National Aeronautics and Space Administration

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The last six months have seen a steady development of a variety of different techniques for studying the ionosphere, using radio signals received from artificial satellites. The work carried out on these different projects is outlined below, and in most cases useful results are being obtained. During 1966 attention will be concentrated on the more promising of these projects, with the aim of producing and publishing finished results.

(1) MEASUREMENTS ON THE GEOSTATIONARY SATELLITE SYNCOM 3.

The 136 Mc/s signal from the satellite Syncom 3 has been recorded continuously at Auckland (Lat 37°S) since May 1965. The equipment used was described in the last report, and gives a direct, linear record of the total electron content of the ionosphere. These records have an absolute accuracy of a few percent, and a relative accuracy of about 0.2% for rapid changes and 0.5% for long term changes. Similar equipment constructed at the University's field station at Invercargill (Lat 46.5°S) has been operating continuously since August 1965. The Department of Scientific and Industrial Research have agreed to operate a third recorder at Wellington (Lat 41.2°S) and an instrument will be installed there early in 1966. The continuous records from these three stations will then completely replace observations of the Ionosphere Beacon satellites as a means of studying the total electron content of the ionosphere. Measurements on the Beacon satellites will, however, continue for the irregularity studies described in (7), and for total content studies at the stations south of Invercargill.

The records at Auckland and at Invercargill relate to ionosphere points about 850 km south-west of Raoul Island and 360 km west of Amberley respectively. The Dominion Geophysical Observatory has provided hourly values of the F region critical frequency at these places, and these will be punched on cards along with hourly values of the total content and the magnetic index K_p (when the latter becomes available). Hourly values of the effective thickness of the ionosphere will then be computed, and correlated with the critical frequency and with K_p. In the meantime all records are traced to show the diurnal variations in total content, with results from each two-week period superposed. This reveals a well-defined diurnal variation, which changes consistently from one two-week period to the next. The day to day scatter in total content at any time is often quite small, particularly during August when the electron content between noon and 4 p.m. at Auckland was always between 0.68 and 1.05 x 10^{17} electrons/m^2.

The regular behaviour is even more marked at higher latitudes. Thus at Invercargill in September the sunrise effect always commenced abruptly at 6.30 a.m. with the total content increasing at a constant rate of 6.1 x 10^{14} electrons/m^2 per minute. At 7.20 a.m. this decreased suddenly to another constant rate of 1.45 x 10^{14} els/m^2 per minute. The same effect was present but less marked at Auckland, and disappeared at both stations on September 27. This change coincides with a transition to summer conditions with increased noon values of total content and critical frequency.

The continuous records from Syncom 3 also provide a valuable tool for studying large irregularities in the ionosphere. These are seen as fluctuations in total content, commonly of around 5%. At Invercargill a regular train of fluctuations often begins near 9 a.m., marking the end of the second smooth, linear increase in total content mentioned above. These fluctuations often have a well-defined period of about 20 minutes, suggesting a wave motion in the ionosphere. The fluctuations become more irregular, with widely varying amplitudes and periods, after noon and at Auckland. The wave motion may therefore be produced south of Invercargill, and become more irregular as it travels north during the day.

To study the form and movement of these disturbances a network of five recording stations is being established. These are at Auckland (37°S), Invercargill (46.5°S), Wellington (41.2°S) and New Plymouth and Gisborne (39°S). The rotating aerial system at New Plymouth is ready for operation, while the recorders for Wellington and Gisborne will be constructed early in 1966. The stations Auckland - New Plymouth - Gisborne and Wellington - New Plymouth - Gisborne form equilateral triangles with sides of approximately 300 km. The time delays between observing similar fluctuations at the different stations will be measured and used to determine the size, shape, velocity and direction of movement of the irregularities.

(2) THE ELECTRON CONTENT OF THE POLAR IONOSPHERE.

Records of the Polar Ionosphere Beacon satellite taken at Scott Base over the winter have now been received, so that 14 transits per day are available from October 1964 to November 1965. The total electron content of the ionosphere is being determined from the relative phase of the Faraday fading on 40 and 41 Mc/s. Since the direction of the Faraday rotation is continually changing (due to large horizontal gradients of ionisation) only the points at which the fading on the two frequencies is in phase or out of phase are defined unambiguously. The times at which this happens are being recorded, and used to calculate the total electron content of the ionosphere. It has been found possible to obtain an average of about four values of total content per transit, so that a reasonably good idea of the diurnal, seasonal and longitude effects will be obtained.

Results for November 1964 show that the total content is commonly about 7×10^{16} electrons/m^2, at all times of day. This implies an effective slab thickness for the ionosphere of about 280 km, or a scale height of 70 km if a Chapman layer is assumed. When the ionosphere is reasonably smooth the total content may vary by less than ±10% throughout a transit, although the number of Faraday rotations is continually increasing and decreasing because of the presence of large irregularities in the ionosphere. On other occasions, particularly near a region in which the ionosphere is highly irregular, the total content can increase by 30% in a few hundred kilometres.

To overcome the limitations caused by the unknown direction of rotation, equipment for obtaining continuous records of the polarisation angle of the 40 Mc/s signal has been constructed. This equipment uses an aerial system which separates the received signal into two circular polarisations, and a double-channel triple-conversion receiver with output frequencies of 99.8 and 100kc/s. The two outputs are mixed and passed through a narrow band 200 c/s amplifier to a transistorised phase recorder, which gives an accurate, linear record of the polarisation angle of the received satellite signal. Two complete sets of equipment were constructed, and test-run at Auckland during November. The results were very satisfactory, and the system proved slightly more sensitive to weak signals than the spinning aerial recorder used at Auckland. Both sets of equipment have been shipped to Scott Base, so that records will not be lost in the event of equipment failure. With these records the direction of rotation of the plane of polarisation will be known at all times, so that total content calculations can be made throughout each transit. The continuous polarisation angle records will also greatly assist the irregularity studies described below, since the effects of large and small irregularities will be continuously displayed.

(3) IRREGULARITIES IN THE POLAR IONOSPHERE.

All the transits recorded at Scott Base during the four summer months (November 1964 to February 1965) have been analysed in detail to investigate the occurence of small irregularities in the polar ionosphere. The degree of irregularity of the records was determined at 0.2 minute intervals throughout each transit, using a scale of 1 to 6. The results for each day are then displayed by mapping the 14 recorded transits, using different colours to denote the different irregularity states.

observed at Scott Base being similar to the roughest ionosphe[illegible] Auckland. A record will often be reasonably smooth apart from a short section where there is a sudden transition to highly irregular fading. This shows the presence of a well-defined region in the ionosphere containing small, dense irregularities. Such regions commonly have dimensions of a few hundred kilometres. They can generally be observed on several successive transits, showing that they persist for many hours, and because of the overlapping nature of the transits their shape and position can be determined. Such regions are being studied in conjunction with ionosonde records obtained at Scott Base by the Department of Scientific and Industrial Research. It has been found that dense sporadic E shows up clearly on the satellite records, which can then be used to determine the size and movement of the patch of sporadic E. Most of the observed irregularities are, however, produced in the F region and sometimes appear to correlate with spread F on the ionograms. Some regions of unusually smooth ionosphere are also observed, and several of these (when over Scott Base) have coincided with the ionospheric G condition in which the F2 critical frequency is abnormally depressed.

The mean irregularity state was found to vary significantly over the polar cap. Thus during December the ionosphere between longitudes of 0 and 70 degrees east was more irregular than elsewhere on nearly all days. This cannot be explained entirely by diurnal effects, since the same general region of the ionosphere is observed during about five successive transits covering a period of seven hours. In January and February the whole ionosphere was consistently smoother, and the irregular area observed in December was not present. To obtain a reliable measure of such changes a computer program has been produced to determine the mean irregularity state throughout each of 42 transits each month. Each result is the average from 10 transits recorded at 3 day intervals. This averaging has revealed a surprising consistency in the overall behaviour of the polar ionosphere, with the mean irregularity state changing smoothly with time and position. Further programs are being produced to give mean roughness contours for each month, and the entire year's records will then be treated in this way.

(4) TOTAL ELECTRON CONTENT CALCULATIONS

The 20-40 Mc/s differential doppler shift and the 40 Mc/s polarisation angle of the signals from the satellites BE-B and BE-C have been recorded at Auckland since June 1965. These records were used for a comparative study of different methods for calculating the total electron content of the ionosphere. For analysing the Doppler records, a rapid procedure similar to that used by Weekes was evolved. In this method the number of Doppler cycles was counted, from the point of *minimum* phase, to points equally spaced about the time of closest approach. From the two numbers obtained the total electron content of the ionosphere, and the size of the horizontal gradients of ionisation, can be simply obtained. The total content was also calculated independently from the relative phase of the Faraday fading on 40 and 41 Mc/s. At elevation angles above 40 degrees the agreement was good, with the Doppler results averaging three percent less than the Faraday results. This suggests that the magnetic field factor currently used in Faraday calculations is 3% too low. With this correction, 95% of the results from the two methods agreed to within 7%. It is therefore concluded that both methods are accurate to within 5%.

A new hybrid method which is particularly simple to apply was also used. This relies on the fact that when the differential phase record shows a minimum, the phase path lengths are not changing so that Faraday rotation is caused only by changes in the longitudinal field component H . The total electron content is then proportional to the Faraday rotation rate divided by the rate of change of H , and this result is unaffected by gradients (linear or otherwise) in the ionosphere. The accuracy of the results appears to be about the same as the Doppler and Faraday measurements during the day, but should be much superior to Doppler calculations near sunrise when large non-linear gradients of ionisation occur.

On the rare occasions when a Beacon satellite passed close to the ray-path from Syncom 3, the total electron contents calculated using the two different satellites were compared. The Syncom 3 results are generally about 8% higher than those from the Beacon satellites, so that the ionisation at heights above 1,000 km increases the Faraday rotation by about 8%. This is 20 to 100% less than the amount required by some current ideas of the electron density at these heights.

Most of the total content methods used will also give values for the horizontal gradient of ionisation. These commonly show the presence of local gradients corresponding to changes of 2 or 3% in total content in 100 km, while gradients of up to 10% are observed. When averaged over several hundred kilometres the east-west gradients seldom exceed 1% during the day, with the electron content increasing towards the sun. North-south gradients are generally larger, with the total content increasing to the north at up to 3% per 100 km at all times of day.

(5) RAY PATHS THROUGH THE IONOSPHERE.

Several computer programs have been developed for accurate calculations of the effects of the ionosphere on satellite signals. The ionosphere is represented by a large number of horizontal slabs, of constant density; by this means any required electron density profile can be represented with any required accuracy. The effect of the earth's magnetic field is fully included, so that an iteration procedure is required to determine the ray direction and the refractive index in each slab. When these quantities are determined to the full 8 figure accuracy permitted by the computer, a complete ray trace through 40 slabs takes approximately $3\frac{1}{2}$ minutes.

Tables have been prepared giving the refraction of the ordinary and extraordinary rays at different frequencies, for satellites at different zenith angles. The calculations are for Chapman layers with a range of heights, critical frequencies, scale heights and scale height gradients. These tables are used to determine the total electron content and the scale height at the peak of the layer, from the elevation angle measurements described in (6). The calculations were also carried out for the case of a flat earth and no magnetic field, and the corrections which must be applied to simple first order theory were evaluated.

A large number of detailed calculations of the differential Doppler and Faraday effects were also carried out. These effects depend on the difference in phase path of two separate rays between the satellite and the receiver. The initial direction of one of the rays must therefore be adjusted until both rays start and finish at the same point. To obtain agreement to 8 significant figures 5 to 10 iterations are required, so that a single calculation takes about 30 minutes. The sources of error in first order Doppler and Faraday theory were investigated by separately determining the changes caused by the high frequency approximation, the longitudinal approximation, refraction, magneto-ionic path splitting and ray-wave normal separation. The last two effects were generally unimportant, while the effect of refraction is a minimum for propagation parallel to the magnetic field. The corrections to be applied to first order results were tabulated for a number of different conditions.

(6) ELEVATION ANGLE MEASUREMENTS.

The 20 Mc/s satellite signals were received on two aerials spaced 400 ft apart in a north-south line, and the relative phase of the two signals was recorded. Some difficulty was experienced in removing the Faraday fading of the signal at low elevations, and fluctuations in the recorded phase were traced to a mechanical filter in the receiver. To eliminate the effects of long-term drift in the equipment, a crystal oscillator radiating from a fixed point between the aerials was arranged to give an automatic calibration at the beginning of each transit. With these precautions the relative phase at the two aerials could be recorded with an absolute accuracy of about 5 degrees, and useful records were obtained for several months.

For a close transit of the satellite S-66, in a north-south orbit, the phase records give a continuous measure of the elevation angle of the received signal with an accuracy of about 0.2 degrees. The application of the records to studies of the ionosphere was investigated. Calculations of total electron content, from the refraction of the satellite signals, are quite feasible.

quire a more precise knowledge of the satellite orbit. The effects of large ionospheric irregularities are barely discernible and not easily measured. At low elevations, however, the refraction increases and provides a reasonably direct measure of the second order effects which occur near the peak of the ionosphere. The aerial systems will therefore be altered to give improved reception at low elevations. The records will then be used to determine the amount of ionisation (and hence the scale height) near the peak of the ionosphere.

(7) STUDIES OF LARGE IONOSPHERIC IRREGULARITIES.

Specially designed chart readers are being used to plot the Faraday fading period from the 20 Mc/s satellite records. Results for the summer and winter months at Auckland and Invercargill are almost complete, and the corresponding plots for Wellington and Campbell Island will be produced when these records are received from the Department of Scientific and Industrial Research early next year. Reliable information on the latitude dependence of the occurrence and characteristics of ionospheric irregularities with sizes between 20 and 1,000 km, will then be obtained. Since the four stations are in a line parallel to the satellite heading, comparison of the different plots will also give the height of isolated irregularities.

Irregularities with sizes between about 2 km and 200 km are conveniently displayed by the continuous 40 Mc/s polarisation angle records obtained at Auckland using the spinning aerial. During the last six months a similar trace, giving one sixteenth of the difference in phase path of the 20 and 40 Mc/s satellite signals, has also been recorded. The two traces, obtained by entirely different means, have about the same sensitibity to ionospheric irregularities. Comparison of the two records therefore provides a valuable check on the irregularity calculations. When isolated irregularities are observed in an otherwise smooth ionosphere the two traces agree very closely, giving the same shape for the cross-section of the irregularity. For irregularity sizes greater than 10 km, the electron contents calculated from the two traces agree to within 20% in 75% of cases. This suggests that the individual calculations are accurate to about 15%, whereas the experimental error is generally about 5%. The difference probably arises from path splitting effects, which calculations have shown can alter the measured density of an irregularity by 5 to 20%. At irregularity sizes less than 10 km, contents calculated from the Doppler trace are about 30% greater than from the Faraday trace; this result agrees with calculations of the refraction of the 20 Mc/s ray by the irregularity.

Film records of the differential phase shift (not divided by 16) were found to show very clearly the presence of small ionospheric irregularities. These irregularities, with sizes between about 5 and 25 km, generally occurred in chains of similar size. The spacing of 930 irregularities was measured, but the results showed no evidence of a preferred size. The number of irregularities increased rapidly as the size decreased, agreeing with the earlier results on irregularities in the range 20 to 500 km.

PAPERS ACCEPTED FOR PUBLICATION.

Titheridge J.E. "Direct manual calculations of ionospheric parameters using a single polynomial analysis," Radio Science.

Titheridge J.E. "The polynomial analysis of ionospheric h'(f) records," Radio Science.

Titheridge J.E. "The calculation of the heights of the peaks of the ionospheric layers," J. Atmosph. Terr. Physics.

Stuart G.F. and Titheridge J.E. "The height of large ionsopheric irregularities," J. Atmosph. Terr. Physics.

Titheridge J.E. "The use of satellite signals to investigate the polar ionosphere," Polar Record.