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D-Region Radio Wave Propagation Experiments, Their Significance and Results during the Western European Winter Anomaly Campaign 1975/76

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Abstract. During the Western European Winter Anomaly Campaign 1975/76 at 'El Arenosillo' (Huelva/Spain) *D*-layer radio wave absorption was measured 'on line' in Spain, Germany and Austria using the continuous wave propagation (A_3) method.

The task of the receiving station at the launching site was to announce absorption events of the winter anomalous type. Further, the results of both its absorption and ionosonde measurements were integrated into a number of ground based and rocket measurements in order to calibrate in situ electron density profiles.

Common quasi-periodic oscillations of *D*-layer absorption at the widely separated stations became evident together with the drifts of the associated spatial patterns from the analysis of the records. Comparisons of the daily absorption with *D*-region winds between about 80 and 100 km measured simultaneously by rocket experiments from the same site show correlations between winter anomaly and transport processes at *D*-layer heights.

Key words: Aeronomy – Ionospheric absorption – Winteranomaly.

1. Method of Measurement and the Average Daily Variation of *D*-Layer Absorption during a Year in Southern Europe

During the Western European Winter Anomaly Campaign of 1975/76 at 'El Arenosillo' (Huelva/Spain) *D*-layer radio wave absorption was continuously measured in Spain, Germany and Austria. The geographical locations and the distribution of the stations are shown in the preceding paper (Offermann). The transmissions paths in Spain were continuously operated for several years. In each year of observation (1967/68, 1970/71, 1971/72, 1972/73, 1973/74, 1974/75) winter-anomalous conditions were found to be present, January being the month in which the probability of its occurrence was highest and to meet both, high winter-anomalous absorption and conditions of very low absorption. This result of a rather long period of monitoring which was supplemented by observations of winter-anomalous conditions over Sardinia on an earlier occasion (1964/65) were one of the reasons for planning the campaign and for D-layer in situ experiments performed over Arenosillo during the past years (Rose et al., 1972a, 1972b; Rose and Widdel, 1972, 1973). There was no sound reason or support for the belief that winter-anomalous conditions should not be present over a sufficiently long time during December 1975 and January 1976.

The so-called A_3 method was used (Schwentek, 1958; Dieminger et al., 1966; Rose, 1967; Rose et al., 1971, 1974; Friedrich et al., 1976). The amplitudes of the sky waves of continuously transmitting short radio wave transmitters were recorded at receiving stations which were located at distances up to about 500 km. (The transmission was interrupted every five minutes for one minute to discriminate the noise and interference level.) Antennas, distances and transmitting frequences were well selected according to the local ionospheric propagation conditions in order to be able to determine D-layer absorption quasi 'on line' all over the year between about sunrise and sunset.

The absorption measurement is obtained by the transmission of a wave frequency that is reflected at E-layer heights ($h' \approx 100 \dots 125$ km) during daytime. In this case the absorption-free reference value which is necessary to determine absorption does not depend too much on the height of reflection if the antennas are designed to favour $1 \times E$ hop propagation. This mode is advantageous because the signal observed from different E-layer heights during the day can then be related to one constant (mean) reference value (instead of using a strongly height-dependent one for which the height has to be determined independently in each case) without introducing a significant error.

A proof of this is given in Figure 1 which shows the change of apparent absorption on the Aranjuez-Arenosillo transmission path when the height of reflection

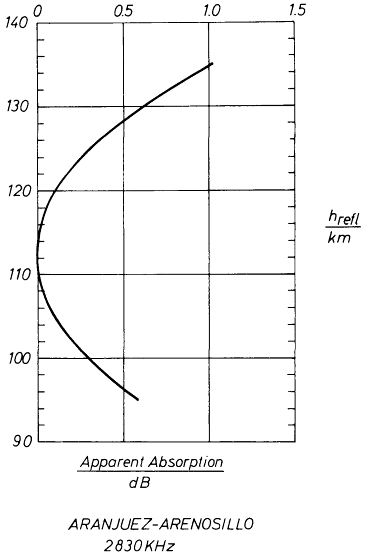


Fig. 1. Change of (virtual) absorption as a mere function of reflection height at vanishing D-layer absorption calculated for the technical equipment of the Aranjuez-Arenosillo path

changes (at vanishing *D*-layer absorption). The error introduced by using a mean constant instead of a height dependent reference value is only of the order of half a dB and can therefore be neglected for most of the day. For this reason the absorption L can readily be determined 'on line' by using the simple formula:

$$L(t)\,(\mathrm{dB}) = E_0(\mathrm{dB}) - E(t)\,(\mathrm{dB}) \tag{1}$$

E_0 is the mean reference receiver input voltage (e.g. in dB over 1 μV) without absorption. It is determined and controlled in principle by averaging a great number of night-time values obtained during blanketing sporadic *E*-layer propagation conditions. $E(t)$ is the relevant (mean) input voltage centered around the time t of observation. For the different A_3 paths only ordinary mode propagation is of importance. This is because of the orientations of the propagation paths relative to the geomagnetic field and because of the antenna geometries.

The length of the transmission path Aranjuez-Arenosillo is 424 km and the transmission frequency is 2830 kHz. Ground wave propagation is therefore practically non existent. As was proved by simultaneous ionosonde observations, *E*-layer propagation occurs during the day on this path all over the year for solar zenith distances $\chi < 80°$. At the same time, absorption can be as high as about 60 dB relative to the corresponding absorption-free nighttime value when strong winter anomalous conditions are present. These are values which can still be handled by the receiving equipment without significant loss of accuracy.

In order to investigate what would happen to different *E*-layer propagated wave frequencies along this transmission path during average winter anomalous conditions, relative differential absorption profiles $(1/L_{\mathrm{tot}}) \cdot (dL/dh) \cdot (\cos\varphi)^{-1}\varphi$ for the more strongly absorbed downcoming wave were calculated and plotted for 2.0, 2.5 and 3.0 MHz in Figure 2. (The measured profile for 2.83 MHz is not included in this figure.)

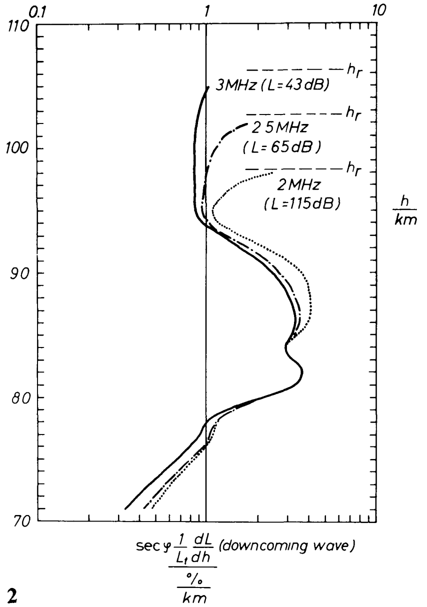
Some consequences are evident from Figure 2: A 2 MHz wave is absorbed so strongly during anomalous conditions that it cannot be measured over that distance. At the same time it is clear, that waves which penetrate increasingly into the *E*-layer with increasing wave frequency undergo an increasing amount of (unwanted) deviative *E*-layer loss (Bibl and Rawer, 1951; Rose, 1967). As another example of the response of the transmission path Aranjuez-Arenosillo to low and winter anomalous high absorption conditions, 3 relative differential absorption profiles $(1/L_{\mathrm{tot}}) \cdot (dL/dh) \cdot (\cos\varphi)^{-1}\varphi$ one of them belonging to low absorption conditions, are displayed in Figure 3.

The propagation paths in Spain and Germany have been operated very close to optimum experimental conditions, whereas the path from Meeder (Coburg/Germany) to Graz (Austria) might have been somewhat shorter, but this was impossible because of technical difficulties.

As is well known, the daily variation of absorption can be approximated by a $\cos^n \chi$ law according to (Best and Ratcliffe, 1938):

$$L(t)\,(\mathrm{dB}) = L_0(\mathrm{dB}) \cdot \cos^n \chi(t) \tag{2}$$

where $L(t)$ is the absorption relative to the absorption-free reference value and χ is the solar zenith angle at the time of observation. The exponent "n" may vary



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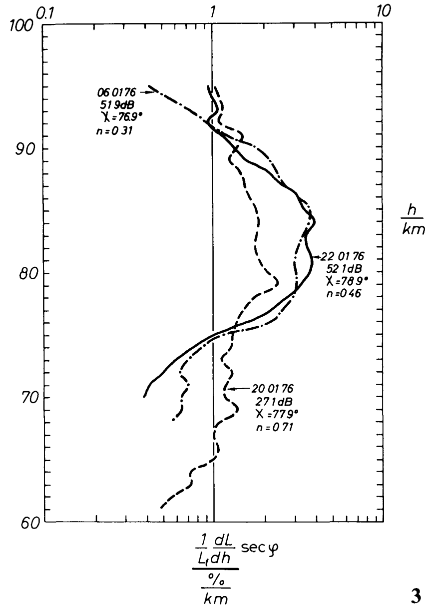

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Fig. 2. Relative differential absorption $(1/L_{\text{tot}})\cdot(dL/dh)\cdot(\cos\varphi)^{-1}$ φ for the parameters of the Aranjuez-Arenosillo path and different wave frequencies during winter anomalous conditions. The stronger absorbed down-coming wave is presented

Fig. 3. Relative differential absorption for 2830 kHz during winter anomalous ($L = 52.1$ dB and $L = 51.9$ dB) and during normal conditions ($L = 27.1$ dB) in winter. Propagation path: Aranjuez-Arenosillo. (Stronger absorbed down-coming wave)

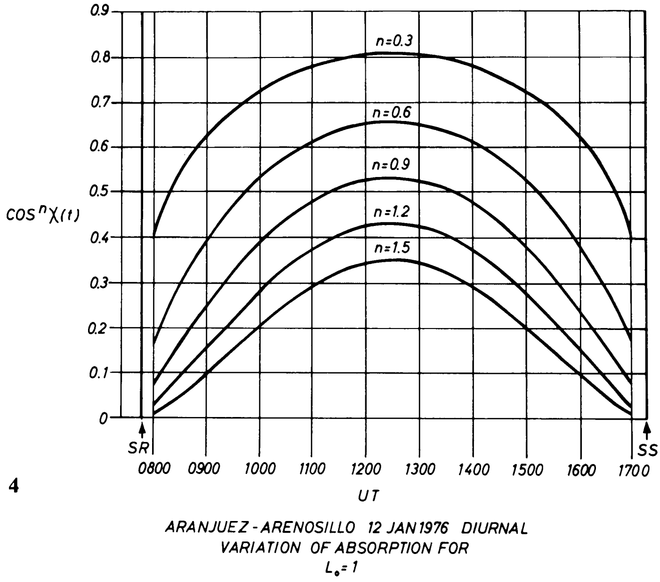
between about 0.5 and 1.5 and determines the shape of the daily curves of absorption; L_0 is the subsolar absorption.

In Figure 4 some $\cos^n \chi$ curves with different exponents are plotted, which were calculated as examples for the midpoint of the Aranjuez-Arenosillo path for 12 January 1976. As is seen from (2) and Figure 4 absorption increases with decreasing "n" and increasing L_0. This property of the daily variation of absorption must be considered if a suitable parameter, characterizing the absorption of a whole day, has to be defined. If in (2), $\cos\chi$ is chosen as the independent variable and the expression is integrated from $\cos\chi = 0$ to $\cos\chi = 1$, one obtains:

$$L_0/(n+1) = \int_0^1 L(\cos\chi)\cdot d(\cos\chi) \tag{3}$$

with $L_0/(n+1)$ being the parameter with the desired features (Rose, 1967).

The actual process by which $L_0/(n+1)$ is determined is quite different from a real integration: One determines the best fit straight line through all the points $\log L(t)$, $\log\cos\chi(t)$ belonging to E-layer propagation of the relevant day (e.g. $\chi < 80°$ for the Spanish transmission paths). The slope of this line equals "n" and



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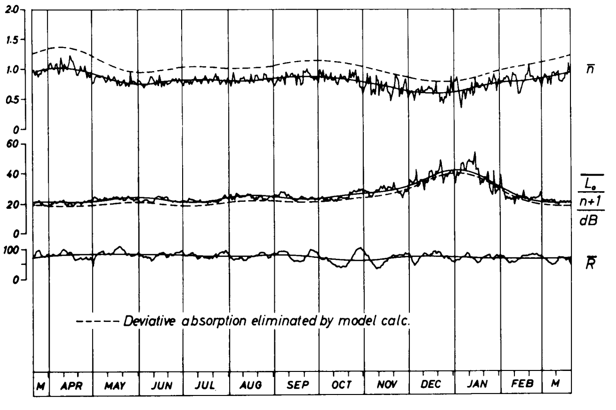


5 *ARANJUEZ-BALERMA, MEANS: 1967/68, 70/71, 71/72, 72/73 AND 73/74*

Fig. 4. Dependence of the diurnal variation of absorption on the exponent "n" in Equation (2), calculated for January 12, 1976. Propagation path: Aranjuez-Arenosillo

Fig. 5. Average variation of the absorption parameters "$\bar{n}$" and "$\overline{L_0/(n+1)}$" (and of the sunspot numbers $\bar{R}$) during a year. Average from five years of observation

the intersection of the line with the ordinate at $\log\cos\chi=0$ equals $\log L_0$. The "integrated absorption parameter" $L_D=L_0/(n+1)$ has the advantage that it merges L_0 and "n" in one meaningful parameter. This turns out to be very useful for comparison purposes.

The average daily variations of $\bar{n}$, $\overline{L_0/(n+1)}$ and of the Zürich sunspot numbers $\bar{R}$ which were obtained from five years of observations (1967/68, 1970/71, 1971/72,

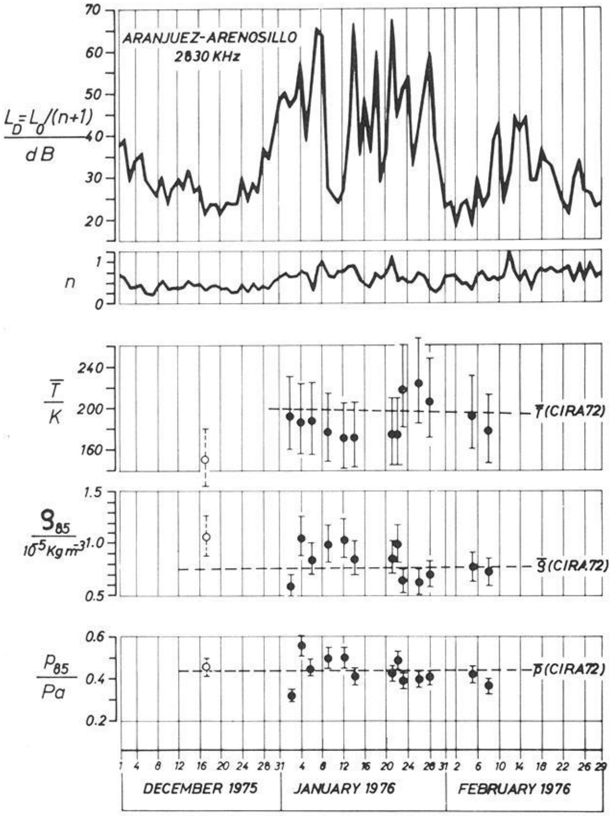


Fig. 6. Variation of the daily absorption parameters "L_D" and "n" (upper half) and of the rocket temperature data $\bar{T}$ (83–95 km), density at 85 km ρ_{85}, and pressure at 85 km p_{85} observed during the Winter Anomaly Campaign

1972/73 and 1973/74) are plotted in Figure 5. The solid lines are Fourier synthesized by using the coefficients up to the fifth order. Winter-anomalous high absorption is generally evident between November and February as seen from the high $\overline{L_0/(n+1)}$ values and the relatively large variations of absorption from day to day during the winter season, which do not average out even if five years of observations are superimposed. At the same time the exponent "n" is on the average significantly lower during winter too.

The dashed lines in Figure 5 were obtained from model calculations which were performed to estimate the influence of deviate absorption (mainly occurring close to the level of reflection in the E-region) on the measurements (Rose, 1967). As far as $L_0/(n+1)$ is concerned deviative absorption is of the order of 10% and is therefore of no significant importance for the conditions found on our transmission path in Spain. The same is true for the absorption $L(t)$ as long as it is not observed during those periods in the early morning or late afternoon, when the waves are deeply penetrating into the E-layer.

2. The Forecast Capabilities of Ground Based *D*-Layer Measurements at the Launching Site and Their Integration into Rocket Borne Experiments

The special task of the A_3 receiving station at the El Arenosillo launching site was to announce anomalously high or subnormally low absorption events as early as possible in order to allow sufficient time for the extensive payload and launching preparations. Together with the ionosonde and chaff cloud measurements (Rose et al., 1972a; Rose and Widdel, 1972, 1973) performed at the range, the A_3 measurements were also used to calibrate the rocket borne guarding probes in terms of electron densities versus height.

Our ability to forecast winter anomalous high or low absorption events are based on statistical considerations because no other reliable methods for forecasts exist. In this respect the experience which was gained from the A_3 measurements in Spain during the different previous winters before the campaign (Rose, 1976) was of great value. These data were used for model forecasts and reliability evaluations.

From this experience we decided to define a day of high absorption as a day for which the average absorption $\bar{L}$ between 11.30 and 12.30 UT was higher than 50 dB for the Aranjuez-Arenosillo transmission path. A day of low absorption was one in which $\bar{L}$ was smaller than 25 dB during that time interval. These two characteristic values corresponded on a statistical basis to 47 dB and 23 dB as far as the interval from 14.00 to 15.00 UT was concerned. This time interval was centered around the different launching times of the rockets.

From inspection of the individual daily variations of absorption during the different winters before the campaign it was clear, that winter anomalous conditions or normal conditions continued in nearly all cases over the whole day but changed from one day to the other (if at all). Because of this behaviour no useful forecasts were possible from one day to the other.

A first indication of the conditions to be expected for a given day could be anticipated in the morning at about 09.00 UT, however, with low reliability. If, moreover, the average values for the interval between 09.30 and 10.00 UT were larger than 40 dB or smaller than 20 dB, the probability that the desired conditions would be present during the launch period was between 65 and 70 %. If the absorption of the days were larger than 50 dB or smaller than 25 dB around noon, the desired conditions were present in more than about 80% of the launching hours. This outlined procedure worked sufficiently well during the campaign. Only low absorption conditions did not appear as often as expected from the observations of the previous winters.

In the upper part of Figure 6 the variation of the daily absorption $L_D = L_0/(n+1)$ between December and February 1975/76 is shown for the transmission path Aranjuez-Arenosillo together with the daily variation of the exponent "n". Air temperatures, densities and pressures measured by the rocket borne chaff cloud experiment (Rose and Widdel, 1972, 1973) are displayed in the lower part of Figure 6 in comparison with the average CIRA 72 values.

From the air pressure values electron collision frequencies were estimated for *D*-region heights (Phelps and Pack, 1959) and were used together with the simultaneously measured (integrated) absorption and the virtual height of wave

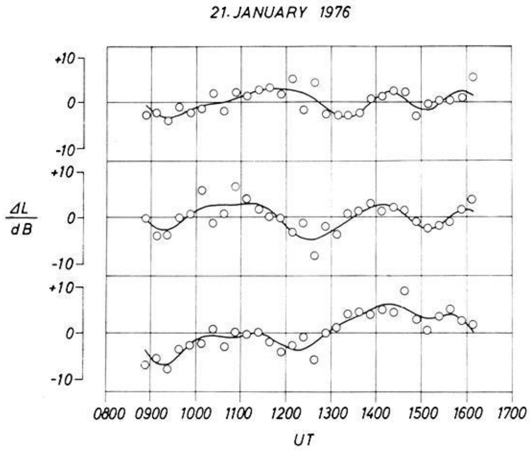


Fig. 7. Wave-like fluctuations of absorption around their associated cos$^n\chi$ curves of best fit at the three Spanish stations observed on January 21, 1976

reflection to calibrate the relative electron density profiles as obtained from the rocket borne guarding probes. The virtual reflection height was determined by using the transmission curve technique applied to the Arenosillo ionograms with regard to the Aranjuez-Arenosillo transmission path. A more detailed description of this method will be given elsewhere.

3. On the Existence of Common Quasi-Periodic Oscillations of Different Scales at the Separated A_3 Stations

From the results collected with the different A_3 paths in Spain (from Aranjuez to Arenosillo – midpoint: 38.58° N, 5.21° W, $D=424$ km; to Balerma (Almeria) – midpoint: 38.38° N, 3.23° W, $D=374$ km; and to Tortosa – midpoint 40.45° N, 1.57° W, $D=360$ km) it became clear that the days of winter anomalous low or high absorption generally appeared simultaneously all over Spain (the correlation coefficient was $r=0.97$).

Small deviations of absorption from the best fit smoothed cos$^n\chi$ curves were observed at the different Spanish stations. Suitably filtered, they could be traced in some cases to irregularities moving at speeds of several tens to up to about 100 m/s. An example for this type of moving wave-like structure is shown in Figure 7. In this figure the above mentioned deviations ("fadings") of absorption around the relevant cos$^n\chi$ curves for the three Spanish stations observed during 21 January 1976 are displayed. The points are average values for each quater/h. The curves are Fourier-synthesized. Coefficients up to the fifth order for the displayed time interval were used. The average drift velocity of the associated pattern during that day (calculated by cross correlation) was about 30 m/s. The direction of the movement was from the north-east to the south-west. The drift direction can also be estimated by comparing the temporal locations of the valleys

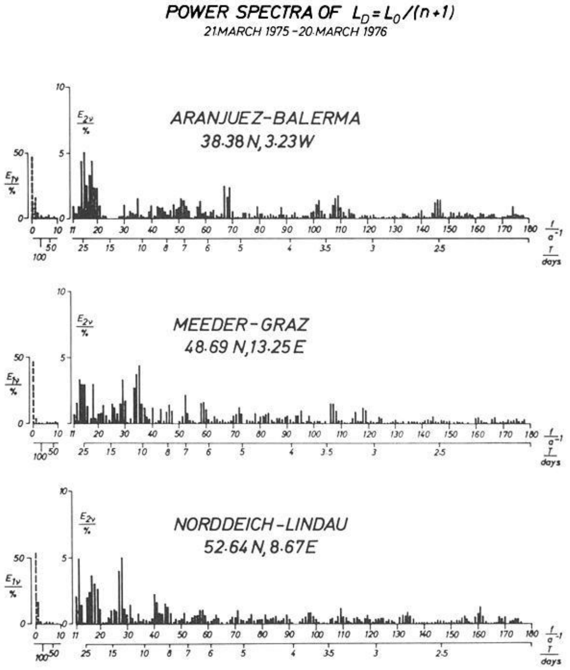


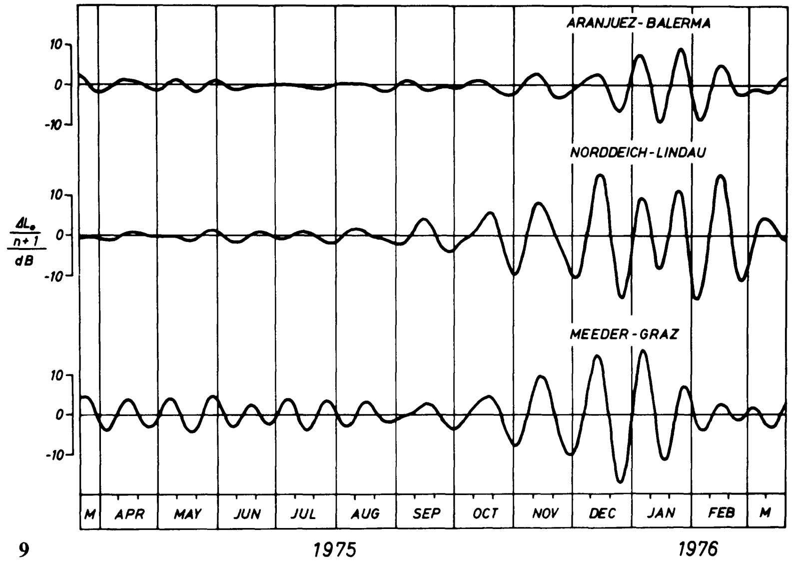
Fig. 8. Relative power spectra of the daily variations of absorption for one year of measurements in Spain, Austria and Germany. The first ten power lines at the left are drawn relative to the relevant total annual energies, the rest in each diagrams is related to the remaining energies

between about 12.30 and 13.30 UT of Figure 7 with the geographic locations of the midpoints of the different Spanish paths.

Common quasi periodic oscillations of absorption of the order of 3 weeks became evident from the spectral analysis of the daily variations of absorption L_D observed during one year of measurements in Spain, Germany and Austria. The power spectra of the absorption parameters L_D of the mentioned widely separated stations are shown in a (double) normalized form in Figure 8. If the filtered partial waves, significantly present at all the 3 stations at the same time, are synthesized (e.g. $11\,a^{-1} \leqq f \leqq 20\,a^{-1}$), maximum and rather similar amplitude variations for all the three stations were only present during the winter months starting at about November 1975 and lasting to about the beginning of March 1976 (see Fig. 9). Cross correlation calculations including the 100 days from 1 December–9 March revealed a drift of the associated spatial pattern from the west-north-west to the east-south-east at an average speed of about 3 m/s. This value corresponds roughly to an average wave-length of 5000 km.

Other quasi-periodic oscillations of absorption common to all 3 stations contained spectral components with periods around 7 and about 3.5 days (e.g. $40\,a^{-1} \leqq f \leqq 59\,a^{-1}$ and $95\,a^{-1} \leqq f \leqq 115\,a^{-1}$). These components exhibited the same trend as above: namely large amplitudes are present only during the winter months.

The trends of winter anomaly as observed during the year 1975/76 at the widely separated stations in Germany, Austria and Spain were compared with each other in different ways: The sums of the annual, half-annual and 1/3-annual



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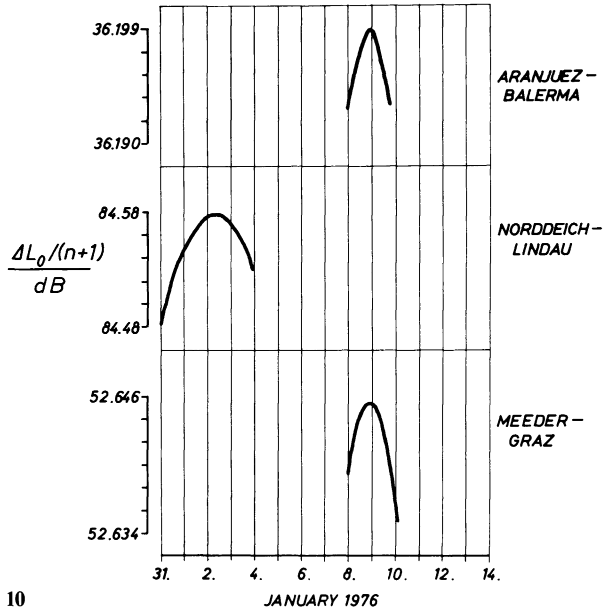

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Fig. 9. Fourier-synthesized waves including $11a^{-1} \leqq f \leqq 20a^{-1}$ for the widely separated stations

Fig. 10. Trends of winter anomaly (sums of the annual, half-annual and 1/3-annual waves) for the widely separated stations at expanded scales

waves of the daily absorption resulted in single winter maxima of these synthesized trend curves which occurred simultaneously on the Spanish (Aranjuez-Balerma) and the German-Austrian (Meeder/Coburg-Graz) transmission paths, whereas the maximum was reached one week earlier in Germany on the Norddeich-Lindau path. This is evident from Figure 10 where these maxima are displayed for clarity at a rather expanded scale. If one confines the calculations to the simple sinoidal trends of the 180 days from 24 September, 1975–21 March, 1976 only for these 3 stations, one arrives at exactly the same result as mentioned above. This corresponds to an average virtual drift of the whole "absorption front" in Central Europe during that winter from the north-east to the south west at a speed of roughly 80 km/day e.g. 1 m/s.

4. Winds at *D*-Region Heights and A_3 Absorption

Comparisons of the daily absorption with the *D*-region winds which were measured simultaneously during the last winters by in-situ rocket experiments between about 80 km and 100 km show a correlation between winter anomaly and transport processes at *D*-region heights. These comparisons were performed by a special correlation-finding procedure (Rose et al., 1972b) which resulted in beam diagrams which indicate the directions in the different heights from which, on the average, increasing winds were accompanied by increasing A_3 absorption.

This procedure was accomplished with all afternoon measurements performed during the Winter Anomaly Campaign and with all other winter observations which were gathered during daytime since 1972/73. The oval beam diagrams obtained for the different heights are shown in Figure 11. They are positioned like maps with the north at top and the directions from which winds were accompanied by the most significant increase of A_3 absorption on the average are indicated by arrows. The circular arcs in the figures represent the 95% or, if in the case when two are drawn, the 95% and 99% significance levels. The numbers of the measurements available for the different heights are given in brackets below the indicated height of each individual diagram of Figure 11.

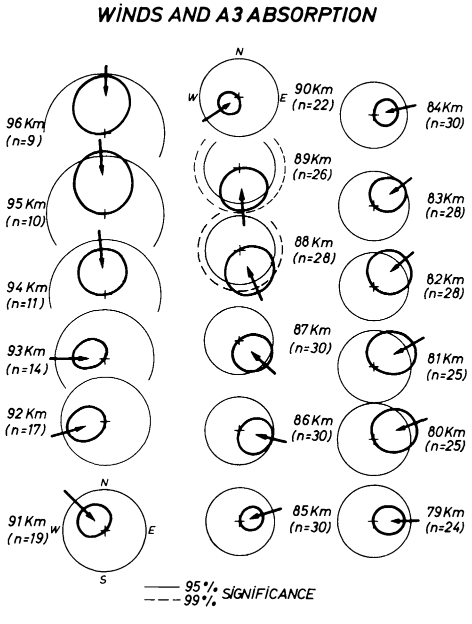

Fig. 11. Beam diagrams which indicate the directions from which increasing winds in the different heights were accompanied most significantly by increasing (integrated) absorption

There appear to be at least three levels of significance, each separated by about a scale height. It was further found by comparisons that the directions of maximum correlations at the different heights were not necessarily the same as the prevailing wind directions observed in these heights.

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