)	Total velocity coverage (kms^{-1} at 1 GHz)
128	4	64	2000	600/ν(GHz)	38,400/ν(GHz)
64	4	64	1000	300	19,200
32	4	64	500	150	9,600
16	4	64	250	75	4,800
8	4	64	125	37.5	2,400
4	4	64	62.5	19	1,200
2	4	64	31.25	9.4	600
1	4	64	15.625	4.7	300
0.5	4	64	7.813	2.3	150
0.25	4	64	3.906	1.2	75
0.125	4	64	1.953	0.59	37.5
0.0625	4	64	0.977	0.29	18.75
0.03125	4	64	0.488	0.15	9.375

RSRO capabilities: per subband, with recirculation

- In the end WIDAR will provide 64 completely independent subband pairs (independent tuning, bandwidth, pol'n products, numbers of channels, etc.)

Sub-band BW (MHz)00	Number of poln. products	Number of channels/poln product	Channel width (kHz)	Channel width (kms^{-1} at 1 GHz)	Total velocity coverage (kms^{-1} at 1 GHz)
128	4	64	2000	600/ν(GHz)	38,400/ν(GHz)
64	4	128	500	150	19,200
32	4	256	125	37.5	9,600
16	4	512	31.25	9.4	4,800
8	4	1024	7.813	2.3	2,400
4	4	2048	1.953	0.59	1,200
2	4	4096	0.488	0.15	600
1	4	8192	0.122	0.037	300
0.5	4	16384	0.031	0.0092	150
0.25	4	16384	0.015	0.0046	75
0.125	4	16384	0.0076	0.0023	37.5
0.0625	4	16384	0.0038	0.0011	18.75
0.03125	4	16384	0.0019	0.00057	9.375

Upcoming Proposal Deadlines

- VLA correlator will be turned off at the end of the next D-configuration, January 2010
  - see “EVLA Information for Astronomers” web page, at http://www.aoc.nrao.edu/evla/astro/
- Configuration cycle will also reverse at this time, from A→B→C→D to D→C→B→A
- June 1, 2009: proposal deadline for the last VLA D-configuration
- October 1, 2009: proposal deadline for the first EVLA D-configuration
- October 1, 2009: first call for RSRO proposals

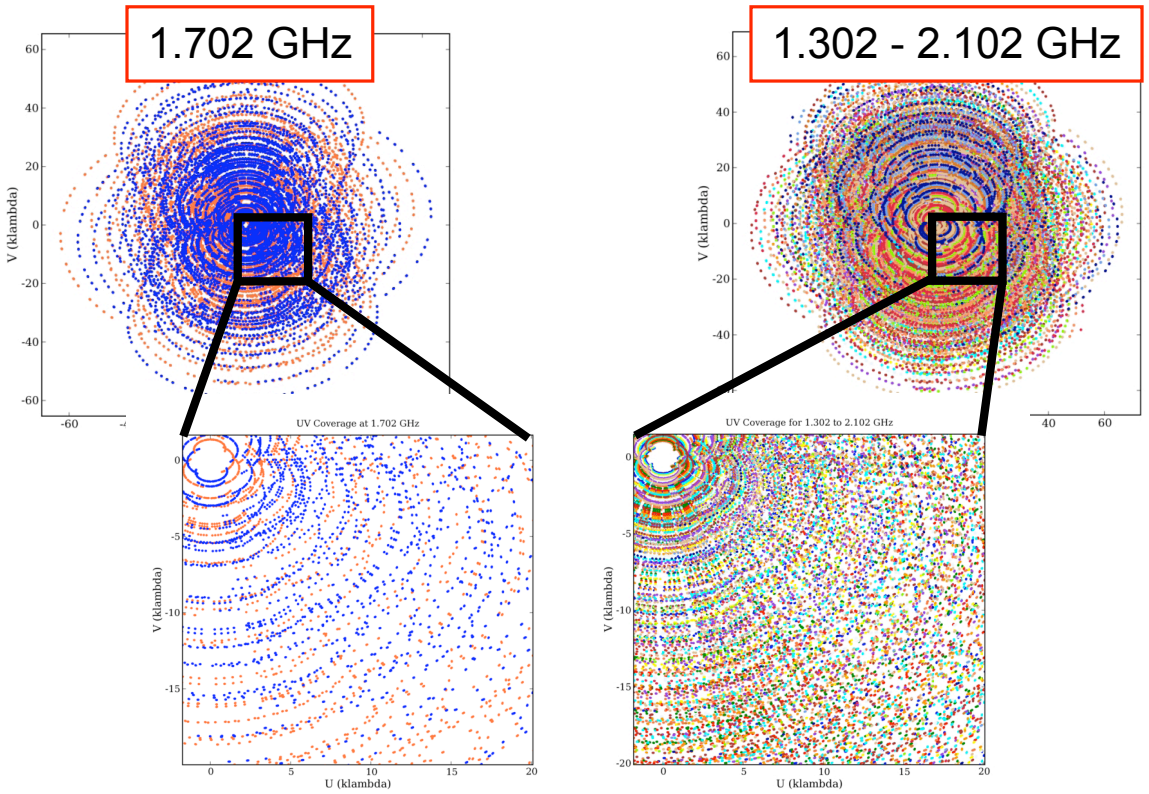
Data Rates and Volumes

Driver	Target Date	% time	Max rate (Mby/s)	Mean rate (Mby/s)	Volume (Tby/yr)
Now		100	.06	.02	0.5
PTC	Aug08	small	8	n/a	n/a
WIDAR0	Mar09	small	20	0.1	4
256 MHz bandwidth; 1024 channels max; 1 sec min dump (OSRO)	Mar10	90	0.23	0.08	2
2 GHz bandwidth; 8096 channels max; 0.1 sec min dump (RSRO)	Mar10	10	2	0.6	2
8 GHz bandwidth; 32384 channels max; 0.1 sec min dump; ~10 antennas with 3-bit samplers (RSRO)	Jun10	10	16	5	16
8 GHz bandwidth; 1048576 channels max; 0.1 sec min dump (RSRO)	Oct10	10	75	20	60
2 GHz bandwidth; 8096 channels max; 0.1 sec min dump (OSRO)	Jun11	90	2	0.6	20
8 GHz bandwidth; 1048576 channels max; 0.1 sec min dump (End of construction)	Jan13	100	75	20	600

Early testing indicates we should have no trouble supporting these data rates

Backup slides

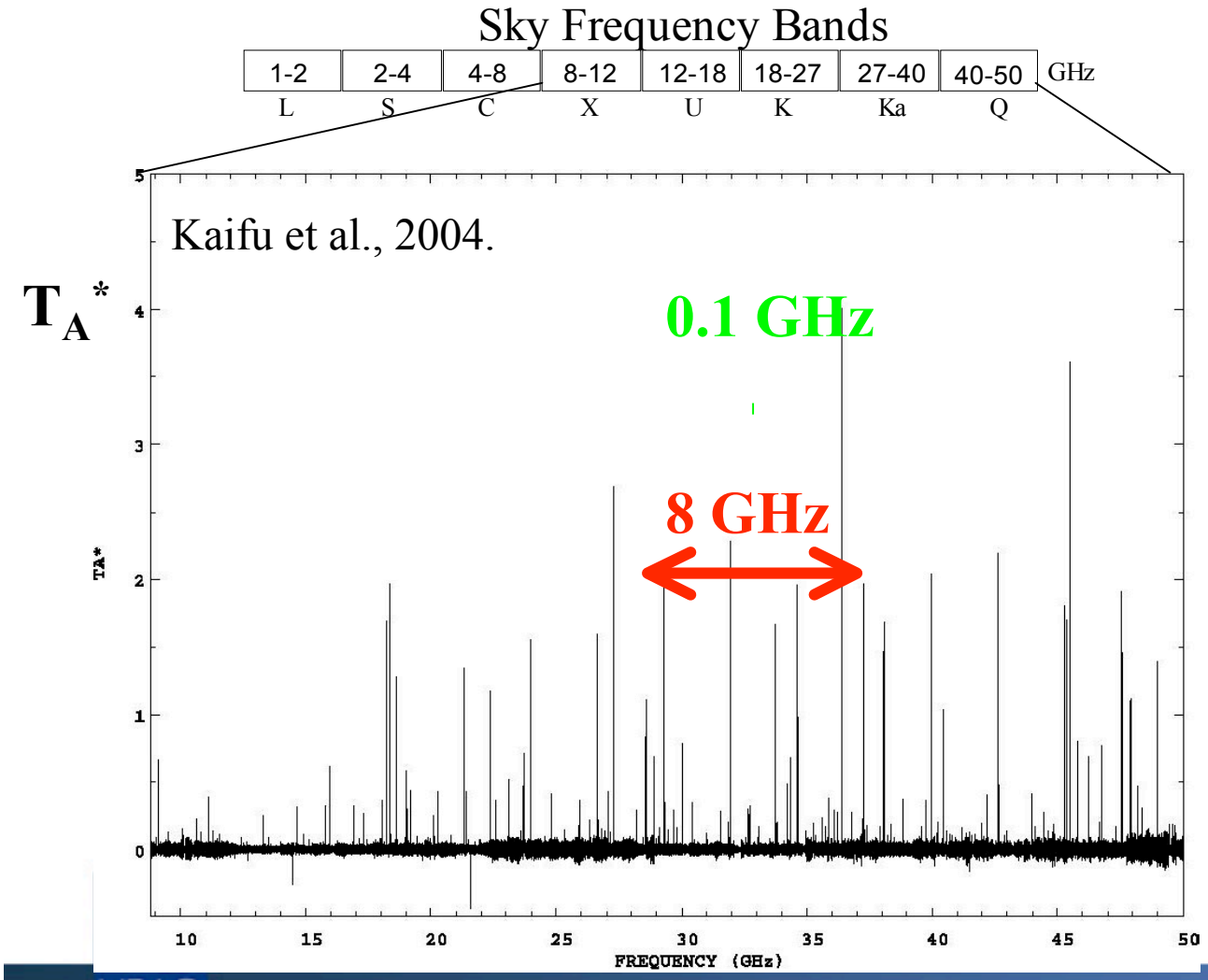
Wide Bandwidths



- **2:1 bandwidth ratios…with lots of channels**
  - ✓Sensitivity
  - ✓UV-coverage

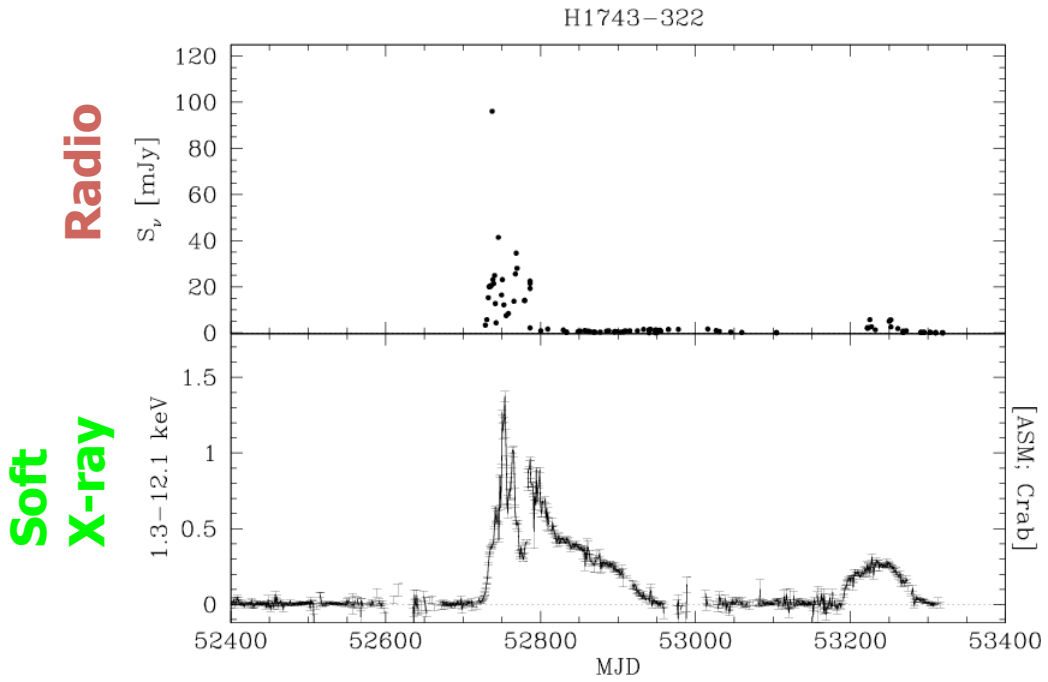
Rau, *Owen, Cornwell, Eilek*

Wide Bandwidths



- **2:1 bandwidth ratios…with lots of channels**
  - ✓Sensitivity
  - ✓UV-coverage
  - ✓Spectral index & curvature
  - ✓Polarization & rotation measures
  - ✓Spectral lines & redshifts

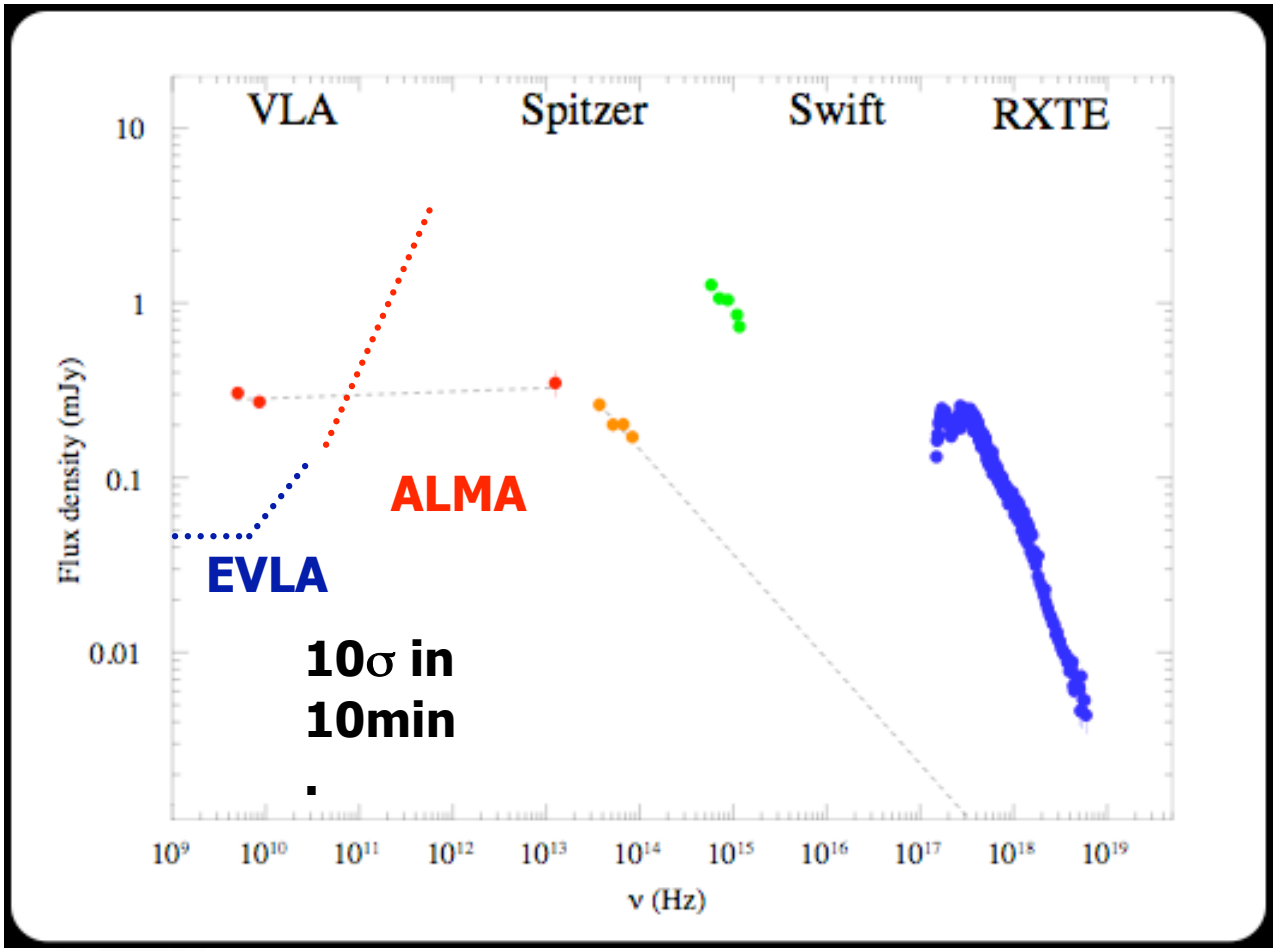
Wide Bandwidths



H1743-322 *(McClintock et al. 2007)*

- **2:1 bandwidth ratios…with lots of channels**
  - ✓Sensitivity
  - ✓UV-coverage
  - ✓Spectral index & curvature
  - ✓Polarization & rotation measures
  - ✓Spectral lines & redshifts
  - ✓**…all the time!**

Wide Bandwidths



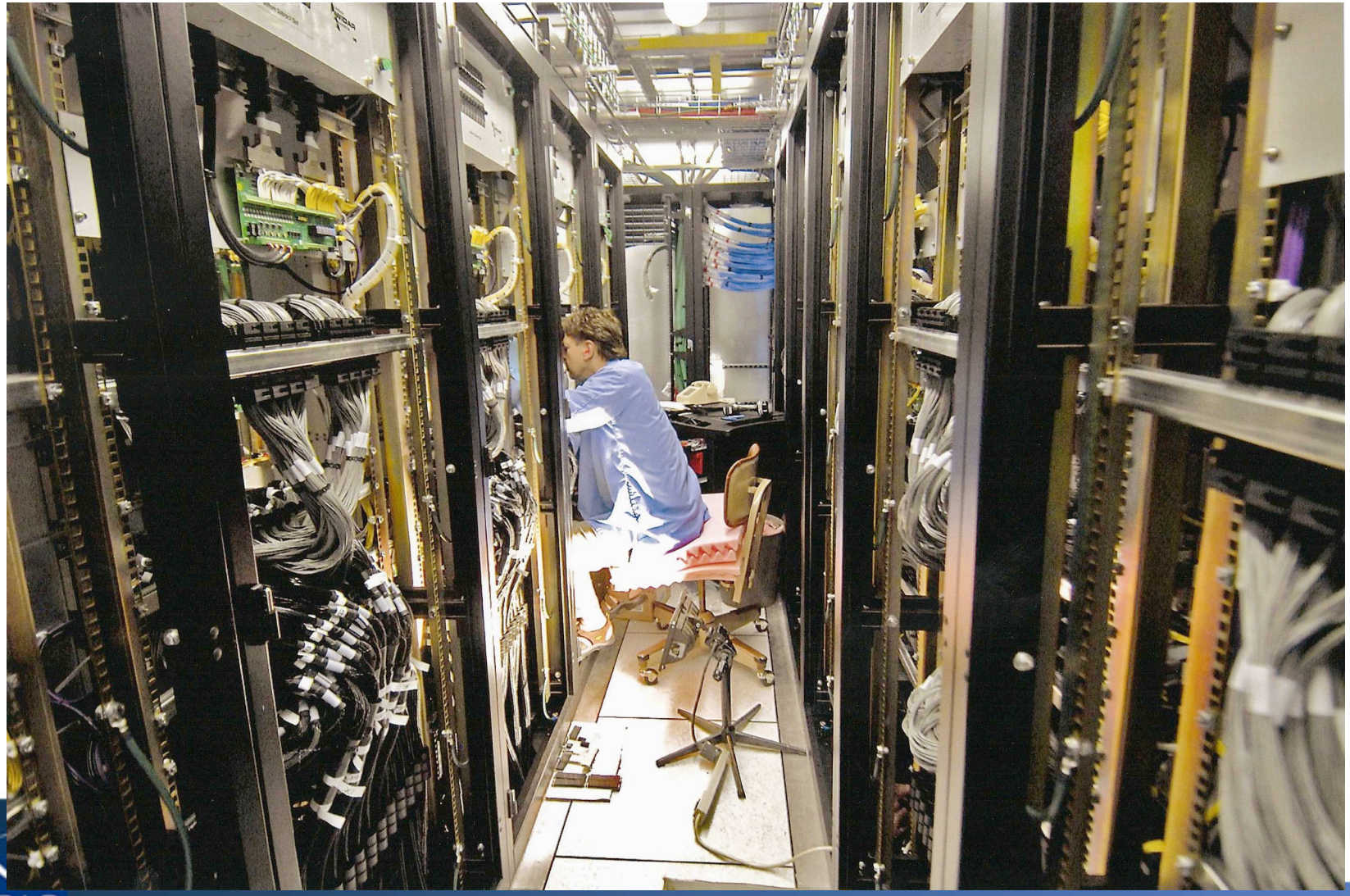
4U0614-091 (Migliari)

- **2:1 bandwidth ratios…with lots of channels**
- ✓Sensitivity
- ✓UV-coverage
- ✓Spectral index & curvature
- ✓Polarization & rotation measures
- ✓Spectral lines & redshifts
- ✓**…all the time!**

Project manager's summary

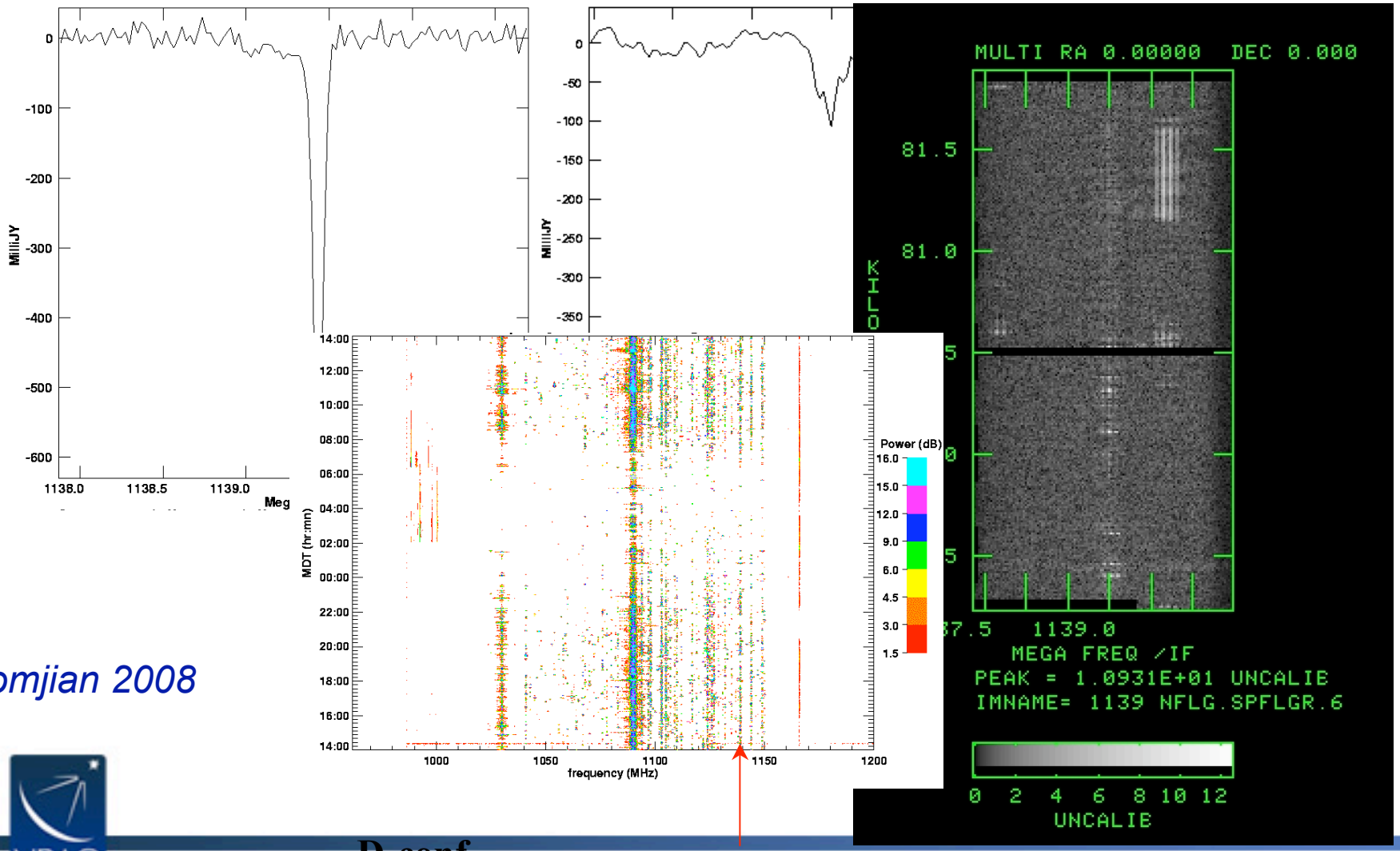
- Project is going well
- Financial health of the project is good
- Technical issues largely resolved
- Project is on schedule:
  - Antenna retrofits will be complete in Q3 CY2010
  - Receiver installation complete in Q4 CY2012
  - Correlator scheduled for completion in Q1 CY2010
  - Software development on track to support commissioning and early science

Correlator Rack Installation, Aug 2008



Correlator Room Infrastructure

RFI 1: PKS 1413+135 (z=0.25; 1139 MHz)

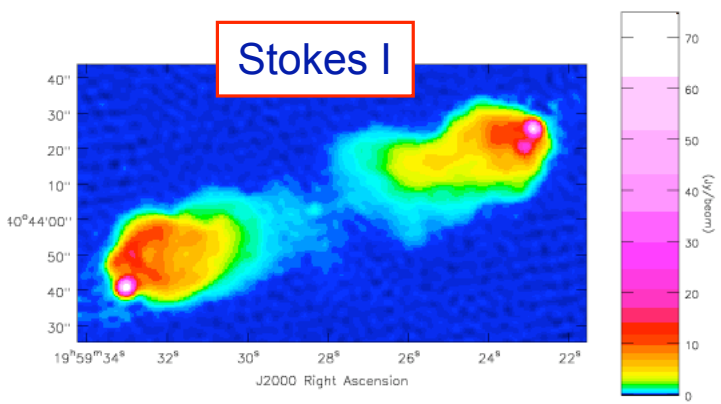


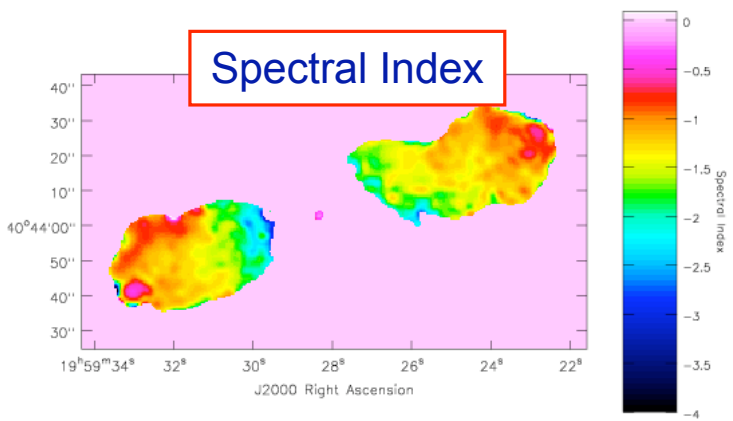
Momjian 2008

D-conf.

Baseline 16-17~ 60 m

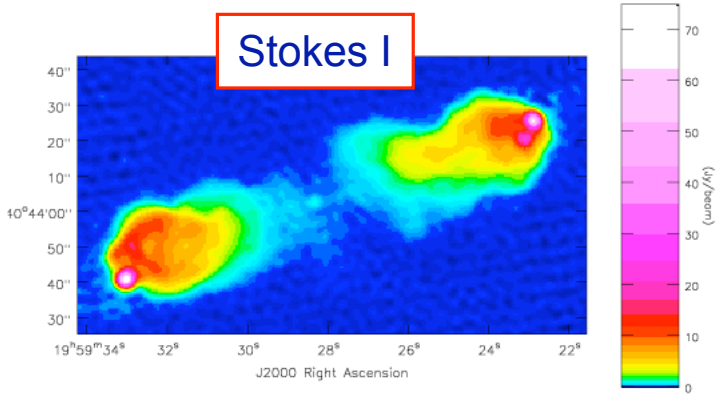
Cygnus A: MS-MFS

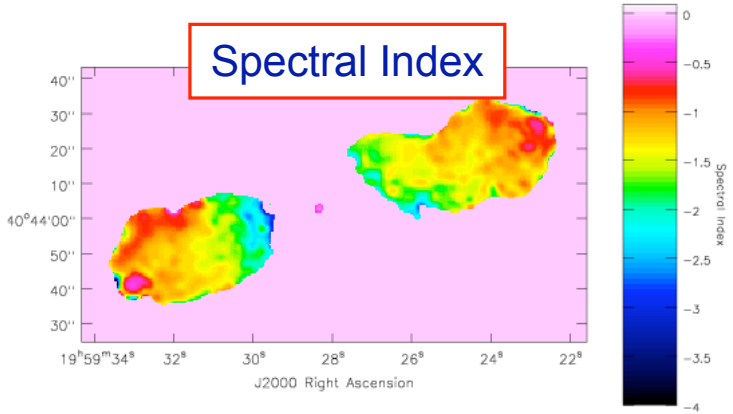




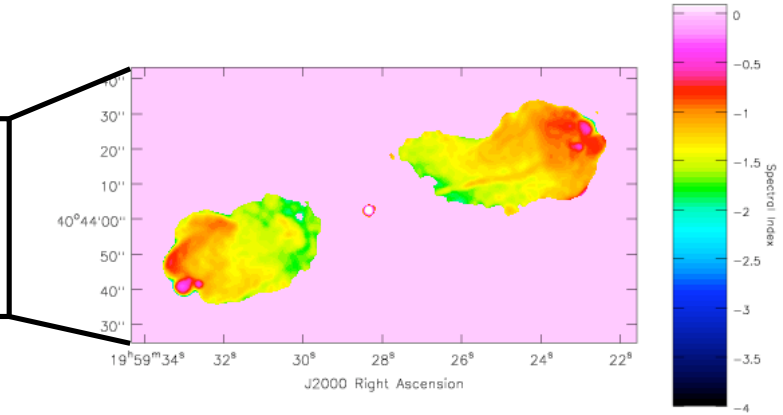
Rau, *Owen, Cornwell, Eilek*

Cygnus A: MS-MFS





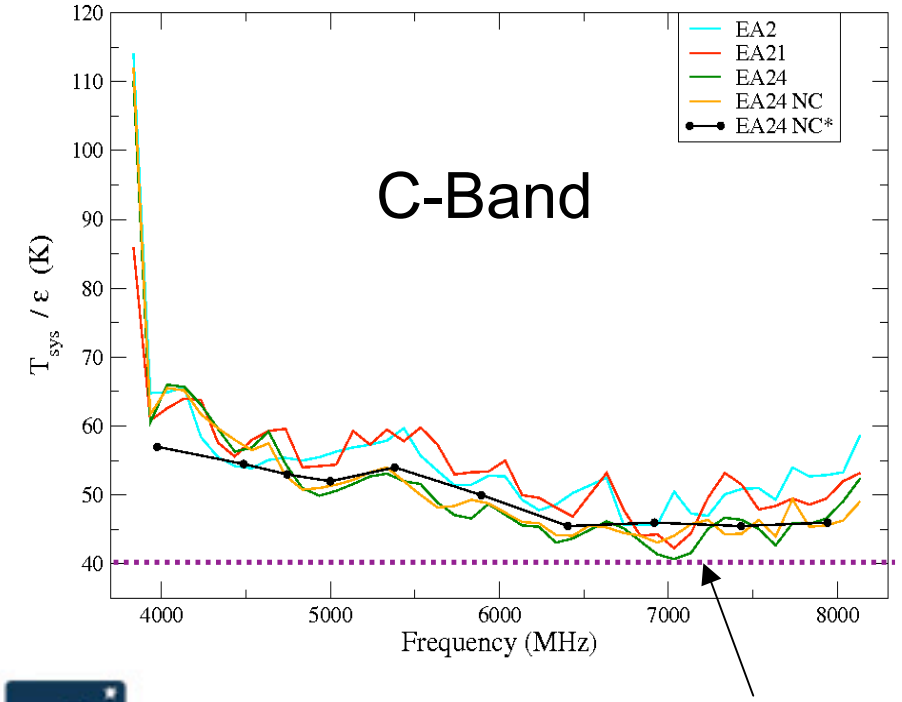
Carilli et al. 1991:
VLA A+B+C+D, 1.4+4.8 GHz
1 arcsec resolution)

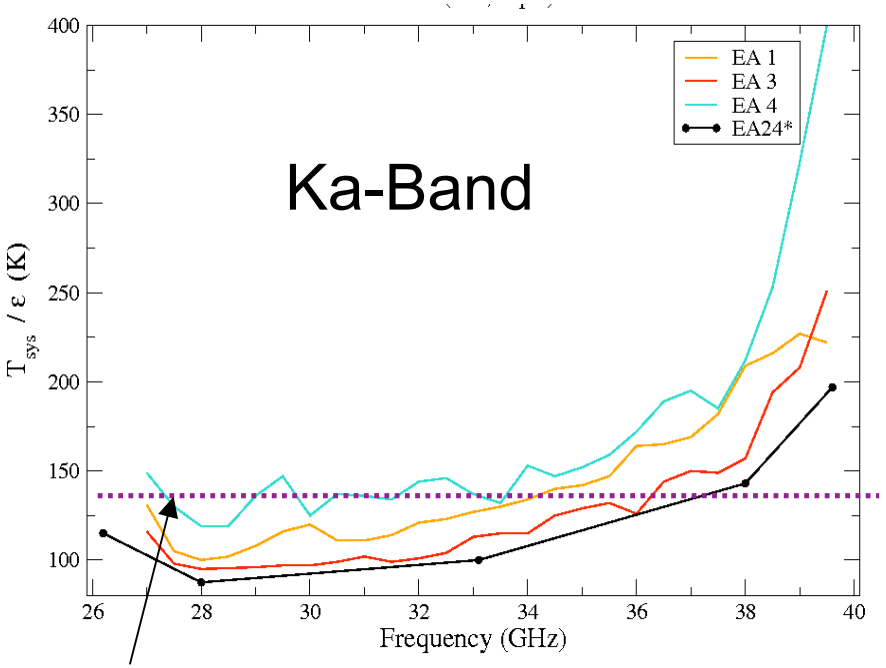


Rau, *Owen, Cornwell, Eilek*

C and Ka Band Sensitivity Detail

- Sensitivity as a function of frequency:
  - Colored lines are derived via correlation coefficients
  - Black line with dots are from direct antenna measurements.

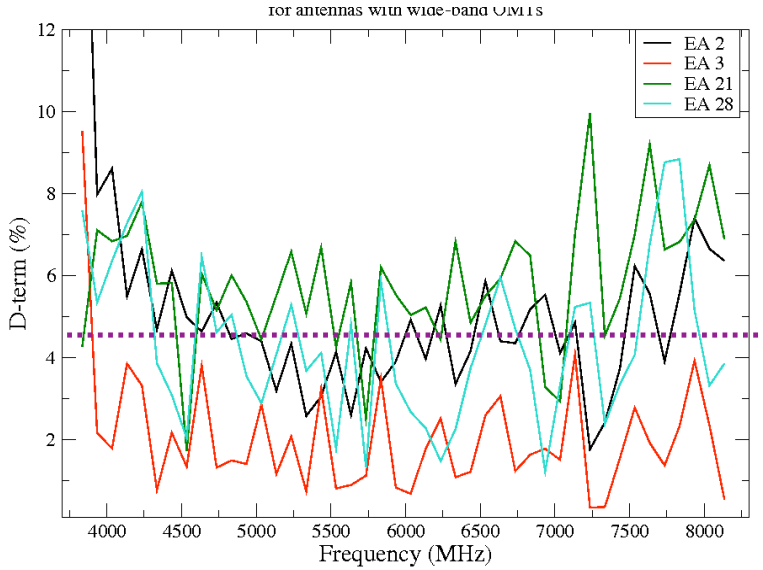


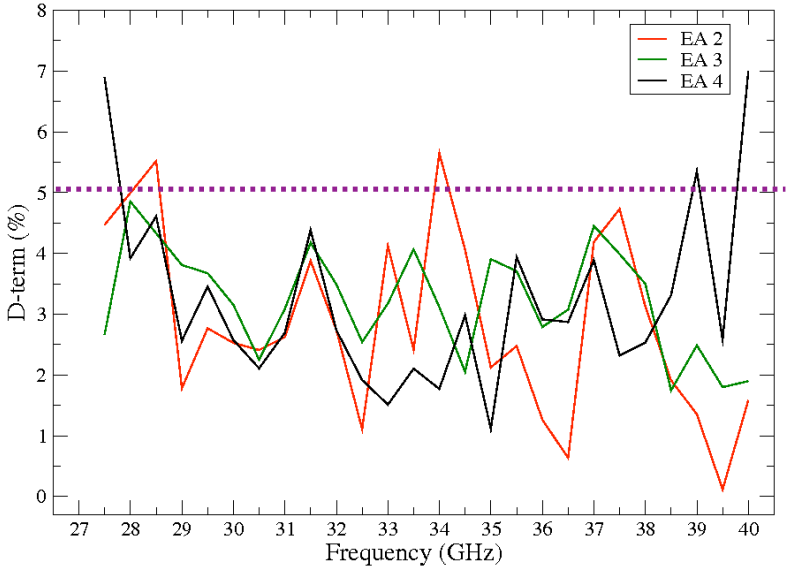


Project Requirement

C and Ka-Band Cross-Polarization

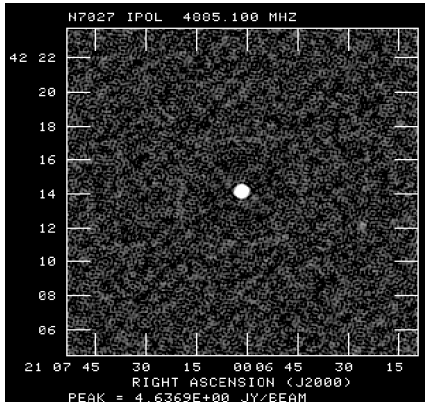
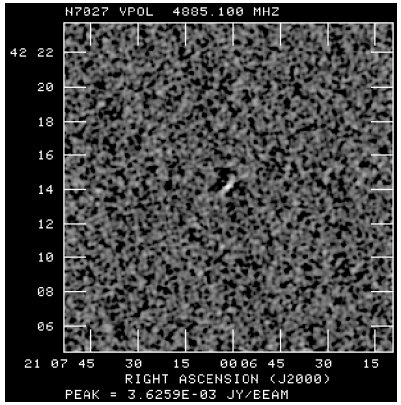
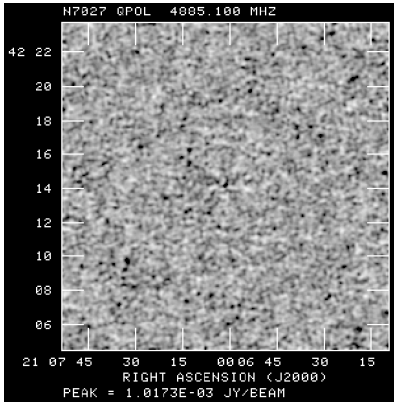
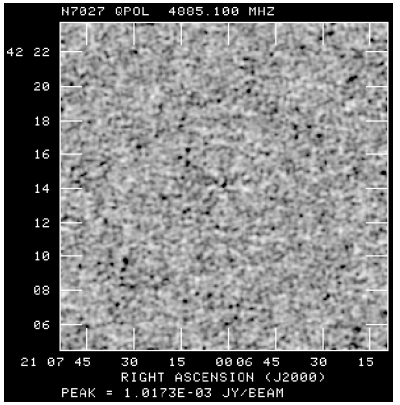
- Antenna ‘D-Term’ polarization with the new OMT design close to the specs at C-band.
- Ka-band polarization, with waveguide OMT meets specs, except at the band edges.





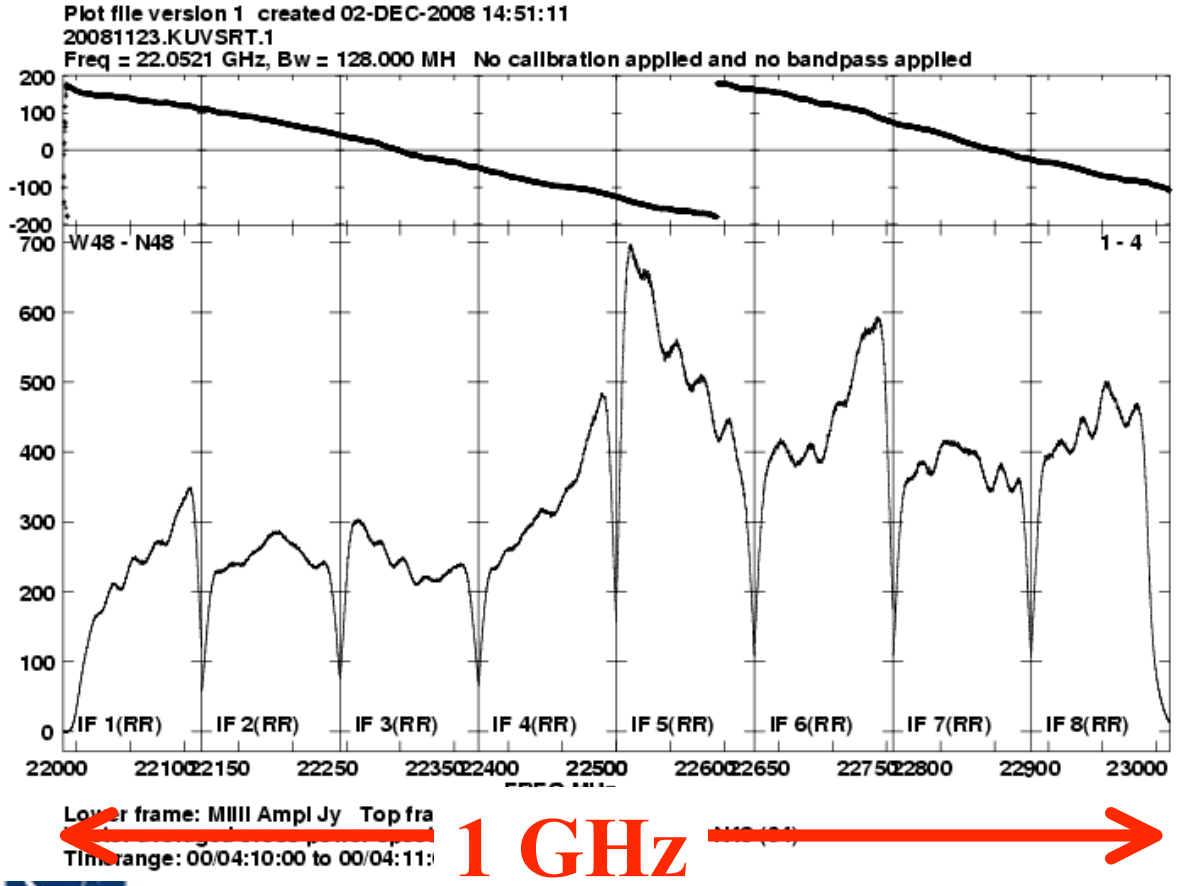
Pol'n stability: C-Band

- N7027 is a planetary nebula – no polarization is expected.
- D-Configuration. 4885 MHz. Data taken in pieces over 16 days.
- Phase self-calibration, flat amplitude calibration. Single polarization solution.

I	V	Q	U
			
Peak 4637 mJy	3.6 mJy	1.01 mJy	1.02 mJy
Pk/I	.07 %	.025%	.025%

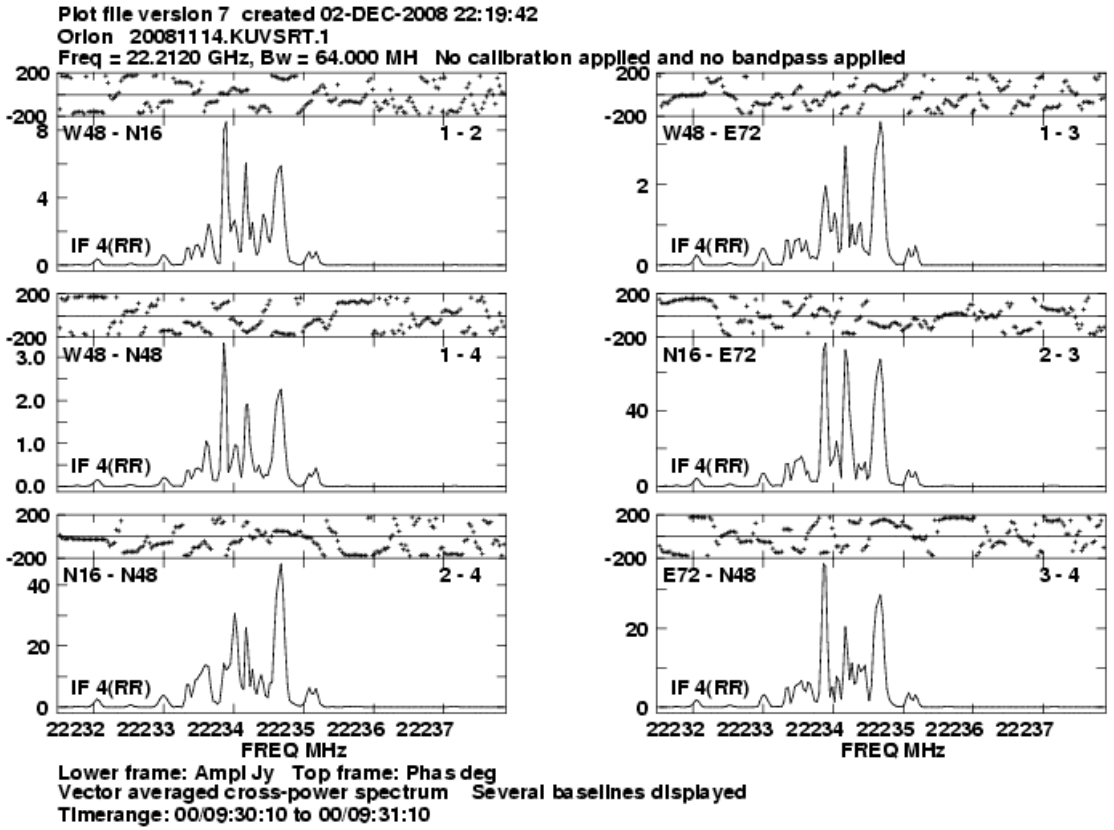
Polarization images are (nearly) noise-limited!

3C84 @ 22 GHz



- 21988-23012 MHz
- 8192 x 125 kHz (1.7 km/s)
- Full EVLA:
  - **8 GHz** (BWR 1.5:1)
  - **Full pol'n**
  - 8192 x 1 MHz (14 km/s)

Recirculation: Orion water masers



- 64 MHz, x2 recirc.
  - 31.25 kHz/channel
- 1.4% shown here