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Ion Velocity Measurements for the Ionospheric Connections Explorer

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Abstract

The Ionospheric Connections Explorer (ICON) payload includes an Ion Velocity Meter (IVM) to provide measurements of the ion drift motions, density, temperature and major ion composition at the satellite altitude near 575 km. The primary measurement goal for the IVM is to provide the meridional ion drift perpendicular to the magnetic meridian with an accuracy of 7.5 ms^{-1} for all daytime conditions encountered by the spacecraft within 15° of the magnetic equator. The IVM will derive this parameter utilizing two sensors, a retarding potential analyzer (RPA) and an ion drift meter (IDM) that have a robust and successful flight heritage. The IVM described here incorporates improvements in the design and operation to produce the most sensitive device that has been fielded to date. It will specify the ion drift vector, from which the component perpendicular to the magnetic field will be derived. In addition it will specify the total ion density, the ion temperature and the fractional ion composition. These data will be used in conjunction with measurements from the other ICON instruments to uncover the important connections between the dynamics of the neutral atmosphere and the ionosphere through the generation of dynamo currents perpendicular to the magnetic field and collisional forces parallel to the magnetic field. Here the configuration and operation of the IVM instrument are described as well as the procedures by which the ion drift velocity is determined. A description of the subsystem characteristics, which allow a determination of the expected uncertainties in the derived parameters, is also given.

Keywords

Ionosphere Dynamics; Plasma Measurements

1 Introduction

The Ionospheric Connections Explorer (ICON) mission is poised to discover fundamental connections between the dynamics of the neutral atmosphere at altitudes between 100 km and 300 km and the charged particle motions at low and middle latitudes, which are tied to the magnetic field that threads the entire region. A comprehensive description of the links between the charged and neutral species will be revealed with a unique combination of

remote measurements of the plasma and neutral density and the neutral winds [2,16, 17] and in-situ measurements of the plasma density and plasma drift.

These measurements will be made from a circular orbit at an altitude near 575 km with 27° inclination using a unique ability to image, at higher latitudes on the limb, that part of the neutral atmosphere that drives the current, and is connected along the magnetic field to the satellite location where the resulting plasma motions can be observed directly [13]. The in-situ ion drift motion can be translated to all points along a magnetic flux tube under the assumption that magnetic flux lines are electric equipotentials. The neutral winds however, must be measured as a function of altitude and weighted by the electric conductivity in order to determine their influence on the plasma motion. By making the required measurements of plasma drifts, neutral winds, neutral density and plasma density, their contribution to the observed plasma motions can be resolved utilizing a suite of ionosphere and thermosphere models [12].

In-situ determination of the plasma density and plasma drift are made by an Ion Velocity Meter (IVM), a planar detector that views approximately along the spacecraft velocity vector and measures the energy and the angle of arrival of the thermal ions that move supersonically with respect to the spacecraft. Two IVM sensors, one that views along the ram and another along the anti-ram, allow measurement of the ion drift when the remote instrument suite either views the limb perpendicular to the satellite track to the north or the south.

Instruments similar to the IVM have been successfully deployed on many science missions beginning with OGO6 [4] and continuing through the era of Atmosphere Explorer [5], Dynamics Explorer [6,7], the Defense Meteorological Satellite Program and ROCSAT [15] and the Coupled Ion Neutral Dynamics Investigation [10]. For the ICON mission this flight-proven approach is further developed to produce a robust and sensitive device that meets the rigorous measurement requirements of the mission. The principles of operation of the IVM sensors have been previously described [8, 9] but are reviewed here in the context of the ICON measurement requirements in addition to the specific instrument performance details and the geophysical parameters that will be delivered by the instrument.

The ICON IVM instrument performance is bolstered by design advancements that include the following. The inclusion of a proven sensor potential (SenPot) reference plate and circuit ensures that instrument-sensing circuits operate near the plasma potential, providing protection against the effects of spacecraft ground bias. The current sensing circuit resolution is improved by a factor of 4 over the previous design. Noise levels are reduced by a number of circuit design improvements. A number of command and configuration advancements provide additional on-orbit flexibility and capability, including fully programmable retarding voltage sweep levels, on-orbit electrometer gain calibration and improved drift meter switch modes.

2 IVM Mechanical Configuration

Figure 1 has three panels showing a photograph of the flight IVM sensor and projections that detail the major mechanical systems. The ICON IVM consists of two planar sensors. A retarding potential analyzer (RPA) and an ion drift meter (IDM) are mounted to view approximately along the spacecraft velocity vector and are optimally configured to accomplish the separate functions of constituent ion energy determination and ion arrival angle respectively. The sensors are attached to a baseplate to which the electronics compartment is affixed at the rear. The rear cover is attached to a flexure mount that provides a mechanical interface to the spacecraft payload interface plate (PIP). The rear cover also contains passive radiator surfaces. In low earth orbit the spacecraft velocity V_s is in excess of 7 km s^{-1} and provides the constituent ions with mass dependent ram energies $\frac{1}{2}mV_s^2$, of about 0.3 eV/amu and thermal energy widths $mV_s V_{th}$, where V_{th} is the ion thermal speed, of about $0.4 \text{ eV/amu}^{1/2}$ with respect to the sensor.

In order to minimize the effects of the sensors themselves on the plasma, it is important that the local electrostatic environment present small and planar potentials parallel to the instrument aperture plane so that the ion arrival angle and energy distribution are modified in a predictable way by electric fields that are parallel to the sensor look direction. A planar conducting aperture plane, which surrounds the instrument apertures, is utilized to accomplish this task. It is attached to the sensors from the front and also provides key radiative surfaces to dissipate instrument and solar heat inputs. Optimum sensitivity to arrival angle and incident energy is also obtained if the sensor ground reference is maintained near the plasma potential.

The spacecraft reference ground with respect to the plasma is dependent on the conducting properties of the spacecraft exposed surfaces and to exposed potentials that may be part of the solar power system. While best practices are employed to maintain a spacecraft ground close to the plasma potential, the IVM sensors are electrically isolated from the spacecraft to provide an independent ground reference that is established by a section of the aperture plane called the SenPot surface, which is maintained at the floating potential.

Figure 2 shows schematic cross-sections of the RPA and IDM sensors. Each is constructed similarly, consisting of a gridded aperture plane and a series of internal planar grids that are precisely positioned using ceramic spacers to maintain parallel potential planes that are biased to provide the appropriate functionality. In both sensors the woven grids are $0.001''$ diameter gold-plated tungsten wire with a density of 50/inch or 100/inch.

Referring to figure 2 the RPA presents a gridded circular entrance aperture G1, of radius 2 cm, tied to the sensor ground and a solid collector at which the ion flux is measured as a current. The grid G2 is a double retarding grid that is stepped through a series of positive potentials to control the energy of incoming ions that have access to the collector. A suppressor grid, G3, is negatively biased with respect to the sensor ground to reject thermal electrons incident on the grid and to suppress photoemission currents that are produced from the collector. The grid stack transparency is $\approx 48\%$ giving an effective collection area of $\approx 6 \text{ cm}^2$.

The IDM presents a square aperture, with side length 2.8 cm, to the incoming plasma. The grids G3 and G4/G5 are grounded, providing a field-free region through which the supersonic ions flow before forming an image of the aperture on a segmented collector. A suppressor grid G6 is negatively biased between 0 and -10.5 volts with respect to the sensor ground to reject thermal electrons incident on the grid and to suppress photoemission currents that are produced from the collector surfaces. The collector, located 1.65 cm from the aperture edge, is divided into four quadrants with the dividing lines parallel to the aperture edges allowing currents to collector halves to be measured along two mutually perpendicular axes. The grid stack transparency is $\approx 49\%$.

The grid G1 forms a grounded plane across the aperture while a repeller grid G2 is positively biased between 0 and $+3.5$ volts with respect to the sensor ground. This grid serves to reject the admission of H^+ ions prior to the collimation of the beam produced by the entrance aperture. The removal of this signal allows the arrival angle associated with the bulk flow of all the species to be determined by the signal from the supersonic O^+ ions.

3 Principles of Operation

3.1 Retarding Potential Analyzer (RPA)

The RPA views approximately along the spacecraft velocity vector and has a small entrance aperture compared to the collector size. Within the instrument a retarding grid is stepped through a sequence of potentials between 0 and 25.5 volts, which determine the energy of the incoming ions that have access to the collector. For the low inclination ICON orbit near 575 km altitude, the plasma drift velocities are expected to be less than 500 m s^{-1} and the total plasma density will usually be above 10^3 cm^{-3} except perhaps in equatorial plasma bubbles [11]. Further, during normal operations the spacecraft will maintain a look direction for the IVM that is within 3° of the ram velocity. Under such conditions we do not expect any departures from thermal equilibrium in the plasma and the angle of arrival of the ions will be small ($< 10^\circ$) compared to the angular acceptance of the sensor ($> 30^\circ$). Thus, the current collected may be simply obtained by integrating the one-dimensional flowing Maxwellian distribution function along the instrument look direction from infinity to the velocity of the ions that will be stopped by the potential on the grid as seen by the plasma. The current for a single ion species of mass m and number density N_i is given by

$$I(\phi) = qA_{\text{eff}} \frac{N_i}{2} V_r \left(1 + \text{erf}(\beta f) + \frac{1}{\sqrt{\pi}\beta V_r} \exp - \beta^2 f^2 \right) \quad (1)$$

where A_{eff} is the effective area of the collector, $f = V_r - \sqrt{2q\phi/m}$, with q the electron charge, represents the average velocity of the ions that have access to the collector and $\beta = \sqrt{m/2kT_i}$ is the reciprocal of the thermal velocity of the ions. Here, $V_r = (\mathbf{V}_d + \mathbf{V}_s) \cdot \hat{n}$ is the total velocity of the ions given by the sum of the ambient ion drift $\mathbf{V}_d$ and the spacecraft velocity $\mathbf{V}_s$ and $\hat{n}$ is the unit vector along the sensor look direction. $\phi = R_v + \psi_s$ is the potential on the grid as seen by the plasma and is thus the sum of the retarding potential with respect to the sensor ground and the sensor ground potential with respect to the plasma ψ_s . The

measured current will be the sum of currents for all constituent ions that are present. The current at zero retarding potential provides the total plasma number density and a least-squares fitting procedure, applied to the normalized current-voltage characteristic, yields a common temperature, a bulk flow velocity for the ions and the fractional population of the major constituent ions. In addition, the sensor plane potential with respect to the plasma is also retrieved. Corrections to account for the lack of perfect potential planes produced by wire grids are also included in the fitting procedure [14]. Further details of the fitting procedure and associated uncertainties are given in section 6 below.

Figure 3 shows typical current-voltage (I - V) characteristics obtained from the RPA aboard the Communication Navigation Outage Forecast System (C/NOFS) satellite. In each panel the open symbols denote the retrieved data and the solid line represents the result of the fitting procedure with the results shown to the right of the current-voltage characteristic in each panel. In panel A are data taken near 650 km altitude and 05:25 local time indicating the presence of a small fractional population of H^+ in addition to the major ion, O^+ . Note that the I - V characteristic represents the integral contribution from all species that are present and the major species are distinguished by the differences in their ram energy as mentioned previously. A simple examination of the relative values of the ion current near zero volts and 3 volts can therefore detect the presence of light ion species and thus indicate the masses that need to be considered in the least squares analysis procedure. This current difference can be detected with a sensitivity of less than 1%. In panel B is shown the I - V characteristic taken near 500 km altitude and 14:30 local time where O^+ is the only ion present.

3.2 Ion Drift Meter (IDM)

The IDM also views approximately along the spacecraft velocity vector and uses a simple geometric relationship between the arrival angle of the incoming ion beam and the area illuminated, and thus the current collected, at the collector segments. Figure 4 shows a schematic representation of the ion beam (in red) and its displacement along one axis aligned with an aperture edge within the field-free region of the sensor. During their transit from the ambient medium to the collector the ions change their energy due to the aperture plane potential and are displaced from straight-line trajectories by the negative suppressor potential. Since both the entrance aperture and the collector are at the same potential, no change in the ion arrival angle occurs. However a displacement in the beam that is dependent on the arrival angle is produced by the potential on the suppressor grid. The collector quadrant dividing lines and aperture edges are aligned with the local horizontal and the local vertical so that by appropriately configuring collector halves, the arrival angle in each of these planes containing the unit vectors $\hat{h}$ and $\hat{z}$ respectively, can be measured. If the arrival angle of the plasma in one of these planes is given by α , then the ratio of the collector currents, which are each proportional to the area illuminated, is given in terms of the sensor dimensions and the arrival angle by

$$\frac{I_1}{I_2} = \frac{W/2 + D \tan \alpha}{W/2 - D \tan \alpha} \quad (2)$$

where W is the length of the square aperture and D is the depth from the external aperture face to the collector. Thus by measuring the current ratio we may determine the ion arrival angle. The corresponding transverse drift velocity is given by

$$(\mathbf{V}_d + \mathbf{V}_s) \cdot \hat{\mathbf{t}} = \sqrt{V_r^2 - \frac{2q\psi_s}{m}} \tan \alpha \quad (3)$$

where $\hat{\mathbf{t}}$ is the unit vector along the selected transverse direction. The arrival angle is corrected for the displacement of the beam produced by the suppressor grid (G6 in figure 2) by accounting for the acceleration and deceleration of the ions during their transit to the collector. In addition, the suppression of photoemission currents from the collector can lead to some current exchange between the collector halves and correction procedures to account for this effect are also applied [18].

The IVM provides the ion drift with respect to the sensor in the sensor frame of reference. In order to translate this measurement into an inertial frame of geophysical significance, it is necessary to remove the spacecraft velocity in the instrument reference frame and to translate the instrument reference frame to an inertial frame. This procedure requires knowledge of the instrument pointing with respect to the spacecraft reference frame and knowledge of the inertial attitude of the spacecraft reference frame. Precise mounting knowledge to within 0.01° is achieved using a laser tracker and spherical mounted reflector, while the spacecraft attitude control system maintains a ram pointing configuration within 3° for IVM during normal operations. A sophisticated spacecraft attitude determination system provides the inertial pointing directions of the spacecraft reference axes with an accuracy of 0.01° .

3.3 Sensor Potential (SenPot)

All IVM potentials are generated with respect to the floating potential established by a section of the aperture plane that is electrically isolated from the remainder of the sensor [19]. An amplifier establishes the difference between this floating potential and the spacecraft ground. The sensor ground is then biased with respect to spacecraft ground by this potential difference called SenPot. The IVM data, command and timing signals are optically coupled to the spacecraft across this potential difference. This approach establishes a relatively uniform instrument ground potential with respect to the plasma that is not changed by electrical elements on the spacecraft itself.

4 IVM Electrical Configuration

Figure 5 shows a block diagram of the major electrical subsystems that make up the IVM. In the RPA, the retarding potential is generated through the contents of a memory block containing 32 discrete locations that are used to generate a voltage in the range 0 to 25.5 volts from a 12-bit D/A converter. Ground calibration provides each voltage with an accuracy of 0.001 volts. At each step the dwell time is approximately 32 milliseconds allowing the content of the memory block to be executed in one second. The content of the memory that describes the sweep format is designed to optimize the point distribution based

on the environment that the satellite encounters. While experience allows a well-informed distribution of points to define a default sweep, the content of the sweep memory may be changed by command from the ground.

An automatically ranging linear electrometer measures the ion current after the retarding grid is stepped to a discrete potential. The electrometer has 8 sensitivity ranges, differing by approximately the square-root of ten, allowing currents between 50 pA and 3.9 μA to be measured. At each step the RPA output consists of the memory location that provides the retarding voltage, the current recorded with 14-bit accuracy and accompanied by 3 bits that designate the electrometer sensitivity level.

In the IDM, low leakage JFET switches allow the collector segments to be combined to provide a current from collector halves that are aligned either along the local horizontal or the local vertical axis. For a designated axis the current from each collector half is measured by a logarithmic electrometer having a dynamic range from 250 pA to 9.5 μA , which is subsequently registered with 14-bit accuracy for transmission to the ground. The outputs from each logarithmic electrometer are sampled at 16 Hz. The outputs from each logarithmic electrometer also provide the inputs to a linear difference amplifier that delivers the ratio of the ion currents to be used in the expression described earlier to derive the ion arrival angle. The output of the difference amplifier is recorded with 14-bit accuracy and accompanied by one bit (axis) that describes the collector halves orientation (horizontal or vertical) and one bit (polarity) designating which collector half is connected to which logarithmic electrometer. The difference amplifier outputs and configuration indicators are sampled at 32 Hz. The instrument may be configured by ground command to alternate between horizontal and vertical arrival angles with a 16 Hz or 8 Hz cadence or to remain measuring a fixed axis arrival angle (horizontal or vertical). In both cases biases in the logarithmic electrometers are removed by periodically changing the polarity of the inputs. The rejection of thermal electrons and the suppression of photoemission currents are accomplished with the suppressor grid, which precedes the collector and may be biased between 0 and -10.5 volts in 1.5-volt steps. In addition the repeller grid may be biased with a potential between 0 and 3.5 volts, in 0.5-volt steps, to reject the admission of H^+ ions.

5 Instrument Calibration

There is a single IVM goal for the ICON mission to measure the daytime meridional ion drift perpendicular to the magnetic field within 15° of the magnetic equator and in the range $\pm 750 \text{ ms}^{-1}$ with an accuracy of 7.5 ms^{-1} . When applied to conditions near the magnetic equator, this drift component is referred to as the vertical ion drift [13]. This requirement, levied on a component of the ion drift vector, must be parsed to separate requirements on the ion drift components derived from the RPA and IDM sensors. Near the equator, the local vertical ion drift measured by the IDM dominates the meridional ion drift perpendicular to the magnetic field. However, the changing magnetic inclination and declination around the orbit result in small contributions from the local horizontal ion drifts measured by the IDM and the RPA. The meridional ion drift, V_m is given in terms of the magnetic inclination I and the local vertical and horizontal ion drifts V_v and V_h respectively by $V_m = V_v \cos I + V_h \sin I$, where the local horizontal drift is given in terms of the angle between the satellite track

and the magnetic meridian, and the transverse and ram ion drifts V_t and V_d respectively, by $V_h = V_t \cos \alpha + V_r \sin \alpha$. A worst-case analysis assumes that the angle $I = 30^\circ$ and $\alpha = 40^\circ$, allowing the requirements to be parsed as indicated in table 1, which additionally specifies a range in plasma density for the mission extracted from that predicted by the International Reference Ionosphere (IRI) [1]

Verification of this performance requires specification of the instrument electronic subsystems. This specification is then utilized using simulated instrument data and the ICON ground software to verify the instrument performance. First, analysis numbers are utilized to simulate a worst-case instrument performance, which is shown to satisfy the requirements. Subsequently, laboratory calibrations are conducted to characterize the flight instrumentation and produce instrument characteristics that will be used in the processing of mission data. Table 2 lists the analysis values used to generate simulated data and final calibrated values of the instrument subsystems over the expected operational temperature range. Note that a significant margin exists in all the parameters, indicating that the on-orbit performance of the instrument will exceed that derived from the simulated data.

The RPA utilizes an automatic ranging linear amplifier for which the voltage output is given by $V = G_i I + O_i$ where I is the input current, G_i is the sensitivity at level i and O_i is the electrometer offset associated with sensitivity level i . The sensitivity and offset for each level are established in the laboratory using a calibrated and certified current source that is directly applied to the collector. By injecting current over the full operating range, the output at all sensitivity levels can be obtained and linear straight-line fitting is utilized to establish the sensitivity and offset for each level. This procedure is repeated over the range of operating temperatures expected for the instrument. A calibration mode that fixes the retarding potential and steps through the different sensitivity levels may be exercised in flight to verify and update the laboratory calibration files if appropriate. The retarding voltage is generated utilizing a D/A converter and the voltage for each digital level is recorded over the expected operating temperature range in the laboratory. An uncertainty of ± 2 mV accounts for the maximum possible drift expected over the mission lifetime. However a sweep voltage monitor is included in the data downlink to monitor the on-orbit performance. The electrometer calibration and retarding voltage calibration data are retained for use in the data reduction procedure exercised on the ground.

The IDM utilizes a linear difference amplifier to determine the ratio of input currents that are measured using logarithmic electrometers. The logarithmic electrometers are designed with the same sensitivity level, but may have different offsets. Thus the voltage proportional to the current ratio, from which the ion arrival angle is determined, is given by

$$V = G_d \left(G \log \frac{I_1}{I_2} + O_a - O_b \right) + O_d = G_s \log \frac{I_1}{I_2} + O_l + O_d \quad (4)$$

where G_d and O_d are the difference amplifier gain and offset respectively, G is the gain of the logarithmic electrometers and O_a and O_b are the electrometer offsets. The overall system sensitivity level, G_s is determined in the laboratory by utilizing a calibrated and certified

current source to inject a known current ratio directly to the sensor collectors. The offset $O_l + O_d$, which has contributions from both the difference amplifier and the logarithmic electrometers, may be removed by repeating the calibration procedure with the inputs to the logarithmic electrometers inverted. Then the voltage proportional to the current ratio, from which the ion arrival angle is determined, is given by

$$V = G_d \left(G \log \frac{I_2}{I_1} + O_a - O_b \right) + O_d = G_s \log \frac{I_2}{I_1} + O_l + O_d \quad (5)$$

The two calibration curves may then be subtracted to remove the offset from the logarithmic electrometers. The sensitivity level is retained for use in the ground data processing. We do not expect any changes in the response of the IDM to ion arrival angle over the course of the mission. Furthermore, under normal operations any change in orientation of the spacecraft reference axes will be very slow and thus changes in response of the IDM to ion arrival angle would be difficult to detect. However, the ICON operations include slews every orbit to allow optical instruments viewing the limb to the north to acquire limb viewing to the south [13]. Such controlled operations with known slew rates will rapidly scan the ion arrival angle through the entire range accessible by the IDM. These measurements will be used to verify the angular sensitivity established in the laboratory and monitor any systematic changes that might occur during the mission.

6 IVM Specifications and Performance

Table 3 details the instrument physical properties. The modest power requirements allow the sensor to be operated with a 100% duty cycle. However operation of the IVM on ICON will be performed by two identical configurations of the sensors allowing an interchange between ram and wake that is required for the optical instruments to view on either side of the satellite orbit plane. The IVM, either the IVM-A or IVM-B instrument, will be operated continuously when it is pointed nominally in the ram direction and will continue to operate during slewing maneuvers to re-orient the satellite for calibrations of the optical instruments and to conduct conjugate point observations on the limb [13]. During continuous operations, the RPA is configured to produce current-voltage characteristics at a 1 Hz rate. The IDM will nominally alternate between measurement of the horizontal and vertical ion arrival angles so that each are obtained at 8 Hz. This operational mode of the instrument is expected to dominate the data obtained throughout the mission. However, changes in the operational profile are possible to allow acquisition of current-voltage curves at 2 Hz and 32 Hz sampling of a fixed ion arrival angle. Data from the IVM are packaged for a 4-second period and the content of a data packet is independent of the mode of instrument operation and configuration of the other grid potentials. This additional information is included in the header of each 4-second data packet allowing autonomous processing of the data in each packet.

Uncertainties in the derived parameters arise from specification of the gain, offset and noise floor of the linear electrometer, in the specification of the retarding voltage and in the discretization of the output by the analog to digital converter. Uncertainties in deriving the

transverse ion drift arise principally from the angular sensitivity of the device itself, which translates to an uncertainty in the derived ion arrival angle. This angle is then used with the ram ion drift derived from the RPA to determine the transverse ion drift. Thus, given an uncertainty in the ram ion drift, the uncertainty in the transverse ion drift can be easily specified.

For the RPA, geophysical parameters are derived in a least square analysis procedure. It is therefore not possible to distribute uncertainties in the derived ion drift velocity to separate uncertainties in subsystem parameters or variability in geophysical conditions. The uncertainties in geophysical parameters from the RPA can only be determined from controlled least-squares fitting of simulated data for which the real result is known. Thus the instrument performance is simulated with the uncertainties in the instrument parameters specified by the analysis values given in table 2. Simulated I–V curves are produced by randomly selecting geophysical parameters in the range specified in table 4. Each curve is then fit utilizing the ICON ground software to derive the ram ion drift, the ion temperature, the fractional ion composition and the aperture plane potential. The total plasma density is also derived from the RPA saturation current at low retarding voltages. Figure 6 shows the derived accuracy of the ram ion drift as a function of total ion density and fractional composition. This figure is constructed by calculating the deviation between the derived ion drift and the input ion drift for more than one thousand curves for which the temperature, the ion drift and the aperture potential are randomly chosen. Each curve is fit multiple times to improve the statistical representation of the uncertainty. The black dots indicate the predicted total plasma density and fractional composition encountered during the ICON mission from the IRI model. It can be seen that, over the expected operating range, the anticipated uncertainty in the derived ram ion drift is less than 15 ms^{-1} . Notice that the largest uncertainties arise when the total ion density is low and the O+ fraction either at its highest or lowest. When the total ion density is low and the O+ fraction is high the electrometer noise level dominates the uncertainty. When the total ion density is low and the O+ fraction is low, both the noise level and the poor sensitivity of the H+ ram energy to the ram drift contribute to the uncertainty. Figure 7 shows the uncertainty in the ram ion drift as a function of local time over the ICON mission lifetime. During the daytime and through most of the evening, when the prime ICON science objectives are to be met, the expected ram drift uncertainty is less than 10 ms^{-1} . As the total plasma density declines after local midnight the uncertainties increase. A further uncertainty will be introduced for large plasma density variations that occur over the duration of a sweep ($\approx 8 \text{ km}$). This may occur after sunset, in regions of equatorial irregularities, which will be appropriately flagged in the data produced.

Convolving an uncertainty in the ram ion drift of 19 ms^{-1} with an angular uncertainty of 0.02° for the IDM, we can derive an uncertainty in the transverse ion drift of 4.5 ms^{-1} . This uncertainty assumes a worst-case misalignment between the ram and the instrument look direction of 3° and a maximum ion drift of 750 ms^{-1} . Table 4 summarizes the performance of the IVM derived in this way. The performance of the sensors will be verified in flight by comparisons with ground based facilities whenever possible. However, the calibration results shown in table 2 indicate a performance that will exceed the requirements.

It should be emphasized that the derived ion drift vector comprises the sum of the ambient plasma drift, with which we conduct science investigations, and the spacecraft velocity vector. The spacecraft velocity vector is specified in a spacecraft reference frame and the sensor look directions are also specified with an accuracy of 0.01° in this reference frame, by an alignment procedure conducted on the ground prior to launch. The spacecraft attitude determination system provides the spacecraft velocity in the spacecraft reference frame with an accuracy of 1.5 ms^{-1} , and it is thus a straightforward exercise to remove the spacecraft velocity to specify the ambient ion drift vector in the sensor reference frame. More useful to the scientist and to the removal of systematic offsets in the data, is an expression of the plasma drift in magnetic coordinates that specify the plasma drift parallel and perpendicular to the local magnetic field. The unit vectors that define the directions along the magnetic field and perpendicular to the magnetic field in the meridian and perpendicular to the meridian are determined from the inertial attitude of the spacecraft and the International Geomagnetic Reference Field (IGRF) [3].

Once expressed in magnetic coordinates two different conditions are applied to remove systematic dc offsets that may exist due to errors in the specification of the instrument pointing with respect to the spacecraft reference axes. First, it may be recognized that averages of the vertical (meridional) plasma drift in longitude and local time must be zero in order to satisfy the requirement that the field be electrostatic and that $\nabla \times \mathbf{E} = 0$. Second, the plasma density in the middle ionosphere is sufficiently high and the ion-neutral collision frequency sufficiently low that magnetic flux lines may be regarded as electric equipotentials. Thus a condition for conjugacy in the magnetic east-west drift is imposed on the average measurements taken in restricted local time and longitude sectors. These two conditions allow the removal of offsets in the transverse drifts computed by the IDM in a manner described in more detail by [18]. The removal of the spacecraft velocity vector, removal of offsets in the manner described above and the rotation of the vector from an inertial frame into the magnetic frame further increases the uncertainty in the derived perpendicular ion drift perpendicular to the magnetic meridian by as much as 3 ms^{-1} . Table 4 lists the parameters that will be retrieved during the operation of the IVM with all sources of error included in the stated accuracies.

The ICON ground processing will be carried out at a central location with files of geophysical parameters, browse products and data analysis tools available to the community. Within each data file, geophysical parameters will be assigned individual uncertainties and quality flags to aid in the appropriate use of the data.

The IVM derived parameters of primary interest to the ICON science objectives are also those derived from the IVM that was part of the payload for the Coupled Ion Neutral Dynamics Investigation (CINDI). Figure 8 shows an example of one day of these key parameters as illustrative of the information that will be provided by the IVM for ICON. In this display the primary variations around the orbit are produced by local time and altitude, while for the ICON orbit the variations will be dominated by local time and latitude. Each orbit traverses the equatorial region at a different longitude and thus the variations seen here during one day reflect variations in longitude, as will also be the case for ICON. Key to the science objectives of the ICON mission are comparisons of the longitude variations in the

zonal and meridional drifts with the corresponding wind fields observed by Michelson Interferometer for Global High-resolution Thermospheric Imaging (MIGHTI) [2] and weighted by the ionospheric conductivity determined by the neutral and ion density profiles derived by the Far Ultra-violet Sensor (FUV) [16] and the Extreme Ultra-violet Sensor (EUV) [17].

7 Summary

The ICON mission brings together for the first time a unique set of measurements of the neutral and charged particle number density and drift motions to enable the connections between the dynamo action of the winds and the drift motions of the plasma to be revealed. The IVM instrument, which provides the measurements of plasma drift, is based on a strong heritage from previous missions and incorporates the most capable electrical and mechanical designs, while capitalizing on previous experience in data retrieval and reduction procedures. The resulting measurements are expected to uncover systematic longitude variations in the plasma drift associated with tidal modes in the neutral atmosphere as well as determine the importance of altitude variations in the wind on the electrodynamics of the F region plasma.

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Fig. 1.

Photographs of the ICON IVM show the mounting configuration of the RPA and IDM and a segment of the aperture plane (SenPot) utilized to establish a floating ground reference potential with respect to the plasma. The aperture plane is removed in the photographs to the left and right.

Fig. 2.
Schematic cross sections showing grid configurations for the Retarding Potential Analyzer and the Ion Drift Meter.

Fig. 3.
Sample current voltage characteristics from CINDI show the information content when both O+ and H+ is present (A) and when O+ only is present (B). When both O+ and H+ are present, they are easily distinguished by the difference in ram energy.

Fig. 4. Cross-sectional schematic of IDM indicating grid placement and trajectory of incoming supersonic ion beam. The beam is displaced by the repeller grid prior to collimation and by the suppressor grid prior to the collector.

Fig. 5.
Simplified electrical block diagram indicating major subsystems in the ICON IVM.

Fig. 6.

The rms error in derived drift velocity over a range of plasma density and O+ relative composition. For a given density and fractional population the average uncertainty is obtained over the temperature range from 400 K to 8000 K and aperture potential range from +2 V to -3V.

Fig. 7.

RMS in ram ion drift as a function of local time for the expected range of plasma density experienced during the mission. The range of uncertainty is produced by variations in the ion temperature between 400 K and 8000 K and variations in the aperture potential between +2V and -3V and variation in the fractional O⁺ concentration between 0.2 and 1. A horizontal line at 19 m/s is shown during the prime science operations period.

Fig. 8. Typical local time variations in key IVM parameters derived from the CINDI mission as representative of the longitude variations that will be seen by ICON. During this phase of the mission the satellite perigee is near 370 km at 0200 local time and the apogee near 595 km at 1400 local time.e

ICON IVM Key Measurement Requirements

Table 1

Name	Precision (m/s)	Spatial Sampling	Temporal Sampling	Local Time Range	Dynamic Range	Plasma Density Range (cm ⁻³)
RPA	19	240 km	32 s	06:00–24:00	± 500 ms ⁻¹	$7 \times 10^3 - 3 \times 10^6$
IDM	4.5	240 km	32 s	06:00–24:00	± 750 ms ⁻¹	$3 \times 10^3 - 3 \times 10^6$

Table 2

Instrument subsystem characteristics used for instrument simulations and ground data processing

Parameter	Analysis #	Room Temp	45C	−10C
RPA Min Cur (nA)	0.475	0.05	0.05	0.05
RPA Max Cur (nA)	2371.0	3929.0	3909.0	3954.0
RPA Elec Slope Error	0.12%	0.007%	0.013%	0.007%
RPA Elec Offset Error	5 counts	0.32	0.6	0.31
RPA Elec Noise Floor (pA)	5.0	1.6	3.0	2.2
RPA RV uncertainty	3 mV	2	2	2
IDM Min Curr (nA)	0.473	0.25	0.25	0.25
IDM Max Curr (nA)	834.0	9500.0	9500.0	9500.0
IDM Angle Error (deg)	0.02	0.0003	0.00024	0.00041

Table 3

ICON Instrument Resources for each IVM

Mass	4.25 kg
Power	2.5 W
Volume : Sensor Package	33 cm × 20 cm × 14 cm
Aperture Plane	38.8 cm × 28 cm
Telemetry	2048 bps
Pointing wrt ram	2.5°
Pointing Knowledge	0.01°
Instantaneous Field of View	45°

Table 4

ICON IVM Measured Parameters

Parameter	Range	Accuracy
Cross Track Ion Drift	-750 to 750 ms^{-1}	± 4.5 ms^{-1}
Ram Ion Drift	-500 to 500 ms^{-1}	± 19 ms^{-1}
Vertical Ion Drift perp to B	-500 to 500 ms^{-1}	7.5 ms^{-1}
Total Ion Number Density	1.5×10^3 to 5×10^6 cm^{-3}	$\pm 1 \times 10^3$
Major Ion Constituents	0-100%	$\pm 2\%$
Ion Temperature	400 to 8000 $^{\circ}\text{K}$	± 100 $^{\circ}\text{K}$
Sensor Plane Potential wrt Plasma	-3 to $+2$ V	± 0.02 V