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Satellite Wake Structure Observed by the Gyro–Plasma Probe Installed on TAIYO

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Abstract: Observations of the wake behind a moving obstacle in the ionospheric plasma are made by the impedance probe onboard the TAIYO satellite. The wake structure is obtained with high angular resolution in a form of the beat pattern in the obtained electron density due to the difference of the spin period and the sampling period of the data for the observation. The detection of the wake structure was made both from the measured upper hybrid resonance frequency and measured sheath capacity of the probe. The measured wake structures by these two methods show slight difference due to the difference of the pick up area of the information to deduce the electron density. The preliminary analysis of the wake structures for various ionospheric conditions show that these results contain the information on the ionospheric plasma parameters such as the ion temperature, as well as the electron density. We have obtained ion temperatures both for the daytime and nighttime ionospheres; the results are consistent with each case expected for the ionosphere under the daytime or the nighttime conditions.

1. Introduction

Observation by the gyro-plasma probe (a swept frequency impedance probe IMP) onboard the TAIYO satellite provides the data of electron number density profiles and capacitance of the spherical probe at 406 KHz in the ambient plasma surounding the satellite. Several interesting features such as the equatorial anomalies of the F-layer and various irregular structures of the nighttime ionosphere have been observed. These results and the instrumentation were described in the other articles (Oya and Morioka, 1975; Oya et al. 1979). Here we will present the results on the satellite wake structure obtained by the IMP observations.

Many theoretical studies on the wake structure of a space craft in the ionosphere are in articles. These were summalized in several review papers (A'lpert et al. 1963, Liu, 1969, Gurevich et al. 1969). On the other hand, only a few experimental works on the disturbed region around an ionospheric spacecraft have been reported. Gurevich et al. (1969) has indicated a satisfactory agreement between their theoretical computation based on the quasi-neutral condition and the experimental results of Ariel-1 satellite at a radial distance from center of the satellite $5R_0$, where R_0 is the radius of the satellite. Oya (1970) has investigated the disturbance around a rocket body in the ionosphere using the results of the K–9M–21 rocket experiment with a gyro-plasma probe using the data obtained by a Langmuir probe mounted on

Explorer 31, Samir and Warren (1969) discussed the relation of the wake structure to the ion composition. Samir and Jew (1972) also compared the results with the theoretical model after Liu (1969). In this case of the probe mounted flush on the satellite, it is found that for the maximum rarefaction zone most of the computed values of electron densities are lower than experimental values except at perigee altitude. More resently Samir et al. (1979) discussed in some detail the nearwake structure of the satellite on the basis of measurements of ion current, electron temperature and values of space potential obtained from the cylindrical electrostatic probe onboard the Atmosphere Explorer C (AE-C) satellite. In general the observation of the wake of a spacecraft in the ionosphere largely depends on the observational situations, especially on the distance of the prove from the satellite, and the angular resolution of the used probe. The observation by the IMP installed on TAIYO has several merits to study the wake structure as the following;

a) The spin axis of the satellite is controled to be in the normal direction of the orbital plane, so the probe intersects the midst of the wake in every rotation of the satellite.

b) The dimension of the probe with radius of 6 cm is sufficiently small to make high resolution observation of the wake structure of the satellite of which radius is about 35 cm.

c) The observations of the local electron density were carried out for two different parameters, i.e. the upper hybrid resonance frequency and the sheath capacity of the probe measured at 406 kHz. These two observed parameters reflect the wake structure in different ways, so the comparative analysis of these data will give more detailed information on the wake structure.

2. Conditions of the Wake Observation

In Fig. 1 the relation of the gyro-plasma probe (IMP) onboard the TAIYO with the wake formed behind the satellite is depicted schematically. The TAIYO satellite

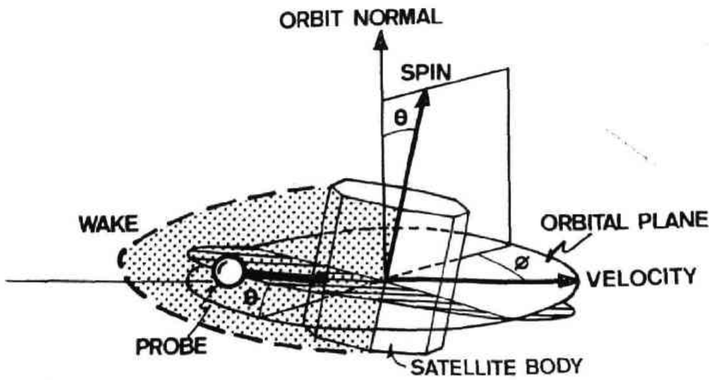

Fig. 1. A schematical illustration of the probe geometry of the IMP system installed on TAIYO satellite moving through the ionosphere making the wake. The spin axis is controled to keep in the normal direction to the orbital plane. The deviation angle θ of the spin axis from the normal of the orbital plane is kept within about ten degrees.

has an octagonal coloumnar shape of 70 cm high and 75 cm diameter, the probe of 6 cm radius is set at the tip of the boom of 50 cm length. The boom is attached in the direction perpendicular to the spin axis; and then, observation of the wake of this satellite is carried out by sweeping in the spherical surface with radius about 2.6 R_0, due to the spining motion of the satellite. The attitude of the TAIYO satellite was controled to keep the spin axis in the normal direction with respect to the orbital plane, making the so called rotating wheel mode. Since two weeks after the launch the deviation of the spin axis from the orbit normal had been kept within a range of the deviation angle of 10° by the magnetic attitude control system. Except for the initial two weeks, then, the probe sweeps the midst of the wake region for each spin period. With control of the direction of the spin axis, the satellite spin period is also controled to be in a range between 8.0 rpm and 11.0 rpm throughout the observational period. Measurements of the UHR frequency and the probe capacitance at 406 kHz are made for every 4 seconds. As indicated in the corresponding points in Figure 2, the observations are made so as to sweep widely in the wake region. In this case, illustrated in Figure 2,

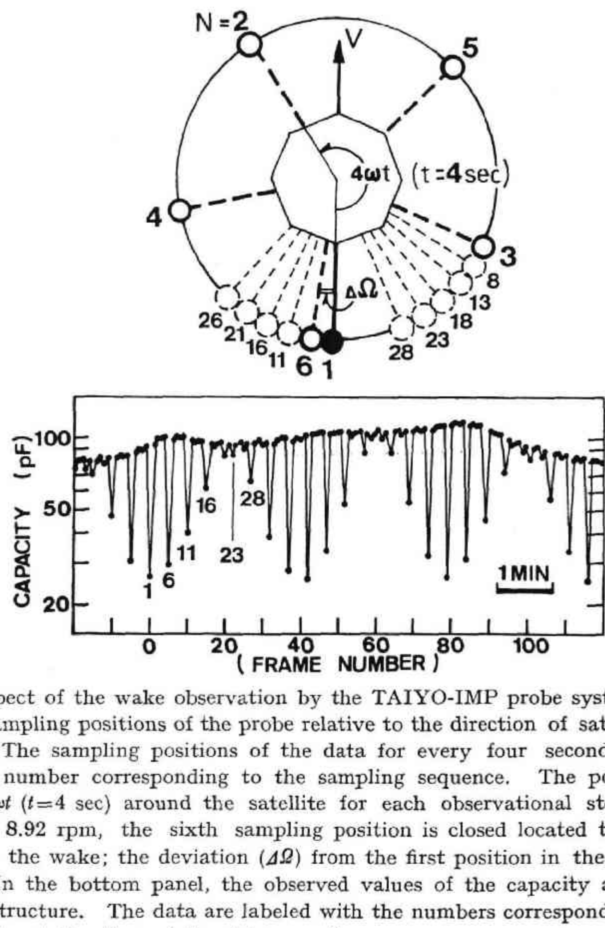

Fig. 2. An aspect of the wake observation by the TAIYO-IMP probe system. In top panel, the data sampling positions of the probe relative to the direction of satellite motion (V) are depicted. The sampling positions of the data for every four seconds are labeled with successive number corresponding to the sampling sequence. The position of the probe advances ωt ($t=4$ sec) around the satellite for each observational step. In the case of spin rate 8.92 rpm, the sixth sampling position is closed located to the first sampling position in the wake; the deviation ($\Delta\Omega$) from the first position in the wake is about 9.4 degrees. In the bottom panel, the observed values of the capacity are plotted showing the wake structure. The data are labeled with the numbers corresponding to the positions of the probe at the time of the data sampling.

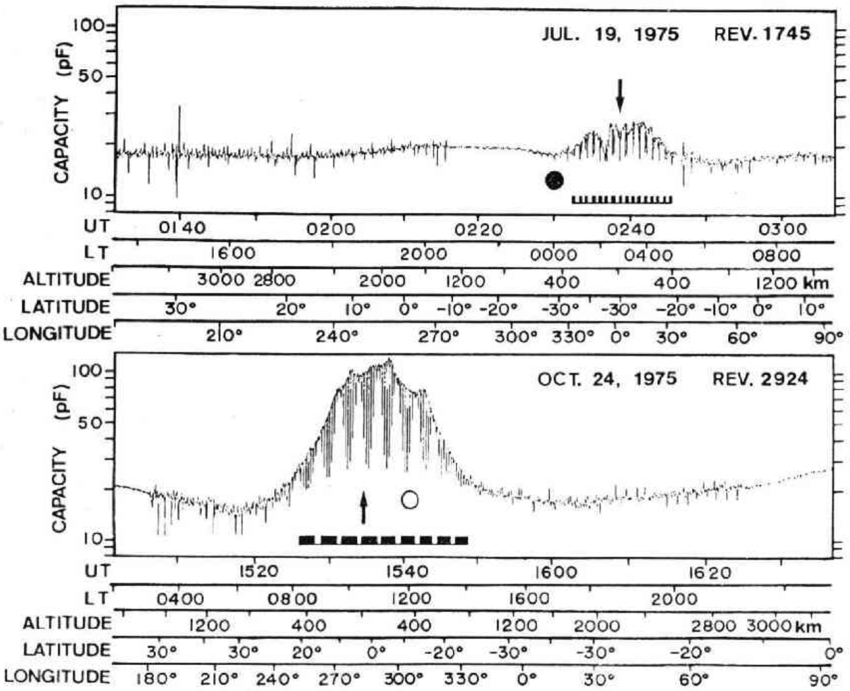

Fig. 3. Effective capacitance of the probe at 406 kHz with the orbital data of the satellite. The position of the perigee is indicated by an arrow, and the positions of the local midnight and the local noon are indicated by a solid circle and an open circle, respectively. Near the perigee, the upper and the lower figures correspond to nighttime ionosphere and daytime ionosphere, respectively. The wake structure is evident at the ionospheric height in both cases. The observed wake structures are emphasized by squre blocks in the figure.

the angular velocity (ω) of the spin motion is 0.934 rad/sec. For each sample of 4 sec, then, measurements were made every 3.74 radians. As shown in the figure the difference of the phase angle of the probe position and the sampling of the data provides the shift of the position with a small angle $\Delta\Omega$, 9.4 degrees in this case, at every 5 sampling points. Thus, we can obtain the structure of the wake with the angular resolution of $\Delta\Omega$. Corresponding to these sampling points, the measured wake structure are given in the bottom panel of Figure 2 for the capacitance at 406 kHz. For the entire coverage of the satellite wake, therefore, about 50 samplings are required and it takes about three minutes for this case.

The wake observations by the IMP are carried out in various conditions of the ionosphere, along the satellite path. In Figure 3 two examples of the observed effective probe capacitance at 406 kHz are shown with the parameters of the satellite position. The position of the perigee is indicated by an arrow, and the positions of the local midnight and the local noon are indicated by a solid circle and an open circle, respectively, in the figure. That is, the wake structures are indicated for the nighttime and daytime conditions of the ionosphere. As will be mentioned in the following sections, the observed value of capacitance is approximately proportional to square root of the electron number density and is inversely proportional to square root of the electron temperature. It becomes, therefore, difficult to observe the wake structure in higher altitude region of the satellite path. It is interesting that at high altitude in sunlit condition of the satellite the capacitance of the probe shows anomalous values of positive or negative deviations in the narrow regions in the sunward direction of the satellite corresponding to special configurations of the probe-satellite-sun system. It is only recommended here that the photoelectric processes at the surface of the satellite may affect the effective capacitance of the probe in a structure dependent manner.

3. Examples of the Wake Observation

Figure 4 shows examples of the well defined wake structures in the daytime ionosphere observed in the measurements of the probe capacitance at 406 kHz, for four different paths. In the figure the location of the local noon and the perigee are indicated by an open cricle and an arrow, respectively. Revolution numbers, dates, spin rates and values of $\Delta\Omega$ for these paths are given in the figure caption. As shown in the figure the resolution angle ($\Delta\Omega$) and, therefore, total period required to make

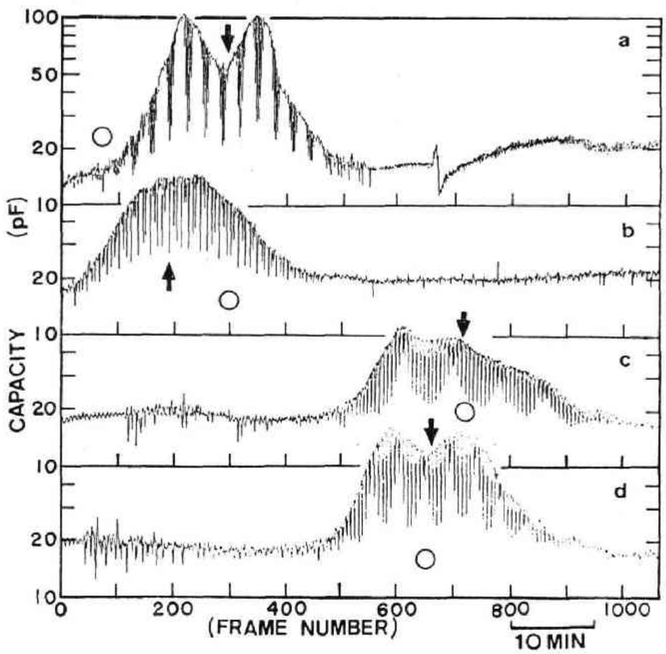

Fig. 4. Four examples of the detected probe capacity at 406 kHz, in the daytime ionosphere, versus the frame number where the observations had been made. The time passage of one frame correspond to 4 sec. The observation periods of the data and the spin rate for that time (with the estimated $\Delta\Omega$) of the observation are a) Mar. 7, 1975 on Rev. 143 with the spin rate of 10.26 rpm ($\Delta\Omega=18.7$ deg.), b) Oct. 14, 1975 on Rev. 2805 with the spin rate of 9.27 rpm ($\Delta\Omega=20.3$ deg.), c) Nov. 10, 1975 on Rev. 3127 with spin rate of 8.54 rpm ($\Delta\Omega=4.4$ deg.), and d) Nov. 12, 1975 on Rev. 3152 with spin rate of 8.52 rpm ($\Delta\Omega=7.9$ deg.).

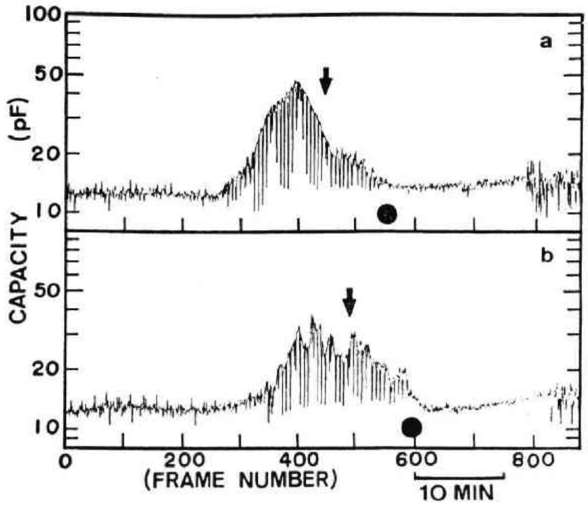

Fig. 5. Data in the same format as Fig. 4, for the results of the nighttime ionospheric condition. The positions of the local midnight is indicated by a solid circle. The data are given for a) May 19, 1975 on Rev. 1009 with spin rate of 10.67 rpm ($\Delta\Omega=8.0$ deg.), and b) May 20, 1975 on Rev. 1021 with spin rate of 10.65 rpm ($\Delta\Omega=11.6$ deg.).

sufficient sampling of the data to measure the wake structure varies widely due to the variation of the data sampling rate and the satellite rotation period. Thus for a preferable condition of the spin period, well defined wake structures were observed within a suitable time period in low altitude region of the satellite path.

In Figure 5, two examples of the wake observation in the nighttime ionosphere are indicated. The portion of the local midnight is pointed by a solid circle in the figure. Reflecting the low ion temperature in the nighttime ionosphere, the observed capacity in the wake seems to decrease more steeply than the cases in the daytime ionosphere.

4. The Wake Structures Obtained from the TAIYO IMP Observation

The effective capacity of the spherical probe, surrounded by the ion sheath in the frequency range sufficiently lower than the sheath resonance frequency, is approximately expressed as follows

$$C = 4\pi\varepsilon_0(r^2+r\cdot l)/l\,, \tag{1}$$

and

$$l = \xi\cdot\lambda_D = \xi\sqrt{\frac{\varepsilon_0 KT_e}{N_e e^2}}\,,$$

where r, l λ_D, and ξ are the radius of the probe, the thickness of the plasma sheath around the probe, the Debye length, and the proportional constant of structure dependent value, respectively. In the ionospheric altitude the Debye length (less than 1 cm) is small enough compared with the probe radius; the capacitance is,

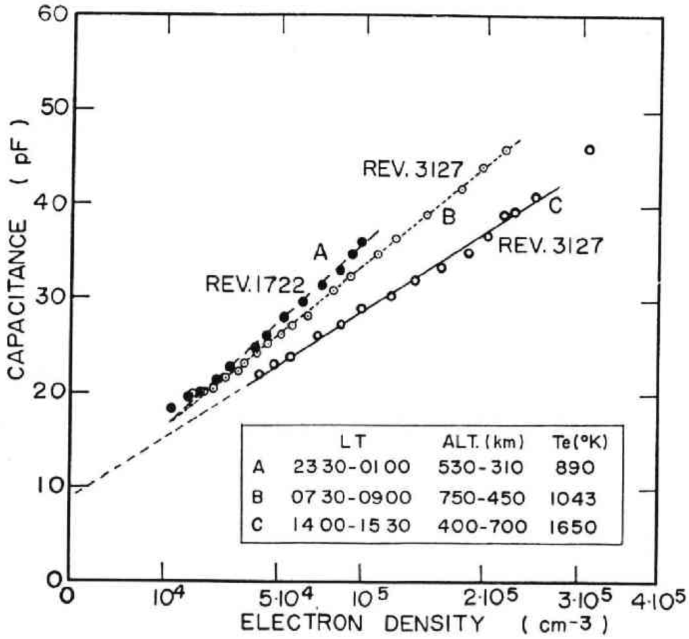

Fig. 6. The relation between the observed capacitance and the electron number density for three paths of the satellite. The local time and altitude range are indicated with estimated electron temperatures corresponding to plotted curves from A to C.

therefore, nearly proportional to the square root of electron number density as indicated by equation (1). To check this functional relation the observed values of the probe capacitance are plotted in Figure 6 versus electron number densities obtained from the measured upper hybrid resonance frequency (Oya et al. 1979). The abscissa is scaled as proporitional to the square root of the number density. The data are plotted for several orbital paths at ionospheric height in which distinct detections of the upper hybrid resonance frequency are made. The linear relationship is evident between the sheath capacitance and the square root of the electron density, that is,

$$C_s = \alpha \sqrt{n_e} + C', \tag{2}$$

where α is a constant; and C' corresponds to the constant part arising from equation (1). Since the value α includes the information on $\xi \sqrt{(\varepsilon_0 KT_e/e^2)}$, we can obtain the electron temperature from the α value. The values of electron temperature are obtained and indicated in the figure assuming the constant temperature within a given portion of the satellite path. Then, using the values of α and C' we can evaluate the electron distribution of the depleted region in the satellite wake.

Figure 7 shows the observed wake structures infered both from the measurement of the upper hybrid resonance frequencies (upper panel) and the probe capacitance (lower panel). As a consequence of the automatic detection of the resonance point the meaningful results of the F_{UHR} are obtained for every two sweeps, so the observational time resolution is eight seconds for the F_{UHR}. Sometimes, there are noise data in F_{UHR} due

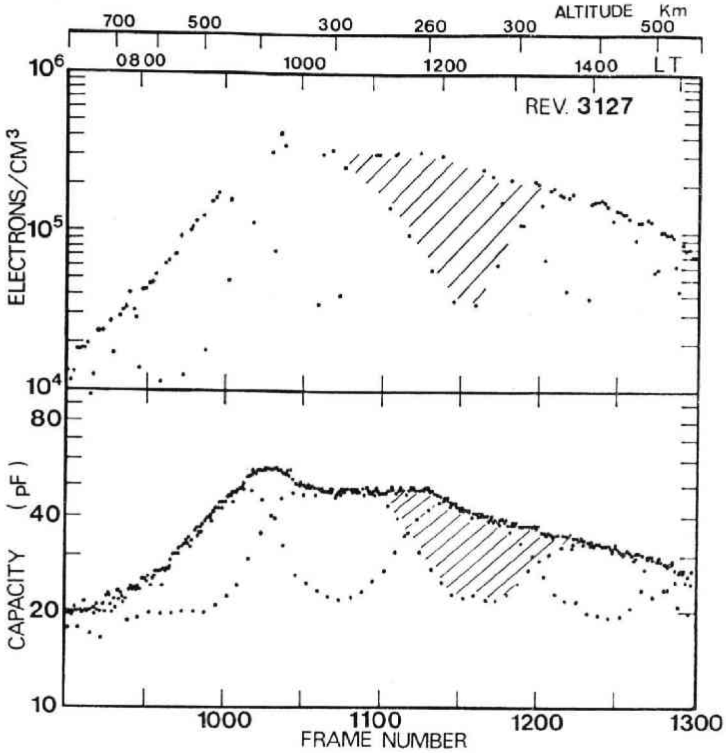

Fig. 7. Observed wake structures for the electron number density from F_{UHR} (upper) and for the effective probe capacity (lower). Data sampling of the wake is indicated for one entire sweep of the wake area by an hatched region for both cases.

to misdetection of the automatic frequency measurement system caused by the including noise. The results of the capacity, in lower panel of the figure, show a more precise structures as can be seen in the figure, but in this case, it is necessary to reduce the result with some processes discussed previously. We describe the wake structure in terms of the normalized value of the electron number densities, using the unperturbed value as a standard. Figure 8 shows the observed electron density distribution around the moving satellite with the angular sizes of the satellite and the probe used for the detection of the electron density; the results are shown for five full sweeps of the wake region. In the innermost region of the wake, the electron density indicated by the ratio to that of the undisturbed region becomes as low as 0.03.

The resolution of the wake observation is possibly restricted by the probe size rather than the resolution of the observational points with distribution angle difference of $\Delta\Omega$ (see Figure 8). In Figure 9 a wake structure obtained by the measurement of the upper hybrid resonance frequency is compared with that obtained from the capcitance value at 406 kHz; both structure are given by the averaging the data for 5-half sweeps with the assumption of the symmetric structure of the wake. It is interesting that the innermost wake density obtained from the F_{UHR} is larger than that obtained from the

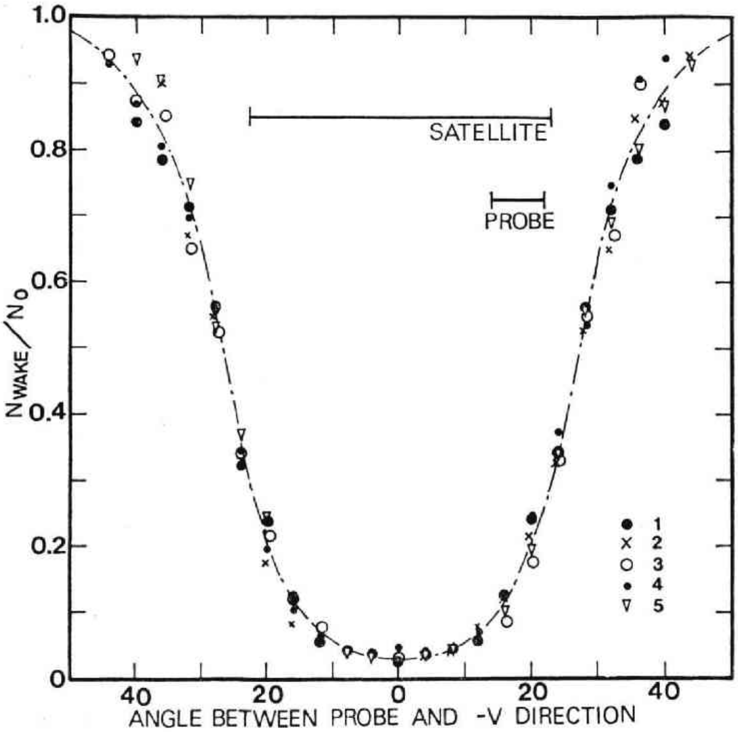

Fig. 8. Normarized wake structure obtained from the effective probe capacitance for the cases of observation in the orbit of the Rev. 3127. The angular distribution of the satellite and the probe compared with the wake detected at the distance of the probe are indicated by corresponding bars.

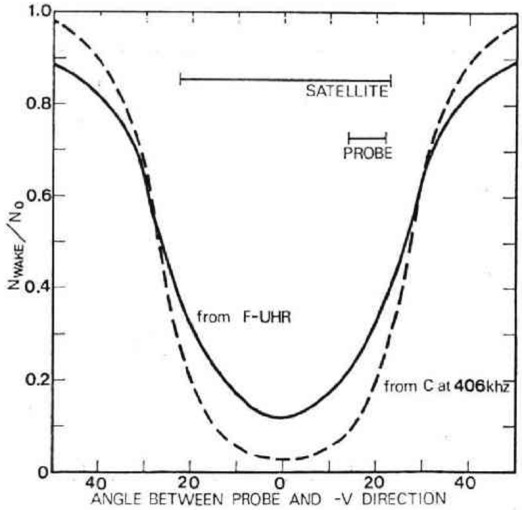

Fig. 9. Normarized wake structure obtained for the same data indicated in Fig. 8. The wake structures are given by a solid line for the data obtained from the UHR resonance and by a broken line for the data obtained from the capacitance at 406 kHz.

data of the sheath capacity, and the structure of the wake seems rather spread in the case of F_{UHR}. This is caused by the range of regions affecting on these two methods i.e., the sheath capacitance is controled by an localized area of the ion sheath surounding the probe, while the UHR resonance frequency is resulted as an integrated effect of the inhomogeneous plasma over the ion sheath region. For the quest of the wake structure, we can conclude that the detection using the capacitance value at the sufficiently low frequency for the detection of the ion sheath is much more suitable than the data of UHR resonance.

5. Discussions

In an approach of the studies on a neutralized gas approximation after Al'pert (1963), the plasma density behind a moving disk with radius R can be represented as a ratio to the undistrubed density, as,

$$\frac{N_w}{N_0} = \exp\left\{-\frac{M_i V_s^2}{2KT_i}\left(\frac{R}{Z}\right)^2\right\} \tag{3}$$

where T_i, M_i, V_s, and Z are ion temperature, ion mass, velocity of the disk and distance from the disk, respectively. Equation (3) becomes a good measure for the discussion of the results obtained by the spherical probe onboard TAIYO satellite. As observed from equation (3), the density ratio takes a constant value for a state of the constant ion composition and temperature. Fig. 10 shows a observed relation between the probe capacitance C_w in the midst of the wake region and the capacitance C_0 in the undistrubed ambient plasma. A good linearity in the C_0-C_w relation is evident in the figure. These relations can be represented approximatly in a generalized form as

$$\frac{C_w - C'}{C_0 - C'} = \text{costant}. \tag{4}$$

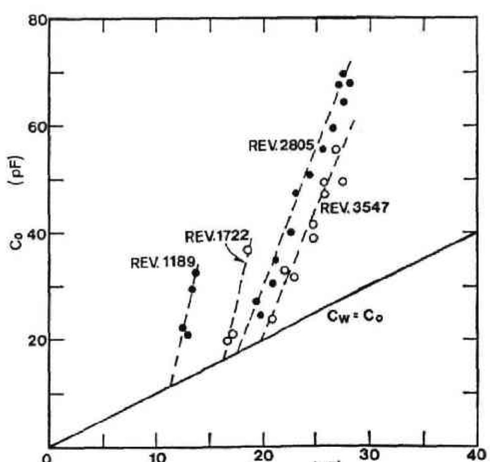

Fig. 10. Observed relation between the probe capacities in the undisturebed ambient plasma (C_0) and in the midst of the wake (C_0). The data are plotted both for the daytime conditions (revolutions 2805 and 3547) and in the nighttime conditions (revolutions 1189 and 1722).

As discussed in the previous section, the value C' is the constant part given by equation (2). The good linearity of these relation indicates that the ion temperature is nearly constant for each observational sequences; the gradient of each curve, then, gives information on the ion temperature since the ion species is fixed to 0^+ in the low latitude region of the ionospheric F-layer.

Subtracting the constant part C' from the observed capacitance the relation of the midst wake capacity to the capacity of the ambient plasma are shown in Fig. 11. The values plotted are taken in the observed wake in regions within 5 deg. arround the antidirection of the moving satellite. In the figure, open and solid circles indicate the data in daytime (0900∼1700 LT) and nighttime (2100∼0300LT) respectively. The straight line through the origin of the diagram maens the constant ratio of the electron density in the wake to the unperturbed density. Borken lines are drawn in the figure for the cases of the ratio 0.01 and 0.03. These lines correspond to ion temperatures 1500°K and 1980°K respectively. Although there is rather scattering nature in the results the difference of the ion temperatures in daytime and nighttime is evident.

For the more precise analysis of the wake structure and the studies on related subjects the information on the geometical relation of the probe and the satellite in the wake region is important. Figure 12 shows a concept of the configuration of the probe in the satellite wake. In the figure a side view of the satellite is shown with dashed line, the boom is attached in an offcentric position. The parameters of the amibent plasma are assumed as, electron number density of 5×10^5 cm^{-3}, the electron temperature of 1500° K, and the Mach number of 7.1. Contours of the electron number density in the wake and the thickness of the sheath around the probe for three different

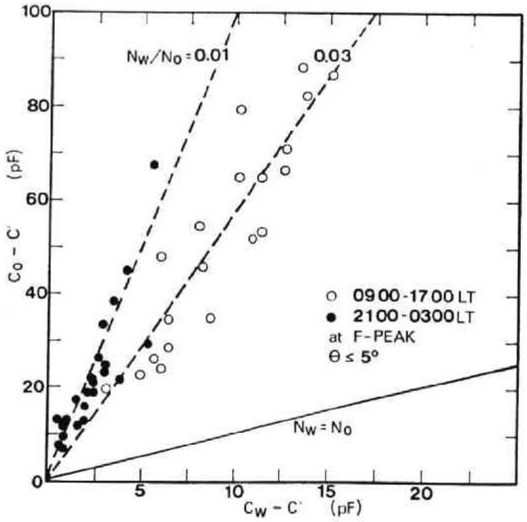

Fig. 11. Relation of the net capacities subtracting a constant value C' from observed value (see Text). The data were obtained near the F-layer peak for every orbits in which the clear wake structure were obtained.

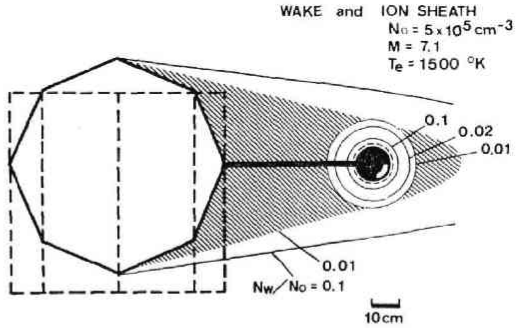

Fig. 12. Schematic illustration of the probe in the satellite wake, depicted for the conditions of the electron number density 5×10^5 cm^{-3}, Mach number 7.1 and the electron temperature 1500°K. The contours of the relative electron density N_w/N_0 in the wake are indicated for values 0.1, and 0.01. The thickness of the sheath around the probe in the undisturbed ambient plasma is indicated by a broken line surounding the spherical probe and features of the ion sheath formed in the wake region are expressed by solid lines for N_w/N_0 values of 0.1, 0.02 and 0.01.

plasma parameters are also indicated in the figure: The sheath region in the depletion area in the wake becomes large to be comparable with the wake size. The observed wake density in the midst of the wake gives, then, a larger values than the actual wake density. The figure of the sheath around the probe may be somewhat excentric. Therefore, the more realistic analysis including the inhomogenuity of the plasma in the wake region and the strict configuration of the satellite-probe system is necessary for further investigation of the wake structure to obtain the related parameters such as the ion temperature in the ionosphere. The detailed studies are then beyond the scope of this preliminary report.

6. Concluding Remarks

Observation of the moving satellite wake are made by the impedance probe onboard TAIYO satellite. The difference of the data sampling period and the spin rotation period provide us the good sweep data of the wake region as well as the unperturbed ambient plasma. The data are then revealed with the modulation of a beat pattern of the spin rate and the rate of observation sampling; the structure of the wake of the moving satellite was obtained with high angular resolution for various ionospheric conditions. The detection of the wake structure was made from both of the measured upper hybrid resonance frequency and the sheath capacity of the probe. There is slight difference between the observed wake structures obtained from these two methods. This difference is mainly caused by the difference of the resolution area for these two measurements; the ion sheath area is much more concentrated than the region where the RF electric fields are affected at the upper hybrid resonance. The preliminary analysis of the wake structure shows that these results provide information on the ionosphere plasma parameters such as ion temperature and the composition. The obtained ratios of the electron density to the ambient plasma at midst of the wake indicate the difference of the ion temperature between the daytime and nighttime clearly. The precise studies on the wake structure considering the inhomogenuity of the plasma in the wake region, under the realistic model of the geometrical configuration of the satellite-probe system taking accounting of the effects of the nonspherical structure of the ionsheath, will provide more quantitative information on the ionospheric parameters. The present preliminary report shows that the usage of the data of the wake structure provides important information with the moving vehicle to obtain the plasma parameter such as the accurate ion temperature, however, studies are remained for the future works.

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