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

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Or,

One Flux Scale to Rule Them All!

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

Atacama Large Millimeter/submillimeter Array
Expanded Very Large Array
Robert C. Byrd Green Bank Telescope
Very Long Baseline Array
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 heterogenous 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 -- 1

- 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.
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<tr>
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<th>4</th>
<th>P</th>
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Observations -- II

• 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.
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.
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.

<table>
<thead>
<tr>
<th></th>
<th>New</th>
<th>S&amp;H</th>
<th>Ratio</th>
<th>Baars</th>
<th>Ratio</th>
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<td>3C48</td>
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<td>43.5</td>
<td>1.02</td>
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<td>3C123</td>
<td>145.9</td>
<td>52.7</td>
<td>1.03</td>
<td>135.2</td>
<td>1.08</td>
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<td>58.3</td>
<td>1.04</td>
<td>60.3</td>
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<td>42.4</td>
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<td>41.9</td>
<td>42.4</td>
<td>0.99</td>
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</tbody>
</table>

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

3C123

3C196

3C286

3C295
What about the Southern Sources?
Good News – Close to Baars et al.

![Graph showing spectral flux density vs frequency.](image)
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)
Incorporating MWA, NVSS, SUMSS, VLSSR values
Two More …
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:

<table>
<thead>
<tr>
<th>Source</th>
<th>A0</th>
<th>A1</th>
<th>A2</th>
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<tr>
<td>3C348 = Herc A</td>
<td>1.829</td>
<td>-1.001</td>
<td>-0.0124</td>
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<tr>
<td>3C218 = Hydra A</td>
<td>1.798</td>
<td>-0.827</td>
<td>0.038</td>
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<td>3C353</td>
<td>1.865</td>
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<td>Pictor A</td>
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<td>-0.759</td>
<td>-0.1118</td>
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<td>3C444</td>
<td>1.112</td>
<td>-0.994</td>
<td>-0.035</td>
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<td>J0444-3809</td>
<td>0.974</td>
<td>-0.892</td>
<td>-0.0</td>
</tr>
</tbody>
</table>

\[
\log(S) = A0 + A1 \log(v_G) + A2 (\log(v_M))^2
\]

- Fornax A and J0133-3629 are too large for the C configuration.
Taurus A = 3C144 = Crab Nebula

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

\[
\log(S) = 2.948 - 0.190 \log(v_G) + 0.0683 (\log(v_M))^2
\]
Virgo A = 3C274

- Baars et al values increasingly discrepant below 1 GHz.
Cassiopeia A

\[ \log(S) = 3.371 - 0.708 \log(\nu_G) + 0.071 (\log(\nu_M))^2 \]

- Discrepancy here is entirely due to secular decrease of Cas A.
- Decrease seen here is about -0.3%/year at 1480 MHz.
- Decrease \(~\sim\) -0.5%/yr at lower frequencies.
- This is a little less than the Baars value (-0.6 to -0.9 %/year)