Topical Review

Review of in-space plasma diagnostics for studying the Earth’s ionosphere

Luis Fernando Velásquez-García1,∗, Javier Izquierdo-Reyes1,2 and Hyeonseok Kim3

1 Microsystems Technology Laboratories, Massachusetts Institute of Technology, Cambridge, MA, United States of America
2 School of Engineering and Science, Tecnologico de Monterrey, Mexico City Campus, Mexico
3 Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA, United States of America

E-mail: Velasquez@alum.mit.edu

Received 26 September 2021, revised 5 January 2022
Accepted for publication 4 February 2022
Published 28 February 2022

Abstract
This review details the state of the art in in-space plasma diagnostics for characterizing the Earth’s ionosphere. The review provides a historical perspective, focusing on the last 20 years and on eight of the most commonly used plasma sensors—most of them for in situ probing, many of them with completed/in-progress space missions: (a) Langmuir probes, (b) retarding potential analysers, (c) ion drift meters, (d) Faraday cups, (e) integrated miniaturized electrostatic analysers, (f) multipole resonance probes, (g) Fourier transform infrared spectrometers, and (h) ultraviolet absorption spectrometers. For each sensor, the review covers (a) a succinct description of its principle of operation, (b) highlights of the reported hardware flown/planned to fly in a satellite or that could be put in a CubeSat given that is miniaturized, and (c) a brief description of the space missions that have utilized such sensor and their findings. Finally, the review suggests tentative directions for future research.

Keywords: Faraday cup, Fourier transform infrared spectrometers, in-space plasma diagnostics, integrated miniaturized electrostatic analyser, ion drift meter, Langmuir probe, multipole resonance probe, retarding potential analyser, UV absorption spectrometer

(Some figures may appear in colour only in the online journal)

1. Introduction

The ionosphere is one of the upper regions of the Earth’s atmosphere, located roughly between 50 km and 1000 km above ground level [1]. The Earth’s ionosphere is mainly composed of N2, O2, O, H, He, and Ar [2]; however, the ionosphere is a cold plasma, i.e. a quasi-neutral mix of electrons, ions, and neutral gas molecules; the ionized species present in the ionosphere are generated by solar radiation [3]. The Earth’s ionosphere plays important practical roles in today’s modern world, e.g. it makes possible radio wave propagation across distant points on Earth without using satellites (skywave) [4]. However, very little is known about some of the layers of the ionosphere, e.g. the thermosphere (i.e. the atmosphere between 80 km to 600 km height). Understanding the processes occurring in the thermosphere are vital for understanding local and global weather, and for understanding global

1361-6463/22/263001+26$33.00 Printed in the UK © 2022 The Author(s). Published by IOP Publishing Ltd
warming [5]. There is also evidence that global warming is cooling down the thermosphere, causing very serious problems such as variation in satellites’ drag and less recycling of water [6]. In many cases, in situ measurements would provide richer and better data compared to ground/remote measurements, helping improve model benchmarking and forecasting.

Plasma diagnostics encompasses a group of instruments and measuring techniques used to characterize plasmas. A complete classical description of a plasma entails specifying the electromagnetic fields and all the particles’ positions and velocities throughout the volume of interest [7]. However, in practice, many plasma sensors measure one or more properties that can be derived from the position and velocity distributions of the particles that make up the plasma; examples include number density, temperature, and flux [7]. The Debye length \( \lambda_D \) is a measure of how far electrostatic fields penetrate the plasma and is given by:

\[
\lambda_D = \sqrt{\frac{\varepsilon_0 k_B T_e}{n_e e^2}}
\]

where \( \varepsilon_0 \) is the permittivity of free space, \( k_B \) is Boltzmann’s constant, \( T_e \) is the electron temperature, \( n_e \) the electron density, and \( e \) the electron’s charge. Plots of selected plasma properties versus height between 100 km (the Kármán line, where arguably ‘space’ starts) and 600 km (the end of the thermosphere) are shown in figure 1. The characteristic Debye length in the ionosphere is in the order of a millimetre.

Even though there have been significant advances in growing a strong and diversified private, commercial space industry (New Space), access to space is still quite expensive. The typical cost of a launch to Low Earth Orbit (LEO, i.e. the region of space within 2000 km height from Earth’s ground) during the last two decades has been between US $62 M and US $140 M, resulting in a cost per kilogram of payload between US $1400 and US $23 300 [9]. The high cost is due in part to the physics of rocket propulsion that requires rockets to eject propel- lant many times the mass of the spacecraft to reach space [10]. Therefore, technologies that result in smaller, lighter, and cheaper spacecraft, without sacrificing performance are of great interest. Spacecraft hardware is also expensive because of the space industry’s cost-complexity death spiral [11] that reflects its risk aversion, resulting in long development cycles, large and heavy hardware, and low rates of innovation. Since the late 1990s, there is a big push for developing mission-focused, miniaturized satellites, i.e. CubeSats (1–10 kg, a few L in volume) [12]. CubeSats can work alone or in constel- lations with collective behaviour to accomplish one or more tasks. CubeSats offer a low-entry barrier to introduce to space the latest technology developments in software, hardware, and manufacturing methods. CubeSats require miniaturized, low-power scientific payload, including plasma diagnostics, to comply with their size, weight, and power constraints.

The plasma in the Earth’s ionosphere can be characterized from the ground using large-scale imagers, from space using long-distance imagers, or in situ using sensors attached to rockets or as the payload of satellites; the latter facilitates making high-resolution measurements on a scale unmatched by any other manner [13]. This review reports the state of the art in in-space plasma diagnostics for characterizing the Earth’s ionosphere. The review provides a historical perspective, focusing on the last 20 years of reported work and on eight of the most reported plasma sensors—most of them are in situ sensors, many of them with completed/in-progress space missions:

- Langmuir probes (LPs);
- retarding potential analysers (RPAs);
- ion drift meters (IDMs);
- Faraday cups (FCs);
- integrated miniaturized electrostatic analysers (iMESAs);
- multipole resonance probes (MRPs);
- Fourier transform infrared (FTIR) spectrometers;
- ultraviolet (UV) absorption spectrometers.

For each sensor, the review covers (a) a succinct description of its principle of operation, physical considerations, (b) highlights of the reported hardware flown in a satellite or that could
be installed in a CubeSat given that it is miniaturized, and (c) a brief description of the space missions that have utilized such sensor and their findings. The figures included in the review focus on images of the fabricated hardware and on schematics that illustrate the structure of the devices or how the devices operate. Finally, the authors suggest five tentative directions for future research: (a) further reduction of the weight and size of the plasma diagnostics hardware, (b) implementation of multiplexed sensing systems, (c) multi-sensor integration, (d) exploration of new plasma sensor designs, and (e) development of better electronics.

2. Langmuir probes (LPs)

LPs are arguably the simplest, and perhaps most versatile sensors for in situ plasma diagnostics. Despite their simplicity, LPs can estimate quite a few plasma parameters including electron temperature, ion temperature, electron density, and plasma potential. In addition, LPs can work in a wide range of plasma densities \(10^6\)–\(10^{19} \text{ m}^{-3}\), temperatures \(0.1 \text{ eV}–100s \text{ of eV}\), plasma potentials \(0.1 \text{ V}–\text{kV}\), and pressures \(10^{-6} \text{ Torr}–1 \text{ Torr}\) \([14]\), covering at full range the plasma properties of Earth’s ionosphere. As a matter of fact, quite a few space missions have used LPs to conduct in-space plasma diagnostics, including missions implemented with CubeSats.

In its most basic configuration, a LP is a conductive wire covered by a dielectric jacket except at its tip, where the wire is exposed to the plasma. A bias voltage with respect to the vacuum chamber (in the case of an on-ground application) or the satellite body (in the case of an in-space application), \(V_{\text{LP}}\), is applied to the LP using a power supply, resulting in a certain current flowing through the probe \(I_{\text{LP}}\); by sweeping the bias voltage, the current–voltage (\(I–V\)) characteristic of the LP is collected. From the \(I–V\) characteristic, the plasma parameters can be estimated based on the tip geometry and the specifications of the plasma (e.g. how the Debye length compares to the tip dimensions, whether the plasma is magnetized) \([15]\).

An idealized LP \(I–V\) characteristic is shown in figure 2. If the LP is biased at a very negative potential, all electrons are repelled, i.e. the current is composed of only ions; in this case, the current varies little with varying bias voltage and is approximately equal to the ion saturation current \(I_{\text{os}}\), which is directly related to the electron temperature and the ion density if the electron temperature is far larger than the ion temperature (this is usually the case). The bias voltage at which there is no net current (i.e. the magnitude of the electron and ion currents is the same) is the floating potential \(V_{\text{FP}}\). The onset bias voltage at which the electrons’ contribution dominates the probe current is called the plasma potential \(V_{\text{pp}}\). The current collected at a bias voltage above \(V_{\text{pp}}\) is mostly composed of electrons and directly related to the electron density (to 1st order identical to the ion density, as plasmas are quasi-neutral) and the electron temperature. The width of the electron retardation region (voltage difference between \(V_{\text{pp}}\) and \(V_{\text{FP}}\)) is directly related to the electron temperature. Given that ions are far less mobile than electrons and the electron and ion densities are very similar, the ion saturation current is significantly smaller than the electron-dominated current. Combinations of LPs, e.g. dual probes \([16]\), triple probes \([17]\), estimate the plasma parameters more precisely or measure them faster. In a multi-LP sensor, the minimum spacing between adjacent tips needs to be in the order of several Debye lengths to avoid interference between the tips.

For over a century, since Langmuir et al used electrostatic probes in the study of gas discharges \([18]\), LP theory and technology have matured, becoming fundamental probes for plasma diagnostics. Since 1949, when Reifman and Dow used an LP installed in a modified V-2 rocket to measure for the first time the electron density and temperature of Earth’s ionosphere \([19]\), LPs have had a long history of applications and use in space missions, including the last two decades; furthermore, given their simplicity and versatility to estimate quite a few plasma parameters, LPs are the most common plasma sensor mounted on a satellite. For example, Lebreton et al reported in 2006 an LP system onboard DEMETER (detection of electromagnetic emissions transmitted from earthquake regions)—a French, 130 kg microsatellite operating at 700 km above Earth that was launched in 2004 and that concluded scientific operations in 2010 \([20]\). DEMETER had two kinds of single LPs: a standard 6 mm diameter cylindrical probe, and a 5 cm diameter segmented spherical probe intended to measure the bulk plasma velocity besides the typical \(I–V\) characteristics. Their system swept the bias voltage range once every 1 s, obtaining estimates of the electron’s density and temperature with about 8 km in-orbit spatial resolution (the minimum speed of a satellite with a stable LEO orbit is 7.8 km s\(^{-1}\) \([21]\)); given the size of the Earth (its circumference around the equator is about 40 000 km), this is a good spatial resolution to map the ionosphere. However, finer spatial resolution could be possible with faster electronics (see section 10.5) or with multi-LP sensors that can instantaneously measure plasma properties without sweeping any voltages or frequencies \([17]\). DEMETER’S LPs detected ionospheric disturbances during the 2010 eruption of Mount

![Figure 2. Schematic of the \(I–V\) characteristic of an LP. For very negative bias voltages only ions are collected; similarly, for very positive bias voltages mostly electrons are collected.](image-url)
Merapi (Indonesia) [22], offering the opportunity to conduct data fusion between measurements from ionospheric plasma diagnostics and seismic and tropospheric (the troposphere is the lowest region of the atmosphere, up to 10 km height from the ground) measurements.

Several Korean satellites including KITSAT-3, KOMPSAT-1, STSAT-1 and STSAT-2, launched between 1999 and 2009, were equipped with LPs to measure plasma properties in the upper ionosphere (~600 km orbit height) [21]. The probe design varied little across the space missions. The probe consisted of a 1 mm diameter, high-purity W rod surrounded by an alumina jacket; although tungsten is a refractory metal, this is an unideal choice for an LP intended for ionospheric probing as researchers have shown that tungsten LPs degrade in the presence of residual oxygen [23]. The alumina jacket is covered by a guard ring made of stainless steel (SS) that reduces the edge effect as the same probe voltage is applied to it. The guard is encircled by a Delrin jacket that is protected by an Al fitting grounded to the satellite (figure 3(a)). The probes were installed at the front edge or at the ends of the solar panels to reduce wake effects. The data obtained from these Korean missions have been used to study the climatology of the ionosphere [24].

In 2011, Zakharov et al reported a double LP with 50 µm diameter W/Pt wire intended to characterize the effect on the ionospheric plasma that surrounds the International Space Station of residual magnetic fields from the large-scale superconducting magnet system of AMS-02 (alfa magnetic spectrometer—a device designed to measure in space high-energy particles) [25]; these collateral effects can be potentially dangerous, e.g., produce waves and turbulence. The use of a tungsten wire coated with platinum addresses the degradation concerns raised while discussing the tungsten LPs onboard KITSAT-3, KOMPSAT-1, STSAT-1 and STSAT-2. Although Double LPs also operate by sweeping a bias voltage and measuring current, they are less sensitive to plasma fluctuations than single LPs, facilitating following plasma oscillations. The $I-V$ characteristic of a symmetric, double LP is a symmetric hyperbolic tangent as it is the superposition of two single-LP $I-V$ characteristics, facilitating data analysis. Via lab experiments and particle-in-cell (PIC) simulations, the investigators concluded that AMS-02 would produce plasma and field perturbations more pronounced than previously thought.

In 2011 the DICE (dynamic ionosphere CubeSat experiment) mission was launched, consisting of two identical 1.5 U CubeSats (1 U is 10 cm $\times$ 10 cm $\times$ 10 cm in volume and up to 1.33 kg in mass). Each 'Sensor-sat' had two 1.3 cm diameter spherical LPs to measure the ionospheric plasma density and temperature (figure 3(b)) [26]. The probe tips were coated in gold because of its high stability in an atomic oxygen environment. The LPs were operated in the ion saturation region to
measure ion density in the $1 \times 10^{10}$ to $2 \times 10^{13}$ m$^{-3}$ range, attaining a minimum resolution of $1 \times 10^9$ m$^{-3}$. However, the LPs also periodically swept the bias voltage in one direction, from $-4$ V to $+1.7$ V, to generate an $I$–$V$ curve and obtain from it the electron temperature, electron density, and floating potential. The DICE LP measurements exhibit, in general, good agreement with the predictions from established ionospheric models, while also demonstrating novel, fine structure detail [26]. An improved configuration of the DICE LP sensor could entail adding a third probe to implement a triple LP and be able to produce data in real time, without sweeping any voltages, attaining even finer spatial resolution.

In 2019, Bendoukha et al. reported the development of a double LP part of the nanosatellite Ten-Koh—a 23.5 kg satellite launched in 2018 to study the space environment in LEO [27]. Their LP system is composed of two gold-plated (10.3 $\mu$m thick film), 1.5 cm diameter spherical electrodes placed outside the spacecraft structure; the probes are separated about 29 cm (figure 3(c)). The probe voltage is swept between $-10$ V and 10 V to collect $I$–$V$ characteristics. The electrodes were mounted on top of a glass fibre-reinforced polymer plate to keep the electrodes floating with respect to the spacecraft ground. The control electronics were housed in a 3 mm thick aluminium box. From their report, it is not clear whether the LP electronics had additional shielding besides the Al box (e.g. from the external panels of the satellite); however, an aluminium wall thickness of about 10 mm would prevent the great majority of ionizing radiation in space from reaching the electronics [29].

In the last couple of decades, variations of the basic single-LP design have been reported, as well as miniaturized probes that can measure cold, dense plasmas (i.e. with a small Debye length). The original application of the miniaturized LPs was to measure laboratory plasmas and to characterize electric micropropulsion plumes. However, miniaturized plasma probes are attractive for a satellite, particularly a CubeSat, because of the reduction in weight, size, and power that is associated to them. Nonetheless, miniaturized probes have a larger surface-to-volume ratio compared to standard counterparts, hence being more prone to degradation via chemical attack and sputtering. In addition, if the cross-section of the conductive core of the LP is small enough and the probe is long enough, there could be a significant voltage drop across the probe that needs to be considered when processing the data. Also, an LP with a very small collection area could need preamplification due to the magnitude of the signal. Moreover, multi-LP probes designed for laboratory plasmas might need to be modified to measure ionospheric plasma as the minimum separation between probes might not be satisfied for a larger Debye length. In 2001 Eckman et al. reported a triple LP to characterize the plume of a pulsed plasma thruster (PPT) operating inside a vacuum chamber [30] (in a PPT a spring-loaded Teflon bar is ablated by a series of ultrashort plasma discharges, producing thrust [31]). Their sensor was mounted on a movable arm to collect data at various locations of the plume; the researchers also varied the operating conditions of the PPT. Using their sensor, the investigators showed that the electron density and temperature in the PPT plume decrease with increasing radial distance from the centre of the Teflon surface.

Also, in 2004, Gatsonis et al. reported miniaturized triple and quadruple LPs to characterize flowing, pulsed, and collisionless plasmas such that the plume emitted by a PPT [32]. Triple and quadruple LPs can measure the plasma parameters without sweeping any voltages, which is advantageous in quickly varying plasmas. Their LPs had 127 $\mu$m diameter W wires spaced 1 mm, covered by a 6.28 mm diameter joint aluminia jacket; the wires protruded 6 mm from the jacket. Given the large surface-to-volume ratio of these probes, it would be beneficial to coat their exposed surfaces with a resilient film, e.g. Pt, to avoid rapid degradation of the W core in oxygen environments. The authors presented a current-mode method that involves biasing all probe electrodes and measuring all collected currents, making possible to measure in real time the electron temperature and density. Their probes were satisfactorily benchmarked with a standard double LP.

In addition, in 2007 Klingsworth et al. reported a compact LP system developed to measure dusty plasmas (plasmas with suspended, charged particles sized in the nanometre to micrometre range) [33]. The LP used in their system was a 50 $\mu$m diameter W wire with up to 8 mm exposed length; the wire was protected by a 1.1 mm diameter dielectric jacket. Their design also included features such as random sampling and radiofrequency compensation. The authors satisfactorily used their system during parabolic flights to characterize dusty rf plasmas inside a small chamber (the chamber volume was a cylinder with 8 cm diameter and 3 cm height).

There are also reports of LPs made via microelectromechanical systems (MEMS) technology to attain very small features and massive parallelization, i.e. to monolithically create LP heads with high probe density. Probe tip miniaturization reduces the current collected, perturbing less the plasma; in addition, miniaturized probes can be used to measure in parallel plasma properties with high spatial resolution, or to implement multi-LP sensors that can measure plasma properties in real time. These miniaturized, low-power sensors could be used as scientific payload in a CubeSat. Two kinds of MEMS LPs have been reported, i.e. surface-micromachined MEMS LPs and bulk-micromachined MEMS LPs. Surface-micromachined MEMS LPs might not be compatible with a long-term space application because they are made of stressed thin films with thicknesses in the order of a micrometre [34]. In 2006, Pribyl et al. reported surface-micromachined MEMS LPs [28]. Their LPs are electroplated Au wires 2.5 $\mu$m thick and 20 $\mu$m wide, spaced 60 $\mu$m, with a 13 $\mu$m thick polyimide insulating jacket (figure 3(d)). The group reported in 2009 an improved version of their LP technology and showed their sensor can operate at frequencies up to 1 GHz [35]. In 2014, Chimamkpm et al. reported planar arrays of bulk-micromachined MEMS LPs for real-time characterization of plasma potential fluctuations [36]. Their LP heads are 10 mm by 10 mm, 0.5 mm thick tiles made in SiC or alumina with ultrasonically drilled vias that are filled-in with electroless plated Ni, resulting in LPs with 250 $\mu$m tip diameter. Their devices intended to address the shortcomings of previously reported surface-micromachined MEMS LPs in terms of the
resilience of the materials employed and the small diameter of the LP electrodes and thickness of the dielectric jacket, extending their lifespan in an in-space mission without sacrificing the batch fabrication capabilities of MEMS technology. Their devices had as many as 25 LPs distributed in a 5 × 5 array (1.6 mm LP separation). Their sensor system had a frequency response between 2 MHz and 3 GHz. Their devices were characterized using a helicon plasma source; the measurements of the plasma potential using their devices compared well with independent measurements using a hot emissive probe and an ion-sensitive probe [36].

In the last couple of decades, interesting work in the development of electronic systems that control LPs on board Cube-Sats has been reported, looking to fulfill their mission while complying with significant constraints in the size, weight, and power consumption. For example, Fish et al. reported an electronic system used in the DICE mission previously described [26]. The electronics consisted of an integrated printed circuit board that manages an electric field probe, an LP, and a science magnetometer. The total weight of the electronic system was only 45 g. The analogue and digital sections of the board were physically isolated to minimize electromagnetic interference and rf coupling between signal measurement, data acquisition, and signal conditioning circuitry. The maximum reported energy consumption at full processing was about 0.5 W, which is compatible with the power levels typically available for scientific payload in a CubeSat. A field-programmable gate array (FPGA) controls the operation of the probes, as well as data acquisition, digitization, time stamping, data formatting, and serial communications with the control and data handling sub-system such that packets of data passed are merely stored in the telemetry buffer, ready for transmission by the radio. The measurements of the three plasma sensors onboard DICE are sampled simultaneously with a phase delay between each multi-probe measurement below 90 ns, with a sampling rate of either 35 or 70 Hz. Similarly, in the Korean satellite KOMPSAT-1 previously described, an FPGA controls the electronic system that consists of a power module, microcontroller, signal generator, AD converter, and housekeeping module, in addition to the preamplifier module that is directly attached to the LP [21]. Having a preamplifier right after the probe can greatly help with signal-to-noise ratio issues.

It is common that a satellite has more than one kind of plasma sensor onboard. However, these sensors are often not used for redundancy, e.g. to determine a certain plasma parameter in multiple ways; instead, the sensors are run sequentially and generate different data. For example, the FORMOSAT-5 [37] has three sensors (LP, RPA, IDM) that are run sequentially at different sampling rates to measure ionospheric plasma in a cycle mode. Also, the GOSAT-2 (greenhouse gases observing satellite-2) mission [38] has a variety of plasma sensors such as a charged particles detector, a double LP, and a magnetometer, all of them running sequentially and storing the acquired data in secure digital (SD) cards—the oldest kind of memory card, with up to 2GB memory capacity. Given the limitations for servicing satellite hardware in orbit, it would be desirable to gather redundant plasma data using a set of similar sensors or different sensors that generate data that to some extent overlap. Redundant data would also facilitate corroborating measurements, increasing their reliability. These multi-sensor scientific payloads would consume less power, weigh less, and occupy less volume if miniaturized.

3. Retarding potential analysers (RPAs)

RPAs are in situ plasma sensors that use a series of electrodes to selectively filter portions of the charged species that make up the plasma to determine the plasma’s ion energy distribution. RPAs are well-studied sensors, used in spatial missions since 1958. Arguably, the first reported RPA in space was a spherical ion trap onboard the Sputnik 3 [39]. However, the performance of the sensor was not satisfactory until Hanson et al. developed an ion trap with a multi-grid planar design in 1961 [40]. Since then, RPA technology and theory have matured, and the use of RPAs as in-space plasma sensors has increased over the years, hence finding many examples of RPAs onboard satellites.

A typical RPA is composed of five electrodes, i.e. (from the outermost electrode to the innermost electrode) floating electrode, 1st electron-repelling electrode, ion-retarding electrode, 2nd electron-repelling electrode, and collector electrode (figure 4). The floating electrode is a grid that is left floating (i.e. it is self-biased at the plasma floating potential) to minimize the perturbations caused by the RPA to the plasma. The 1st electron-repelling electrode is a grid biased at a negative potential V_{e1}, typically around −10 V, to remove the electrons from the mix of species injected into the sensor. The ion-retarding electrode is a grid biased at a varying positive voltage V_{ir}, typically between 0 V and 15 V, to discriminate between ions of different energies. The 2nd electron-repelling electrode is also biased around −10 V and is used to remove any secondary electrons due to ion bombardment within the RPA; for simplicity, some RPA designs do not include this electrode, although its inclusion yields more precise measurements [41]. The collector electrode is a solid plate that intercepts the current transmitted by the grid stack. The collector current I_{c} is modulated by the ion-retarding voltage V_{ir}. The derivative of the collector current with respect to the ion-retarding voltage is proportional to the ion energy distribution f(E) [42]:

$$\frac{dI_{c}}{dV_{ir}} = -\frac{Z_{i}^{2}e^{2}n_{i}A_{p}}{m_{i}}f(E)$$

(2)

where $Z_{i}$ is the charge-state of the ion, $n_{i}$ is the ion density, $A_{p}$ is the probe’s effective collection area, $m_{i}$ is the mass of the ions, and $E$ is the energy of the ions. Equation (2) is usually normalized to reflect a probability distribution.

Typical ion energies in the ionosphere are a small fraction of an eV (see figure 1); however, for each species, an RPA in orbit measures a peak of average energy $E_{p} = \frac{1}{2}m_{i}v_{i}^{2}$, where $v_{i}$ is the speed of the spacecraft supporting the sensor, with peak spread equal to the thermal energy of the ions, i.e. the ions have an energy distribution equal to [43]:

$$f(E) \sim \frac{1}{2} \sqrt{\frac{k_{B}T_{i}}{\pi E_{p}}} \exp \left[ -\frac{(E - E_{p})^{2}}{4E_{p}k_{B}T_{i}} \right].$$

(3)
Figure 4. Schematic of an RPA.

where $T_i$ is the ion temperature and $E_{oi} \gg k_B T_i$. The measurement of the thermal ion energy (i.e. the energy spread of the peak) is not influenced by $E_{oi}$. If the satellite is in a stable trajectory in LEO and the RPA is in the ram direction (i.e. in the direction of the movement of the satellite), the RPA can be used as a mass spectrometer, i.e. a device that uses electromagnetic fields to measure the mass-to-charge ratio of ions [44], although using significantly simpler hardware, e.g. quasi-static bias voltages. The minimum average speed of a satellite with a stable orbit in LEO is about 7.8 km s$^{-1}$ [21, 38] which corresponds to an ion energy $E_{oi} = 0.32N_i eV$, where $N_i$ is the mass number of the ionized species. Therefore, each species will show in the RPA data as a peak with a different average ion energy. For the minimum average speed for a stable LEO orbit, the main components of the ionosphere (N$_2$, O$_2$, O, H, He, and Ar [2]) have average ion energies in the $\sim$0.3–13 eV range. Consequently, by knowing the speed of the satellite at the time of the measurements (e.g. from astrodynamics), is it possible to determine the species that were detected by the RPA as the energies linearly scale with the mass number of the species.

The design of an RPA is dominated by the Debye length of the plasma it measures. Specifically, the diameter of the apertures of the floating electrode needs to be at most twice the Debye length to avoid space charge effects that smear the RPA measurements [7]. In a typical RPA the grid apertures are not aligned across the electrode stack, causing a reduction of the current transmitted by each grid; the total transmission across the grid stack scales geometrically with respect to the optical transparency of the grid $T_G$ and the number of grids $n_G$ (i.e. $\propto T_G^{n_G}$). To avoid ion interception and maximize the optical transparency across the grid stack, an RPA can employ an electrode stack with aligned grid apertures; in this case, the diameter of the apertures of the electron-repelling electrodes or the ion-retarding electrode can be larger than that of the floating electrode to accommodate for the inertia of the ions as they travel within the RPA [45]. For an RPA with aligned electrode stack used in a space application, only the floating grid and the collector electrode need to be very resilient to chemical attack and ion bombardment, e.g. via coating of a conformal Pt film, as they are the grids that intercept an ion flux. However, to the best of our knowledge, no RPA with aligned grids has been used in space.

An RPA can also be used to measure the energy distribution and temperature of electrons if certain modifications in its operation and hardware are introduced. The 1st repelling grid, which receives a stream of mixed species from the floating grid, would need to be biased at a large enough positive voltage to remove the ions from the stream (effectively becoming an ion-repelling electrode). Also, the retarding grid would need to sweep a range of negative bias voltages, looking to gauge the energy distribution of the electrons (effectively becoming an electron-retarding electrode). The 2nd repeller can be removed if the RPA is dedicated to measure electrons (the original function of this grid is to stream back secondary electrons produced by ions hitting the collector electrode; no secondary ions will be emitted from the electrons hitting the collector), or it can be biased at either a positive voltage or the retarding voltage, so all electrons transmitted by the retarding grid are collected by the collector electrode. The shift in the average energy of the electrons due to the speed of the satellite would be very small compared to that of the ions because electrons are over three orders of magnitude lighter than ions and the effect is linear with respect to the mass of the species.

It is readily feasible to implement a rugged RPA grid design for probing the ionosphere, as the Debye length that controls the size of the apertures of the floating grid and the inter-electrode spacing is about 1 mm (figure 1). Consequently, RPAs have been extensively used for characterizing the Earth’s ionosphere, including in missions flown in the last two decades. For example, in 2007 Frederick-Frost et al reported the use of an RPA to measure the energy distribution of the electrons in the SERSIO (Svalbard EISCAT rocket study of ion outflows) mission designed to quantify the effect of wave-particle interactions, ambipolar electric fields, and Joule heating in the flow of cold, heavy ions from the ionosphere [46]. Their device consisted of four nickel mesh screens and a series of concentric brass collimators. Their RPA was used at altitudes between 100 km and 700 km; in 2016 the same sensor was used to measure electron temperature and density at >700 km altitude [47], showing good correspondence with previously reported data, and demonstrating that an RPA can be used to characterize the ionosphere at heights well beyond the thermosphere.

In 2017 Roberts et al reported the development of eight RPAs installed in a ~1.7 l spacecraft for multipoint measurement of Earth’s ionospheric plasma [13]. The spacecraft had a main payload and four little ‘Bobs’, each of them equipped with two RPAs, known as Petite Ion Probes (PIPs). Their sensor consisted of a collection anode preceded by three 90% transparency screens. An exploded 3D schematic of the PIP RPAs is shown in figure 5(a).

Lee et al reported in 2018 the plasma sensors developed for NEXTsat-1 (next-generation small satellite-1)—a 100 kg satellite designed to observe the ionosphere’s thermal plasmas in the low and middle latitude regions, launched at the end of
that year \cite{48}. Their RPA had a mass of about 600 g and had a 40 mm diameter sensing area (figure 5(b)). All the grids were constructed using high-transparency (>90\%) square meshes with a wire separation of 1 mm and 0.05 mm wire thickness. With six grids, the transparency of the grid stack is estimated at 56\%.

Also in 2018, Collinson et al reported an instrument for measuring ion energy in plasmas with high resolution by combining a top-hat electrostatic analyser (ESA) followed by an RPA (figure 5(c)) \cite{49}. Using a laboratory vacuum chamber, the authors showed that their sensor attains a 1.6\% energy resolution, constant over all energies and angles.

In 2020, Fraunberger et al reported a coarse-resolution RPA for measuring auroral ionospheric plasma flow \cite{50}. Their device contained three nickel screens coated with a gold flash, followed by a spacer, and then an anode electrode that collects the particles. The aperture of their RPA was a circle of 7 cm$^2$ in area. The overall envelope of the sensor was a cube of 3 cm of side. Each RPA had a mass of 44 g. A prototype was installed on the Isinglass (ionospheric structuring: \textit{in situ} and ground-based low-altitude studies) rocket launched in 2017 and was used to measure the ion energy, ion density, and plasma potential of the ionosphere.

There are also reports of miniaturized RPAs, many of them used to characterize the cold, dense plasma plume ejected by an electric space thruster with high spatial resolution. An RPA can measure plasmas with a Debye length down to that of the floating grid aperture and inter-grid separation criteria. Consequently, these miniaturized, low-power sensors could be used as the scientific payload in a CubeSat to characterize the ionosphere (the criterion is a lower bound, i.e. an RPA capable of measuring a plasma with a certain Debye length

---

\(\text{(a) An exploded 3D schematic of a PIP RPA. The black screens are grounded, while the blue screen is the ion-repelling electrode. The secondary electron-repelling electrode is the transparent grid right after the innermost grounded electrode. Panel adapted from [13], with the permission of AIP Publishing. (b) The RPA on board NEXTsat-1. Image provided by Dr Junchan Lee, Satellite Technology Research Center, Korea. (c) Picture of a high-resolution ion energy detector composed of an ESA and an RPA with inset schematic of its operation. Panel adapted from [49], with the permission of AIP Publishing. (d) Clockwise from top: a MEMS RPA as seen from its back (collector electrode removed), a collector electrode, and a US penny for size comparison; CAD of assembled RPA and cross-section; backlit MEMS RPA without collector electrode evidencing good aperture alignment across the grid stack. © 2015 IEEE. Panel adapted, with permission, from [45].}\)
is in principle capable of measuring a plasma with a larger Debye length. For example, in 2003, Beal and Gallimore reported a miniaturized RPA with an 18.54 mm diameter sensing area [51]. Their RPA had a SS 316 housing that contained 127 µm thick Cu grids with 279 µm diameter apertures and 38% total open area, separated by Macor® washers; the smallest inter-grid separation was set at 1.73 mm. However, the use of an RPA with bare copper grids as ionospheric plasma sensor would cause reliability problems as LEO’s atmosphere contains oxygen. Also, in 2007 Azziz reported a miniaturized RPA with a 6.35 mm diameter sensing area [52]. The sensor had a SS 316 housing that contained 33 µm thick Mo grids with 140 µm diameter apertures and 72% total open area, separated by ceramic washers; the smallest inter-grid separation was equal to 500 µm. Moreover, in 2015, Heubel and Velásquez-García reported a miniaturized RPA made using MEMS technology (figure 5(d)) [45]; these sensors were not surface micromachined like some of the MEMS LPs discussed in section 2; instead, they are bulk-micromachined, i.e. fusion-bonded, multi-wafer stacks with conformal thin film coatings for electrical insulation. The housing of their RPA was made in Si coated with silicon dioxide and silicon nitride and hosted 500 µm thick Si grids coated in W or Au with 100 µm grid apertures and 200 µm inter-grid separation. The use of wafer substrates for making the housing and electrodes improves the reliability of the device compared to a surface-micromachined counterpart, as structural parts are significantly thicker and stiffer; however, using microfabricated thin films for electrical insulation could pose reliability issues for a long-term space application. Besides attaining smaller grid apertures and inter-grid separation than previously reported miniaturized RPAs, their sensor enforced aperture alignment across the grid stack using microfabricated Si deflection springs, resulting in over two orders of magnitude stronger signal, as the optical transparency of the grid was conserved across the grid stack. Their sensor enforced aperture alignment across the grid stack using microfabricated Si deflection springs, resulting in over two orders of magnitude stronger signal, as the optical transparency of the grid was conserved across the grid stack. Their sensor was successfully characterized using a helicon wave plasma with Debye length as small as 50 µm [45].

The development of a compact, light, low-power electronic system that can produce the required control signals for running an RPA and collecting data on board a CubeSat is challenging. Specifically, the typical ranges and accuracies of parameters associated with such instrument, based on knowledge gained from the success of past missions are [53]:

- Measured current range: 100 pA–5 µA
- Measured current accuracy: greater of 50 pA or 2.5%
- Samples per I–V curve: 16 or more
- I–V curve sweep time: 2 s or less
- Retarding voltage range: 0–10 V or more
- Suppressor bias: −12 V or less
- Power consumption: less than 0.5 W
- Weight: less than 0.5 kg
- Operating temperature range: −5 °C to 50 °C.

In the last couple of decades, interesting reports on electronics for running RPAs in CubeSat platforms have been published. For example, Fanelli et al implemented an RPA and its circuitry for the CubeSat platform CuRPA designed to operate in the F-region of the ionosphere (i.e. above 160 km altitude; it is the most important of the ionospheric regions, capable of reflecting electromagnetic waves with up to about 35 MHz) [53]. The main functional elements of the reported electrical system are four, i.e. (a) a logarithmic transimpedance amplifier for converting the collector current into a voltage; (b) an analogue-to-digital converters (ADCs) for digitalizing this voltage; (c) a digital-to-analogue converter for setting the voltages on the various grids; and (d) a FPGA for controlling the converters and communicating with external electronics. The normal operating range of the electronics is from −5 °C to 50 °C, and the survival range is from −20 °C to 85 °C. Also, Davidson et al reported in 2020 the electronics that drive the RPA part of the 6U PetitSat CubeSat mission [54]. Their RPA can also be run as an IDM (see section 4) and utilizes two electrical boards: the smaller of the two houses the four-channel electrometer, and the mainboard contains all the necessary circuitry to perform all other instrument functions. In conjunction, both boards conduct five major functions:

- Measure the four currents collected by the collector segments (their RPA has a segmented collector instead of a monolithic collector to be able to operate as an IDM—see section 4);
- generate the voltages needed by the different electrode grids;
- generate the power needed for the internal circuitry of the instrument;
- conduct health monitoring;
- digitize and transmit the collected data to the bus.

The electronics collect the data through a series of ADCs that use various integrated circuits to measure each of the power rail voltages, the current being used on each power rail, and the temperature at various points on each board. In addition, two other quantities are included in the housekeeping: (a) a real-time-clock chip is polled at regular intervals to help ease data processing and ensure that measurements are analysed in the correct time sequence; and (b) a three-axis magnetometer is included to identify data taken during attitude manoeuvres, since these may be compromised. All these functions are controlled by an FPGA on the mainboard. In addition to control the other components on the boards, the FPGA is also responsible for ordering the data collected into packets and transmitting them to the bus. One data packet is sent to the bus every 2 s via an RS422 interface.

4. Ion drift meters (IDMs)

IDMs are in situ plasma sensors that measure ion velocity, which is used to estimate the ion drift and, if the local magnetic field is known, e.g. using a magnetometer, the local electric field (the ion drift is the \( E \times B \) drift). IDMs were first proposed by Hanson et al in 1973 [55]. An IDM has a multi-grid structure like an RPA with the noticeable differences of having a diaphragm and a segmented collector electrode.
In an IDM the ions enter through an aperture as a collimated beam. The beam then passes through a stack of grids, each of them biased at a certain potential, or grounded, to filter and focalize the ions to the collector electrode. If the angle of attack of the ions is zero, all collector segments receive the same ion current; however, if the angle of attack is not zero, the currents collected by the different segments are not the same. If the orientation of the sensing area of the IDM with respect to the velocity vector of the satellite is known, the ion-drift velocity perpendicular to this vector can be derived from the measured ratios of currents of the different collector segments.

A typical IDM design has six grids, a diaphragm, and a collector electrode divided into four sectors (figure 6). The inlet of the IDM can be circular, as proposed by Lee et al [48], or squared, as suggested by Heelis and Hanson [56]. The outermost grid (G1) and the chassis of the sensor are grounded to prevent leaking outside the sensor the electric fields inside. The next grid (G2) is biased at a small voltage \( V_{gr} \), e.g. 2 V, to remove the hydrogen ions from the beam as they are very fast and detecting them in the collector would reduce the accuracy of the ion drift estimates. The drift region of the IDM is the space between a structure composed of a diaphragm sandwiched between two grids (G3) and a back grid (G4)—all grounded. Finally, the electron-repelling grid (G5) is biased at a large negative potential \( V_{er} \), e.g. \(-15\) V, to block any electrons from reaching the collector electrode. The segments of the collector electrode are connected in pairs and their currents \( I_{C1} \) and \( I_{C2} \) are measured.

In an IDM with a circular inlet aperture, the arrival angle \( \alpha \) of the incoming ions is given by [37]:

\[
\alpha = \tan^{-1} \left( \frac{W_D}{2D} \cos \left( \frac{\theta}{2} \right) \right)
\]

(4)

where \( W_D \) is the diameter of the inlet aperture, \( D \) is the separation between the aperture and the collector, and \( \theta \) is a parameter obtained by solving numerically the equation:

\[
\theta = \sin (\theta) + \left[ 1 - \left( \frac{I_{C1} - I_{C2}}{I_{C1} + I_{C2}} \right) \right] \pi.
\]

(5)

Similarly, in an IDM with a square inlet aperture the ratio between the collector currents is given by [56]:

\[
\ln \left( \frac{I_{C1}}{I_{C2}} \right) = \frac{W_S - 2D \tan (\alpha)}{W_S + 2D \tan (\alpha)}
\]

(6)

where \( W_S \) is the side of the square aperture.

IDMs have been used in several missions during the last two decades for \textit{in situ} characterization of Earth’s ionosphere. For example, in 2006, Berthelier et al reported the design and ionospheric data of an IDM part of the plasma sensors of the DEMETER satellite previously described (see section 2) [57]. With their sensor, the authors determined the ion bulk velocity vector in the Earth’s frame of reference; the practical range of the velocity along the axis of their analyser was from 0 to \( \sim 2 \) km s\(^{-1}\) and its accuracy was around 10\%. Using the data from the IDM and other plasma instrumentation onboard the satellite, the authors measured ion densities between \( 5 \times 10^2 \) and \( 5 \times 10^5 \) ions cm\(^{-3}\) with an absolute accuracy of 5\% for the major species (O\( + \)), and ion temperatures between 500 K and 5000 K with an accuracy of \( \sim 2\%–3\% \). In 2010 Marchand et al reported anomalous measurements from this instrument [58]; the authors modelling accounted for appreciable angular deflections, although smaller than what was measured, concluding that the electrostatic sheath effects are not enough to explain the anomaly.

In 2007, Hartman and Heelis reported longitudinal variations in the equatorial vertical drift in the topside of Earth’s ionosphere from the IDM on board of the DMSP (defence meteorological satellite program) F15 satellite [59]. The DMSP satellites are in Sun-synchronous polar orbits at near 840 km altitude. In the F15 satellite, the ion drift is sampled at a 6 Hz rate. There is no description of their IDM hardware, but the reported uncertainty in the ion drift measurements is between 70 m s\(^{-1}\) and 140 m s\(^{-1}\) (i.e. 0.5°–1.0°). The authors reported clear longitudinal variations in the ion drift that suggest they are produced by meridional winds in the ionosphere’s F-region (150–800 km height) [59].

In 2012 Stoneback et al reported an IDM part of the ICON (ionospheric connections explorer) mission, launched in 2008, that aimed to discover fundamental connections between the neutral atmosphere dynamics at altitudes between 100 km and 300 km and the charged particle motions at low and middle latitudes tied to the magnetic field present in the region [60]. Their IDM had a squared inlet aperture and implemented Heelis and Hanson’s design [56] with a modified segmented collector electrode that, instead of having straight cuts in the collector’s separations, it had cuts inclined 45° (figure 7(a)). The modification intended to reduce the effect that photocurrents had in previous IDM designs. Photoemission levels within the instrument are dictated by the satellite’s orientation with respect to the Sun and thus vary seasonally and with local time [60]. The authors’ simulation results showed that most photoemission returns to the source that created it. However, most of the remaining photoelectrons are exchanged between collector plates, causing a deviation in reported drifts. Zheng et al reported in 2017 ionospheric plasma measurements from the CESES (Chinese seismo-electromagnetic
satellite) mission launched in 2013 [61]. Among the instruments on board the satellite, there was a squared inlet aperture IDM. The sensor consisted of a six-grid stack and a collector electrode. The grids were made of beryllium copper plated with gold. Polyimide was used to electrically insulate the grids. The grid transmission rate of the signal layer was designed to be 82.64%, and the total transmission of the stack is estimated at 31.85%. The side of the square aperture and the depth of the sensor were equal to 40 mm and 20 mm, respectively. The radius of the segmented planar collector was 50 mm. The velocity perpendicular to the ram direction (the direction the satellite is traveling) is calculated using the arrival angle of the ions and the ion velocity parallel to the ram direction, which an RPA measures. The electronics that run the IDM can measure between 20 pA and 6 µA with an accuracy better than 0.4% [61].

Also in 2017, Lin et al reported plasma ionospheric data from the FORMOSAT-5 satellite, launched in 2016 [37]. FORMOSAT-5 used a special instrument called the AIP (advanced ionospheric probe) that joints the benefits of using an RPA, an IDM, and an ion trap (a kind of mass spectrometer) (figure 7(b)). The AIP is a multi-grid planar ion probe integrated within a 10 cm diameter circular inlet aperture that is based on a similar instrument used in the ROCSAT-1 satellite that operated between 1999 and 2004 [62]. The same hardware used differently results in making IDM, RPA, or ion trap measurements, generating a wide range of ionospheric plasma parameters at a high sampling rate (e.g. it can measure ion density at a rate of up to ~8 kHz).

In 2018, Lee et al reported the plasma sensors on board the NEXTsat-1 satellite (previously described in section 3); the sensors included an RPA, an IDM and an LP [48]. The reported data from the plasma detectors was generated in a vacuum chamber at the KAIST’s satellite technology research center. The square inlet aperture of their IDM (figure 7(c)) had grids made of 50 µm diameter wire that defined 1 mm wide square holes; the collector of the IDM was divided into four 15 mm long squared sections separated by a 1 mm gap. The expected maximum drift angle is 12.65°, which corresponds to 1.7 km s⁻¹ drift velocity with an orbital speed of 7.57 km s⁻¹ at an altitude of 575 km.

5. Faraday cups (FCs)

An FC is an in situ sensor that measures current, and from such measurement ion and electron fluxes can be estimated. A basic FC has three electrodes (figure 8), i.e. a ground shield, a repelling electrode, and a collector electrode. The three electrodes are separated and electrically isolated from each other by a dielectric jacket. The ground shield acts as the sensor’s housing, surrounding the other two electrodes to prevent electromagnetic interference that could affect the measurements. The repelling electrode is a mesh that keeps the plasma outside the sensor (similarly to an RPA, the grid apertures should be at most about two times the Debye length of the plasma probed), biased at a repelling voltage V_r so that the electrons or the ions of the plasma are removed from the beam of particles reaching
the interior of the sensor (a large positive bias voltage removes the ions, a large negative bias voltage removes the electrons). The collector electrode receives the current not filtered by the repelling electrode.

The most basic measurement of an FC entails grounding the collector \( V_C = 0 \) and measuring the collector current \( I_C \) i.e. transmitted by the repelling electrode; the current divided by the transmission area of the repelling electrode is the current density. When using an FC on board a satellite to measure positive ions, a negative potential is applied to the repelling grid to block negative species (electrons, negative ions) from arriving to the collector electrode. In practical terms, the minimum potential \( V_{\text{min}} \) needed to remove the negative ions would be based on the speed of the satellite and the mass of the negative ions, i.e. \( V_{\text{min}} = \frac{1}{2} \frac{q}{m} v^2 \). For the species that make up the ionosphere, \( O_3 \) is the heaviest molecule that can generate negative ions [64]; therefore \( V_{\text{min}} \) should be at least about \(-10.5\) V (i.e. for \( v_c = 7.8\) km s\(^{-1}\), i.e. the minimum speed of a satellite with stable orbit in LEO). Similarly, when using a FC on board a satellite to measure negative ions, \( Ar \) is the heaviest molecule in the ionosphere that can generate positive ions, resulting in a \( V_{\text{min}} \) of at least about 13 V. An FC can also be run as an RPA, i.e. \( V_C \) is swept while measuring the collector current and the energy distribution is proportional to the derivative of the collected current with respect of the collector voltage (see section 3). However, an RPA is a better sensor for measuring ion energy distribution as it addresses issues that the FC does not do, e.g. secondary electrons, space charge effects, backscattering [7].

At altitudes above 90 km, the ionosphere is mostly free of negative ions (i.e. the negative current is mainly due to electrons); below that height, the negative current is essentially due to ions [64]. However, in general, to discriminate between negative ion current and electron current, one could take advantage of the large difference in mass between ions and electrons. For example, if the FC is onboard a satellite and is used as an RPA, given that the shift in the average energy of the peaks due to the speed of the satellite is linear with the mass of the species (see section 3), the electrons would show a negligible average energy shift compared to the shift of the ions, making possible to tell one species from the other as the two energy peaks do not overlap.

FCs have been extensively used in space research, including missions to study solar wind and the plasmasphere (inner region of the magnetosphere right above the ionosphere) [65] and missions to diagnose the D-region of the ionosphere (50–100 km altitude; the ions present are formed from ionizing NO, N\(_2\), and O\(_2\); the plasmasphere has high recombination rates, i.e. there are far more neutral molecules than ions [66]) [67, 68]. For example, in 1990 the rocket S-310-20 was launched from the Kagoshima Space Center (Japan) to study the D-region of Earth’s ionosphere [64]. An FC was used to measure the saturation currents at positive and negative voltages at altitudes between 65 and 185 km; plasmas at altitudes higher than 90 km were considered free from negative ions. The FC consisted of an SS repelling electrode made of a mesh with 20 openings per inch (0.8 mm wide holes) and an SS collector, both 80 mm in diameter. The spacing between the repelling grid and the collector electrode was 4 mm. The ground shield was 100 mm in diameter and had a thickness of 40 mm. The FC was attached to an electrically insulated arm about 30 cm in length. The FC data showed that the negative-to-positive ion density ratio is above 80%–88% in the D-region at heights lower than 82 km and decreases with altitude above 82 km toward the E-region (\(\sim 100–150\) km). On the other hand, the effective negative ion density is nearly constant below 74 km, increases from \(10^7\) to \(10^9\) cm\(^{-3}\) toward 85 km height, and then decreases toward the E-layer.

In 1996, Havnes et al reported data from two FCs onboard a spacecraft launched from the Andoya Rocket Range (Norway) in 1994 [69]. The probes were designed to characterize dusty plasmas, i.e. the probes block out the electron and ion components and detect primary currents due to impacts of charged dust and secondary plasma production during dust impacts. The structure of their FC consisted of a double repelling grid biased at ±6.2 V to repel ions and electrons (dust particles have a lot more inertia than electrons and ions; therefore, the bias voltages are not enough to block the dust from getting into the sensor). The collector electrode was biased at \(-2\) V. The data show that large amounts of dust (many thousands of particles per cubic centimetre) with an average diameter equal to 100 nm and less were present during polar mesospheric summer echoes and noctilucent cloud conditions. Dust particles of both polarities were detected; the negatively charged dust particles seem to be sinks of electrons, while the positively charged dust particles cause a larger electron density due to photoionization [69].

In 1997, Safrankova et al reported FC data from the INTERBALL-1 satellite (launched in 1995 to study Earth’s magnetosphere) [65]. Their instrument, called VPD, was designed to determine ions and electrons’ integral flux and energetic spectrum in the 0.2–2.4 keV energy range using six independent FCs (the sensors were deployed in three orthogonal directions, two per direction). Each FC had an entrance grid connected to the housing and the satellite body to protect the environmental space from the influence of the device.

---

**Figure 8.** Schematic of an FC. In the schematic, the repelling electrode is biased at a negative voltage to repel electrons from coming into the interior of the sensor.
The design of the modified FC was based on the original design of Havness et al [69] and uses the same voltages for each repelling grid. The Xe lamp was operated a 20 Hz with 0.5 J flashes. The broadband spectrum of each flash contained a sufficiently large number of UV photons down to a minimum wavelength of ∼110 nm, corresponding to a maximum photon energy of 11.3 eV. Thus, the detector had two measurement channels: one channel for detecting a priori charged MSPs that can penetrate the FC, and their charge can be measured from the collector, and another channel for the detection of the photoelectron pulses created by xenon-flash photons. The direct FC measurements showed signatures of negatively charged MSPs in the limited altitude range between 80 and 90 km; the authors argued that the limited altitude range is probably due to the aerodynamical effects and does not reflect a layering process in the atmosphere. In agreement with this conclusion, measured photocurrents were detected in a much broader altitude range between 60 and 110 km [72].

In 2010, three more flights were launched within the umbrella of the ECOMA project. The flights were conducted before, during maximum activity, and after the decline of the Geminids, which is one of the major meteor showers each year. For these flights, the sensors were modified by adding two more xenon flashlamps (figure 9(b)). Each of the three lamps had a different window material resulting in different cut-off wavelengths. The data showed that the observed MSPs in the 0.5–3 nm size range generally increased particle size with decreasing altitude. Remarkably, the size information can be obtained from the FC data because different MSP particle sizes were expected to result in different work functions. The MSP’s work function was estimated in the 4.0–4.6 eV range. Data analysis indicates that Fe and Mg hydroxide, instead of metal silicates, are the major constituents of the smoke particles [68].

6. Integrated miniaturized ESAs (iMESAs)

The iMESA is a multi-channel, multi-electrode plasma sensor (figure 10(a)) designed to measure ionospheric plasma density, plasma temperature, and the spacecraft’s potential with respect to the ionosphere’s potential [73]. The iMESA sensor has been developed for about two decades by the Space Physics and Atmospheric Research Center at United States Air Force Academy (SPARC at USAFA) in collaboration with the US Air Force Academy, the University of Colorado at Colorado Springs, Los Alamos National Laboratory, and the United States Naval Research. To the best of our knowledge, the iMESA sensors are not commercially available. The key idea behind the iMESA sensor is to configure regions of space with non-uniform electric fields that are designed to only transmit ions with energy within an narrow range around a certain value (i.e. a bandpass energy filter—a principle routinely used in deflector energy filters part of mass spectrometers to increase the resolution of the mass filter [44]). The iMESA sensor estimates the ion energy distribution from measuring the anode current $I_{anode}$ as a function of the deflection plate voltage $V_D$; for a given voltage, only ions with a certain energy...
can be transmitted, i.e. collected as anode current. The geometries of the iMESA deflector plates were designed using SIMION, simulating trajectories of singly ionized atomic oxygen (the main species present at 500 km, i.e. the average height at which the instrument would be deployed) with a range of kinetic energies $E$. From the simulation results, the analyser constant $f_p$ (i.e. peak ion energy detected divided by deflection plate voltage), the instrument efficiency $\varepsilon$ (i.e. number of detected ions with peak energy divided by the number of ions simulated at the same energy), and the angular resolution $T(\theta_y, \theta_z)$ (i.e. metric that benchmarks the effect of having ions incoming with non-zero angles) are quantified. The ion energy distribution $f(E)$ is then equal to [74]:

$$f(E) = \varepsilon \cdot \frac{T(\theta_y, \theta_z) \cdot I_{\text{anode}}(E)}{v_i q_i A_a N_a},$$

(7)

where $E = f_p V_D$, $v_i$ is the spacecraft velocity, $q_i$ is the ion’s charge, $A_a$ is the area of the channel’s aperture, and $N_a$ is the number of apertures. If the ion energy is assumed to follow a drifted Maxwell–Boltzmann distribution, i.e.:

$$f(E) = \frac{n_i}{\sqrt{4\pi k_B T_i E}} \exp \left[ \frac{-(E + E_0 - 2\sqrt{EE_0})}{k_B T_i} \right],$$

(8)

where the ion density $n_i$, ion temperature $T_i$, and kinetic energy due to the bulk flow of plasma $E_0$ can be inferred. The spacecraft’s potential $\Phi$ is calculated as:

$$\Phi = \frac{1}{2} m_i v_i^2 - E_0 q_i,$$

(9)

where $m_i$ is the mass of the ions. From simulations, the energy resolution $\Delta E$ (full width at half maximum divided by the peak energy) of the iMESA sensor is estimated at $0.131 \pm 0.009 \text{ eV eV}^{-1}$. The reported accuracy of the plasma parameters inferred from the iMESA data depends on how strong the signal was compared to the noise floor, e.g. the accuracy of the ion density data is between 5% and 19%, the accuracy of the ion temperature measurements falls between 9% and 46%, and the accuracy of the spacecraft potential data is between 0.6% and 3.7% [74].

The first iMESA design was introduced by Enloe et al in [75] and used a plurality of channels with a certain electric field configuration produced by a stack of photolithographically etched SS electrodes with Teflon insulating layers to selectively detect ions that had a given energy (figure 10(b)). The design focused on its miniaturization so that multiple sensors with multiple ion-sorting channels could be sent to orbit around the Earth to measure the plasma environment at several different locations simultaneously. A multiplexed
sensor array can certainly produce data with high spatial resolution in a laboratory setting. However, given that spacecraft move in orbit at speeds of about 8 km s$^{-1}$ or more, the measurements conducted by an iMESA onboard a satellite are the average across a distance directly proportional to the time it takes to make the measurement; this distance can be orders of magnitude larger than the separation between channels in the array. Consequently, depending on the orientation of the sensor with respect to the ram direction of the satellite, the data from adjacent channels would overlap unless the electronics sample fast enough the signal (e.g. $\mu$s data sampling for $\sim$8 mm level spatial resolution would be compatible with $\sim$1 cm or larger channel separation).

In 2013, the Space Test Program’s STPSat-3 satellite was launched with the 1st iMESA sensor [74]. The device occupied a 10.16 cm by 10.16 cm by 3.45 cm volume, had 620 g of mass, and required 882 mW of power under normal conditions. The ESA part of iMESA consisted of three filter plates and two deflection plates with a 255 $\mu$m separation distance. The filter plates were 635 $\mu$m thick and had 150 $\mu$m by 14.90 mm slit apertures cut by electrical discharge machining. Eleven apertures were stacked in as a group, and one filter plate had 16 groups of apertures (176 apertures in total) (figure 10(c)). The deflection plates were 1.140 mm thick and had the same number of slit apertures at the same positions, but the apertures were wider (580 $\mu$m by 14.90 mm). The electric field in the space between the electrodes deflects the ions in a meandering trajectory, so only ions with a specific energy pass through the stack; the ion energy that was transmitted was selected using the bias voltages applied to the deflection plates. The ions that passed through the 3rd filter plate were measured as anode current. As explained before, the ion energy distribution function can be derived from the anode current, and the ion number density, ion temperature, and spacecraft potential can be computed assuming the ion energy function follows a drifted Maxwell–Boltzmann distribution. The data collected from the iMESA on STPSat-3 showed that the ionosphere at 500 km altitude has $1.25 \times 10^{11}$ m$^{-3}$–$3.2 \times 10^{12}$ m$^{-3}$ ion density, 0.065 eV to 0.37 eV ion energy, and 750 K–4250 K ion temperature. The spacecraft potential measured varied between $-39$ V and $-15$ V. The measured data were in good agreement with published data [74].

Five satellites, i.e. GPIM (158 kg, $\sim$715 km altitude, launched in 2019), OTB-1 ($\sim$720 km altitude, launched in 2019), STPSat-4 ($\sim$420 km altitude, launched in 2019), STPSat-5 (115 kg, planned), and STPSat-6 (geosynchronous orbit, planned) have or will have onboard an improved version of the iMESA called integrated miniaturized ESA-reflight (iMESA-R). The iMESA-R was developed to act as simultaneous multi-point sensors to measure plasma density, temperature, spacecraft charging, and total ionizing dose (TID), which was not included in the original iMESA [76]. The design of the iMESA-R used in the five satellites is very similar to ensure consistency across their data.

The TID is measured with a microdosimeter manufactured by Teledyne Microelectronic Technologies. The capability of measuring the TID was added to the iMESA-R to investigate the radiation environment of the SAA (South Atlantic anomaly) and the auroral regions. SAA and auroral region show relatively high radiation compared to other regions at the same altitude in LEO. Therefore, it is important to identify momentarily changing boundaries and structures of both regions. Besides demonstrating that the sensors were accurate, the ground tests of the iMESA-R also showed that the Al housing encasing the sensor effectively filters out low-energy electrons and protons, and it only mildly attenuates gamma rays. The initial data from iMESA-R on STPSat-5 is available in [76], and future integration of data from all five iMESA-R sensors is expected to make the measurements more accurate.

The measurement range of iMESA is largely dependent on how strong the signal is compared to the noise floor, which is greatly influenced by the electronics that are implemented to drive it and collect the data. For example, the iMESA sensor on the STPSat-3 satellite was initially designed to operate at 350 km; however, the launch vehicle was changed late in the program, changing its orbital altitude to 500 km [74]. The electron density at 500 km is an order of magnitude lower than at 350 km, so the signal-to-noise ratio was relatively low given that the electronics were not modified to work well at 500 km, which required the data to be aggressively selected. Nonetheless, for the next iMESA-R sensors, the electronics were designed for their orbital altitude and could cover an altitude range between 300 km to 720 km [76]. The electronics for iMESA-R were fully integrated to the instrument of size 118.75 mm $\times$ 101.60 mm $\times$ 34.42 mm with energy consumption between 2.1 W (when dosimetry is inactive) and 2.5 W (when dosimetry is active) [73]. This small size and low power consumption makes iMESA-R suitable for a CubeSat, which is made of a few litre-sized cubic modules and has available power in the order of 10 W, with exact value depending on the configuration of its solar panel.

7. Multipole resonance probes (MRPs)

A plasma resonance probe is an in situ plasma sensor that utilizes electromagnetic waves at or near the electron plasma frequency $w_{pe}$:

$$w_{pe} = \sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}},$$

where $m_e$ is the electron’s mass, to measure the properties of a plasma. The MRP, first proposed by Lapke et al in [77], is a kind of plasma resonance spectrometer. The original MRP is a spherical probe divided into two metallic hemispheres separated by a thin insulator (figure 11(a)). The hemispheres are covered by a dielectric layer to avoid direct contact with the plasma. A holder supports the probe and supplies symmetrical rf signals of opposite polarity to the hemispheric electrodes. The signal generated by the probe is its dissipated power spectrum $S(\omega)$, recorded between 100 MHz and 10 GHz (i.e. spanning frequencies much larger than the ion plasma frequency but comparable to the electron plasma frequency; consequently, the plasma current is due to displacement and
trical symmetry of the problem simplifies its solution. In such an insulator of negligible thickness, the geometrical and electrical parameters can be neglected and the hemispherical electrodes are separated by a dielectric coating, and in the dielectric, where 

\[ \epsilon_D \] is the electrical permittivity of the dielectric coating, and

\[ \epsilon_r = 1 \] in the plasma sheath. For the ideal case where the holder can be neglected and the hemispherical electrodes are separated by an insulator of negligible thickness, the geometrical and electrical symmetry of the problem simplifies its solution. In such case, the potential can be solved analytically using Legendre polynomials with multipole expansion, i.e.:

\[ \Phi(r, \vartheta) = \sum_{k=1}^{\infty} A_k r^{2k-1} + B_k r^{-2k} P_{2k-1} (\cos(\vartheta)) \]  

where \( r \) and \( \vartheta \) are the radial distance and polar angle in spherical coordinates. The absorption spectrum \( S(\omega) \) is then the volume integral over the bulk of the plasma of one half the potential times the real part of the current, i.e. [77].

\[ S(\omega) = \int \frac{\sigma(\omega)}{2(\omega^2 + \nu^2)} |\nabla \Phi|^2 \, d\text{vol}. \]  

A more general framework was reported by Lapke et al in [79]. In practice, the probe is driven by a network analyser. The probe’s dissipation power spectrum is measured; the spectrum shows a dominating resonance; the resonance frequency is expressed as a function of electron plasma frequency and geometrical parameters, independent of collision rate. Consequently, the electron density can be calculated from the dominant resonance frequency, and the collision rate can be inferred from the resonance width. Finally, the electron temperature can be found from the collision rate.

However, at low pressure, e.g. a few Pa, energy can also be lost by escaping electrons. This kinetic effect is not considered in the previous model and, given that the effective collision rate is composed of the actual collision rate and the kinetic collision rate that represents the rate of electrons deflected by the electric field of the probe, a complete analysis cannot be done using the Drude model. Instead, a kinetic model [80] is used to describe electron physics for general active plasma resonance spectroscopy, which was applied to the modeling of the MRP [81]. The kinetic model explains the damping caused by the kinetic part of the collision rate and clarifies the relationship between collision rate and electron temperature.

The 1st prototype of an MRP was reported in 2011 by Lapke et al [82]. The total radius of the probe was 4 mm, including a 1 mm thick dielectric coating. The spectral response of the sensor between 100 MHz and 3 GHz was characterized using a mixture of argon and nitrogen at 10 Pa (75 mTorr); the MRP was placed at the exact symmetric position of an LP for comparison. The predictions from the analytical model for the ideal case [77], the numerical result from conducting an electromagnetic simulation using CST Microwave Studio [83], and the experimental data from the MRP matched well; in addition, the measurements from the LP were similar.

In 2015 Schulz et al reported an improved MRP sensor, i.e. the planar MRP (pMRP). The pMRP reduces the perturbation caused by the probe while surveying the plasma [84]. The pMRP has a planar design in which two half-discs replace the original two hemispherical electrodes, i.e. the electrodes do not stick out of the wall (figure 11(b)). Although the pMRP is less intrusive than the original MRP design, the frequency range that the probe can detect is narrower, reducing the dynamic range of the probe.
So far, no MRP has been used in space missions or planned to be part of the payload of a satellite, as it is a relatively new sensor concept. In addition, no MRP has been shown to operate in the range of plasma parameters found in the ionosphere (the work has focused on characterizing laboratory plasmas of interest to manufacturing, with Debye length at least an order of magnitude smaller). However, a MRP has several advantages compared to other plasma sensors:

- The geometrical and electrical symmetry of the probe makes the measurement truly local, and, in general, the interference of the probe to the plasma is minimized, particularly in the pMRP design. For example, the MRP prototype reported in [82] had a radius \( R_p \), equal to 4 mm including a dielectric coating \( D_0 \) equal to 1 mm. The probe perturbs a region of plasma around its surface with thickness in the order of a Debye length \( \lambda_D \) and volume \( \text{Vol}_p \) equal to:

\[
\text{Vol}_p \sim \frac{4}{3} \pi \left( R_p + \lambda_D \right)^3 - R_p^3
\]

for a spherical probe, and equal to:

\[
\text{Vol}_p \sim \pi \lambda_D R_p^2
\]

for a disk probe. Therefore, a plasma volume larger than about 26 mm\(^3\) (spherical probe) or about 5 mm\(^3\) (disk probe) could be adequately probed with an MRP with \( R_p = 4 \) mm, and plasma with \( \lambda_D \sim 0.1 \) mm.

- It is simple to get the plasma properties from the probe measurement: the resonance frequency is a clear peak in the dissipated power spectrum, and it is straightforward to use mathematical modeling to extract the desired plasma parameters within sub-ms scale [23]. This makes the MRP sensor more reliable in real-time measurement compared to other types of sensors like a single LP that requires fitting of the probe characteristics.

- The probe is insensitive to dielectric coating (e.g. the MRP has been used to characterize plasma dielectric deposition [78, 85, 86]), which could be of interest to address contamination by space dust [33].

- The MRP sensor is insensitive to oxygen (of great practical importance when operating at LEO), while LPs suffer from the etching of the exposed electrode when oxygen is present [23].

- The MRP has high sensitivity to detect small fluctuations in plasma properties [87], and MRP probes using low-temperature co-fired ceramic technology have been shown to operate at temperatures as high as 500 °C [88].

In order to use an MRP in the ionosphere, some adjustments are necessary from the reported sensors. In the ionosphere, the Debye length is an order of magnitude larger than the Debye length of the laboratory plasmas used to characterize the MRP; consequently, the size of the probe should also increase accordingly so that the Debye length is much smaller than the probe and the model used to predict MRP’s behaviour is still valid. Experimentally, the MRP has been shown to measure electron densities between \( \sim 4 \times 10^{14} \) m\(^{-3}\) and \( \sim 1 \times 10^{17} \) m\(^{-3}\), and electron temperatures between 2 eV and 20 eV [82, 84, 86]. However, the electron density in the ionosphere at 500 km ranges between \( \sim 5 \times 10^{10} \) m\(^{-3}\) and \( \sim 1 \times 10^{12} \) m\(^{-3}\) [89], corresponding to a range of electron plasma frequency of 2 MHz–9 MHz using equation (10). Therefore, to cover the lower range of electron plasma frequency, a lower excitation frequency is required. For a spherical MRP, the ratio between the resonance frequency \( \Omega_s \) to the plasma frequency \( \omega_{pe} \) can be calculated as [77]:

\[
\frac{\Omega_s}{\omega_{pe}} = \sqrt{\frac{2\pi}{4\pi - 1} \left[ 1 - b_i \left( 1 + \frac{\delta}{R_p} \right)^{1-4\pi} \right]}
\]

where \( \delta \) is the plasma sheath thickness (on the order of the Debye length), \( s \) is the resonance mode, and \( b_i \) is an algebraic, dimensionless function of the parameters \( R_p, D_0, \) and \( \epsilon_D \). In addition, the size and power consumption of the electronics used to drive the MRP and collect data would also require adjustments to be able to fit inside a CubeSat (the reported MRPs were driven with rack electronics that take a lot of space and consume as much as 300 W (peak power)).

8. Fourier transform infrared (FTIR) spectrometers

The FTIR spectrometer covered in this section and the UV absorption spectrometer discussed in section 9 are unlike the other types of plasma sensors discussed in this review, as they are long-distance imagers rather than in situ sensors. Both sensors analyse the light that passes through the atmosphere and measure its properties. Consequently, both sensors measure properties of the atmosphere in a wide area as a distribution and suffer from resolution issues (besides any spatial resolution issues caused by the movement of the spacecraft). Also, both sensors are typically large and heavy, and have high power consumption (e.g. thermal and near-infrared sensor for carbon observation Fourier-transform spectrometer (TANSO-FTS) is 329 kg and consumes 400 W of power [90]). Although there are reports of miniaturized Michelson interferometers (a typical implementation for an FTIR spectrometer) [91], to the best of our knowledge there are no reported FTIR spectrometers onboard a CubeSat. It might be possible to implement a distributed optical system using a CubeSat constellation that performs like one of these optical plasma sensors if the relative positions of a CubeSat constellation are tightly controlled using high-specific impulse, highly throttleable micropropulsion thrusters, e.g. [92].

A plasma FTIR spectrometer observes molecules using infrared absorption. A molecule can absorb infrared light when its vibration or rotation changes its dipole moment [93]. The molecule’s change in energy level is unique, making it feasible to identify molecules from their spectral response. FTIR spectrometers can also measure the densities and temperature of the constituents of a gaseous mix using the Beer–Lambert law, which explains how radiation flux decreases by absorption along the path the light travels [94]. For plasma diagnostics, FTIR spectrometers are used to measure stable downstream
species. The concentration and temperature of radical and by-product neutrals can be measured.

FTIR spectrometry uses a Michelson interferometer or a variation of it to obtain the spectral response [95]. In a classical Michelson interferometer, the incident ray is divided into two by a beam splitter and reflected on a fixed mirror and a movable mirror; the reflected rays come back to the beam splitter and interference is made by the optical path difference depending on the movement of a movable mirror. The detected light intensity as a function of the location of the movable mirror (or the time when the mirror moves at constant speed) is called interferogram and the spectral response can be obtained from the inverse Fourier transform of the interferogram data [95]. There are many variations in the interferometer design for FTIR spectrometry, but they share the basic principle of getting an interferogram from optical path differences.

The performance of an FTIR spectrometer depends on many variables, but one of the key parameters is the maximum optical path difference. Ideally, an infinite range of optical path difference is needed for perfect spectral response after inverse Fourier transform. Since size is limited in a real instrument, spectral resolution of FTIR is inversely proportional to the maximum optical path difference [95]. Also, an oblique angle of the light rays or a misalignment in the optical system change the optical path difference and create errors. Therefore, an FTIR is sensitive to vibration and temperature changes, making the instrument complex when having moving parts. However, this disadvantage is compensated by the capability of single detection in wide spectrum, which is not possible in dispersive spectrometry.

FTIR instruments on satellites can be distinguished by whether they use limb view or nadir view [96]. Limb view FTIR spectrometers measure the sunlight scattered in the atmosphere from the horizon, while nadir view FTIR instruments measure the sunlight reflected on Earth’s surface and atmosphere by downward view. Limb view FTIR spectrometers have better spectral and vertical resolution than nadir view FTIR spectrometers, but their spatial resolution along the line of sight is poorer. Moreover, the troposphere cannot be observed by limb view because clouds and water vapor block the sight at low altitude. Nadir view FTIR spectrometers have a higher spatial resolution, and measurement from low altitude is possible for an area without clouds, but their vertical resolution is limited.

Many space missions have employed FTIR spectrometers for the atmospheric sounding of the Earth. Detection of trace gases in the atmosphere, temperature profile, cloud properties, and many other data from FTIR spectrometers are useful in weather forecasting and the study of dynamics and chemistry of the atmosphere. However, the great majority of space missions with FTIR spectrometers have focused on characterizing the troposphere, including the nadir viewing TANSO-FTS on board the GOSSAT [99]—launched in 2009, the nadir viewing infrared atmospheric sounding interferometer on board the satellites METOP-A, METOP-B, and METOP-C [100]—launched between 2006 and 2018, and the nadir viewing cross-track infrared sounder on board the Suomi NPP satellite—launched on 2011 [101]. Nonetheless, there are in-space FTIR spectrometers used to characterize the lower regions of the ionosphere. For example, the limb viewing MIPAS instrument on board ENVISAT (782 km mean altitude; launched in 2002, deactivated in 2013) can measure the vertical temperature profile and trace species in the region between upper troposphere and lower thermosphere [97]. Its spectral range is 685–2410 cm\(^{-1}\) and its spectral resolution is 0.025 cm\(^{-1}\). MIPAS (figure 12(a)) can observe parameters between 5 km and 160 km height with minimum and maximum steps equal to 1 km and 8 km, respectively (smaller step for lower altitude) [97]. Also, the ACE (atmospheric chemistry experiment) mission onboard the ACE satellite launched in 2003 (139 kg, 650 km altitude; still operating as of February 2021) uses a limb view FTIR spectrometer to provide height profiles between 10 km and 150 km of temperature, pressure, and volumetric ratios of several dozen molecules (figure 12(b)) [98]. This FTIR measures the vertical distribution of trace gases with 4 km vertical resolution across a spectral range between 750 and 4400 cm\(^{-1}\) with a spectral resolution of 0.02 cm\(^{-1}\).

9. UV absorption spectrometers

In many molecules, the energy difference between quantized electronic levels corresponds to the energy of photons in the UV spectrum. An UV absorption spectrometer uses these energy transitions as a signature to identify the molecules that makeup a sample. In the case of a space-borne UV absorption spectrometer, the reflectance spectrum of the atmosphere is obtained by measuring both Earth’s radiance and solar irradiance, using the latter as reference. Most UV absorption spectrometers use filters or dichroic mirrors to narrow the range of wavelengths measured and prisms or diffraction gratings to spread the incident light by wavelength. Then, a position-sensitive detector is used to measure the light intensity in each wavelength.

Many satellites with a UV absorption spectrometer onboard have been put in orbit to study the chemistry and physics of Earth’s atmosphere; some of these satellites have characterized the atmosphere’s composition in the lower regions of the ionosphere. The SCIAMACHY (scanning imaging absorption spectrometer for atmospheric chartography) was launched as a payload of ENVISAT (8100 kg satellite launched in 2002, active until 2012) to measure the vertical distribution of trace gases up to 90 km above Earth’s surface [102]. SCIAMACHY covers a wide spectrum range between 240 nm and 2380 nm, including UV, visible, and near-infrared wavelengths with spectral resolution between 0.2 nm and 1.5 nm. SCIAMACHY measures in nadir, limb, and solar/lunar occultation views. For heights above 50 km, the instrument is designed to measure O\(_3\), O\(_2\), H\(_2\)O and CO\(_2\) during occultation view, and singlet oxygen (O\(_2\) in a quantum state where all electrons are spin paired) and NO during occultation and limb views. Unlike the other traces, NO and singlet oxygen are determined with their emission profile instead of their absorption profile. The data from SCIAMACHY have been used to study the distribution of water and ozone (O\(_3\)) and their global circulation, and the destruction of ozone due to NO.
The GOME-2 (global ozone monitoring experiment 2), on board METOP-A (launched in 2006 and currently active, 817 km elevation orbit), METOP-B (launched in 2012), and METOP-C (launched in 2018), is focused on measuring the atmosphere’s ozone profile but also measures other gases, e.g. H\textsubscript{2}O, NO\textsubscript{2} [103]. GOME-2 (figure 13(a)) has four main channels covering light wavelengths between 240 nm and 790 nm with spectral resolution between 0.26 nm and 0.51 nm. GOME-2 is designed to measure trace gases up to \( \sim 90 \) km height (\( \sim 0.1 \) Pa) [104].

The OMI (ozone monitoring instrument) is based on the instrument flown in SCIAMACHY [105]; however, unlike SCIAMACHY, which measured the atmosphere in a wide area by moving a scan mirror across the track, OMI does not have a scanning mirror. Instead, it has a large field of view of 114°, and it uses a 2D charge-coupled device detector to get spectral information in 1D and spatial information in the other dimension. Therefore, the high spatial coverage of 2600 km swath width is possible in single detection.

Several of the UV absorption spectrometers in orbit were built to measure far UV (FUV) and extreme UV (EUV) light to observe the emission from ionized atoms in the ionosphere. For example, the GUVI (global UV imager) instrument installed in the thermosphere TIMED (ionosphere mesosphere energetics and dynamics) satellite (660 kg, launched in 2001, still active, 625 km altitude orbit) investigates the region between 60 km to 180 km [106]. GUVI (figure 13(b)) measures the temperature, density, composition, and wind structure of mesosphere and lower thermosphere, and studies various radiative, chemical, electrodynamical, and dynamical sources and sinks in the region. GUVI has a spectral range in FUV from 120 to 180 nm, so H, O, N\textsubscript{2}, and O\textsubscript{2} can be observed. Also, the Appleton Anomaly region in the ionosphere’s F-region, which has higher plasma density due to the plasma flow due to the \( E \times B \) drift, can be studied using the emission from singly ionized oxygen at 135.6 nm.

The IMAGE (magnetopause-to-aurora global exploration) satellite (494 kg, launched in 2000, contact lost in 2005) uses a FUV spectrometer to study the ramification of solar wind on the magnetosphere, specifically to determine the energy input from the solar wind into the ionosphere during quiet and disturbed times and assess how the temporal variation of the energy dissipation during all phases of the storm/substorm cycle [107]. The IMAGE FUV instrument is composed of two subsystems: (a) the wideband imaging camera senses photons in the 140 nm–170 nm range to detect Lyman–Birge–Hopfield band N\textsubscript{2} and singly ionized nitrogen; and (b) the spectrographic imager (a dual-wavelength monochromatic instrument) images Doppler-shifted Lyman-\( \alpha \) emission for proton detection and measures the oxygen emission at 135.6 nm. In addition, IMAGE also uses an EUV spectrometer to measure the distribution of He\textsuperscript{+} ions in the plasmasphere by capturing irradiance at 30.4 nm.

The spatial heterodyne imager for mesospheric radicals (SHIMMER) is different from other reported UV absorption spectrometers because it is based on spatial heterodyne spectroscopy (SHS) [108]. SHS uses an interferometer like FTIR, but without moving parts; instead, it creates a fringe pattern by different reflecting angles on grating depending on the wavelength. Because it is mechanically less complicated, SHIMMER could be made lighter than other similar instruments, having a mass of 30.53 kg and consuming 50 W of power. SHIMMER is on board the experimental spacecraft for space test program (STPSat-1) (launched in 2007, 164 kg). SHIMMER was
Figure 13. (a) The GOME-2 instrument (left) and its optical layout (right). In the optical layout, the optics are in one plane (except insets A and B). Nadir is in the \( z \) direction. The spectral light source for wavelength calibration is indicated as ‘hcl’, and the quartz tungsten halogen white light source is indicated as ‘qth’. Panel adapted from [103]. CC BY 3.0. (b) Illustration of the scan operation of the GUVI instrument. The slit dimension is subdivided into 14 pixels. Panel adapted from [106] John Wiley & Sons. Copyright 2003 by the American Geophysical Union. (c) Top view of SHIMMER optics assembly (left) and ray trace model for the same orientation. In the schematic T1, T2, and T 3 are telescope lenses, F1 and F2 are fold mirrors, IN is the interferometer, EX is the exit optics, and FPA is the focal plane array. Panel adapted from [108] John Wiley & Sons. Copyright 2010 by the American Geophysical Union.

The first SHS in-space mission, and it successfully observed the solar resonance fluorescence of hydroxyl radicals at 309 nm.

There is an early mission concept of a 12U CubeSat with an UV absorption spectrometer to study Venus’ atmosphere called CUVE [109]. However, to the best of our knowledge there are no reported UV absorption spectrometers onboard a CubeSat.

10. Outlook

During the last two decades, a wide variety of in-space plasma diagnostic hardware has been developed and utilized to characterize the electrons, ions, and neutral molecules that make up the Earth’s ionosphere. We identify five tentative directions for further development of in-space plasma sensors, i.e. (a) further reduction of the weight and size of the hardware, (b) implementation of multiplexed systems, (c) multi-sensor integration, (d) exploration of new sensor designs, and (e) development of better electronics.

10.1. Miniaturization of plasma diagnostics hardware

The use of plasma sensors onboard satellite constellations makes it possible to gather high-resolution, \textit{in situ} measurements of the ionosphere on a scale unmatched by any other approach [13]. Furthermore, size and weight reduction of spacecraft [12] would not only provide greater spatial resolution and redundancy by deploying larger constellations, but also would significantly reduce mission manufacturing costs and times. However, surface-micromachined MEMS plasma sensors might not be resilient enough for a long-term space application as they are made of thin films with a thickness in the order of a micrometre, and each film typically has a high level of stress that could limit the mechanical performance of the structure [28, 34]. In the case of the bulk-micromachined MEMS plasma sensors, there are still issues for long-term reliability if important aspects of their operation, e.g. electrical insulation, are still implemented with thin films, e.g. [45]. Additive manufacturing, i.e. the process of joining materials to make parts, usually layer by layer [110], is unmatched to produce complex, small-batch hardware such as a satellite.
10.3. Multi-sensor integration

There is an opportunity to create better plasma sensors by integrating more functionality in fundamentally the same hardware. For example, RPA (see section 3) can have the collector electrode slightly modified (i.e. segmented, to be able to independently electrically probe each segment) to operate as an IDM (see section 4) or can be run as an FC (see section 5). The idea is then to monolithically create sensing hardware that gives different data because of how the hardware is operated or because of slight modifications, supported by versatile software. Efforts along these lines have been already reported, for example, the sensor reported by Lin et al onboard FORMOSAT-5 is multifunctional thanks to its software-programmable hardware that can operate as RPA, IDM and ion trap [37]. Sequentially, using the sensor on each mode, different kinds of measurements can be collected, resulting in a broader, richer dataset.

Another key opportunity for multi-sensor integration is obtaining redundant data to improve the accuracy and reduce the risk of the space mission. Collecting data with some degree of redundancy would contrast with the current general trend where satellites that have on board a plurality of plasma sensors operate them to determine non-overlapping data.

In addition, data integration from multiple sensors probing the same plasma will increase the accuracy of the measurements [76] and make possible to conduct more consistent, accurate, and useful assessments via data fusion. For example, in 2000, the Ukrainian satellite SICH-1M was launched as part of the VARIANT space experiment project [70]. The satellite had as scientific payload a split LP, a Rogovski coil, and an FC. The 1st two instruments were dedicated to measure current density variations, while the FC was used for measuring charged particles’ fluxes. One of the key objectives of the mission is to compare significantly overlapping data (compare the measured, field-aligned current structures with the characteristics of the ionospheric convection observed by the system of radars SuperDARN) and to correlate the new data to multidisciplinary knowledge (e.g. seismic and volcanic signatures; man-made impact upon the ionosphere) [70].

10.4. Exploration of novel plasma sensor designs

It would be interesting to try new plasma sensors in space, looking to extend current capabilities in terms of dynamic range, signal-to-noise ratio, and measurable plasma properties. For example, no MRP (see section 7) has been used or planned to be used in space missions, perhaps because they are relatively new sensors. However, MRPs have several advantages compared to other plasma sensors. For example, the geometrical and electrical symmetry of the probe makes the measurement truly local, and, in general, the interference of the probe to the plasma is minimized, particularly in the pMRP design. Also, it is simple to get the plasma properties from the probe measurement. Moreover, the probe is insensitive to dielectric coating, which could be of interest to address contamination by space dust [33]. In addition, MRPs have high sensitivity to detect small fluctuations in plasma properties.
Additionally, MRPs are more reliable in real-time measurements compared to other types of plasma sensors [23]. Furthermore, MRPs are insensitive to oxygen—of great practical importance when operating at LEO [23]. The reported work on MRPs has focused on the characterization of laboratory plasmas with Debye lengths at least a tenfold smaller than the typical Debye length in the ionosphere; consequently, an ionospheric MRP probe would need to be scaled at least in the same proportion, so the Debye length is a lot smaller than the characteristic dimensions of the probe and the theory that describes the operation of the sensor is still valid. Extending the measurement range of the probe to values of relevance to the ionosphere will also require changing the range of frequencies of operation of the electronics, utilizing an array of sensors (see section 10.2) and developing compact, low-power electronics compatible to the size, weight, and power restrictions in a satellite, or even better a CubeSat.

Although there are reports of miniaturized Michelson interferometers and other optical systems, e.g. [91], and there is an early mission concept of a CubeSat with an UV absorption spectrometer to study Venus’ atmosphere [109] to the best of our knowledge there are no reported FTIR spectrometers or UV absorption spectrometers onboard a CubeSat. It would be interesting to see if a miniaturized optical plasma instrument such as a FTIR spectrometer or an UV absorption spectrometer could be implemented in a CubeSat. Also, it might be possible to implement a distributed optical system using a CubeSat constellation if the relative positions of the CubeSats are tightly controlled, perhaps yielding a better optical system compared to a single-CubeSat counterpart.

10.5. Development of better electronics

Given that satellites travel across space at speeds on the order of 8 km s\(^{-1}\) or more, having faster electronics (shorter measuring time, faster sampling rate) to run the plasma sensors would make possible to capture localized and spatially dense data. For example, if the sensor takes a second to measure a property, the measurement is, in reality, the average across a multi-kilometre long strip; however, if the sensor can measure the property orders of magnitude faster, the satellite would be able to locally measure the property, and, if the sampling rate is large enough, the data would also be dense.

In the past, the use of basic microcontrollers like the peripheral interphase controller chips in some of the space missions resulted in operational difficulties due to their processing limitations. More recently, the use of FPGAs has demonstrated to have good performance and capabilities to manage the sensor sequentially. In principle, electronics developed for Earth-bound applications can be made radiation hard for space applications by putting them inside a ~1 cm thick Al box [29], making possible to bring to space the latest developments in electronics technology, using low-cost platforms such as a CubeSat to mitigate the risk. Graphics processing unit (GPU) chips, originally developed for rendering images, can process many pieces of data in parallel, which is of great interest for an autonomous platform such as a satellite. Current GPU-based boards are improving in aspects such as low-energy consumption, high computational power, and small size, making them attractive for a CubeSat platform. As well, this kind of systems have a processing capacity that can reach to Giga floating point operations per second. Thus, by taking advantage of new electronics like those used in autonomous electric vehicles that can acquire big data from massively parallelized sensors, it could be possible to collect and process on board plasma data, and via artificial intelligence, give a larger degree of autonomy to the spacecraft.

The on-board plasma sensors could benefit from being run by more sensitive, less power-hungry electronics that also have less noise and are capable of a larger measurement range (e.g. [113]). Recent advances in ultra-low power, artificial intelligence-accelerated electronics (e.g. [114]) could be leveraged to demonstrate electronics using a combination of commercial, off the shelf and ASICs (application-specific integrated circuits) to attain low power consumption, fast wakeup/sleep response and high energy efficiency. Cryogenic operation of ASICs, made possible by the low ambient temperature in space, could greatly reduce leakage current and greatly reduce operating power in the electronics. The designs could be radiation hard through a combination of resilient design techniques, redundancy, and algorithmic error correction [115].

Data availability statement

No new data were created or analysed in this study.

Acknowledgments

The authors would like to thank Junchan Lee, Satellite Technology Research Center, Korea, for furnishing figures 3(a) and 5(b), Parris Neal, Space Physics and Atmospheric Research Center, US Air Force Academy, for furnishing figure 10(a), and Marc-André Soucy, ABB Inc., Québec, Canada, for furnishing figure 12(b). In addition, the authors would like to thank Jens Oberrath, South Westphalia University of Applied Science, Soest, Germany for helpful discussions on theoretical and practical aspects of the MRP sensor. This work was sponsored by the Monterey Tec-Massachusetts Institute of Technology (MIT) Nanotechnology program and the NewSat project. The NewSat project is co-funded by the Operational Program for Competitiveness and Internationalisation (COMPETE2020), Portugal 2020, the European Regional Development Fund (ERDF), and the Portuguese Foundation for Science and Technology (FCT) under the MIT Portugal program.

ORCID iDs

Luis Fernando Velásquez-García https://orcid.org/0000-0002-9232-1244
Javier Izquierdo-Reyes https://orcid.org/0000-0001-9698-4355
Hyeonseok Kim https://orcid.org/0000-0002-2061-366X
References

[1] Zolesi B and Cander L R 2014 The General Structure of the Ionosphere (Ionospheric Prediction and Forecasting) (Berlin: Springer)
[2] U.S. National Oceanic and Atmospheric Administration 1976 US Standard Atmosphere (Washington: US Government Printing Office)
[3] Kelly M 2009 The Earth’s Ionosphere (Plasma Physics and Electrohydrodynamics) (NY: Academic)
[4] Rawer K 1993 Wave Propagation in the Ionosphere (Netherlands: Kluwer Academic Publishing)
[5] Bailey S M, Thurairajah B, Hervig M E, Siskind D E, Russell J M and Gordley L L 2021 Trends in the polar summer mesosphere temperature and pressure altitude from satellite observations J. Atmos. Sol. Terr. Phys. 220 105650
[6] Solomon S C, Liu H-L, Marsh D R, Mcinerney J M, Qian L and Vitt F M 2018 Whole atmosphere simulation of anthropogenic climate change Geophys. Res. Lett. 45 15567–1576
[7] Hutchinson I H 2002 Principles of Plasma Diagnostics (Cambridge: Cambridge University Press)
[8] Bilitza D, Altadill D, Truhlik V, Shubin V, Galkin I, Klein M, Merikallio S, Lagoutte D, Poirier B, Lagoutte D, Poirier B, Marklund M, Oblozinsky P, Fisk M and Hong X 2017 International Reference Ionosphere 2016: from ionospheric climate to real-time weather predictions Space Weather 15 418–29
[9] Jones H W 2018 The recent large reduction in space launch cost 48th Int. Conf. on Environmental Syst. (Albuquerque: ISES) pp 2018–81
[10] Sutton G P and Biblarz O 2017 Rocket Propulsion Elements (Hoboken, NY: Wiley)
[11] Knudsen Salazar V 2012 Emerging trends in the satellite industry MBA Thesis (Massachusetts Institute of Technology, Cambridge)
[12] Atem de Carvalho R, Estela J and Langer M (eds) 2020 Nanosatellites: Space and Ground Technologies, Operations and Economics (NY: Wiley)
[13] Roberts T M, Lynch K A, Clayton R E, Weiss J and Hampton D L 2017 A small spacecraft for multipoint measurement of ionospheric plasma Rev. Sci. Instrum. 88 073507
[14] Hershkowitz N 1989 How Langmuir Probes Work (NY: Academic)
[15] Lobbia R B and Beal B E 2017 Recommended practice for use of Langmuir probes in electric propulsion testing J. Propuls. Power 33 566–81
[16] Lobbia R B and Gallimore A D 2010 High-speed dual Langmuir probe Rev. Sci. Instrum. 81 073503
[17] Qayyum A, Ahmad N, Ahmad S, Deeba F, Ali R and Hussain S 2013 Time-resolved measurements of plasma parameters by means of triple probe Rev. Sci. Instrum. 84 123502
[18] Langmuir I 1923 Positive ion currents from the positive column of mercury arc Science 58 290–1
[19] Reifman A and Dow W G 1949 Dynamic probe measurements in the ionosphere Phys. Rev. 76 987–8
[20] Lebreton J P, Stervak S, Travinpek N, Maskimovic Knigle M D, Merkallio S, Lagoutte D, Poirier B, Bliely P L and Kozacek Z 2006 The ISL Langmuir probe experiment processing onboard DEMETER: scientific objectives, description and first results Planet. Space Sci. 54 472e486
[21] Lee J C, Min K W, Han J W, Kim H J, Lee J J and Hong S K 2013 Langmuir probe experiments on Korean satellites Curr. Appl. Phys. 13 846–9
[22] Zlotnicki J, Li F and Parrot M 2013 Ionospheric disturbances recorded by DEMETER satellite over active volcanoes: from August 2004 to December 2010 Int. J. Geophys. 2013 530865
[23] Fiebrandt M, Oberberg M and Awakowicz P 2017 Comparison of Langmuir probe and multipole resonance probe measurements in argon, hydrogen, nitrogen, and oxygen mixtures in a double ICP discharge J. Appl. Phys. 122 013502
[24] Kim H, Min K, Park J, Lee J, Lee E, Kil H, Kim V P and Park S 2006 Comparison of satellite measurements of the low-latitude night time upper ionosphere with IRI J. Atmos. Sol. Terr. Phys. 68 2107–18
[25] Zakharov Y P, Antonov V M, Shaikhislamov I F, Boyarintsev E L, Melekhov A V, Vchikov K V and Prokopov P A 2011 Experimental design and probe diagnostics for simulation of AMS02-Magnet effects in ionospheric plasma flow near International Space Station Contrib. Plasma Phys. 51 182–6
[26] Fish C S et al 2014 Design, development, implementation, and on-orbit performance of the dynamic ionosphere CubeSat experiment mission Space Sci. Rev. 181 61–120
[27] Bendoukha S, Fajardo Tapia L, Okuyama K-I and Cho M 2019 An experimental and theoretical study of spatial Langmuir probe plasma system for a small lean satellite called Ten-Koh Int. Rev. Aerosp. Eng. 12 131–40
[28] Pribyl P, Gekelman W, Nakamoto M and Lawrrence E 2006 Debye size microprobes for electric field measurements in laboratory plasmas Rev. Sci. Instrum. 77 073504
[29] Mörk A 2020 Radiation analysis for moon and Mars missions Int. J. Astrophys. Space Sci. 8 16–26
[30] Eckman R, Byrne L, Gatsonis N and Pencil E 2001 Triple Langmuir probe measurements in the plume and background region of a pulsed plasma thruster 37th Joint Propuls. Conf. Exhib., American Institute of Aeronautics and Astronautics (Reston, VA) (https://doi.org/10.2514/ 6.2001-3640)
[31] Tummala A R and Dutta A 2017 An overview of cube-satellite propulsion technologies and trends Aerospace 4 58
[32] Gatsonis N A, Byrne L T, Zwahlen J C, Uchida E and Kamihata H 2004 Current-mode triple and quadruple Langmuir probe methods with applications to flowing pulsed plasmas IEEE Trans. Plasma Sci. 32 2118–29
[33] Klindworth M, Arp O and Piel A 2007 Langmuir probe system for dusty plasmas under microgravity Rev. Sci. Instrum. 78 033502
[34] Campbell S A 2013 Fabrication Engineering and the Micro-and Nanoscale (Oxford: Oxford University Press)
[35] Stillman J A, Chiang F C, Pribyl P, Gekelman W, Nakamoto M and Judy W 2009 MEMS electric-field probes for laboratory plasmas J. Microelectromech. Syst. 18 983–9
[36] Chimamkpam E F C, Field E S, Akinwande A I and Velasquez-Garcia L F 2014 Resilient batch-fabricated planar arrays of miniaturized Langmuir probes for real-time measurement of plasma potential fluctuations in the HF to microwave frequency range J. Microelectromech. Syst. 23 1131–40
[37] Lin Z-W, Chao C K, Liu J Y, Huang C M, Chu Y H, Su C L, Mao Y C and Chang Y S 2017 Advanced ionospheric probe scientific mission onboard FORMOSAT-5 satellite Terr. Atmos. Ocean. Sci. 28 99–110
[38] Fajardo I et al 2019 Design, implementation, and operation of a small satellite mission to explore the space weather effects in LEO Aerospace 6 108
[39] Krassovsky V 1959 Exploration of the upper atmosphere with the help of the third soviet Sputnik Proc. IRE 47 289–96
results of space radiation dosimetry using the iMESAR-R Space Weather 18 e2020SW002473

[77] Lapke M, Mussenbrock T and Brinkmann R P 2008 The multipole resonance probe: a concept for simultaneous determination of plasma density, electron temperature, and collision rate in low-pressure plasmas Appl. Phys. Lett. 93 051502

[78] Pohle D, Schulz C, Oberberg M, Awakowicz P and Rolfe S I 2020 The planar multipole resonance probe: a minimally invasive monitoring concept for plasma-assisted dielectric deposition processes IEEE Trans. Microw. Theory Tech. 68 2067–79

[79] Lapke M, Oberraith J, Mussenbrock T and Brinkmann R P 2013 Active plasma resonance spectroscopy: a functional analytic description Plasma Sources Sci. Technol. 22 025005

[80] Oberraith J and Brinkmann R P 2014 Active plasma resonance spectroscopy: a kinetic functional analytic description Plasma Sources Sci. Technol. 23 045006

[81] Oberraith J 2020 The spherical multipole resonance probe: kinetic damping in its spectrum Plasma Sources Sci. Technol. 29 055005

[82] Lapke M et al 2011 The multipole resonance probe: characterization of a prototype Plasma Sources Sci. Technol. 20 042001

[83] Schulz C, Rolfe S, Styrnoll T, Awakowicz P, Lapke M, Oberraith J, Mussenbrock T, Brinkmann R P, Storck R and Mush T 2012 The multipole resonance probe: investigation of an active plasma resonance probe using 3D-electromagnetic field simulations 42nd European Microwave Conf. (Amsterdam) (https://doi.org/10.23919/EuMC.2012.6459256)

[84] Schulz C, Styrnoll T, Awakowicz P and Rolfe S I 2015 The planar multipole resonance probe: challenges and prospects of a planar plasma sensor IEEE Trans. Instrum. Meas. 64 857–64

[85] Steves S, Styrnoll T, Mitscherl F, Bienholz S, Nikita B and Awakowicz P 2013 Characterization of low-pressure microwave and radio frequency discharges in oxygen applying optical emission spectroscopy and multipole resonance probe J. Phys. D: Appl. Phys. 46 445201

[86] Styrnoll T, Harhausen J, Lapke M, Storck R, Brinkmann R P, Foest R, Ohl A and Awakowicz P 2013 Process diagnostics and monitoring using the multipole resonance probe in an inhomogeneous plasma for ion-assisted deposition of optical coatings Plasma Sources Sci. Technol. 22 045008

[87] Pohle D, Schulz C, Oberberg M, Awakowicz P and Rolfe S I 2019 Monitoring of industrial plasma processes using the multipole resonance probe 2019 European Microwave Conf. in Central Europe (Eumce) pp 622–5

[88] Pohle D, Schulz C, Rolfe S, Oberberg M, Awakowicz P and Serwa A 2018 An advanced high-temperature stable multipole resonance probe for industry compatible plasma diagnostics 11th German Microwave Conf. (Gemic) pp 235–8

[89] Kelley M C 2009 The Earth’s Ionosphere: Plasma Physics and Electrodynamics (NY: Academic)

[90] Moreau L, Veilleux J and Suto H 2014 The GOSAT/TANSO interferometer after five years on orbit Proc. SPIE 9219, Infrared Remote Sensing and Instrumentation XXI (San Diego) p 921902

[91] Maciel M J, Costa C G, Silva M F, Peixoto A C, Wolfenbuttel R F and Correa J H 2016 A wafer-level miniaturized Michelson interferometer on glass substrate for optical coherence tomography applications Sens. Actuators A 242 201–16

[92] Melo Máximo D and Velásquez-Garcia L F 2020 Additively manufactured electrophysiological ionic liquid pure-ion sources for nanosatellite propulsion Addit. Manuf. 36 101719

[93] Cruden B A, Rao M V V S, Sharma S P and Meyyappan M 2002 Fourier transform infrared spectroscopy of CF4 plasmas in the GEC reference cell Plasma Sources Sci. Technol. 11 77–90

[94] Reuter S, Sousa J S, Stancu G D and van Helden J-P H 2015 Review on VUV to MIR absorption spectroscopy of atmospheric pressure plasma jets Plasma Sources Sci. Technol. 24 054001

[95] Persky M J 1995 A review of spaceborne infrared Fourier transform spectrometers for remote sensing Rev. Sci. Instrum. 66 4763–97

[96] Beer R, Glavich T A and Ridder D M 2001 Tropospheric emission spectrometer for the Earth observing system’s Aura satellite Appl. Opt. 40 2356–67

[97] Fischer H et al 2008 MIPAS: an instrument for atmospheric and climate research Atmos. Chem. Phys. 8 2151–88

[98] Bernath P F et al 2005 Atmospheric chemistry experiment (ACE): mission overview Geophys. Res. Lett. 32 15

[99] Kuze A, Suto H, Nakajima M and Hamazaki T 2009 Thermal and near infrared sensor for carbon observation Fourier-transform spectrometer on the greenhouse gas observing satellite for greenhouse gases monitoring Appl. Opt. 48 6716–33

[100] Le Barbier L et al 2020 Monitoring and performances evolutions of the 3 in-flight IASI instruments on-board METOP satellites EGU General Assembly Conf. Abstracts, EGU pp 2020–7007

[101] Strow L L, Motteler H, Tobin D, Revercomb H, Hannon S, Buijs H, Predina J, Suwinski L and Glumb R 2013 Spectral calibration and validation of the cross-track infrared sounder on the suomi NPP satellite J. Geophys. Res. Atmos. 118 12486–96

[102] Bovensmann H, Burrows J P, Buchwitz M, Frerick J, Noël S, Rozanov V V, Chance K V and Goede A P H 1999 SCIAMACHY: mission objectives and measurement modes J. Atmos. Sci. 56 127–50

[103] Munro R et al 2016 The GOME-2 instrument on the Metop series of satellites: instrument design, calibration, and level 1 data processing—an overview Atmos. Meas. Tech. 9 1279–301

[104] Kauppi A, Tuinder O N E, Tukiainen S, Sofieva V and Tamminen J 2016 Comparison of GOME-2/Metop-A ozone profiles with GOMOS, OSIRIS and MLS measurements Atmos. Meas. Tech. 9 249–61

[105] Levelt P F et al 2006 The ozone monitoring instrument IEEE Trans. Geosci. Remote Sens. 44 1093–101

[106] Christensen A B et al 2003 Initial observations with the global ultraviolet imager (GUVI) in the NASA TIMED satellite mission J. Geophys. Res. Space Phys. 108 1451

[107] Frey H U, Mende S B, Immel T J, Gérad J-C, Hubert B, Habraken S, Spamp J, Gladstone G R, Biskaku D V and Shematchov I V 2003 Summary of quantitative interpretation of IMAGE far ultraviolet auroral data Magnetospheric Imaging—The Image Prime Mission ed J L Burch (Berlin: Springer) pp 255–83

[108] Englert C R, Stevens M H, Siskind D E, Harlander J M and Roesler F L 2010 Spatial heterodyne imager for the Earth’s ionosphere: Plasma Physics and Electrodynamics 1 ed

[109] Hewagama T, Ignatiev N and Piccioni G 2017 Mesospheric radicals on STPSat-1 Proc. SPIE 9219, The Earth’s Ionosphere: Plasma Physics and Electrodynamics 1 ed

[110] Maciel M J, Costa C G, Silva M F, Peixoto A C, Wolfenbuttel R F and Correa J H 2016 A wafer-level miniaturized Michelson interferometer on glass substrate for optical coherence tomography applications Sens. Actuators A 242 201–16

[111] Cottini V, Aslam S, d’Aversa E, Glaze L, Gorius N, Hewagama T, Ignatiev N and Piccioni G 2017 CUVE—CubeSat UV experiment: unveil Venus’ UV absorber with CubeSat UV mapping spectrometer European Planetary Science Congress, EPS 2017–771
[110] ASTM Int 2015 ISO/ASTM 52900–15, standard terminology for additive manufacturing—general principles—terminology (West Conshohocken: ASTM International)

[111] Michalak A 2019 Generative design optimization of thermal management systems for high output power electronics MS Thesis University of Toronto

[112] Schulz C, Runkel J, Oberberg M, Awakowicz P and Rolfes I 2016 Diagnostics of plasma processes based on parallelized spatially resolved in situ reflection measurements IEEE Trans. Microw. Theory Tech. 64 616–23

[113] Andreev S N, Bernatskiy A V and Ochkin V N 2020 Increasing the measurement range of plasma electron parameters in the single Langmuir probe method Bull. Lebedev Phys. Inst. 47 317–9

[114] Karthi S P, Kavitha K, Babu G, Kumar J R D, Visvesvaran C and Girinath N 2021 Ultra-low power memory circuit unit for space application IOP Conf. Ser.: Mater. Sci. Eng. 1084 012059

[115] Gao Z, Reviriego P, Xu Z, Su X, Zhao M, Wang J and Maestro J A 2016 Fault tolerant parallel FFTs using error correction codes and Parseval checks IEEE Trans. Very Large Scale Integr. Syst. (VLSI) 24 769–73