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Transmission of Electric Fields and Photoelectron Fluxes between Conjugate Ionospheric F2-Regions*

E. F. Petelski

Dornier System, Space Division, Friedrichshafen

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Abstract. The dynamic behaviour of the ionospheric F2-layer requires considerable vertical transport of ionization. Possible causes of such transport are ambipolar diffusion, neutral air winds and electric fields. Here mid-latitude electric fields are investigated. Real height variations of the F2-layer indicate that the phases and amplitudes of these fields are similar at well conjugate points and that the field strengths can become unexpectedly high. It is further shown that photoelectrons can migrate between the two hemispheres along the geomagnetic field lines.

Key words: Ionospheric F2-layer — Real Heights — Critical Frequencies — Conjugate Points — Electric Fields — Neutral Winds — Declination Effect — Photoelectron Fluxes — Numerical Filtering — Correlation Coefficients.

1. Introduction

Even at magnetically quiet times the mid-latitude ionospheric F2-layer undergoes large height and density fluctuations. These variations cannot be due to photochemical processes only but require considerable vertical transport of ionization. Possible causes of such transport are ambipolar diffusion, neutral air winds and electric fields.

So far, experimental results do not provide a detailed and reliable picture of the winds and the electric fields in the upper atmosphere. Therefore, attempts to theoretically understand the dynamic peculiarities of the ionosphere have to proceed from models. In this way numerous authors have come to the conclusion that wind effects predominate in middle and high latitudes whereas electric fields have some importance in equatorial latitudes, at most. However, there does exist experimental evidence indicating that wind and field models are insufficient and that electric fields may exert appreciable influence on the mid-latitude ionosphere, too. Regrettably, effects of this kind cannot easily be identified by conventional methods of ionospheric sounding. That is why an attempt was made to take advantage of the geomagnetic coupling of conjugate ionospheric regions with a view to distinguish wind- and electric field induced effects in the F2-layer. Another intention was to assess the strength of the involved fields and to derive information about photoelectron fluxes between the two hemispheres.

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2. Background and Method

From measurements of the orbital periods of earth satellites, atmospheric density variations within the F2-layer can be deduced which stem from the daily succession of heating and cooling of the air. These data render feasible the preparation of atmospheric models giving information on the global distribution of pressures as well as temperatures. According to King and Kohl (1965), the pressure gradients drive large systems of horizontal winds within the F2-layer. Many papers have already been dedicated to the calculation of such winds from the world-wide pressure distribution. A typical result is that by Challinor (1970).

Evidently, models of this kind are of limited validity because they are not derived from direct measurements but calculated indirectly from satellite observations. Moreover, geophysical models usually represent space and time averages which exclude predictions of local or irregular effects.

The influence of neutral winds on charged particles is exerted by air drag, i.e. by frictional forces. Within the F2-layer, the resulting movements of the ionization are restricted to directions corresponding those of the earth's magnetic field. Analytically, this means

$$\mathbf{V} = (\mathbf{U} \cdot \mathbf{B})\, \mathbf{B}/B^2 \; ; \qquad (1)$$

$\mathbf{V}$: velocity of electrons and ions, $\mathbf{U}$: velocity of neutral air, $\mathbf{B}$: geomagnetic field. Although the neutral gas moves horizontally, the magnetic inclination introduces vertical components in the ionization velocity:

$$V_z = U_x \sin I \cos I \; ; \qquad (2)$$

V_z: vertical velocity component of $\mathbf{V}$, U_x: north-south component of $\mathbf{U}$, I: geomagnetic inclination.

To estimate the effects of ionization drifts on the F2-layer, continuity equations for all plasma components have to be solved. For example, the concentration N_i of one kind of ions in a certain height z behaves like

$$\left.\frac{\partial N_i}{\partial t}\right|_z = q - \beta N_i^2 - \operatorname{div}(N_i V_i), \qquad (3)$$

where q is the ionization rate, β the recombination coefficient and t the time. To be sure, the ionization is not exclusively accelerated by winds. It also diffuses under the influence of gravity and its own partial pressure and it is exposed to Lorentz forces as well as to electric fields. In order to account for all these parameters, the equations of motion for ions, electrons and the neutral gas have to be taken into consideration. In case of charged particles, these equations are of the following kind:

$$m_i \frac{d\mathbf{V}}{dt} = m_i \mathbf{g} - \frac{1}{N_i} \nabla p_i + e\mathbf{E} + e(\mathbf{V} \times \mathbf{B}) - m_i \nu_{in} (\mathbf{V} - \mathbf{U}) \; ; \qquad (4)$$

p_i: partial pressure of ions

$\mathbf{E}$: electric field

ν_{in}: collision frequency ions-neutral particles

m_i: ion mass

$\mathbf{g}$: gravitational acceleration

e: elementary charge

$\mathbf{B}$: geomagnetic field

$\mathbf{U}$: neutral wind velocity

For neutral particles one gets:

$$m\frac{d\mathbf{U}}{dt}+2\,m\boldsymbol{\Omega}\times\mathbf{U}=m\mathbf{g}-\frac{1}{N}\nabla p-m\nabla\psi+\frac{\mu}{N}\nabla^2\mathbf{U}-m\nu_{ni}(\mathbf{U}-\mathbf{V})\,; \quad (5)$$

m: mass of single particle
N: density of particles
ψ: scalar potential of tidal forces
ν_{ni}: collision frequency neutral particles-ions
$\boldsymbol{\Omega}$: earth's angular velocity
p: pressure
μ: molecular coefficient of viscosity

By simultaneously solving the complete set of Eqs. (3) to (5), one can show that vertical motions of the F2-layer ionization finally result in two effects: they change the height of the ionization density maximum, the "layer height", and they alter the maximum ionization density itself. The latter effect is a consequence of the fact that in different heights different recombination rates apply: an upward drift increases both the layer height and the ionization density and a downward drift acts in the opposite way.

A lot of research has already been done concerning wind induced effects of the above kind. Mostly, the authors have solved the system of coupled equations twice, once inserting and once omitting neutral air winds, and compared the results with experimental ionospheric data. In this way it could be demonstrated that winds do act a vital part among those factors which determine the F2-layer dynamics. In particular, it was established that winds are the reason for the well-known evening enhancement of the F2-layer height. However, most of these studies suffer from an essential drawback in that the theoretical values are compared to averaged experimental results which do no more contain short-time, individual events. Moreover, only a few stations have been brought into play so far.

When calculating the variations of ionospheric parameters, most authors neglected electric fields. This somewhat perfunctory treatment of a potentially important parameter has its roots in current field models. A famed one is that by Matsushita (1969) which has been computed from geomagnetic Sq-variations (Sq for solar quiet) and reasonable assumptions on winds and conductivities in the ionospheric E-layer. Matsushita's starting point was a theory according to which thermal and gravitational "tides" within the E-layer produce dynamo electric fields. Owing to the low resistivity along the geomagnetic field lines, these fields are supposedly projected up to the F2-layer without attenuation. There the strength as well as the direction of the "Sq-field" change continuously, having a period of 24 hours and typical amplitudes of 2 V/km in middle latitudes.

Electric fields in the F2-layer must basically have the same effects as winds in that they induce ionization drifts and thus change the height and the density of the layer. Ions as well as electrons will achieve velocities **V** given by

$$\mathbf{V}=\mathbf{E}\times\mathbf{B}/B^2\,. \quad (6)$$

Their vertical velocity components will depend on the azimuthal field E_y and the geomagnetic inclination I:

$$V_z=E_y\cos I/B. \quad (7)$$

Presupposing electric fields of uniform strength, the vertical drift should be largest about the equator because there the inclination vanishes. In fact, successful attempts have already been made to explain the equator anomaly of the F2-layer in terms of electric fields. According to Hanson and Moffet (1966) west-east electric fields of less than 1 *V*/km make the ionization rise at the equator and fall down along the magnetic field lines elsewhere. So the characteristic meridional distribution comes about with humps in middle latitudes and a groove at the equator. On the other hand, the Sq-field seems to be unsuited for the explanation of ionospheric properties in higher latitudes. From his own calculations Rüster (1971a) concluded that the effects of Matsushita's dynamo fields may well be ignored in relation to those of the neutral air winds. According to Stubbe and Chandra (1970) the dynamo electric fields would have to be augmented by a factor of 3 to 5 in order to match the winds.

At this point, the validity of models must be queried once again. As is commonly known, strong electric perturbation fields occur during magnetically disturbed periods. It is therefore conceivable that at quiet times supplementary fields have to be reckoned with, too. Regrettably, a definite solution to this problem has not yet been found. Though one now disposes of a bunch of methods for measuring electric fields, experimental data are still sparse. This is essentially due to the fact that most methods are either inexact, or restricted to certain times (dawn, dusk), or too expensive or delicate for large scale, routine application. Nevertheless, considerable evidence has been accumulated that even at magnetically quiet intervals the dynamo field can be superimposed with additional fields of remarkable strength. These may be fields of magnetospheric origin which have protruded into the plasmasphere and there been guided down along the magnetic field lines into the ionosphere.

Some supporting evidence has been collected by Mühleisen *et al.* (1971). From potential measurements on balloons, they inferred fields of up to 8 *V*/km in middle latitudes, i.e. the dynamo values times four. Other balloon flights were done by Mozer (1971) in auroral latitudes. Here fields were encountered of up to 100 *V*/km. These values by far exceed all dynamo estimates. Carpenter and Bowhill (1971) also hit upon large electric fields. They made use of the incoherent backscatter facilities at Millstone Hill ($\varphi = 43\,^\circ$N, $I = 72\,^\circ$N) and compared the experimental results with theoretical ones which were deduced from Cho and Yeh's (1970) wind model. The resulting velocity differences were treated as being caused by electric fields. In this way they ascertained field amplitudes of 9.6 to 15 *V*/km.

To be sure, Carpenter and Bowhill's result is not fully convincing, since wind models were used to determine the electric fields. It would be more satisfactory if wind- and field induced motions within the F2-layer could be discriminated directly. At first sight this could be achieved most easily by simultaneously watching vertical and horizontal ionization drifts. As can easily be shown, an electric field induced vertical drift is accompanied by a northward horizontal component, whereas in the wind case a southward horizontal component will appear. Deplorably, this method necessitates sophisticated incoherent backscatter sounders which were not at hand for the study in question. As a consequence, it was tried to find out whether the magnetic coupling of conjugate points can be utilized to discriminate wind- and field induced effects.

Now, what is the meaning of "conjugate?" It refers to pairs of points on the earth's surface which are linked by a magnetic field line. The geographic positions of such points can be roughly estimated from dipole approximations of the geomagnetic field. More exact calculations, however, must take into account the distortions of the magnetic field lines caused by the solar wind and by the magnetospheric current systems. For this end, multipole models have been prepared by Cain *et al.* (1971). They incorporate magnetic field data gathered on the earth's surface as well as in satellite heights.

Since magnetic field lines may serve as ducts for charged particles and waves, close relationships should exist between geophysical phenomena at their nadirs. Presumably, "conjugate events" might set in simultaneously or alternately and they might pass off similarly or adversely. If they were coupled, the degree of correlation should vary in time and space following the shape and the position of the field lines. That is why observations at conjugate points give promise of new insight into the generation and transmission of various effects as well as into the exact configuration, and its variation, of the geomagnetic field lines. Accordingly, the number of conjugate experiments has increased sharply after the IGY.

A somewhat peculiar conjugate effect has been suggested by Gold (1959): The Geomagnetic field lines being near equipotentials, electric potentials in and above conjugate F2-regions should be balanced. Since this would also apply to the corresponding electric fields, good correlation should exist for those ionospheric motions which are exclusively caused by electric fields. In contrast to electrodynamic movements, wind induced drifts will be subject to differing geographical and/or seasonal conditions. Hence, the similarity of conjugate ionospheric motions is a criterion for the identification of electric field effects.

Starting from these considerations, real height variations of the ionospheric F2-layer were examined above several pairs of conjugate stations. They were deduced from ionograms using a method by Becker (1967). This method comprises the necessary apparatus and software for the digitization of ionograms as well as an extensive program for the final computation of real heights and ionization densities.

Instead of doing own soundings, ionograms were procured from routinely operated stations. This procedure posed formidable problems in that it was difficult to find near conjugate stations which produced suitable data. As a first step, the few stations in the southern hemisphere were selected which could be roughly associated with a northern counterpart. Then Lenhart (1969) calculated the exact coordinates of the conjugate points in order to refine the selection. Finally, the number of pairs was reduced by applying the following requirements:

As conjugate points should be connected by closed field lines, high latitude stations were to be ignored.

To avert geographically induced correlations, the geographical latitudes of any two stations had to be different.

The declination effect had to be allowed for.

The latter effect, which has been discovered by Eyfrig (1963), denotes the control of the F2-layer behaviour by the declination of the earth's magnetic field. This effect was interpreted in terms of the daily variation of the neutral air winds by Kohl *et al.* (1969) and will become evident from Fig. 1.

The upper part of this sketch applies to the northern hemisphere. For the sake of simplicity the wind velocity is considered a vector of unity length rotating clock-

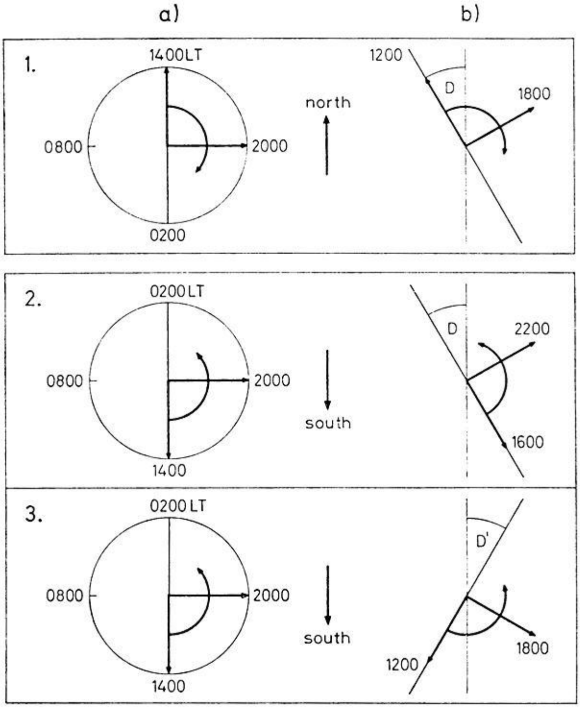

Fig. 1. Declination effects in different hemispheres. 1. Northern hemisphere, a) D = 0°, b) D = 30° W. 2. Southern hemisphere, a) D = 0°, b) D = 30° W. 3. Southern hemisphere, a) D = 0°, b) D' = 30° E. The daily variation of the wind velocity vector as computed by Challinor (1970) is indicated by the left hand "clocks"

wise once within 24 hours and pointing northwards at 2 p.m. In the case of zero declination this time coincides with the maximum downward drift of the ionization. Six hours later the drift vanishes since the wind vector is now perpendicular to the magnetic field. In the second case a declination of 30° west has been assumed. Now the extremes of the ionization transport come about 2 hours earlier. On the other hand, an easterly declination would shift the phase in the opposite sense. Obviously, this explanation of the declination effect is not confined to winds but might as well proceed from dynamo electric fields which also rotate. The southern hemisphere is referred to in the lower section of Fig. 1. Here the wind vector's sense of rotation reverses and so does the declination effect. As different declination effects may conceal the correlation of ionospheric motions at conjugate points, stations with equal declination effects should be preferred for conjugate studies. To meet this requisition the sum of the declinations must vanish. However, only a few appropriate pairs of stations exist in the world.

Eventually, 9 combinations of conjugate stations were sorted out (Table 1). Among them Canberra and Petropavlovsk were deemed preferable because of the following attractions: The distance between each of these stations and the exact conjugate point of its counterpart is less than 65 km, the geographical latitudes are quite different and the sum of the declinations amounts to only 5°.

Table 1. Names, positions and geomagnetic data of conjugate stations

		geographic		geomagnetic	
pair of stations	abbreviation	latitude	longitude	declination	inclination
Argentine Island-	AI	65,3°S	64,3°W	17,5°O	57,9°S
Wallops Island	WI	37,9°N	75,5°W	8,5°W	69,6°N
Canberra-	CB	35,3°S	149,2°O	11,3°O	66,1°S
Petropavlovsk	PE	53,0°N	158,7°O	5,8°W	64,0°N
Capetown-	CT	34,1°S	18,3°O	24,2°W	64,2°S
Poitiers	PO	46,6°N	0,3°O	6,8°W	62,6°N
Garchy	GA	47,3°N	3,1°O	5,6°W	63,3°N
Hobart-	HO	42,9°S	147,3°O	13,6°O	72,8°S
Magadan	MD	59,5°N	150,8°O	10,8°W	70,7°N
Kerguelen-	KE	49,4°S	70,3°O	50,8°W	67,0°S
Archangelsk	AR	64,6°N	40,5°O	13,0°O	76,3°N
Gorki	GO	56,2°N	44,3°O	10,3°O	71,6°N
Sogra	SO	62,8°N	46,3°O	14,5°O	75,3°N
Marion Island-	MI	46,9°S	37,9°O	35,1°W	62,3°S
Lindau	LI	51,7°N	10,1°O	2,3°W	66,6°N
Rarotonga-	RA	21,2°S	159,8°W	13,0°O	38,2°S
Maui	MA	20,8°N	156,5°W	11,0°O	38,3°N
Townsville-	TO	19,3°S	146,7°O	7,3°O	48,4°S
Kokubunji	KO	35,7°N	139,5°O	6,0°W	48,9°N
Tsumeb-	TS	19,2°S	17,7°O	15,4°W	56,8°S
Capo San Lorenzo	CS	39,5°N	9,6°O	3,8°W	55,0°N

3. *Results*

At first, it was aimed to confirm the equivalence of electrodynamic ionization drifts above conjugate points. For this purpose, periods with geomagnetic bays were analyzed. According to Rüster (1969), disturbances of this kind are accompanied by strong electric fields which force drastic height variations upon the F2-layer. The presence of such fields has been confirmed by Maynard *et al.* (1973).

The next drawing, Fig. 2, presents information about two bays which occurred in October 1959. Magnetograms for Hermanus (near Capetown) and Chambon-la Forêt (near Garchy) are presented in the lower left. Both the H- and D-components show the typical bay disturbances. Above, height variations of the F2-layer are given for the conjugate pair Capetown and Garchy as well as for the non-conjugate combination Tsumeb and Lindau. The straight lines indicate the occurrence of sunset as a function of height. Obviously, the vertical motions above Canberra and Garchy are in much better agreement than those above Tsumeb and Lindau. This finding is in favour of Gold's (1959) concept of a potential equilibrium at conjugate points.

It could be objected that the conformity of electric fields at conjugate points and during magnetic bay disturbances be given a priori, superseding any equalizing influence of the magnetic field lines. This argument could be refuted by detection of similar motions of the F2-layer during asymmetric disturbances. In this context solar eclipses are of great importance. Carlson and Walker (1972) forecasted fluctuations of the ionospheric electric field during sunrise and sunset which would induce motions of the F2-layer. Correspondingly, field variations should occur during eclipses. If these variations could also be established for the non-eclipse conjugate regions, this would mean a direct proof for the transmission of electric fields along the geomagnetic field lines.

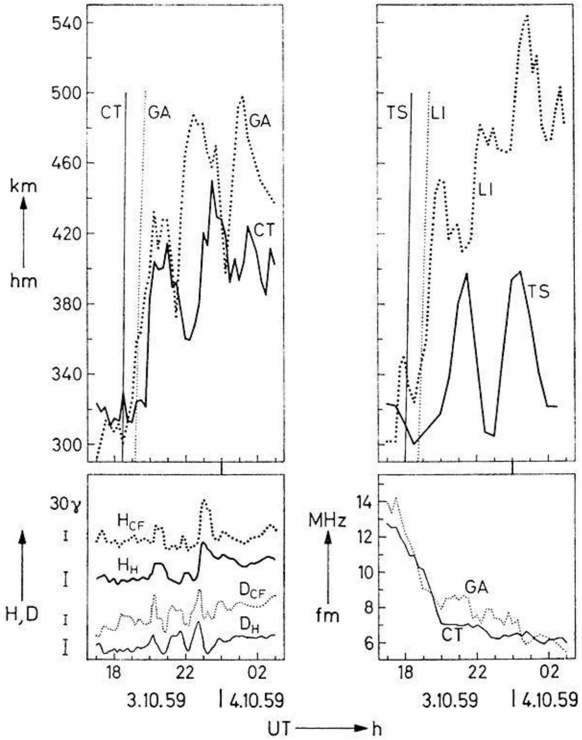

Fig. 2. F2-layer behaviour at Capetown-Garchy (CT—GA) and Tsumeb-Lindau (TS—LI) during two bay disturbances; magnetograms from Chambon-la-Forêt (CF) and Hermanus (H)

In Fig. 3 real height variations of the F2-layer are pictured for Argentine Island and Wallops Island, and during an eclipse. The event took place in the northern hemisphere on March 7, 1970, and its onset and termination are marked by short vertical bars in the drawing. It was excepted that, within this interval, vertical motions should occur at both stations. However, no such movement can be discerned above Wallops Island, whilst there is a sharp rise of approximately 65 km at Argentine Island. Although the ascent of the F2-layer at the southern station may well be a conjugate effect a more viable explanation is in terms of magnetic disturbances since *Kp* was rather high about that time. Generally speaking, the transmission of electric fields between the two hemispheres could not be substantiated in this direct way. On the other hand, it was shown in the previous section that during geomagnetic bays the correlation of F2-motions is confined to well conjugate points. This fact may suffice as an indirect proof of the coupling concept.

We now turn to the normal behaviour of the F2-layer, i.e. its behaviour during magnetically quiet times. In Fig. 4 the jagged curves represent measured height variations of this layer at Canberra and Petropavlovsk in March and September 1969. The smooth curves are appropriate theoretical values which were calculated using a program by Kohl (1972). This program took into account solar as well as neutral

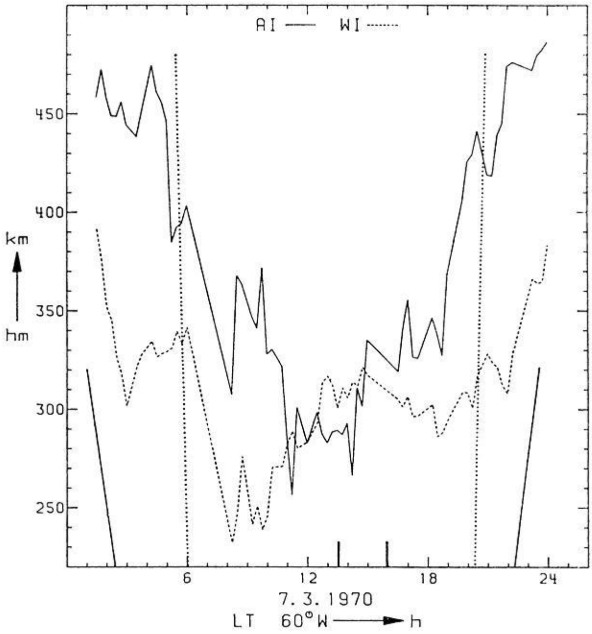

Fig. 3. Height variations of the F2-layer above Argentine Island (AI) and Wallops Island (WI) during an eclipse. Magnetic indices: 4+ 30 40 4+ 5— 6— 4+

wind effects but ignored electric fields. One again notices straight lines denoting the occurrence of sunrise and sunset for each station as a function of height. The experimental results almost exactly match each other but slightly deviate from the theoretical values. Phase differences between the morning drops of the layers are considerably smaller in the experimental case than in the theoretical one. Furthermore, there are striking similarities between the experimental minima which are not reflected by theory.

Surprisingly, the accord of the empirical height variations above Canberra and Petropavlovsk is well maintained in June (Fig. 5), a solsticial month, when the seasonal conditions are different in the two hemispheres (difference of solar elevation angles for CB and PE = 28°).

For this period, theoretical predictions neglecting electric fields postulate phase differences of up to 3 hours. Admittedly, the plot reveals some small scale deviations from conjugacy but the envelopes of the traces are quite similar. Most of the jitter stems from ionospheric disturbances like spread-F which gave rise to random errors in the evaluation of the ionograms. It should be stressed, however, that the morning peaks of the layer height above Canberra correspond to real motions.

In December (difference of the solar elevation angles for CB and PE = 64°), the phase coincidence of the experimental data is still better than that of the theoretical values, although the phase difference has now shrunk to 1.5 hours (Fig. 6). About midnight peculiar depressions occur at both stations which are well-nigh simultaneous, have amplitudes of up to 100 km and do not show up in the theoretical forecasts.

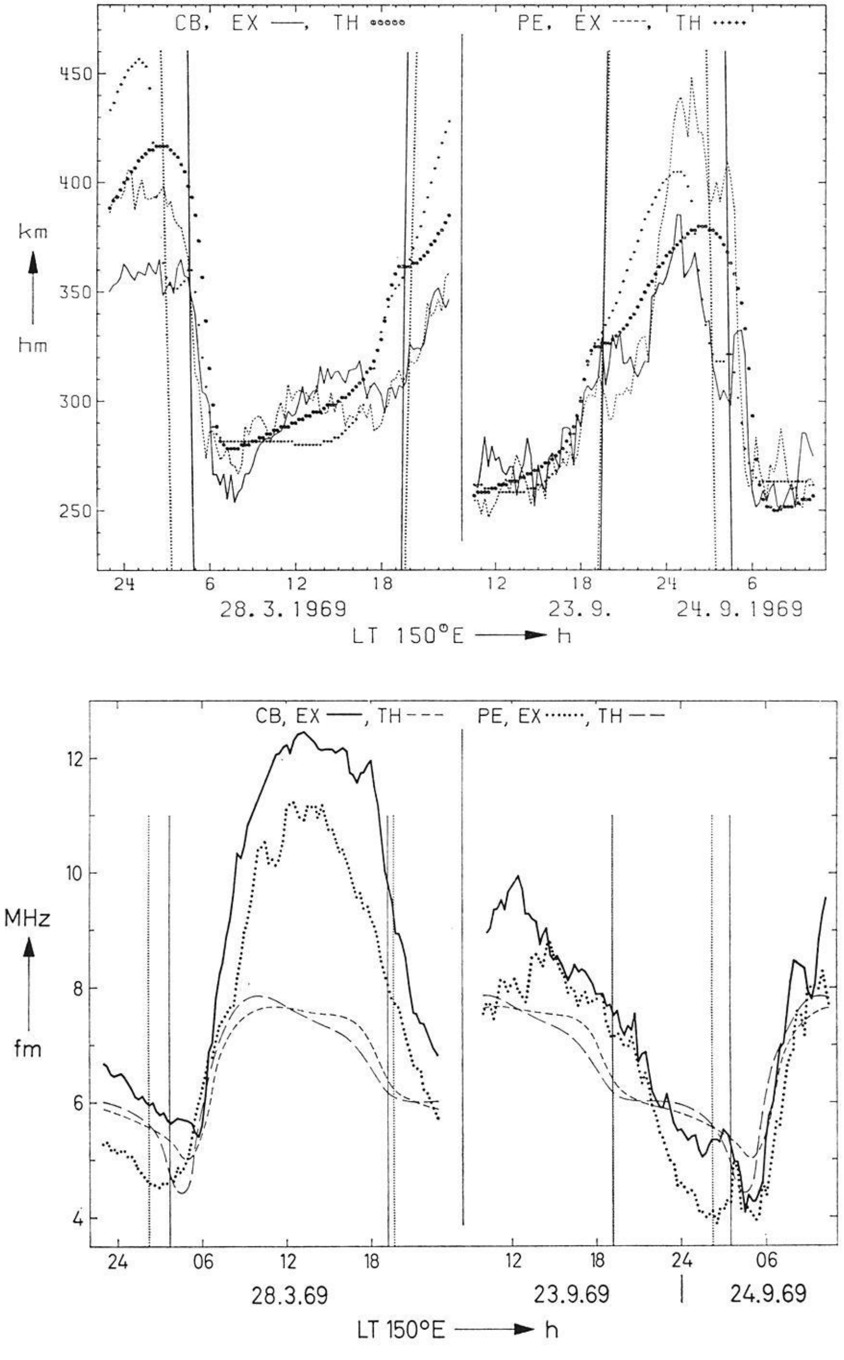

Fig. 4. Above: height variations; below: critical frequency variations of the F2-layer at Canberra (CB) and Petropavlovsk (PE) in March and September. EX: experimental values, TH: theoretical values. Sounding intervals: 15 minutes. Sunrise, sunset: CB --------, PE......... Magnetic Kp-indices: March: 20 10 0+ 0+ 10 2— 2— 1+; September: 0+ 0+ 0+ 1— 30 20 2+ 3+

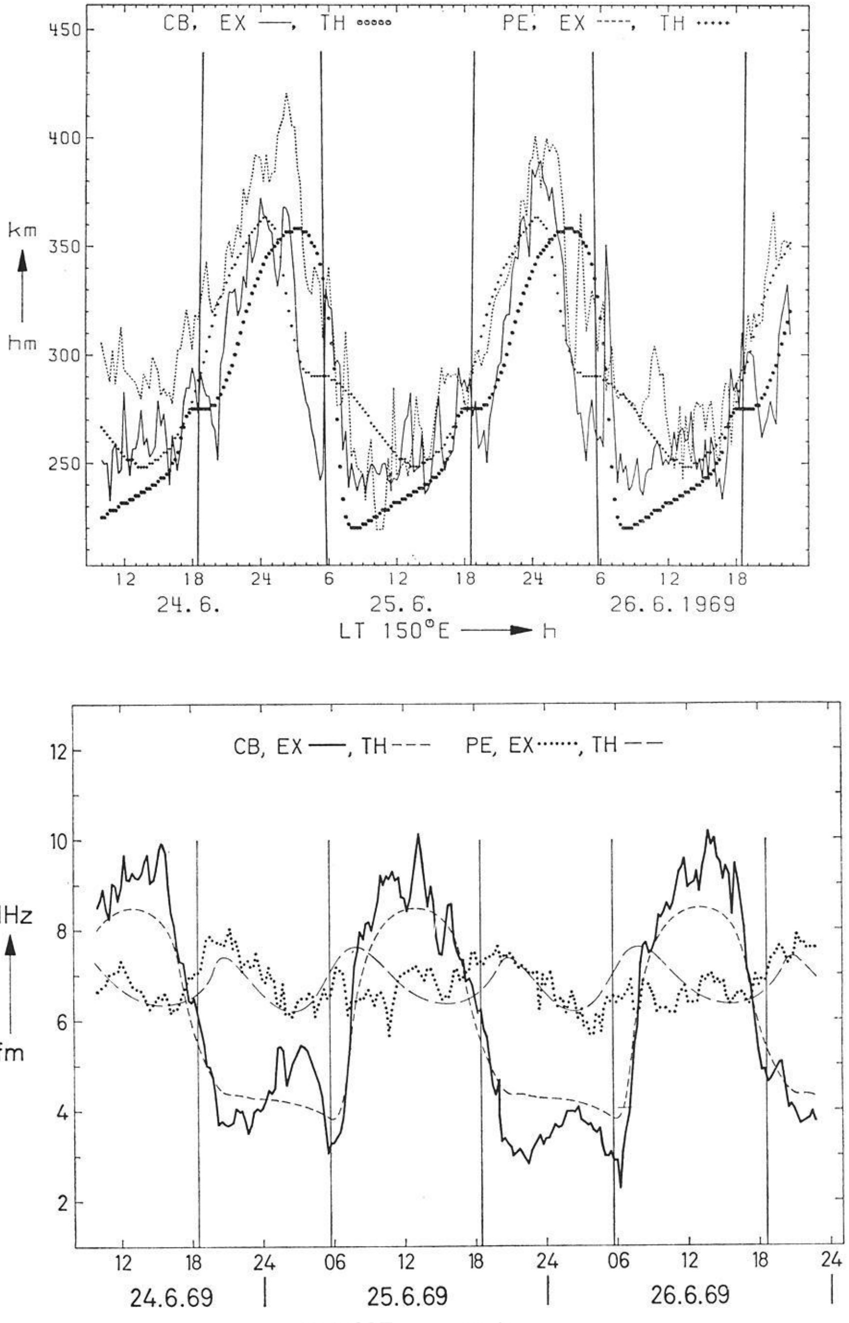

Fig. 5. Above: height variations; below: critical frequency variations of the F2-layer at Canberra (CB) and Petropavlovsk (PE) in June. EX: experimental values, TH: theoretical values. Sounding intervals: 15 minutes. Sunrise, sunset: CB --------, PE........ Magnetic Kp-indices: 30 30 2+ 20 3+ 2+ 20 3— 1+ 2— 2+ 1+ 20 30 30 30 20 2— 1+ 2+

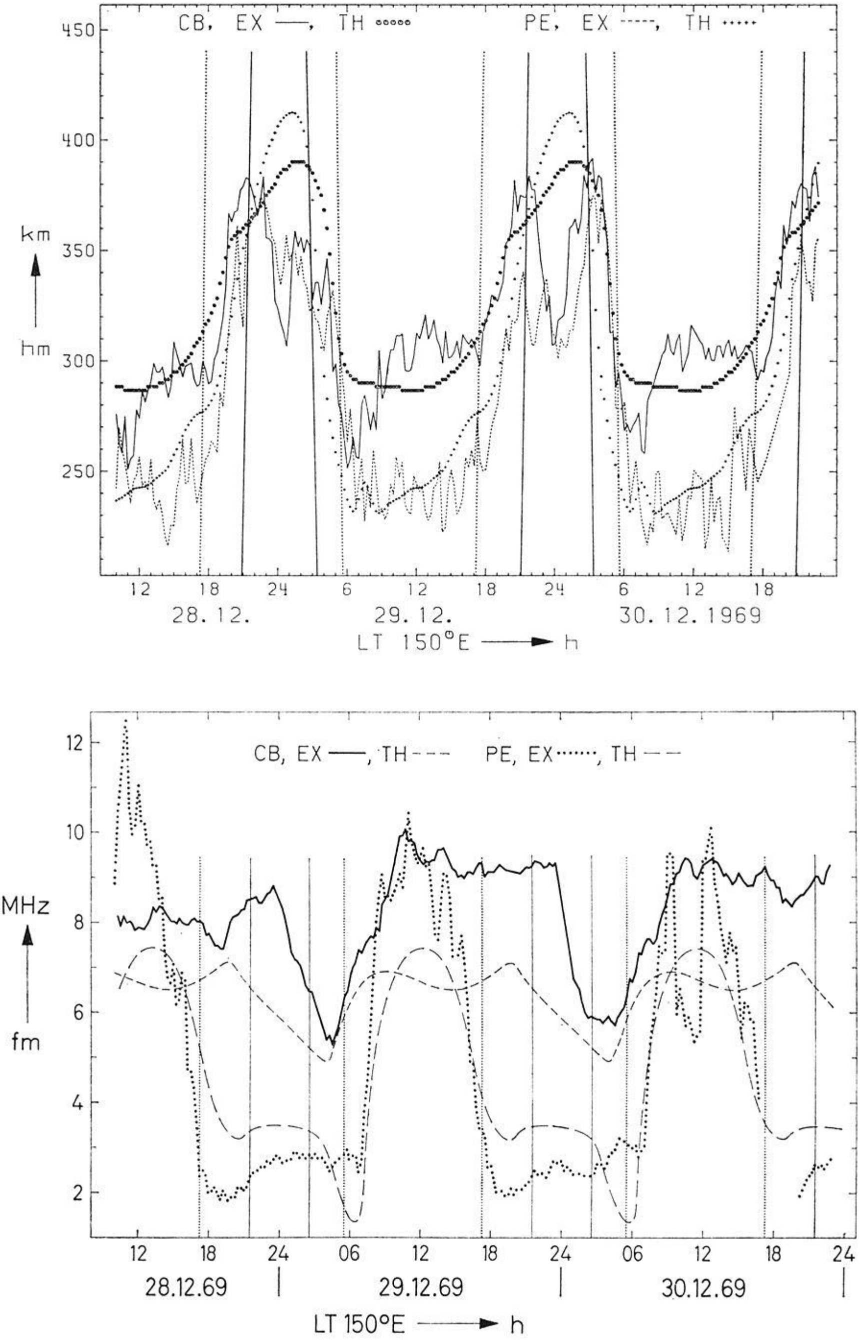

Fig. 6. Above: height variations; below: critical frequency variations of the F2-layer at Canberra (CB) and Petropavlovsk (PE) in December. EX: experimental values, TH: theoretical values. Sounding intervals: 15 minutes. Sunrise and sunset: CB --------, PE........ Magnetic Kp-indices: 0+ 0+ 0+ 10 0+ 2+ 10 1+ 2— 10 1+ 1+ 1+ 1+ 1— 0+ 0+ 10 00 1—

They certainly result from electric fields. Other mechanisms must be involved in the enhancement of the layer height between 6 a.m. and 1 p.m. at Canberra because there are no corresponding motions at the conjugate point.

It is worth mentioning that midnight depressions are far from being rare or exceptional events. Rather, Nelson and Cogger (1971) have found a multitude of similar variations at single stations. These facts are at variance with a theory by Stubbe and Chandra (1970), according to which nighttime height variations of the ionization are inexistent above 300 km.

Along with real F2-layer heights critical frequencies f_0 were calculated. They are related to the maximum electron densities n_e by the relation

$$n_e = 12400 \ f_0^2 \,. \tag{8}$$

The aim was to check the influence of photoelectron fluxes on the ionosphere which was claimed by Shawhan *et al.* (1970) to consist in significant increases of the electron density by impact ionization.

In the lower half of Fig. 4 critical frequencies were shown for equinoctial conditions. Their excellent agreement indicates that during these times geographic asymmetries of conjugate points may be offset by particle fluxes along the magnetic field lines. Similar results have been published by e.g. Benkova *et al.* (1969). In June, however, the two curves do no longer concur (see Fig. 5, below). Obviously, large differences of the solar flux go beyond any compensational mechanism. This also applies to December (see Fig. 6, below); yet, at second sight, pre-dawn enhancements. are perceptible in the Petropavlovsk plot which are apparently related to sunrise at Canberra. Bukin *et al.* (1968) have found corresponding humps and attributed them to photoelectron transport from the sunlit into the dark hemisphere.

According to the results mentioned so far height variations of the F2-layer at Canberra and Petropavlovsk are almost identical in all seasons (whereas the critical frequencies differ widely in the solstices). It is concluded that electric fields are among the most important parameters bearing on the ionospheric dynamics. One might protest that nothing has been said as yet about the situation at less or non-conjugate stations. Possibly, the ionosphere behaves uniformly everywhere and the above inference is not justified.

This conjecture is impaired by Fig. 7. It shows real height variations of the F2-layer above Tsumeb and Capo San Lorenzo. Either station is situated approximately 350 km from the exactly conjugate point of its counterpart and the declinations sum up to 19.2 degrees. Although this is not so very bad a conjugacy the height variations do no more reveal any correlation. One may therefore lend confidence to the assumption that identical motions at well conjugate points are indicatory of electric fields.

Now what about the amplitudes of these fields? This problem was tackled in the following way: The nighttime height depressions above Canberra and Petropavlovsk in December being the most conspicuous individual conjugate effects, the electric field was estimated which could have produced them. To this end a program by Rüster (1971 b) was used for model calculations, the results of which are pictured in Fig. 8. First the behaviour of the F2-layer height was computed from the variation

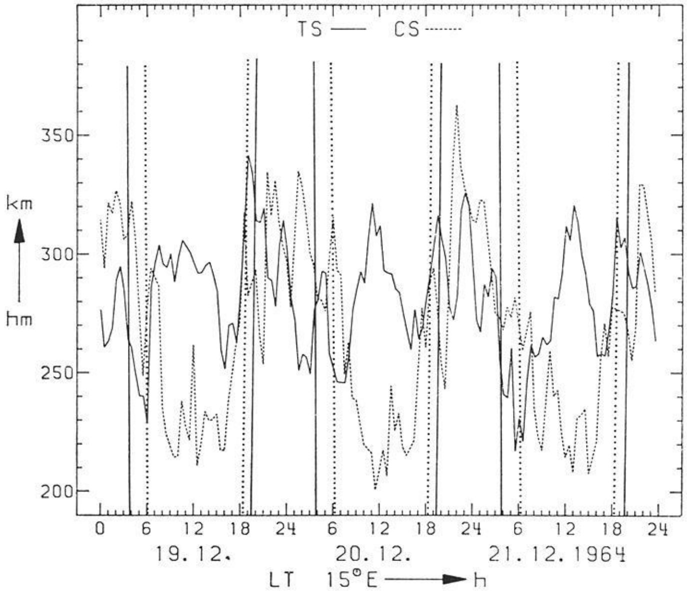

Fig. 7. Height variations of the ionospheric F2-layer at Tsumeb (TS) and Capo San Lorenzo (CS). Sounding intervals: 30 minutes. Sunrise and sunset: TS --------, CS......... Magnetic Kp-indices: 2— 20 1+ 1+ 20 30 3+ 20 0+ 00 00 20 1— 1— 20 20 10 0+ 2— 10 10 20 1— 0+

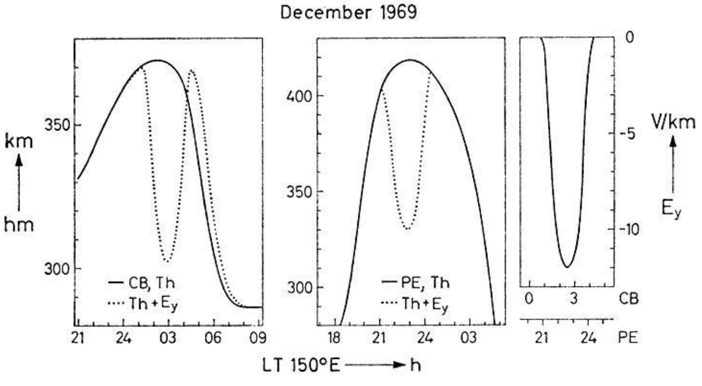

Fig. 8. Theoretical simulation of the F2-layer nighttime behaviour at Canberra and Petropavlovsk in December

of the usual parameters, i. e. the solar elevation angle and neutral winds. In this way the continuous curves (Th) were obtained. Then reasonable model fields were included in the calculation with a view to reconstruct the nighttime depressions.

The best fitting field is plotted on the right hand. It caused variations of the streaked kind (Th + Ey) which closely resemble the actual behaviour of the F2-layer. The amplitude of these fields was 12 *V*/km, compared to less than 3 *V*/km as predicted by Matsushita (1969). That is, the dynamo electric field model does not ad-

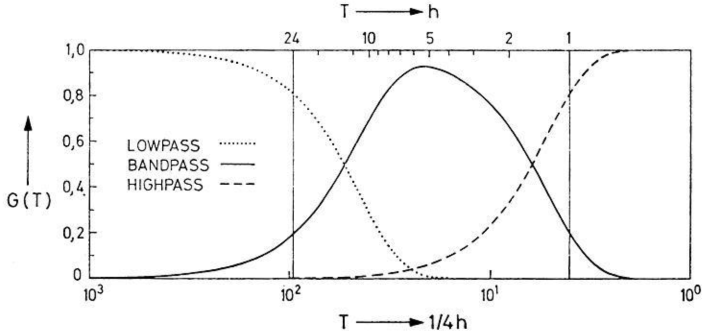

Fig. 9. Filter characteristics G as a function of period T

equately describe the situation at magnetically quiet times. This finding is consistent with the results of measurements which were performed by Mozer (1973) at slightly higher latitudes.

Daily variations of the F2-layer height encompass a large range of frequencies, amplitudes and phases. As various components may differ with regard to their conjugate behaviour, the Canberra and Petropavlovsk data were subjected to numerical filtering. It was aimed to separately correlate individual groups of spectral components. Three filters were prepared whose characteristics are reproduced in Fig. 9. They were conceived to facilitate the separation of a 24-hour basic period, of short oscillations at the sounding frequency (once a quarter hour) and of fluctuations in an intermediate wavelength range centered at about six hours.

In Fig. 10 original as well as filtered data are grouped for equinox conditions. The drawing is self-explanatory in so far as it emphasizes the conformity of the long and medium term variations and the complete lack of correlation for the high frequency oscillations.

In June (Fig. 11) the long period variations are still parallel. This accordance is noteworthy because seasons as well as neutral winds are different now, and electrodynamic drifts with periods as long as a full day were expected to be severely damped (cf. Jones, 1971). The band pass results do show several *in*-phase peaks but also include some uncorrelated sinusoidal variations which might correspond to gravity waves. December height variations (Fig. 12) are characterized by an increased similarity of the intermediate wavelength components. The low pass curves, however, diverge in the daytime. Possibly this digression reflects the extraordinarily high difference between the solar elevation angles in December (64° instead of 28° in June). Summing up, it appears that the fundamental wave ($T = 24$ h) is largely governed by the solar radiation, whilst shorter oscillations with periods of a few hours are dominated by electric fields.

In order to quantitatively compare height variations at different pairs of conjugate stations, correlation coefficients were calculated (Table 2). Though not fully compatible due to a lack of appropriate data they do permit the following conclusions: The correlation coefficients decrease rapidly with increasingly different declination effects and with growing distance between a given station and the conjugate point of its counterpart. This distance is a maximum for Townsville and Kokubunji, a pair of stations with almost identical declination effects. Here the correlation coef-

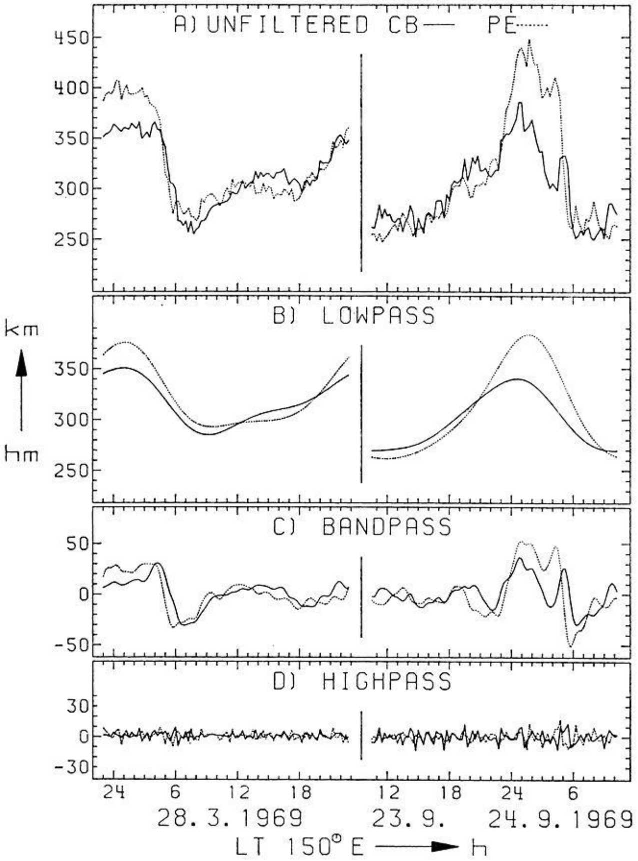

Fig. 10. Measured and filtered height variations of the F2-layer for Canberra and Petropavlovsk in March and September

ficient has fallen to 0.15. It is comparably small for Kerguelen and Sogra, which are closely conjugate but suffer from extremely different declination effects. The smallest correlation coefficient, i.e. —0.1, has been calculated for Tsumeb and Capo San Lorenzo which are poorly conjugate and have rather different declination effects. Considering the high quality and the great number of the respective ionograms, this value is of outstanding significance. Special attention was paid to Hobart and Magadan because these stations are situated almost on the same meridian. They have similar declination effects but are weakly conjugate. From the resulting correlation coefficient of only 0.35 one may infer that simultaneity of ionospheric height variations at Canberra and Petropavlovsk cannot be attributed to local time coincidence.

These observations demonstrate that high correlation coefficients are not a trivial feature of the ionospheric behaviour in different hemispheres but are confined to near conjugates with approximately equal declination effects. This evidence confirms the concept of a coupling mechanism for ionospheric motions above conjugate points. It appears that east-west electric fields of the order of magnitude 10 *V*/km are responsible for this effect.

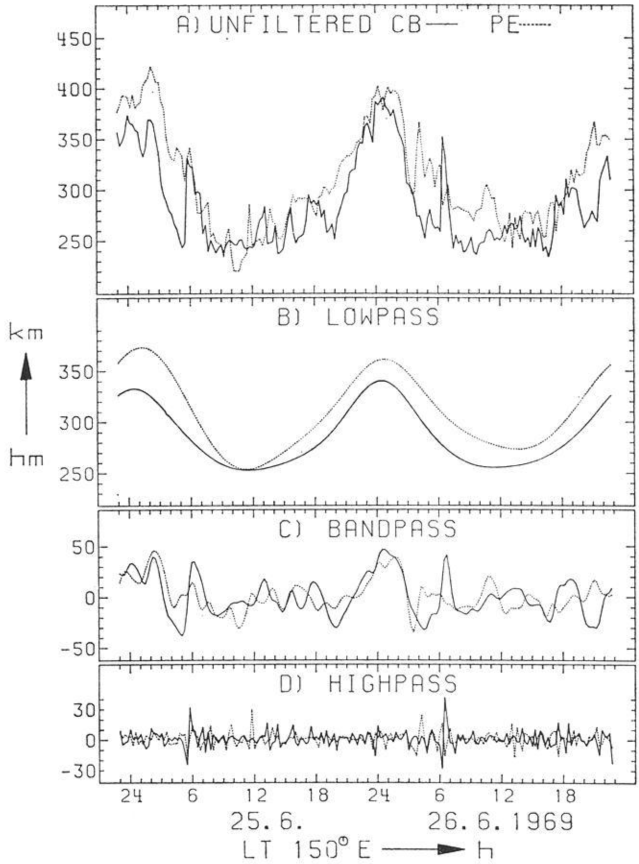

Fig. 11. Measured and filtered height variations of the F2-layer for Canberra and Petropavlovsk in June

Ordinary correlation coefficients being of limited value, a more refined analysis was performed employing correlation functions. It was aspired to find out whether defined phase lags exist between ionospheric events at weakly conjugate stations. The point was that a difference in geographical longitude or magnetic declination could possibly be compensated for by commensurate displacements of the conjugate height sequences relative to each other. However, no clear-cut relationship could be detected between discrepancies of the local times or the declination effects on the one hand and mutual phase shifts of the daily hight variations on the other hand (cf. Petelski, 1973).

4. *Outlook*

In conclusion, it ought to be stressed that the results of this study are preliminary and demand elaboration in many respects:

At least one pair of exactly conjugate stations with identical declination effects should be established and furnished with high performance ionosondes of the same kind.

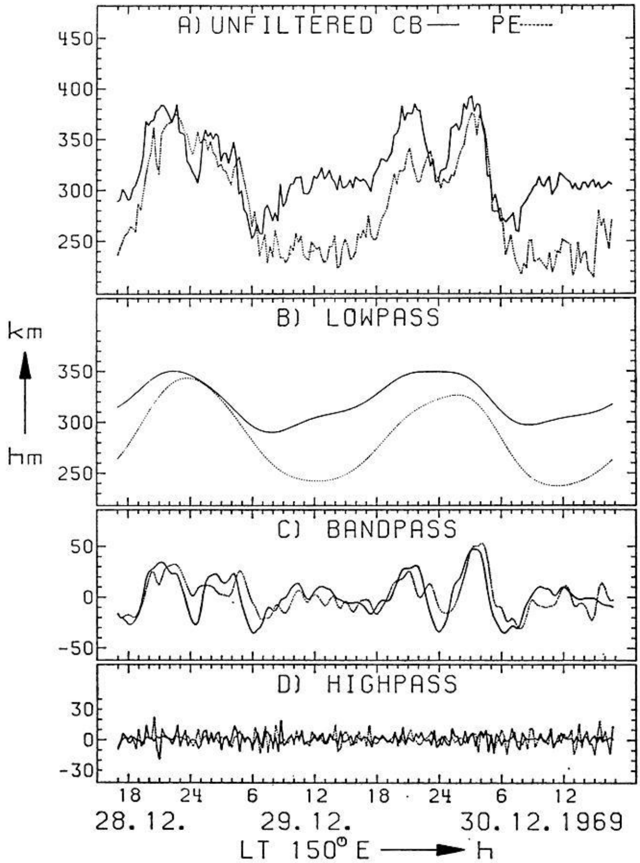

Fig. 12. Measured and filtered height variations of the F2-layer for Canberra and Petropavlovsk in December

Australia/north-east Asia and Argentine/Carribbean Islands are considered most suitable for this undertaking.

Shorter sounding intervals and longer periods of observation would be desirable to promote reliability and temporal resolution.

It is recommended that the geomagnetic conditions be supervised by magnetometers at both stations.

Theoretical investigations would have to be implemented concerning the generation of electric fields during magnetically quiet periods and the velocity of transmission of such fields along the geomagnetic field lines. The latter problem may turn out to be a messy one since the field line conductivity appears to be complicated by plasma turbulence. Coarse estimates by Boström (1973) come out to a time constant of about eight minutes which is a reasonably short time.

In order to check magnetic field models and to trace magnetospheric phenomena, an idea by Roederer (1969) should be caught on. He suggested to inject high energy protons (some GeV would do) into a magnetic flux tube and to watch the effects of the resulting cascades at the conjugate point. Geneva with its CERN proton-syn-

Table 2. Correlation coefficients

pair of stations	local time difference (hours)	angular sum of declinations÷	distance (km) †	interval (month/year)	length of interval (hours)	number of soundings	correlation coefficient for hmF2 (and fmF2) solstice	equinox
				a) solar eclipse				
Argentine Island-Wallops Island	+0,75	+ 9,0°	820	3/70	23	64		0,609
				b) bay disturbance				
Capetown-Garchy	+1,01	-29,8°	280	10/59	10	41	0,802	
Tsumeb-Lindau	+0,51	-18,0°	1700	10/59	10	19	0,424	
				c) magnetically quiet days^x				
Canberra-Petropavlovsk	-0,63	+ 5,5°	60	3/69	24	90		0,900(0,977)
				6/69	48	186	0,825(-0,176)	
				9/69	24	96		0,838(0,932)
				12/69	48	191	0,758(0,509)	
Capetown Poitiers	+1,20	-31,0°	155	12/58	24	92	-0,035	
				3/65	24	64		0,460
Hobart-Magadan	-0,23	+ 2,8°	600	12/68	24	86	0,354	
Kerguelen-								
Archangelsk	+1,99	-37,8°	280	6/68	24	92	0,611	
Gorki	+1,73	-40,6°	750	9/58	22	23		0,670
				12/65	8	26	0,219	
Sogra	+1,60	-36,3°	55	7/66	10	35	0,208	
				9/66	17	64		0,421
Marion Island-Lindau	+1,85	-37,4°	430	7/57	20	62	0,599	
				12/57	12	50	0,266	
Rarotonga-Maui	-0,22	+24,0°	490	1/58	23	48	-0,072	
				6/58	17	33	0,343	
				9/58	22	44		0,591
				3/64	21	43		0,508
				6/64	24	89	0,058	
Townsville-Kokubunji	+0,48	+ 1,3°	900	3/64	24	77		0,359
				12/65	24	67	0,153	
Tsumeb-Capo San Lorenzo	+0,54	+19,2°	350	12/64	72	144	-0,084	
				3/70	48	50		0,275
				d) comparison of stations				
Lindau-Gorki	-2,28	+12,6	2200	9/58	48	132		0,721

÷ the angular sum of the declinations measures the difference of the declination effects
† distance between the northern station and the conjugate point of the southern station
x $Kp \leq 3+$

chrotron and Mossel Bay in South Africa would be an optimum combination of conjugate stations for this purpose.

Generally speaking, conjugate ionospheric observations are means of cheaply and continuously controlling electric fields in the higher atmosphere, particle fluxes between the two hemispheres, distortions of the geomagnetic field lines, and the ionospheric behaviour in remote or inaccessible regions of the earth. In the light of these options the present study is a mere beginning which is hoped to stimulate further investigations.

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Dr. E. F. Petelski
Dornier System, Space Division
D-7990 Friedrichshafen
Federal Republic of Germany