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LINDA – the Astrid-2 Langmuir probe instrument

B. Holback[1], **Å. Jacksén**[1], **L. Åhlén**[1], **S.-E. Jansson**[1], **A. I. Eriksson**[1], **J.-E. Wahlund**[1], **T. Carozzi**[1], **and J. Bergman**[2]

[1]Swedish Institute of Space Physics, Uppsala Division, Ångström Laboratories, Box 537, SE 751 21 Uppsala, Sweden
[2]Department of Astronomy and Space Physics, Uppsala University, Ångström Laboratories, Box 515, SE 751 20 Uppsala, Sweden

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Abstract. The Swedish micro-satellite Astrid-2, designed for studies in magnetosperic physics, was launched into orbit on 10 December 1998 from the Russian cosmodrome Plesetsk. It was injected into a circular orbit at 1000 km and at 83 degrees inclination. The satellite carried, among other instruments, a double Langmuir Probe instrument called LINDA (Langmuir INterferometer and Density instrument for Astrid-2). The scientific goals of this instrument, as well as the technical design and possible modes of operation, are described. LINDA consists of two lightweight deployable boom systems, each carrying a small spherical probe. With these probes, separated by 2.9 meters, and in combination with a high sampling rate, it was possible to discriminate temporal structures (waves) from spatial structures. An onboard memory made it possible to collect data also at times when there was no ground contact. Plasma density and electron temperature data from all magnetic latitudes and for all seasons have been collected.

Key words. Ionosphere (plasma temperature and density; plasma waves and instabilities; instruments and techniques)

1 Introduction

The Swedish micro-satellite Astrid-2 (Marklund et al., 2001) was launched, piggyback on a Cosmos-3M rocket, into a circular orbit at 1000 km altitude on 10 December 1998, from the Russian cosmodrome Plesetsk. The high inclination of 83 degrees ensured auroral oval crossings on every orbit, both in the north and in the south. Auroral physics phenomena were of prime interest, although the spacecraft was also designed to perform global survey measurements by use of onboard memories. Although small and lightweight, the satellite contained a full set of scientific instruments designed for studies of the near earth plasma, especially in the auroral zones.

The most fundamental parameter for characterising a plasma is its electron density, which, together with the electron temperature, can be derived by fitting the current-voltage characteristic of a Langmuir probe to expressions provided by relevant probe theory. The Langmuir INterferometer and Density instrument for Astrid-2, LINDA, implemented this technique, as well as constant bias voltage operations for the study of slow and fast variations of plasma density. For studies of fast density variations, LINDA used two probes for the determination of correlation functions and the discrimination of stationary structures from plasma waves. LINDA was designed and built at the Uppsala division of the Swedish Institute of Space Physics (IRF-U), and thus, bears heritage from previous IRF-U Langmuir probe instruments developed from the 1960s onward, including several sounding rockets (e.g. Holmgren et al., 1980), the Earth-orbiting satellites Viking and Freja (Eriksson et al., 1997; Holback et al., 1994), and the Saturn-bound Cassini mission (Gurnett et al., 2000). LINDA was closely integrated with the EMMA instrument.

In this paper, we give a general description of the LINDA instrument, its capabilities, operations and scientific objectives. LINDA scientific results can be found, for example, in the accompanying paper Ivchenko et al. (2001), while technical documentation, at a more detailed level, has been provided by Jacksén (1998).

2 Scientific objectives

The following topics should not be taken as an exhaustive list of all the scientific possibilities created by LINDA: several other phenomena undoubtedly can be studied using LINDA data. However, in the design of LINDA, the following four scientific objectives were considered central:

Large-scale plasma density structures in the auroral zone. It has been known for a long time that the auroral zones show very complicated structures and are highly dynamic. In later years, satellites, such as Viking, FAST, Freja, and Astrid-2 have studied the auroral zones equipped with instruments well suited to studying, in particular, the low plasma density commonly observed in these regions (e.g. Hilgers et al.,

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Correspondence to: B. Holback (bh@sol.irfu.se)

1992; Eriksson et al., 1997; McFadden et al., 1999; Hamrin et al., 2000). As can be seen in the Freja results, reported by Mäkelä et al. (1998) from altitudes in the range of 1500–1750 km, these large-scale cavities are very structured and dynamic even at altitudes below the principal auroral acceleration region. For lower altitudes, around 1000 km, Astrid-2 measurements give valuable and complementary data on this issue, which, together with the results from Freja and FAST at higher altitudes, give better insight into how the latitudinal structuring varies with altitude. Our present understanding of the altitude variations is rudimentary at best. Though Astrid-2 cannot provide direct observations of the altitude variation, future comparison of statistical studies at different altitudes may give insight also into this question.

Small-scale plasma density structures. Sounding rockets (e.g. Vago et al., 1992) and the Freja satellite (Eriksson et al., 1994; Pécseli et al., 1996) have revealed transversely small density depletions (ion gyroradius scale), while along the magnetic field, very elongated density depletions with enhanced wave activity in the lower hybrid frequency range have been observed. The sounding rockets, which move slowly and have high telemetry bandwidth, have provided great detail for just a few events (e.g. Pinçon et al., 1997), while Freja, in its nearly three years of operation, yielded a wealth of observations providing occurrence statistics (Dovner et al., 1997; Kjus et al., 1998). It is of great interest to supplement the Freja results from 1500–1750 km altitudes with statistics from the Astrid-2 altitude of 1000 km. With its limited sampling frequency, LINDA cannot normally resolve the full waveform of the lower hybrid waves, but the associated density depletions are accessible. Other kinds of small-scale plasma structures, such as the polar cap irregularities studied by Holmgren and Kintner (1990), can also be studied by LINDA.

Auroral plasma waves. The auroral zone is well known to be rich in plasma wave phenomena. Though wave instruments preferentially address the vector quantities of electric and magnetic field variations, plasma density variations provide useful extra information, as shown by Kelley and Mozer (1972). The technique to measure the relative density variations by means of Langmuir probes has recently been described by Wahlund et al. (1998). Of particular use are the interferometric two-point measurements, pioneered in space on sounding rockets (Kintner et al., 1984) and first used on satellites with Viking (Holmgren and Kintner, 1990). The possibility of this kind of measurement enables LINDA to establish phase velocities and to distinguish spatial structures from propagating waves. One should also note that at high frequencies, the LINDA probes will behave as an electric field antenna rather than as classical Langmuir probes (Sect. 3.3).

Global distribution of plasma density and temperature in the upper ionosphere. Despite decades of studies, many important aspects of the thermal plasma density and temperature distribution in the upper ionosphere are still unknown, even at low latitudes. Although IRI, the International Reference Ionosphere (Bilitza, 1990), provides a model of the electron density, electron temperature, ion temperature, and ion composition in the altitude range from about 50 km to about 2000 km, much work still remains on improving its predictions for the topside ionosphere (Titheridge, 1998). While bottomside measurements are abundant from ionosondes, IRI and similar models must rely on data from a relatively small number of satellites and incoherent scatter facilities for information on the topside; further input from this region, such as that provided by LINDA, is, therefore, highly desirable.

3 Measurement principles

3.1 General

The Langmuir probe is the standard laboratory tool for determining electron density and temperature in a plasma, by analysis and fitting of a measured current-voltage relation to a theoretical expression. On Astrid-2, two instruments, LINDA and EMMA, employed this method, although with slightly different techniques and using probes of a different size. LINDA used the classical laboratory technique of sweeping the bias voltage and measuring the current, while EMMA varied instead the bias current while measuring the probe voltage. Though the techniques are equivalent in theory, they have their own practical advantages and disadvantages. It is often simpler to cover a wide dynamic range with bias voltage sweeps, while the voltage measured in the current sweep method can easily be referred to a second probe at constant bias current, thereby removing potential problems with insufficient return current (Brace, 1998). Further comparisons of LINDA and EMMA methods and data can be found in the paper by Ivchenko et al. (2001).

Although conceptually a very simple device, the performance of a spherical Langmuir probe can be very hard to understand in all aspects, in the general case. However, in the limit of a collissionless and unmagnetized low-density plasma, the classical theory for orbital motion limited (OML) current collection by electrostatic probes (Mott-Smith and Langmuir, 1926) applies. In the ionosphere at 1000 km, collisions can clearly be neglected and magnetisation effects on the current collection are expected to be small.

The thermal electron gyroradius in a 0.1 eV plasma is a few centimetres, which is significantly greater than both the probe radius and the Debye length (Rubinstein and Laframboise, 1982). However, the relatively high density requires some further consideration. Debye lengths, down to a few millimetres, may be expected, and taking the Debye length, as an estimate of the probe sheath thickness, and comparing it to the LINDA probe radius of 5 mm (Sect. 5.1 below), shows that the sheath cannot always be considered thick, and thus, the simple OML theory will not be universally applicable. This difficulty can be solved, in practice, by calculating the Debye length from the density and temperature derived from the probe sweeps, to self-consistently verify that it is much greater than the probe radius. If not, the derived parameters

Table 1. LINDA specifications summary

Electronics boards (2)	Size	177.5 × 122.1 mm
Booms (2)	Mass including probe and cable	80 g (for 1 boom)
	Retaining mechanism mass	20 g (for 1 boom)
Spherical probes	Size	10 mm diameter
	Material	Titanium
	Surface treatment	TiN
Density ($I \sim n$) signal	Sampling frequency	16 Hz
	Resolution	16 bits, 2 ranges
	Probe current limits	1×10^{-10} to 5×10^{-5} A
	Density limits	10^{7} to 5×10^{12} m^{-3}
	Low pass filter	8 Hz
$\Delta n/n$ signal	Sampling frequency	8 kHz
	Resolution	8, 10 or 12 bits
	Amplitude	Corresp to 0.01–50% of n
	Low pass filter	4 kHz
	High pass filter	10 Hz
Telemetry	Average allocation to LINDA	16 kbits/s (out of 128)
	Used for 2 DC (n) signals	0.5 kbits/s (approximately)
	Used for 2 AC ($\Delta n/n$) signals	15 kbit/s (approximately)
	Used for status etc.	0.5 kbits/s (approximately)
	Buffer memory	2 MBytes

must be interpreted with care.

3.2 The relative density variation, $\Delta n/n$

One of the appealing properties of a probe operating in the OML regime, magnetised or not, is that the probe current is always proportional to the plasma density. This means that the relative density fluctuations, $\Delta n/n$, can always be estimated from the relative variation in the probe current, $\Delta I/I$, assuming constant temperature. Using the numerical results of Laframboise (1966) as input to their calculations, Eriksson and Boström (1995) showed that $\Delta I/I = \Delta n/n$ with a good accuracy, even for Debye lengths as small as the probe radius. In that situation, they found the relative error $(\Delta I/I - \Delta n/n)/(\Delta I/I)$ to stay at a level of 0.1 or less for moderate fluctuation amplitudes. If the temperature can be assumed to stay constant, the LINDA $\Delta I/I$ record can thus be taken as an estimate of the density variation to this order of accuracy.

3.3 Probe signals due to density variations and to electric field variations

Besides being sensitive to density variations, Langmuir probes are also sensitive to varying electric fields causing displacement currents that contribute to the probe current. The displacement current is determined by the sum of the probe-to-plasma and instrument input capacitances (C), as well as by the amplitude and frequency of the electric field variation. This effect can be so high that it can exceed the current variation due to $\Delta n/n$, and happens primarily at higher frequencies (Eriksson and Boström, 1995). The frequency at which this happens depends on the ratio of the density fluctuation and electric field amplitudes of the phenomenon under study. As a general rule, the RC time, where R is the probe sheath resistance and C is the total capacitance mentioned above, will give a good indication. We can determine R experimentally from the slope of the probe current-voltage relation, and C can be assumed to stay constant at a few pF. For LINDA, the limiting frequency will typically be in the few kHz range, so that the high-frequency end of the data (close to the Nyqvist frequency of 4 kHz) often represents electric field variations rather than plasma density signatures. Coupling to electric fields by resistive effects at low frequencies may also occur, but are usually unimportant and simple to identify. As electric field measurements will be subject to the opposite error, i.e. contamination by density fluctuations, the possibility to compare EMMA and LINDA data is very useful in cases of doubt.

3.4 Spatial or temporal structures

The Langmuir probe density measurement gives a scalar quantity, i.e. it refers to no particular orientation in space, and using more than one probe, makes it possible to detect spatial structures in the plasma provided the probes are well apart from each other (Kintner et al., 1984; Holmgren and Kintner, 1990). LINDA, therefore, included two probes in order to be able to distinguish spatial from temporal structures.

To resolve spatial structures using an interferometer with a baseline of typical 1 m (the full 2.9 m probe separation

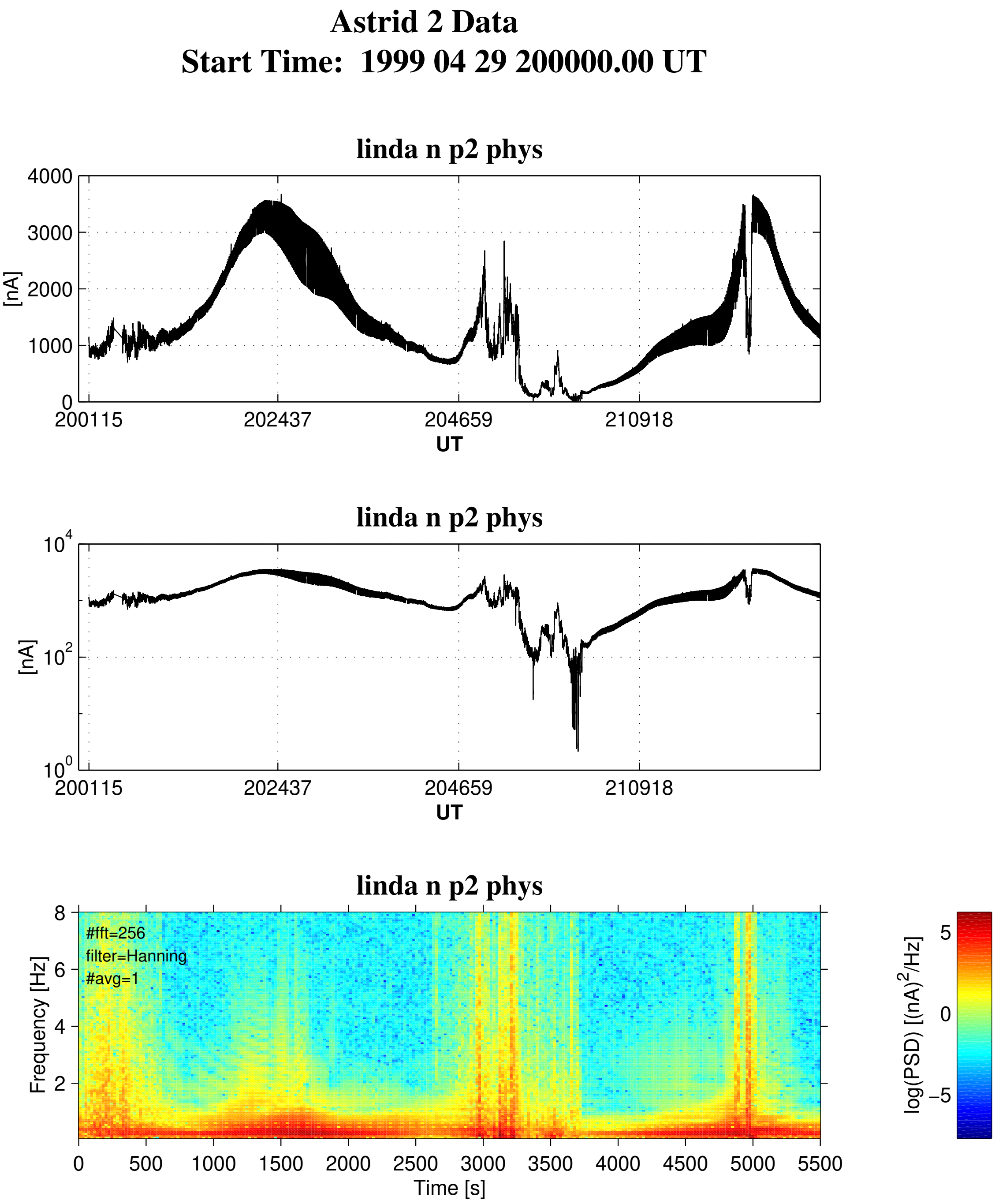


Fig. 1. One orbit overview of LINDA probe current data. The upper two panels show the same time series of the probe current with two different scalings, linear and logaritmic, respectively, emphasizing different parts of the information. The lower panel show a spectrogram of the same data. The data collection starts in the northern summer auroral regions (until 20:10 UT), continuing through the daytime equatorial region (until 20:40 UT) into a very structured southern winter polar region, and ends in the evening equatorial region. The spectrogram in the lower panel shows a nice example of a set of MHD pulsations with density perturbations in the dayside ionosphere between 20:07 UT to 20:35 UT.

is rarely directed exactly along the orbit) and travelling at 7 km/s, one needs a sampling frequency of at least 7 ksamples/s. The two LINDA probe signals were sampled true parallel at 8 ksamples/s, thus fulfilling this condition. It should be noted that for this purpose, the high sampling frequency is needed primarily for establishing the time lag between two signals whose frequency content may be significantly lower than the sampling frequency. The fact, discussed above, that high-frequency electric field fluctuations may couple to the probes is not, therefore, a fundamental problem to the interferometric method.

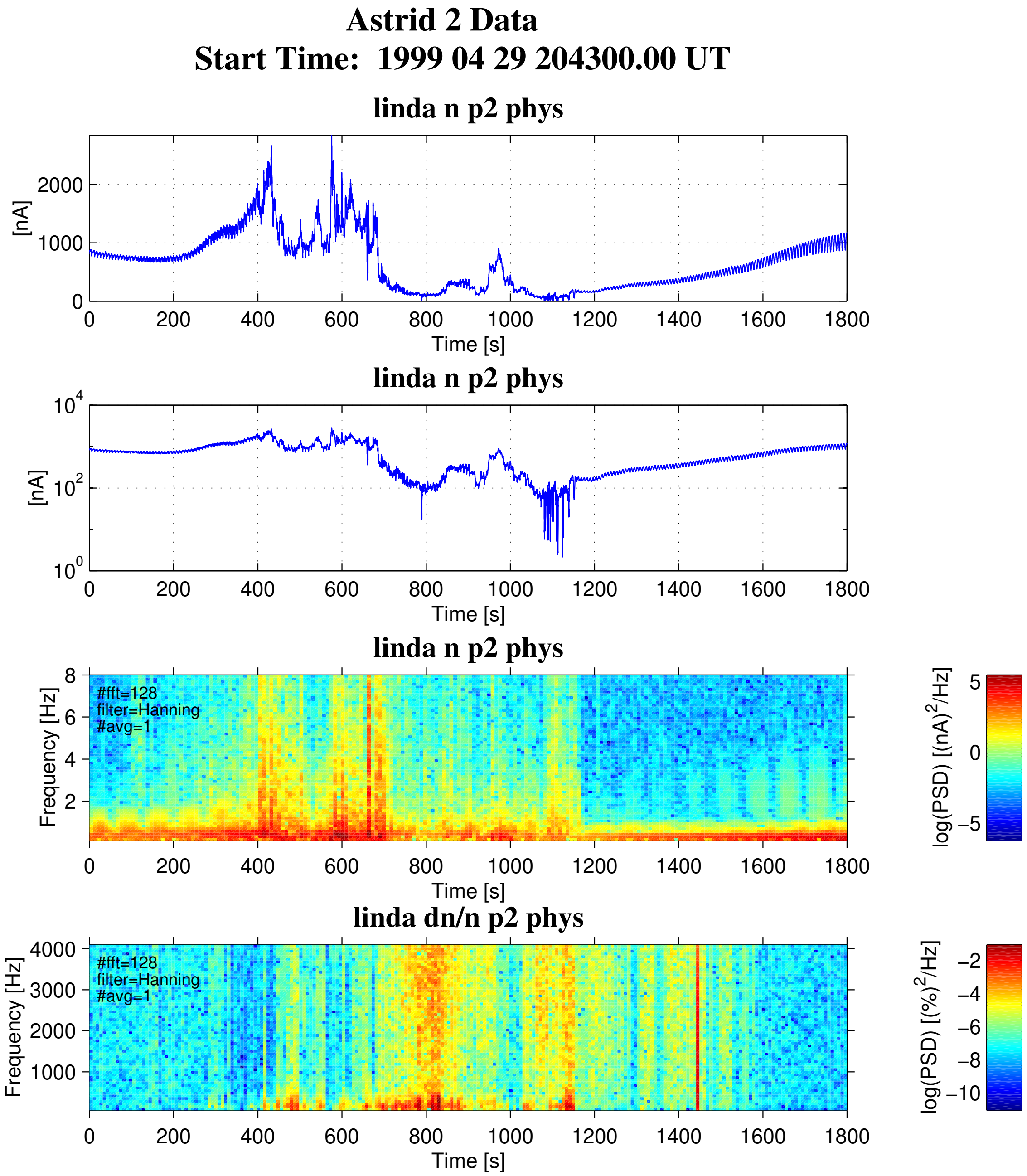


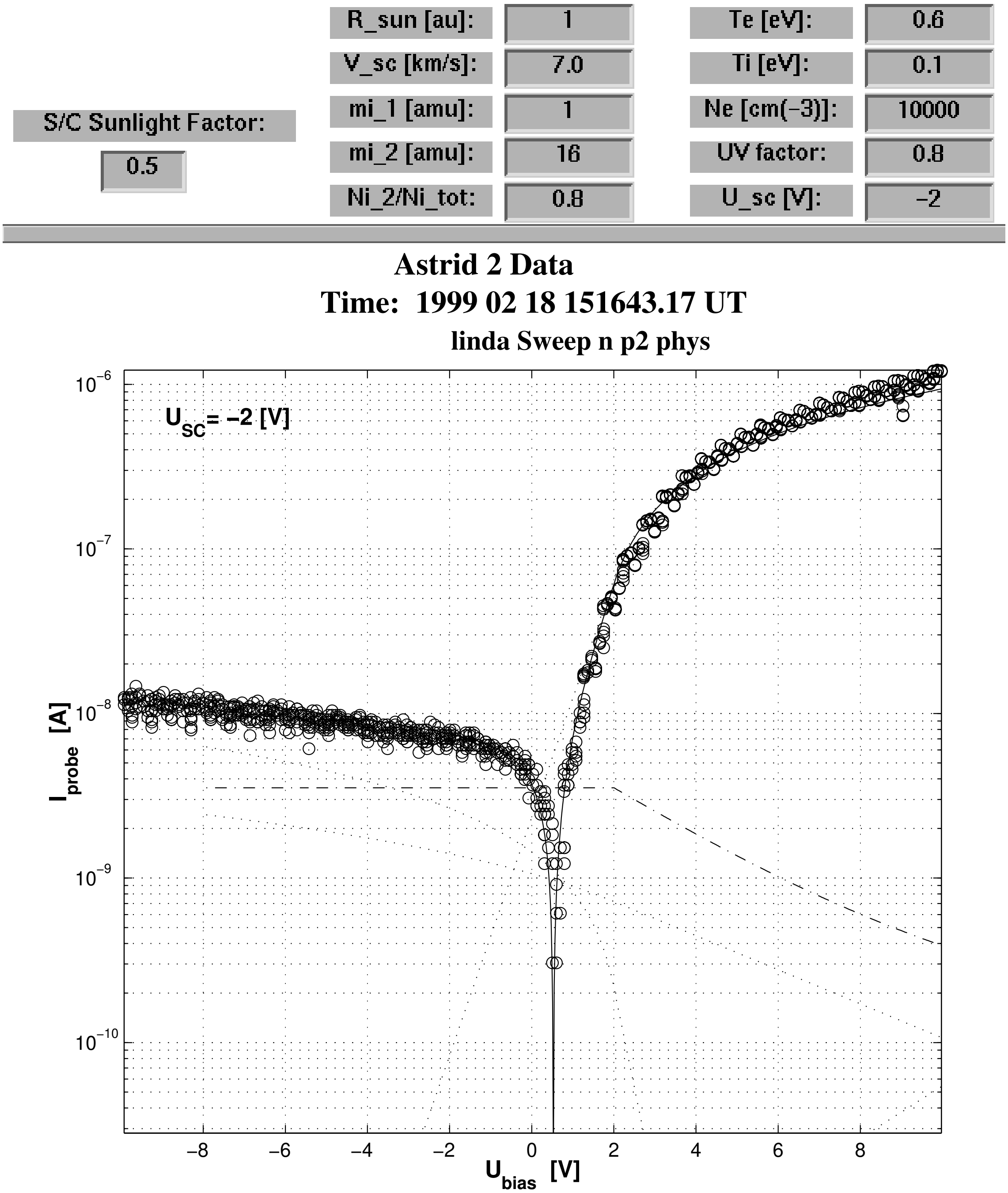
Fig. 2. A blow-up of the event in Fig. 1 showing 30 minutes of data from the southern auroral oval and polar cap regions. A spectrogram of the $\Delta I/I$ quantity up to 4 kHz has been added (lowest panel), showing broadband emissions filling the large scale auroral cavity (e.g. Wahlund et al., 1998).

4 Measured quantities

The leading philosophy, regarding the LINDA data handling, is to transmit the time series (waveform) of the signals to ground without any treatment onboard, except for sampling and filtering (Nyqvist filters). This makes possible extensive analysis of the wave data on the ground, which would not be possible to perform onboard. However, to transmit all samples of the time series would require telemetry capacities far beyond what is available. Thus, the wave channels, i.e. the $\Delta n/n$ quantities, are sampled in snapshots only, with a duty cycle that is typically less than 10%. In special cases, continuous sampling of the $\Delta n/n$ signals can be made for short time intervals by using the burst memory for intermediate storage of the samples. A similar approach was used in the F4 wave experiment on Freja (Holback et al., 1994).

In order to achieve the scientific goals, the instrument was designed with key parameters, as shown in Table 1, to provide the following output:

The Probe current (I) from one or both probes sampled



R_sun [au]: 1
V_sc [km/s]: 7.0
mi_1 [amu]: 1
mi_2 [amu]: 16
Ni_2/Ni_tot: 0.8
Te [eV]: 0.6
Ti [eV]: 0.1
Ne [cm(-3)]: 10000
UV factor: 0.8
U_sc [V]: -2
S/C Sunlight Factor: 0.5

Fig. 3. An example of a probe bias voltage sweep performed by LINDA. As is typical for sweeps in Normal-Burst operations (Sect. 8), the bias voltage is swept in 256 steps from +10 V to −10 V and then back again, typically in 2 seconds. A fit to the theoretical (OML) expression by Mott-Smith and Langmuir (1926) yields the physical parameters stated on top of the plot.

continuously at 16 samples per second. The current is measured at fixed bias voltage of about 10 V above the satellite ground. The plasma density can often be assumed to be proportional to the probe current (Sect. 3.2). Example data are shown in Figs. 1 and 2.

Occasionally, the probe currents resulting from a bias voltage sweep are recorded. Besides providing plasma characteristics, such as electron temperature and density, this also yields the probe sheath resistance and other useful diagnostics of the probe. Sweeps were performed once every minute or once every two minutes depending on the mode of operation. An example of a LINDA bias voltage sweep is shown in Fig. 3.

The relative probe current variations ($\Delta I/I$) from one or both probes were sampled at 8 ksamples per second in snapshots. The length of the snapshots, as well as the interval

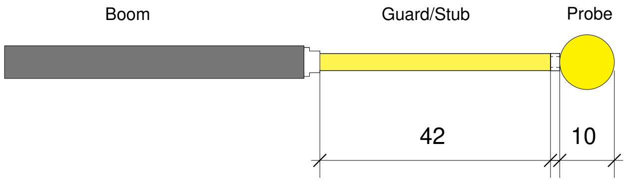


Fig. 4. The probe assembly showing the dimensions of the different parts.

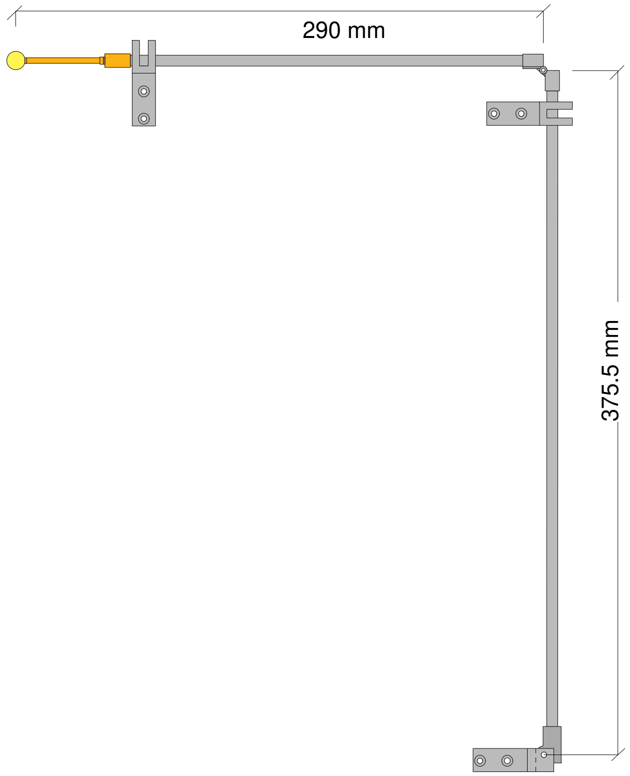


Fig. 5. The boom and Probe assembly shown in the folded position.

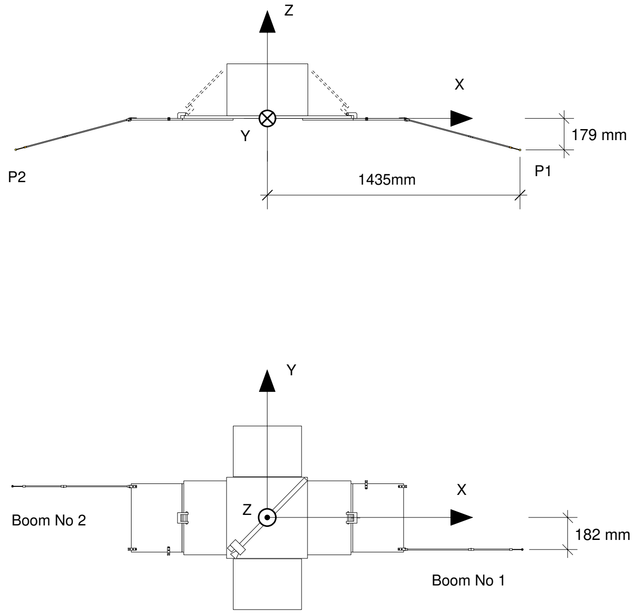


Fig. 6. The Astrid-2 co-ordinate system and LINDA boom geometry.

between them, varied dependent on mode of operation. An example spectrogram of $\Delta I/I$ data is given in panel 4 of Fig. 2.

5 Instrument design

5.1 Probes

There were two identical probe assemblies mounted on two stiff booms. Each probe assembly consists of the spherical probe itself and a stub made of a thin conducting brass tube of 42 mm length (Fig. 4). In order to lower the influence of the photoelectron contamination to the probe current, the potential of the stub was set to the same value as the probe bias voltage.

The probes are made of Titanium and coated with Titanium Nitride (TiN). In tests by Wahlström et al. (1992), this coating has proven to be superior in several important aspects to the frequently used DAG 213. The maximum work function variation measured over the surface was some 15 meV, theoretically enabling temperature estimates down to this range of values (Brace, 1998). TiN is also chemically very inert, which is an important property for a good performance during a long duration in space. In contrast to TiN, DAG 213 was found to occasionally show spurious hysteresis effects in probe bias sweeps (Wahlström et al., 1992), and observation of its changing photoemission properties has shown that it ages in space (Pedersen et al., 1984). TiN coating is also used on the EMMA probes and on our Langmuir probe in the Cassini RPWS assembly (Gurnett et al., 2000).

The probe is connected to the electronics via a tri-axial cable, where the inner conductor carries the probe signal. The inner shield is bootstrapped to the inner conductor, i.e. set to the same potential as the inner conductor, and connected to the stub. The outer shield is used as a screen and connected to the satellite ground.

5.2 Booms

In order to obtain as large a separation distance as possible between the probes, the booms were mounted at the corners of the outermost solar panels. During launch, each boom was folded along a solar panel edge and kept in place by two retaining mechanisms. As the solar panels were relatively weak and not designed to hold heavy booms, it was important to design the booms for low mass, to avoid excessive mechanical stress on the panels. The booms, designed and qualified at IRF-U, were composed of two segments, each consisting of aluminium tubes with a 6 mm outer diameter, and a latching hinge in between. The total length was 665.5 mm from the inner hinge to the probe, which, including the

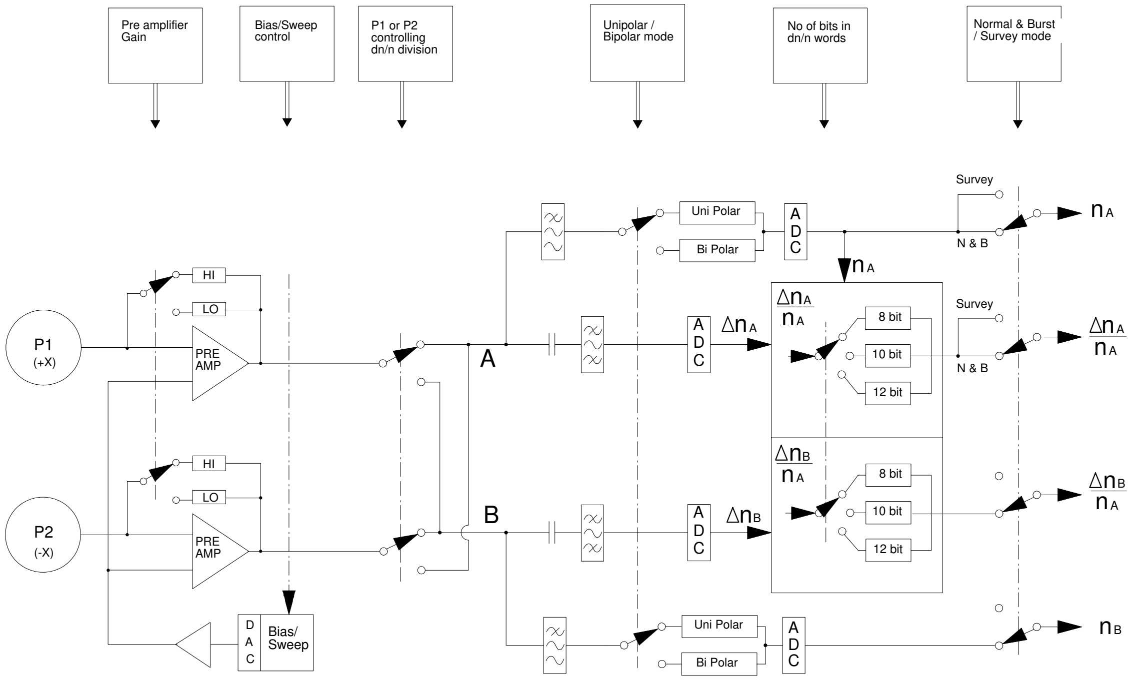


Fig. 7. Graphical representation of the LINDA signal handling showing the different hardware alternatives for mode settings. Switches interconnected by dashed lines are always set simultaneously.

solar panels and the satellite structure, gave a probe-to-probe separation distance of 2.9 metres. The weight of each boom was only 80 grams, including probe assembly and cable. The retaining mechanisms weigh 20 grams per boom.

The deployment of the booms was coupled to the deployment of the solar panels. A locking pin was pulled out of the boom retaining mechanism by the deploying solar panel and, therefor the boom was released. No additional pyros or electromechanical devices were needed. Figure 5 shows one of the booms in a folded position.

To avoid interferense with the wire booms of the EMMA instrument, the booms were mounted at a 15° angle to the spin plane, away from the wire booms. See Fig. 6 for boom geometry.

5.3 Electronics

The LINDA electronics were integrated into the EMMA electronics box and consisted of two printed circuit boards of the size 177.5×122.1 mm. For each of the probes, there were separate input stages with two selectable gains, high pass and anti-aliasing filters (Nyqvist filters), and analog to digital (A/D) converters. A Xilinx circuit was used for calculating $\Delta n/n$ and buffering memories. For control of the probe bias, there was one digital to analog (D/A) converter connected to both probes, placing them at the same bias. In addition, LINDA had access to 2 MBytes of the common EMMA-LINDA burst memory. This memory was used as a short-term buffer for the $\Delta n/n$ data sampling during snapshot operations, as well as for the long-term storage of data (Sect. 6). Figure 7 is a graphical representation (not an electronics block diagram) of the LINDA mode options and shows how the different functions can be controlled. Further details on the LINDA hardware and software are documented by Jacksén (1998).

EMMA and LINDA were controlled by one and the same processor, and the software for each of the instruments was integrated into one software package. The telemetry architecture was unconventional in the sense that all the data from both EMMA and LINDA were organised into frames, in which the data were sorted, depending on the mode of operation. Each instrument and its different modes of operation had its dedicated frame formats. LINDA had 9 different frame formats, each representing a set of submodes. This way of packing the data made the experiments very flexible and the data transmission to the ground very efficient.

6 Flight software and operational modes

As stated above, all signals were sampled and sent to the ground as time series, without analysis onboard . However, the $\Delta n/n$ quantity, which is of primary interest for wave studies, had to be calculated onboard, in order to save telemetry capacity. Each sample of the probe current I, sampled at 8 ksamples per sec and to 16 bit resolution, was converted to the relative value $\Delta I/I$, with a maximum resolution of 12 bits (selectable between 8, 10 and 12 bits). Thus, the true time series of the signals were maintained and normal analysis of the signals can be made on the ground.

The calculation of the $\Delta I/I$ values are made by extracting the “AC" part of the probe signal, amplifying it by means of an automatic gain control, and finally dividing it with the "DC" part. For simplicity, the DC value, or n, from only one of the probes, was used for the division and which signal to use was selected by ground command.

In order to support all the different scientific and technical demands that were put on the instrument, LINDA was very flexible regarding the number of bytes sampled per unit of time. The burst memory, where all the data had to be stored, was 12 MBytes in total for EMMA and LINDA, out of which, approximately 2 MBytes were allocated to LINDA by default. A larger part of the memory could be allocated to LINDA by ground command. Whatever studies should be done, either fine scale measurements or survey measurements, the aim was to design the measurement modes so that the data rate (memory fill rate) should fill up the dedicated memory just in time before the next data dump. As the time between ground contacts could vary from 20 minutes up to 18 hours, the memory fill rate varied between wide limits, and the key parameters that were adjusted were the length of the snapshots and the interval between them. The many different modes that had to be defined were put in a mode database as macros, for easy command of the instrument.

All the different modes could be sorted into three main categories: i) Normal-Burst, ii) Survey and iii) Sweep modes. The Normal-Burst and Survey modes are used for the normal data collection. They are similar in their functionality and the main difference is that in Normal-Burst mode, both probes are operated, whereas in the Survey modes, only one probe is used. In addition, the time between bias sweeps differ.

The Sweep mode performs probe bias voltage sweeps by stepping the bias from a high voltage down to a low voltage and up to high again. Typical values are between +10 V and −4 V, with respect to the satellite potential (normally close to 0 Volts, with respect to the plasma). The step height, length, and number of steps are set by ground commands. The sweep sequence length depends on the settings, but is rather short in time, at most a couple of seconds. The intervals between the sweeps are fixed to 1 min and 2 minutes, for Normal-Burst and Survey modes, respectively.

During the mission, two different sweep sequences were used: one using 256 steps for a double sweep (one down-sweep and one up-sweep), and one using 64 steps for a double sweep. The former took about 2 seconds of time, giving a fill rate of 4096 bytes per minute in Normal-Burst mode. The latter took about 0.2 seconds, giving a fill rate of only about 400 bytes per minute. An example of a sweep sequence is shown graphically in Fig. 8.

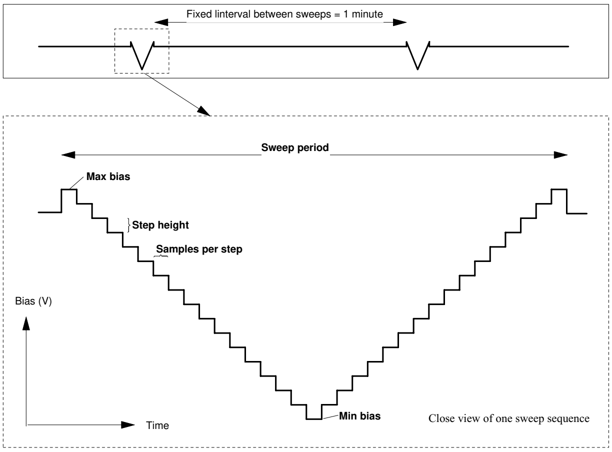


Fig. 8. A graphical representation of a 32-step bias sweep sequence showing the different parameters that were set by ground commands. Normal-Burst mode sweep shown (1 minute interval).

7 Ground data analysis: hardware and software

All communications with LINDA from IRF-U were conducted using an internet link relayed through the ground station at Solna. This comprised of both the commanding and the retrieving of all telemetry data, in either real-time or off-line modes. The commanding of LINDA was performed through purpose-built software maintained by KTH, while the command sequences themselves were constructed manually by the LINDA team at IRF-U. For real-time monitoring of LINDA, a UDP datagram broadcast connection was used; but nominally, for data archiving, retrieval of telemetry data files using ftp was preferred.

A novelty with this mission was that it was feasible to store the full satellite dataset on direct-access memories (hard-disks), where previously, sequential-access (magnetic tape) was used. We employed a RAID (Redundant Array of Independent Disks) level 5 system connected to a PCI controller on a PC running Linux. The RAID system comprised of five (expandable to eight) 18 GByte, 10000 rpm, Ultra2 LVD (Low Voltage Differential) SCSI hard disks with a data transfer rate of 80 MBytes/s. On average, 100 MBytes/day of Astrid-2 data, (Solna telemetry), was archived using the system mentioned above. This archiving setup was found to be so fruitful that it has now become the baseline for the archiving of future satellite data at IRF-U. The vast amount of on-line data, almost 30 GBytes in total, makes it possible to easily formulate new forms of scientific queries and analysis, such as large statistical studies or studies on a global scale. The data analysis was performed using a database dissemination system for scientific data called ISDAT (http://www.irfu.se/isdat) developed by IRF-U. On the low-end of the data processing pipe-line, ISDAT can import raw telemetry data directly without the necessity of producing intermediate data files, and on the high-end, it can interface with legacy software packages such as MATLAB or IDL. ISDAT modules for the decommutation of both LINDA and EMMA have been developed. Specialised routines, e.g., for the analysis of Langmuir probe sweeps, interfaced to ISDAT have been used to produce additional data products.

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