An Accurate, All-Sky, Absolute, Low Frequency Flux Density Scale

EVLA

Rick Perley, Bryan Butler (NRAO)
Joe Callingham (U. Sydney)

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

NRAO

Or,

One Flux Scale to Rule Them All!

(A proposed flux scale from 50 MHz to 50 GHz)

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Flux Density Scales in Radio Astronomy

1. **Baars et al. (1977)**
   - Basis of most quoted results.
   - Four absolute sources (Cas A, Cyg A, Tau A, Vir A), and 13 compact sources, referenced to Virgo.

   Valid between 400 MHz and 15 GHz for most compact sources.
2. **Scaife & Heald (2012)**
   - A rationalization of various low frequency scales for six sources.
   - Valid from 30 to 300 MHz.
3. **Perley and Butler (2012)**
   - Based on absolute WMAP observations of Mars, and 30 years' VLA observations of calibrator observations.
   - Valid from 1 to 50 GHz.

Needed: High accuracy low frequency flux density measurements, based on an established absolute standard.

The Flux Density Scale below 1 GHz

- An extensive literature, much of it in conflict at the ~10 -- 20% level.
- S&H published a rationalized scale – very useful – but based on a heterogenious set of data.
- Better would be to measure ratios between standard calibrators and Cygnus A – the only source with a reliable absolute spectrum.
- Problem: Cygnus A is >100X stronger than calibrators. And it multiplies total system power by factor of ~ 5. Furthermore – it is located near the galactic plane – much confusing nearby brightness.
- Needed: A highly linear low-frequency interferometer system – the old VLA was not!
- The upgraded VLA – and the new 'Low-Band' receivers – are designed for high linearity.

Southern Woes

- Most of the old work done in establishing the flux density scales done on northern sources.
- All the best-known (and trusted) sources: 3C295, 3C286, 3C48, 3C123, 3C147 etc. are all at fairly high northern declinations – none of these are useful for southern hemisphere observations.
- Surprisingly little known about southern declination flux density standards.
- A program was designed to use the VLA to:
  1. Determine flux densities of known (large) southern sources based on Cygnus A (including Herc A, Hydra A, Pictor A, etc .)
  2. Find new, compact southern sources suitable for accurate calibration purposes.

Observations -- I

- 30 Hour 'Flux Models/Densities' Run Oct 6/7 2014, with VLA in the 'C' configuration. Resolution at 327 MHz ~ 1 arcminute.
- This run added to a similar run taken in 'A' configuration in 2013.
- Goals:
  - To obtain accurate models for the standard VLA flux density calibrators at all frequencies from 50 MHz to 50 GHz.
  - To extend the Perley&Butler scale to southern sources at low frequencies.
- We added extensive observations of: 3C218 (Hydra A), 3C348(Hercules A), 3C353, 3C444, Pictor A, Fornax A, J0444-2809, J0133-3629, at P-band, L-band (1 – 2 GHz) , and (for selected sources) S-band (2 – 4 GHz).
- Also included Cas A, Taurus A, Virgo A.
- Flux densities for these based directly on Cygnus A.

IAU	3C	`A-List'	4	P	L	S	C	X	U,K,A,Q
J0133-3629									
J0137+3309	3C48								
J0322-3712		Fornax A							
J0437+2940	3C123								
J0444-2809									
J0521+1638	3C138								
J0519-4546		Pictor A							
J0543+2200	3C144	Taurus A							
J0542+4951	3C147								
J0813+4813	3C196								
J0918-1205	3C218	Hydra A							
J1230+1223	3C274	Virgo A							
J1331+3030	3C286								
J1411+5212	3C295								
J1651+0459	3C348	Hercules A							
J1720-0058	3C353								
J1829+4844	3C380								
J1959+4044	3C405	Cygnus A							
J2214-1701	3c444								
J2323+5848	3C461	Casseopeia A							

Observations -- II

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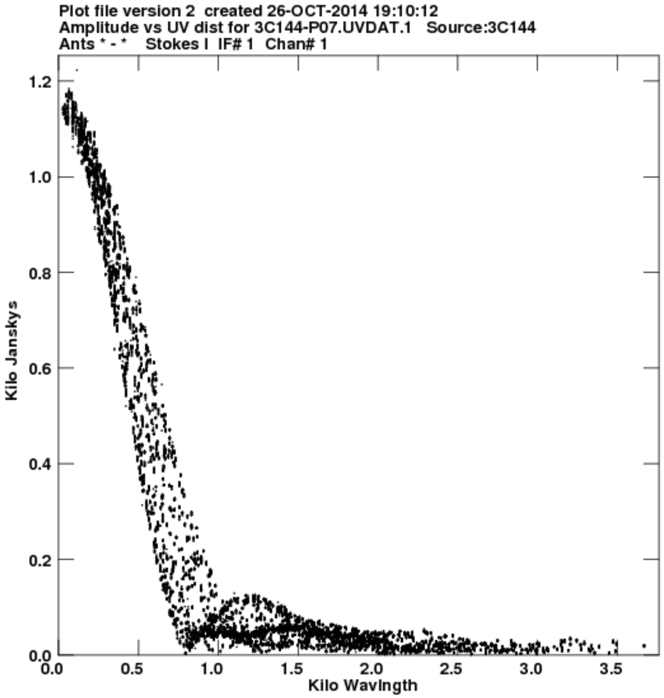
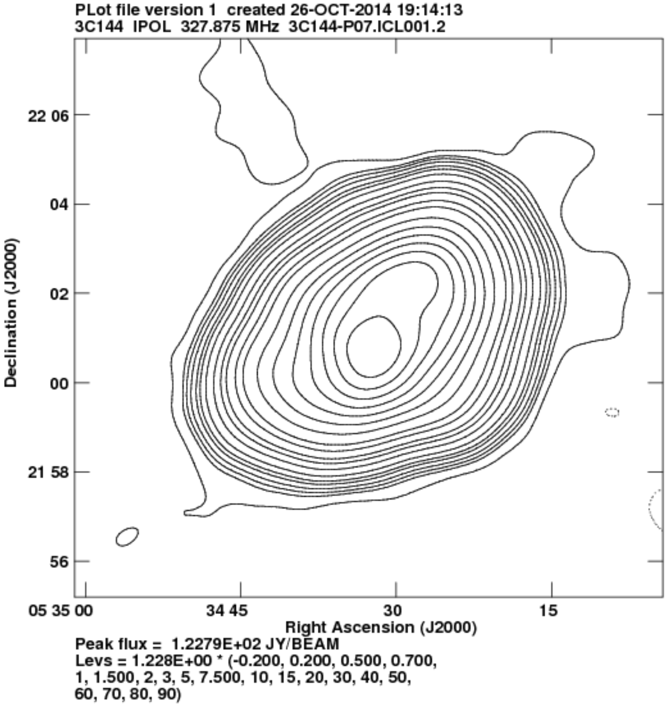
- Eight hours of VLA observations at P-band in CnB and B configurations of 47 proposed southern calibrator sources made over the summer.
- All the proposed sources are in the 00 – 08 LST range.
- Criteria for selection:
  - Unresolved in SUMSS or NVSS (or FIRST, if available).
  - > 1 Jy at 150 MHz. (MWA)
- Calibration based on the flux density of 3C48 – linked to Cygnus A as related below.

VLA Low Frequency Data Quality

- The VLA's new LowBand System provides outstanding quality data.
- Shown is the basic visibility plot for 3C144 – no self-calibration! Six unstable antennas have been removed.
- Gain variations are at the ~5% level, over 30 hours.





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Results (1) – New Fluxes comparisons

- The table below shows our new determination, along with the S&H and Baars et al. values, for one of the spectral windows, at 328 MHz.

	3C48	3C123	3C147	3C196	3C286	3C295	3C380
New	44.2	145.9	54.2	46.6	26.7	60.8	41.9
S&H	43.5		52.7	46.7	24.1	58.3	42.4
Ratio	**1.02**		**1.03**	**1.00**	**1.11**	**1.04**	**0.99**
Baars	44.7	135.2	53.2		26.9	60.3	
Ratio	**0.99**	**1.08**	**1.02**		**0.99**	**1.01**	

- Results show agreement to 4% or better, except for 3C286 (S&H is low) and 3C123 (Baars is low).

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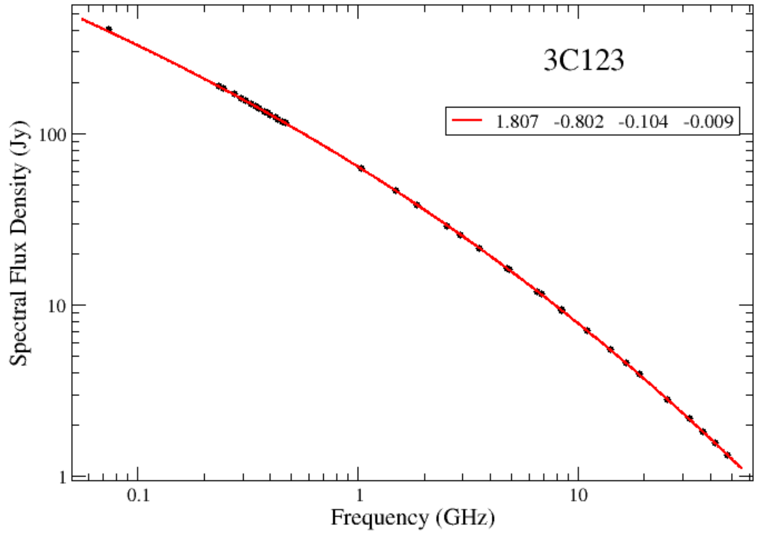
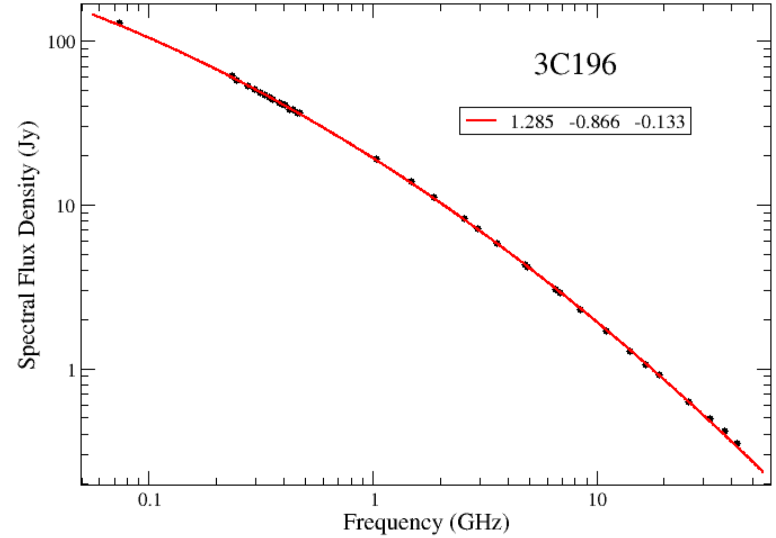
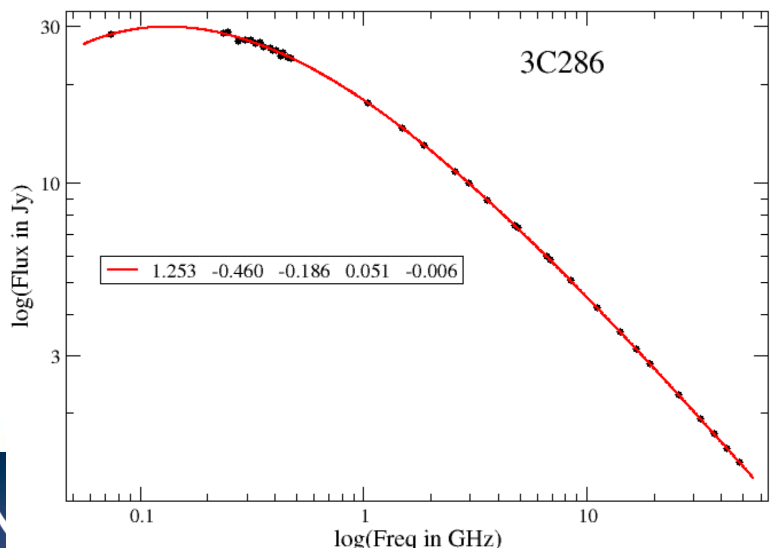
Fitting the Spectra

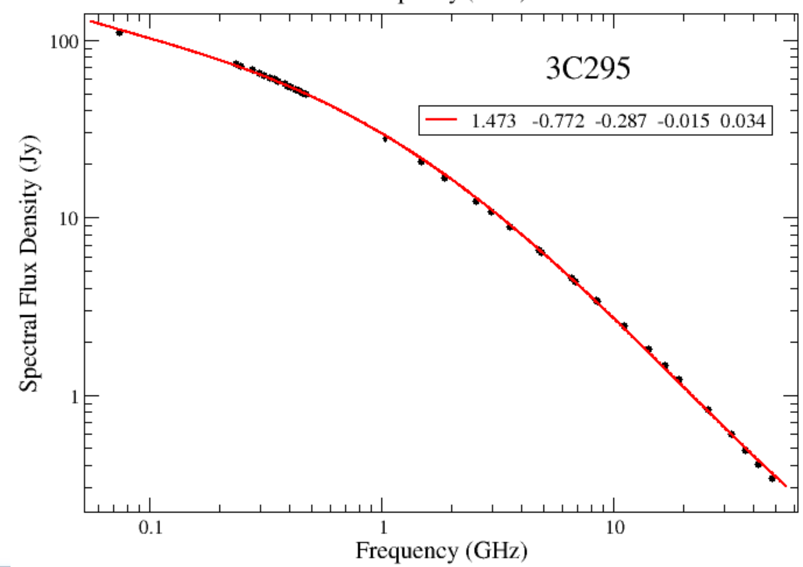
- Four of these sources are known (from P&B 2012A) to be non-variable over > two decades of time: 3C123, 3C196, 3C286, 3C295.
- For these, we have fit 4th-order polynomial fits, incorporating:
  - The October 2014 data at L through Q bands, based on P&B 2012
  - These new Cyg-A based values from 224 to 464 MHz
  - Data from the VLA's 'legacy' 73 MHz system (also based on Cygnus A).
- These give very acceptable fits over the full range of 50 MHz – 50 GHz.

The Four Steady Calibrators









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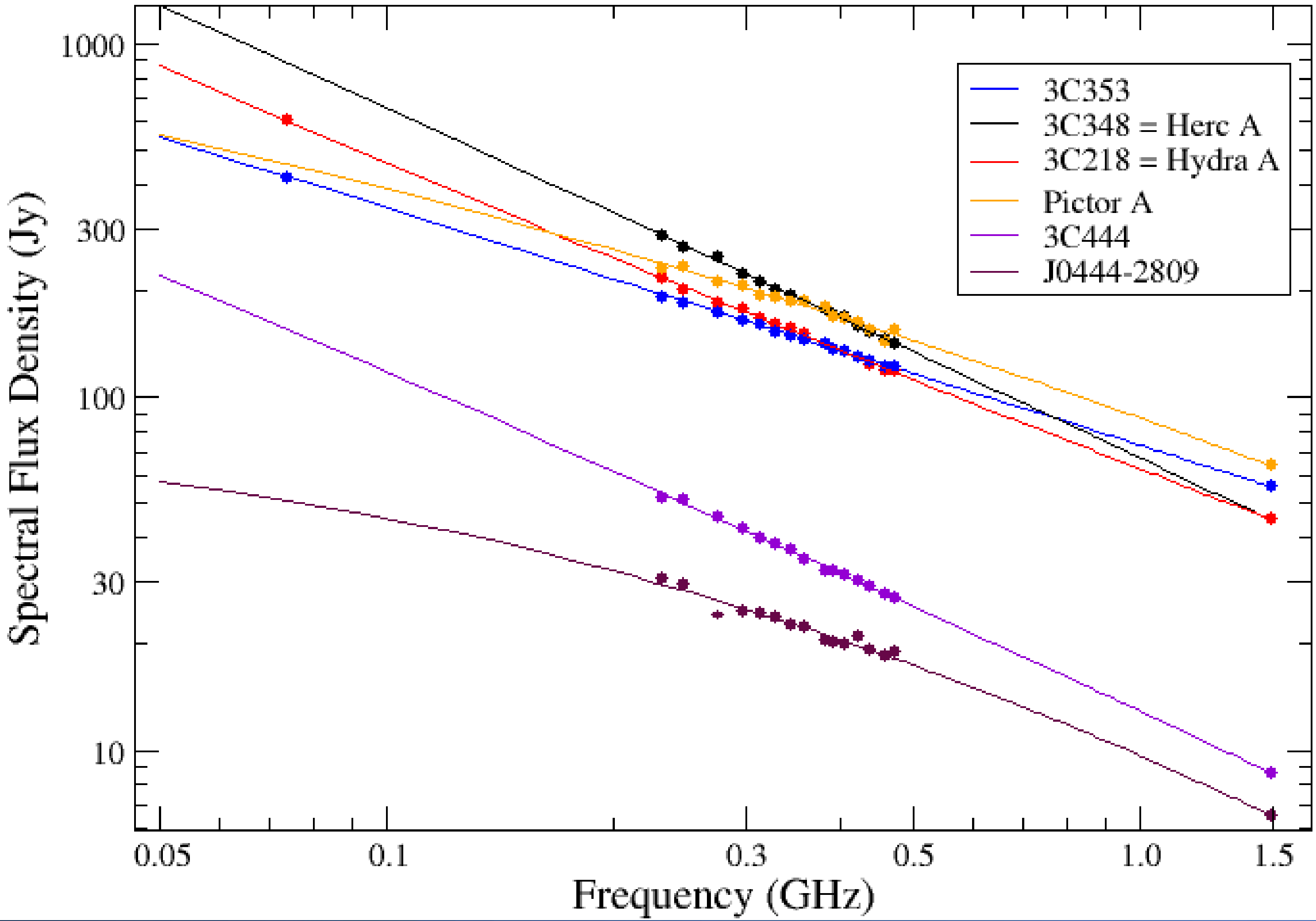
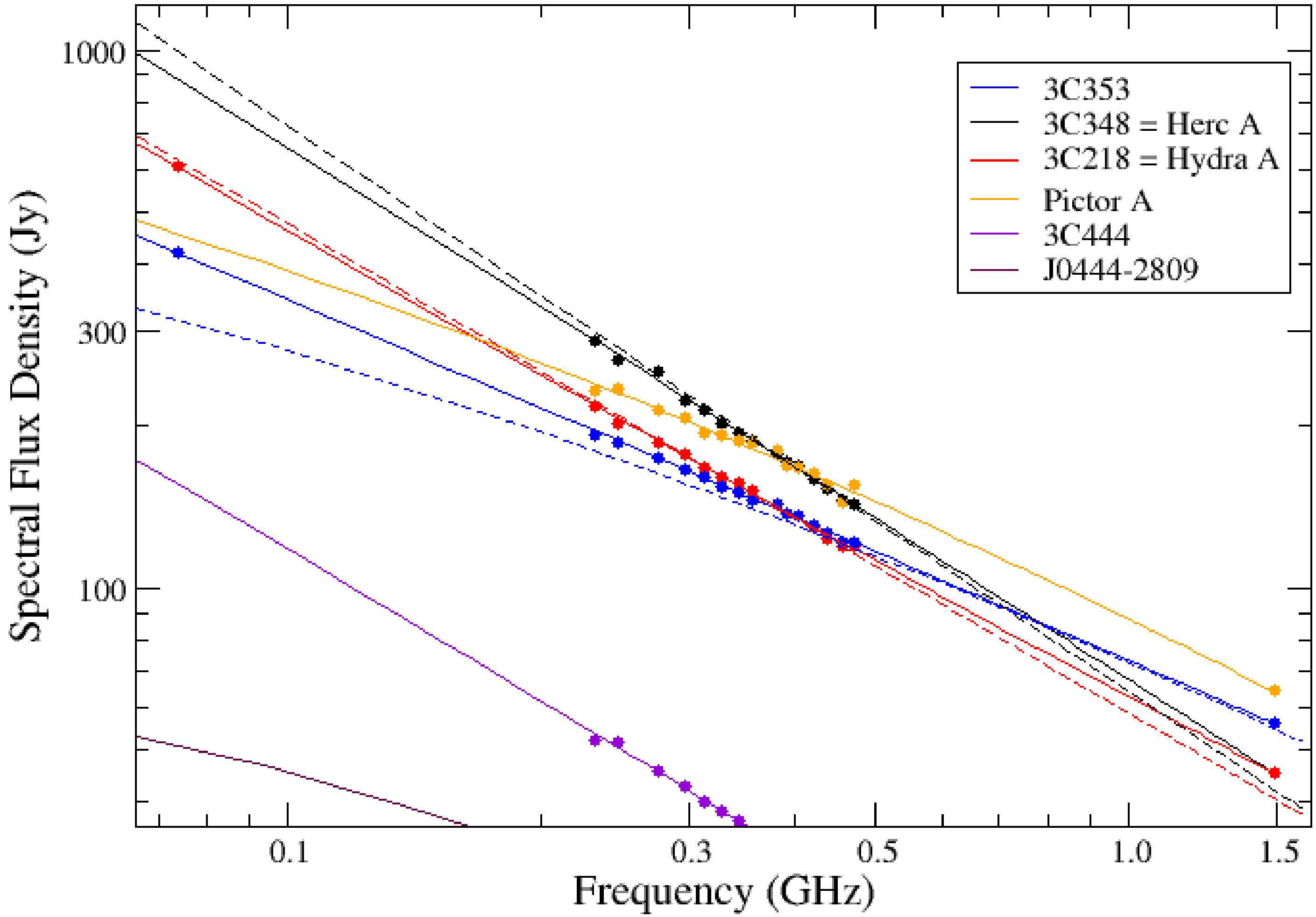
What about the Southern Sources?



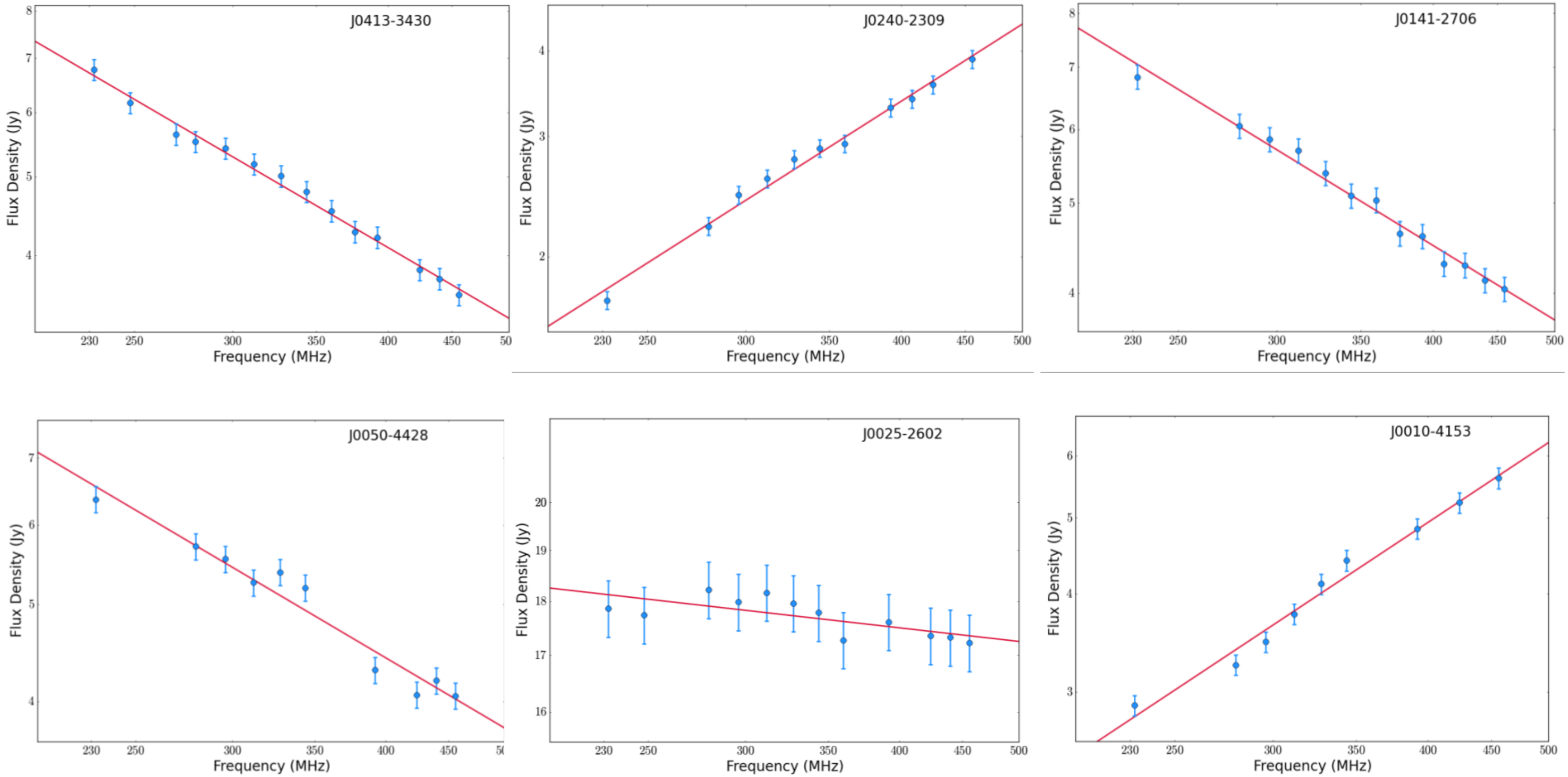
Good News – Close to Baars et al.



The Search for New Southern Calibrators

- 47 compact objects observed with the VLA, in LST range 0h to 08h.
- Typically two short snapshots were taken.
- Of these, 20 were resolved on the VLA's B-configuration resolution (~15 arcseconds).
- The remaining 27 look promising as calibrators.
- Six example spectra shown below

Six Example Spectra (220 – 480 MHz)



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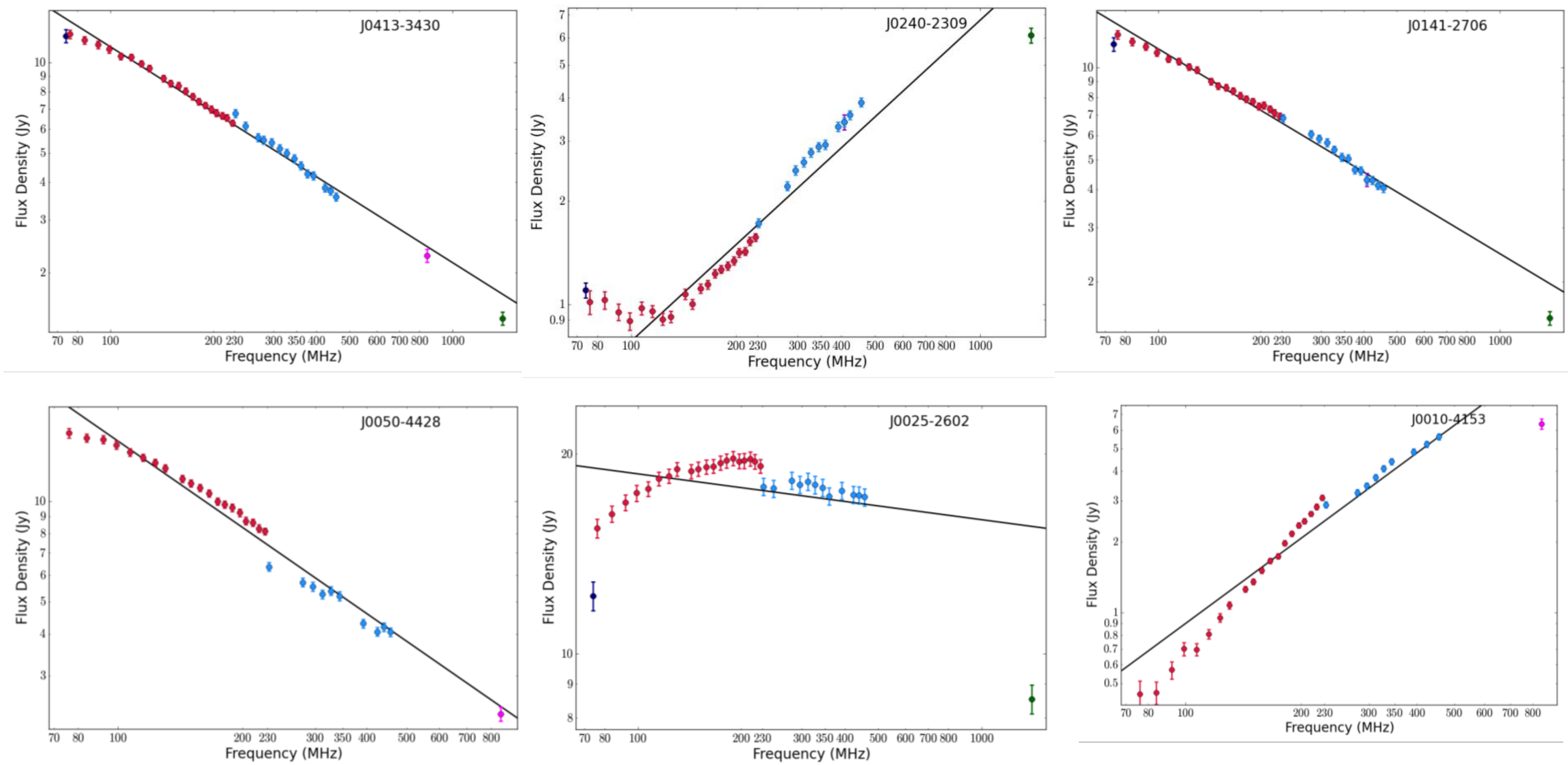
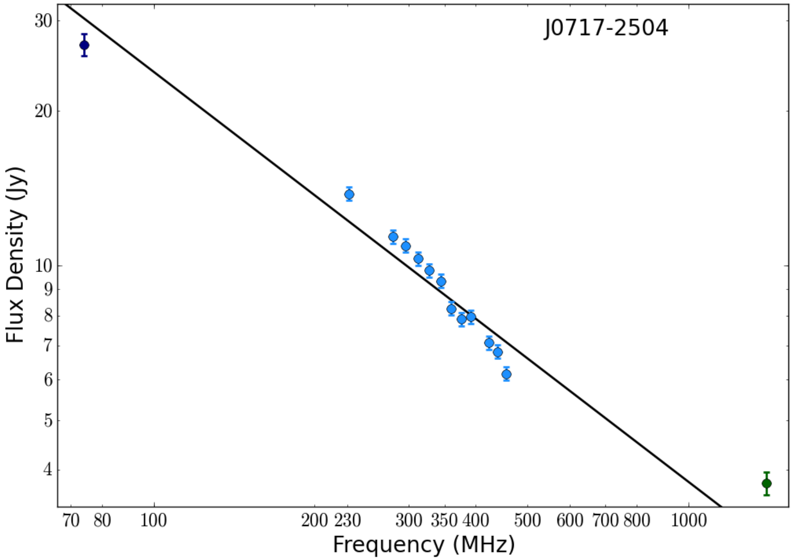
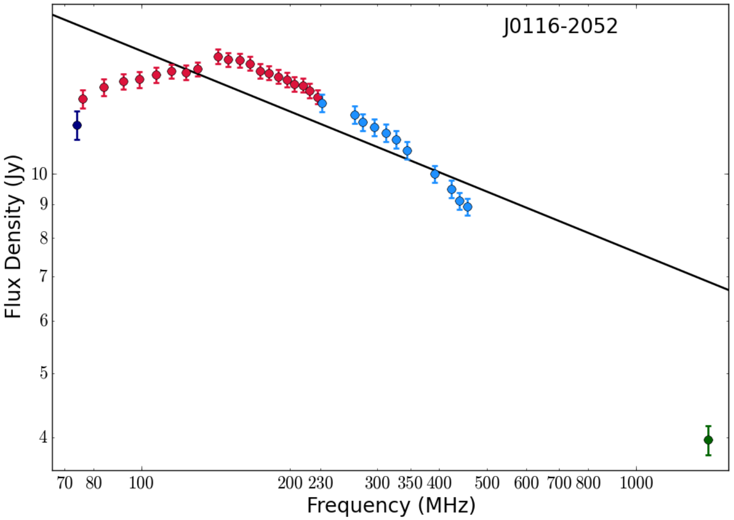
Incorporating MWA, NVSS, SUMSS, VLSSR values



Two More …



J0717-2504
Flux Density (Jy)
30
20
10
9
8
7
6
5
4
70
80
100
200
230
300
350
400
500
600
700
800
1000
Frequency (MHz)



J0116-2052
Flux Density (Jy)
10
9
8
7
6
5
4
70
80
100
200
230
300
350
400
500
600
700
800
1000
Frequency (MHz)

What Next?

- Results are very encouraging.
- VLA's low frequency system appears to be very stable, repeatable, and linear. Ideally suited for calibration and imaging.
- No estimate of measurement errors yet – but will be small, probably <5%.
- Observations by other low-frequency instruments would also be very useful – A LOFAR proposal has been accepted, and the data taken.
- Low frequency (< 100 MHz) remains uncertain – based on a single 'legacy' VLA value for some of these sources.
- It is likely we'll repeat the 'Calibration' run, at the end of the current 'D' configuration. This will recover the flux for most of the larger objects, up to ~C band. The `4-Band' system (10 antennas) will be included.
- More searches for sources compact objects are contemplated.

Preliminary Coefficients:

Source	A0	A1	A2
3C348 = Herc A	1.829	-1.001	-0.0124
3C218 = Hydra A	1.798	-0.827	0.038
3C353	1.865	-0.673	-0.0027
Pictor A	1.942	-0.759	-0.1118
3C444	1.112	-0.994	-0.035
J0444-3809	0.974	-0.892	-0.

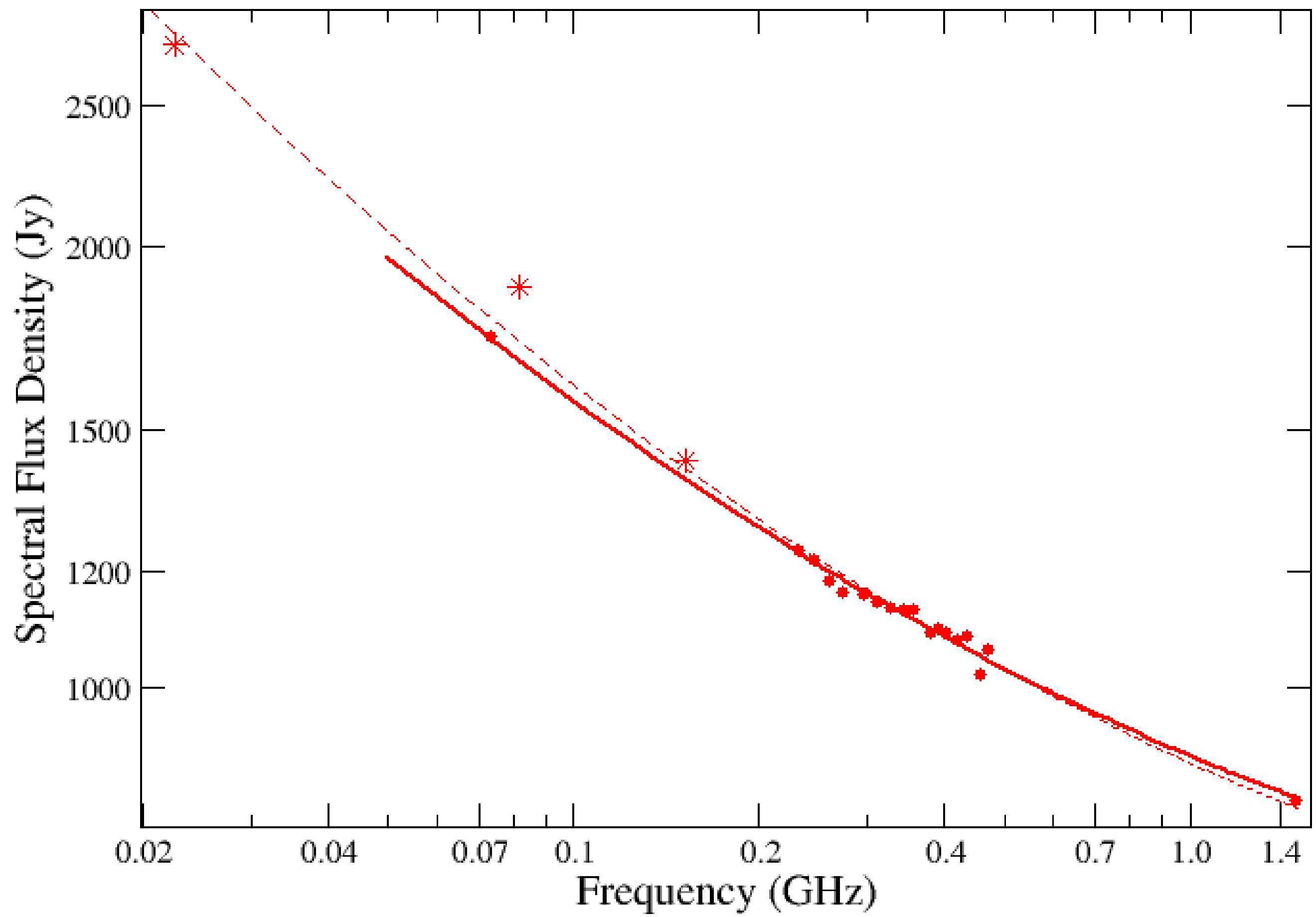
$$\mathrm{Log}(S) = A0 + A1\ \log(\nu_G) + A2\ (\log(\nu_M))^2$$

- Fornax A and J0133-3629 are too large for the C configuration.

Taurus A = 3C144 = Crab Nebula

$$\mathrm{Log}(S) = 2.948 - 0.190\ \log(\nu_G) + .0683\ (\log(\nu_M))^2$$

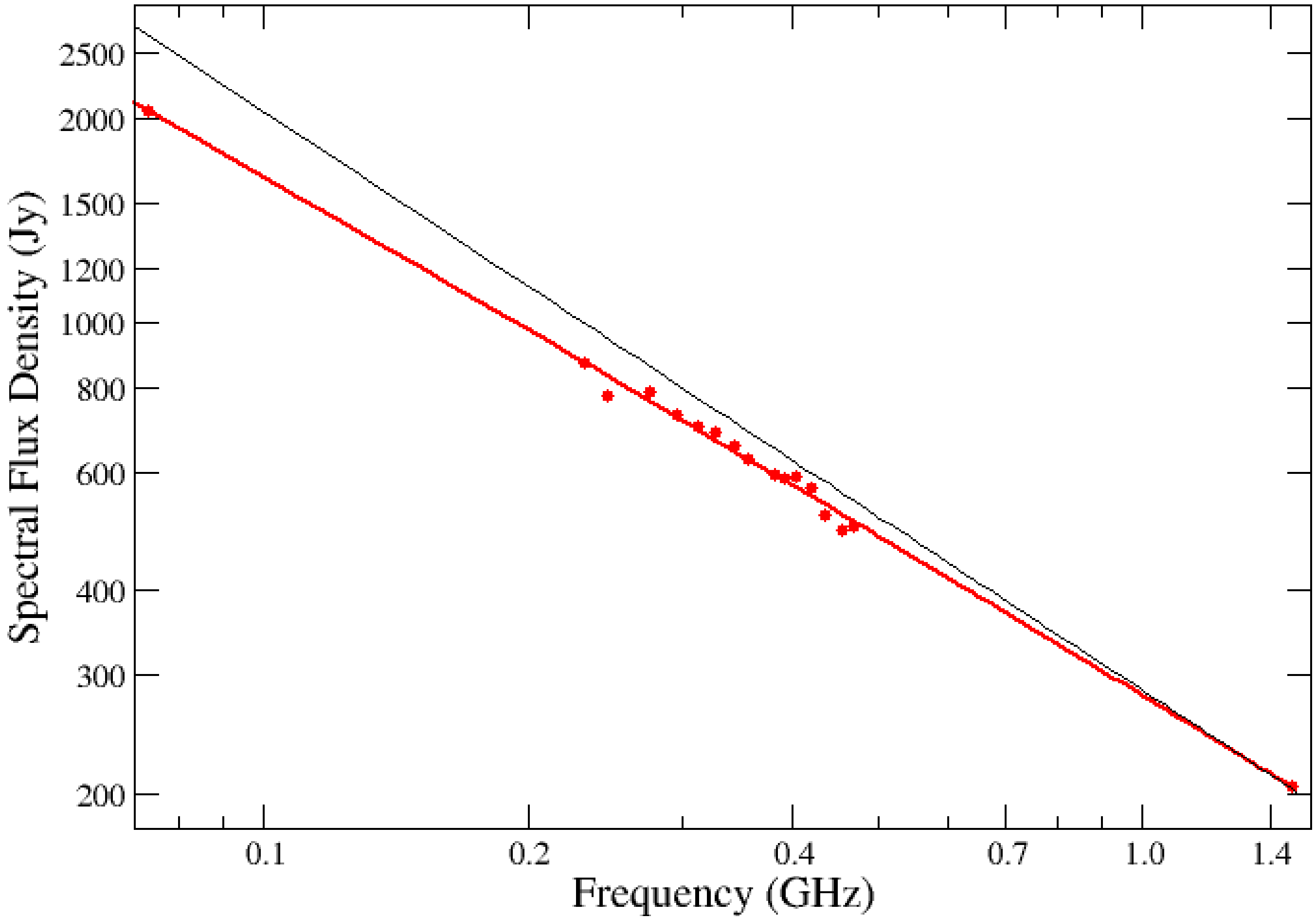
- Starred values are from Baars et al.
- Solid line is a fit using VLA data only.
- Dashed line uses all data.



Virgo A = 3C274

- Baars et al values increasingly discrepant below 1 GHz.

$$Log(S) = 2.447 - 0.791\ log(\nu_G) - .024\ (log(\nu_M))^2$$



Cassiopeia A

$$\mathrm{Log}(S) = 3.371 - 0.708\,\log(\nu_G) + .071\,(\log(\nu_M))^2$$

- Discrepancy here is entirely due to secular decrease of Cas A.
- Decrease seen here is about -0.3%/year at 1480 MHz.
- Decrease ~ -0.5%/yr at lower frequencies.
- This is a little less than the Baars value (-.6 to -.9 %/year)