This file contains the Appendix extracted from

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which describes some of the problems associated with the inter-calibration of the charged particle detectors aboard PVO.

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Appendix. The PVO Data Base and Sources of Measurement Error

This Appendix contains a more detailed discussion of the PVO data base, the spatial resolution and accuracy of the measurements, and some of the discrepancies in N{i} and N{e} that have been reported. In general, it can be said that the measurement errors have not fundamentally limited PVO investigations of the ionosphere. The same statement cannot be made for the limited breadth of the PVO science payload, particularly the lack of energetic particle instruments which would have aided investigations of solar wind interaction processes. Instrumentation for high-resolution measurements of vector ion and neutral wind velocities and temperatures was also lacking. But PVO was, after all, a low cost mission with broad exploratory goals and a payload weight and data rate that were too low to permit many additional valuable instruments to be carried.

A.1. THE UNIFIED ABSTRACT DATA SYSTEM (UADS)

To aid in the exchange and interpretation of the PVO measurements, an online Unified Abstract Data System (UADS) was established by the PV Project. The UADS combined the various in situ measurements that were averaged in a way to assure simultaneity and a uniform spatial resolution. Entries occur at specific times defined at 12 s intervals during each passage. The entries are limited to 30 min either side of periapsis. The actual measurements may have been made more or less frequently than 12 s, depending upon the particular instrument, its measurement mode, and the spacecraft telemetry bit rate being used. The radio occultation profiles are not included in the UADS data base, since they do not fit into the 12 s data format. These, and other remote measurements, are available in other forms.

The UADS on line system was discontinued in 1981 and the data then available were submitted via magnetic tapes to the National Space Science Data Center at Goddard Space Flight Center for further analysis by interested investigators. These tapes contain data for most of the first 1000 orbits. In 1981, cost constraints made it infeasible to continue to maintain and expand the online UADS data base. Since then, each investigator has independently submitted the measurements from his own instrument as they become available, mainly in the common 12 s format of the original UADS.

The UADS files are not static. As new data are acquired or older data are reprocessed with improved algorithms, new

UADS tapes are generated to replace earlier versions. In this way the investigators plan to meet their goal of assembling the most complete and accurate data base possible by the end of the mission. This approach inevitably means that later versions of the UADS files, while more complete and more accurate, may differ in detail from earlier versions.

Many studies require data with higher spatial resolution than is provided by the UADS files. Most instruments are capable of providing this higher resolution data, and these are submitted to the NSSDC as High Frequency Data Files, or they may be obtained directly from the appropriate PV investigators.

A.2. MEASUREMENT CAPABILITIES

As noted in Section 3.2, PVO carries three instruments which make in situ measurements within the ionosphere. These are the OIMS, ORPA, and OETP. A fourth instrument, the ONMS, measures the neutral gas densities that are needed for understanding many aspects of ionosphere behavior. The ONMS also detects superthermal ions having energies greater than about 40 eV, the retarding potential of an outer shield that was intended to exclude cold ionospheric ions while the instrument was measuring the concentrations of the neutral thermospheric constituents. The ONMS also has a cold ion composition mode in which the outer shield is grounded and the filament is off, but this mode excluded the measurement of neutral densities, so it has seldom been used. The radio occultation experiment, ORO, provides height profiles of N_e both above and below the periapsis altitude. These measurements are available only during the occultation seasons, however.

Each of these instruments has its own strengths and limitations. For detailed instrument descriptions we refer the reader to the instrument descriptions presented in the special issue of IEEE Trans. Geoscience and Remote Sensing (1980). The OIMS reports the concentration of all ion species present, including minor ion species, and has an inflight data selection system which permits high spatial resolution. The OETP provides similarly high resolution in N_e, N_i, and T_e. The measurements of the photoemission current from the OETP sensors can be employed as a measure of the total EUV flux from the Sun (Brace et al., 1988a). The ORPA measures the individual concentrations of the major ions, the ion temperature, T_i. However, the ORPA is not able to distinguish between ions of similar mass (O_2^+ and CO^+, or O^+ and N^+) or can it detect the presence of minor ions that represent less than a few percent of the total. In its electron mode, the ORPA measures T_e and the integral electron flux for energies up to about 50 eV. Its sensor head was tilted off the spin axis at an angle of 25 deg. to permit it to look nearly directly into the velocity vector once per spin. Thus the spatial resolution of the ORPA measurements is limited to the spacecraft spin period of approximately 13 s. The ORPA also measures the ion drift velocity when the total density exceeds about 10^3 cm^{-3}, but with poorer spatial resolution.

The actual spatial resolution of the ORPA measurements may be poorer than one value per spin period, because the instrument has several modes of operation in which it measures different parameters. These modes are mutually exclusive, so the thermal electrons and ions are not measured simultaneously with the superthermal electrons. The measurement mode can be alternated throughout a passage to obtain sequential measurements of these parameters, with a corresponding loss of spatial resolution. The OETP and OIMS, on the other hand, provide continuous high resolution measurements on every passage through the ionosphere. This high resolution (order of 1 s^{-1} at typical telemetry rates), is attained through the use of adaptive inflight servo systems. Spin modulation was minimized in the OIMS measurements by mounting the sensor parallel to the spin axis, an approach that further increases the effective spatial resolution. The OETP radial sensor is mounted perpendicular to the spin axis for the same reason. but shadowing of that sensor by the spinning spacecraft introduces measurement errors at certain spin angles. The resulting reductions of spin effects turned out to be very valuable for resolving ionospheric structure having much smaller spatial scales than 120 km, the distance the spacecraft travels in one spin period. The nightside ionosphere has many such small scale features, and the ionopause crossings often occur within one or two spacecraft spin periods.

Thus the apparently overlapping capability of the various PVO instruments does not necessarily make their measurements redundant. Instead, their differences in spatial resolution. sensitivity, and sources of measurement error combine to make their measurements complementary. It will be important for future users of data to take these factors into account when choosing data sets for a particular study.

A.3. DISCREPANCIES AMONG THE MEASUREMENTS

The high degree of measurement redundancy among the PVO instruments has naturally lead to inconsistencies, particularly in the measurements of the ion composition and the ion and electron densities, N_i and N_e, which can be obtained in at least four ways. The OIMS and ORPA measure N_i. The OETP also measures N_i at high densities and N_e at low densities, with overlap between 1×10^3 and 1×10^5 cm^{-3}. The radio occultation analysis yields height profiles of N_e down to densities of the order of 10^3 cm^{-3}. These profiles have been useful in checking the absolute accuracy of the in situ measurements. However, these profiles can be compared only statistically with the direct measurements because they usually represent a region quite remote from the satellite. They also represent N_e averaged over a relatively long horizontal path through the ionosphere, so small-scale structure is not resolved.

Systematic comparisons of the early UADS data base, conducted by Miller et al. (1984), uncovered a number of discrepancies, particularly in the ion composition and density measurements. They found that the OIMS values of N_i were larger than those from the ORPA by a factor of between 1.5 and 2.5 in portions of the day side ionosphere. with the largest discrepancies in the afternoon at altitudes between 170 and 200 km. Miller et al. attributed this to OIMS O_2^+ concentration that were about a factor of 3 higher in that region. The density measurements above 200 km, where O^+ dominates, are in better agreement. The ORPA measurements of N_i were in essential agreement with the OETP measurements of N_e except at the lowest altitudes on the nightside, where N_e values were a bit higher. The ORO density profiles agreed well statistically at these altitudes with the ORPA and OETP densities, and generally gave lower densities than those given by the OIMS. The T_e values from the OETP were in general agreement with those from the ORPA, except on the dayside below 200 km, where the OETP values were several percent higher.

It is important to recognize in making such comparisons that the UADS files are continually being updated and corrected as the investigators receive new data and increase their understanding of the sources of measurement error. These changes can be expected to alter the remaining discrepancies among the various measurements to some degree, but the major differences described above are likely to remain until a consensus is reached on how to, and whether to, attempt to make the entire ionosphere data base more internally consistent. In the next section we will discuss some possible sources of measurement error.

A.4. POSSIBLE SOURCES OE MEASUREMENT ERROR

The accuracy of the PVO measurements varies with the parameter in question and depends upon the conditions present. In most situations the accuracy is believed by the investigators to be adequate to resolve the major features of ionospheric behavior, particularly considering the wide dynamic range of these parameters. However, this mission offered new challenges that were not encountered in the Earth missions, so it is not surprising to find significant measurement errors under some conditions. The very low data rate afforded by the spacecraft required the instruments to include onboard data processing schemes to transform their raw spectra or volt-ampere curves into physical parameters. Without onboard processing the small scale structure of the ionosphere could not have been resolved. These systems were limited in sophistication by strict payload weight limitations; most of the instruments weighed only a kilogram or two. Part of the challenge was to recover representative raw experimental data (mass spectra, energy spectra, or volt-ampere curves) to verify the accuracy of the onboard processing scheme. In general, these systems performed well, but the discrepancies among the measurements show that undetected errors are still present in some cases.

In addition to the above problems, the complexity of the Venus ionosphere itself may have presented conditions that are beyond the capabilities of the simple PVO instruments. The following section gives some examples.

A.4. 1. Suprathermal Electron Effects

Suprathermal, or energetic, electrons are common in the nightside ionosphere. They cause errors in the measurements of cold ionospheric electrons by making the spacecraft potential so negative that the thermal electrons cannot reach the sensors. This situation occurs when the spacecraft is in darkness and spacecraft photoelectron emission is not available to prevent charging of the spacecraft to high negative potentials. This electrostatic shielding is most important for the ORPA measurements because its sensor is mounted on the spacecraft surface so the cold electrons must overcome the full spacecraft potential to enter the sensor. The OETP is less affected by the spacecraft sheath because its sensors are mounted 40 cm (axial probe) and 100 cm (radial probe) from the spacecraft surface where the local plasma potential is closer to that of the undisturbed ionosphere. In general, only the radial probe measurements are reported for regions of low density in darkness, where spacecraft charging has been most severe.

A.4.2. Non-Maxwellian Electron Effects

Another example of an unexpected complexity that may cause measurement problems is the case of non-Maxwellian electrons in the nightside ionosphere. Brace et al. (1980) noted that thermal and superthermal electrons often exist together there with similar densities, making it difficult to characterize the electron temperature accurately. The OETP volt-ampere curves obtained in these regions are not well fitted for a single value T_{e}. Often a good fit can be obtained by assuming a two temperature distribution, but these fits are not performed routinely. Such distributions are common in the ionospheric holes (Brace et al., 1982b) and in the lower nightside ionosphere in the vicinity of small-scale N_{e} structure (Hoegy et al., 1989). Even in the absence of superthermals, however, strong spatial gradients in T_{e} cause the electron energy distribution to be non-Maxwellian, thus causing poor curve fits and clouding the definition of temperature. The UADS file did not envision this kind of complexity, so the T_{e} measurements in these regions do not properly describe the thermal energy of the electrons. Usually the temperature that is entered in the file is that of the cold component, but the higher temperature component may be given when no cold electrons are present.

A.4.3 Superthermal Ion Effects

Superthermal ions may affect the accuracy of the various PVO measurements of total ion density. Taylor et al. (1980) observed superthermal ions at the ionopause and within the nightside ionosphere. At higher altitudes on the nightside the OIMS measured increasingly larger percentages of superthermal ions, but the response of the instrument to these ions is not well understood (Brace et al., 1987). The evidence for their existence is a shift in the apparent mass of O^{+} from 16 to 14 amu, a shift that corresponds to ion energies in the range of 9 eV to 16 eV. Superthermal H^{+} ions are not observed because H^{+} at these energies would fall below the mass range of the OIMS. Thus the OIMS total density may be underestimated when superthermal ions are present because the H^{+} ions are not included.

The N_{i} measurements by the OETP radial probe are also affected by superthermal ions if they represent a significant fraction of the total density. The calculation of N_{i} assumes that the ion flux to the collector is produced by the velocity of the collector through the ionosphere (10 km s^{-1}). If the thermal velocity of the ions is comparable to the spacecraft velocity, additional ion current is collected and N_{i} is overestimated.

A.4.4. Ion Drift Effects

High ion velocities in the ionosphere can introduce important errors into the ion measurements. Knudsen et al. (1980b) and Taylor et al. (1980) have shown that very high ion drift velocities are present, particularly at high altitudes near the terminator. The cold plasma instrument designs generally assume that the ion drift velocity will be small compared to the spacecraft velocity, thus requiring the ion sensors to be mounted to look into the velocity vector. Ion drift produces changes in the ion velocity into the sensor and changes in the angle of approach, both of which affect the ion fluxes that reach the collector of the instrument. The ORPA and the OIMS are mounted to provide small angles of attack near periapsis, but the minimum angle of attack tends to increase with altitude. The ORPA measures the ion drift component normal to the sensor, so its N_{i} measurements are affected by ion drift only to the extent that the correction for the assumed angle of arrival may be incorrect. The OETP measurements of N_{i} depend linearly upon knowledge of the ion drift velocity, which is assumed in the data processing to be the satellite velocity. The angle of arrival is unimportant because the maximum in the spin modulated ion flux to its cylindrical collector is used to derive N_{i}, and this always occurs at the two points in the spin cycle where the velocity vector is perpendicular to the probe axis. These ion measurements are used only at low altitudes, however, where the ion drift velocities are small. The N_{e} measurements are used at the higher altitudes. Off-axis ion drift velocities cause errors in the OIMS measurements because they reduce the transmission efficiency of the analyzer, an effect that is particularly important for the heavier ions. Thus ion drift leads to an underestimate of the density and an apparent change in the relative ion composition, but these effects should be limited to high altitudes where the ion drift velocities may be a significant fraction of the spacecraft velocity. It is interesting that both of these factors, high ion drift velocities and large angles of attack, tend to be important to the measurement accurately at higher altitudes. but the discrepancies among the PVO density measurements are greater at lower altitudes.

A.4.5. Spacecraft Photoelectron Effects

Spacecraft photoelectrons represent another source of error in the in situ electron measurements. When the spacecraft is in sunlight, its sunlit side is surrounded by a cloud of photoelectron whose thickness depends upon the spacecraft potential, which itself depends upon the ionospheric plasma density (Brace et al., 1988b). At densities greater than a few hundred cm^{-3}, the instruments operate in an electron environment that is dominated by the ionospheric electrons. Spacecraft photoelectrons dominate when the ambient density is lower, but the lower limit for reliable measurements depends on the mounting location of the particular sensor and its sensitivity to the photo-electron background. The OETP radial sensor is least affected because of its greater distance from the spacecraft, and because one can select the measurements taken only when the collector is on the dark side of the spacecraft where the spacecraft photoelectron background is lower (Brace et al., 1988b). The ORPA is mounted on the spacecraft surface where much larger photoelectron fluxes are available, and this limits the density range over which cold ionospheric electrons can be measured when the spacecraft is sunlit. The photoelectrons have energies of only a few eV, however, so more energetic ambient electron populations can still be measured (Knudsen et al., 1980).

A.4.6. Periapsis Effects

An entire class of instrumental errors can occur at very low altitudes due to spacecraft atmosphere interactions. These errors can be grouped under the general term 'periapsis effects'. These effects are not well understood, and their importance varies with altitude, with the parameter being measured, and with the location and type of sensor. The main known effects are described below.

Perhaps the most well established periapsis effect arises from impact ionization (Hanson et al., 1981; Whipple et al., 1983; Curtis et al., 1985). The spacecraft, traveling through the dense lower thermosphere at high velocities, behaves somewhat like a meteorite. At the PVO periapsis velocity of 10 km s^{-1}, the impact energy $(1/2mv^2)$ for CO, is 23 eV. This is enough energy to ionize a small fraction of the CO_2 that the spacecraft encounters and produce a measurable cloud of 1 to 2 eV secondary electrons above the leading surface of the spacecraft. Lighter molecules (O_2 and CO) contribute less impact ionization because their impact energies are only slightly greater than their ionization potentials.

The OETP axial sensor is mounted on the ram end of the spacecraft, so it is ideally located to observe impact electrons. Easily measurable fluxes of these electrons are seen when the spacecraft is below about 165 km on the dayside and 150 km on the nightside. The impact electron density at periapsis may be as high as 10% of the ambient N_e at the nightside peak (order of 10^4 cm^{-3}). Their density has been shown proportional to the thermospheric CO_2 concentration, one of the neutral gas parameters that is measured by the ONMS (Whipple et al. 1983). Since their temperature is more than 10 times that of the ionosphere at 150 km, the two electron components are easily distinguishable in the electron retardation region of the volt-ampere curves from the axial sensor. The radial OETP sensor observes no secondary electrons at its location, probably because of it is mounted further from the spacecraft (1 m) and views only lateral spacecraft surfaces which receive only a small fraction of the ram flux of CO_2.

Impact ionization is also seen in other PVO instruments. Miller et al. (1984) suggested that impact electrons may be responsible for the anomalous increase in T_e in the ORPA measurements below about 167 km in the daytime ionosphere. The ORPA is mounted on the forward looking surface of the spacecraft where this effect is greatest. Plasma waves in the vicinity of 100 Hz have been observed consistently when periapsis is very low. These waves have also been attributed to the impact process (Curtis et al., 1985).

Impact ionization may indirectly produce errors in the ion measurements as well. A byproduct of the impact ionization process is the creation of a dc electric field upstream of the spacecraft (Parker and Holeman, 1980). This electric field is produced by the difference in mobility of the sputtered ions and electrons. The resulting charge separation creates a region of positive space charge near the surface and a region of negative spacecharge farther ahead. Ambient ions must pass through these electric fields to reach the ion sensors, so the composition and energy of the measured ions may be perturbed. No analysis of this effect on the PVO ion measurement techniques has been reported.

An analogous periapsis effect involves the thermospheric neutrals that are not ionized by impact with the spacecraft. These neutrals tend to be thermalized at the spacecraft surface and re-emitted at much lower velocities, thus creating a dense cloud of neutrals just upstream of the spacecraft. This enhancement is caused by the low departure velocity of the gas that has become thermalized by collision(s) with the ram surface. If complete thermal accommodation occurs, the maximum density of the ram cloud is more than a hundred times greater than the ambient density at that point in the thermosphere. At typical periapsis altitudes (about 150 km), the ambient neutral density is greater than 10^{10} cm^{-3}, and the ram cloud density at the surface may be of the order of 10^12 cm^-3. At this density the ion and neutral mean free paths that are comparable to the size of the cloud, which extends several spacecraft diameters upstream (a few meters). Some of the incoming ions and neutrals will experience collisions with the outflowing neutrals in the cloud, changing their energies and velocities in the reference frame of the spacecraft. The effect of the ram cloud upon the measurements may be difficult to separate from impact ionization effects since they occur together near periapsis.

In summary, these 'periapsis effects' affect the various PVO instruments differently, but no quantitative analysis of the resulting errors has been reported. From various signatures in their data the investigators can often recognize when these effects are present. We suspect that, in assembling data for their own analyses, or for submission to the NSSDC. the investigators have deleted the measurements that have been most obviously affected. However, one cannot be sure that all of these effects have been recognized and removed.

A.5. VIRA ATTEMPTS TO DEAL WITH MEASUREMENT ERRORS

In a first attempt to mitigate the discrepancies in the density measurements by different instruments, Bauer et al. (1985) assembled the VIRA ionosphere model with these differences in mind. A series of tables were presented listing the altitude variations of each major ionosphere parameter. The global model by Theis et al. (1984), based on the OETP measurements. was adopted for the VIRA electron density and temperature. The densities were normalized at 150 km to the average radio occultation density measurements, which are believed to be more reliable at the high densities usually present at the peak. The OIMS results were employed only to establish the relative ion composition rather than the absolute ion densities. Since the ORPA measures only the major ions, its data could not be the basis for a complete ion composition model. The ORPA measurements were used to define the ion temperature in the VIRA model, and to provide the pattern of global ion drift velocities.

In conclusion, the accuracy of the PVO measurements is difficult to assess. While the periapsis effects can be expected to cause errors at the lowest altitudes, the largest disagreements occur in the afternoon near 175 km, well above periapsis. The investigators, aware of these disagreements, have been comparing measurements to further identify areas of disagreement, and to correct errors where possible. These efforts are expected to lead to continuing improvements in the accuracy of the UADS data and of future VIRA models. In the meantime, the choice of PVO data for a particular investigation will fall to the user.

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