SPEDE instrument paper

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Abstract

This paper describes the SPEDE (Spacecraft Potential, Electrons, and Dust Experiment) instrument on-board the SMART-1 satellite of European Space Agency. SPEDE is a Langmuir probe plasma instrument, making measurements from which plasma parameters in the surroundings of the spacecraft can be derived. In the analysis and interpretation of data, knowledge of many instrument details are important. The aim of the paper is to describe the SPEDE implementation to the accuracy that most questions of the users of the data are answered. In addition to general parameters such as probe geometry, this also implies a quite thorough description of the electronics. The digital electronics is implemented using a novel design with a voltage-to-frequency converter, performing essentially integrating measurements over a given time window. Known features of the implementation are also discussed, where appropriate.

1 Introduction

SMART-1, Europe's first mission to the Moon, has a dual task of at the same time of being a technology demonstration and a science mission. The most important technology experiment for ESA is for the first time using a Hall type electric propulsion thruster as the main engine. The advantage of the electric propulsion (EP hereinafter), compared to traditionally used combustion thrusters, is the low mass that is required to be carried as propellant. The propellant is Xe gas, which is ionised, and accelerated in the thruster by energy from the solar panels. The engine can be operated for very long times without interruption, and the thrust can be controlled very accurately. The drawback of the electric propulsion engine is the small thrust (approximately 70 mN for the SMART-1 engine), which means that the acceleration that the engine provides is very small. Thus, on a short trip (like the mission to the Moon), this is not the most cost-efficient solution. However, on a longer (inter-planetary) mission, the EP approach is very attractive.

The ESA is preparing a mission to Mercury in year 2012 timeframe. This mission, called BepiColombo, will use a Hall thruster as the propulsion engine. In order to validate the technology and gather experience on any possible side effects the engine and its exhaust may have on the spacecraft and the payload, the SMART-1 mission is serving as a testbed for BepiColombo.

The target of SMART-1 is the Moon. The spacecraft is carrying a suite of imaging instruments designed for measuring the Moon using different methods and wavelengths. In addition, there are technology experiments, testing novel communication methods, and two plasma instruments to monitor the plasma environment of the spacecraft.

The two plasma instruments of SMART-1, SPEDE and EPDP (Electric Propulsion Diagnostics Package) complement each other. EPDP is designed specifically to monitor the dense plasma that is the result of the operation of the EP engine. The instrument design parameters are optimised for relatively dense plasmas (electron and ion densities between 10^{10} and 10^{14} m^{-3}). EPDP has one Langmuir probe (LP) for electron measurements and a retarding potential analyser (RPA) for ion measurements. Both these probes are located very close to the EP exit, however not in the plasma beam itself. (See figure 1.) In addition to the plasma sensors, EPDP has sensors monitoring possible contamination on the solar panel and spacecraft body surfaces. The plasma sensors of EPDP are not operated in a monitoring mode in the sense that they would sample the plasma continuously. Both the LP and the RPA perform data acquisitions by (time-tagged) command. This is different than the operation of SPEDE, where nominally data is collected in a low sampling rate continuously as described later.

This paper is organised as follows. In section 2 we present the objectives of the SPEDE instrument, and how they have been translated into long-term operations plans for the duration of the SMART-1 mission. Section 3 contains the instrument description, starting with a brief introduction to Langmuir probes, and continuing with probe design, electronics design and electronics readout description. Known instrument features are also included, to the extent known at the time of the writing of this document. Section 4 presents the operations: basic mode configurations and the data acquired. List of data products is also included in this section. The paper concludes with a summary.

2 SPEDE Instrument Objectives

The SPEDE (Spacecraft Potential, Electron and Dust Experiment) experiment, consisting of two electric sensors and an electronics unit, will measure the electron flux and wave electric fields. The cylindrical sensors are mounted on the tips of two 60-cm booms, located at the +X and –X faces of the spacecraft (see Figure 1.). The sensors are connected to the electronics unit via a single triaxial cable each without any active electronics outside the board; the SPEDE electronics is housed on two electronics boards, located in a box inside the spacecraft body.

Insert figure 1: SMART-1 with EPDP and SPEDE probes indicated.

The mission of the SPEDE experiment is two-fold: it will monitor

- The disturbances (electron flux, wave electric fields, and spacecraft potential variations) induced by the propulsion system, and
- The variability of the electron density and wave electric fields during the Earth spiralling and cruise phases and during the Moon phase

2.1 Monitoring of disturbances produced by the SMART-1 propulsion system

Gas releases, most commonly from thrusters used to control the spacecraft velocity and attitude, can disturb observations of some instruments as well as contaminate the spacecraft structure. Because of possible interference effects and spacecraft contamination can be detrimental to sensitive instruments, it is important that the disturbances produced by the thruster operations in the spacecraft environment are monitored. This is especially important for the SMART-1 mission, for the first time using electrical propulsion on an ESA mission. Charged clouds expanding from the propulsion system may introduce a variety of phenomena when interacting with the ambient plasma and the spacecraft surface. These include

- variations in the spacecraft potential and electron flux,
- contamination of the spacecraft surfaces for an extended period of time, and
- generation of wave electric fields.

Especially, large effects in the spacecraft potential can be immediately observed if, for some reason, the exhaust ions are not properly neutralized by the cathode electron emitter. It is also important to gain knowledge of the reactions of the plasma environment to changes in EP engine parameters of operation.

2.2 Monitoring of electron density in the inner magnetosphere

In the first part of the SMART-1 mission, the Earth spiralling phase, the spacecraft will be accelerated by the ion propulsion engine and remain in the inner magnetosphere. In addition to monitoring the effects of the propulsion as described above, the SPEDE observations are used for measuring the distribution of thermal plasma of the plasmasphere whenever the EP is not operating. Particularly the measurements aim at detecting the position of its outer boundary, the plasmapause, usually located at a distance of 3-7 Earth’s radii at the equator.

As long as the perigee of the orbit is less than 3-4 R_e (20 000 km), the plasmapause is crossed twice per orbit. When the perigee is between 20 000 and 40 000 km, the plasmapause is not always encountered, particularly so during magnetic storms, when the plasmasphere becomes smaller in size.

2.3 Monitoring of plasma density and waves in the Earth's magnetosphere and in the Solar Wind

After the perigee of the orbit is raised outside of the plasmasphere boundary (see above), SPEDE observations will concentrate on low-rate monitoring of the magnetospheric and solar wind plasma. These regions have been extensively investigated on earlier missions with plasma instrumentation optimised for tenuous plasmas, and no scientific break-throughs are expected. The measurements will consist of monitoring variations of plasma density by operating the instrument in a constant-bias low-sampling mode.

2.4 Monitoring of space weathering of the Moon

The target of the SMART–1 mission is the Moon which has no magnetic field and atmosphere. Therefore, it is continuously exposed to the interplanetary space environment. The fast solar wind stream hits the dayside lunar surface and is possibly capable of lifting up small dust grains from the surface. Behind the moon, the solar wind produces a wake that is more tenuous than the solar wind.

On lunar orbit, SPEDE observations are used for studying solar wind – moon interaction processes. The uplifted dust particles can be detected as variations in the spacecraft potential, as the particles are ionised when hitting the spacecraft surface. A high sampling rate will be used at the region of the predicted wake boundary, to obtain the best data both for dust impact detection and studies of the plasma density and turbulence at the wake. Optimised modes initiated by time-tagged commands will be used.

3 Instrument description

The general philosophy of the SMART-1 mission follows the principles of "faster, cheaper, better – SMARTer". As SMART-1 is a testbed for new technologies, also many payload instruments are implemented using novel technologies for relatively conventional measurements. The technology aspect also holds for the SPEDE instrument.

From the measurement principle point of view, SPEDE is a conventional Langmuir probe instrument. The two SPEDE probes are covered with titanium nitrite (TiN), in order to ensure minimal side effects due to contamination and ageing of the surfaces. The electronics is implemented using as much digital electronics as possible. The final result is an instrument with a wide dynamic range, good resolution, and at the same time low mass, low power consumption, and low cost.

3.1 Measurement principle

The principle of plasma measurements using Langmuir probes is as follows. Since plasma consists of free charges (electrons and ions), it seeks for quasineutrality: Even a slightest imbalance in charge results in a quick neutralising current, normally carried by the more mobile electrons. The system consisting of the spacecraft, the probe(s), and the plasma, seeks for equilibrium through generating electric currents either towards or away from the probe. At the same time, all currents to the spacecraft-probe system must balance each other, which defines the equilibrium potentials the spacecraft and the probe must be in. The current between the probe and the plasma can be measured, and with modeling, plasma parameters such as electron and ion densities, electron temperature, and the potential of the spacecraft, can be derived. The theory of the measurement has been well developed and thoroughly tested, and the general behavior of Langmuir instruments is well understood. However, each spacecraft-instrument combination is unique, and adjustments to theory are necessary to accurately model the behavior, and obtain best possible results.

The SPEDE instrument – like any Langmuir probe instrument - does not directly measure any plasma parameters. There are only two directly measurable parameters: the current to or from each probe, and the potential difference between a probe and the reference voltage at the instrument. Depending on the configuration of the instrument, we can measure either the current or the voltage. All other results are derived from these parameters. The two measurements provide possibilities for different derived products, as will be described below.

3.2 Basic modes of operation

The basic modes of operation are

- measure current as function of bias voltage (Langmuir sweep),
- measure current with constant bias voltage (Langmuir mode),
- measure voltage with respect to (spacecraft ground) reference voltage (voltage mode).
- plasma wave measurements (in voltage mode).

These modes will be discussed below.

3.2.1 Langmuir sweep

In the Langmuir sweep mode, the bias potential is varied stepwise, with programmable voltage step size and voltage range. This measurement provides the characteristic Langmuir response curve, to which one can fit plasma parameters (Figure 2.).

Insert Figure 2: Textbook Langmuir curve.

From the Langmuir response, one can use a parametric fit, and derive electron density, electron temperature, ion density, ion temperature and spacecraft potential. The accuracy of the estimates depends on the performance of the instrument, but also on background knowledge of the plasma. Not all parameters are independent, but depend for example on ratio of temperature and density, and thus a good fit may not be unique. However, in most cases ambiguities can be solved with *a priori* knowledge of what can be assumed.

The shape of the curve is very sensitive to electron density and temperature (actually the ratio $n/\sqrt{T}$), around the region where ion current (negative in the plot) changes to electron current. This is the region one attempts to sample in order to obtain the most from the measurement.

The SPEDE instrument can (by hardware design) sample a voltage range from -13 V to +14,4 V with reference to the spacecraft ground. The voltage can be varied in 255 steps with spacing that is smallest around zero, and sparser closer to the extremes. The range between 4,4 V and + 14 V is covered by one step (see Figure 3.). This decision was made to have the best sampling close to zero, where the curvature of the Langmuir response was expected to be tightest. The last point close to +15 V would then give the (saturation) electron current.

Insert Figure 3: SPEDE voltage step spacing.

In practice, the SMART-1 spacecraft potential with respect to the surrounding plasma tends to be between 17 and 24 V negative. In Figure 2 the curve crosses I=0 at X V, corresponding approximately to the plasma potential. To the left of this point, the net current is towards the probe (emitting electrons or collecting ions). If the spacecraft potential is negative, the curve shifts to the right in order to the crossing point to arrive at the plasma potential. In the case of SMART-1 and SPEDE, this point moves to around 18 volts, beyond the range of bias voltages SPEDE can reach. This reduces the possibilities for deriving parameters from SPEDE sweeps, as discussed more in detail later.

3.2.2 Langmuir mode

The second mode (Langmuir mode) provides data of plasma flux variations. Depending on bias voltage, either ion (negative bias with respect to the plasma) or electron (positive bias) current is collected. Basically one attempts to select a working point on the Langmuir curve that is most sensitive to variations in either plasma density or spacecraft voltage. As discussed above, the ability of SPEDE is reduced by the SMART-1 spacecraft potential. In figure 4 a family of Langmuir curves has been plotted, assuming a plasma with Xe^{+} as the dominant ion species. The red rectangle indicates the range of voltages and currents that can be obtained with SPEDE, assuming a spacecraft potential of -17 V. We see that in this situation, with any parameter setting that can be obtained for SPEDE, we sample the ion side of the Langmuir curve, providing information about the temperature and density of the ions.

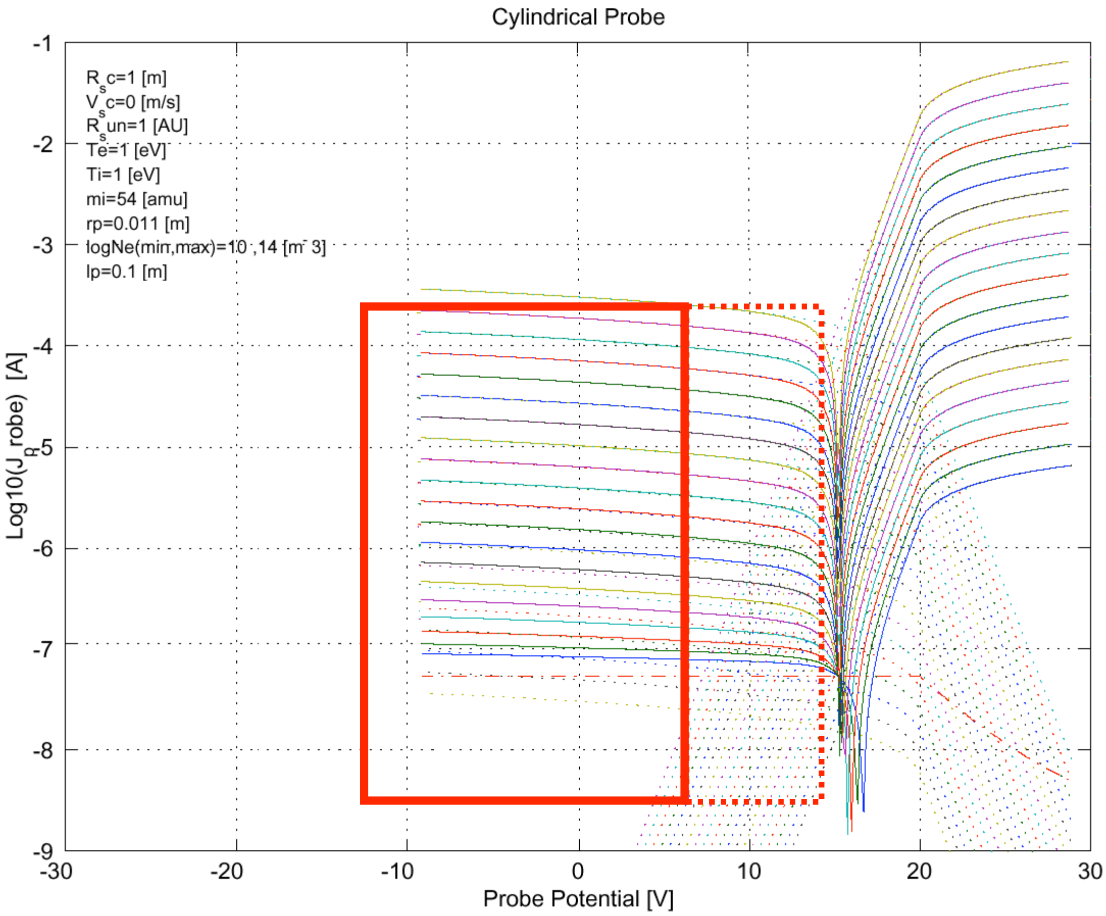

Figure 4: Family of Langmuir curves, with SPEDE measurement range indicated.

3.2.3 Voltage mode

In the third basic mode, the probe is in a passive mode measuring variations in the potential difference between the probe and the reference voltage. As the probe potential should not be modified by the measurement itself in this mode and as also small scale variations should be detected, the voltage is sampled with very high input impedance and capacitive offset suppression

In SPEDE, there is not bias current generator, and thus in the voltage mode the potential of the probe is floating freely. As discussed by, e.g., *Pedersen et al. (1984)*, the probe potential is closer to the plasma potential, when an appropriate bias current is applied. Thus the SPEDE probes cannot be taken as to accurately float in the plasma potential. On the other hand, the probes are very close to the spacecraft, and thus photoelectron effects, as well as the effect of the spacecraft structure on the electrostatic potential of the surrounding plasma would introduce uncertainties in interpreting DC voltage measurements. As a consequence, voltage mode measurement is used only for measuring wave fields generated by plasma fluctuations.

3.2.4 Wave measurements

TBW, mode not used in current data set.

3.3 Probe design

The probes are made of two 0.1mm Titan foils at the end of the 60cm long slightly conical carbon fiber booms. The foils are sputtered with TiN (as mechanically and chemically inert surface material), insulated from one another and the boom carbon fiber material by 0.05mm adhesive Kapton foils. The inner layer has a length of 150 mm, the outer layer of 100 mm (acting as the probe), leaving 25 mm free on both sides as guard. The purpose of the guard is to prevent capacitive leakage current between the sensor foil/wire and the spacecraft ground including boom structure. The boom has a diameter of 22mm at the tip, which is covered by a lid from the same sensor foil material, electrically connected to the guard layer. For low density plasma the 10 cm x 2.5 cm probe cylinder can be considered spherical. The mechanical layout of the boom and probe is presented in Figure 5.

Insert Figure 5: SPEDE probe mechanical design.

The probe is connected to the electronics via a double shielded wire (Triax) with the outer shield at the electronics end connected only to the analog ground as electrical shield. The inner shield is connected to the inner guard layer of the probe foils, which is actively kept at the sensor potential. The innermost cable wire connects the outer sensor probe foil with input of the first amplifier stage and the current measurement resistor.

The mechanical design of the booms was determined by spacecraft constraints: a very stiff, but with 128g lightweight design protruding only 60 cm from the s/c panel was enforced by the satellite's launch configuration. As also no moving parts were allowed, the SPEDE probes are located rather close to the s/c surface compared to the original suggested locations at e.g. the tips of the solar panels. This limits the possibilities of monitoring natural plasma, but enhances SPEDE's capability of monitoring possible impacts of the thruster on scientific instruments mounted along the s/c panels.

3.4 Electronics design

The electronics is built around one Field Programmable Gate Array (FPGA) containing all processor functions, and two separate analog channels with operational amplifiers and Voltage-to-Frequency-Converter (VFC). The processor functions in the FPGA include the boot code, real-time clock and the analog control and measurement functions. For Langmuir measurements, the bias voltage for each channel is generated by an FPGA-driven resistor network dividing the channel-specific reference voltage in 256 different ways, corresponding to digital control values between 0 and 255. A buffered level shifter provides low-impedance bias voltages in the range of -13V to +14V. The resistive network is selected in such a way that small step sizes are possible between -3V and +3V, with increasing steps beyond this range up to +4.5V for control value 254. One additional bias voltage of +14V is provided for measurements in the expected electron saturation current regime (electron density measurements), assuming spacecraft potentials inside the +/- 3V range.

The probe current is connected through the measurement resistor and the bias generator to instrument ground, causing a voltage drop across the resistor. This voltage drop is monitored as potential difference with respect to reference ground by high-impedance amplifiers. The resulting voltage difference is converted to a frequency in the VFC. The range of the VFC corresponds to 100 Hz for large positive voltages to 150 kHz for large negative voltages with 0V close to 50kHz.

For potential measurements, the connection between the 200 Ω resistor and the rest of the electronics is decoupled by a relay. Pre-amplifier 1 connects directly to a specialized amplifier which in this case also drives the guard. The final amplification stage with connection to the VFC is separated at its input by a capacitor to suppress offset voltages. The functional electronics diagram is shown in Figure 6.

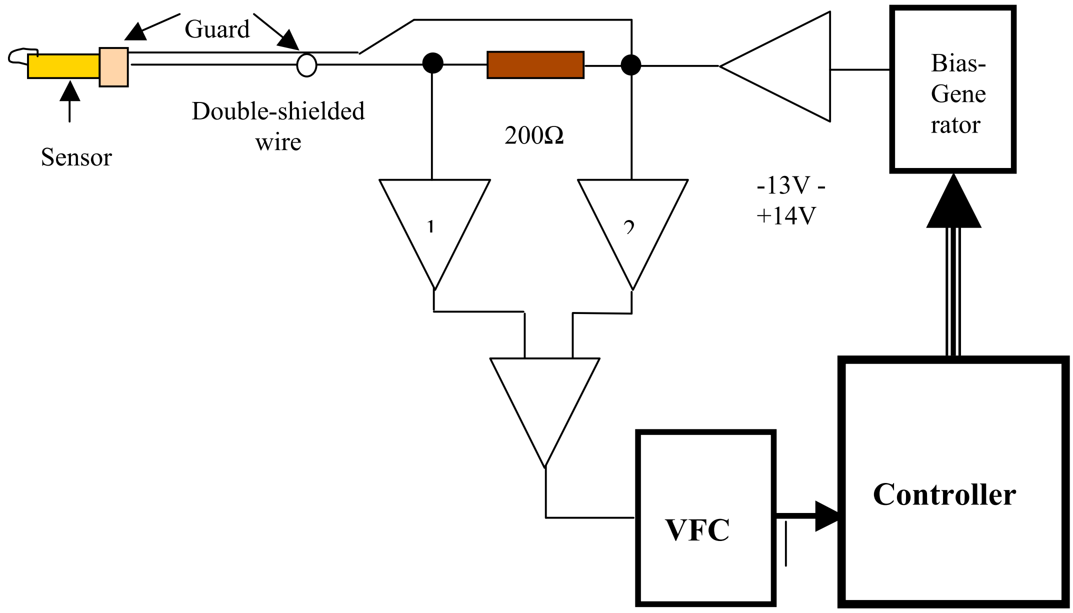

Figure 6: SPEDE measurement electronics diagram.

The measurement result is the frequency coming from the VFC, compared with the internal fixed 16MHz clock frequency. Using a measurement window defined by the 16 MHz clock as e.g. 1 sec the number of observed VFC pulses correspond directly to the VFC frequency averaged over the measurement window. Defining the measurement window by e.g. 150 VFC pulses, the number of observed 16 MHz clock pulses give the average pulse length of the VFC signal. The nominal measurement windows are 998 ms and 4 ms, or alternatively 20 or 150 reference clock pulses.

3.4.1 Technology aspects

Using a Voltage to Frequency conversion to digitalize the analog signals offers several advantages: Covering the full dynamic range of the front end electronics, the resolution can be optimized to the signal range of interest. Opposite to the sample measurement method of standard ADCs, a VFC is an integrating device covering all short duration signals if they deviate significantly from the background. A relevant example in the case of SMART-1 is the EP valve operation and the same advantage is expected to be very useful for dust impact detection in Lunar orbit. In addition, signals that deviate only little from zero current can be measured with high resolution and short integration times, as they result in frequencies close to the center frequency of the device (50 kHz). The bit-resolution can also be optimized for the observation objectives, as there is no principle restriction to the number of bits generated per conversion. SPEDE uses between 8 and 22 bit data depending on the observation mode and measurement data and integration times between 4ms and 1 sec.

In SPEDE design, as few analog components as possible were used as possible. This was because in many cases their availability, radiation resistance, size, mass, flexibility and power consumption are in contradiction to the design drivers for the instrument. Implementing most of the electronics in a programmable digital device also allows major design changes after most of the device is already designed or even built. This approach makes future miniaturization possible, including implementing all components on a single die carrier.

Replacing a commercial Digital-to-Analog-Converter against a digitally controlled resistor network offers the possibility to design for different resolution in the various voltage ranges. The SPEDE approach is also considered better in terms of power consumption and radiation sensitivity. For Langmuir Probe measurements one large negative bias voltage for ion-density and one large positive voltage for electron density would be sufficient, while the bias voltage step width close to the area with fast current changes defines the precision of the electron temperature and composition analysis. The resistor network that is used in SPEDE consists of one resistor in series with 8 parallel resistors, which can be connected to ground via 8 separate control lines. Using 8-bit control values to drive these lines, a wide range of resistor ratios can be defined. With the network connected to a 2.5V reference, an inverting level shifter moves the resulting voltages between 2.5V (all lines open) and 0V (all lines plus short-circuit connected to ground) to -14.4V and +14.4V. Due to restrictions of the amplifiers, the lowest useful voltage is -13V, corresponding to a control value of 5.

4 Operations and Data

4.1 General description

SPEDE has ten different operational configurations ("modes") stored simultaneously in the instrument memory. Mode 0 is idle mode for Safe or no telemetry configuration. Mode 1 is the housekeeping mode, which is activated when SPEDE is ON, if not other mode is commanded. This mode collects data in Langmuir mode from both probes, with one sample per minute.

All modes can be activated by simple spacecraft command. Each mode definition consist of 4 parameters plus a control byte for each of the two probes, defining the mode of operation. The two probes (+/- X) can be programmed individually, with timing of measurements being identical for the two probes. The details are given in the SPEDE User Manual (reference TBA). The mode configuration parameters define whether a Langmuir or Voltage measurement is used, the time step interval, number of measurements in one measurement sequence, time interval between measurement sequences, and in the Langmuir mode also the voltage step, and whether a two-way measurement (sweep with hysteresis measurement) is performed. The voltage range can also be adjusted. For each measurement and probe, different sampling philosophy (pulse length or frequency measurement; see electronics description above) can be used.

As discussed above, SPEDE performs measurements within a time window, thus defining the frequency output from the voltage to frequency converter. Thus the time between samples cannot be shorter than this time window. In practice, the shortest time windows are of the order of 4 milliseconds, and this is not a serious limitation. For each measurement, one needs to consider the balance between measurement reading accuracy (better with a long window) and measurement duration. For sweep measurements, shorter windows are preferred, whereas for Langmuir measurements, a long window with 1 second is usually used. The integrating measurements record even small signal variations during the measurement time window, which makes them suitable for detecting small variations in Langmuir current.

Description of wave measurement **TBA**.

Parameters for each measurement are included in the header of the data file, and actual mode configuration tables or mode numbers do not need to be available for data analysis.

SPEDE is operated using Input Timelines (ITLs). Smart-1 Science Operations Centre converts these to Payload Operation Requests, which are uploaded to SMART-1 during ground contact. For most operations, standard timelines with SPEDE operations related to orbital or spacecraft events (especially EP operations), are used. For specific activities such as calibration measurements and configuration table or software updates, dedicated timelines are developed. Timelines during different phases of the mission will be discussed in below.

4.2 Operations timelines

During the first two weeks of the mission, instrument commissioning was performed. The commissioning activities consisted of health checks and in-flight calibration measurements coordinated with the EPDP instrument. The result of the commissioning was that SPEDE was fully functional, and that satisfying agreement between the results of the two plasma instruments could be reached. Mode configuration tables were also adjusted, in order to improve the scientific performance.

After the initial commissioning period, the SMART-1 mission entered a more than three month phase of almost continuous EP thrusting. This was performed to raise the apogee of the orbit above the Earth's radiation belts, in which the energetic particles are known to be harmful for both the spacecraft subsystem electronics and the instruments. During the thrusting phase, SPEDE was operated almost continuously, collecting data according to the EP monitoring timeline. These data need to be correlated with simultaneous measurements of the EP engine housekeeping parameters, as well as EPDP measurements.

As an example, for EP operations monitoring the nominal sequence is to

- measure the ambient plasma before EP switch-on with a full-range Langmuir sweep,
- monitor switch-on transients in a fast sampling Langmuir mode with constant bias,
- perform another sweep to obtain plasma parameters when EP is on,
- measure Langmuir current during EP operation with a constant bias and slower sampling,
- before EP switch-off perform the switch-on measurements in a reversed order, and
- return to ambient plasma measurement mode.

After the initial thrusting phase, SMART-1 spends a lot of time in a spiraling orbit in the Solar Wind and magnetosphere, and the EP engine is only used during part of the orbit. When the EP is off, SPEDE measures the ambient plasma. The selected operational timeline uses the housekeeping mode during most of the orbit. Faster sampling has been used on five 2-hour periods located at regular intervals around orbit, and complemented with Langmuir sweeps at the beginning, middle, and end of each fast sampling period. As discussed above, SPEDE is not fully optimised for measuring low density plasmas, but data is collected to monitor the performance of the instrument, and compare measurements with other satellites at the vicinity when possible.

<Sample ITL **TBA**>

After insertion to Lunar orbit, the planned operations will include high frequency sampling in Langmuir mode plus wave measurements around the predicted location of the boundary of the kinetic wake behind the Moon. At these regions, dust impacts may be detected, in addition to novel data on plasma turbulence behind the moon. A dedicated timeline will be developed for that purpose.

At suitable intervals and occasions, in-flight calibration and performance monitoring measurements are performed. In order to monitor the instrument response in vacuum, a background calibration is performed when SMART-1 is in eclipse, and its location is predicted to be inside the extremely tenuous lobe part of the magnetotail. A corresponding reference measurement has been performed on ground.

4.3 Measurements to products: sweep, voltage, and current

The Langmuir measurements produce data with probe current as a function of time and probe bias voltage. If the probe is operated with constant bias, the result is a time series of probe current, reflecting the plasma flux variations. If in sweep mode, time is not an important parameter to the same extent, and voltage vs. current gives the Langmuir response in the plasma.

For voltage measurements, the data provides probe voltage vs. time and for plasma wave measurements, wave energy in a given frequency band. For data products, see Section X below.

4.4 Derived quantities

The plasma parameters that can be derived from the measurements, grouped by measurement modes as described above in section 3, are as follows.

4.4.1 Langmuir sweep

From the Langmuir sweep, one can derive

- electron (and ion) density and
- electron temperature, and
- spacecraft potential

assuming that the plasma composition is known. Electron temperature and density are related, with the ratio T_e/n_e basically determining the shape of the curve in the range where the current is most sensitive to the bias voltage. The best fit may also in some cases not be unique. Often, however, one can fix one parameter to a limited range, using *a priori* information, and obtain a solution. For this evaluation it is assumed that the probe current is given by the instrument. In fact the instrument compares the voltage drop caused by the probe current through a measurement resistor with the voltage difference between reference voltage and reference ground. While the reference is rather stable, a temperature dependence in the order of one per mille can be observed and has to be taken into account.

The SMART-1 spacecraft equilibrium potential is strongly negative (typically between 17 and 24 V, as derived from EPDP Langmuir sweeps), and thus goes beyond the bias voltage range of SPEDE. This means that we can only seldom measure anything else than an ion current, reducing our possibilities to derive electron parameters or the spacecraft potential. With the SPEDE range of voltages and currents illustrated in Figure 4, we can that for the plasma used in modeling for that figure (m_i = 54 amu), the range of densities that can be measured is 10^{10} to 10^{14} m^{-3}. In Figure 4, a spacecraft potential of 17 volts has been assumed.

The measurements are thus almost always in the ion current regime, and up to relatively high densities result in probe currents within the SPEDE accepted range. At low densities, the measurements are limited by measurement noise, which is of the order of 20 nA, resulting in lowest reliable ion density of 10^{10} m^{-3}. For comparison, the saturation photoelectron current for a proton plasma is of the order of our measurement noise (~ 20 nA).

4.4.2 Langmuir mode

In the Langmuir mode, the data is interpreted as electron flux variation (or ion flux, due to strongly negative spacecraft potential), which is proportional to electron (ion) density variation. Again, this interpretation is not unique, since the current is coupled with plasma temperature and s/c potential variations, the sensitivity depending on the bias voltage used.

4.4.3 Voltage mode

The voltage mode of SPEDE provides measurements of

- s/c potential variations, and
- wave electric fields.

The sampling frequency can be set as discussed in Section 4.1 above. The shortest time between samples that can be set is 4 ms, resulting in 250 samples/ second. This means that fluctuations above 125 Hz are undersampled, which needs to be taken into account in the analysis and interpretation of the data. This limitation of course does note apply to the wave mode measurements, but there the waveform is not transmitted to ground.

This mode is intended for monitoring fast varying probe potential as a consequence of thruster parameter changes, impact of dust particles with the s/c or interaction with varying solar wind. While the actual measurement is independent of slowly varying s/c potential, an offset beyond ±13V can drive the input amplification stage into saturation, making any measurement impossible. Therefore this mode was not implemented for scientific purposes on a routine basis.

4.5 Data products

4.5.1 Level 1b

- o probe readings in raw units

4.5.2 Level 2

- o probe current
- o probe voltage
- o wave spectrum

4.5.3 Level 3 derived parameters

- o only from sweep mode

5 Summary

We have presented the SPEDE instrument on board SMART-1. At the time of writing this paper, SPEDE has been operating for 6 months, and a lot of data has been collected. Analysis is underway, and calibrated and quality checked data will be made available at the archive of ESA as it becomes available.

6 References

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More references **TBA**.