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Report for the period December 1, 1965 to May 31, 1966

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The main projects on which progress has been made during the last six months are listed below. This work has been carried out with the assistance of two research students working at the Ph.D. level, and one at the M.Sc. level.

During this period a modernised C2 ionosonde, on loan from the Environmental Science Services Administration, Boulder, was brought into operation. An efficient aerial system, with a baseline of 500 ft and a height of 100 ft, was constructed and records of high quality are being obtained. These provide an on-the-spot measurement of the traditional ionospheric parameters, and will considerably increase the value of all the satellite measurements being carried out at Auckland. The digital recording and plotting equipment obtained under last year's grant has also been installed, so that measurements and results can be handled with much greater speed and accuracy.

1. MEASUREMENTS ON THE GEOSTATIONARY SATELLITE SYNCOM 3.

1.1 Routine recording.

The polarisation angle of the 137 Mc/s signal from Syncom 3 has been recorded continuously at Auckland (lat 37°S) and at Invercargill (47°S) throughout the last six months. There have been no equipment failures, and it is hoped to continue this series of records for many years. The records obtained give a continuous measure of the total electron content of the ionosphere with a long-term accuracy of better than 1%. Fluctuations of only 0.1% in total content, occurring in periods of 10 seconds or more, can be followed. The records obtained each day are traced and scaled to show the diurnal variation in total content. This work is kept up to date, and figures showing the diurnal curves superposed for each half-monthly period are prepared and forwarded to several other research organisations in New Zealand as a service.

1.2 Diurnal and seasonal changes in the total electron content of the ionosphere.

From the superposed plots showing the diurnal variations in the total electron content (N_T), monthly median curves are obtained. Most of the work carried out so far has been based on these curves, since a knowledge of the average behaviour of the ionosphere is required before individual events are studied.

The diurnal curves obtained over a period of 12 months at Auckland fall into two distinct groups, representing summer and winter conditions. The transition between these groups takes less than one month, suggesting that the symmetrical 'equinox' form of the upper atmosphere is not very stable. The noon median values of N_t were 80% greater in summer than in winter. This agrees exactly with the change in the cosine of the sun's zenith angle, so there is no trace of the large seasonal anomally observed in the northern hemisphere. The diurnal changes in N_T (2.5:1 in winter and 3:1 in summer) are less than half as large as corresponding results from the northern hemisphere.

The continuous nature of the records makes them very suitable for studying the rapid changes which occur near sunrise. These changes give an integrated production rate for an overhead sun of 1.3×10^{14} electrons/m^2/sec at the equinoxes, agreeing closely with some equinox results from Stanford. At other seasons, however, the calculated values are less than half as large.

Some of this variation can be removed by correcting for the steady loss rate after midnight, giving an overall mean result of $(0.9 \pm 0.2) \times 10^{14}$ electrons/m^2/sec. This value is consistent with the observed critical frequencies of the ionosphere if the recombination coefficient in the F1 region is $\alpha = 10^{-8}$ cm^3/sec.

Similar calculations at sunset give an effective loss coefficient β' of 1.2×10^{-4} sec^{-1} in winter, and 0.5×10^{-4} sec^{-1} in summer. These figures agree with measurements of the rate of decay at the peak of the ionosphere, and so confirm the theoretical prediction that the electron density will decay with the same effective loss coefficient at all heights.

1.3 Diurnal and seasonal changes in the slab thickness of the ionosphere.

Dividing the median values of total content (N_T) by the electron density at the peak of the ionosphere (N_m) gives the effective slab thickness of the ionosphere (S). This quantity has been calculated by several workers using results from orbiting satellites. However the present work, which gives an accurate diurnal curve for each month, shows that many of the conclusions obtained by averaging isolated measurements are incorrect. The large peak in slab thickness which occurs before sunrise in all published results is a seasonal effect, and disappears completely in summer. This peak is not caused by the effects of sunrise (and hence the production of electrons) occurring earlier at greater heights, since the increase in N_T begins after the increase in N_m.

The values of slab thickness are about 240 km near noon at Auckland, at all seasons, corresponding to a fixed ionospheric temperature of 1,000°A. This contrasts with the seasonal variation of about 40% found in the northern hemisphere. At Invercargill (lat 47°S), the slab thickness is 15% greater than at Auckland (37°S), indicating a temperature increase to the poles. The diurnal variation in summer consists of a gradual, steady increase for most of the day, with a rapid drop of about 25% at sunset. In winter, however, S starts to increase in the afternoon and reaches a value of 350 to 400 km by 9 p.m. The value remains high overnight with a sharp peak (about 500 km) followed by a rapid decrease (to 240 km) at sunrise.

The large night-time values of S occur only during the winter. They suggest a considerable increase in the temperature of the ionosphere, or an influx of electrons from above. The second explanation seems most likely. It is strongly supported by the fact that N_T commonly increases throughout the night in winter. The ray-path from Syncom 3 to Auckland is almost parallel to the magnetic field at heights between 200 and 1,000 km, so that the records obtained give quite closely the total electron content of a single tube of force. This tube crosses the equator at a height of 3,500 km, connecting the northern and southern ionospheres. The attempt to establish diffusive equilibrium in this tube requires a considerable flow of electrons from the summer to the winter hemisphere, beginning near noon and continuing until after midnight. Calculations suggest a time constant of a few hours for this process, which seems fully capable of explaining the anomalies observed during the winter night.

1.4 Irregularities.

The movement of irregularities in the ionosphere causes fluctuations of up to 10% in the recorded values of N_T. A periodic structure is often evident, with up to 8 regular cycles spread over a period of several hours. The period, amplitude and number of cycles of all such events have been measured at Auckland and at Invercargill. There is a marked semiannual variation in the occurrence of these wave motions, which are twice as common in winter and summer as at the equinoxes. They are also twice as common at Invercargill as at Auckland, suggesting that the wave motion is generated near the auroral zone. The period is generally between about 20 and 40 minutes, falling into the gravity wave range. A study of the diurnal, seasonal and latitudinal variations in the period and amplitude of these travelling disturbances is continuing.

1.5 Construction of equipment.

A semi-portable version of the 137 Mc/s polarisation angle recorder, incorporating a continuously rotating aerial, has been designed. The mechanical construction of three instruments is almost complete, and the associated electronic equipment has been built. These recorders will be installed at different sites inside (and possibly outside) New Zealand to study the changes in total electron content at different latitudes, and the speed and direction of travel of the regular wave motions mentioned above.

2. MEASUREMENTS ON THE IONOSPHERE BEACON SATELLITES.

2.1 Routine studies.

Recording of signals from the Polar Ionosphere Beacon Satellite S-66 has continued at Rarotonga (21°S, 200°E), Auckland (37°S, 175°E), Invercargill (47°S, 168°E) and Scott Base (78°S, 167°E). Similar records from Wellington (41°S, 175°E) and Campbell Island (52°S, 169°E) are provided by the Department of Scientific and Industrial Research. Four or five transits are recorded each day and the results are used to study the total content and irregularities at different latitudes. To speed up the analysis, attention is being concentrated on the three summer months and the three winter months in each year of recording (since October 1964). The period of the 20 Mc/s Faraday fading is plotted throughout each transit to show the occurrence, size and density of large irregularities in the ionosphere, and the total electron content is determined near the beginning, centre and end of each transit. Measurements for most of 1965 have been completed, and the results are being put on to punched cards for analysis and correlation on the University's computer.

2.2 Special studies in Auckland.

In addition to records of the amplitude of the 20, 40 and 41 Mc/s signals, the following quantities are recorded at Auckland:

(a) the polarisation angle of the 40 Mc/s signal, obtained using an aerial rotating at 300 rpm.
(b) the polarisation angle of the 40 Mc/s signal, obtained from the relative phase of the ordinary and extraordinary components.
(c) the relative phase of the 40 Mc/s signal (divided by 32) and the 20 Mc/s signal (divided by 16).

All quantities are recorded during 4 north-south transits of the satellite S-66, and 5 east-west transits of the satellite Be-C, each day. These additional records give a continuous display of the small changes in phase and polarisation caused by ionospheric irregularities. The size and density of irregularities with dimensions down to 1 or 2 km can be determined, and the height can be estimated from the relative extent of the changes in phase and amplitude. The records are also used in studying the second order effects of the ionosphere on satellite signals, as outlined in section 5.

3. STUDIES OF THE POLAR IONOSPHERE.

3.1 The records obtained.

The amplitude of the 20, 40 and 41 Mc/s signals from the Polar Ionosphere Beacon Satellite are recorded during 14 transits each day at a quiet site several miles from Scott Base. The equipment operates automatically, and less than 5% of records are lost through power and equipment failures. To give improved results on the more distant transits, logarithmic amplifiers have been installed. The two polarisation angle recorders constructed last year reached Scott Base in January and have proved very succdssful. A continuous plot of the polarisation angle of the 40 Mc/s signal is obtained even in the presence of strong scintillations, so that changes in total content can be followed during about 80% of all transits. Records up to June 5

were brought out on the recent mercy flight to McMurdo, so that polarisation records for 4 months are now available for analysis.

3.2 The electron content of the polar ionosphere.

Normal techniques for obtaining total content from Faraday fading records cannot be used in the polar regions, where the fading rate depends primarily on horizontal changes in the ionosphere. At one time during each transit the fading rate depends only on the rate of change of total electron content. These times have been calculated, and the corresponding fading rates measured, for each transit over a 12 month period. The actual values of total content can also be obtained when the fading on 40 and 41 Mc/s is in phase or out of phase. This generally occurs several times in each transit, and scaling of these times for the summer records of 1964/65 is almost complete. The results will then be transferred to punched cards and the values of total content and horizontal gradient calculated on the computer.

The new polarisation angle records give a continuous plot of the Faraday rotation of the 40 Mc/s signal. Since the direction of rotation is shown the absolute number of rotations can be determined at any time from the relative phase of the Faraday fading on 40 and 41 Mc/s. The polarisation plot then gives an accurate record of the total electron content throughout the transit. The values of total content will be determined at intervals of 0.2 minutes, and the computer program described in section 3.3 used to prepare monthly maps showing the average variation of the total electron content over the polar cap. Fluctuations in the values of total content will also be investigated to determine the size, occurrence and position of large-scale irregularities in the ionosphere.

Preliminary results show that the total electron content has a broad minimum near the south pole. However, isolated regions in which the total content increases by 10 to 50 percent, with dimensions of a few hundred kilometres, are generally present. Outside the central region the total content increases rapidly across the auroral zone in summer, and can double in a distance of 500 km. This rapid change is not, however, apparent in the winter records just received.

3.3 Irregularities in the polar ionosphere.

The degree of irregularity of the ionosphere has been scaled at intervals of 0.2 minutes throughout each of the 1600 transits recorded during the four summer months of 1964-65. Similar values are now being obtained for four months in the following winter. The results are mapped to show the presence of any smooth or disturbed regions in the ionosphere, and a computer program is used to determine the mean irregularity state at different times in each month.

A second computer program has been developed to read all the data obtained in one month, fit the different transits on to a grid covering the Antarctic, and determine the average irregularity state at each point of the grid. The results are then printed out in the form of a map, using different symbols to represent the different degrees of irregularity. These maps cover a circular region with a diameter of about 3,500 km, including the geographic, geomagnetic and dip poles and extending over the auroral zone. They generally show a number of large, well-defined regions in which the ionosphere was particularly smooth (or disturbed) throughout the period considered.

The maps vary considerably from month to month, because of diurnal changes. To study these changes, separate maps with a time difference of about 8 hours are obtained by analysing the south-bound and north-bound sections of the transits separately. The largest and most widespread changes occur at longitudes of 100 to 150 degrees. In this region, extending from the geomagnetic pole to the dip pole, the ionosphere is particularly smooth from 0000 to 0400 U.T., and is very irregular from 0800 to 1400 U.T. The first interval is from 8 a.m. to noon local time, indicating that the rapid production of electrons in the morning occurs smoothly throughout the ionosphere.

The second interval, from 4 p.m. to 10 p.m. local time, occurs when the electron content of the ionosphere is still large but irregularities have had time to develop. There is also a general tendency for the ionosphere to be smooth for several hours near 0400 U.T., corresponding to local noon near the magnetic poles. To study these effects in detail, separate maps for each three hours of universal time will be produced by combining results obtained over periods of four months in summer and in winter. Separate maps are also being produced for each month for quiet, average and disturbed magnetic conditions. These generally show a uniform increase in the degree of irregularity at all points as the magnetic activity rises.

4. DISTURBANCES IN THE IONOSPHERE.

4.1 The effects of magnetic activity.

Several attempts have been made to determine how the total electron content and the slab thickness of the ionosphere vary with the magnetic activity index K_p. The results, using isolated values of total content obtained from orbiting satellites, are unsatisfactory and conflicting. Accurate values of total content, and an index specifying the amplitude of irregular fluctuations, have therefore been scaled for each hour of every day using the continuous Syncom 3 records taken at Auckland and at Invercargill. These results are currently being compiled on to punched cards along with the values of K_p, the critical frequency of the ionosphere and the occurrence of spread F. The computer will then be used to determine the correlations between total content, peak density, slab thickness, magnetic activity, ionospheric irregularities and spread F at different times of day and different seasons.

Preliminary results indicate that there are two opposing effects, which may account for the conflicting results obtained previously. An increase in magnetic activity gives an almost immediate increase in the rate of production of electrons in the ionosphere. This effect lasts only as long as the magnetic activity. There is also a large increase in the electron loss rate, lasting for several days (and probably caused by an increased molecular concentration when the normal diffusive separation is disturbed). The total content is therefore increased by a large current value of K_p and decreased by large previous values. Similar changes are often, but not always, observed in the peak density.

4.2 The effects of large magnetic storms.

Since regular recording of Syncom 3 began in May 1965, the only major magnetic storm was on June 16, 1965. This gave the largest day-time values of total content recorded that month. On June 17 the day-time and night-time values of total content were the lowest ever observed in 12 months recording. The storm was preceded and followed by a number of particularly quiet days, so a detailed study is being made of the changes which occurred at all heights in the ionosphere. Ionograms were obtained from Raoul Island and from Godley Head, and real height profiles have been calculated for every 15 minutes. An accurate polynomial analysis was used to give the height of the peak, the scale height at the peak and the sub-peak content. Using the values of total content obtained from Syncom 3 the scale height gradient above the peak is also determined, giving a good approximation to the complete electron density profile. The results show an initial increase of about 40% in the relative amount of ionisation above the peak, caused presumably by heating and expansion of the ionosphere. On June 17, however, the relative amount of ionisation above the peak dropped to half the normal value, with a scale height gradient of only 0.05 (instead of 0.2). This suggests that the normal diffusive separation was disturbed. At night the total content dropped more quickly, and to a larger extent, than the peak density. This also indicates a decreased diffusive separation, lasting for several days.

5. SECOND ORDER EFFECTS IN THE PROPAGATION OF SATELLITE SIGNALS.

5.1 Ray tracing.

For accurate calculations of the effect of the ionosphere on radio signals received from artificial satellites, the actual path followed by the ray must be determined for different model ionospheres. This involves a lengthy numerical integration using an iteration loop to determine the refractive index at each height. The entire calculation is repeated many times, using slightly different initial directions, until a ray is found which starts and finishes at the required points. For polarisation angle studies this process must be carried out with both the ordinary and extraordinary rays, so that about one hour is required to obtain a single result on a 1620 computer.

This time makes it impracticable to use a straightforward ray tracing program for the analysis of experimental records. A thorough investigation of the basic theory was therefore carried out, with the result that a new type of program giving a more accurate result in one twentieth of the time has been produced. This is based on the fact that, at frequencies above 10 Mc/s, the effect of the magnetic field can be treated as a small perturbation. An estimate of the initial ray direction is first obtained by calculating the exact first-order curved earth refraction, and applying second-order and magnetic-field corrections. The number of iterations at each height is reduced by treating the change in electron density as the most important parameter. The range and phase-path sums are accumulated with double precision, and a third sum is obtained giving the value of $\partial(\text{range}/\partial(\text{initial direction})$. The correction to the initial direction, to obtain the required range, can then be accurately determined. Successive rays are traced until the calculated range is within .01 km of the desired value. A correction to give the exact phase path to the satellite is then obtained from the relation

$$(\text{change in phase path}) = (\text{change in range}) \times \cos\delta$$

where δ is the elevation angle at the ground. It can be shown that this relation holds exactly for a curved isotropic ionosphere. For elevation angles greater than 30 degrees, and working to 8 significant figures, the required phase path is obtained with 9 figure accuracy after only 2 or 3 rays have been traced. This very high speed and accuracy means that accurate ray tracing procedures can be used freely in all future investigations.

5.2 Second order relations.

The computer program described above was used to obtain exact values for the Faraday rotation of satellite signals under a wide range of conditions. The results were compared with values given by normal first and second order relations. It was found that the second order result was not always more accurate than the first order, and both expressions could give appreciable errors. The best results were generally obtained by using the simple first order expression for the Faraday rotation, with an accurate correction for the high frequency approximation. This correction is $(1 - X)^{-\frac{1}{2}}$ where $X = 0.8\ f_c^2/f^2$ and f_c is the critical frequency of the ionosphere.

5.3 Experimental measurements.

First order theory predicts that the Faraday fading of a satellite signal will be four times faster on 20 Mc/s than on 40 Mc/s. Measurements of this ratio therefore provide a simple means of studying second order effects. The digitising equipment obtained under last year's grant is being used to record the positions of the 20 and 40 Mc/s fading nulls on punched cards, for analysis by computer. Plots are then produced showing the ratio of the second and first order effects throughout each transit.

Results show that the second order effect is not negligible even at the centre of a transit, but causes about 10% of the Faraday rotation on 20 Mc/s. However calculations using the program of section 5.1 showed that this effect depends only slightly on the shape of the ionosphere, and can be accounted for by the simple correction given in 5.2

At low elevation angles the second order effects increase rapidly and are concentrated near the peak of the ionosphere. It was therefore hoped that measurements under these conditions could be used to determine the thickness of the peak. Combining these results with values of total content would then give the variation of electron density with height above the peak. It has been found, however, that the second order effects do not always increase with peak thickness, but tend to decrease at large satellite ranges. At some ranges, therefore, the second order effects depend only on the critical frequency. This limits the conditions under which useful information on the layer shape can be obtained, but work is proceeding to see if measurements at intermediate ranges can yield useful results.

6. THE ANALYSIS OF IONOGRAMS.

6.1 The effect of collisions on the virtual heights.

Most of our information about the ionosphere is obtained from the analysis of sweep-frequency virtual height records, or ionograms. This analysis assumes, for simplicity, that the effect of electron collisions is negligible. To examine the errors introduced by this assumption, a computer program was written for calculating the exact, complex value of the group refractive index μ'. The virtual heights of the ordinary ray were then obtained by normal ray theory, in which μ' is integrated up to the reflection level X=1. It was found that the inclusion of collisions commonly reduced the virtual heights by more than 10% at medium frequencies.

A further program for integrations in the complex plane was used to determine the virtual heights by the accurate phase integral method. These results showed that the inclusion of collisions altered the virtual heights by less than 1 part in 10^4. The changes shown by the ray theory calculations were therefore caused entirely by basic errors in the use of ray theory under these conditions. The simplest ray theory calculations ignoring collisions should therefore be adhered to; they agree well with phase integral results and are considerably more accurate than ray theory calculations which include collisions.

6.2 The absorption of the reflected wave.

The absorption of a wave reflected from the ionosphere is normally calculated by integrating the absorption coefficient k up to the reflection level X=1. Accurate phase integral calculations showed that this process gives results which can be in error by 10 or 20% at medium frequencies, because of ray theory limitations. If however a simple asymptotic form (k_o) is used, the ray theory calculation gives results which are correct to within 0.1%. The comparatively simple expression for k_o can therefore be used for all absorption calculations and gives results which are more accurate, by several orders of magnitude, than if the exact and cumbersome expression for k had been used.

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