Astron. Astrophys. 184, 381–385 (1987)

ASTRONOMY
AND
ASTROPHYSICS

Observations of anomalous refraction at radio wavelengths

W.J. Altenhoff[1], J.W.M. Baars[1], D. Downes[2], and J.E. Wink[1]

[1] Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-5300 Bonn, Federal Republic of Germany
[2] Institut de Radioastronomie Millimétrique (IRAM), Grenoble, France

Received February 6, accepted March 27, 1987

Summary. Anomalous refraction has been observed at millimeter wavelengths with the IRAM 30-m telescope, and at centimeter wavelengths with the Effelsberg 100-m telescope. During refraction "events", radio sources are displaced by up to 40″, in both azimuth and elevation, for periods up to 30 s of time. More typically, sources are displaced by a few arcsec for a few seconds of time. The most likely explanation is in terms of moist air packets of a size comparable to the aperture, moving through the beam of the telescope. The effect is observed at high and low elevation angles, and does not require a long line of sight through the atmosphere, indicating that the moist air packets are in the lower troposphere. The effect is clearly dependent on meteorological conditions, as temperature and humidity.

Key words: atmospheric propagation – refraction – radio astronomy

1. Introduction

In this paper we report observations of anomalous refraction at millimeter and centimeter wavelengths with the Institut de Radio Astronomie Millimétrique (IRAM) 30-m and Effelsberg 100-m telescopes, respectively. During the commissioning tests of the IRAM 30-m telescope (Baars et al., 1987), it was noticed that radio sources appeared to drift or jump away from their nominal positions on the sky by several arcsec, for periods of several seconds of time. The initial suspicion was that the effects might be caused by telescope tracking errors, but simultaneous monitoring of the actual tracking errors and of the telescope structure with highly sensitive inclinometers proved this not to be the case. Additional investigations with the Effelsberg 100-m telescope showed that the effect was also present at short centimeter wavelengths. This phenomenon is quite different from the familiar atmospheric scintillation, observed at visible and near infrared wavelengths, in that the variations observed in the millimeter and centimeter range are much slower, by nearly two orders of magnitude. It occurs in observations of both pointlike and extended sources. Similar effects may have been seen with the Onsala millimeter telescope (Rydbeck et al., 1985).

Send offprint requests to: W.J. Altenhoff

2. Observations

2.1. *Events at Pico Veleta: exclusion of instrumental effects*

During the commissioning of the IRAM 30-m telescope, located at 2850 m elevation on Pico Veleta, Spain, a series of pointing and tracking tests were made at a frequency of 86 GHz with the antenna following the planets, strong radio galaxies and SiO masers. The sources were monitored at the peak and half-power points, both in azimuth and elevation of the 27″ beam. The receiver was a Schottky mixer with typical receiver noise temperature of 220 K, double sideband. This receiver is reliable and stable over long time periods. During tests on 1985 March 28, intensity variations of up to 50% were noticed while the telescope was tracking Saturn, which could be explained by displacements of more than 12″ of the source relative to the antenna beam.

At this time, the wind was varying between 2 and 10 m s^{-1}, which normally has no significant influence on the telescope tracking. The microprocessors monitoring the tracking displayed no significant errors. They obtain information on the orientation of the telescope from angle encoders with 0.″1 resolution, located on the azimuth and elevation axes. Each axis has two independent encoders. To eliminate the possibility that the telescope structure might be moving without this motion being registered by the encoders, sensitive inclinometers have been mounted on the telescope axes as well, independent of the encoders and their associated microprocessors. The inclinometers have a read-out accuracy of better than 0.″1 and are read at 6 ms intervals. During the observations, the changes recorded by the inclinometers were less than 0.″5, indicating that the telescope tracking was not effected by structural changes.

The position readout of the subreflector was also monitored and was found to be stable. Receiver instabilities could also be excluded, since the variations never occured off the source. Figure 1 shows a phenomenon, observed on 1 April 1985. These data were also recorded on magnetic tape. With each data point the tracking errors in azimuth and elevation and the difference between the commanded and the actual position in scan direction was registered. In all cases the instrumental errors were negligible in comparison to the observed effect.

Subsequently, the effect has been observed at the 30-m telescope on numerous occasions. Displacements were seen in both azimuth and elevation, for sources at all elevations, in many different azimuth directions, at night and in daytime, with and without wind. In one session, data were recorded simultaneously with receivers at 86 and 230 GHz. The two beams were separated by 12″ in elevation, and sources were tracked midway between

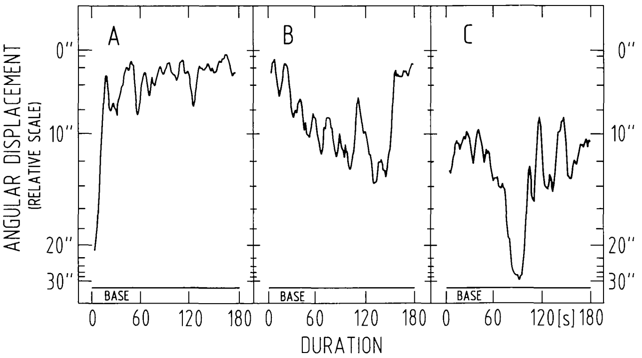

Fig. 1. Measurement of Orion A on Pico Veleta in the quasi-continuum of the integrated SiO-line at 86 GHz. The intensity scale has been converted into a relative scale of angular displacement (see Table 1). A) Tracking the peak position, which was determined before by a pointing measurement. B) Tracking near the half-power point, 13" north of the determined position. C) Same, but 13" to the West

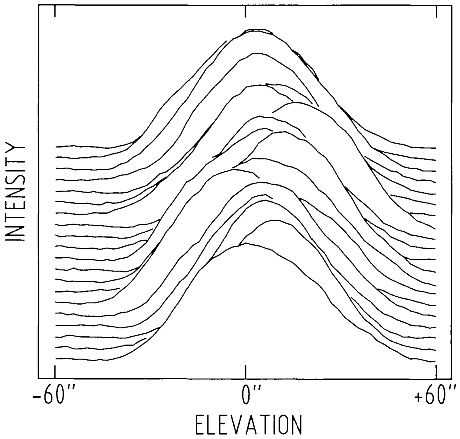

Fig. 3. Twenty consecutive scans in elevation direction of 3C 273 at 23 GHz in Effelsberg. Details in Table 1

the two beams. Decreases in intensity at 86 GHz coincided exactly with increases in intensity at 230 GHz and reverse, again indicating apparent position shifts rather than extinction, and ruling out receiver instabilities.

2.2. *Events at Effelsberg*

Since many years observers have occasionally reported problems with focussing the 100-m telescope, while observing at wavelengths of 2 cm or less, where the half-power beam width is smaller than 60". These problems were believed to be of unknown, intermittent instrumental origin.

With the experience of recognizing the position displacements on Pico Veleta the next focussing problem at the 100-m telescope was used to search systematically for similar effects. Figure 2 shows some observations of 3C 273 at 1.3 cm on 6 July 1985, tracking the source at peak and at half-power levels in elevation. This event displays a quasi-periodic pattern with a cycletime of about 27 s and an amplitude of $\pm 8''$; the total peak to peak difference is 34". Also in this case additional tests and checks proved, that these displacements were not instrumental.

A further test of these position displacements was made by direct position comparisons of many consecutive scans. The stacked scans are presented in Fig. 3. They were observed immediately before the observations displayed in Fig. 2. The biggest position difference, measured from these scans, is 20". The big scatter of the positions (more than one order of magnitude bigger than under undisturbed conditions) is directly visible.

Considering that the position measurements by scans represent a time average over about 10 s, the observed position displacements are expected to be smaller than those observed by tracking at the half power point. This is confirmed by the measurement results.

Figure 4 shows similar stacked scans, observed at 3.5 mm on Pico Veleta. Because of the lower scan velocity the time on source is about 20 s. In some of the scans one sees clearly that the beam is distorted from the usual Gaussian shape.

2.3. *Main characteristics of the events*

It is of high importance to be able to discern cases of anomalous refraction. There are three indications, that such an event is occuring:

a) unexpected jumps in pointing,
b) apparent instabilities, while tracking a source,
c) non-gaussian scan profiles across point sources.

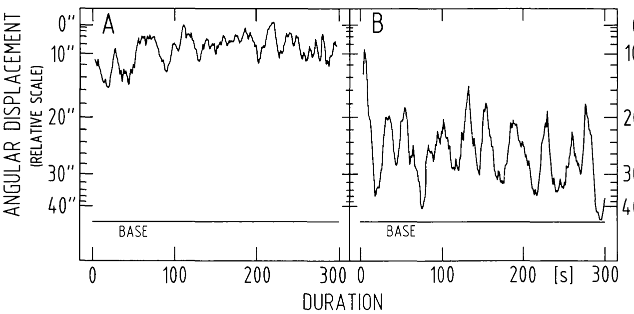

Fig. 2. Measurement of 3C 273 in Effelsberg in continuum at 23 GHz (Table 1). A) Tracking the peak position, determined before by a pointing measurement. B) Tracking near the half-power point, 20" north of the determined peak

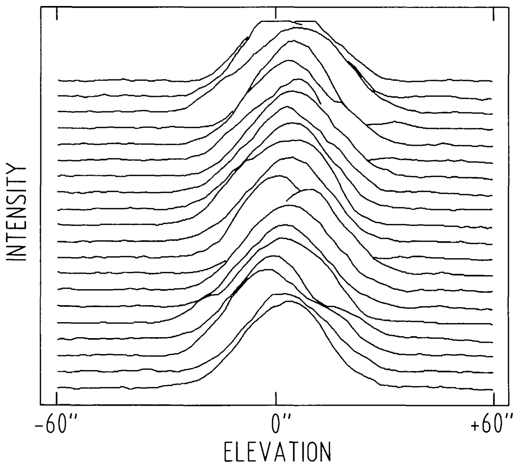

Fig. 4. Twenty consecutive scans in elevation direction of Orion A at 86 GHz on Pico Veleta (Table 1)

Table 1. Summary of conditions during anomalous refraction events

Source	Obs. Mode	Date	U.T.	Azm [deg]	Elv [deg]	Scan rms	pp[a]	Wind Dir. [deg]	Wind Vel. [ms^{-1}]	t [°C]	p [mbar]	rh[a] [%]	Sky	Obs. dur.	Remark
Pico Veleta, λ = 3.5 mm, HPBW = 27″															
Jupiter	track	85.03.31	05 30	135	22	–	10″.	240	7.	−1	702	25	–	18 m	Fig. 5a
Ori A	track	85.04.01	13 02	111	19	–	19.	240	6.	+1	706	69	clear	15 m	Fig. 5b, Fig. 1
Ori A	track	85.04.01	16 18	162	46	–	8.	–	0.	+2	706	73	clear	15 m	Fig. 5c
Ori A	scan	85.04.03	14 10	118	25	1″.6	5.6	316	1.	0	696	99	clouds	60 m	Fig. 4
Ori A	track	85.05.19	12 34	149	43	–	12.	225	4.	+2	700	96	scd[a]	60 m	Fig. 5d
Saturn	track	85.05.19	23 35	173	36	–	6.5	–	0.	−2	700	86	–	40 m	Fig. 5e
Saturn	scan	85.05.20	00 05	185	36	1.8	8.5	–	0.	−1	701	100	–	20 m	
Saturn	track	85.05.21	00 50	197	34	–	5.5	180	3.	+1	701	37	clear	75 m	Fig. 5f
Saturn	scan	85.05.21	01 48	212	29	0.6	1.7	200	4.	+2	702	28	clear	20 m	No anom. refr.
Effelsberg, λ = 1.3 cm, HBPW = 40″															
3C273	scan	85.07.06	14 50	139	34	4″.5	20.0	0	10	+20	968	70	scd	40 m	Fig. 3
3C273	track	85.07.06	15 15	145	37	–	43.	0	6	+20	969	68	scd	15 m	Fig. 5g, Fig. 2
3C273	scan	85.07.06	17 40	193	41	2.5	10.7	0	6	+20	969	55	scd	20 m	
3C84	scan	85.07.07	08 20	216	79	1.6	7.8	330	2	+10	974	75	clear	20 m	
3C84	scan	85.07.18	02 40	71	41	0.6	2.4	260	2	+17	964	66	clear	40 m	No anom. refr.

[a] pp = peak to peak change, rh = relative humidity, scd = scattered clouds

To rule out instrumental effects, special observations should be done, like tracking at the half power level of a strong source, or multiple scans, which allow both quantitative analysis and a monitoring of instrumental errors, as demonstrated above.

In Table 1 the collected data are compiled, together with the observing conditions. The meteorological data were either noted during the observations or were later extracted from the observatory weather records.

In the tracking mode only the maximum (peak to peak) displacement is given, in the scanning mode also the r.m.s. of all position measurements. For both telescopes a measurement in the scanning mode is given for a time, when no anomalous refraction was noticeable, indicating a r.m.s. repeatability for both telescopes of 0″.6.

From this table alone it is impossible to deduce meaningful correlations between the observed displacements and the telescope position, the meteorological condition or the time of observation. It should be noted that the phenomenon was never observed at low temperatures ($T \leq -10$°C), when the water vapor content in the atmosphere is very small.

For those events in Table 1, which were observed in the tracking mode, the histogram of the displacement distribution has been constructed, shown in Fig. 5. These displacements are systematically lower limits, because they are measured relative to the average and because the source extent has not been considered. It is not clear, whether the shape of the individual histograms is indicative of a particular meteorological condition.

All data from Table 1, observed on Pico Veleta in the tracking mode, were combined to analyse the time patterns. Also here the duration of a single displacement is a lower estimate, because of the sampling time of 3 to 5 minutes. The histogram of these durations (Fig. 6) has a maximum around 4 to 6 seconds of time, and a long tail extending to durations as long as 30 seconds.

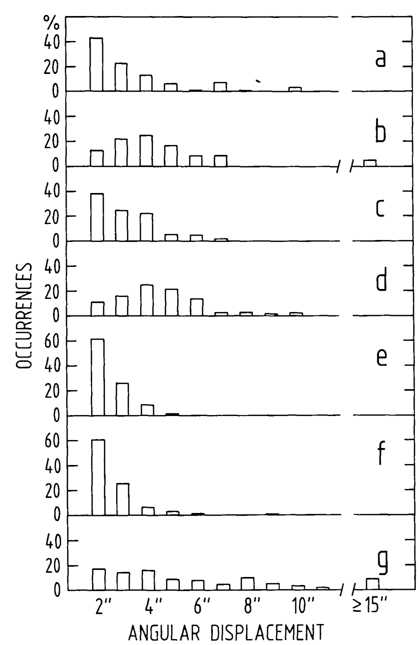

Fig. 5. Histograms of the frequency distribution of angular displacements for different anomalous refraction events, listed in Table 1

On the basis of the present results it is impossible to determine the fraction of time anomalous refraction occurs. Under similar general weather conditions we have experienced periods of strong anomalous refraction, as well as periods, where the effect was not measurable. Since it is only possible to identify its occurence during observations of strong sources, its influence on the observation of weak objects will remain unnoticed.

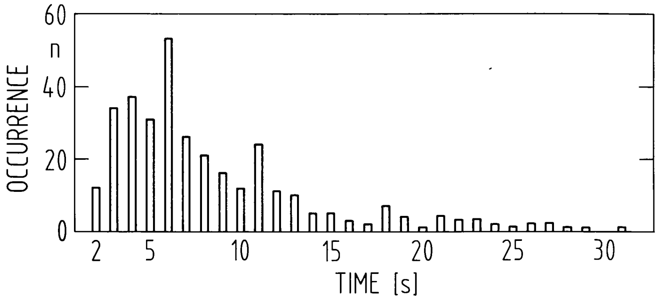

Fig. 6. The occurrence of single angular displacements as function of the duration of the displacement for all events on Pico Veleta, listed in Table 1

3. Interpretation

The simplest interpretation of this effect is in terms of anomalous refraction, caused by moist air packets, moved by the wind or by convection, with a characteristic size comparable to the size of the telescope. The fact that the effect is observed at high as well as low elevation angles suggests that the beam of the telescope only includes one packet at a time, and that the moist air packets are located relatively close to the telescope (likely within a few km, as to be expected on the basis of the scale height of water vapour of about 2 km). In this respect, the phenomenon differs from the type of anomalous refraction described extensively in the radio propagation literature, which is usually a low-elevation angle effect, in which the long, almost horizontal paths intersect atmospheric layers of different refractive index. Since the effect is observed with about the same amplitude in positional displacement at the Effelsberg telescope, we surmise that it is not strongly related to characteristics of the site.

3.1. Model for anomalous refraction

The observed displacements can be accounted for by moist air (at temperatures above 0°C), with an increase in relative humidity of about 20%. A simple model would consist of a moist air packet in the shape of a prism or a wedge. Alternatively a wavy structure at the interface of humid and dry air layers could also cause the observed effect. The latter model might be applicable to the quasi-periodic phenomenon observed at Effelsberg (Fig. 2b). The period of about 30 s is comparable to that found by others from autocorrelation analysis of atmospheric noise fluctuations (Kemp, 1980). It should be noted, however, that these arise from water vapour density fluctuations along the entire line of sight through the atmosphere.

Let us make a numerical estimate using the model of a humid wedge moving into the beam of the telescope. This wedge is certainly in the Fresnel region of the antenna beam, which has there a width of about the diameter of the telescope.

The refractivity N of the troposphere is given by the formula (Smith and Weintraub, 1953; see also Bean and Dutton, 1966)

$$N = (n-1)\cdot 10^6 = \frac{77.6}{T}\left(P + \frac{4810e}{T}\right) \tag{1}$$

where n is the refractive index, T the absolute temperature [K], P the atmospheric pressure [mbar] and e the partial water vapour pressure [mbar]. Here we are concerned with variations in the "wet part" of N arising from a change in e:

$$\Delta N_W \approx 5\cdot \Delta e\,[\text{mbar}]\,.$$

At a temperature $T = 280\,\text{K}(7°\text{C})$ the saturated water vapour pressure $e_s = 9\,\text{mbar}$. For a relative humidity (RH) of 50%, i.e. $e = 4.5\,\text{mbar}$, we have $N_W \approx 22$ and a change in RH of 20% leads to $\Delta e \approx 1\,\text{mbar}$ and $\Delta N_W \approx 5$. For a thickness gradient of the humid wedge $\Delta L = 100\,\text{m}$ over the aperture diameter the resulting change in electrical pathlength is

$$\Delta l = \Delta N_W \cdot 10^{-6}\cdot \Delta L \approx 0.5\,\text{mm} \tag{2}$$

This pathlength difference between opposite edges of the telescope aperture (D) is equivalent to a change in the angle of arrival

$$\Delta\alpha = \Delta l/D \tag{3}$$

which for values of $D = 30\,\text{m}$ and $\Delta l = 0.5\,\text{mm}$ yields $\Delta\alpha = 1.67\,10^{-5}\,\text{rad} \approx 3''\!.5$. This value is typical for the measured effect. Changes in relative humidity of the order of 20% are measured regularly at the earth's surface. From the ideal gas law the absolute humidity (water vapour density) ρ follows directly as

$$\rho = \frac{M}{R}\cdot\frac{e}{T} \approx 217\,e/T\,[\text{g m}^{-3}] \tag{4}$$

with M the molecular weight and $R = 8.31\,\text{J/K}$ the universal gas constant. For $\Delta e = 1\,\text{mbar}$ and $T = 280\,\text{K}$ we find $\Delta\rho = 0.8\,\text{g m}^{-3}$, which, for the assumed gradient of 100 m over the aperture, corresponds to a change in precipitable water vapour of less than 0.1 mm. Significantly larger values are not unlikely, accounting for the largest measured changes in the angle of arrival. Although this model is very simple, the numerical values used are realistic and consistent with meteorological measurements. Thus we believe this model to be a reasonable description of the observed anomalous refraction phenomenon.

3.2. Comparison with interferometer measurements

VLA phase-data (Armstrong and Sramek, 1982) can be interpreted as representing the fluctuations in electrical path length as:

$$\Delta l = 0.024\,B^{0.7} \tag{5}$$

where Δl is the differential electrical path (mm), and B is the baseline length (m) (see Resch, 1984; Resch et al., 1984). Similar experiments by Kasuga et al. (1986), with ten baselines ranging from 27 m to 540 m with the Nobeyama interferometer at 22 GHz, can be interpreted as giving approximately

$$\Delta l = 0.01\,B^{0.8} \tag{6}$$

The results of Bieging et al. (1984) with the Hat Creek interferometer at a wavelength of 3.4 mm, yield, for one of their possible fits,

$$\Delta l = 0.003\,B^{0.8} \tag{7}$$

If one substitutes $B = 30 - 80\,\text{m}$, (the range from the Pico Veleta antenna to the solid portion of the Effelsberg telescope), one obtains from these formulae differential electrical lengths of typically $0.1 - 0.3\,\text{mm}$. From this we conclude that interferometers are probably detecting the same atmospheric disturbances as seen at Pico Veleta and at Effelsberg. The events apppear not as pointing displacements with the single dishes, but as phase noise with the interferometers, which broadens the synthesized beam. We note, however, that as millimeter interferometry moves to shorter wavelengths and larger dishes, the primary beams of the interferometer antennas will become smaller, and the anomalous refraction events will occasionally move the sources out of the primary beams and reduce the observed fringe amplitudes.

4. Implications for observing

Anomalous refraction presents a hazard, which observers should be aware of. It affects the observations in two ways:

i) the derived pointing correction might be faulty,

ii) during a long integration the beam is effectively broadened with a reduced efficiency.

Actually a signal reduction by a factor of 2 has been observed for an integration time of 1 hour. Since anomalous refraction is highly variable with time, it cannot be overcome by calibration. It can make precise intensity and position measurements impossible, because one cannot use the observed position difference to correct the intensity.

Continuum and line observations are affected, regardless whether they are done with a single dish or an interferometer.

Since the identification of the phenomenon as reported above, it has been seen repeatedly at the 30-m telescope. The danger of it remaining unnoticed could be reduced by measuring it independently, simultaneously with astronomical observations.

It is our intention to do this, but we have not yet found a way of achieving this with sufficient accuracy. Once a method has been realized, it could be used in tests of prospective new observatory sites to evaluate the magnitude of the effect.

Acknowledgements. We thank the telescope operators for their unfailing help in the collection of the data. Discussions with J.B. Schraml are gratefully acknowledged.

References

Armstrong, J.W., Sramek, R.A.: 1982, *Radio Science* **17**, 1579

Baars, J.W.M., Hooghoudt, B.G., Mezger, P.G., de Jonge, M.J.: 1987, *Astron. Astrophys.* **175**, 319

Bean, B.R., Dutton, E.J.: 1966, *Radio Meteorology*, U.S. Govt. Printing Office, Nat. Bur. Standards Monograph 92, (reprinted 1968, Dover Publications, New York), p. 7

Bieging, J.H., Morgan, J., Welch, W.J., Vogel, S.N., Wright, M.C.H.: 1984, *Radio Science* **19**, 1505

Kasuga, T., Ishiguro, M., Kawabe, R.: 1986, *IEEE Trans. Ant. Prop.* **AP-34**, 797

Kemp. A.J.: 1980, *Int. J. Infrared Millimeter Waves* **1**, 469

Resch, G.M.: 1984, in *Geodetic Refraction*, ed. F.K. Brunner, Springer-Verlag, Berlin, p. 53

Resch, G.M., Hogg, D.E., Napier, P.J.: 1984, *Radio Science* **19**, 411

Rydbeck, G., Hjalmarson, Å., Rydbeck, O.E.H.: 1985 *Astron. Astrophys.* **144**, 282

Smith, E.K., Weintraub, S.: 1953, *Proc. IRE* **41**, 1035