Results from the Plasma Experiments on AEROS

A. DUMBS, G. EMMENEGGER, R. KIST, D. KLUMPAR,* E. NESKE,
J. SLAVIK, K. SPENNER, and H. WOLF

Institut für Physikalische Weltraumforschung der FhG, Freiburg, F.R.G.

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The two plasma experiments aboard the AEROS-B satellite determined the main plasma quantities in the height range 220–880 km. These complementary instruments, a Retarding Potential Analyser and an Impedance Probe, provided the electron and ion temperatures, the main ion constituents, the suprathermal electron flux and the plasma density.

This paper summarizes a selection of the obtained results. Comparisons of several quantities with other observations demonstrate the high reliability of the AEROS plasma data. As a contribution to sensor theory a dependence of RPA measurements on the magnetic field vector has been established. The ion temperature and composition turn out to undergo a strong latitudinal variation, the highest hydrogen concentration in the upper atmosphere being located at $\pm 20^\circ$ latitude. Concerning the longitudinal variation of electron density discrepancies between measured data and existing models have been revealed. The statistical relation between the position of the mid-latitude trough and magnetic activity was studied for a fixed local time. First results of a synoptic study of the high latitude day-side ionosphere using AEROS-B and ISIS-II data are presented.

1. Introduction

The AEROS Retarding Potential Analyser (RPA) was designed to measure most of the ionospheric plasma parameters. In the electron mode the instrument measured primarily electron temperature and suprathermal fluxes. In the ion mode ion density, temperature and the main constituents were determined.

When the RPA was designed in the late sixties the determination of the electron temperature was a very uncertain measurement by in-situ probes. It was noted, that mainly the satellite borne Langmuir probes were not in agreement with the Incoherent Scatter Radar (ISR) observations (CARLSON and SAYERS, 1970). The comparisons indicated a considerably higher electron temperature derived from the probe measurements (BOOKER and SMITH, 1970). Therefore we did not use the more traditional Langmuir probe technique and

* On leave from the University of Texas at Dallas.

we designed a versatile RPA which could be used for electron and ion measurements (SPENNER and DUMBS, 1974).

The Impedance Probe (IP) experiment is to measure the in-situ electron density in a fast sequence with high absolute accuracy. Although this parameter is the most frequently measured and analysed parameter in ionospheric research and the main relationships between the electron concentration and altitude, latitude as well as local time are basically known, a large variety of superimposed structures exists, so that a measurement of the actual local density is needed in most cases.

2. Selected Results from the RPA

The electron temperature values determined by the AEROS-RPA compare very well with the ISR results for all available encounter passes (SPENNER and RAWER, 1978). This particular result has also been confirmed on a statistical basis using mean temperatures over a longer time period (SPENNER and PLUGGE, 1978). The results demonstrated that the planar AEROS-RPA is able to determine correct electron temperatures thus overcoming the problems of earlier Langmuir probe measurements.

The plasma density was determined by both the Impedance Probe (IP) and the RPA. In principal the RPA allows to determine the density using either the ion or electron current-voltage characteristic, since in the considered altitude range the ionospheric plasma is quasineutral.

The ion parameters, partial densities and temperature are calculated by fitting a theoretical curve (KNUDSEN, 1966) to the experimental points. The total ion density is defined as the sum of all partial densities.

The ion density derived from the ion current has been compared with the IP density. The result for one typical orbit is shown in Fig. 1. The agreement of both measurements is in general better than 15%, provided the RPA sensor looks in the flight direction. Only few measurements are obtained when the angle between the sensor normal and the flight vector becomes larger than 35° . As a consequence the data at latitudes larger than 35° yield too low density values as shown in Fig. 1. Discrepancies are particularly observed for low densities ($n < 2 \times 10^{10} \text{ m}^{-3}$). For appropriate conditions, however, both densities are in good agreement.

A similar comparison, using the electron saturation current values as the basis for the density calculation, indicated that these data are related to the angle between the geomagnetic field and the sensor normal. The ratio between the RPA electron saturation current and the IP density is shown in Fig. 2 for two different orbits. It reveals an angular dependence of the measured current

Fig. 1. Plasma density derived by the RPA and the IP during one orbit.

Fig. 2. Dependence of the electron saturation current on the magnetic field direction.

so that the plasma density derived from the electron current must be corrected for the magnetic field direction. A detailed study also showed that changes of the satellite potential and the Debye length, which both depend on the plasma density, influence the measured current. This makes it obvious, that the plasma density can be determined more accurately from an RPA using the collected ion rather than the electron current.

The ion temperature was simultaneously measured by AEROS and ISR

Fig. 3. Ion temperatures simultaneously measured by the AEROS-RPA and the ISR.

over Malvern and Chatanika. The available data, shown in Fig. 3, are in good agreement. Even when there are only a few values, they give increased confidence in the derived AEROS ion data since they do not show systematic deviations from the well-established ISR results. In addition a comparison of the AEROS ion temperature with neutral temperature obtained simultaneously by the AEROS-NATE shows full agreement for low altitudes (DUMBS *et al.*, 1978), where neutral and ion temperatures are equal.

The sunsynchronous AEROS orbit and the spin stabilization of the satellite lead to changing angles of attack for the ion sensor along the orbit during one RPA scan. AEROS crosses altitude ranges where O^+ is by far the dominant ion species. Therefore the light ions H^+ and He^+ generally contribute to the measured current voltage characteristic in such a way that their separation is almost impossible. As a consequence only the sum of the two densities $H^+ + He^+$ is used.

In order to model the ion temperature, the temperature data were selected according to time periods, local time (day–night), geomagnetic latitude, and longitude. The latitudinal intervals were chosen to be 10° , the longitudinal to 45° , the time periods to 2 months. No classification was made concerning geomagnetic or solar activity. An example of the statistically produced height profiles is shown in Fig. 4. The data belong to the time period October–November 1974, the longitudinal intervals being 225° to 270° and 315° to 360° . During the selected time period of 2 months, the satellite does not cover all latitudes in a given longitudinal range, so that two longitudinal intervals are mixed in Fig. 4. The data of the latitudes -20° until $+80^\circ$ belong to the longitude interval 315° to 360° , the residual data to 225° to 270° . This combination of data seems to be allowed, since no significant longitudinal dependence was found in analyzing a great amount of data.

A very apparent result is the scatter of the data. At low and middle latitudes, except for near equatorial latitudes and high altitudes, the scatter is very

Fig. 4. Ion daytime temperature profiles for 17 latitude intervals to 10° each.

low. This means that in these cases averaged height profiles can be established without taking special conditions into account. Some restrictions have to be made only for the *F*-region, where deviations occur. The condition for these deviations remain to be examined in more detail.

Around the equator the ion temperature is coupled more strongly to the neutrals even at higher altitudes. This feature is clearly shown in the statistically produced profiles. At the equator the ion temperature has values around 1,000 K up to 550 km, then the increase occurs very rapidly. With increasing latitude the profiles become more and more flat. No significant differences in the profiles are found between the northern and southern hemisphere.

Going to latitudes higher than 60° in both hemispheres the data scatter increases strongly. This means that the criteria for the data selection are chosen in a too simple way. Section 4 of this paper shows for example, that the orbit of AEROS crosses quite different polar regions where even cleft conditions are included. Thus a classification according to geomagnetic latitude alone cannot give a clear picture. An analysis of the special conditions of each polar region of the AEROS orbit is necessary and classifications have to be introduced which include more than Kp or Ap indices.

During night, the height profiles are nearly constant. They are plotted in Fig. 5 together with the conclusions of Fig. 4. The nighttime profiles are independent on longitude and have only a weak dependence on latitude: At low and middle latitudes the height profiles are constant, at high altitudes the temperature increases slowly with increasing height.

For establishing composition profiles the same selection criteria as for the ion temperature data are used. As O^+ is the complementary ion species to $O_2^+ + NO^+$ at altitudes below 300 km and to $H^+ + He^+$ above this level, the plot of the relative O^+ density is sufficient to demonstrate the relative ion composition. The result is given in Fig. 6. Again a dominant feature is the scattering of the data. One can see the relative constancy at middle latitudes, where the ions consist of O^+ to a high percentage. At low latitudes and high altitudes the variability is clearly indicated. This variability is due to geophysical changes from one orbit to the other. Along a given orbit the curve of the O^+ data is smooth. A parameter for describing the orbit to orbit change cannot be given yet.

Around $\pm 25^\circ$ latitude contribution of O^+ to the total ion density reaches its minimum. This means that at these latitudes H^+ comes down to the lowest altitudes. At the magnetic equator the O^+ concentration has a relative maximum. The two minima on both sides of the equator are typical for all AEROS measurements at altitudes above about 500 km.

Fig. 5. Dependence of the ion temperature height profiles on geomagnetic latitude.

Fig. 6. Ion daytime O^+ profiles of 17 latitude intervals of 10° each.

At low latitudes (below $\pm 40^\circ$) and for altitudes between 300 and 500 km O^+ is the only ion species present; towards the poles concentration of the light ion species increases.

Figure 7 gives a daytime latitudinal profile of relative O^+ concentrations at the altitude of about 750 km. As the data belong to the time period October–November, Fig. 7 gives also the seasonal dependence. In the winter hemisphere the light ion concentration at around 25° geomagnetic latitude is higher than in the summer hemisphere.

The ion data shown demonstrate some aspects of the general behaviour of

Fig. 7. Dependence of the O^+ concentration on geomagnetic latitude at 750 km altitude.

ionospheric parameters and give an indication for the errors which are to be expected for the AEROS-ion model that is presently being constructed.

3. Selected Results from the Impedance Probe

The IP experiment is a swept frequency (10.24–0.64 MHz) self impedance probe, which responds to plasma-dependent impedance changes of a plasma condensor. This condensor is formed by a cylindrical rod antenna (length 180 cm, diameter 2 cm) and the satellite's surface. A detailed description is given by NESKE and KIST (1974).

Characteristic resonances occurring in this frequency range are related to the ambient electron density. Especially the (modified) upper hybrid resonance can easily be transferred into electron density. Electron temperature has no influence on the position of this resonance and therefore cold plasma theory can be used for the data reduction.

Regarding data reliability, low telemetry rate and long-term stability an electronical concept was chosen for the IP, which essentially consists in measuring the phase shift of an *RF* signal, fed to the plasma condensor, with respect to a reference signal and in detecting and telemetering frequencies corresponding to four discrete and fixed phase levels. The sensor is positively dc-biased from time to time in order to study the effect of the ion sheath, which turned out to be negligible in this configuration. By means of an in-flight calibration a stability of the test frequencies better than 1% throughout the whole 14-month mission time has been confirmed.

A representative example of measured data is shown in Fig. 8, demonstrating the consistency as well as giving an impression of the reduction of the data. From the consecutively measured frequencies in the upper part the densities, plotted in the middle, are deduced having a spread of less than $\pm 4\%$. The lower curve consists of median values of four frequency sets with a resulting

Fig. 8. Measured frequencies, derived densities and median density.

spatial resolution of 48 km for the electron densities. In this form the data are used for further investigations. In cases where the density is low and the gyro-frequency is high (e.g. polar regions at night at high altitudes) the lower of the four phase levels might not be reached and the accuracy is worse. For densities higher than $3 \times 10^{10} \text{ m}^{-3}$ the absolute accuracy is better than $+4/-6\%$.

The field of geophysical research with data from satellites may be roughly divided into two parts, namely the investigation of localized phenomena and the investigation of the global parameter distribution. Two selected examples from previous and current electron density studies are given in the following.

3.1 Comparison with existing model

The CCIR model describes the global electron density distribution as a function of latitude, solar activity, etc. at the height of the F_2 -layer maximum (hmF_2). In order to have comparative data, the AEROS-B electron densities must be reduced to hmF_2 by means of reliable height profiles. We used those profiles given by (BENT and LLEWELLYN, 1970). For different geographic locations and altitudes Bent's profiles were compared with IP measurements and the agreement was found to be generally good. The reduced data have then been compared with the CCIR monthly median values for several months. The daytime IP values covering all longitudes reveal apart from general agreement

Fig. 9. Global differences in f_oF_2 between CCIR and AEROS-B.

a moderately pronounced southern hemisphere density peak. Selecting different longitude range this structure is more or less maintained. It is concluded that an overestimate of southern hemisphere mid-latitude density is given by the CCIR model, probably due to the minor coverage of ground stations (SHEIKH *et al.*, 1978). In addition the observed longitudinal variations are stronger than predicted by the model. In Fig. 9 comparison of the measured and predicted critical frequencies on a global scale for one month is shown, indicating the most pronounced differences over the Pacific area and in the northern and southern anomaly regions.

3.2 Global fluctuations

In order to study fluctuations in electron density and temperature about 6,000 orbits have been processed. The fluctuating part was separated from the slowly varying part by numerical filtering. By dividing the fluctuating part by the mean value relative fluctuations are obtained. Arranging the fluctuation data as a matrix where altitudes and geomagnetic latitudes are given in polar coordinates, a global picture of the fluctuations in the orbital plane can be given (MÜNTHER *et al.*, 1978). The transition from quiet conditions at low and middle latitudes during daytime to the structured polar region is clearly seen as a boundary at about $+60^\circ$. At night the overall higher fluctuation level indicates an equatorward shift of the high latitude boundary. In addition pronounced fluctuations occur at low altitudes and around the equator, probably related to irregularities.

3.3 Electron density trough

The middle latitude electron density trough (MLT) is a persistent feature of the nighttime ionosphere. It is located in the transition range between cor-

Fig. 10. Dependence of MLT position on magnetic activity.

puscular induced ionisation and solar produced plasma, being related to the plasmopause. Due to the orbit parameters of AEROS-B the geomagnetic latitude range of interest between 50° and 70° is seen at night at an almost fixed local time of 04.30 hr. Thus diurnal variations are negligible, which apart from the geomagnetic activity represent the dominant influence on the location of the MLT. The MLT position in L co-ordinates has been studied as function of Kp for 498 events. The best fit line shows a difference of approximately $0.4 L$ when compared with other published results. This is explained by an equatorward shift of the MLT during night. The location of the plasmopause, however, is not dependent on time and therefore generally a better correlation of the plasmopause is obtained with the poleward density increase rather than with the MLT itself (NESKE, 1978). The control of the MLT location by magnetic activity is shown in Fig. 10 for the strong magnetic storm in September 1974. The immediate response and the observed recovery time of the MLT on the order of days illustrate that the actual MLT position is strongly related to the corresponding Kp history and a correlation can only be deduced on a statistical basis.

3.4 South Atlantic Anomaly (SAA)

In a recent study the electron distribution was investigated in the vicinity of the SAA with respect to other longitude ranges. It was reported, that at night distinct density peaks arise in the SAA region. We found that during daytime the electron concentration shows no enhancement but there exists a higher gradient when crossing the anomaly area compared with other longitudes. This fact is preferably seen in L co-ordinates.

Summarizing this selection of results from the AEROS-B Impedance Probe it is stated that electron density data alone, measured with good accuracy and high spatial resolution, allow for a whole set of investigations which are of high interest in themselves.

4. A Synoptic Study of the High Latitude, Day-Side Ionosphere from Two Polar Orbiting Satellites (AEROS-B/ISIS-II)

The low altitude magnetospheric cleft has an internal, local time-dependent structure that was not apparent in early cleft observations (BANKS, 1977). This structure is exemplified by the throat region (HEELIS *et al.*, 1976) where convection is directed poleward, by the regions outside of the throat where the convection pattern undergoes a strong tangential reversal. These and other phenomena make the day-side polar region of the ionosphere one of intense interest.

The AEROS-B orbit is ideally placed for investigating this region since it continuously intersects the cleft over a wide range of magnetic local times and invariant latitudes. This can be seen in Fig. 11, in which the orbital paths of a 3-day period are shown along with the quiet-time ($Kp \approx 2^+$) cleft location as determined by ISIS-I particle data (WINNINGHAM, 1972), and the day-side convection pattern (HEELIS *et al.*, 1976).

A program of correlating high latitude AEROS-B plasma data with plasma and particle data of the ISIS-II satellite, which has a circular orbit at 1,400 km, is being undertaken with the following intentions:

- To study Magnetic Local Time and Invariant Latitude variations of plasma parameters and particle fluxes in and close to the cleft region.
- To compare plasma data measured at different altitudes on the same or adjacent magnetic field lines.
- To provide higher energy particle data for complementing and interpreting the AEROS-B plasma measurements.

An encounter analysis has been performed at the Communications Research Center (CRC), Ottawa, by which 77 cases were identified in which AEROS-B

Fig. 11. Orbital paths followed by AEROS over a 3-day period in a MLT/INVAR LAT co-ordinate system. Shaded region represents quiet time cleft location, dashed curves indicate convection pattern.

T_e . . .

$\phi_{int} (\leq 28\text{eV})$ x x x

Fig. 12. Electron density, electron temperature and supra-thermal electron flux measured by the AEROS-B plasma experiments.

and ISIS-II have been nearly on the same magnetic field line, and data from both satellites being available.

As an example synoptic data for an encounter event that occurred on October 26, 1974 at about 72° geomagnetic latitude are presented. Both satellites crossed the cleft within about 1.5-min time interval.

Figure 12 shows electron density N_e and temperature T_e as well as the integral suprathermal electron flux ϕ_{int} as measured with the AEROS-B plasma experiments. The cleft position is identified by the sharp increase of T_e and ϕ_{int} at about 71° invariant latitude A associated with a strong northward positive density gradient. The spatial coincidence of this gradient in N_e with the cleft position has been demonstrated in an earlier statistical study (Neske, 1978). Electron density values deduced from the ISIS topside sounder for the AEROS altitude agree within about 20% with the N_e values measured by the AEROS impedance probe. Figure 13 shows the density N_e and temperature T_e measured by the ISIS-II Langmuir probe at 19.59 hr UT when the satellite passed the cleft. Comparing T_e and N_e as function of A for both satellite altitudes the following common features are seen:

- 1) A strong enhancement in T_e at $A \approx 71^\circ$ for both satellites;

Fig. 13. Electron density and electron temperature measured by the ISIS-II Langmuir probe.

- 2) A minimum in T_e at $\lambda \approx 62^\circ$ for ISIS-II, and at $\lambda \approx 63^\circ$ for AEROS-B;
- 3) A positive poleward gradient in N_e at $\lambda \approx 71^\circ$ for both satellites;
- 4) A steady increase of T_e equatorward of the T_e minimum for both satellites.

The thermal plasma data of both satellites thus show a close positive correlation as function of invariant latitude. The mean N_e values at ISIS-II altitude are approximately one order of magnitude lower than those at AEROS-B altitude. The ISIS-II soft particle spectrometer (SPS) registered the onset of intense fluxes of electrons up to 2 keV at $\lambda \approx 70.8^\circ$. These fluxes completely disappeared after 24 sec indicating a latitudinal extent of the burst of about 2° . Apart from this burst the SPS saw no substantial electron fluxes on this pass, but the fluxes of the burst perfectly correlate with the suprathermal electron fluxes measured with the AEROS-RPA at 500 km.

Carrying further this synoptic study by using the large data base from both satellites it is expected that more insight can be gained to clarify the configuration and signature of the cleft in terms of ionospheric parameters as well as the effects of magnetospheric convection upon the polar ionosphere.

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