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The Absolute Spectrum of Cas A; An Accurate Flux Density Scale and a Set of Secondary Calibrators

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Summary. A new analysis of the absolute radio spectrum of Cassiopeia A is presented which uses the latest absolute measurements and takes account of the frequency dependence in the secular rate of decrease. The spectrum is established to an accuracy of $\approx 2\%$. Between 0.3 and 30 GHz it is given by a flux density $S_{1\,\mathrm{GHz}} = 2723$ Jy and a spectral index $\alpha = -0.770$ (epoch 1980.0).

The absolute spectra of Cygnus A and Taurus A are also given. An accurate "semi-absolute" spectrum for Virgo A is established from direct accurate ratios to Cas A and Cyg A yielding $S_{1\,\mathrm{GHz}} = 285$ Jy, $\alpha = -0.856$ (valid for $0.4 \lesssim \nu \lesssim 25$ GHz).

This Virgo A spectrum is used as a basis for accurate relative spectra of a number of sources with simple spectra. These are proposed as secondary calibrators for the routine calibration of flux density measurements. Their spectral data are presented for the frequency range 0.4–15 GHz and are believed to have an *absolute* accuracy of about 5%.

Finally a comparison with other flux density scales is made and the paper concludes with some suggestions for future work.

Key words: absolute radio spectrum — Cassiopeia A — flux density scale — flux density calibration — radio telescope calibration

1. Introduction

The calibration of radio telescopes, both in terms of the pointing direction and aperture efficiency, forms an essential part of observational radio astronomy. Radio astronomers have developed the methods of using radio sources as calibration beacons (see e.g. Kuz'min and Salomonovich, 1966; Baars, 1973).

A knowledge of the aperture efficiency of the telescope over a large range of frequencies is needed for the determination of radio source spectra. Here the method has been to obtain the absolute flux density of the three strongest sources (Cassiopeia A, Cygnus A and Taurus A) with small antennas, whose gain (aperture efficiency) has been theoretically calculated or measured with the aid of a pattern-range (see e.g. Findlay, 1966). The flux density of the sources, so established, can be used to derive the gain of a larger telescope. In the course of the last 20 years several groups have provided the necessary absolute measurements over an ever extending frequency region and with improving accuracy.

In 1962, Conway et al. (CKL, 1962) presented a flux density scale based on the absolute spectrum of Cas A and suggested several weaker sources with power-law spectra as secondary standards. Absolute spectra of Cas A, Cyg A, Tau A and Vir A over an enlarged frequency range (to 15 GHz) were presented by Baars et al. (BMW, 1965) and by Parker (1968). On this basis, Kellermann et al. (KPW, 1969) updated the CKL-scale. By 1971 many new absolute measurements had become available and Baars and Hartsuijker (BH, 1972) published the spectra of the four strongest sources in the range 100 MHz to 20 GHz.

Still the situation was not entirely satisfactory. The main reason is that the strong sources are not adequate calibrators for large telescopes at high frequencies, where the beamwidth is only a few minutes of arc. Cas A, Tau A and even Cyg A are then partially resolved, so that corrections to the measurements for the finite source angular size are necessary. Such corrections always introduce an additional error. The sources also possess other characteristics, which are undesirable for a calibration source. Cas A exhibits a secular decrease of flux density, which is moreover frequency dependent. Cyg A and Tau A both have a significant degree of polarization, the magnitude and position angle of which vary with frequency. The low galactic latitude of these sources causes difficulties in the determination of the zero level, particularly at the lower frequencies, because of the galactic background radiation.

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Table 1. The secular decrease of Cas A

Frequency (MHz)	Epoch	Decrease (% p.y.)	Ref.
81.5	1949–1969	1.29 ± 0.08	Scott et al. (1969)
950	1964–1972	0.85 ± 0.05	Stankevich et al. (1973a)
1420	1957–1976	0.89 ± 0.02	Read (1977)
1420	1957–1971	0.89 ± 0.12	Baars and Hartsuijker (1972)
3000	1961–1972	0.92 ± 0.15	Baars and Hartsuijker (1972)
3060	1961–1971	1.04 ± 0.21	Stankevich et al. (1973b)
7800	1963–1974	0.70 ± 0.10	Dent et al. (1974)
9400	1961–1971	0.63 ± 0.12	Stankevich et al. (1973b)

Nevertheless, these sources are among those studied in greatest detail and they still form the most accurate basis for the flux density scale of radio sources. Cas A serves as the primary standard. On the other hand the sensitivity of contemporary radio telescopes allows relatively weaker sources to be used as calibrators. There are several such sources which do not show the disadvantages of the stronger ones and are more suitable for daily use at the telescope.

The aim of this paper is twofold. Firstly, we present an updated analysis of the spectrum of Cas A which incorporates results obtained since the BH-paper, and in particular the now well established frequency dependence of the secular decrase. The spectra of Cyg A and Tau A are also given, together with a semi-absolute spectrum of Vir A, which is proposed as a good secondary calibrator, especially at frequencies above 5 GHz. Secondly, we use the absolute spectra and a set of accurate relative measurements to determine the spectra of additional secondary standards, which we propose for daily use in the frequency range of 0.3–30 GHz. These sources are stronger than 0.2 Jy at 15 GHz, mostly have a small angular size, do not show variations with time and generally have a simple spectrum. They can be used in a straightforward way without the need for corrections which are frequency-, time- and telescope-dependent.

2. The Absolute Spectra of Cas A, Cyg A and Tau A

Essentially, three different types of antennas have been used for the absolute measurements of flux density. Necessarily all have been calibrated, either by theoretical calculation or by experiment, without any reference to a celestial radio source.

i) The gain of a dipole or dipole array above a groundplane can be calculated theoretically. The method is used for the low-frequency part of the spectrum ($\lesssim 400$ MHz). The achievable accuracy of the gain calculation is 2–3% (Parker, 1968; Wyllie, 1969).

ii) At the higher frequencies a horn antenna appears to be the best. The gain can be calculated theoretically; the accuracy is about 1%, which has been checked in some cases by measurements (Jull and Deloli, 1964; Wrixon and Welch, 1972).

iii) Since the gain of a parabolic reflector antenna cannot be calculated theoretically to the desired accuracy, only an experimental calibration is possible. For an antenna of limited size this can be done on a so-called pattern-range. The measurement is difficult and the accuracy is at best about 5%. An original version of this method has been developed at the Scientific-Research Radiophysical Institute, Gorkii (USSR). Generally known as the "artificial moon" method it uses a black disc, located in the farfield of the antenna, as the calibrated "transmitter". The method has been described e.g. by Troitskii and Tseitlin (1962), Kuz'min and Salomonovich (1966) and Findlay (1966). The accuracy is claimed to be between 3 and 6%.

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The most important advance is the confirmation of the frequency-dependence of the secular decrease, which was first suggested by Baars and Hartsuijker (1972). The most accurate values of the secular decrease are given in Table 1, together with their references. The resulting relation for the secular decrease d in the flux density of Cas A as a function of frequency is

$$d(\nu)[\% \text{ per year}] = 0.97(\pm 0.04) - 0.30(\pm 0.04)\log \nu\,[\text{GHz}]\,. \quad (1)$$

This result is identical to that of Dent et al. (1974). In the following spectral analysis we have applied (1) to the frequency range 20 MHz to 30 GHz.

The data for the spectral analysis are assembled in Table 2. To the BH-data we have added 8 measurements with dipole antennas below 38 MHz and a few high frequency points. The table also presents the flux density corrected to epoch 1965.0 with (1) and the weight with which each point entered the analysis. The least-squares procedure indicates that the spectrum can best be represented by a second degree curve over the band 20–300 MHz and by a straight spectrum from 0.3–30 GHz. Table 3 and Figure 1 give the result of the analysis. The spectrum in Table 3 is given for epoch 1965.0 and also for 1980.0, for convenience of use. Note that the flattening of the spectrum over these 15 years is significant in view of the errors.

The following comments are in order.

i) We have used only those measurements with a published error of less than 6%, apart from some low frequency points which are less accurate. The weight assigned to each point is inversely proportional to the square of the error.

ii) The proper use and weighting of the artificial moon results (called Gorkii data hereafter) is not obvious. The method has been improved over the years, resulting in several corrections, which had not been applied to the older data. Therefore we have not used data which were published before 1969. Usually these

Table 2. Absolute flux density measurements of CasA, CygA, TauA

	CasA					CygA			TauA				
Freg. [MHz]	Flux meas. [Jy]	Epoch	Flux 65.0 [Jy]	Error [1σ, %]	Weight	Flux [Jy]	Error [1σ, %]	Weight	Flux [Jy]	Error [1σ, %]	Weight	Method	Author
10.05	28000.	65.9	28300.	10.0	2	13500.	11.	1				dipole	Bridle (1967)
12.6	58500.	66.	60000.	14.	1	21900.	14.	1	5300.	11.	1	dip.+arr.	Braude (1969)
14.7	65000.	66.	66000.	14.	1	31700.	14.	1	5300.	14.	1	dip.+arr.	Braude (1969)
16.7	60000.	66.	61000.	14.	1	26600.	14.	1	3830.	14.	1	dip.+arr.	Braude (1969)
20.	65000.	66.	66000.	14.	1	27000.	14.	1	3170.	14.	1	dip.+arr.	Braude (1969)
22.25	51400.	66.5	52400.	5.	8	29100.	6.	5	2750.	6.	5	dip.+arr.	Roger (1969)
25.	58000.	66.	59000.	14.	1	31500.	14.	1	3420.	14.	1	dip.+arr.	Braude (1969)
26.3	44100.	69.8	47000.	4.6	9	29600.	5.2	7	2990.	5.2	7	dip.+arr.	Viner (1975)
38.	36200.	66.9	37200.	3.7	14	25500.	4.2	11				dipole	Parker (1968)
81.5	21100.	66.9	21630.	2.9	23	16300.	4.2	11	1880.	4.2	11	dipole	Parker (1968)
152.	12800.	66.5	13040.	2.9	23	10500.	4.2	11	1430.	4.2	11	dipole	Parker (1968)
320.	7330.	62.7	7629.	5.	8	5870.	6.	5				horn	MacRae (1963)
550.	5170.	67.5	5313.	3.2	5	4140.	4.	3				disc	Bondar (1969)
625.	4670.	67.5	4792.	3.3	4	3400.	4.	3				disc	Bondar (1969)
710.	4240.	67.5	4349.	3.5	4	3100.	4.	3				disc	Bondar (1969)
780.	3870.	67.5	3968.	3.5	4							disc	Bondar (1969)
800.		67.5				2670.	4.	3				disc	Bondar (1969)
900.	3470.	67.5	3556.	4.	4							disc	Bondar (1969)
1000.	3110.	67.5	3186.	4.	3							disc	Bondar (1969)
1117.	2830.	69.9	2966.	4.	3	1900.	3.	5	990.	6.	1	disc	Vinogradova (1971)
1150.	2840.	67.5	2908.	4.	3							disc	Bondar (1969)
1.304.	2580.	69.9	2701.	6.	1	1690.	3.	5	980.	6.	1	disc	Vinogradova (1971)
1415.	2369.	69.5	2470.	2.	49							horn	Encrenaz (1970)
1440.	2372.	63.	2328.	2.2	40							horn	Findlay (1965)
1440.	2260.	70.	2367.	3.	22							horn	Findlay (1972)
1765.	2000.	69.9	2090.	5.5	2	1210.	3.	5	940.	6.	1	disc	Vinogradova (1971)
2000.	1860.	69.3	1932.	3.	5	1000.	6.	1	840.	6.	1	disc	Dmitrenko (1970)
2290.	1660.	69.3	1723.	5.	2	935.	6.	1	810.	6.	1	disc	Dmitrenko (1970)
2740.	1380.	69.3	1430.	5.5	2	710.	6.	1	795.	6.	1	disc	Dmitrenko (1970)
3150.	1265.	64.4	1258.	3.	22	645.	3.5	16	700.	3.5	16	horn	Medd (1972)
3200.	1340.	59.4	1279.	4.5	10	680.	5.	8	710.	5.	8	horn	Broten (1960)
3380	1145.	69.3	1185.	5.5	2	615.	5.	1	718.	6.	1	disc	Dmitrenko (1970)
3960.	1025.	69.3	1060.	4.5	2	515.	6.	1	646.	6.	1	disc	Dmitrenko (1970)
4080.	1086.	64.8	1084.	2.4	34	459.	3.	22	687.	3.	22	horn	Penzias (1965), Wilson (1966)
5680.	740.	68.5	759.	3.5	4	317.	6.	1				disc	Dmitrenko (1970)
6660.	684.	65.	684.	3.	22	265.	3.8	14	577.	3.5	16	horn	Medd (1972)
8250.	612.	65.9	615.	3.6	15				563.	4.	12	horn	Allen (1967)
9380.	510.	68.5	522.	3.5	4							disc	Dmitrenko (1970)
13490.	384.	69.9	396.	3.5	16				520.	3.8	14	horn	Medd (1972)
15500.	374.	65.9	376.	4.8	9				461.	5.2	7	horn	Allen (1967)
16000.	343.	70.6	354.	3.	22				447.	3.5	16	horn	Wrixon (1971, 1972)
22285.	272.	73.1	285.	3.7	14	60.2	3.8	14	397.	4.	12	transm.	Janssen (1974)
31410.			194.	20.	1	55.	36.	1	387.	18.	1		Hobbs (1968)
34900.		67.3							340.	20.	1		Kalaghan (1967)

measurements have resulted in a set of flux densities over a large frequency range, all observed in one continuous session. The presence of a systematic, possibly frequency-dependent error would produce a bias and a correlated error between points. In the more recent publications the systematic error is estimated at 3% and 6%. In two recent papers (Troitskii et al., 1972; Stankevich et al., 1973b) new measurements made between 0.3 and 9.4 GHz have been presented. A reduction of these observations and the ones used in Table 2 to epoch 1965 with (1) shows differences in the measurements at similar frequencies of 6% on the average with several being as large as 10%.

In view of these facts we have given the Gorkii data an error twice the published value in our analysis. Moreover we have not incorporated the points of the last two references, first, because this would considerably increase the risk of a systematic error and, second, because the distribution between horn/dipole and artificial moon measurements would become too lopsided. Actually, we find that addition of either of these two series to the data of Table 2 does not change the resulting spectrum significantly.

Later we shall meet other considerable discrepancies between Gorkii data and other results for Cyg A and

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Table 3. Spectral parameters of main calibrators

Source	Frequency interval	Spectral parameters $\log S[\mathrm{Jy}] = a + b \log \nu\,[\mathrm{MHz}] + c \log^2 \nu\,[\mathrm{MHz}]$		
		a	b	c
CasA 1965.0	22 MHz...300 MHz	5.625 ±0.021	−0.634 ±0.015	−0.023 ±0.001
	300 MHz... 31 GHz	5.880 ±0.025	−0.792 ±0.007	—
CasA 1980.0	300 MHz... 31 GHz	5.745 ±0.025	−0.770 ±0.007	—
CygA	20 MHz... 2 GHz	4.695 ±0.018	+0.085 ±0.003	−0.178 ±0.001
	2 GHz... 31 GHz	7.161 ±0.053	−1.244 ±0.014	—
TauA	1 GHz... 35 GHz	3.915 ±0.031	−0.299 ±0.009	—
VirA	400 MHz... 25 GHz	5.023 ±0.034	−0.856 ±0.010	—

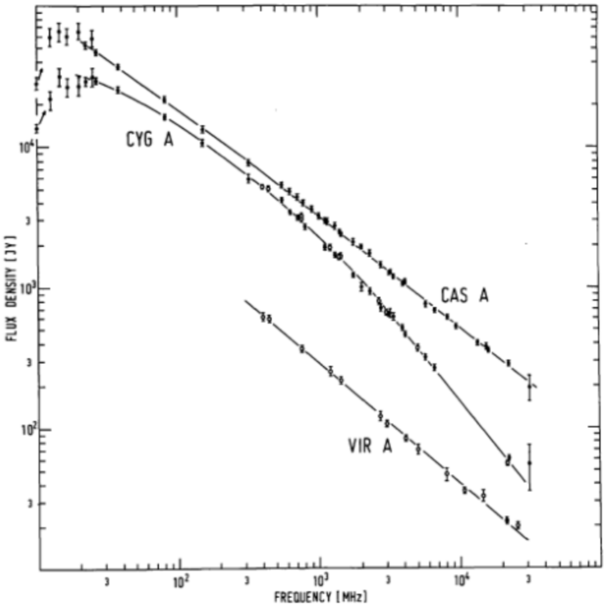

Fig. 1a. The absolute spectra of Cas A and Cyg A and the semi-absolute spectrum of Vir A. Solid symbols are absolute measurements, open symbols relative measurements

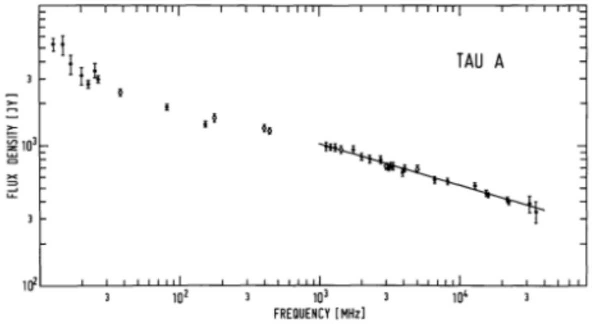

Fig. 1b. The absolute spectrum of Tau A

Tau A. Their effect is always to produce a systematic change in the spectral index. The most likely cause of the discrepancies lies in the sensitivity of the artificial moon method to the effect of the background radiation near the source and to the atmospheric absorption.

iii) Recently an increase in the flux density between 1966 and 1974 has been reported at 38 MHz (Erickson and Perley, 1975), and has been independently confirmed (Read, 1977). While the general small secular decrease at 81.5 MHz and higher frequencies appear well determined (see Table 1), care should be taken in using the spectrum presented here below about 50 MHz.

The spectrum of Cas A now appears well established. The mean error of the flux density scale is about 2% between 0.3 and 30 GHz and increases to probably 5% below 300 MHz. We conclude that a flux density scale over a large frequency range (20 MHz–30 GHz) can best be based on the Cas A spectrum.

The differences with the BH-spectrum are very small (<2%), except at the lowest frequencies, where the straight line of BH is bound to deviate increasingly. In our analysis we have not used 8 older Gorkii points, which were contained in the BH-analysis. On the other hand we have included several new measurements. The final spectrum however remains almost the same. The spectrum derived here causes correction factors in the widely used flux density scales. We discuss these in Section 5.

Cygnus A and Taurus A

The available absolute data for these sources are also contained in Table 2. The total number of measurements is smaller and generally the accuracy is less than for Cas A. Since in certain circumstances the use of these sources for calibration may be of advantage, we have analysed the spectra; the results are given in Table 3 and Figure 1. There are several very accurate measurements of the *ratio* of Cyg A and Tau A against Cas A. The best ones, described or referred to in BH and BMW have also been used here. The flux densities are calculated on the basis of the present Cas-spectrum. The addition of these relative points does not change the spectrum significantly but it improves the accuracy of the fit.

For both sources there are discrepancies with the most recent Gorkii data. Those by Troitskii et al. (1972) for Cyg A all lie below the other observations and increasingly so with increasing frequency, indicating a possible systematic error of considerable magnitude. The situation with Tau A is complicated by the claim of the Gorkii group that there are several steps in the spectrum between 700 and 3000 MHz, where the spectral index is about zero. As long as this situation has not been cleared up by relative measurements there remains some doubt about the true spectrum of Tau A. Because it is the strongest source above 10 GHz, we nevertheless include our results in Table 3. There is a fairly good agreement with the BH-result.

3. The Semi-absolute Spectrum of Vir A

An ideal calibrator should have a small angular size, be constant in time and have a simple spectrum. Also, in order to avoid alinearity problems in low-noise receivers, its flux density should not be too high. At the higher frequencies Virgo A (3C274, M87) satisfies these requirements and hence appears to be a suitable *secondary standard*. First the source is strong enough to have been well observed at many frequencies. In particular there exists a large set of very accurate measurements of the ratio of Vir A to Cas A. We use these to derive the *semi-absolute* spectrum of Vir A. Second the flux density is sufficiently low to avoid the danger of scaling errors in observations of weaker sources.

We use 16 observations relative to Cas A, Cyg A and Tau A together with a few absolute measurements. All data with their reference are given in Table 4, which requires little comment. The circumstances of the observations have been described in the references. From the original articles we know that the ratio measurements have been done with great care. The ratios at 10.7 GHz are observations by us at the NRAO 140-ft and the MPIfR 100-m telescopes, where we use the Cyg A spectrum of Table 3.

The resulting spectrum of Vir A is presented in Table 3 and Figure 1. It is well approximated by a straight line over the range 0.3–300 GHz. There is however one complication, which should be noted. The brightness distribution of Vir A is rather intricate. A core source of approximately 40″ diameter contains a weak nucleus of 0.5″ and is surrounded by a halo of about 14′ × 10′. The spectra of the components are different, while the overall spectrum is straight, as shown above (see also Turland, 1975). The spectrum of the halo steepens considerably above 1 GHz and (according to observations at Effelsberg, von Kap-Herr and Wielebinski, pers. comm.) the spectral index lies between −3 and −4 above 5 GHz. Thus the contribution of the halo is about 10% at 5 GHz and 1% at 10 GHz. We conclude that Vir A is a convenient secondary calibrator, especially for the higher frequencies (≳5 GHz). At lower frequencies the influence of the halo must be taken into account properly to avoid systematic errors.

Table 4. The data for Virgo A

Frequency (MHz)	Vir/Cas (observed)	S (Vir) (Jy) (derived)	Error (%)	Ref.
400	0.085	617	5	BMW
440	0.091	598	5	BMW
750	0.086	362	4.5	BMW
750	0.0914	372	4	KPW
1200	0.086	251	4.5	BMW
1400	0.0896	221	4	KPW
1420 (3 ×)	0.0945	218	2.5	BH
1440	0.084	212	4.5	BMW
2695	0.0818	120	4	KPW
3000	0.077	106	8	BMW
3000	0.0836	105	3.5	BH
4080	0.0807	84.4	5	WP
5000	0.0799	71	4	KPW
5000	0.105 (Tau)	67	5	BMW
8000	0.083 (Tau)	46.6	11	BMW
10700 (2 ×)	0.252 (Cyg)	35.5	4	PT
14500	0.068 (Tau)	32.6	11	BMW
22285 (3 ×)	Absolute	21.3	4	JGW

Note to ref. WP = Wilson and Penzias (1966), PT = Pauliny-Toth (unpublished), JGW = Janssen et al. (1974)

4. Sources Suitable as Routine Calibrators

The usual method of determining flux densities of radio sources is to measure the ratio of the source strength to that of a well-known calibrator. In the foregoing sections we have indicated what requirements a routine calibrator should satisfy, and also mentioned the disadvantages in this respect of the strong sources Cas A, Cyg A and Tau A.

To avoid as much as possible the effects of varying telescope efficiency with position and time it is desirable to have a set of calibrators which is reasonably equally distributed over the sky. Clearly Vir A alone does not fulfill this purpose. We present now a group of suitable secondary flux density calibrators, the spectra of which have been carefully determined from relative measurements against one or more of the standards, presented in the foregoing sections. These measurements have been taken mainly from the literature, notably Kellermann and Pauliny-Toth (1973) (10.7 GHz), KPW (1969) (0.75, 1.4, 2.7 and 5 GHz), Ross and Seaquist (1975) (3.2, 6.6 and 10.6 GHz) and Klein und Stelzried (1976) (2.3 GHz). Additional measurements have been made at Effelsberg with the 100-m telescope, mainly at 15 GHz. These results have been published separately (Genzel et al., 1976). Unpublished data at 408 MHz from the NRAO 300-ft telescope, obtained by Pauliny-Toth and Kellermann, have also been used.

Table 5. Spectral parameters of telescope calibrators

Source	Frequency interval	Spectral parameters $\log S$ [Jy] $= a + b \cdot \log \nu$ [MHz] $+ c \cdot \log^2 \nu$ [MHz]					
		a		*b*		*c*	
3 C 48	405 MHz...15 GHz	2.345	±0.030	+0.071	±0.001	−0.138	±0.001
3 C 123	405 MHz...15 GHz	2.921	±0.025	−0.002	±0.0001	−0.124	±0.001
3 C 147	405 MHz...15 GHz	1.766	±0.017	+0.447	±0.006	−0.184	±0.001
3 C 161	405 MHz...10.7 GHz	1.633	±0.016	+0.498	±0.008	−0.194	±0.001
3 C 218	405 MHz...10.7 GHz	4.497	±0.038	−0.910	±0.011	—	
3 C 227	405 MHz...15 GHz	3.460	±0.055	−0.827	±0.016	—	
3 C 249.1	405 MHz...15 GHz	1.230	±0.027	+0.288	+0.007	−0.176	±0.003
3 C 286	405 MHz...15 GHz	1.480	±0.018	+0.292	±0.006	−0.124	±0.001
3 C 295	405 MHz...15 GHz	1.485	±0.013	+0.759	±0.009	−0.255	±0.001
3 C 348	405 MHz...10.7 GHz	4.963	±0.045	−1.052	±0.014	—	
3 C 353	405 MHz...10.7 GHz	2.944	±0.031	−0.034	±0.001	−0.109	±0.001
DR 21	7 GHz ...31 GHz	1.81	±0.05	−0.122	±0.010		
NGC 7027	10 GHz...31 GHz	1.32	±0.08	−0.127	±0.012		

The derived spectra, valid between 0.4 and 15 GHz, are given in Table 5, while Table 6 presents salient features of the sources, together with the calculated flux density at several standard observing frequencies. The thermal sources DR21 and NGC7027 are particularly useful at frequencies above 10 GHz. Recently Dent (1972) has discussed the compact H II region DR21 as a calibrator for high frequencies ($\gtrsim$8 GHz). The source has the clear advantage of possessing the well-predictable and flat spectrum of an optically thin H II region. For that reason we present our results for its spectrum here. This source should be used with care in view of its angular size (20″) and the brightness structure of the surrounding region (see Dent for details). In the same way the planetary nebula NGC7027 has been analysed and presented in Table 5.

Only three of the sources are suitable for the calibration of interferometers and synthesis telescopes, viz 3C48, 3C147 and 3C286. Of these the first two are universally used as interferometer calibrators. The highly accurate positions of these sources have been taken from Elsmore and Ryle (1976). Some of the other sources may need a correction for angular size, when used with the largest single telescopes at high frequencies. Because their sizes are well-known the correction is readily applied. When using these sources with antenna beams of only a few arc minutes one should note that some have a frequency-dependent brightness distribution resulting in a variation of the centroid position of a few seconds of arc.

We believe that this set of sources forms a solid basis for the calibration of source surveys and flux density observations over a wide range of frequencies. Together with the primary calibrators any flux dependent variation in the scale should be avoidable. We believe that the systematic error of the scale over the frequency region 0.4–15 GHz is not more than 3–4%. Thus, with sufficient signal to noise ratio, flux density measurements might be carried out over this frequency range with an absolute accuracy of about 5%. Any further improvement might only be expected from direct absolute measurements of the sources in Table 5, for instance with the interferometric method as used by Wyllie (1969).

6. Comparison with Other Flux Density Scales

It is of interest to point out the quantitative differences between our new scale and other widely used flux density scales. Although we have presented here a new analysis of the absolute Cas A-spectrum over the large frequency range 20 MHz–30 GHz, the other, secondary, calibrators, presented in Table 3 and 5, have only been analyzed for frequencies from 400 MHz upwards.

Table 7 shows the correction factors needed to bring the CKL, Kellermann (K, 1964), KPW, BMW, Wills (1973) and BH scales to the new scale presented here. The table is calculated from a comparison of the basic derived Cas A spectra.

The largest discrepancies arise at the lower frequencies. In particular the CKL- and KPW-scales are significantly low below 1 GHz. These scales have formed the basis for the spectral analysis of large sets of weaker sources, notably 3CR. Later observations of these sources have already given indications that these scales are in error (Niell and Jauncey, 1971).

Also evidence has been presented for a flux density dependent scale factor at several frequencies (Scott and Shakeshaft, 1971; Braude et al., 1971). An investigation into this effect, based on new accurate relative measurements and calibrated against the present Cas A-spectrum would be very useful, but is beyond the scope of this paper. The discrepancies undoubtedly arise partly from the different frequency regions over which the spectra have been analysed. We feel that the method of establishing the spectra of the secondary calibrators, as applied for instance in the CKL and Wills papers, also contribute to the flux density dependence of the scales.

Table 6. Position and flux densities of telescope calibrators

Source	RA (1950.0) [h m s]	Dec (1950.0) [° ′ ″]	b^{II} [°]	S_{1400} [Jy]	S_{1665} [Jy]	S_{2700} [Jy]	S_{5000} [Jy]	S_{8000} [Jy]	$S_{10\,700}$ [Jy]	$S_{15\,000}$ [Jy]	$S_{22\,235}$ [Jy]	Spec.	Ident.	Polar. (at 5 GHz) %	Ang. size (at 1.4 GHz) ″
3 C 48	01 34 49.8	+32 54 20	−29	15.9	13.9	9.20	5.24	3.31	2.46	1.72	1.11	C^-	QSS	5	< 1
3 C 123	04 33 55.2	+29 34 14	−12	48.7	42.4	28.5	16.5	10.6	7.94	5.63	3.71	C^-	GAL	2	20
3 C 147	05 38 43.5	+49 49 42	+10	22.4	19.8	13.6	7.98	5.10	3.80	2.65	1.71	C^-	QSS	< 1	< 1
3 C 161	06 24 43.1	−05 51 14	− 8	19.0	16.8	11.4	6.62	4.18	3.09	2.14	—	C^-	GAL	5	< 3
3 C 218	09 15 41.5	−11 53 06	+25	43.1	36.8	23.7	13.5	8.81	6.77	—	—	S	GAL	1	core 25 halo 200
3 C 227	09 45 07.8	+07 39 09	+42	7.21	6.25	4.19	2.52	1.71	1.34	1.02	0.73	S	GAL	7	180
3 C 249.1	11 00 25.0	+77 15 11	+39	2.48	2.14	1.40	0.77	0.47	0.34	0.23	—	S	QSS	—	15
3 C 274	12 28 17.7	+12 39 55	+74	214	184	122	71.9	48.1	37.5	28.1	20.0	S	GAL	1	halo 400[a]
3 C 286	13 28 49.7	+30 45 58	+81	14.8	13.6	10.5	7.30	5.38	4.40	3.44	2.55	C^-	QSS	11	< 5
3 C 295	14 09 33.5	+52 26 13	+61	22.3	19.2	12.2	6.36	3.65	2.53	1.61	0.92	C^-	GAL	0.1	4
3 C 348	16 48 40.1	+05 04 28	+29	45.0	37.5	22.6	11.8	7.19	5.30	—	—	S	GAL	8	115[b]
3 C 353	17 17 54.6	−00 55 55		57.3	50.5	35.0	21.2	14.2	10.9	—	—	C^-	GAL	5	150
DR 21	20 37 14.2	+42 09 07	+ 1	—	—	—	—	21.6	20.8	20.0	19.0	Th	H II	—	20[c]
NGC 7027[d]	21 05 09.4	+42 02 03	− 3	1.35	1.65	3.5	5.7	—	6.43	6.16	5.86	Th	PN	< 1	10

[a] Halo has steep spectral index, so for $\lambda \leq 6$ cm, more than 90% of the flux is in the core
[b] Angular distance between the two components
[c] Angular size at 2 cm, but consists of 5 smaller components
[d] Data up to 5 GHz are the direct measurements, not calculated from fit

Table 7. Ratio of the present to other flux density scales

Frequency (MHz)	CKL	K	KPW	BMW	BH	Wills
38	1.029	0.979	0.981	—	0.880	0.976
81.5	1.074	1.021	1.020	—	0.935	1.013
178	1.110	1.054	1.051	—	0.974	1.042
400	1.129	1.074	1.065	1.080	1.007	1.048
750	1.114	1.059	1.046	1.044	1.004	1.035
1400	1.099	1.038	1.029	1.015	1.000	1.017
2700	1.083	1.030	1.011	0.981	1.000	0.997
5000	—	1.016	0.993	0.951	1.000	0.979
10600	—	1.000	0.974	1.065	0.990	0.959
15000	—	—	0.966	1.218	0.989	0.949

While we consider it unlikely that the effect is present in the secondary calibrator spectra, the effect would still be present in an adjustment of the older scales at the lower frequencies to our new Cas A-spectrum.

It is of interest to compare our results with the *absolute* scale of Wyllie (1969) at 408 MHz, which is based on absolute measurements of a set of relatively weak sources (10–150 Jy). We have compared his results with the predicted flux density of the straight spectrum sources in Genzel's analysis (pers. comm.), which are based on our Cas A-spectrum. We find the ratio Genzel/Wyllie = 0.97, indicating that Wyllie's scale is only 3% above our Cas A-scale.

6. Conclusion

This paper is the first to present an analysis of the absolute spectrum of Cas A, in which the data have been corrected for the now well-established frequency dependence of the secular decrease in flux density. We consider the resulting spectrum to be very well determined with an estimated uncertainty in calculated flux density at frequencies between 0.1 and 30 GHz of ≈2%. A comparison with the most recent analysis by Baars and Hartsuijker (1972), who used a crude version of the frequency dependent secular change, shows that the differences are smaller than 1% over the applicable frequency range.

A further improvement in the accuracy of the spectrum will be difficult to achieve. The most useful effort would be a flux measurement with a horn-antenna at several frequencies between 200 and 1200 MHz and at about 2, 10 and 30 GHz. The lower frequency points especially would give a good comparison with the artificial moon data.

The definition of an accurate spectrum of Vir A and several other sources, directly based on the Cas A spectrum and extending to above 15 GHz, allows the accurate calibration of flux density observations over a wide frequency range. The use of these sources will avoid scaling discrepancies between measurements of different observers without the need to refer to Cas A in the actual observations.

A possible scheme to update and improve the present situation might be the following international observing campaign. All observers, who have an absolutely calibrated antenna at their disposal (horn, dipoles, pattern-range or artificial moon calibration) measure Cas A at the same epoch (1980?). By mutual agreement it is arranged to have a regular coverage over as large a frequency region as possible and to distribute the different calibration techniques over the band.

At the same epoch the ratios of the secondary standard against Cas A would be determined to the highest accuracy at all "standard" observing frequencies. With the new absolute Cas A spectrum the spectra of the secondary calibrators could be updated. Ideally by that time we would also have available direct absolute measurements of several secondary calibrators at a few standard frequencies, obtained by the interferometric method.

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