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Comparison of plasma densities in the daytime polar *F*-region measured by the AEROS-B and S3-1 satellites

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Abstract—A comparative study of ionospheric measurements obtained by different sensors on two satellites has shown excellent agreement between the principal techniques used to measure the plasma density and ion composition. Results from an ion mass spectrometer on the S3-1 satellite and from an impedance probe and a retarding potential analyzer on the AEROS-B satellite have been compared for five cases that represent the closest coincidence of measurements that occurred during the satellite lifetimes. The crossings occurred at high polar latitudes and the studies have indicated that invariant latitude is more important than altitude, geodetic latitude, or geomagnetic latitude in systematizing the data. The ratios of the mass spectrometer ion densities to the impedance probe electron densities resulted in an average value of 1.00 with a standard deviation of 6%. The composition percentage for the molecular and atomic ions from the retarding potential analyzer agreed generally within about 20% of the mass spectrometer measurements.

INTRODUCTION

Many different techniques have been used by several different laboratories to measure the properties, such as density, temperature, and composition of the ionospheric plasma. While several comparisons of ground-based techniques, such as incoherent scatter radar and ionosondes, with satellite measurements have been made (TAYLOR and WRENN, 1970; ROBLE *et al.*, 1978; BENSON *et al.*, 1977; SPENNER and RAWER, 1978) it has been difficult to locate really close comparisons between various measurements and techniques. In a few cases, intercomparisons between different sensors on the same satellite have been made (HOFFMAN *et al.*, 1973 and HOFFMAN *et al.*, 1974). The present study has succeeded in locating five cases of close crossings between two satellites and permits an intercomparison of the ion and electron density and ion composition.

One of the difficulties in intercomparing the results from different satellites has been that the large variations that occur in the ionosphere require the spatial and temporal separations to be small if the comparisons are to be meaningful. The AEROS-B and S3-1 satellites had a common period from early November 1974 through June 1975 when they were both in orbit and making measurements. In the time period of 29 November to 3 December 1974, five cases have been found which meet rather restrictive conditions to minimize the effects of spatial and temporal variability. In general, the orbits selected must cross the same latitude and longitude within several minutes of each other. In addition, the requirement that the altitude separation be not more than a few kilometers in the lower *F*-region nor more than tens of kilometers in the upper *F*-region appears to be justified based on examination of the data sets of the two satellites.

The orbital plane of the AEROS-B satellite corresponded to local times near 0400 and 1600 and that of the S3-1 to times near 1100 and 2300. The time difference between the orbit planes means that crossings will only occur at high latitude and for these cases the crossings are near 79°N. At this high latitude, the ionospheric plasma is often highly irregular and it has been found that comparisons in terms of invariant latitude appear to be more important than do altitude differences of tens of kilometers in the 250–400 km altitude range. The relationship between the orbital periods of the two satellites allows one time period during each of the five consecutive days when close coincidence in time and space occurs.

AEROS-B IONOSPHERIC DATA

AEROS was a cooperative German–U.S. aeronomy satellite program designed to obtain simultaneous measurements of the most important properties of the neutral gas and the plasma in the upper atmosphere, together with the flux of ionizing solar radiation in the extreme ultraviolet, in order to investigate the coupling between the atmospheric components and its control by solar energy (LÄMMERZAHL and BAUER, 1974; LÄMMERZAHL *et al.*, 1979). The second of the two satellites, AEROS-B, was launched on 16 July 1974 and had an orbital and operational lifetime of more than 14 months. The orbit of AEROS-B was moderately eccentric (apogee/perigee at 648/213 km on 1 December 1974) and nearly polar ($i = 97.4°$). The local times were almost constant throughout the mission at about 0400 and 1600 in low and midlatitudes. By the time of the comparison with S3-1 the tape recorder had failed, and data were recorded over telemetry stations in real-time. The data coverage was nevertheless satisfactory, particularly in northern high latitudes where four stations were available. When the altitude was low, however, these data records did not extend beyond about 80° geodetic latitude.

The *in situ* electron density was measured by an impedance probe (IP) using the fact that the impedance of a sensor (a cylindrical monopole of 180 cm length and 2 cm dia) immersed in the ionospheric plasma exhibits a characteristic frequency depending upon the electron density. The plasma response in terms of phase shift of the sensor signal with respect to a reference signal was observed each one second period alternating between four fixed phase levels. In addition, one of the phase levels was held for measurements at two other DC-bias conditions. When applying positive voltages the ion sheath around the sensor was temporarily reduced which showed that its effect on the measured density is negligible, in the configuration of this experiment. By means of frequency sweeping (10.24–0.64 MHz) combined with a fast phase detector the modified upper hybrid resonance is detected, the frequency of which is easily referred to electron density. A detailed description of the instrument was given by NESKE and KIST (1974).

According to the different measuring modes a spread of the deduced densities, 4% in the mean, is observed. The high degree of internal consistency gives confidence in the reliability of this technique. The median value of a full sequence of 6 s corresponding to a spatial resolution of 48 km provides smooth data. The accuracy of the absolute values of electron density is generally better than 10% throughout the measurement region. For the densities considered in this paper, generally greater than 10^5 cm^{-3}, the accuracy should be near 5%. Comparisons have been performed between IP densities and densities obtained by other instruments. A direct comparison was possible between the IP and the onboard retarding potential analyzer (RPA) experiment. The RPA electron density shows a similar relative behavior, however, absolute numbers (deduced from the saturation currents) are uncertain due to limitations of the probe theory. An empirically derived constant conversion factor would bring the IP and RPA electron densities into reasonable agreement when the density is high. For densities below $\sim 10^4$ cm^{-3} unexplained discrepancies still exist. An intercomparison was made with regard to the gyro plasma probe experiment on the TAIYO satellite (NESKE *et al.*, 1979) using encounters between that satellite and AEROS-B. The altitude differences, which were generally between 20 and 100 km, allowed comparisons only by means of model altitude profiles or by plasma scale heights inferred from the measurements. No systematic discrepancies were observed but it was not possible to check the absolute accuracies of the two sets of data.

A retarding potential analyzer (RPA) of planar geometry was used to determine the temperature and densities of the major ions and, with the same instrument, the temperature, density and suprathermal fluxes of electrons. The AEROS spacecraft was spin stabilized with a spin rate maintained at 10 rev/min and the axis aligned towards the sun. Because of the sensitivity of the experiment to the angle of attack the scanning period of one second was synchronized with the spin phase, providing measurements at angles within $\pm 30°$ of ram. The ion parameters were obtained in a measuring mode that was periodically repeated every third spin revolution, i.e. every 18 s corresponding to a spatial resolution of 140 km. The experiment has been described in detail by SPENNER and DUMBS (1974). For data evaluation it was assumed that the ionospheric plasma consists of the four constituents H^+ (mass 1), He^+ (mass 4), O^+ (mass 16), and molecular ions (mean mass 31) which all have a common temperature and do not change during a scan of 1 s. The evaluation is done by fitting a theoretical curve to the measured current–voltage-characteristic by varying the four partial densities, the temperature, and the spacecraft potential relative to the plasma, as free parameters. If one or more of the assumptions are not valid the quality of the fit deteriorates, and the data are considered no longer as correct when the residuals become too large; in this case, an interpretation of the measured curve was not made. The light ions H^+ and He^+ could not always be separated. Therefore, in the routine analysis, only the sum of their partial densities $(H^+ + He^+)$ is given.

The total ion density which is defined as the sum of the four partial densities has been compared with the electron density from the impedance probe (IP) onboard the same satellite. A typical result is shown in Fig. 1. The difference of 20–30% by which the RPA values are systematically lower than the IP data might

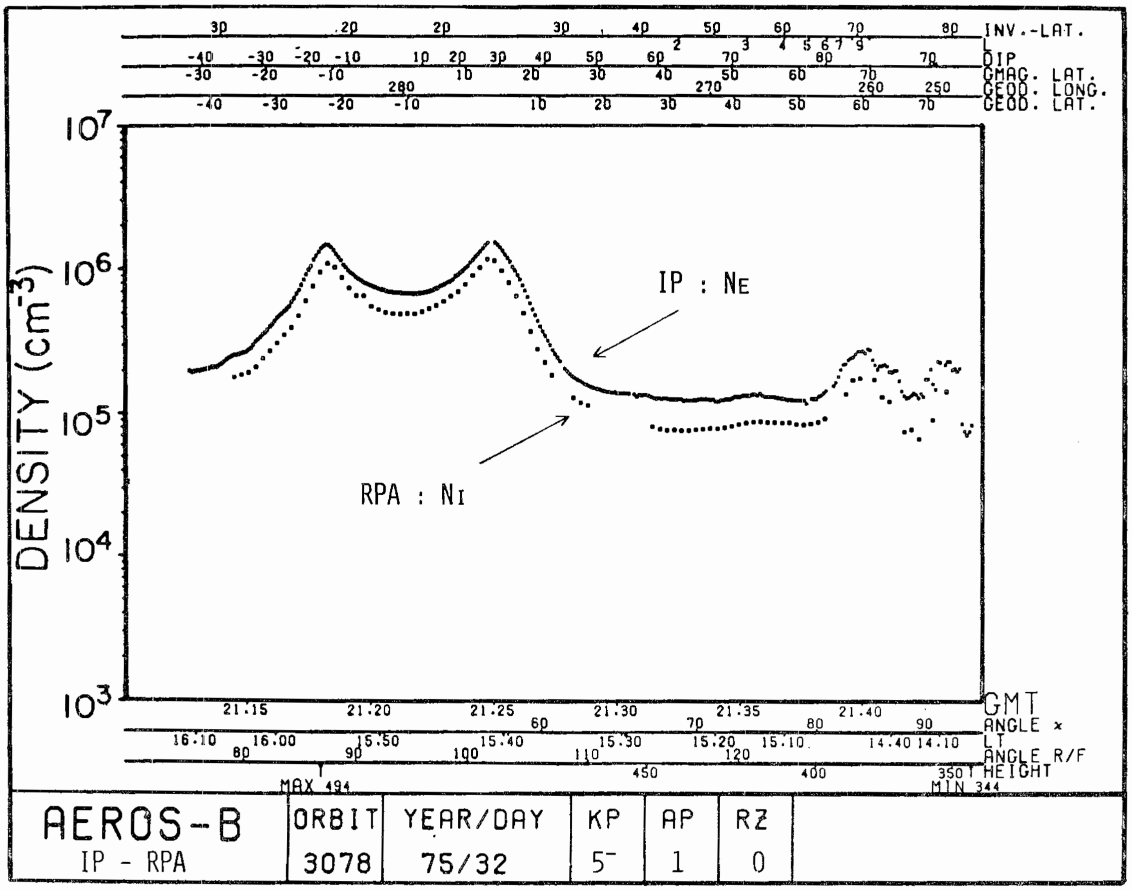

Fig. 1. Plasma densities measured on AEROS-B. The example shows that total ion density from the retarding potential analyzer (RPA) is 20–30% below the electron density from the impedance probe (IP) due to a grid transmission error that was not corrected in this presentation.

be explained as due to a transmission loss in the RPA grid assembly for ion flow. The transmission coefficient used in the analysis was the same as the transparency measured for visible light. The densities from the IP are believed to be the more accurate ones, and if one assumed the discrepancy being the result of a wrong transparency, the partial densities must be corrected by the same factor as the total density from the RPA. This correction has not been made in the results presented.

S3-1 IONOSPHERIC DATA

The S3 satellite program was designed to provide a scientific study of the properties of the upper atmosphere and obtain data on the coupling between the neutral atmosphere, the ionosphere and the magnetosphere. The S3-1 satellite, which was the first in a series of three satellites, is the one with which the present discussion is concerned. It was designed to emphasize the investigations of the neutral atmosphere properties and the coupling between the neutral atmosphere and the ionosphere over the altitude range between 150 and 500 km. The near polar orbit of the S3-1 was highly eccentric with a perigee near 150 km and an apogee initially near 4000 km. Data were obtained from early November 1974 through June 1975 when the satellite re-entered the atmosphere. During this period the motion of the node and the line of apsides allowed a coverage of almost all latitudes at four ranges of local time, near 1100, 2200, 0700 and 1700. The satellite was spin stabilized with a spin rate maintained near 5 rev/min. The normal operation consisted of a preprogrammed operation of the experiments and tape recorder from near 500 km through perigee and back up to 500 km on each orbit. Up to six of these perigee passes could be stored on the tape recorder for later playback, allowing sequential perigee measurements.

Among the several experiments which were included on the satellite was a mass spectrometer which measured both the neutral atmosphere and ionosphere species densities. This instrument, MSIV, was a rf quadrupole mass spectrometer with a semi-open ion source geometry (PHILBRICK, 1974; PHILBRICK, 1976). The configuration of the ion source was of plane parallel geometry and during the ion measurement the electron beam was cut off from entering the region above the quadrupole by bias voltages applied to the filament region rather than by switching the filament heater power. During these measurements, the maximum voltages applied to any of the ion source elements was kept less than 10 V in order to eliminate the production of ions within the region. In each one second period of operation there were 64 samples which were divided into 16 sets of measurements. At each of 10 mass peaks in the neutral mode and 5 mass peaks in the ion mode there were 4 measurements which were spaced around the region of the planned mass peaks. The spacing of the measurements around the peak was to allow for any possible drift in the electronics which might lead to errors in measurements of the mass spectrum peaks. Only the one measurement at the mass peak was selected for the analysis. The last of the 16 groups was used for measurements of the total ions, or integrated current through the analyzer field, and for a calibration signal.

The first grid on the outside of the instrument was maintained at the spacecraft vehicle potential and all other apertures and grids were used to draw the ambient ions into the analyzing region with a weak electric field. The wide aperture geometry resulted in a fairly flat angular response for angles of incidence of up to about 40° between the ion velocity and the instrument axis. At the 5 rev/min spin rate there were always 3 sets of measurements for each spin within the region of the angular response which were not discriminated by more than about 25% by the spinning motion. The set of ion peaks with the smallest angle of incidence was chosen and corrected to zero degree angle of attack. The five ion masses which the spectrometer was tuned to measure were N^+, O^+, N_2^+, NO^+ and O_2^+. The resolution of the instrument was sufficient that no correction at the 1% level would be needed for overlap from adjacent ion peaks. The dynamic range of the instrument was set to measure concentrations of ions between about 10^1 and 10^7 ions/cm^3. During the laboratory calibrations, the quadrupole analyzing field was found to provide a linear response over the mass range. The calibrations with various gas mixtures showed that the mass discrimination was less than 5%. It is difficult to calibrate the absolute sensitivity of the ion mode of the instrument in the laboratory because of difficulties in simulating the ion flow to the instrument. The relative sensitivity of the instrument could be carefully monitored because the current collected on a grid in the source region, ahead of the quadrupole, was measured. Also, the current on a grid after the quadrupole, but ahead of the multiplier, was measured. Thus, the multiplier gain factor and the quadrupole transmission could be checked during periods corresponding to high currents.

The conversion to absolute density has been done using the flight data together with ground-based ionosonde data. A total of 73 cases were located where good correlation between ionosonde station and the satellite measurements should exist. The criteria applied to select these cases was that the satellite should be at F_2 peak, as determined by the satellite altitude profile of summed ion current, and simultaneously be crossing a latitude and longitude box of $5° \times 5°$ centred about an ionosonde station, and further, that the f_0F2 critical frequency was measured within about 15 min. There were 54 of the world wide ionosonde station lying between 50°S and 50°N surveyed for data meeting these criteria over the lifetime of the satellite. The comparison between the f_0F2 determined electron density and the summed ion current yielded an instrument sensitivity to ions of 4.93×10^{-13} A/ion cm^{-3} with a standard deviation of $\pm 26\%$. No long term trend of changing sensitivity was detected. Specific care was taken to keep the vehicle potential stable and at low values, typically less than 1 V. This included three precautions. First, no experiment was allowed to expose any surface with an applied voltage, i.e. all experiment apertures were at spacecraft ground. Second, the edges and solar cell interconnections were insulated; and third, a large percentage of the total spacecraft area was made electrically conductive. Figure 2 shows one typical orbit of data from the mass spectrometer ion measurements. The five principal ions of the F_1 and F_2 regions are seen to exhibit a rather smooth set of profiles in this case which is typical of daytime mid- and low-latitude results. However, the high latitudes and the night-time F-region are more frequently highly structured and irregular. This point will be demonstrated in the data from the intercomparisons. Based on the consideration of the calibrations and the on orbit performance, the ion densities reported should be better than about $\pm 15\%$ and the relative composition better than $\pm 10\%$ for ion densities greater than 10^2 cm^{-3}.

COMPARISONS AND RESULTS

An examination of the data collected by the S3-1 and AEROS-B satellites has located five cases which

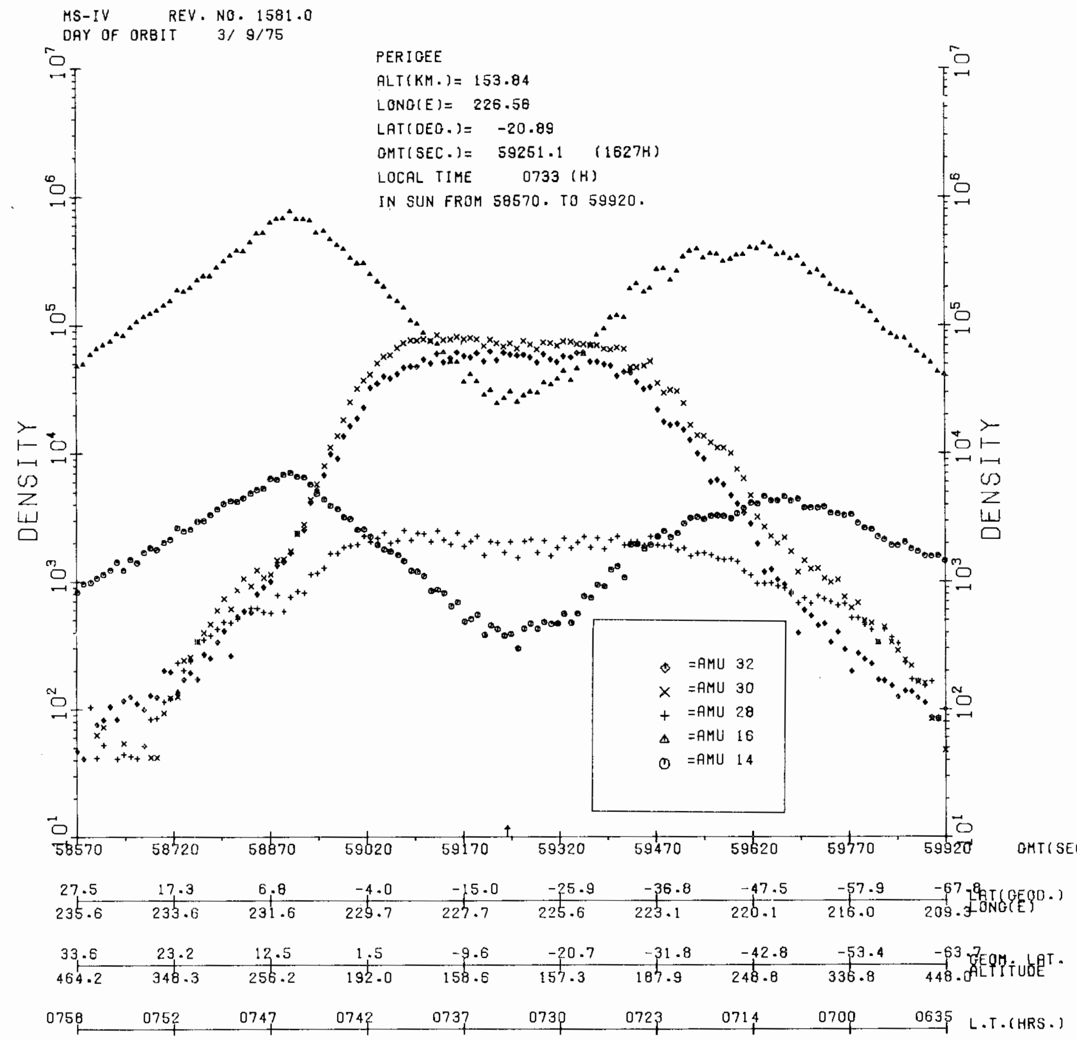

Fig. 2. Ion composition profiles measured by the mass spectrometer on the S3-1 satellite as a function of time, with altitude, geodetic and geomagnetic coordinates, and local time shown. The five species profiles shown are O_2^+ (◇), NO^+ (×), N_2^+ (+), O^+ (△), and N^+ (ʘ).

exhibit sufficient propinquity that a valid intercomparison of the measurements can be made. The information on these five cases is listed in Table 1. In each case the trajectories of the two satellites crossed the same longitude and latitude with relatively small differences in time and altitude. The parameters listed for each case represent the actual measurement points closest to the intersecting longitude and latitude. The altitude differences range from about 2 to 35 km and time differences from about 4 to 16 min. The first three cases correspond to extremely quiet geomagnetic conditions and the others to moderately disturbed periods.

Figure 3 shows the measurements from the comparison of Case 1 plotted as a function of altitude. The S3-1 data shown extends from 190 to 330 km while the AEROS-B satellite is much nearer its perigee and thus the altitude range is only between 240 and 270 km. At the crossing, the altitude of S3-1 was 253 km and that of AEROS-B was 265 km. The IP data for electron density and the RPA data for atomic and molecular ion densities are shown together with the mass spectrometer data which has been appropriately summed to make the comparison. The S3-1 satellite crosses into the region of the auroral oval just after the intersection corresponding to the altitude range 260–300 km. The AEROS-B satellite passes through the auroral oval, in the altitude range 258–264 km just before reaching the crossing point of the trajectories. Several orbits of data,

Table 1.

PARAMETERS FOR THE NEAREST IONOSPHERIC MEASUREMENT TO THE CROSSING POINT OF S3-1 AND AEROS-B SATELLITES

	Case 1	Case 2	Case 3	Case 4	Case 5
Date	29 Nov 74	30 Nov 74	1 Dec 74	2 Dec 74	3 Dec 74
Kp	1^+	0	0^+	4	3
S3-1					
Time (GMT)	12:43:51	13:21:29	13:57:48	10:27:15	11:01:12
Orbit	344	356	368	378	390
Latitude (°N)	79.37	79.04	79.20	78.91	78.93
Longitude(°E)	4.05	352.93	343.91	34.96	26.08
Invariant Latitude	77.10	78.05	79.29	74.35	74.96
Altitude (km)	252.9	273.6	290.3	311.3	332.6
n_i(cm^{-3})	2.35×10^5	1.36×10^5	2.66×10^5	8.26×10^4	2.02×10^5
AEROS-B					
Time (GMT)	12:36:57	13:25:49	14:14:23	10:23:37	11:11:18
Orbit	2074	2090	2106	2119	2135
Latitude (°N)	79.22	78.79	78.75	79.12	79.16
Longitude(°E)	2.37	352.44	340.56	36.35	24.26
Invariant Latitude	77.04	77.80	79.29	74.31	75.14
Altitude (km)	265.2	271.7	279.5	288.3	297.0
n_e(cm^{-3})	2.26×10^5	1.45×10^5	2.71×10^5	7.68×10^4	2.07×10^5
Ratio (S3-1/AEROS-B)	1.04	0.94	0.98	1.08	0.98

Average Ratio (S3-1/AEROS-B) = 1.00 ± 0.06

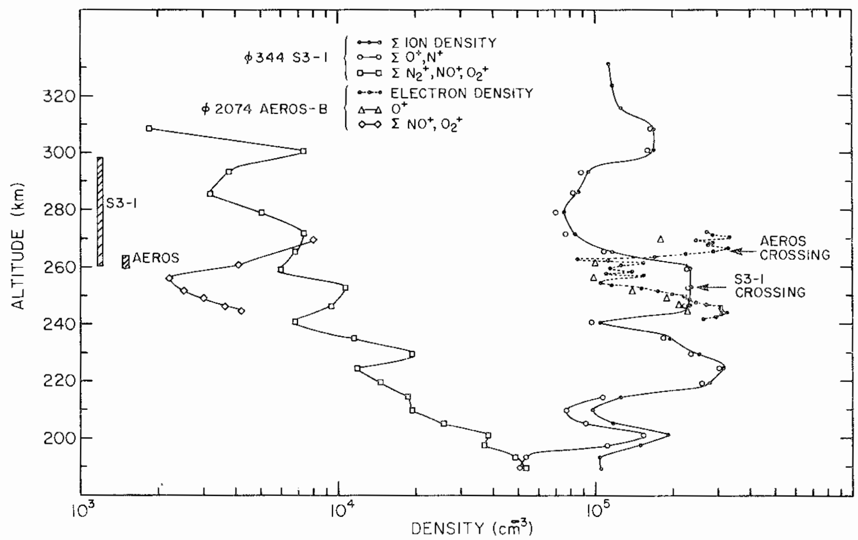

Fig. 3. Total and partial density profiles from AEROS-B and S3-1 experiments near a crossing of both satellites (case 1 of Table 1). Regions where the satellites passed through the auroral oval are marked by bars, and arrows indicate the respective altitudes at the latitude and longitude of the intersection of the satellite orbit planes.

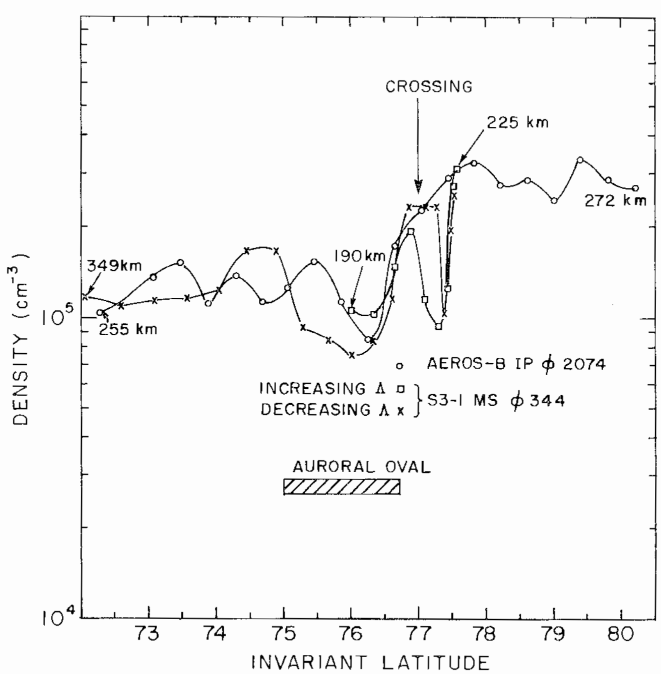

Fig. 4. Comparison of total plasma densities from the AEROS-B impedance probe and the S3-1 mass spectrometer plotted versus invariant magnetic latitude, Λ. The data shown are the same as in Fig. 3.

including these cases, were studied with regard to the structure features observed at high latitude. The conclusion was that comparisons made with respect to invariant latitude exhibited significantly more correlation. Several bases for comparison were attempted including altitude, geomagnetic latitude, geodetic latitude and corrected geomagnetic latitude but the invariant latitude provided the best comparisons.

The same data that was shown in Fig. 3 is displayed in Figs 4 and 5 as a function of invariant latitude. Figure 4 shows the comparison of electron and total ion density from the IP and MS instruments. The generally good agreement which has been observed in the profiles plotted against invariant latitude shows the importance of the magnetic field in constraining the distribution of the ambient plasma. At these high latitudes, the primary ionization in winter is by charged particle precipitation and leads to localized production enhancements together with significant redistribution under the influence of electric and magnetic fields. Since the distribution of the high latitude F-region plasma is primarily controlled by the magnetic field, from the standpoint of both production sources and motion, it is natural to consider a magnetic field coordinate reference. Indeed, the invariant latitude appears to be the most appropriate reference for at least the 200–500 km region at high latitudes.

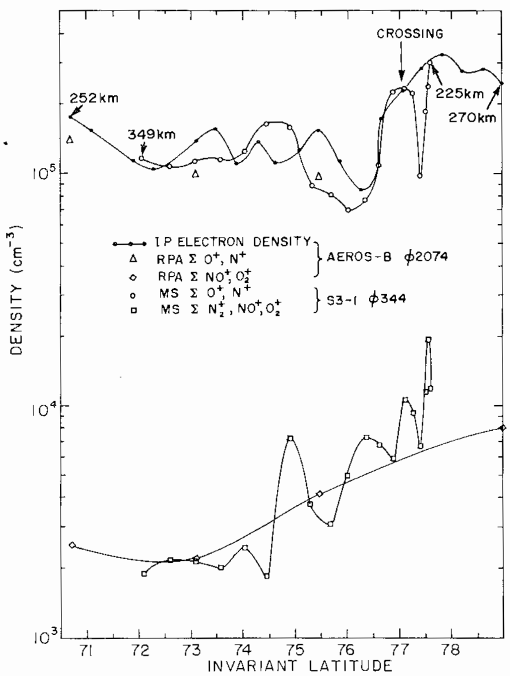

Fig. 5. Comparison of atomic and molecular ion densities from the S3-1 mass spectrometer and the AEROS-B retarding potential analyzer for the same orbits shown in Fig. 3 and Fig. 4. The spacing of the RPA data points is large due to the lower sampling rate in obtaining complete scans and due to the fit convergence requirements in highly structured regions of the ionosphere.

In Fig. 5 the molecular and atomic ion composition measured by the two satellites is compared for Case 1. The RPA densities are lower than the IP density by 20–30% as described earlier. If the RPA density measurements were corrected to agree with the IP data, the conclusion that can be drawn is that the RPA composition and mass spectrometer composition are in general agreement, within about 20%.

Figure 6 shows a summary plot of the crossings for the five cases of intercomparison between the satellites. The crossing points of the trajectories are indicated on each of the cases. The data in Table 1 correspond to the points closest to each of these crossings. On the right side of each case is a projection of the trajectories of the two satellites into the geodetic and corrected geomagnetic coordinates for the segment of the orbits included in the figures in this paper. The orbit plots show the FELDSTEIN and STARKOV (1967) oval for a $Q = 1$ case, corresponding to low geomagnetic activity, using the nomograph developed by WHALEN (1970). The data shown in the figure are the summed ion densities measured by the mass spectrometer compared to the impedance probe measurements of electron density. The curves in some cases are quite different, particularly when crossing the trough region just equatorward of the oval. At the crossing points, however, the densities are always very close. The values for the densities at the data point closest to orbit intersection are given in Table 1. The ratio of the S3-1 to AEROS-B values are given for each case and the average for the five cases was found to be 1.00 with a standard deviation of 6%. The agreement between the two experiments is much closer than the accuracy claimed for the instruments and is probably fortuitous to some degree. It is satisfying to see that the agreement is so close between different types of instruments on different satellites. However, it should be pointed out that the density determination is based on the electron critical frequency in both cases. The AEROS-B impedance probe measures the local critical frequency of the ambient plasma and the S3-1 mass spectrometer density was determined by normalizing the total ion density measured to selected crossings of ionosonde stations near the peak of the F_2-region.

An examination of Fig. 6 indicates the magnitude of the irregular structure which occurs in the vicinity of the auroral oval at F-region altitudes. Since the results presented here were obtained for short time intervals which were nearly coincident for each satellite, the variations in the profiles should represent primarily

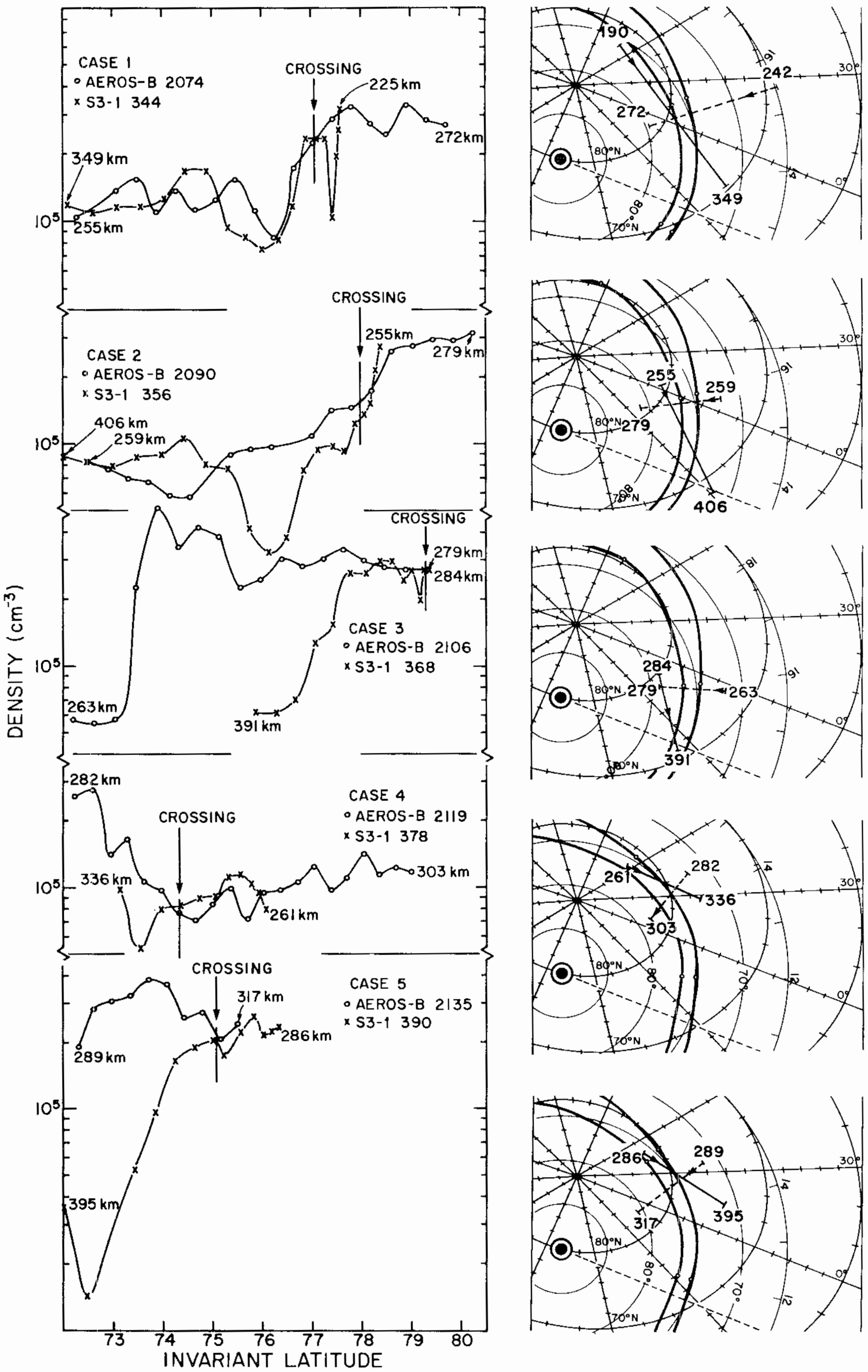

Fig. 6. Plasma density intercomparison at the five closest crossings of the AEROS-B and S3-1 satellites. Densities are plotted vs. invariant latitude. On the right, the corresponding location and motion of the satellites (S3-1——, AEROS-B– – –) is shown in both geodetic and corrected geomagnetic coordinates. Initial and final altitudes (km) are indicated, and the two broad lines represent the limits of the auroral oval for low geomagnetic activity (WHALEN, 1970; FELDSTEIN and STARKOV, 1967).

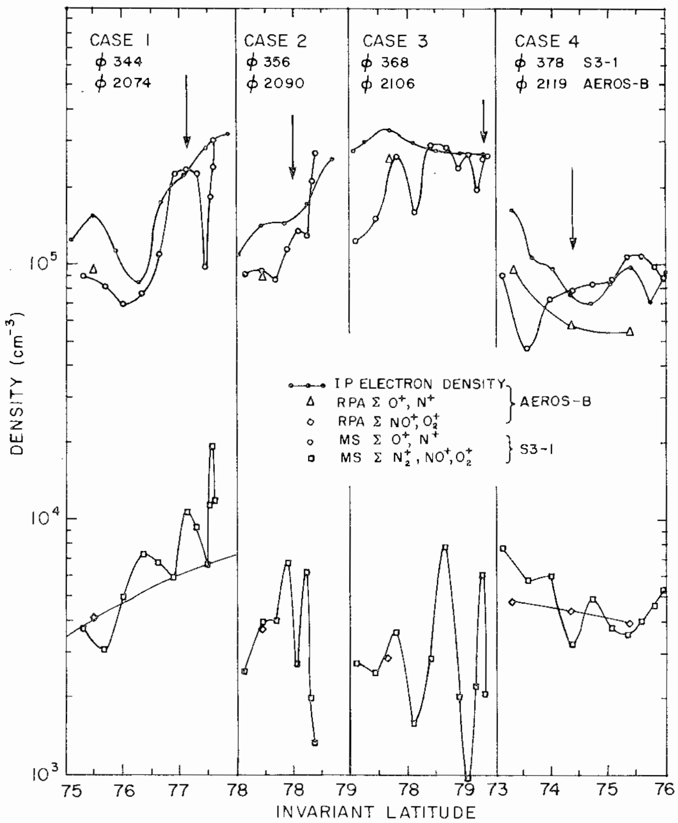

Fig. 7. Intercomparison of atomic and molecular ion densities and electron density measured by the RPA and MS from four crossings of the AEROS-B and S3-1 satellites.

the spatial distributions of the plasma. Case 1 showed very good agreement between the two satellites. Even the retrace of invariant latitude for the S3-1, see Fig. 4, showed the same sharp valley at 77.5° invariant latitude with a wider latitude extent at the more easterly longitudes (and lower altitudes). This feature was too narrow to be observed in the AEROS-B data, which was even further to the west. Cases 3 and 5 exhibit the larger differences between the profiles of the two satellites. In each of these cases, the ionospheric trough region is clearly evident. In Case 3, the data shows the sharp poleward side of the trough region near $\Lambda = 77°$ for S3-1 and $\Lambda = 73.5°$ for the AEROS-B data. This alignment of the trough region, at a higher invariant latitude in the noon sector and a lower invariant latitude in the sunset sector is consistent with the current understanding of the trough morphology (AHMED *et al.*, 1979). In Case 5, the geomagnetic activity had increased to moderate values, see Table 1, and the trough region had moved to lower invariant latitudes. In this case the center of the trough region was located at $\Lambda = 72.5°$ for S3-1 (noon sector) and at $\Lambda = 68.5°$ for AEROS-B (sunset sector). The equatorward progression of the ion trough as a function of increasing geomagnetic activity is in agreement with other *in situ* and ground-based measurements of the trough, plasmapause and oval regions. Although there are significant differences between the profiles shown in Fig. 6, the cases shown and other additional comparisons based on invariant latitude have been found more satisfactory than comparisons based on any other parameters for systematizing the high latitude data.

The ion composition determined by the RPA was compared to the appropriately summed mass spectrometer densities for these cases. These comparisons are shown in Fig. 7 for the four cases for which RPA data exist near the crossing region. The RPA data have not been corrected by the transmission error mentioned earlier but it is possible to conclude that the RPA derived composition, which distinguishes between the atomic and molecular ions, is in agreement within about 20–30% with the mass spectrometer measured composition.

SUMMARY OF CONCLUSIONS

The results that have been presented show the importance of the earth's magnetic field in controlling the ion and electron distribution, and of the invariant magnetic latitude as the most appropriate coordinate for systematizing the structural features in the polar F-region. The AEROS-B measurements of electron density and the S3-1 measurements of ion density have been found to be in excellent agreement. The RPA measurements of relative composition of atomic and molecular ions have been shown to be in good agreement with the mass spectrometer composition measurements. The confidence in these measurements gained through the comparison studies will be helpful in developing ionospheric investigations and modelling efforts using this data base.

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REFERENCES

AHMED M., SAGALYN R. C., WILDMAN P. J. L. and BURKE W. J. 1979 *J. geophys. Res.* **84**, 489.
BENSON R. F., BAUER P., BRACE L. H., CARLSON H. C., HAGEN J., HANSON W. B., HOEGY W. R., TORR M. R., WAND R. H. and WICKWAR V. B. 1977 *J. geophys. Res.* **82**, 36.
FELDSTEIN Y. I. and STARKOV G. V. 1967 *Planet. Space Sci.* **15**, 209.
HOFFMAN J. H., HANSON W. B., LIPPINCOTT C. R. and FERGUSON E. E. 1973 *Radio Sci.* **8**, 315.
HOFFMAN J. H., DODSON W. H., LIPPINCOTT C. R. and HAMMACK H. D. 1974 *J. geophys. Res.* **79**, 4246.
LÄMMERZAHL P. and BAUER S. J. 1974 *J. Geophys.* **40**, 571.
LÄMMERZAHL P., RAWER K. and SCHMIDTKE G. 1979 *J. Geomag. Geoelectr.* **31**, Supplement S9.
NESKE E. and KIST R. 1974 *J. Geophys.* **40**, 593.
NESKE E., OYA H., TAKAHASHI T. and WOLF H. 1979 *J. Geomag. Geoelectr.* **31**, Supplement S31.
PHILBRICK C. R. 1974 *Space Res.* **14**, 151.
PHILBRICK C. R. 1976 *Space Res.* **16**, 289.
ROBLE R. G., STEWART A. I., TORR M. R., RUSCH D. W. and WAND R. H. 1978 *J. atmos. terr. Phys.* **40**, 21.
SPENNER K. and DUMBS A. 1974 *J. Geophys.* **40**, 585.
SPENNER K. and RAWER K. 1978 *J. atmos. terr. Phys.* **40**, 969.
TAYLOR G. N. and WRENN G. L. 1970 *Planet. Space Sci.* **18**, 1663.

Reference is also made to the following unpublished material:

WHALEN J. A. 1970 AFGL Report 70-0422, Environmental Research Papers, No. 327.