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# Ionospheric Refraction in Radio Source Observations at Long Radio Wavelengths

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**Abstract.** Ionospheric refraction effects encountered in radio source observations in the 30 to 75 MHz range with the Clark Lake TPT telescope are discussed. It is found that simple calibration procedures are sufficient to provide positions of unknown sources with an accuracy of approximately one arcmin. Observations made near sunrise, or during disturbed ionospheric conditions must be discarded. If no corrections are applied, RMS errors of a few arcmin are to be expected.

## 1. Introduction

The Clark Lake TPT (Erickson, Mahoney & Erb 1982) is a high resolution radiotelescope which operates in the 15 to 125 MHz frequency range. Its location is (116°17′E, 33°20′N). The best sensitivity of the system (about 1 Jy) is in the 25 to 75 MHz range and its beamwidth varies from 13.8 to 4.6 arcmin over this frequency range. Thirty-two signal outputs from the 3 km East-West arm are digitally correlated with sixteen outputs from the 1.8 km North-South arm of the ‘T’. The resulting 512 correlator outputs are averaged for a few minutes and then Fourier transformed to produce a map of the area of sky under observation. Successive maps are stacked for 30 to 80 minutes; a final map is then produced and cleaned.

Every few days a strong source such as Cyg A is observed and these data are used to adjust the phases and gains of the individual receiver channels. This adjustment compensates for ionospheric refraction existing at the time of this observation. Therefore, no fundamental measurements are made; all measurements are relative to the apparent position of the source used for instrumental calibration.

Further corrections for ionospheric refraction are often possible. The field of view of the system is large, 2 to 5 deg, and many fields contain at least one source of accurately known coordinates which can be used to calibrate the positions of unknown sources in the same field.

We also observe strong ($\gtrsim$ 50 Jy) isolated sources several times a day as a check on the operational status of the system and to determine whether or not data should be discarded because of severe ionospheric scintillation. It will be shown below that the displacements of the apparent position of these sources from the field centre, presumably caused by ionospheric refraction, are generally consistent from source to source observed over intervals of many hours. These data can be used to correct the

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positions of unknown sources when there are no sources of known coordinates simultaneously in the field.

One would be foolish to attempt astrometric observations in this frequency range. Normally it is unnecessary because even steep spectrum sources observed below 100 MHz can be detected by sensitive instruments at gigahertz frequencies. Occasionally, however, the identification of the low-frequency source with the proper

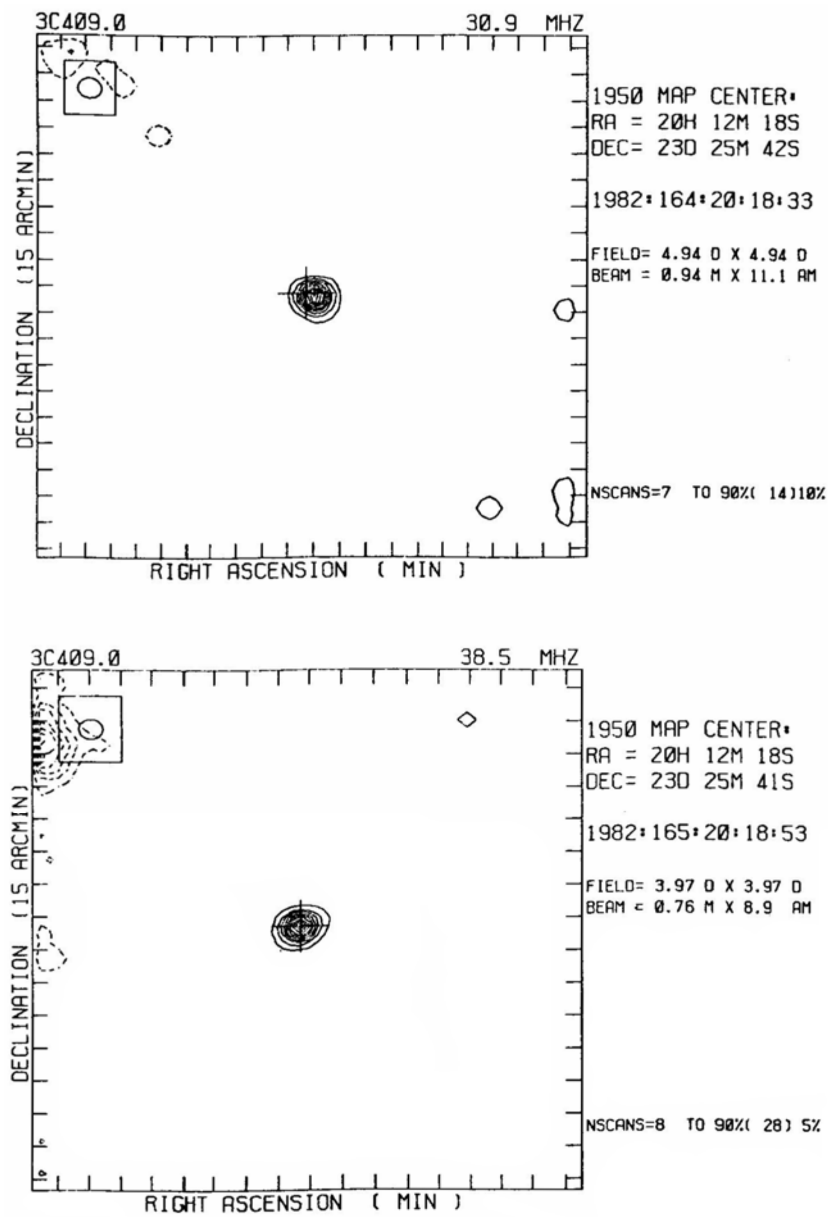


**Figure 1.** Examples of the data used for this analysis. Contours are at ± 5, ± 15, . . . ± 95 per cent of the peak on the map. The beamsize is shown in the upper left corner.

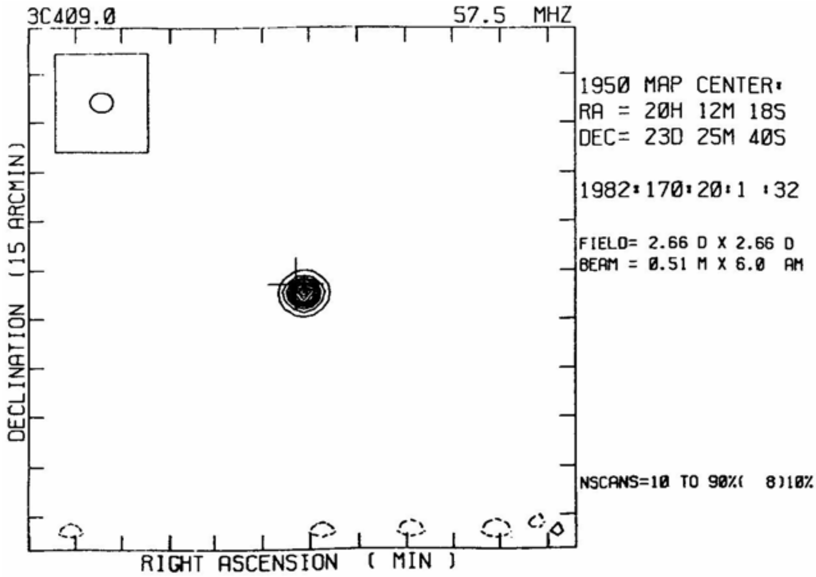


**Figure 1.** continued

high-frequency object is ambiguous and an accurate low-frequency position is needed. A recent example of this was the case of the first millisecond pulsar. The position determined at Clark Lake for the steep-spectrum, low-frequency source was 2–4 arcmin south of the extended source (4C21.53W) and was, in fact, the pulsar (Erickson 1983).

Another reason for studying refraction effects at long wavelengths is that new long-wavelength instruments are being considered at VLA, in India, and elsewhere. Practical information concerning ionospheric stability is important for the design of such instruments.

## 2. Observations

The observations included in this study are from data that I obtained during four observing trips to Clark Lake, each about two weeks long, in 1981 November-December and in 1982 February, March and June. Most of the data were obtained at night because terrestrial interference is less common at night and, also, the telescope is usually occupied by solar programmes in the daytime. The data are thus typical of those that can be obtained at night during most parts of the year, but they certainly do not represent a statistically complete sample. About 20 per cent of the original observations were recognized as being obviously bad because of interference, severe ionospheric scintillations, or severe wedge refraction that occurs near sunrise. Such data were discarded in the early stages of reduction. No further attempt has been made to select particularly good data; all observations of strong, isolated sources made during these observing sessions are included here.

It would be interesting to study the short-period ($\simeq 5$ s) fluctuations in the apparent radio source positions. This can be done but it would require special software and reprocessing of the original data tapes. Only the long-period ($\simeq$ 1 hour average) refraction effects are studied in this paper.

A total of 110 source observations at frequencies of 30.9, 38.5, 57.5 and 73.8 MHz are included in this study. Fig. 1 gives examples of the data. For each observation the displacement of the source was measured relative to the map centre (given by an accurate, high-frequency position). All observations were made fairly close to transit, so displacements in right ascension represent E-W refraction while declination offsets represent N-S refraction.

## 3. Results

Table 1 summarizes the RMS displacements observed at the various frequencies. Although the displacements increase with wavelength, they do not show a clear $\lambda^2$ dependence. However, as shown in Fig. 2 where a line of slope – 2.0 is fitted through the 30–75 MHz data, the magnitude of the low-frequency refraction effects is consistent with that found by Spoelstra (1983) using the WSRT at 608.5 MHz.

Fig. 2 shows that the RMS displacements are not significantly different in the E-W and N-S directions. They may be crudely estimated by

$$\text{RMS error} \sim (80/F)^2$$

where the RMS error is in arcmin and $F$ is the observing frequency in MHz. This is the accuracy that can be anticipated if no corrections for ionospheric refraction are made.

Expressions for the refraction caused by both a spherically symmetrical component and a wedge component of the ionosphere were derived by Komesaroff (1960) and by Lowen (1962). These expressions have been extended by Spoelstra (1983) who shows that quite a good correction can be made if one has sufficient ionospheric data to determine both the vertical profile and the horizontal gradients of electron density. These data are not easily available and the process would be rather difficult to implement in our case, so I have adopted the simple procedure of observing calibration sources before and after the observation of an unknown source. It is useful to determine to what accuracy corrections can be made using such data and whether or not any systematic trends can be found in these data. In order to search for such trends, I have plotted the displacements against many parameters. In particular, one might expect that the N-S displacements would vary systematically with declination, or that the E-W displacements might depend upon local solar time. As is shown in Fig. 3, any such trends are below the noise level.

**Table 1.** RMS displacements observed at different frequencies.

| Frequency MHz | RMS (E-W) $\cos\delta\,\Delta\alpha$ arcmin | RMS (N-S) $\Delta\delta$ arcmin | Number of observations |
|---|---|---|---|
| 30.9 | 4.20 | 3.89 | 21 |
| 38.5 | 3.32 | 2.72 | 15 |
| 57.5 | 3.58 | 3.00 | 67 |
| 73.8 | 1.13 | 1.12 | 7 |
| (608.5) | ~0.0185 | ~0.0185 | . . . |

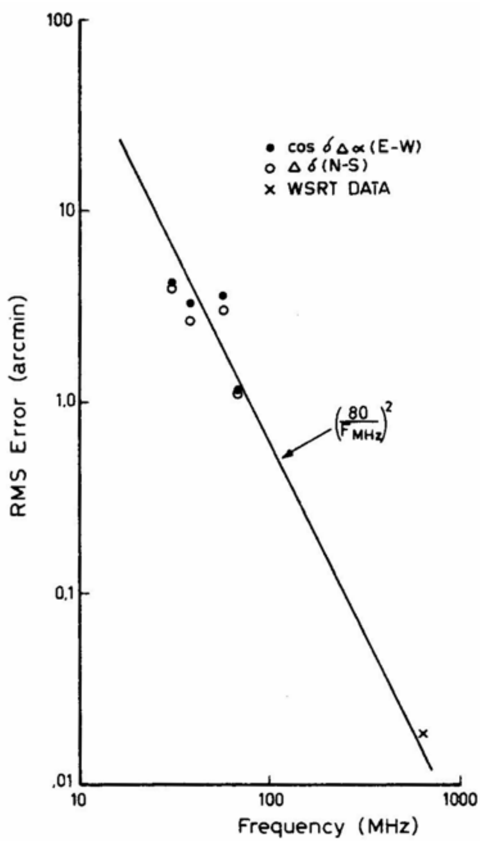


**Figure 2.** The variations of RMS displacements as a function of frequency.

I can find only one effect that appears to be significant. The scatter of the displacements is a factor of two smaller for sources that lie between 6 and 16 h right ascension than for sources that lie outside this range. For sources within this range of right ascension both the E-W and the N-S displacements have a Standard deviation of 1.4 arcmin while for sources outside this range the corresponding Standard deviations are both 2.8 arcmin. One possible explanation for this effect involves the system noise levels. The system noise is dominated by the galactic background which is the lowest during 6 to 16 h interval of sidereal time. However, if system noise were contributing to the errors I would expect that the displacements would be smaller for the stronger sources. A plot of RMS displacements versus source flux shows no such tendency.

Another possible explanation involves solar or seasonal variations in ionospheric activity. Since the observations were made near transit and mostly at night, I tended to observe different ranges of right ascension during the four different observing sessions. If the ionosphere happened to be much more stable during one or two of the sessions, the quality of the data and the scatter of the displacements in the observed range of right ascension might be lower. To check on this possibility I scaled all of the displacements to 57.5 MHz and averaged them for each observing session. The average displacements and the standard deviations from these averages are shown in Table 2. No significant

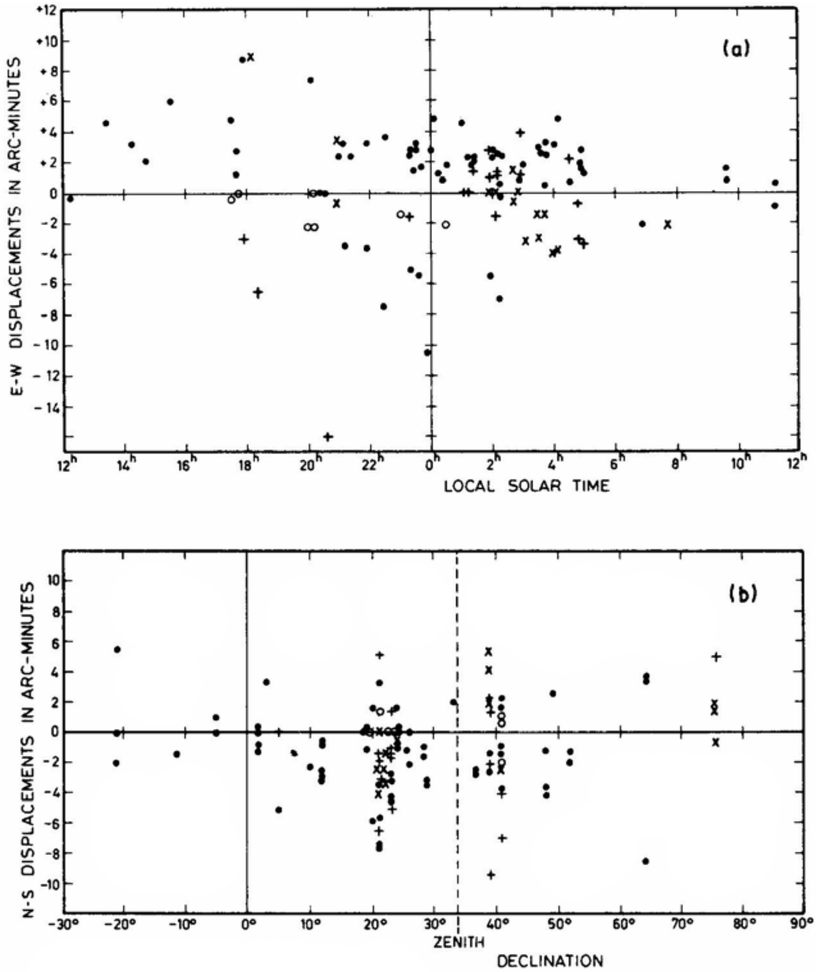


**Figure 3.** (a) E-W displacements as a function of local solar time, (b) N-S displacements as a function of declination. The displacements do not significantly depend upon these or any other parameters for which similar plots were made. Different symbols are used for measurements at different frequencies: 30.9 MHz (+), 38.5 MHz (×), 57.5 MHz (●), 73.8 MHz (O).

**Table 2.** Average displacements observed during different sessions scaled to 57.5 MHz.

| Observing session yr | d | Average E-W displacement arcmin | Average N-S displacement arcmin | Number of observations |
|---|---|---|---|---|
| 1981 | 314–351 | −3.3 ± 3,7 | +1.0 ± 2.1 | 14 |
| 1982 | 029–041 | 0.0 ± 2.0 | −0.1 + 1.6 | 15 |
| 1982 | 067–075 | +2.5 ± 2.0 | −1.4 ± 2.3 | 43 |
| 1982 | 160–177 | +0.4 ± 1.5 | −1.7 ± 2.8 | 38 |

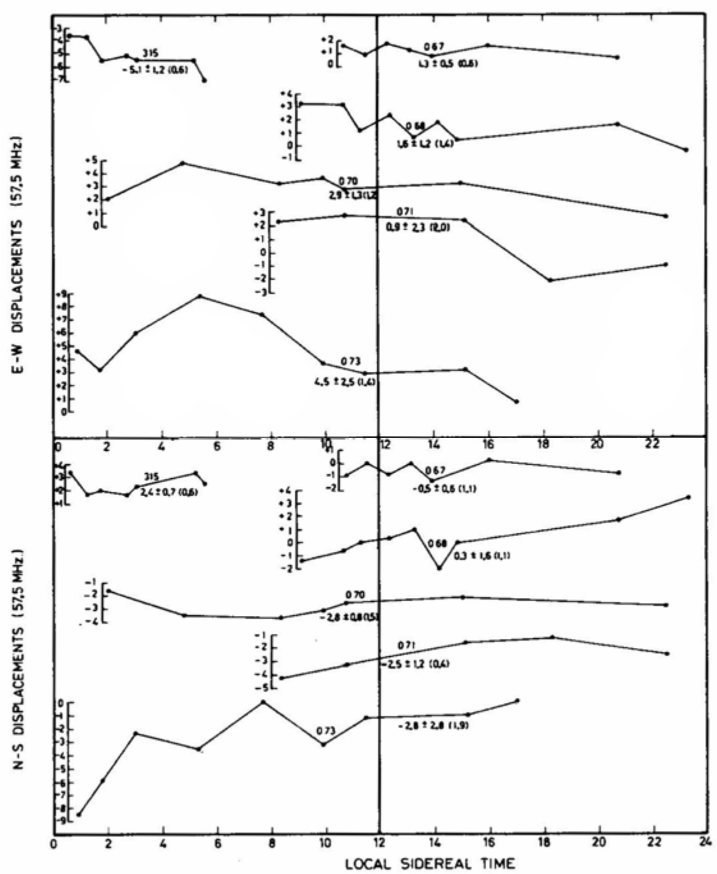


**Figure 4.** The variation of refractive displacements as a function of time. Sources at widely varying declinations were observed near transit. The scale to the left of each plot gives the displacement in arcmin. The date of observation is given above each plot; the average displacement and its standard deviation is given below each plot. Also, the average errors between the measured displacements and those predicted by linear interpolation between adjacent observations are shown in parentheses.

dependence of the quality of the data upon observing session is apparent so the explanation of the effect remains a mystery.

There may also exist a weak correlation between observed displacements in source position and observed errors in source flux, but the correlation is not strong enough to be of any practical use in estimating the error of either quantity.

At 57.5 MHz there exist six days during which I observed 5 to 9 calibration sources successively over periods of 5 to 20 h. These periods can be used to estimate the stability of the displacements over periods of several hours. As shown in Fig. 4, the displacements are quite stable. If I simply calculate a mean displacement for each day and determine the scatter of the observations about that mean, the average errors are 1.5 arcmin (E-W) and 1.4 arcmin (N-S). On the other hand, if I predict source displacements by linear interpolation between observations taken before and after any given one, the average differences between the predictions and the observations are 1.2

**Table 3.** Comparison of Texas Survey source positions with Clark Lake observations.

| Source | Texas survey | | | Clark Lake observation | | | | |
|---|---|---|---|---|---|---|---|---|
| | R.A. (1950) | Dec. (1950) | S (365 MHz) | R.A. (1950) | Dec. (1950) | ΔR.A. | ΔDec. | S (38.5 MHz) |
| Name | h m s | ° ′ | mJy | h m s | ° ′ | s | arcmin | Jy |
| 1008+193 | 10 08 44 | 19 22.1 | 333 | ... | ... | ... | ... | ... |
| 1009+190 | 10 09 14 | 19 04.7 | 329 | 10 09 12 | 19 05.3 | −02 | 0.6 | 1.4 |
| 1009+207 | 10 09 15 | 20 43.7 | 401 | 10 09 18 | 20 46.8 | (−03) | (3.1) | (0.9) |
| 1009+211 | 10 09 26 | 21 11.3 | 453 | 10 09 31 | 21 11.5 | (−05) | (0.2) | (0.7) |
| 1010+197 | 10 10 22 | 19 45.0 | 204 | ... | ... | ... | ... | ... |
| 1010+220 | 10 10 37 | 22 00.9 | 337 | ... | ... | ... | ... | ... |
| 1010+209 | 10 10 57 | 20 56.7 | 410 | 10 10 54 | 20 56.9 | −03 | 0.2 | 1.9 |
| 1012+203 | 10 12 08 | 20 23.4 | 173 | ... | ... | ... | ... | ... |
| 1012+184 | 10 12 26 | 18 24.8 | 578 | ... | ... | ... | ... | ... |
| 1012+196 | 10 12 57 | 19 39.0 | 251 | 10 13 04 | 19 37.4 | (07) | (−1.6) | (0.7) |
| 1013+208 | 10 13 59 | 20 52.8 | 847 | 10 13 58 | 20 51.3 | −01 | −1.5 | 4.4 |
| 1014+217A | 10 14 09 | 21 47.1 | 356 | ... | ... | ... | ... | ... |
| 1014+217B | 10 14 53 | 21 46.2 | 427 | ... | ... | ... | ... | ... |
| 1015+187 | 10 15 03 | 18 47.5 | 1296 | 10 15 04 | 18 47.3 | 01 | −0.2 | 2.1 |
| 1015+201 | 10 15 32 | 20 06.6 | 193 | 10 15 27 | 20 06.4 | −05 | −0.2 | 3.1 |
| 1015+203 | 10 15 56 | 20 21.1 | 228 | 10 15 50 | 20 22.7 | −06 | 1.6 | 1.5 |
| 1016+188 | 10 16 29 | 18 51.1 | 929 | 10 16 31 | 18 51.4 | 02 | 0.3 | 4.2 |
| 1017+201 | 10 17 01 | 20 06.5 | 867 | 10 17 05 | 20 06.1 | 04 | −0.4 | 5.8 |
| 1019+211 | 10 19 08 | 21 08.9 | 397 | ... | ... | ... | ... | ... |
| 1019+199* | 10 19 26 | 19 58.0 | 1303 | 10 19 22 | 19 57.6 | −04 | −0.4 | 4.3 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 1020+191 | 10 20 12 | 19 08.8 | 647 | ... | ... | ... | ... | ... |
| 1020+197 | 10 20 28 | 19 46.9 | 247 | ... | ... | ... | ... | ... |
| 1020+215 | 10 20 45 | 21 32.2 | 386 | ... | ... | ... | ... | ... |
| 1020+205 | 10 20 59 | 20 33.4 | 520 | 10 21 01 | 20 32.6 | 02 | −0.8 | 3.1 |
| 1021+207 | 10 21 23 | 20 47.6 | 305 | ... | ... | ... | ... | ... |
| 1021+182 | 10 21 50 | 18 16.8 | 174 | ... | ... | ... | ... | ... |
| 1022+194* | 10 22 02 | 19 27.6 | 1482 | 10 22 02 | 19 28.4 | 00 | 0.8 | 10.6 |
| 1022+182 | 10 22 28 | 18 13.7 | 285 | ... | ... | ... | ... | ... |
| 1022+204† | 10 22 37 | 20 25.6 | 4368 | 10 22 36 | 20 27.2 | −01 | 1.6 | 24.3 |
| 1023+190 | 10 23 29 | 19 00.3 | 250 | ... | ... | ... | ... | ... |
| 1024+201 | 10 24 02 | 20 10.4 | 467 | 10 24 03 | 20 08.7 | 01 | −1.5 | 2.1 |
| 1024+217 | 10 24 31 | 21 46.0 | 232 | ... | ... | ... | ... | ... |

Average errors: R.A.. −0.9 ± 3.0 s or −0.2 ± 0.7 arcmin; Dec.: 0.0 ± 1.0 arcmin
* 4C 19.33 S(178 MHz) = 2.0 Jy
# 4C 19.44 S(178 MHz) = 2.4 Jy
† 4C 20.22 S(178 MHz) = 6.8 Jy

arcmin (E-W) and 1.0 arcmin (N-S). The reasons why the latter method is not significantly better than the former one are that measurement errors are appreciable at the one arcmin level and also a significant fraction of the displacements are caused by ionospheric gravity waves that have periods much shorter than the interval between observations. Nevertheless, these methods permit position determinations of about one arcmin accuracy.

Finally, I studied the accuracy that can be attained if position measurements are made relative to known sources in the field of view. For this purpose I needed a field which contained many sources with accurately known coordinates, and the best source of such data is the 365 MHz Texas Survey (Douglas *et al.* 1980). I chose a field in Leo that was recently observed at 38.5 MHz by R. J. Hanisch (1983, personal communication) to look for emission from the flare star, AD Leo. This field lies in the declination strip covered by the Preliminary Texas Survey and contains 32 Texas sources. Three of these sources have fluxes greater than 2 Jy at 178 MHz and appear in the 4C catalogue. As shown in Fig. 5, sixteen of the Texas sources appear on the Clark Lake map. Three of them are below 1 Jy at 38.5 MHz and I consider their identification too unrealiable for inclusion in the statistics. The Texas and the Clark Lake positions are in excellent agreement as is shown by Table 3. Again, I find RMS position errors of about one arcmin in each coordinate. A large part of the errors is caused by inaccuracies in measuring the maps and, since the sources are relatively weak, part of the errors may be caused by noise fluctuations.

Using either method of calibration the errors appear to be random. Since errors in the individual measurements are about one arcmin, the average of a number of independent measurements should provide positions accurate to less than an arcmin.

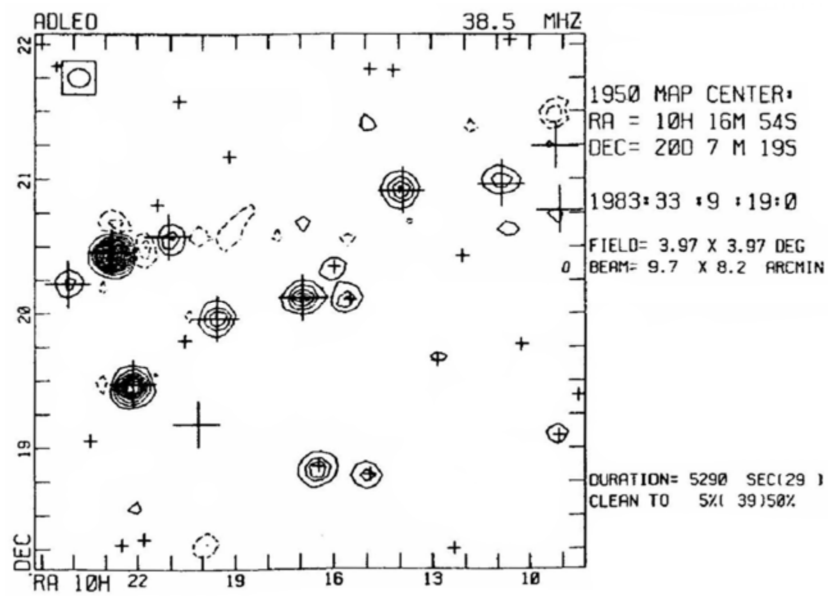


**Figure 5.** The comparison between Clark Lake and Texas Survey positions for a field in Leo. The large '+' indicates source with 365 MHz fluxes greater than 400 mJy; the small '+' denotes sources between 100 and 400 mJy in flux.

## 4. Conclusions

Under normal, night-time conditions the ionosphere is sufficiently stable to permit radio-source position determinations of about one arcmin accuracy in the 30 to 75 MHz range with single observations of about one hour duration. The average refraction is often stable for many hours and is not strongly dependent upon source position. Multiple, independent observations can be expected to yield average positions accurate to a small fraction of an arcmin. Different calibration procedures have been tested and all yield similar accuracies.

## Acknowledgements

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