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of the

OWENS VALLEY RADIO OBSERVATORY

California Institute of Technology

Pasadena, California

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4. ACCURATE MEASUREMENT OF THE DECLINATIONS OF RADIO SOURCES

by

Richard Bradley Read

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ABSTRACT

The two 90-foot steerable paraboloids of the Owens Valley Radio Observatory were used as a two-element interferometer at 960 Mc/s with various separations along a north-south baseline to measure accurately the declinations of a number of radio sources, most of which were of small diameter. The measured values of declination are tabulated for 110 sources with right ascensions between 0 hours and 14 hours 10 minutes. The standard errors of the measured values range from ± 2.6 seconds of arc to ± 46 seconds of arc with an average of ± 13 seconds of arc. A discussion of the sources of error is included.

I. INTRODUCTION

The identification of radio sources with optical objects is especially valuable to radio astronomy, as such identifications make it possible to obtain additional information about the nature of radio sources by optical means. Moreover, the only known way to estimate the distance of an extragalactic radio source (which is necessary, for example, in order to determine the radio luminosity function) is by measuring its optical red shift. Needless to say, this can only be done for radio sources which have been identified with optical objects.

In attempting to identify a radio source, one examines a plate of the region in question looking for a suitable optical object near the radio position. Normally the search is limited to a rectangular area of a size determined by the estimated errors of the radio position. There is no reason to suppose, however, that there is an optically observable object associated with every radio source. One must therefore exclude from consideration those classes of optical objects which are so numerous as to present a significant probability of lying within the rectangular area purely by statistical chance. If the accuracy of the radio position can be improved, the rectangular search area can be made smaller, and the class of optical objects being considered may be safely broadened (to include, for example, galaxies of a fainter magnitude). Thus the better the accuracy of the radio position, the greater the probability of making an identification.

Of the various published lists of the positions of radio sources there are three lists which, because of the large number of sources they contain and relative accuracy of the measured positions, have been especially useful in attempting to identify radio sources. They are the third Cambridge survey (3C) (Edge, Shakeshaft, McAdam, Baldwin, and Archer 1959), the survey by Mills, Slee and Hill (MSH) (1958, 1960), and the list of accurate positions and fluxes by Elsmore, Ryle, and Leslie (ERL) (1959). The accuracies quoted for the declinations in all three of these lists are, however, substantially poorer than the accuracies quoted for the corresponding right ascensions due to the nature of the observational techniques employed. In an effort to improve the accuracy to which the declinations of radio sources are known, the two 90-foot steerable paraboloids of the Owens Valley Radio Observatory were employed as a two-element interferometer at 960 Mc/s on a north-south baseline. The resulting measured declinations, which are tabulated in Table 4, have an average standard error of about $\pm$ 13 seconds of arc. Although it covers only about half of the observable sky, this table contains the declinations of 110 sources.

II. DESCRIPTION OF THE RECEIVING EQUIPMENT

The arrangement of the components of the receiving equipment is shown by the block diagram of Figure 1. The receivers were of the superheterodyne type, and the crystal mixers were connected by short lengths of cable to the antenna feeds without any preamplification at the signal frequency. The local oscillator frequency was 960 Mc/s and the center frequency of the IF amplifiers was 10 Mc/s with a bandwidth of about 4 Mc/s. No attempt was made to reject the image response of the superheterodyne. Note that the IF amplifiers were split into two sections. The IF preamplifier was located at the prime focus of the paraboloid along with the mixer and amplified the signal sufficiently to allow it to be fed through a long connecting

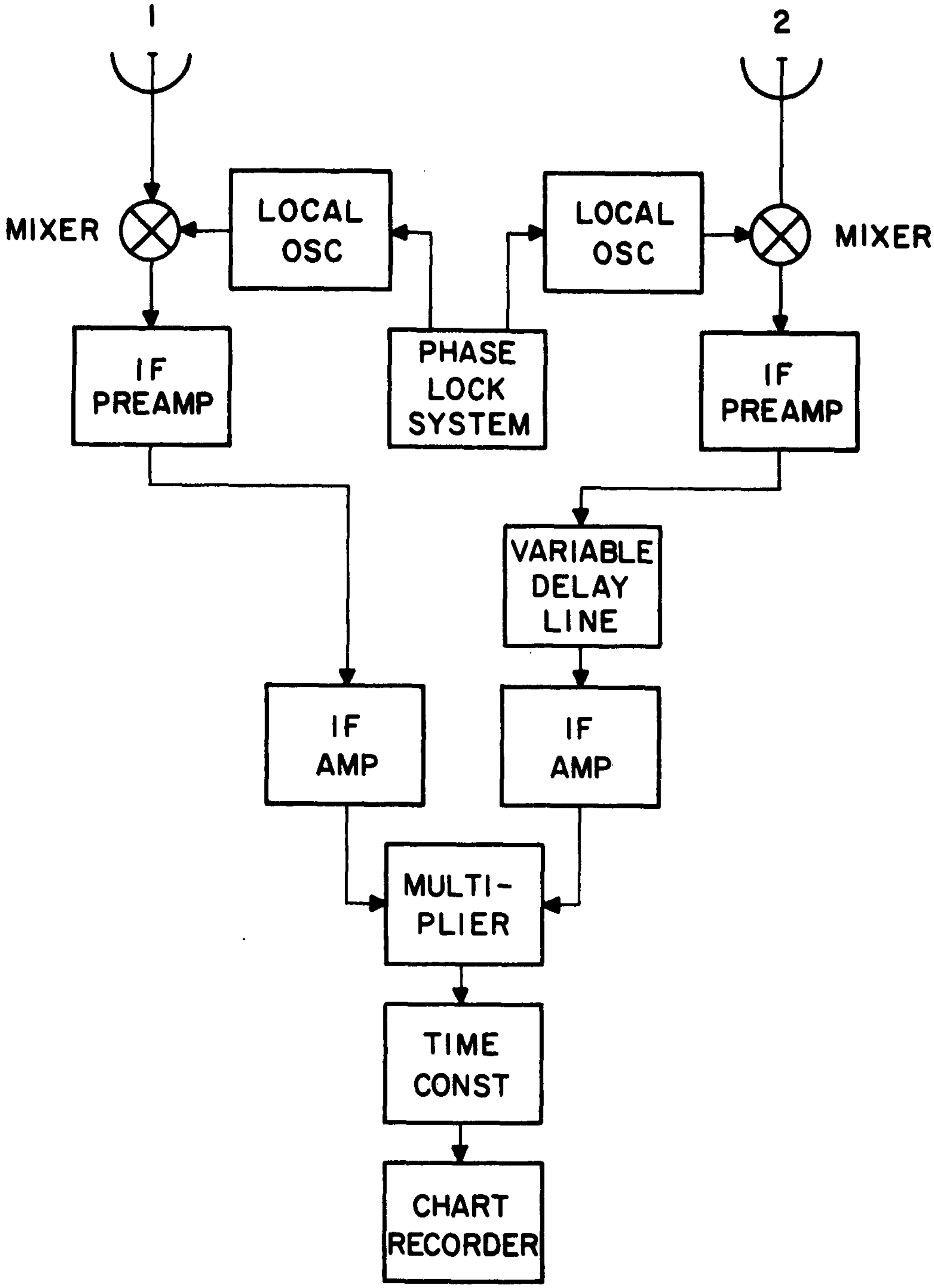

Figure 1. Block diagram of the receiver.

cable to the remainder of the receiver, which was located in the laboratory building.

The phase lock system of the receiver needs special mention, since the observational techniques used for the north-south declination measurements depended upon the ease and precision of the lobe rotation made possible by the system. The phase lock system is shown schematically in Figure 2. The local oscillator power for each half of the receiver was supplied by a separate klystron oscillator which was phase-locked by a closed loop servo system to reference signals of a common, central origin. The high frequency reference signal power required by the system for a satisfactory lock was about six order of magnitude weaker than the available local oscillator power required by the crystal mixers of the superheterodyne receivers. The problem of getting phased local oscillator power to the two antennas when they were being used at large separations was thus greatly simplified. For the 200 and 400-foot spacings the high frequency reference signal was connected to the phase lock servos by means of low-loss coaxial cables. For the larger spacings, however, a different solution had to be found as there was insufficient low-loss coaxial cable available to permit a direct connection at large distances. The low power requirements of the phase lock system for the high frequency reference signal made it possible to transmit the signal to the two antennas from a central location by direct radiation using transmitting and receiving horns. It should be noted that two reference signals were required by the system: a high frequency reference which differed from the local oscillator frequency by 1 Mc/s, and a low frequency reference at 1 Mc/s. This dual frequency scheme circumvented some of the technical difficulties of phase detection and amplification which would otherwise have arisen, and made possible a simple means of lobe rotation.

A sample of the output of the klystron which served as the local oscillator for the receiver was combined in a special mixer with the high frequency reference signal. Since the frequencies differed by 1 Mc/s, a 1 Mc/s beat was present in the output of the special mixer. The 1 Mc/s beat was amplified and then compared in a phase detector with the low frequency reference signal which was also 1 Mc/s. Any phase discrepancy between these two was sensed by the phase detector and applied as an error signal to the repeller of the klystron. Since phase relations are preserved in the heterodyne process and since the reference signals at the separate antennas had a definite phase relationship with each other, the two separate local oscillators also had such a definite phase relationship.

As it will appear later, it is desirable in north-south measurements to be able to rotate the lobes of the interferometer--that is to cause the two local oscillators to have very slightly different frequencies such that their relative phase is a slow, uniform function of time which is accurately known. This was conveniently accomplished in the phase lock system by rotating the phase of the 1 Mc/s reference signal sent to one antenna relative to the phase of that sent to the other. A special 4-plate phase-rotation capacitor fed by appropriate phasing lines was turned by a 1 RPM synchronous motor. An accurate timing mark was generated once each revolution. It was found that the phase rotation of the local oscillators produced in this fashion deviated from the desired linear rotation by only ± 0.9 degree. An accurate measurement of the discrepancy yielded a calibration curve which made it possible to deduce the actual amount of phase rotation to within about one-third of a degree.

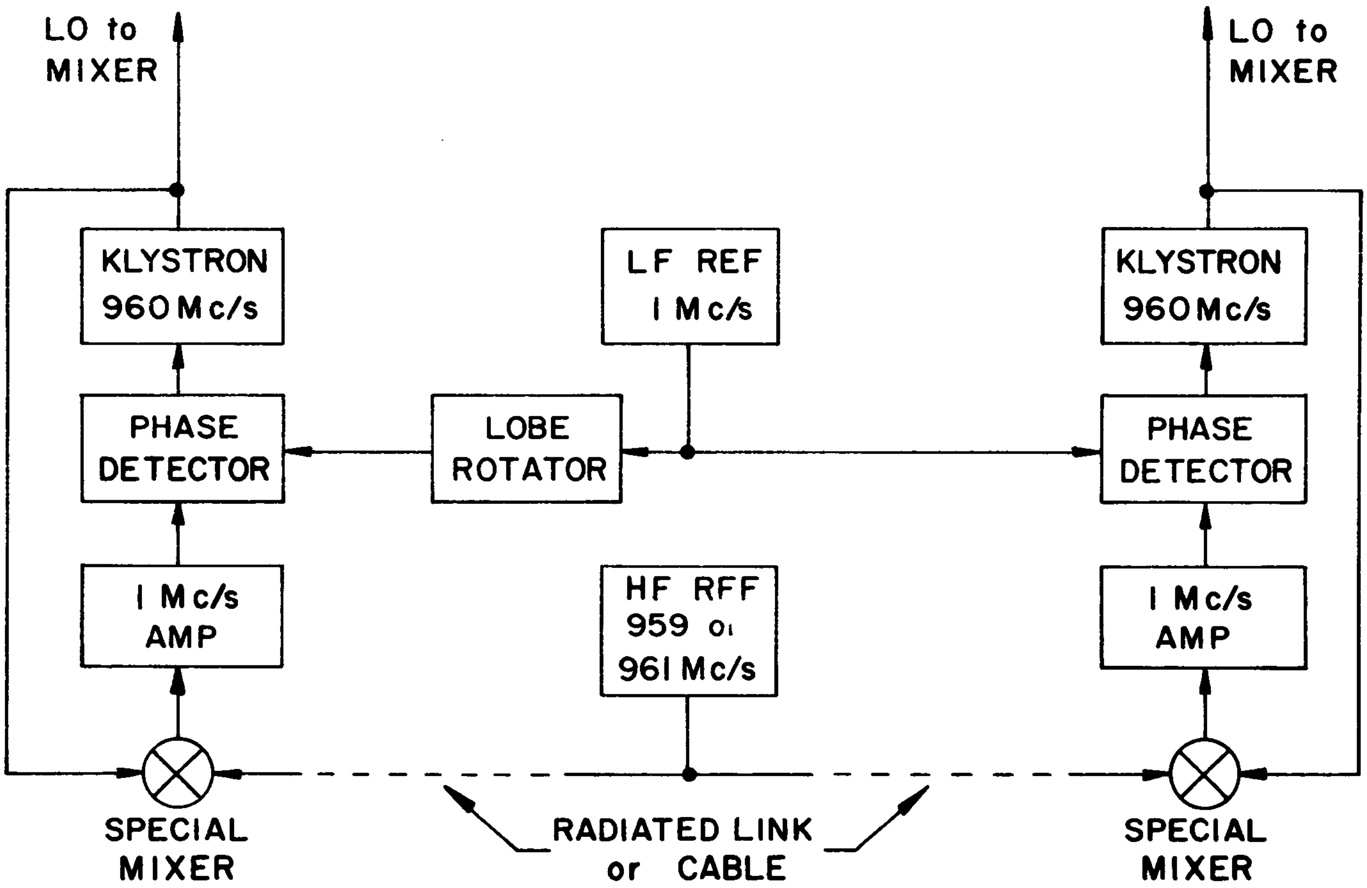

Figure 2. The phase lock system.

III. ANALYSIS OF THE RECEIVER OPERATION

In order to clarify the mathematical analysis of the receiver which is to follow, Figure 3, a simplified block diagram of the receiver, shows only the essential logical functions. Since in position measurements only relative phases are important and not amplitudes, the existence of necessary amplifiers has been ignored. It is assumed for simplicity that the high frequency mixers of the superheterodyne receiver merely multiply the signal by the local oscillator which is assumed to have unity strength. As was mentioned above, no attempt was made in the receiver to reject the image response of the superheterodyne. Indeed, one would be at a loss to say which of the two responses of the receiver was signal and which was image since essentially equal amounts of noise power were received from the source by both responses. To avoid confusion, the responses will hereafter be referred to as upper and lower responses rather than by the misleading terms "signal" and "image".

Let x, y, z be the electrical lengths of the cables connecting the mixer-IF filter combination to the antenna, local oscillator, and multiplier respectively for antenna number 1. Let $x + \Delta x$, $y + \Delta y$, $z + \Delta z$ be the corresponding cable lengths for antenna number 2. Let V be the amplitude of the signal, ω_{LO} be the angular frequency of the local oscillator, and ω_{IF} be the angular frequency to which the IF amplifier is tuned. Then $\omega_{LO} \pm \omega_{IF}$ are the angular frequencies of the upper and lower responses. Since the signal being received by the interferometer is of the nature of random noise, there is no correlation between the upper and lower responses. The principle of superposition may therefore be applied and the effect of the upper and lower responses will be worked out separately by carrying $\pm$ signs, and the combined effect will then be computed by taking the sum of the effects of both responses.

Writing out expressions for the signals at the various points of Figure 3 designated by the letters, we have at (a):

$$V \sin\left[(\omega_{LO} \pm \omega_{IF})\, t\right] \tag{1}$$

at (b):

$$V \sin\left[(\omega_{LO} \pm \omega_{IF})(t - x/c)\right] \tag{2}$$

at (c):

$$\cos\left[\omega_{LO}(t - y/c)\right] \tag{3}$$

and at (d):

$$\begin{aligned} &\tfrac{1}{2} V \sin\left[(\omega_{LO} \pm \omega_{IF})(t - x/c) + \omega_{LO}(t - y/c)\right] \\ &+ \tfrac{1}{2} V \sin\left[(\omega_{LO} \pm \omega_{IF})(t - x/c) - \omega_{LO}(t - y/c)\right] \end{aligned} \tag{4}$$

The IF bandpass filter rejects the first term of expression (4) and introduces a phase shift ϕ. We thus have at (e) after replacing t by $t + \phi/\omega_{IF} - z/c$ and

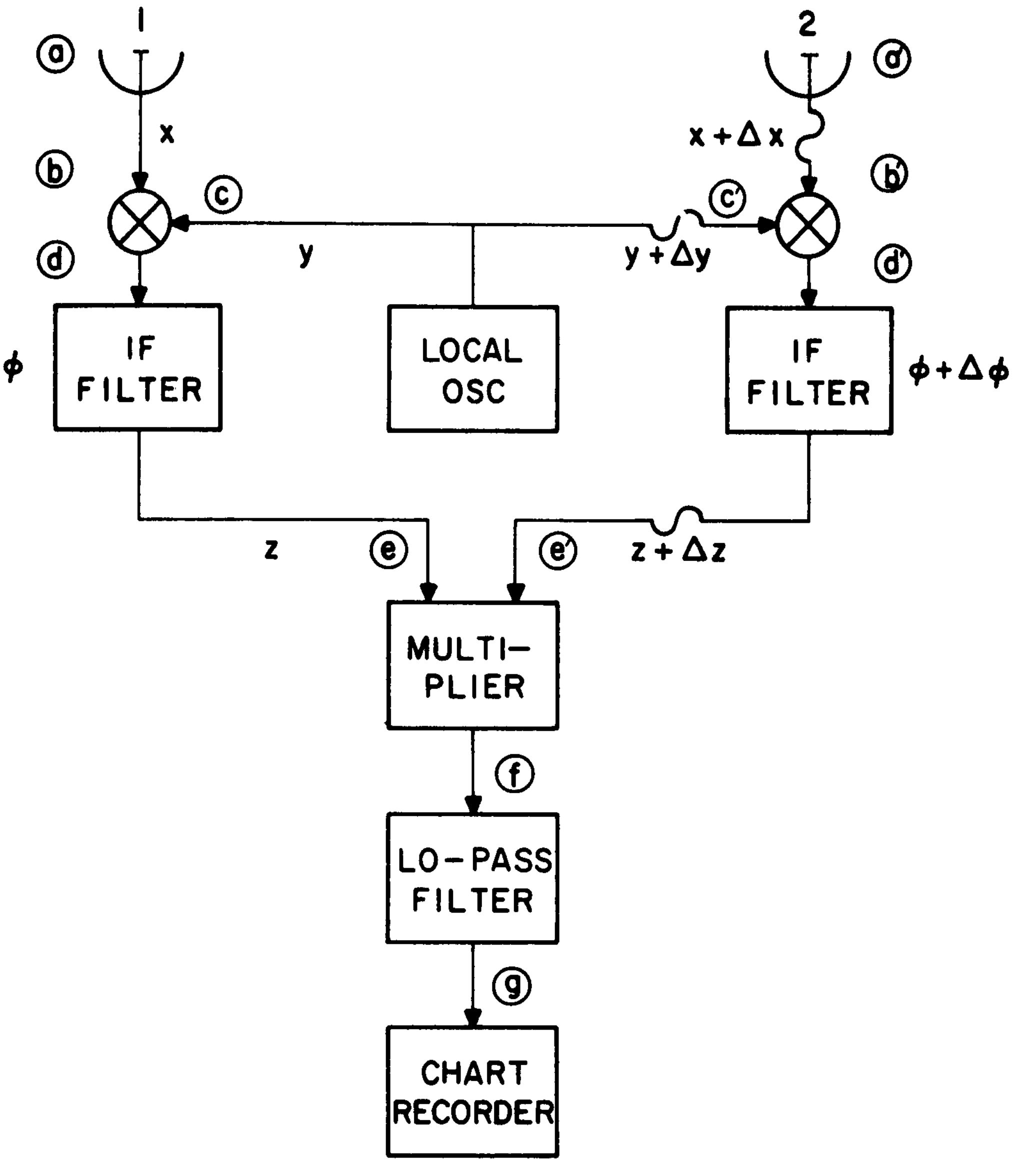

Figure 3. Receiver logic.

simplifying:

$$\pm \frac{1}{2} V \sin\left[\omega_{IF}\left(t - x/c - z/c\right) + \phi \pm \omega_{LO}\left(y/c - x/c\right)\right] \tag{5}$$

A similar calculation can be carried out for the primed letters. If we assume the signal reaching antenna number 2 is delayed by an amount τ compared to antenna number 1 due to geometrical considerations, we find at (e') after making allowance for the different line lengths given above:

$$\pm \frac{1}{2} V \sin\left[\omega_{IF}\left(t - \tau - x/c - \Delta x/c - z/c - \Delta z/c\right) + \phi + \Delta\phi \pm \omega_{LO}\left(-\tau + y/c + \Delta y/c - x/c - \Delta x/c\right)\right] \tag{6}$$

Taking the product of expressions (5) and (6) and employing a trigonometric identity gives as the output of the multiplier at (f):

$$\frac{1}{8} V^2 \cos\left[\omega_{IF}\left(\tau + \Delta x/c + \Delta z/c\right) - \Delta\phi \pm \omega_{LO}\left(\tau + \Delta x/c - \Delta y/c\right)\right]$$
$$- \frac{1}{8} V^2 \cos\left[\omega_{IF}\left(2t - \tau - 2x/c - \Delta x/c - 2z/c - \Delta z/c\right) + 2\phi + \Delta\phi \pm \omega_{LO}\left(-\tau + 2y/c + \Delta y/c - 2x/c - \Delta x/c\right)\right] \tag{7}$$

The low pass filter rejects the second term of expression (7), leaving at (g):

$$\frac{1}{8} V^2 \cos\left[\omega_{IF}\left(\tau + \Delta x/c + \Delta z/c\right) - \Delta\phi \pm \omega_{LO}\left(\tau + \Delta x/c - \Delta y/c\right)\right] \tag{8}$$

Now taking the sum of the effects of the upper and lower responses as discussed above and employing another trigonometric identity, we see that the deflection of the recorder is proportional to:

$$\frac{1}{4} V^2 \cos\left[\omega_{IF}\left(\tau + \Delta x/c + \Delta z/c\right) - \Delta\phi\right] \cos\left[\omega_{LO}\left(\tau + \Delta x/c - \Delta y/c\right)\right] \tag{9}$$

It should be noted that in the derivation of expression (9) a discrete IF frequency ω_{IF} was assumed. Actually, of course, the IF amplifier responds to a band of frequencies so it is necessary to integrate expression (9) over the band-pass of the IF amplifier. This integration is difficult to do explicitly for reasonable forms of the IF frequency response except for a few simple cases. While numerical methods of integration are possible, it is doubtful that their use would be very enlightening since the exact form of the IF frequency response is not accurately known, and a qualitative approach gives results sufficiently good for the purpose at hand. Of the simple frequency response functions which can be easily integrated, a Gaussian is perhaps the most realistic. A large number of cascaded tuned circuits tend toward a Gaussian response, and the receiver used had, indeed, a fair number of such cascaded circuits. If one makes the further simplifying assumption that the differential phase shift $\Delta\phi$ is not a function of frequency, then the required integration yields a recorder deflection of the form:

$$\frac{1}{4}V^2 \exp\left[-\frac{1}{2}\left(\tau+\Delta x/c+\Delta z/c\right)^2(BW)^2\right]\cos\left[\omega_{IF,0}\left(\tau+\Delta x/c+\Delta z/c\right)-\Delta\phi\right]$$
$$\cos\left[\omega_{LO}\left(\tau+\Delta x/c-\Delta y/c\right)\right] \qquad (10)$$

where $\omega_{IF,0}$ is the IF center frequency and BW is the bandwidth of the IF amplifiers. Note that the effect of the bandwidth integration is merely to multiply expression (9) by a Gaussian shaping function which depends on the bandwidth. If the form of the frequency response function is not a Gaussian or if the differential phase shift is a function of frequency, the shaping function may have a somewhat different shape. No matter what frequency response or phase shift is assumed, however, it should be noted that the last cosine factor of expression (9) will survive the integration unchanged as it is not a function of ω_{IF}. Thus $\cos\omega_{LO}(\tau + \Delta x/c - \Delta y/c)$ will appear as a multiplicative factor in the expression for the recorder deflection irrespective of the bandwidth integration. The observed form of the recorder deflection is in good agreement with expression (10).

The delay of the signal reaching antenna number 2 relative to antenna number 1, τ, may be evaluated by referring to Figure 4 The two antennas are separated by a baseline distance D, and the signal arrives from such a direction as to make an angle θ with the normal to the baseline. As indicated in the figure, we may immediately write:

$$\tau = D/c \sin\theta \qquad (11)$$

In order to express θ in terms of celestial coordinates it is necessary to solve the spherical triangle shown in Figure 5. P is the north celestial pole, S is the position of the radio source in question, and A is the interferometer pole--that is the intersection of the baseline from antenna number 2 to antenna number 1 with the celestial sphere. H and δ are the hour angle and declination of the source, respectively. Similarly, h and d are the hour angle and declination of the interferometer pole. θ is as defined in Figure 4. By the relations in a spherical triangle we may write:

$$\cos\left(\tfrac{1}{2}\pi-\theta\right)=\cos\left(\tfrac{1}{2}\pi-d\right)\cos\left(\tfrac{1}{2}\pi-\delta\right)+\sin\left(\tfrac{1}{2}\pi-d\right)\sin\left(\tfrac{1}{2}\pi-\delta\right)\cos(H-h) \qquad (12)$$

which simplifies to:

$$\sin\theta = \sin d \sin\delta + \cos d \cos\delta \cos(H-h) \qquad (13)$$

Of the three factors of expression (10), the last factor, $\cos\left[\omega_{LO}(\tau + \Delta x/c - \Delta y/c)\right]$, is a much faster function of τ than the other two since the local oscillator frequency, ω_{LO}, is about two orders of magnitude greater than either the IF center frequency, $\omega_{IF,0}$, or the IF bandwidth. The last factor, then, is the one which contains the best positional information while the other two factors merely complicate the situation by effecting an undesirable attenuation of the signal for certain directions of arrival. This latter dif-

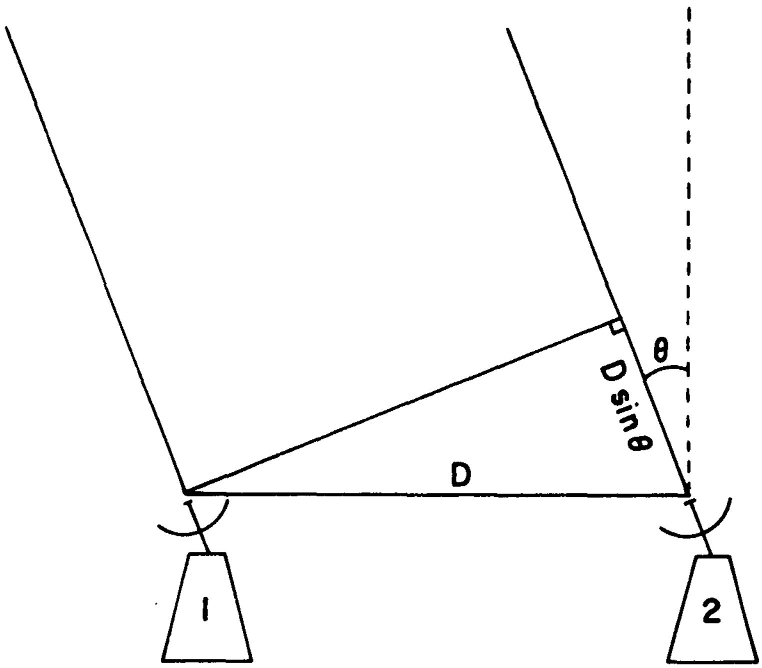

Figure 4. Ray diagram showing the extra path length, D sin θ, traversed by the radiation striking antenna No. 2.

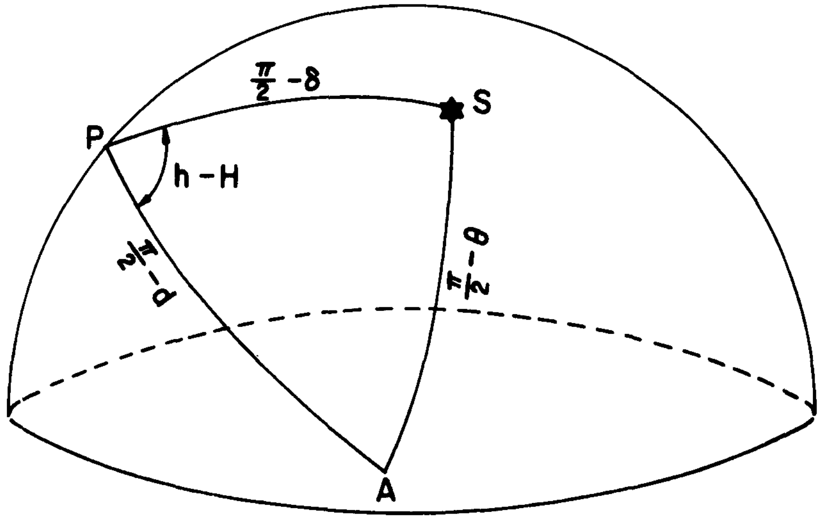

Figure 5. The celestial hemisphere showing the relaticnships between the various angles.

ficulty is easily got around, however, by the simple expedient of adjusting the differential IF cable length Δz by means of a variable delay line for each source observed such that the product of the first two factors of expression (10) (which both contain Δz) is always maximized. The correct adjustment of the delay line for a given source is easily computed from the known approximate position of the source. Note in particular that the last factor of expression (10), the one of interest, does not contain Δz and is therefore not affected by the adjustment of the delay line. Thus slight maladjustments of the delay line, or for that matter phase shifts within the IF amplifiers, do not affect the accuracy of the measured positions. This is a direct consequence of accepting equally both the upper and lower responses of the superheterodyne receiver. (The desired last factor is effectively separated out for phase measurement purposes both by maximizing the other factors and hence minimizing their variation and by measuring the phase by means of zero crossovers.)

If we substitute equations (11) and (13) in the last factor of expression (10), we have for the significant term of the recorder deflection:

$$\cos\left\{(\omega_{LO}/c)\left[D\sin\delta\sin d + D\cos\delta\cos d\cos(H-h) + \Delta x - \Delta y\right]\right\} \qquad (14)$$

IV. REDUCTION OF THE OBSERVATIONS

The lobe rotator was used for the north-south declination measurements made at the 200 and 400-foot spacings of the antennas. The position of the midpoint of two successive zero crossovers (to minimize errors due to improper choice of zero level) of the chart record was measured relative to the once per revolution timing marks placed on the record by the lobe rotator. The measured value in terms of a fraction of a lobe was denoted by the letter η. (The successive zero crossovers were always paired in such a way that their midpoint corresponded to a positive maximum of expression (17).) After replacing the Δy of expression (17) by $\Delta y + 2\pi\eta c/\omega_{LO}$ and requiring the cosine to be +1, we have:

$$\cos\left\{(\omega_{LO}/c)\left[D\sin\delta\sin d + D\cos\delta\cos d\cos(H-h) + \Delta x - \Delta y\right] - 2\pi\eta\right\} = +1 \qquad (15)$$

which requires:

$$(\omega_{LO}/c)\left[D\sin\delta\sin d + D\cos\delta\cos d\cos(H-h) + \Delta x - \Delta y\right] - 2\pi\eta = 2\pi N \qquad (16)$$

where N is an integer. If we now define $t_B = D/c$, $\nu_{LO} = \omega_{LO}/2\pi$, and $\Delta t = (\Delta y - \Delta x)/c$:

$$t_B\left[\sin\delta\sin d + \cos\delta\cos d\cos(H-h)\right] = (N+\eta)/\nu_{LO} + \Delta t \qquad (17)$$

The local oscillator frequency, ω_{LO} , was accurately measured for each observation and was kept nearly constant throughout the night. If in a north-south interferometer with a level baseline antenna number 1 is to the north of antenna number 2, h is π radians and d is the colatitude of the observatory. In practice, of course, one cannot rely on the direction of the baseline being exactly lined up, so we shall write:

$$h' = h - \pi \tag{18}$$

and

$$\phi' = \pi/2 - d \tag{19}$$

where h' is approximately zero, and ϕ' is approximately the latitude of the observatory. Substituting these values in equation (17) yields:

$$t_B\left[\sin\delta\cos\phi' - \cos\delta\sin\phi'\cos(H-h')\right] = (N+\eta)/\nu_{LO} + \Delta t \tag{20}$$

Since the observations were all made quite close to meridian transit, we may ignore the higher order terms of the series expansion of the hour angle cosine and, after rearranging, write:

$$t_B\sin(\delta-\phi') = (N+\eta)/\nu_{LO} + \Delta t - \tfrac{1}{2} t_B (H-h')^2\cos\delta\sin\phi' \tag{21}$$

The $(H-h')^2$ factor of equation (21) was forced to be very small by restricting the observations to be within ten minutes of meridian transit. One may therefore solve equation (21) for a highly accurate value of sin $(\delta - \phi')$ by inserting an imperfect value of cos δ. Equation (21) is the working equation used for determination of declinations. η , H, and ω_{LO} are the measured quantities. N is an integer which is chosen for each source on the basis of the already known approximate declination. Δt is a phase calibration term which is assumed to vary smoothly during the night as a result of equipment drifts and is determined empirically by observations of sources whose declinations are known (calibrators). t_B, ϕ', and h' are instrumental parameters having to do with the geometry of the interferometer. In order to minimize errors, measurements were made on several successive lobes of a record and the declination of the source was computed from the average of these measurements. (Since the hour angle, H, was different for each successive lobe measured, it was necessary to apply the last term of equation (21) separately to each measurement before taking the average.)

A somewhat different analysis is necessary for the declination measurements made at the 1600-foot north-south spacing. These measurements were originally undertaken for a different purpose and the lobe rotator was not used. They consisted of two observations of each source symmetrically spaced about meridian transit at an hour angle (usually 1/2 to 1 hour) sufficiently large to allow the apparent motion of the sky due to the rotation of the earth to produce lobes of a reasonably short period (approximately 4 minutes). The lobe pattern of the north-south interferometer when the lobe rotator is not used is symmetrical about meridian transit (or more precisely about H = h'). The total change in hour angle between corresponding zero crossovers before and after transit was measured by determining the total elapsed sidereal time between them. Let H_1 and H_2 be the hour angles of corresponding zero crossovers before and after transit. Then from the condition for a zero crossover of the recorder deflection we have:

$$(\omega_{LO}/c)\left[D\sin\delta\sin d + D\cos\delta\cos d\cos(H_1 - h) + \Delta x \cdot \Delta y\right] = (M+\tfrac{1}{2})\pi \qquad (22)$$

$$(\omega_{LO}/c)\left[D\sin\delta\sin d + D\cos\delta\cos d\cos(H_2 - h) + \Delta x - \Delta y\right] = (M+\tfrac{1}{2})\pi \qquad (23)$$

where M is an integer. The angular frequency of the local oscillator, ω_{LO}, was held constant at the same measured value for both halves of the observation. If we assume that Δx and Δy do not change significantly between the two halves of the observation, and if we make the same substitutions made in equations (17) and (20), we have after manipulation:

$$t_B\sin(\delta - \phi') = (M+\tfrac{1}{2})/2\nu_{LO} + \Delta t - t_B\left\{1 - \cos\left[\tfrac{1}{2}(H_2 - H_1)\right]\right\}\cos\delta\sin\phi' \qquad (24)$$

Equation (24) is the working equation which is solved for δ by an iterative procedure similar to that used for equation (21). As before, several independent measurements of each record were averaged together, and the instrumental phase term, Δt, was determined empirically by observations of calibrators.

V. CALIBRATION OF THE INSTRUMENT

No attempt was made to measure declinations on an absolute basis. The declinations were measured, rather, relative to the known declinations of certain sources which were used as calibrators. The accuracy of the measured declinations is thus directly dependent upon the accuracy of the assumed declinations of the calibrators.

The sources normally used as calibrators are those sources which have been identified with optical objects. The position of the center of the optical object is taken to be the position of the effective center of the radio emission. While one expects a fair degree of correspondence between the radio and the optical positions of an identified object, the correspondence cannot in general be expected to be exact. For example, it is well known that in the case of certain identified double radio sources the radio and optical emissions cannot both be coming from the same region of the sky, since the separation of the two components of the radio double is much greater than the apparent diameter of the optical object. It is reasonable to suppose, however, that if a radio source and its optical identification both have a rather small overall angular diameter, the radio and optical positions will correspond within some fraction of these diameters. Thus it would appear that small angular diameter should be used as a criterion for the selection of calibrators.

The sources used as calibrators for the declination measurements were all of small angular diameter. All but two of them are listed as "not resolved" by Maltby and Moffet (1962). These two (3C 218 and 3C 274) are both halo-core type radio objects and are given less weight than the other calibrators. At the 200 and 400-foot antenna spacings, use was made of several sources as secondary calibrators. The declinations of these sources were measured very accurately at the 1600-foot spacing, and the values thus found were used for secondary calibration at the closer spacings. All calibrators are listed along with the assumed values of declination in the tables.

The calibration of the instrument involves the determination of four instrumental parameters: the h', t_B, ϕ', and Δt of equations (21) and (24). Of these four quantities, the first three are functions of the geometrical relationship of the antennas and are assumed to be constant for all observations made at the same spacing of the antennas. The fourth quantity, Δt, represents a phase drift of the receiving equipment and is assumed to be a slowly varying function of time during the observing night.

The quantity h', which represents an azimuth error of the baseline, was determined by careful surveying of the relative positions of the two antennas. The magnitude of h' was found to be less than 2 seconds of time for both the 200 and 400-foot spacings. For simplicity it was decided to assume the h' was zero for these spacings. The error in so doing is a function of the hour angle at which the observations were made and is essentially zero for observations made at meridian transit In so far as was possible, the observations were indeed made at meridian transit, and in no case did the magnitude of the hour angle of an observation exceed 10 minutes of time. The error due to the assumption of h' equal zero was therefore no greater than 0.0015 of a lobe. This is much less than other errors, and hence the simplifying assumption does not significantly affect the accuracy of the measured declinations. The quantity h' does not appear in equation (24), the equation for the 1600-foot observations, and hence does not have to be evaluated for that spacing.

The quantity t_B, which is a measure of the spacing of the antennas, was determined for each spacing by finding the value of t_B which best fit the observations of the calibrators. In the case of the 200 and 400-foot spacings the determinations were based on the best fit to a number of calibrators. Because of the small number of sources observed at the 1600-foot spacing, however, the determination of t_B for that spacing was based on two calibrators only: 3C 48 and 3C 71. Allowance was made in all cases for the time variation of Δt. Using subscripts to distinguish between the 200, 400, and 1600-foot spacings, the values which were determined are as follows: $t_{B\,200} = 203.393 \pm 0.007$ nanosecond, $t_{B\,400} = 406.661 \pm 0.014$ nanosecond, and $t_{B\,1600} = 1626.798 \pm 0.050$ nanosecond.

As an additional check on the values determined for t_B, the 200 and 400-foot observations were intercompared by the following procedure. Thirty-five sources were chosen which were observed at both spacings and which were known by the angular size work of Maltby and Moffet to be unresolved "point" sources for these antenna spacings. The assumption was made that there would be no change in the apparent declinations of these sources between the 200 and 400-foot spacings. The unknown phase calibration term, Δt, was eliminated by considering only pairs of sources which were observed on the same night at nearly the same time and by assuming Δt to be the same for the two observations of each pair. This procedure yielded 131 simultaneous equations in two unknowns: the relation between the 200 and 400-foot values of t_B and also the relation between the 200 and 400-foot values of ϕ'. The equations were solved by a least squares procedure which gave the following results:

$$2\, t_{B\ 200} - t_{B\ 400} = 0.121 \pm 0.012 \text{ nsec} \tag{25}$$

and

$$\phi'_{400} - \phi'_{200} = 24'' \pm 14'' \tag{26}$$

The values of t_B for the 200 and 400-foot spacings given above, however, require:

$$2\, t_{B\ 200} - t_{B\ 400} = 0.125 \pm 0.016 \text{ nsec} \tag{27}$$

which is in good agreement with equation (25).

The quantity ϕ', is approximately equal to the latitude of the observatory, but differs from the true latitude by the amount the baseline differs from level. In changing the spacing of the antennas, the south antenna remained fixed and the north antenna was moved to various stations along the north-south track. The assumption was made that the north antenna was placed at the same height relative to the caisson heads at each station. This assumption combined with the known heights of the caisson heads gave the relative heights of the north antenna at the various stations within an estimated standard error of ± 0.3 inch. The relative heights thus obtained were combined with the relation between the 200 and 400-foot values of ϕ' given in equation (26) and with the known latitude of the observatory to give the following values for ϕ': $\phi'_{200} = 37^\circ 13' 06'' \pm 38''$; $\phi'_{400} = 37^\circ 13' 30'' \pm 29''$; $\phi'_{1600} = 37^\circ 13' 40'' \pm 06''$.

The receiver phase calibration term, Δt, was determined by observations of the calibrators and was plotted as a function of sidereal time for each observing night. A simple smooth curve was drawn in each case so as to give a reasonably good fit with the experimental points determined by the calibrators. The curves were then used for the reduction of the observations: the appropriate value of Δt for each source being read from the curve for the time of the observation. Several of the Δt curves are reproduced in the appendix.

VI. DISCUSSION OF ERRORS

1. Random Errors

The magnitude of the random errors was evaluated empirically for the 200 and 400-foot observations as follows. Only sources for which three or more independent observations had been made at the same antenna spacing were considered. The deviations of the individual observations from the average were examined, and a standard deviation of a single observation was computed for each source. An attempt was then made to correlate these deviations with the intensities of the sources. The analysis was carried out independently for the 200 and 400-foot spacings, but the deviation expressed as a fraction of a lobe was essentially the same function of intensity for both spacings. The deviation versus intensity relation thus found is as follows:

$$\sigma = 10^{-3}\left[50 + (67/I)^2\right]^{1/2} \tag{28}$$

where σ is the standard deviation per observation expressed as a fraction of a lobe, and I is the apparent intensity of the source expressed in units of 10^{-26} Watt meter^{-2} (c/s)$^{-1}$. The result is in good agreement with what one would expect on theoretical grounds. The first component of the standard deviation per observation is independent of intensity and represents equipmental instabilities and random inaccuracies in the phase calibration of the receiver. The second component of the standard deviation per observation is inversely proportional to intensity and represents the effect of signal to noise ratio. A plot of equation (28) is shown in Figure 6.

In the case of the 1600-foot observations there were an insufficient number of different sources observed to carry out an error versus intensity analysis. The standard deviation per observation was therefore computed individually for each source on the basis of the root mean square of the deviations of the individual observations from the mean.

The standard deviation of the average of n independent observations, σ_n, was computed from the standard deviation per observation, σ, by the usual relation:

$$\sigma_n = n^{-\frac{1}{2}}\sigma \tag{29}$$

2. Systematic Errors

Three sources of systematic error are considered that significantly affect the accuracy of the measured declinations. They are:

a) uncertainty of calibrator declinations,
b) wrong instrumental parameters,
c) confusion.

a) The declinations of the sources were measured by a relative method and are hence dependent on the accuracy of the positions assumed for the calibrators. While it is felt that the optical identifications of the radio sources used as calibrators are all correct, there are still small but significant uncertainties in the correct radio positions. The origin of these uncertainties is two-fold. First, the optical positions of the sources are not always known to sufficient accuracy. In this connection it should be noted that the author is indebted for many of the optical positions used to Roger Griffin, who recently made accurate measurements using plates taken with the 48-inch Schmidt and the 200-inch Hale Telescope on Palomar Mountain. Second, there is no reason to believe that the radio and optical centers of these sources exactly coincide. It is reasonable to suppose, however, that the discrepancy is only a small fraction of the radio and/or optical diameter of the source. This means that for the small diameter calibrators

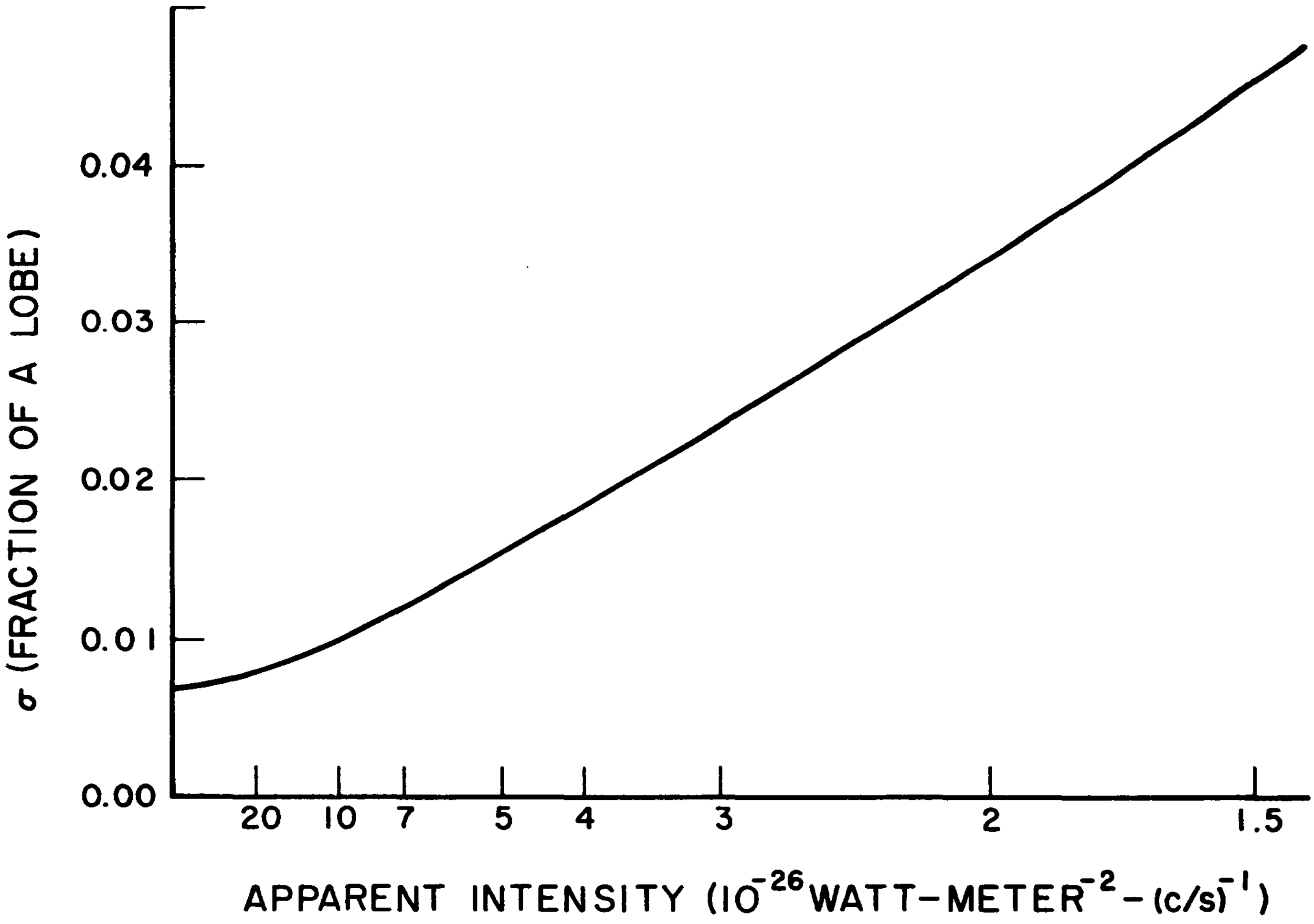

Figure 6. Random error for one observation at the 200 or 400-ft spacing as a function of apparent intensity.

chosen for these measurements the uncertainty of the radio position is typically of the order of one or two seconds of arc.

b) Systematic errors will also arise if the values adopted for the instrumental parameters t_B and ϕ' are incorrect. The estimated standard errors of the values adopted for these parameters at the various antenna spacings were given along with the values themselves in Section VI. The magnitude of the effect of these errors on a measured value of declination depends on the declination of the source in question. The phase calibration function, Δt, was determined in such a way as to give the correct declinations for the calibrators on the basis of the adopted values of t_B and ϕ'. The error in a measured declination due to incorrect values of these parameters must therefore be small for a source observed at roughly the same time as a calibrator if the declinations of the source and the calibrator are approximately the same. If the declinations differ by a large amount, however, the error might be large. Although the calibrators do not, of course, all have the same declination, they are, as it happens, confined to a more limited range of declinations than are the sources whose declinations were measured. The error for declinations measured at the 400-foot spacing, for example, is typically less than 5 seconds of arc for declinations between +5 and +65 degrees, but rises to about 10 seconds of arc for a declination of -5 degrees. For more southerly declinations the error increases rapidly, reaching about 30 seconds of arc at a declination of -24 degrees.

c) An important source of error in the measured positions, but one which is difficult to evaluate, is confusion. By confusion is meant the inadvertant and often unwitting simultaneous observation of more than one radio source due to the close spatial proximity of the sources The interpretation of the aggregate effect as being due to a single source results in error. One common form of confusion which frequently afflicts interferometric position measurements is of no importance for these measurements. That is the confusion produced by an intense source which is spatially some distance from the source being observed. The 90-foot paraboloids, which are the primary elements of the interferometer, are sufficiently directive to discriminate effectively against this type of confusion. Signals from sources substantially off the center of the beams of the paraboloids are severely attenuated, the attenuation exceeding 40 decibels for sources more than a few degrees from the center of the beams. Thus even the most intense sources in the sky can cause no appreciable confusion if they are more than a few degrees from the source being observed. A second form of confusion, that caused by two or more sources of comparable intensity, both lying within the main beam of the antennas, is also of little consequence. The reason for this is that almost all the sources included in these declination measurements were also observed extensively by Maltby and Moffet (1962) with the same instrument in the angular size program and are classified as to their multiplicity and complexity. Thus we are "put on our guard" in the interpretation of the measured positions for those sources determined by Maltby and Moffet to be multiple or complex. The type of confusion that presents the greatest problem to accurate positions is that in which the main beam of the antenna sees in addition to the principal source being observed one or more unrelated sources which are substantially weaker than the principal source--say by a factor of five or more. Such a situation could have escaped detection as being multiple or complex by the angular size program, but could still significantly affect the measured positions, particularly in those cases where the position has otherwise been measured to a high degree of accuracy. It would be well beyond the scope of a primarily experimental paper to attempt a theoretical analysis of this problem, but some information as to its magnitude can be gleaned from an analysis of the experimental data. The type of confusion with which we are concerned here would not in general produce the same shift in apparent position at different spacings of the elements of the interferometer. A group of 67 sources was considered which were observed at both the 200 and 400-foot spacings and for which no significant phase shifts were predicted by Maltby and Moffet results. The observed differences in the apparent declinations of these sources measured at the two spacings were compared with the corresponding composite standard errors predicted by equation (29). A total of eight sources had declination differences exceeding 1.65 times the composite standard error (90th percentile). They were 3C 23, 3C 27, 3C 55, 3C 75, 3C 86, 3C 234, 3C 265, and 3C 270. The Maltby and Moffet amplitude-spacing information for these eight sources was reexamined for any evidence of confusion. In four cases there were minor wiggles in the amplitude spacing plots which had been overlooked in the original work and which were of a sufficient amplitude to account for the observed discrepancies. These four cases have been designated "possibly confused" in Table 4. On this basis one might suspect that of the order of 6% of the positions given in Table 4 are in error due to confusion by amounts significantly greater than the quoted errors.

VII. TABULAR DATA

The observations used for determining declinations were made in three groups. The first group of observations was made with the antennas separated by a distance of 200 feet along a north-south baseline on successive nights from the night of 1960 November 26/27 through the night of 1960 December 6/7, with the exception of the night of 1960 December 1/2 which was omitted due to high winds. During the ten nights of observation a total of 421 observations were made of 123 sources.

The second group of observations was made with the antennas separated by a distance of 400 feet along a north-south baseline on successive nights from the night of 1960 December 18/19 through the night of 1960 December 23/24. During the six nights of observation, a total of 173 observations were made of 90 sources.

The third and last group of observations was made with the antennas separated by a distance of 1600 feet along a north-south baseline on successive nights from the night of 1961 February 4/5 through the night of 1961 February 8/9. During the five nights of observation a total of 35 observations were made of 8 sources.

All observations were corrected for precession and all positions are tabulated in terms of 1950.0 mean positions. The precession corrections included the higher order terms of nutation and aberration as computed from the Besselian day and star numbers. The corrections were computed, however, only for a mean day of each group of observations and applied to all observations of that group.

It can be shown that for zenith angles of less than 75 degrees, if one computes the atmospheric refraction on the basis of a plane parallel stratified atmosphere, the result will differ from the true refraction by less than 1 second of arc (Campbell 1913). If now the interferometer consists of two elements lying in a plane parallel to the planes of stratification, the existence of atmospheric refraction can produce no change in the observed quantity, the difference of the arrival times of the radiation at the two antennas, since the effect of the refraction is to delay the arrival of the radiation at the antennas by precisely the same amount in both cases (Mills 1952). Accordingly no corrections for atmospheric refraction have been applied to the observations.

Ionospheric refraction, however, cannot be treated on the basis of a plane parallel stratified model. Smith (1952) gives as the formula for ionospheric refraction:

$$R = \frac{e^2 n}{2\pi m r \nu^2} \tan Z \sec^2 Z \quad . \qquad (30)$$

where e is the charge of the electron, m is its mass, n is the total number of electrons per unit area, r is the radius of the earth, Z is the zenith angle, and ν is the frequency of interest. If one uses Smith's value for n of 1.6×10^{13} electrons per square centimeter and sets ν = 960 Mc/s, the refraction, R, is:

$$R = 0''.22 \tan Z \sec^2 Z \qquad (31)$$

The largest zenith angle of any of the sources observed was 67°. The corresponding ionospheric refraction is 3.4 seconds of arc. The magnitude of the refraction decreases very quickly with decreasing zenith angle. For the more moderate zenith angle of 40° it is only 0.3 seconds of arc. Since the effect of ionospheric refraction is very much less than the quoted standard errors of the measured declinations, no corrections for this form of refraction have been made.

The numerical results of the north-south declination measurements are contained in four tables. Since the declinations measured at the 1600-foot spacing were used for secondary calibration purposes at the closer spacings, the 1600-foot data are given first in Table 1. The sources used as calibrators at this spacing are listed along with the assumed declinations in the first part of Table 1 and are followed in the second part by the measured values of declination. The errors quoted in Table 1 are standard errors and are computed from the observed night to night repeatability of the measured declinations. These errors do not include any allowance for systematic effects.

The calibrators used for the 200 and 400-foot measurements are listed in Table 2 along with the assumed declinations.

Table 3 contains the results of the 200 and 400-foot declination measurements. The errors quoted are the standard errors predicted by equation (29). These errors do not include any allowance for systematic effects. As an additional aid in determining the amount of credence to be assigned a particular measured value, the number of independent observations that have been averaged into that value is also given.

In order to put the data in a more generally useful form, Table 4 has been prepared. The declinations listed are appropriately weighted averages of the various measurements. All measurements for which the Maltby and Moffet (1962) angular size results predict an excessive phase shift have been excluded from the averages. Because of the lack of reliable calibrators during the early evening portion of the 200 and 400-foot observations, and because of the large equipmental drifts expected during this period, sources observed prior to 0 hours local sidereal time were omitted from Table 4. Sources which were observed only once were also omitted. The quoted errors include allowances for all sources of error (including systematic errors) mentioned in Section VII with the exception of errors due to confusion. As an aid in interpreting the listed declinations, the Maltby and Moffet source type classification has been given when available.

The declinations of two of the sources given in Table 4 are in need of special comment. It will be noted that optical rather than radio declinations have been listed for 3C 48 and 3C 295. The assumed declinations of these two calibrators have entered so heavily into the computations that a meaningful radio position cannot be quoted for these two sources. On the basis of good agreement with the other calibrators, however, one can conclude that the radio declinations of 3C 48 and 3C 295 must not differ from the quoted optical declinations by more than about 2 seconds of arc.

Although it is felt that the correct values of the integer N of equation (21) have been chosen for all the sources listed in the tables, it is possible that an error may have been made in one or two isolated cases. In such an eventuality the tabulated position would be in error by exactly one lobe. The size of the lobes is of course dependent on both the spacing of the antennas and on the declination of the source. For the 200-foot spacing the lobe size is given by:

$$(0^\circ\ 17'\ 36'')\ \text{secant}\ (\delta - \phi') \qquad (32)$$

The lobe size for the 400-foot spacing is exactly half of this.

TABLE 1

Declination Observations at the 1600-Foot North-South Antenna Spacing

Part 1: Assumed Declinations of Calibrators Used

Source	Declination (1950.0)
3C 48	32° 54' 19"9
3C 71	-00 13 31.5
3C 171	54 12 49
3C 295	52 26 13.6

Part 2: Measured Declinations

Source	Declination (1950.0)	Std Error*	No. of Obs
3C 48	32° 54' 20"0	0"53	3
3C 71	-00 13 31.7	0.50	4
3C 123	29 34 09.0	0.40	4
3C 147	49 49 38.9	0.40	4
3C 171	54 12 49.3	0.28	5
3C 196	48 22 05.7	0.34	5
3C 274	12 39 57.6	0.22	5
3C 295	52 26 13.6	0.14	5

TABLE 2

Calibrators Used for Observations at the 200 and 400-Foot North-South Spacings

Source	Declination (1950.0)	Remarks
3C 433	24° 51' 36".3	optical (mean of double)
23-112	-12 23 56.3	optical
3C 48	32 54 19.9	optical
3C 71	-00 13 31.5	optical
3C 78	03 55 13	optical
3C 123	29 34 09	radio--1600 ft N-S
3C 147	49 49 39	radio--1600 ft N-S
3C 171	54 12 49	optical
3C 196	48 22 06	radio--1600 ft N-S
3C 212	14 21 27	radio--lunar occultation (Hazard 1961)
3C 218	-11 53 04.0	optical (mean of double)
3C 254	40 53 57	optical
3C 274	12 39 57.6	radio--1600 ft N-S
3C 295	52 26 13.6	optical

TABLE 3

Declinations Measured at the 200 and 400-Foot North-South Antenna Spacings

Source	Class	200-Foot Spacing declination (1950.0)	std error*	No. of obs	400-Foot Spacing declination (1950.0)	std error*	No. of obs
3C 433	N	24°51'38"	±3".4	7			
3C 436	N	27 56 47	±8.4	4			
3C 438	N	37 46 28	±5.0	4			
3C 441	N	29 14 08	±13.4	2			
3C 442	S	13 35 40	±18.7	3			
3C 444	(S)	-17 15 57	±11.1	2			
3C 445	(E)	-02 20 58	±8.1	5			
3C 446	U	-05 12 09	±12.3	2			
CTA102	N	11 28 49	±7.5	3			
3C 452	(U)	39 25 28	±3.0	8			
3C 456	U	09 03 20	±14.4	3	09°03'52"	±12".8	1
3C 459	N	03 48 52	±15.5	1			
3C 461	G	58 32 48	±3.1	7	58 32 48	±2.8	2
23-1<u>12</u>	N				-12 23 50	±13.1	2
3C 465	(H)	26 44 20	±4.5	6			
3C 469	N	32 38 59	±34	1			
CTA 1	G	71 55 14	±26	1	71 54 44	±26	1
3C 2	N	-00 21 17	±11.3	3			
3C 5	N				00 35 01	±12.6	2
00 -2<u>9</u>	N				-29 44 42	±10.3	5
3C 10	G	63 51 53	±3.6	6			
3C 15	N	-01 25 29	±19.3	1	-01 25 39	±6.5	2

TABLE 3 (continued)

Source	Class	200-Foot Spacing declination (1950.0)	std error*	No. of obs	400-Foot Spacing declination (1950.0)	std error*	No. of obs
3C 17	N	-02°23'53"	±10".8	2			
3C 18	N	09 46 34	±16.1	1	09°46'51"	±8".4	1
3C 19	N	32 54 01	±20	1	32 53 34	±8.8	1
3C 20	N	51 47 11	±5.3	3			
00-222	(U)	-25 33 11	±17.5	2	-25 32 55	±6.4	5
3C 23	N	17 31 54	±36	1	17 30 36	±14	1
3C 26	N	-03 50 08	±27	1	-03 49 45	±16.3	1
3C 27	N	68 06 46	±12.2	1	68 07 09	±6.2	1
3C 28	N				26 08 36	±13.8	1
3C 29	(U)	-01 38 30	±8.3	3	-01 39 21	±8.2	1
3C 32	(N)	-16 20 25	±16.2	3	-16 20 17	±12.2	1
3C 33	U	13 03 33	±3.7	6	13 03 21	±5.3	1
3C 38	U	-15 35 20	±15.0	2	-15 35 21	±12.0	1
3C 40	U	-01 37 11	±10.6	4			
3C 41	(U)	32 57 05	±18.1	1	32 57 47	±8.1	1
3C 43	N	23 22 51	±20.5	1	23 22 41	±10.8	1
3C 46	(U)	37 38 44	±36	1	37 38 24	±21	1
3C 47	N	20 41 57	±14.3	1	20 41 56	±7.4	1
3C 48	NG	32 54 18	±2.7	9	32 54 19	±1.8	5
3C 54		43 17 19	±25	1			
3C 55	N	28 36 37	±10.4	3	28 36 09	±10.6	1
3C 58	G	64 35 25	±6.1	2	64 35 23	±4.5	1
3C 60		21 05 37	±29	1			
3C 62	U	-13 13 26	±17.6	2	-13 13 18	±7.0	2
3C 63	N	-02 10 30	±12.2	3	-02 10 34	±6.7	2

TABLE 3 (continued)

Source	Class	200-Foot Spacing declination (1950.0)	std error*	No. of obs	400-Foot Spacing declination (1950.0)	std error*	No. of obs
3C 65	N	39°46'18"	±12".8	2			
3C 66	U	42 45 47	±3.7	7	42°45'49"	±4".5	2
02-110	N	-19 44 47	±13.9	3			
3C 71	N	-00 13 32	±6.1	5	-00 13 34	±4.5	3
3C 75	E	05 50 34	±5.2	7	05 50 50	±4.2	4
3C 78	N	03 55 17	±5.2	6	03 55 15	±2.7	5
3C 79	N	16 54 36	±7.6	3	16 54 34	±6.8	1
CTA 21	N	16 17 45	±6.3	3			
3C 84	H	41 20 02	±4.3	4	41 19 56	±4.4	1
3C 86	U	55 10 55	±10.9	1	55 10 23	±5.7	1
3C 88	S	02 23 19	±15.8	1	02 23 05	±8.3	1
3C 89	U	-01 21 35	±13.9	3	-01 21 16	±7.9	2
03 -19	S	-14 38 09	±15.7	3			
03-212	S				-27 53 12	±10.1	2
3C 98	U	10 17 37	±4.2	6	10 17 35	±3.5	3
3C 103	E	42 52 17	±8.8	2	42 52 16	±6.8	1
3C 105	H	03 33 17	±10.5	2	03 33 19	±8.5	1
04 -12	N	-12 19 43	±29	1	-12 19 28	±14.2	1
3C 109	N	11 04 29	±15.3	1	11 04 33	±7.9	1
04 -24	N				-21 03 25	±12.4	2
3C 111	E	37 54 32	±3.3	6	37 54 26	±3.0	2
3C 119	N	41 32 03	±7.5	2	41 31 54	±5.3	1
04-112	S				-13 30 38	±14.2	2
3C 123	N	29 34 06	±3.4	5	29 34 13	±3.8	1
04-218	N	-28 15 13	±24	1	-28 14 42	±6.1	4

TABLE 3 (continued)

Source	Class	200-Foot Spacing declination (1950.0)	std error*	No. of obs	400-Foot Spacing declination (1950.0)	std error*	No. of obs
3C 129	(U)	44°56'40"	±5".0	4			
3C 131	N	31 24 49	±18.5	1	31°24'22"	±8".8	1
3C 132	N	22 44 50	±15.4	1	22 44 39	±9.0	1
3C 133	U	25 12 18	±10.4	2	25 12 04	±5.9	1
3C 134	E	38 01 59	±5.2	3			
05 -13	N	-18 41 21	±68	2	-18 41 38	±22	3
3C 135	(U)	00 53 08	±22	2			
3C 138	N	16 35 13	±5.1	4			
3C 141	N	32 45 57	±15.0	2			
3C 144	G	21 59 01	±2.4	10	21 59 04	±2.7	2
3C 145	G	-05 25 14	±10.2	1	-05 25 16	±5.1	1
3C 147	N	49 49 44	±3.4	6	49 49 39	±2.0	4
3C 153	N	48 04 53	±6.5	5	48 04 54	±5.0	2
3C 154	N	26 05 30	±5.2	6	26 05 22	±6.1	1
3C 157	G				22 43 37	±14.5	1
3C 158	N	14 33 23	±17.0	2	14 33 49	±13.2	1
3C 159	N	40 05 27	±13.4	2	40 05 23	±6.8	2
3C 161	N	-05 51 26	±4.9	5	-05 51 22	±5.4	1
3C 163	G	04 51 40	±15.5	2	04 52 07	±39	1
3C 166	N	21 25 08	±10.4	4	21 25 00	±6.2	3
3C 171	N	54 12 55	±7.6	4	54 12 46	±7.5	1
06-216	N	-24 12 12	±24	2	-24 12 46	±9.5	3
3C 172	E	25 18 09	±8.7	4	25 17 54	±10.0	1
3C 175	N	11 51 33	±9.5	4			
3C 178	N	-09 34 05	±21	5			

TABLE 3 (continued)

Source	Class	200-Foot Spacing declination (1950.0)	std error*	No. of obs	400-Foot Spacing declination (1950.0)	std error*	No. of obs
3C 180	(S)	-01°58'49"	±16".2	2	-01°58'22"	±13".2	1
3C 184	N	70 08 51	±34	1			
3C 187	U	02 07 41	±18.9	3			
07-117	U	-19 12 24	±17.5	5	-19 12 01	±21	1
3C 191	N	10 23 40	±20.0	2			
3C 192	S	24 18 42	±8.9	2	24 18 30	±6.5	1
3C 195	N	-10 19 22	±15.5	2			
3C 196	N	48 22 09	±3.3	6	48 22 07	±2.9	2
3C 198	H	06 06 27	±16.0	3			
3C 202	N	17 11 06	±9.0	6	17 10 53	±10.4	1
3C 208	U	14 03 17	±12.3	4			
3C 212	N	14 21 26	±10.9	4			
08-219	N	-25 43 13	±14.9	3	-25 43 13	±5.7	5
3C 216	N	43 05 54	±8.3	3			
3C 218	H	-11 52 54	±3.9	9	-11 53 00	±2.6	5
3C 225	U	14 00 57	±7.5	6			
3C 227	U	07 39 17	±5.1	5			
3C 228	N	14 34 06	±9.9	3			
3C 230	(U)	00 13 02	±10.3	3	00 12 56	±6.1	2
3C 234	(U)	29 01 38	±4.6	7	29 01 26	±3.4	3
3C 237	N	07 45 02	±6.1	4	07 44 59	±4.3	2
3C 238	(U)	06 39 34	±8.6	4			
3C 243	U	06 42 43	±15.1	6			
3C 245	N	12 19 18	±5.8	9			
3C 249		-01 00 16	±14.4	3			

TABLE 3 (concluded)

Source	Class	200-Foot Spacing declination (1950.0)	std error*	No. of obs	400-Foot Spacing declination (1950.0)	std error*	No. of obs
3C 254	N	40°53'46"	±5".3	9	40°53'46"	±8".6	1
3C 261	N	30 23 46	±16.5	4			
11 -18	N	-13 34 03	±10.9	5			
3C 264	H	19 54 06	±7.1	3	19 53 55	±7.0	1
3C 265	N	31 51 07	±10.5	3	31 50 21	±8.2	1
3C 267	N	13 04 10	±25	1	13 04 08	±5.3	4
3C 270	E	06 06 39	±4.7	4	06 06 25	±2.4	4
M 84	N				13 09 37	±6.9	1
3C 273	N	02 19 48	±6.6	2	02 19 42	±3.3	2
3C 274	H	12 39 50	±4.1	4	12 39 57	±1.9	5
3C 275	N				-04 41 35	±5.5	4
Coma A	N				27 54 08	±10.0	1
3C 278	S				-12 17 06	±4.5	3
3C 283	N				-22 00 20	±11.0	1
3C 286	N				30 45 55	±4.2	1
3C 295	N				52 26 16	±1.8	5

* The standard errors indicated in Tables 1 and 3 are based on night to night repeatability and do not include allowances for systematic effects.

TABLE 4

Weighted Average of the Declinations Measured at the Various North-South Antenna Spacings

Source	Class	Declination (1950.0)			Std Error	Remarks
CTA 1	G	71°	54'	59"	±20"	
3C 2	N	-00	21	17	±14	
3C 5	N	00	35	01	±15	
00 -29	N	-29	44	42	±46	
3C 10	G	63	51	53	±7	
3C 15	N	-01	25	38	±11	
3C 17	N	-02	23	53	±14	
3C 18	N	09	46	47	±9	
3C 19	N	32	53	38	±9	
3C 20	N	51	47	11	±7	
00-222	(U)	-25	32	57	±35	
3C 23	N	17	30	46	±14	possibly confused
3C 26	N	-03	49	51	±17	
3C 27	N	68	07	04	±9	
3C 29	(U)	-01	38	30	±12	200-ft spacing only
3C 32	(N)	-16	20	20	±22	
3C 33	U	13	03	33	±6	200-ft spacing only
3C 38	U	-15	35	21	±21	
3C 40	U	-01	37	11	±14	200-ft spacing only
3C 43	N	23	22	43	±11	
3C 46	(U)	37	38	29	±19	
3C 47	N	20	41	56	±8	
3C 48	NG	32	54	19.9		optical position

TABLE 4 (continued)

Source	Class	Declination (1950.0)			Std Error	Remarks
3C 55	N	28°	36'	23"	±9"	possibly confused
3C 58	G	64	35	24	±8	
3C 62	U	-13	13	19	±17	
3C 63	N	-02	10	33	±10	
3C 65	N	39	46	18	±14	
3C 66	U	42	45	47	±6	200-ft spacing only
02-110	N	-19	44	47	±28	
3C 71	N	-00	13	33	±9	
3C 75	E	05	50	44	±9	
3C 78	N	03	55	15	±7	
3C 79	N	16	54	35	±7	
CTA 21	N	16	17	45	±8	
3C 84	H	41	19	59	±6	
3C 86	U	55	10	29	±10	
3C 88	S	02	23	08	±10	
3C 89	U	-01	21	21	±11	
03 -19	S	-14	38	09	±24	
03-212	S	-27	53	12	±41	
3C 98	U	10	17	37	±7	200-ft spacing only
3C 103	E	42	52	16	±7	
3C 105	H	03	33	18	±10	
04 -12	N	-12	19	31	±20	
3C 109	N	11	04	32	±9	
04 -24	N	-21	03	25	±29	
3C 111	E	37	54	29	±5	

TABLE 4 (continued)

Source	Class	Declination (1950.0)			Std Error	Remarks
3C 119	N	41°	31'	57"	±7"	
04-112	S	-13	30	38	±22	
3C 123	N	29	34	09	±2.9	
04-218	N	-28	14	44	±42	
3C 129	(U)	44	56	40	±7	
3C 131	N	31	24	27	±9	
3C 132	N	22	44	42	±9	
3C 134	E	38	01	59	±7	
05 -13	N	-18	41	36	±31	
3C 135	(U)	00	53	08	±23	
3C 138	N	16	35	13	±7	
3C 141	N	32	45	57	±16	
3C 144	G	21	59	02	±5	
3C 145	G	-05	25	16	±12	
3C 147	N	49	49	39	±2.6	
3C 153	N	48	04	54	±6	
3C 154	N	26	05	27	±6	
3C 158	N	14	33	39	±11	
3C 159	N	40	05	24	±8	
3C 161	N	-05	51	24	±12	
3C 166	N	21	25	02	±7	
3C 171	N	54	12	49	±3.1	
06-216	N	-24	12	41	±33	
3C 172	E	25	18	03	±8	
3C 175	N	11	51	33	±11	

TABLE 4 (continued)

Source	Class	Declination (1950.0)	Std Error	Remarks
3C 178	N	-09° 34' 05"	±25"	
3C 180	(S)	-01 58 33	±14	
3C 187	U	02 07 41	±20	
07-117	U	-19 12 14	±27	
3C 191	N	10 23 40	±21	
3C 192	S	24 18 34	±7	
3C 195	N	-10 19 22	±21	
3C 196	N	48 22 06	±2.6	
3C 198	H	06 06 27	±17	
3C 202	N	17 11 00	±8	
3C 208	U	14 03 17	±26	200-ft spacing only
3C 212	N	14 21 26	±12	
08-219	N	-25 43 13	±35	
3C 216	N	43 05 54	±10	
3C 218	H	-11 52 58	±15	
3C 225	U	14 00 57	±9	
3C 227	U	07 39 17	±8	
3C 228	N	14 34 06	±11	
3C 230	(U)	00 12 58	±10	
3C 234	(U)	29 01 30	±6	
3C 237	N	07 45 00	±7	
3C 238	(U)	06 39 34	±11	200-ft spacing only
3C 243	U	06 42 43	±16	
3C 245	N	12 19 18	±8	
3C 249		-01 00 16	±17	

TABLE 4 (concluded)

Source	Class	Declination (1950.0)			Std Error	Remarks
3C 254	N	40°	53'	46"	±7"	
3C 261	N	30	23	46	±17	
11 -18	N	-13	34	03	±20	
3C 264	H	19	54	00	±7	
3C 265	N	31	50	38	±8	possibly confused
3C 267	N	13	04	08	±7	
3C 270	E	06	06	28	±6	possibly confused
3C 273	N	02	19	43	±8	
3C 274	H	12	39	57	±3.6	
3C 275	N	-04	41	35	±12	
3C 278	S	-12	17	06	±16	
3C 295	N	52	26	13.6		optical position

Note: the class designation refers to the angular size work of Maltby and Moffet.

N not resolved at our spacings

S simple, symmetrical source

E equal double

U unsymmetrical

( ) uncertain

G galactic source

VIII. CONCLUSIONS

The accuracy of the measured declinations is in most instances about an order of magnitude better than the accuracy of the best previously available radio declinations. The improvement in positional accuracy should make possible the identification of many more radio sources with optically observable objects. The problem of the positional accuracy necessary to effect the identification of an extragalactic radio source has been treated by Minkowski (1960). His results indicate that a positional accuracy of ± 13 seconds of arc (the average standard error of the declinations of Table 4) in both coordinates should lead to an identification in 60 to 80 percent of the cases. While right ascension measurements of about this accuracy now exist for many of the sources of Table 4, it is still too early to say if such a large percentage of identifications will indeed be forthcoming. The limited experience to date, however, has been quite encouraging. The declination measurements have confirmed several tentative identifications and have suggested a number of others. In addition, four sources, 3C 26, 3C 171, 3C 196, and 3C 286, have been identified as a direct result of the declination measurements. In this connection, it should be noted that these four identifications could be classed as "difficult" identifications. In each case it was necessary to use the 200-inch telescope, since the optical objects were so faint that plates taken with the 48-inch Schmidt were inadequate for the purpose of making an identification.

It is instructive to compute the average number of galaxies brighter than 20th magnitude that will lie by chance within an error rectangle of a given size. According to Holmberg (1957), there are about 1350 such galaxies per square degree. If the new declinations are combined with right ascensions of comparable accuracy (which have also been measured at the Owens Valley Radio Observatory with the same instrument), the probability of a galaxy brighter than 20th magnitude lying by chance within the average standard error rectangle is only 7 percent.

In making a similar calculation for galaxies substantially fainter than this, it is necessary to make allowances for the red shift and the effects of cosmology since most of the galaxies which appear to be very faint are also quite distant. These allowances have been made by Sandage (1961) in estimating the number of galaxies per square degree which are observable with the 200-inch telescope (red magnitude < 23). His estimate of 18 000 to 28 000 implies that on the average slightly more than one observable galaxy will lie by chance within a ± 13 second of arc error rectangle. The 1600-foot measurements indicate that somewhat better positional accuracy should be attainable in future measurements. A standard error of ± 4 seconds of arc is not an unreasonable expectation. The probability of an observable galaxy lying by chance within this error rectangle is only slightly more than 10 percent.

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X. APPENDIX

a. Definition of the Baseline

b. Typical Plots of Δt as a Function of Time

Definition of the Baseline

A question arises in the case of an interferometer with elements of large physical size as to just how the baseline is to be defined. To what point of a large element does one refer when measuring the length and direction of the baseline? For the interferometer used for the declination measurements, the answer is clear. The elements of the interferometer were two 90-foot steerable paraboloidal antennas on equatorial mounts. The polar and declination axes of each mount intersected, and it is these points of intersection that are to be used as the effective points of the antennas. The proof is as follows: During the course of an observation clock drives cause the antennas to track the source being observed. Thus the orientation of an antenna does not change relative to the direction of arrival of the radiation it is receiving. The total distance from the source to any point on the moving structure of the antenna differs from the total distance traveled by the radiation reaching the feed horn by a constant amount independent of the apparent motion of the sky. Also, since the antennas are always pointed directly at the source being observed, this difference in distance is the same for all sources observed. The effective time of arrival of the radiation at the antenna may thus be referred to any point of the moving structure of the antenna by introducing a constant difference in the arrival time. The intersection of the polar and declination axes is not only a point on the moving structure of the antenna but is also fixed with respect to the ground. Thus, since the interferometer measures only the difference in arrival time of the radiation at the two antennas, the baseline may be conveniently defined as that line connecting the intersection of the polar and declination axes of one antenna with the intersection of the polar and declination axes of the other antenna.

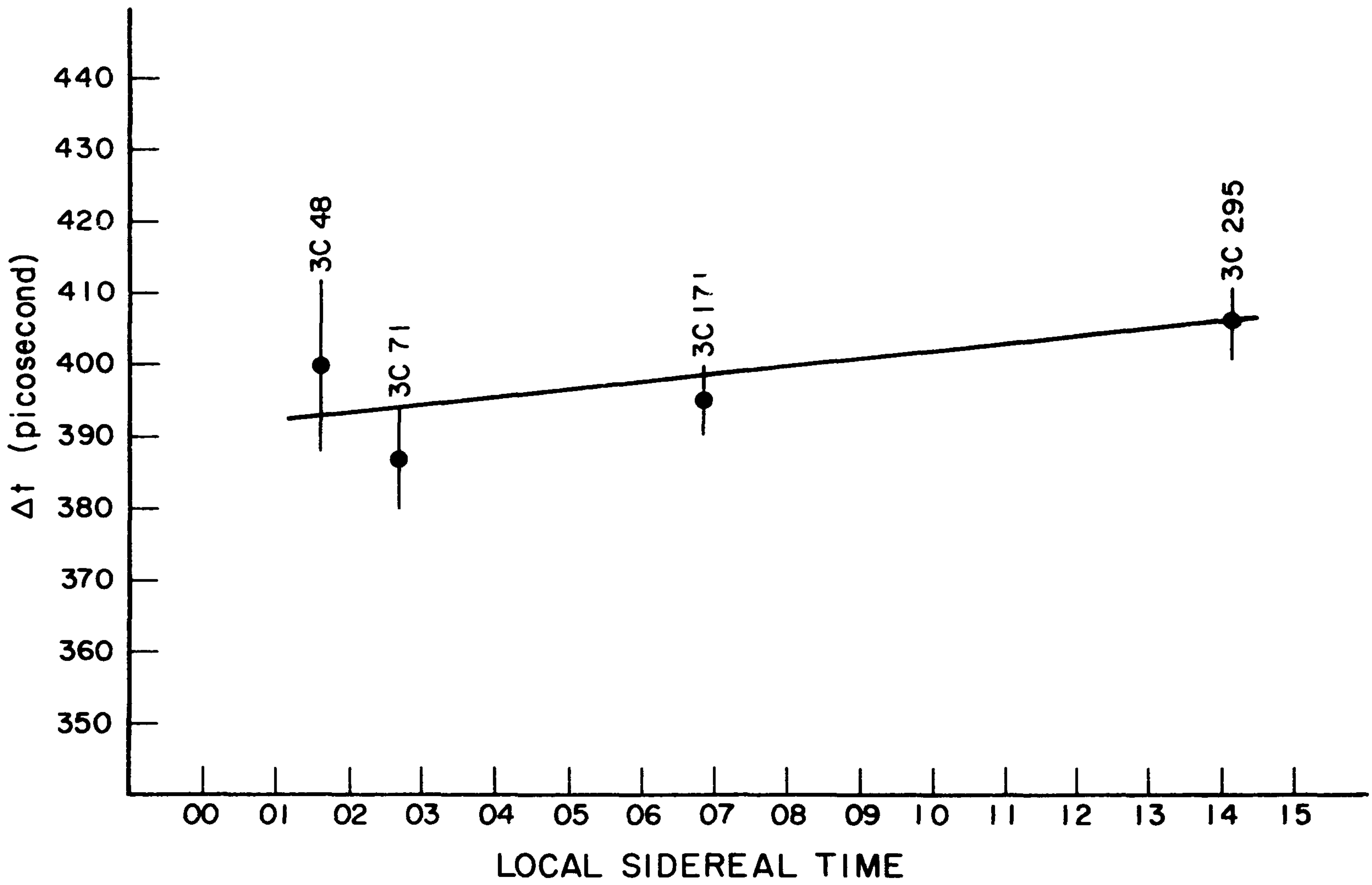

Figure 7. Phase calibration curve for the night of 1961 February 8/9, 1600-ft N-S spacing.

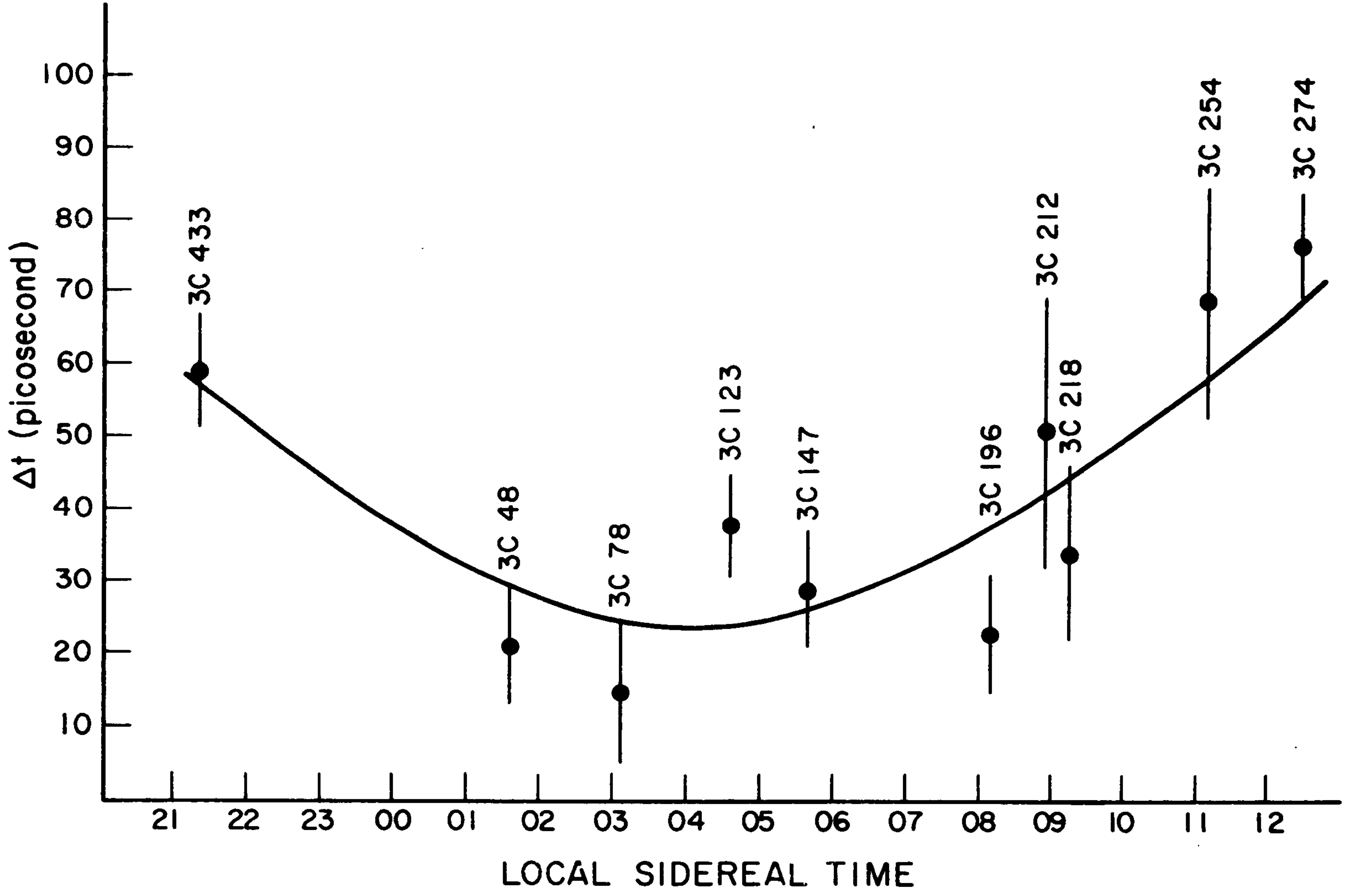

Figure 8. Phase calibration curve for the night of 1960 December 5/6, 200-ft N-S spacing.

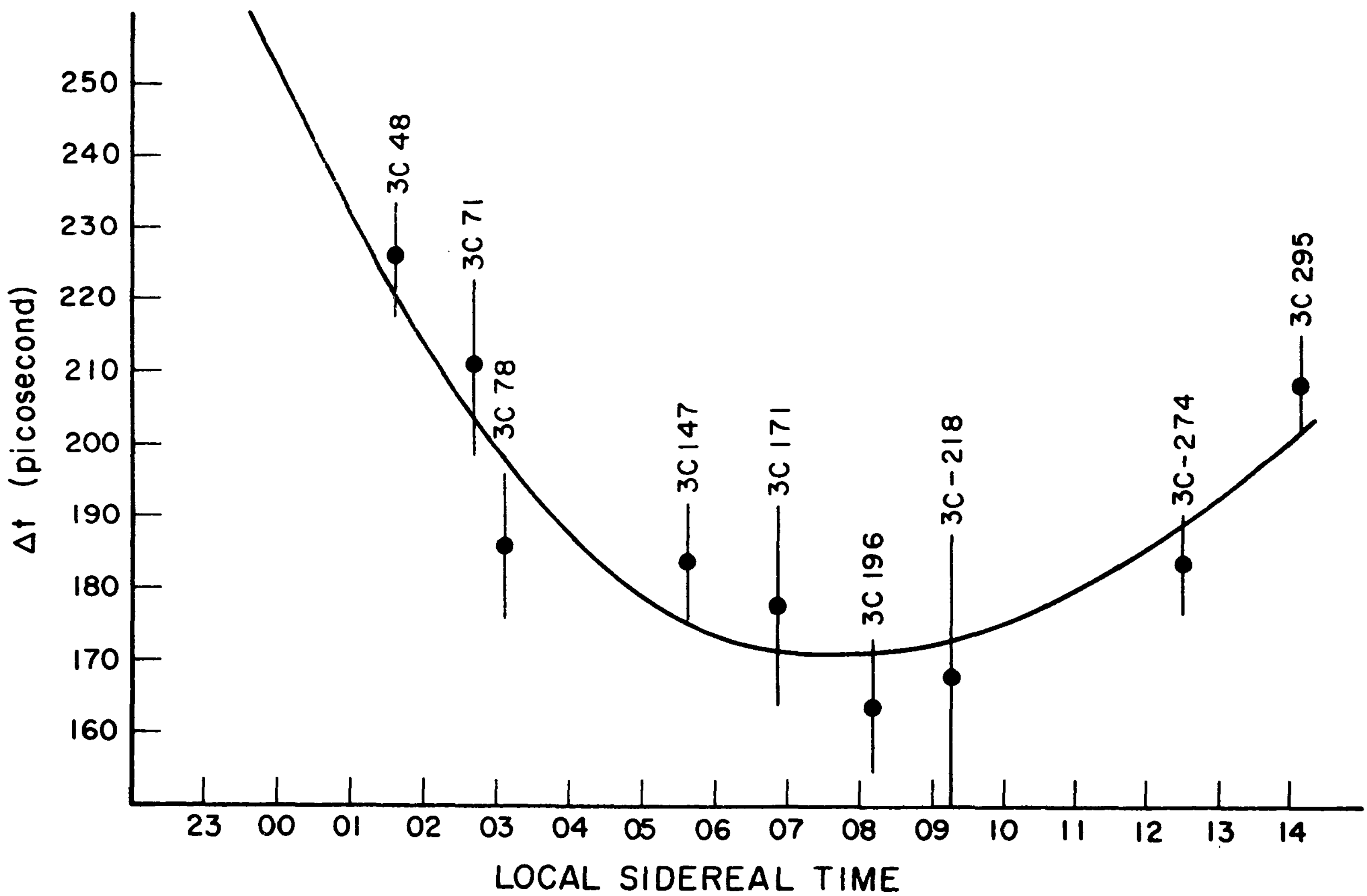

Figure 9. Phase calibration curve for the night of 1960 December 21/22, 400-ft N-S spacing.

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