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MEASUREMENT OF THE FLUX DENSITY OF CAS A AT 4080 Mc/s

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ABSTRACT

The 20-foot aperture horn-reflector antenna at the Crawford Hill Laboratory has been used to measure the flux density of Cas A at 4080 Mc/s. Fifty drift-curve observations were made on six nights in September and October, 1964. In each observation the antenna response due to Cas A was compared with the output of a reference-noise source. The equivalent effective temperature of the reference-noise source was measured by four calibration methods. The gain of the antenna was measured by comparison with a standard horn that was later measured in the laboratory. The resulting flux density of Cas A was 1 086 × 10^{-23} W $m^{-2}(c/s)^{-1}$. The probable error in this result is approximately 2 per cent, based upon a 6.3 per cent limit for 99 per cent level of confidence.

I. INTRODUCTION

Three things are required for an absolute flux measurement: an antenna whose gain is accurately known, a radiometer sensitive enough to permit the precise measurement of the power collected by the antenna, and a calibrated source of noise power for comparison. Ideally, the antenna one would like to use for the measurement is a standard horn that has been previously measured in the laboratory. Unfortunately, however, this is impossible, because such an antenna is not large enough to provide an adequate signal from the radio source. Large antennas, on the other hand, have very long Rayleigh distances that make them difficult to calibrate accurately. The best compromise is reached when the most sensitive radiometer available is employed and an antenna only large enough to provide a suitable signal from the source in question. A 4-Gc/s traveling-wave maser amplifier and the 20-foot aperture horn-reflector antenna (available to us upon completion of the Holmdel participation in the Telstar projects) provided a combination of equipment ideally suited for an absolute flux measurement.

Cas A was selected for the present measurement because it has long been used in radio astronomy as a standard source. At most frequencies it is the strongest radio source in the sky and is not complicated by polarization effects. It has the disadvantages, however, of having a secular decrease of flux of about 1.1 per cent per year (cf. Mayer, McCullough, and Sloanaker 1964) and of not being as small in diameter as would be desired for use in calibrating instruments of the highest resolving power.

II. ANTENNA AND ANTENNA-GAIN MEASUREMENT

The horn-reflector antenna used for the flux measurement has an aperture area of 391 square feet. It has an unlimited rotation altitude-azimuth mount and has been described by Crawford, Hogg, and Hunt (1961). The equivalent temperature of the antenna when pointed at the zenith is about 7° K, 2.3° K of which is due to absorption by oxygen in the atmosphere.

The measurement of the gain of the antenna is described by Hogg and Wilson (1965). Briefly, the gain of the horn reflector was obtained by comparison with that of a 20-db standard horn mounted beside its aperture. During the measurement the whole assembly was pointed at a helicopter-borne source by observing a bore-sight television monitor. During times of good pointing, the receiver was switched from the horn-reflector output (through a precision 31-db attenuator) to the reference horn and the difference in level recorded. The gain of the standard horn was subsequently measured to an accuracy of

0.7 per cent and was found to be in good agreement with the theoretical gain. The final result was that the gain of the horn reflector at 4080 Mc/s was 47.57 db and 47.73 db in the two principal planes of polarization. These values are believed to be within 6.1 per cent (0.26 db) of the actual gains (99 per cent confidence limits).

III. RADIOMETER

The radiometer uses a traveling-wave ruby maser as the first stage. The maser has been described by Tabor and Sibilia (1963). It has a noise temperature of about 3.5° K, a gain of 42 db, and a band width of 15 Mc/s. The average gain of the maser usually changed less than 1 per cent during a 40-min observation period, and this change occurred in a rather monotonic fashion. Superimposed on this average behavior is a fast gain fluctuation probably caused by helium bubbling in the maser structure. It increases the output fluctuation level of the d.c. radiometer by a factor of about 5 over that expected from noise alone when used with a 1-sec time constant.

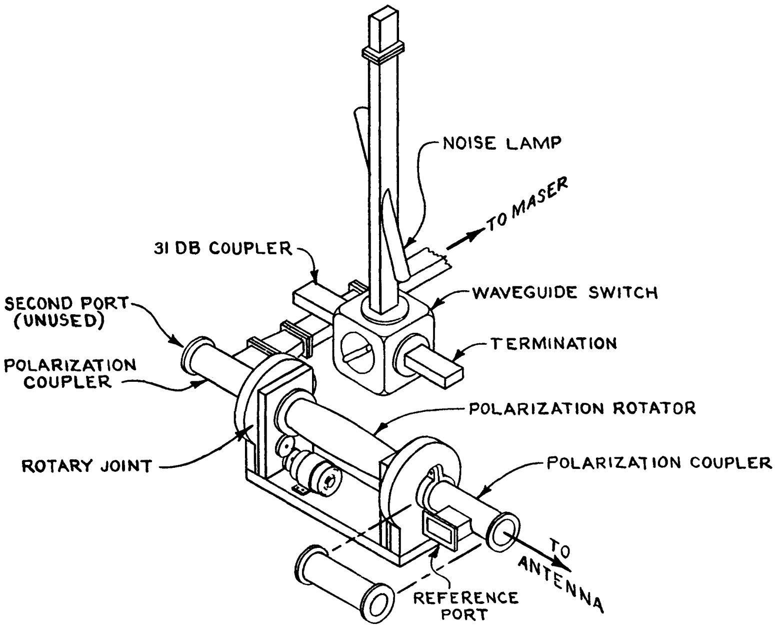

FIG. 1.—The radiometer input waveguide assembly

The maser is connected to the horn-reflector antenna through the waveguide assembly shown in Figure 1. The antenna feed is a round waveguide, while both the reference port and the output to the maser are rectangular waveguides. The required transitions are effected by polarization couplers similar to those described by Ohm (1961); they consist of a "T" formed by a straight-through circular waveguide and a rectangular waveguide side arm. One of the two circular ports accepts two orthogonal TE_{11} modes, passes one straight through, and couples the other out the rectangular guide. The attenuation through the coupler is 0.009 db in either polarization and the cross-coupling between polarizations is more than 40 db down.

The existence of these high-quality polarization couplers makes it possible to build a low-loss waveguide switch from a polarization rotator. Consider a half-wave plate in a beam of linearly polarized radiation with one of its principal planes aligned with the incident polarization. If the principal planes of the half-wave plate are rotated through an angle θ about the axis of the beam, the exit polarization will rotate through an angle 2θ. Our rotating "half-wave plate" was made of a 14-inch piece of 2.125-inch-diameter round copper waveguide (see Fig. 1) which was squeezed between wooden shoes in a hydraulic press until the phase shift from one end to the other differed by 180° in the two principal planes. The squeezed piece was then mounted on ball-bearing races between two double-choke rotary joints. The loss through the whole polarization rotator assembly is 0.018 db in any position. As a switch, it has an isolation of more than 30 db between isolated ports. A small gear-head motor can be used to drive the squeeze section at 150 rpm which results in a 10 c.p.s. switching rate. A light chopper with two photo cells gives in-phase and quadrature signals to drive phase-sensitive detectors.

Figure 1 also shows the parts necessary for calibrating the response of the radiometer. After passing through a waveguide switch noise from the argon-noise lamp is injected through a 31-db directional coupler to the maser input. The rotating polarization switch can be used to switch between the antenna and the side port, either manually or with motor drive, or, with the polarization coupler near the antenna removed, the squeeze section can be used to change the angle of linear polarization received from the antenna.

The equivalent noise temperature of the receiving system can be calculated from the maser temperature, the antenna temperature, and the attenuation of the components shown in Figure 1. The 0.083-db attenuation of the components from the second polarization coupler to the maser plus the attenuation of the polarization rotator and two polarization couplers gives an absorption of 2.8 per cent. The resulting calculated system temperature of 20° K agrees well with the measured value.

Since the return loss from the input of the maser could not be kept more than 20 db for the period of time required for calibration and observation, it was necessary to be very careful about the match of the rest of the system. The waveguide components in Figure 1 were adjusted for a return loss from the whole waveguide assembly looking from the maser terminals of more than 45 db and the reference terminations (described in § IV) and the antenna had return losses of greater than 34 db.

The output of the maser is fed to a mixer, and the remainder of the radiometer is conventional. The IF preamplifier limits the band width of the system to 10 Mc/s. A precision attenuator between the IF preamplifier and the main IF amplifier is used in calibration.

IV. RADIOMETER CALIBRATION

In order to avoid possible systematic errors in any single calibration method, we have employed four separate methods. In each case, the result was expressed as the effective temperature (referred to the antenna terminal) added by the argon-noise lamp shown in Figure 1. This temperature was then used as a secondary standard during observations. The methods for calibrating the noise tube are described below, and the results obtained using the various methods are compared in Table 1 (see below).

a) *System Noise Method*

The system temperature is determined by switching (manually) the radiometer input between the antenna terminal and a room-temperature load, and recording the amount of IF attenuation required to equalize the outputs. The system temperature is then obtained from the following relation

$$T_s = \frac{T_{\rm rm} - T_{\rm ant}}{Y - 1}$$

where Y is the attenuation and T_s, $T_{\rm rm}$, and $T_{\rm ant}$ are the system, "room," and antenna temperatures, respectively. This last quantity is determined by comparison with a liquid-helium-cooled termination.[1]

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[1] This device consists essentially of a 4-foot-long piece of brass waveguide terminated by an absorbing pyramid completely immersed in liquid helium. Its effective temperature (approximately 5° K) is known is known to within 0.2° K. It is described by Penzias (1965).

The effective temperature contribution due to the noise tube is then obtained by measuring the fractional increase in system temperature when the noise tube is "on," employing the same IF attenuator as above.

b) *Cold Load-Attenuator Method*

The radiometer is connected to the waveguide load (cooled by liquid helium) through a calibrated[2] variable attenuator at room temperature. We may then change the effective input temperature of the radiometer by varying the amount of attenuation introduced by the attenuator, thus producing a scale against which the contribution from the noise tube is compared.

c) *Direct Noise-Tube Method*

The noise lamp is connected to the input of the maser, first directly, then through a 10-db attenuator and finally through a 20-db attenuator. In each case the amount of IF attenuation required to equalize the outputs with the noise tube on and off is recorded. We can then compute the effective temperature of the noise tube from the Y-ratios obtained since we know the noise temperature of the maser (3.5° ± 1° K) from other measurements. That is, the system temperature with the noise lamp off is just room temperature plus 3.5° K. Finally, knowing the coupling coefficient of the 31-db directional coupler, we compute the effective temperature contribution of the noise-tube–coupler combination.

TABLE 1

Method	Noise-Tube Temperature (° K) Referred to Antenna Terminals
System noise. . . .	7.66±0.2
Cold load attenuator.	7.79± .2
Direct noise tube	7.75± .3
Heated termination. .	7.85± .2
Weighted mean. . . .	7.75±0.12

d) *Heated Termination Method*

The radiometer is switched between two terminations, one at room temperature and another whose temperature is varied. The former is a standard waveguide termination, while the latter consists of a waveguide fitted with a coaxial load and immersed in a water bath. Both terminations are well matched and fitted with calibrated thermometers. The noise-tube–directional-coupler combination is installed between the coaxial load and the radiometer switch input during the measurement.

Calibration is performed by changing the temperature of the coaxial load by means of various temperature baths, and comparing the resulting radiometer output deflections with those obtained by turning the noise tube off and on.

Here, and in method (*c*) above, the result we obtain is the effective temperature contribution at the terminals of the coupler. In order to obtain the effective temperature at the antenna terminals as listed in Table 1 the above result is increased by 0.06 db, the amount of attenuation between the antenna terminals and the noise-tube coupler.

An examination of the results of the four methods described above, as listed in Table 1, shows them all to be within approximately 1 per cent of the weighted mean of the group (7.75° K).

In order to investigate the possibility of systematic errors in the above result, three of the calibration methods were repeated with different components; the system tempera-

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[2] The calibration of the attenuator (approx. range: 0.01–0.12 db) was carried out by G. S. Axeling. The maximum error is estimated to be 0.001 db.

1965ApJ...142.1149P

ture was remeasured employing the comparison between a room-temperature termination and the cold load immersed in liquid nitrogen, the cold load-attenuator method was repeated using another calibrated attenuator of somewhat different design, and two different warmed loads were used in method (*d*). In no case could any significant difference in result be detected.

With the exception of the direct noise-tube method, which depends upon the calibration of the directional coupler and RF attenuators, all the methods are essentially equally accurate. Owing to the small spread in the final result, we do not feel able to draw any conclusions from the relative differences from the over-all mean in the various methods.

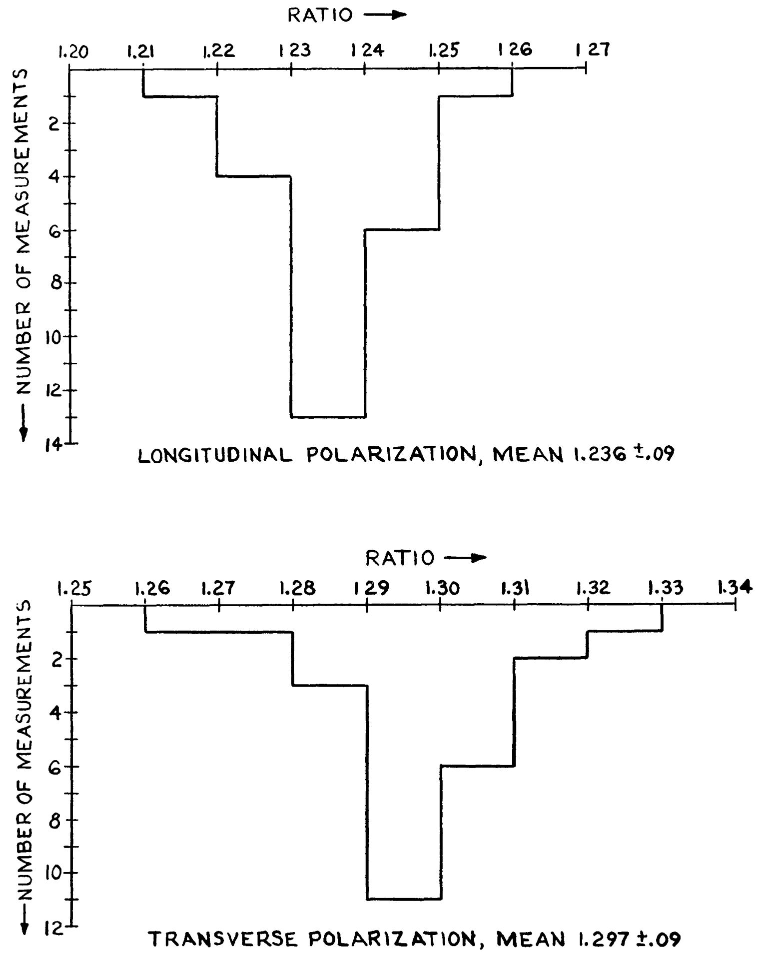

FIG. 2.—Distribution of the ratio of Cas A to noise-tube deflections (corrected for atmospheric absorption).

V. OBSERVATIONS

A total of fifty drift-curve observations, each approximately 40 min in duration, were made on six nights in the fall of 1964. The observations were equally distributed between the two principal planes of polarization of the antenna. The noise tube was turned on at least once during each observation, and the resulting ratio of the power in the output due to the source in the antenna beam to that due to the noise tube was computed and recorded. The results of the observations in the two polarizations are shown in the histogram of Figure 2 (all values have been corrected for atmospheric absorption as explained in § V). The mean values of the observations are 1.236 for longitudinal polarization and 1.297 for transverse polarization. The computed limits for a 99 per cent level of confidence are ±0.7 per cent.

Since the antenna is mounted in an altitude-azimuth configuration, the orientation of the source relative to the principal planes of the antenna pattern changes with hour angle. Furthermore, observations were made alternately in the two polarizations, causing any effect due to linear polarization of the radiation from the source to cancel out of the average.

VI. SKY TEMPERATURE FROM ATMOSPHERIC ABSORPTION

The sky temperature at 4080 Mc/s was measured by recording the change in antenna temperature as the antenna was moved in elevation and then fitting the results to the secant law. The resulting zenith temperature was 2.3° ± 0.3° K, in good agreement with Hogg (1959), DeGrasse, Hogg, Ohm, and Scovil (1959), and Ohm (1961). Taking 270° K as the average temperature at which the atmosphere absorbs, the absorption of the atmosphere as a function of elevation is then computed. Since all observations of Cas A were made at elevations higher than 50°, the correction for atmospheric absorption to the individual values were all less than 1 per cent, introducing a maximum error of less than 0.1 per cent in our final result.

VII. SOURCE-SIZE CORRECTION

The two-dimensional brightness distribution of Cas A has been computed by Thompson and Krishnan (1965) from fan-beam observations at 3.3 Gc/s, and they kindly communicated their result prior to publication. The source is about 4′ in diameter and shows marked limb brightening.

Since the 3-db beam width of our antenna is about 0.8°, the reduction in gain due to the size of Cas A is quite small, and a parabolic approximation to the antenna beam shape is justified. The reduction of gain was measured 4′ from the peak of a number of drift-curves in both polarizations with various directions of motion through the beam. Using the parabolic model the average beam shape was

$$\text{Response} \sim \left[1 - \left(\frac{\theta}{25.2}\right)^2\right],$$

where θ is the angular offset from the center of the beam in minutes of arc. Combining this pattern with Thompson's brightness distribution of Cas A results in a correction of 0.47 per cent.

VIII. RESULTS OF THE ABSOLUTE FLUX MEASUREMENT

The antenna temperature due to Cas A is computed for the two polarizations by multiplying the Cas A–noise-tube ratios obtained from our observations (Fig. 2) by the effective temperature of the noise tube (Table 1). Treating the errors as independent, one obtains 9.57° ± 0.17° K and 10.05° ± 0.17° K for the longitudinal and transverse polarizations, respectively. As has been noted in § V on observations, this result takes atmospheric absorption into account.

We must now combine the antenna temperatures with their corresponding antenna gains as given in § II making a small correction for the finite size of the source in our antenna beam, and average the result to obtain the flux of Cas A. From this we find the flux to be 1.086×10^{-23} W $m^{-2}(c/s)^{-1}$ (average date of observation: September 27, 1964). From a combination of the errors in the antenna measurement and the antenna temperature given above, assuming them independent, the maximum error in our result is found to be 6.3 per cent. For use in comparison with other results (such as in mak-

1965ApJ...142.1149P

ing weighted least-squares fits) where a probable error has been quoted, the use of a 2 per cent probable error is suggested for our value.

It might be of interest to note that the spectrum of Cas A derived by Baars, Mezger, and Wendker (1965) yields 1.092×10^{-23} W $m^{-2}(c/s)^{-1}$ at 4080 Mc/s for the epoch 1964.4. A 1.1 per cent annual decrease would then yield a value of 1.088×10^{-23} W $m^{-2}(c/s)^{-1}$ for the date of our value.

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