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Setting the radio astronomy flux density scale

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The paper by Baars et al. on "*The Absolute Spectrum of Cas A; An Accurate Flux Density Scale and a Set of Secondary Calibrators*" has been used either directly or indirectly by essentially every publication in radio astronomy for the past 30 years to calibrate the flux density scale of new radio observations made at wavelengths longer than about 1 cm.

One of the most important properties needed to understand the physics of discrete radio sources is the measurement of how their flux density varies with frequency and time. The earliest measurements by Karl Jansky and Grote Reber (1940) already showed that the Galactic radio emission decreased with increasing wavelength, contrary to the Raleigh Jeans spectrum expected from ordinary thermal radiation. Later observations showed the strongest discrete radio sources and the same non-thermal radio spectrum (Stanley & Slee 1950; Whitfield 1957). However, due to uncertainties in determining the gain of radio telescopes, these early measurements of radio source spectra were limited by the uncertainties in placing the flux density measurements made at different frequencies on the same absolute scale.

Accurate antenna gains are difficult to measure and can be calculated only for relatively simple antenna systems such as dipoles and horns. However, these more easily understood antenna systems have limited sensitivity and can be used to observe only the very strongest discrete radio sources. For many years considerable effort was devoted to obtaining an absolute calibration of radio telescopes using a variety of techniques to measure the spectrum of the strongest discrete sources in the sky. Nevertheless there were large discrepancies among different observers, which limited the interpretation of the spectral properties of discrete sources.

Heeschen (1961) circumvented the absolute calibration problem by measuring the strength of 13 moderately strong sources by referring observations made at four different frequencies to the strongest source in the sky, Cas A. Later, using data obtained from 5 different instruments at Cambridge, Jodrell Bank, and Caltech, Conway et al. (1963) (CKL) determined the relative flux densities of 160 galactic and extragalactic radio sources at nine frequencies between 38 and 3200 MHZ and placed them on an absolute basis by reference to Cas A. CKL established the first uniform flux-density scale and found that most sources have a well-defined power-law spectrum with a spectral index near –0.8. However, a few sources, such as CTA 21 and CTA 102 (Kellermann et al. 1962), were found to have a steeper index at high frequencies, while other sources, later referred to as gigahertz peaked spectrum sources, showed spectral peaks near 1 GHz. About the same time, Bolton et al. (1964), Price & Milne (1965), and Day et al. (1966) determined the relative flux densities and spectra of some 2000 southern hemisphere sources at three frequencies using the Parke radio telescope, while in the north, Long et al. (1966) and Williams et al. (1968) evaluated the statistics of radio source spectra between 38 and 610 MHz.

However, several problems remained. The only source strong enough for absolute flux density measurements made with simple horn and dipole systems is Cas A. But Cas A is so much stronger than most of the sources of interest that, when observed with more sensitive radio telescopes, the data need to be corrected for the nonlinear response of the radiometers used to study the weaker sources. Moreover, the flux density of Cas A was found to be decreasing at a rate of 1.1 percent per year (Hogbom & Shakeshaft 1961), making it difficult to use as a flux density standard. CKL therefore established the relative spectra of three secondary calibrators, Taurus A (the Crab Nebula), Cygnus A, and Virgo A (M 87). But, these sources, as well as Cas A, have angular dimensions of a few arc minutes and are resolved to various degrees by the large radio telescopes used to study the weaker sources, introducing additional uncertainties by the sometimes large factors needed to correct for angular resolution.

Baars et al. (1965) refined the spectrum of these four calibration sources by using only the most accurate determinations of absolute flux density and paying careful attention to corrections due to receiver nonlinearity, angular resolution, and the secular decrease in flux density of Cas A. Kellermann et al. (1969) extended this technique to establish a set of small angular size secondary calibrators to determine the spectra of 3CR sources between 38 MHz and 5 GHz and made further readjustments to the flux density scales. Later Baars & Hartsuijker (1972) reported evidence that the rate of flux density decrease of Cas A might be frequency dependent and reported new determinations of the absolute spectra of Cas A, Cyg A, and Taurus A.

Baars et al. (1977) then carefully evaluated more than 40 absolute flux-density measurements made between 10 MHz to 35 GHz, including many newly determined values, to establish the absolute spectrum of Cas A, Taurus A, and Cygnus A. After correcting for the frequency-dependent secular change in flux

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density, they found that between 300 MHz and 30 GHz the spectrum of Cas A can be represented within 2 percent by a power law with a 1 GHz flux density of 2723 Jy and a spectral index of –0.77. In addition to giving absolute spectra for Cygnus A and Tau A, they also established a "semi-absolute" spectrum for Virgo A from measured accurate ratios to Cas A and Cyg A. Then, from observed ratios to Virgo A, they went on to determine the spectra of 13 somewhat weaker small diameter sources and tabulated their flux densities at each of eight standard observing frequencies between 1.4 and 22.3 GHz with an estimated accuracy of about 5 percent. Baars et al. also determined the correction factors needed to bring each of six earlier studies to the new flux-density scale.

As it has turned out, those secondary calibrators that are small enough not to require corrections for angular size when observed with high-resolution interferometric arrays have invariably turned out to be time variable at least at the shorter wavelengths. Using the 100 m Effelsberg radio telescope, Ott et al. (1994) later made new relative flux-density measurements of 17 secondary calibrators between 0.7 and 21 cm, and established new analytic expressions for the spectrum of each of these sources.

The Baars et al. (1977) paper has become the standard reference for calibrating essentially all measurements in radio astronomy, including radio source spectra, their time variability, and structural changes as observed with VLBI, as well as observations of pulsars and atomic and molecular spectroscopy. Although there are few papers that have had more visibility among radio astronomers than the paper by Baars et al., this paper itself does not contain any new observational data or new theoretical ideas.

In preparing this article, the present author asked Baars to reflect on his role in one of the most highly cited papers in radio astronomy. He responded that a colleague had once remarked that, although it was the most highly cited paper ever from the Max Planck Institut fur Radio Astronomie, "*there is not a single original result in it*", to which Baars said he responded that "*everyone should use his limited capabilities to his best advantage*".

In determining their flux density scales, Baars et al. used more than 40 experimental measurements of absolute flux density made between 1960 and 1975 and speculated on improvements that might follow from further experiments. It may reflect on the state of modern radio astronomy research that few, if any, have attempted these difficult but important observations since 1975, and this 30 year old paper remains the universally accepted standard.

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