RPC-LAP: The Langmuir probe instrument of the Rosetta plasma consortium

A. I. Eriksson, R. Gill, J.-E. Wahlund, M. André, A. Mälkki, B. Lybekk,
A. Pedersen, J. A. Holtet, L. G. Blomberg, and N. J. T. Edberg

Abstract The Rosetta dual Langmuir probe instrument, LAP, uses a pair of spherical Langmuir probes to measure basic plasma parameters, with the aim of providing detailed knowledge of the outgassing, ionization and subsequent plasma processes around the Rosetta target comet. The fundamental plasma properties to be studied are the plasma density, electron temperature and plasma flow velocity. In addition, it is possible to study electric fields up to 8 kHz, plasma density fluctuations, spacecraft potential, and integrated UV flux. In this paper, we present the LAP instrument and its operational modes, and discuss its performance at the comet in light of data acquired during the Rosetta swing-bys of Mars and Earth. Most of the data hitherto gathered are from the tenuous solar wind plasma. We show that LAP can detect weak density variations in this plasma at high time resolution, which implies that LAP will be a sensitive indicator of early comet activity, useful for mapping of active regions by in situ detection of the ionized component of the outflowing material.

M. André, A. I. Eriksson, R. Gill, J.-E. Wahlund
Swedish Institute of Space Physics
POB 537, SE-751 21 Uppsala, Sweden
e-mail: Anders.Eriksson@irfu.se

A. Mälkki
Finnish Meteorological Institute
Helsinki, Finland

J. A. Holtet, B. Lybekk, A. Pedersen
Department of Physics
University of Oslo, Norway

L. G. Blomberg
Department of Space and Plasma Physics
Royal Institute of Technology
Stockholm, Sweden

N. J. T. Edberg
Department of Physics and Astronomy
University of Leicester, UK

1 Introduction

Rosetta provides a unique opportunity to study a comet at close range for a long time and in conditions varying from the (at least relative) inactivity at 3 – 5 AU through the onset and development of full outgassing activity at perihelion close to 1 AU. The Rosetta Plasma Consortium, RPC [1] exploits this opportunity to study the comet and its environment by providing a set of instruments covering most aspects of the cometary plasma, among them a two-probe Langmuir Probe instrument, LAP (Figure 1). In this paper, we summarize the science goals and the design of the LAP instrument, with particular emphasis on measurements in tenuous plasmas. Such measurements are most relevant for the early comet phase of the Rosetta mission, where we expect LAP to be a sensitive detector of early cometary activity. We also review the operational modes. A more complete description of measurement principles and instrument hardware can be found in reference [2].

The primary tasks of LAP are to measure the fluid parameters of plasma density, electron temperature and plasma flow speed, essential to any characterization of the cometary plasma. However, LAP is a multi-purpose instrument, also providing information on a number of secondary science goals: plasma density fluctuations, electric field measurements up to 8 kHz, spacecraft potential, the integrated solar UV flux, the effective ion mass and to some extent also dust particle impacts (see also Table 1). The scientific problems we want to investigate are discussed in Section 2. Section 3 outlines the measurement principles and illustrates with some data examples. Section 4 is a brief overview of the instrument design and operational modes. We conclude by summarizing the outlook for LAP measurements at the comet in Section 5.

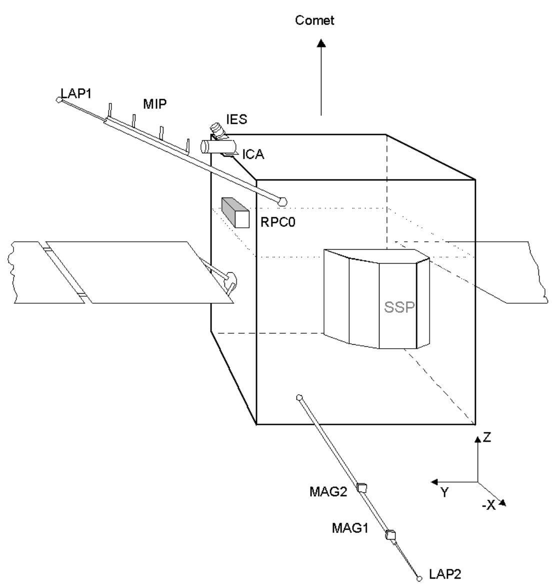

Fig. 1 Mounting of the RPC sensors on the Rosetta spacecraft. The LAP probes, LAP1 and LAP2, are mounted at the tips of the stiff booms. The LAP electronics boards are housed in the common electronics box, RPC0 [1].

2 Scientific objectives

The LAP science objectives relate to the general scientific objectives of the Rosetta mission and of the RPC consortium. The special features of LAP make it particularly useful for the following studies, among others:

1. By monitoring the development of plasma density, electron temperature and flow speed from the onset of cometary activity to the perihelion, LAP will significantly improve our view of cometary outgassing and the buildup of the cometary plasma environment.
2. By studying time and space variations of the fluid parameters of the inner coma, LAP will pave the way for a detailed understanding of this region, including the diamagnetic cavity where no in-situ observations have previously been made.
3. By its ability to measure plasma density structures, LAP can investigate dynamic features in the cometary environment that can be compared to and linked to comet surface events as observed by other Rosetta orbiter instruments.
4. By measuring density fluctuations and electric field variations from zero frequency up to 8 kHz, LAP will be able to investigate the stability and dynamics of the cometary plasma environment in different stages of cometary activity. This is of particular interest on and inside the contact surface, where no wave measurements have yet been done.
5. By analysing LAP data together with data from other RPC instruments, it will be possible to investigate a broad range of problems no single RPC instrument could cover on its own. Examples are interactions between low frequency waves and plasma particles (LAP-ICA-IES), MHD waves and contact surface properties (LAP-MAG), and wave-wave interactions (LAP-MIP).

Table 1 Summary of parameters accessible to LAP. All the parameter range for a given parameter may not be accessible in one single operational mode, or for all plasma parameters. For example, the lowest limit of sensitivity to plasma density fluctuations can only be obtained in the highest density plasmas.

Quantity	Range
Plasma density	1 cm^{-3} – 10^6 cm^{-3}
Electron temperature	$\sim$ 10 meV – 10 eV (100 K - 10^5 K)
Plasma drift velocity	Up to 10 km/s
Electric field fluctuations	Up to 8 kHz
Plasma density fluctuations	0.05 - 50%
Spacecraft potential	$\pm$40 V
Effective ion mass (weighted harmonic mean; assumes density and flow speed known)	1 - 100 AMU
Integrated solar EUV flux	(for $n_e \lesssim 1000$ cm^{-3})

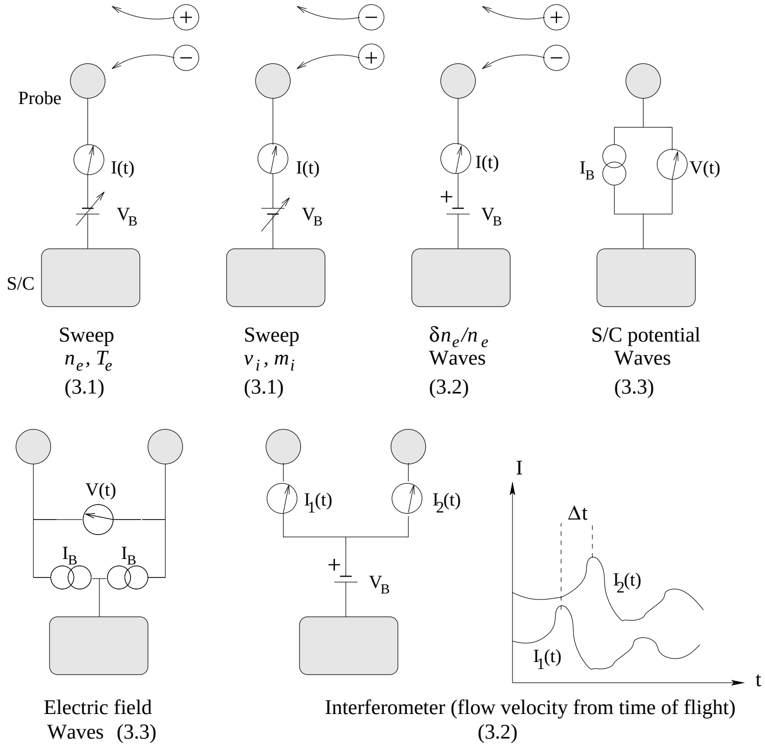

Fig. 2 Principles for LAP measurements. Numbers in parenthesis refer to Sections in the text.

3 Measurement principles

A spherical Langmuir probe is a conceptually simple device, but is nevertheless able to provide data on a multitude of plasma parameters. The use of two probes extends these possibilities further, particularly when coupled to versatile electronics. LAP does the best of these possibilities by implementing several measurement principles, as described below and illustrated in Figure 2.

3.1 Bias voltage sweeps

For the measurement of electron number density and electron temperature, the standard measurement technique is the Langmuir probe bias sweep. The probe potential with respect to the spacecraft, V_B, is varied and the current collected by the probe, I_P, is recorded. By comparison to theoretically predicted current-voltage relations, fundamental plasma parameters can be inferred, most notably the electron number density n_e and temperature T_e. This is a standard technique in the laboratory as well as in space, including the Vega flyby of comet Halley [3] and Cassini at Saturn and Titan [4]. During the Rosetta mission, LAP will encounter widely different plasma regimes, and the appropriate probe theory will vary accordingly.

Details of some bias sweeps, obtained in different space environments, were shown in Reference [2]. In Figure 3, the lower panel contains a colour coded summary of all sweeps obtained near closest approach of the 2nd Earth swing-by on November 13. The plasmasphere was encountered twice (around 20:30 and 21:15), as is clearly seen from the higher currents seen for positive bias values, corresponding to higher electron density. One can see a similar signature also for the ions, collected at negative bias voltages, though the ion current of course is weaker.

For supersonic ion flow (thermal speed above flow speed), which is expected to be the case in the inner coma [5], one can derive an average ion drift kinetic energy. If the flow speed (Section 3.2) and ion charge are known this provides an estimate of the effective ion mass m_{i} [4].

When the photoelectron current emitted by the probe can be measured, it can be used to estimate the integrated solar EUV flux [6], which in turn can give information on the gas and dust in a column of the coma from the spacecraft towards the sun. In tenuous plasmas, sunlight on the probes make it possible to measure the spacecraft potential and the electric field (Section 3.3).

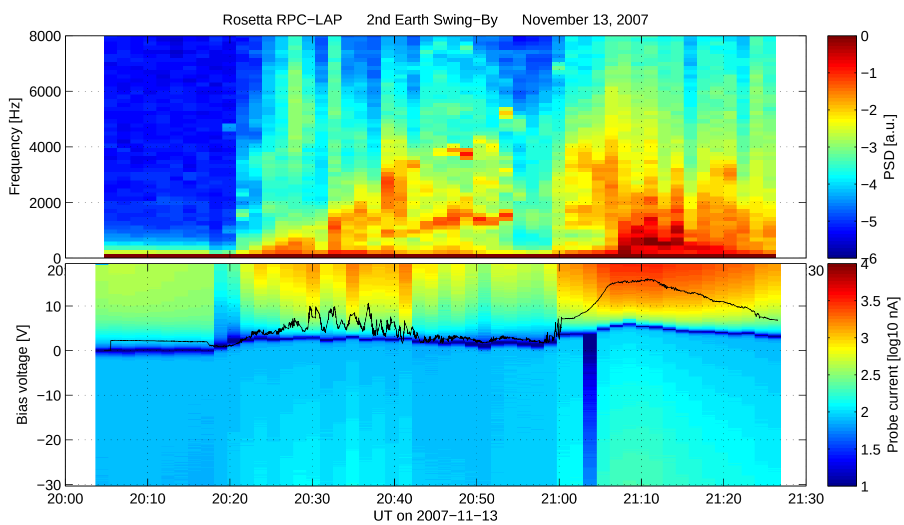

Fig. 3 Summary of LAP data around closest approach on the 2nd Earth flyby. Top panel: power spectrum of current fluctuations seen on probe 1. Lower panel: probe bias sweeps presented in colour code, with the probe current to probe 1 at fixed bias (19.5 V) denoted by a black line (in units of μA multiplied by 4).

3.2 Probe current fluctuations

By keeping the probe bias voltage constant (usually positive) one can study the changes in probe current caused by variations of plasma density and temperature. Assuming isothermal or adiabatic conditions, this can be used to estimate the relative electron density variations, $\delta n_e / n_e$, up to a frequency which varies with the plasma conditions but can be determined from a probe bias sweep and electronics performance [7]. Above this frequency, which for Rosetta typically lies in the kHz range, the current is mainly due to capacitive coupling to the voltage fluctuations in the plasma, so that we measure electric fluctuations rather than density fluctuations at the highest frequencies.

The top panel of Figure 3 shows the power spectrum (up to 8 kHz) of the current to probe 1, at 19.5 V bias w.r.t. the spacecraft, measured around closest approach on Rosetta's 2nd Earth swing-by. Natural waves are easily spotted, with the strongest emissions in the sunlit plasmasphere (around 21:10). In the lower panel, we also show the time series of this probe current at a lower sampling rate (57.8 samples/s, c.f. Section 4.2). While this signal does not give the possibility to disentangle density from temperature in the way possible from the bias sweeps, it provides much better temporal resolution.

By using two probes separated in space, one can also study propagation properties of waves and plasma structures [8]. Close to the comet, the plasma and neutral gas flow should be coupled [5], so LAP can also provide information on the flow speed of the neutral gas.

3.3 Electric fields and spacecraft potential

When Rosetta first arrives at the comet, the solar distance is large and the cometary activity is low. The coma is therefore not fully developed, and the plasma conditions close to the comet are expected to be more like the normal solar wind [5]. Any measurements of probe current, using the principles outlined in Sections 3.1 and 3.2 above, will therefore suffer from contamination of photoelectrons emitted by the spacecraft and its solar panels. For studying the plasma dynamics in these circumstances, the LAP probes can also be operated with a controlled bias current, I_B, generally chosen to be such as to minimise the impact on the probe sheath voltage by changes in the plasma parameters. In this bias mode, the measured quantity is the potential between the probe and the spacecraft, V_{PS}, which is a sensitive measure of the plasma density (see below). This technique actually relies on the probe photoemission [9, 10], and so works well down to very low densities. This is the main science mode used for all cruise phase operations (see Section 4.3) except near closest approach on the Earth swing-bys, where the dense plasmasphere is better studied with the voltage bias mode.

The difference in V_{PS} between the two probes provides an electric field estimate when divided by the probe separation. This technique has been widely used for electric field measurements in space [10], including the Vega comet encounters [9, 3]. While LAP measurements of the quasi-static electric field in low-density situations (Debye length $\lambda_D \gtrsim$ boom length L) are complicated by the obvious asymmetries in the boom configuration (Figure 1), the AC electric field can be monitored up to 8 kHz. Frequencies above 7 kHz are covered by the MIP instrument [11].

The value of V_{PS} itself for a sunlit probe at negative bias current relates linearly [12] to the spacecraft potential with respect to the plasma, V_S, which is the basic parameter describing the spacecraft-plasma interaction and also is a proxy for the the electron number density in tenuous plasmas after calibration to other plasma density measurements. Pedersen et al. [9] used V_{PS} measurents from Vega to infer electron densities and temperatures during the Vega encounter with comet Halley.

Figure 4 shows example data from the Rosetta Mars swing-by in February 2007. While all the orbiter payload had to be switched off at closest approach for eclipse power budget reasons, RPC was switched on in time to capture the outward passage of the Martian bow shock, which is seen in the figure. At the start of the interval, Rosetta is inside the bow shock. We here find a gradually increasing V_{PS}, corresponding to a similar increase in plasma density, probably due to changing solar wind conditions. Preliminary comparisons to Mars Express ASPERA-3 ion data [13] suggest that the range of V_{PS} covered in the plot translates to a plasma density range of approximately 4 to 10 cm^{-3}. Around 04:02, the density drops as Rosetta crosses the bow shock and enters the solar wind. Close to 04:07, the bow shock expands past Rosetta, possibly due to the solar wind pressure returning to lower values, and LAP again observes denser magnetosheath plasma. Rosetta finally leaves the magnetosheath around 04:10.

Figure 4 also shows a lot of other details, corresponding to density variations on the order of 0.1 cm^{-3} or 1%. As expected, the density fluctuations are stronger in the magnetosheath than in the solar wind. The plot illustrates that V_{PS} is a sensitive measure of plasma density available at high time resolution (57.8 Hz in this case). We therefore expect LAP to be able to detect structured and weak cometary outgassing activity through its ionized component soon after arrival at the comet. Mapping LAP V_{PS} around the nucleus may thus be an efficient way to identify active regions on the comet.

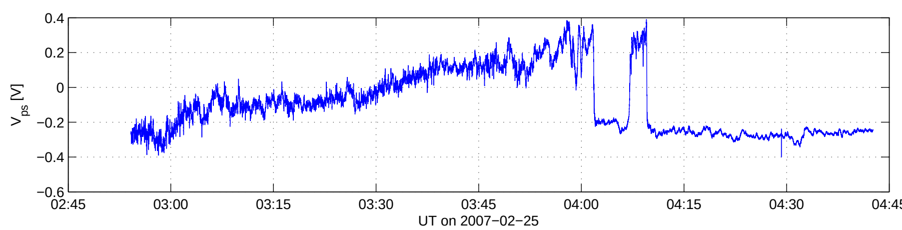

Fig. 4 A slow density increase in the Martian magnetosheath and abrupt density changes at three crossings of the bow shock are observed as signatures in the LAP V_{PS} data gathered on the outward leg of the Rosetta Mars swing-by on February 25, 2007.

4 Instrument hardware and operations

4.1 Sensors

The LAP sensors are spheres of 25 mm radius, mounted on 15 cm ”stubs” which in turn are attached to the ends of the spacecraft booms by a ”foot” (Figure 5). Probe 1 (often referred to as P1 or LAP1) is mounted on the ”upper” spacecraft boom, also carrying the RPC-MIP antenna. This boom, which is 2.24 m in length from hinge to probe, is protruding from the spacecraft at an angle of 45° to the nominal comet direction (the z axis in Figure 1). By pointing to the comet, probe 1 will get access to a plasma flow from the comet as undisturbed as possible by any spacecraft sheath or wakes, wihout interfering with the field of view of other instruments. Probe 2 is mounted on the ”lower” boom, also carrying the RPC-MAG sensors, which is 1.62 m from hinge to probe. The distance between the probes is 5.00 m, and the probe separation in the nominal comet direction, relevant for flow measurements with the interferometry technique (Section 3.2), is 4.55 m.

The probes are lightweight (40 g) titanium shells, and the stubs are made from the same material (Figure 5). The probes are electrically insulated from the stubs, but the stub is bootstrapped to the same potential as the adjacent probe by the instrument electronics (Section 4.2). Probes and stubs have a coating of titanium nitride (TiN), which has a uniform work function, is mechanically robust and is chemically inert [2, 14]. A single probe, identical to the LAP sensors, is operational with the Cassini RPWS instrument [15], providing excellent data [16, 4] with no sign of degradation after ten years in space.

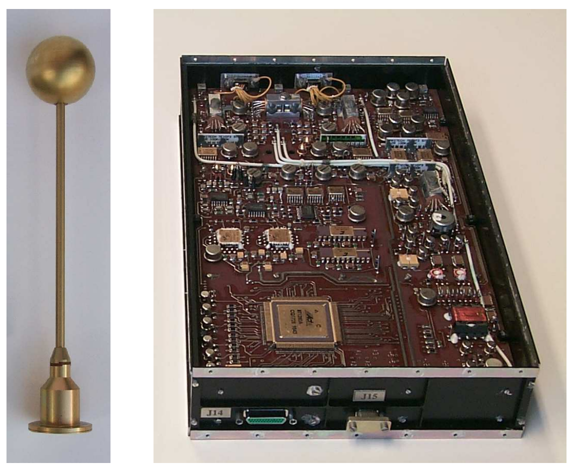

Fig. 5 LAP hardware. At left one of the two probes; at right the top of the RPC0 electronics box with the lid open, exposing the LAP analog board. The probe and its supporting rod (stub) are made of titanium with a titanium nitride coating.

4.2 Electronics

The LAP electronics are mounted on two circuit boards in the RPC0 common electronics box [1]. One of the boards holds the digital processing unit (DPU), while the other board (Figure 5) contains the sensor analog electronics interfacing the DPU to the LAP sensors. The LAP electronics are well described elsewhere [2]: we here just review the basic properties, directly relevant for the measurements.

The analog electronics are designed so that the two probes have identical capabilities and can be operated independently of each other. For example, both can be operated in any of the two bias modes (voltage or current bias, see Section 3 above), and the bias mode of one probe can be chosen to be the same or different from the other.

The two spheres can be individually biased within the range ± 31 V when in Langmuir mode, and within ± 44 nA in electric field mode. Probe bias voltage sweeps can be performed over the full measurement range at resolutions down to 0.25 V. In the inner coma, electron temperatures (in eV) below this minimum step size value are expected [5]. To properly resolve such low values of T_e, it is possible to perform high-resolution sweeps at step sizes down to 10 mV over ± 1.2 V around an offset bias which can be set by command or onboard software to values in the range -8 V to $+9$ V. Electrostatic cleaning [17] of the probes is provided by the ± 31 V bias voltage.

Probe 2 can be used by the RPC-MIP instrument for its long-Debye-length (LDL) mode [11]. In this mode, MIP uses LAP probe 2 for transmission and the MIP antenna on the upper boom for receiving, thereby getting a longer base line, appropriate for low plasma densities. LAP cannot use probe 2 at the same time as MIP, but can continue operations using probe 1 only or time-share probe 2 with MIP.

The plasma densities expected during the Rosetta mission spans some six order of magnitudes, from sometimes below 1 cm^{-3} in the solar wind to possibly as high as 10^6 cm^{-3} in the fully developed cometary coma. This implies an approximately equal variation in probe currents, though there is little need to cover the full bias voltage range in the densest plasmas. Two measurement ranges are therefore implemented: low gain spanning ± 10 μA, and high gain spanning ± 200 μA. The voltage measurements (electric field mode, Section 3.3) always cover ± 40 V.

Two analog-to-digital converters (ADCs) are connected to each probe: one 16 bit, operating at 18 750 samples/s, and one 20 bit, acquiring 57.8 samples/s. The inclusion of two ADCs for each probe makes it possible to save processing power in low-telemetry mode operations and provides some redundancy. Three four-pole analog low-pass filters are implemented for each probe: two filters, selectable by multiplexor, for the 16 bit ADCs with corner frequencies at 4 kHz and 8 kHz, and one for the 20 bit ADC, with a corner frequency of 20 Hz. Additional digital filtering is available in software (Section 4.3).

4.3 Operational modes

LAP can transmit data to the PIU at three different rates: 1.6 bit/s (low telemetry rate, or LM), 62.5 bit/s (normal telemetry rate, or NM) or 2253 bit/s (burst telemetry rate, or BM). Even the highest TM rate barely allows the transmission of all data produced by even the two low rate 20-bit ADCs, and nothing near the 600 kbit/s produced by the two high rate 16-bit ADCs can ever be transmitted. For the highest frequencies, the mainly used approach is to take data at full time resolution during a short time span, to get information on phase as well as amplitude for any observed waves.

To provide flexibility over the mission lifetime of more than ten years, the instrument operational modes are defined as ”macros”, i.e. repeatable command sequences that can be uploaded to the spacecraft and stored either in EEPROM for execution at any time or directly into RAM for immediate use. A set of basic macros are also included in PROM. The macros can control any aspect of the instrument, including bias modes, bias values, measurement range, sweeps, analog and digital filtering, and ADC selection, but must conform to the telemetry rate.

The macro programming makes it possible to optimize operations for each science task and mission phase without need for large command uplink volumes: the macros are short lists, and once loaded, they are invoked by a single command se-

Table 2 LAP macros used during the second Earth swing-by, November 2007, examplifying the LAP measurement capabilities. I1 is current to P1, V2 voltage on P2 etc. The f_{samp} is the resulting sampling frequency after possible downsampling in software. Bias sweeps and wave snapshoths are not continuous but occur with a cadency (repetition rate) which is a multiple of 32 s. Further explanations are given in the text.

Macro ID	**104**	**600**	**604**	**704**	**705**	**706**
Purpose	Calibration	Sweeps, waves	Sweeps, waves, cont. current	Vsc, waves	Vsc, waves	Vsc, waves
TM rate	NM	NM	BM	BM	NM	BM
Bias mode	NN	NN	NN	E- (LDL)	EE	EE
Fix bias P1	-	+20 V	+20 V	-29 nA	-29 nA	-29 nA
Fix bias P2	-	+20 V	+20 V	-	+3 nA	+3 nA
Continuous data (20-bit ADCs)						
Sampled data	-	-	I1, I2	V1	V1	V1, V2
f_{samp} [Hz]	-	-	28.9	57.8	0.9	57.8
Wave snapshots (16-bit ADCs)						
Sampled data	-	I1, I2	I1, I2	V1	V1-V2	V1-V2
f_{samp} [Hz]	-	18750	18750	18750	18750	18750
Samples	-	256	1840	2416	272	2624
Cadency [s]	-	256	96	32	160	96
Bias voltage sweeps (16-bit ADCs)						
Probes	Internal	P1, P2	P1, P2	-	-	-
Cadency [s]	288	256	96	-	-	-
Range [V]	[-30, +30]	[-30, +20]	[-30, +20]	-	-	-
Step [V]	0.25	0.25	0.25	-	-	-

quence. Table 2 shows the macros used during the second Earth swing-by in November 2007. Of these, the first two can be seen as diagnostic modes, while the last four are science macros. Macro 104 performs internal calibrations, sweeping the bias voltage with the probes disconnected to establish internal offsets for on-ground calibration of the data from other macros. Macro 600 was also used for diagnostic purposes, to establish the photoelectron saturation current from the probes at a few times during the swing-by.

LAP operated for two weeks around closest approach, and as the bulk of this time was spent in the tenuous plasmas of the solar wind and the terrestrial magnetotail, the macros used for the science operations mainly concentrated on V_{PS} measurements (3.3). Macro 705 provides such measurements at a rate of 0.9 samples/s for the normal mode (NM) telemetry allocation, together with a short record of wave data to 8 kHz every 160 s. For the 24 hours around closest approach when RPC had burst mode (BM) data rate, macro 706 provides the same data at much better time resolution. When probe 2 was handed over to the MIP instrument for the LDL mode (Section 4.2), macro 704 was used instead. Only at closest approach did Rosetta enter plasmas of sufficient density for making the voltage bias mode (Sections 3.1 and 3.2) useful. For this period we used macro 604, provided sweeps, continous probe current measurements at 28.9 samples/s and fixed bias voltage, and short burst of data to 8 kHz: an overview of the resulting data is shown in Figure 3.

5 Outlook

In this paper, we have summarized the scientific expectations on the LAP instrument and the methods it implements for fulfilling these, illustrating with data from the Earth and Mars flybys. The first task facing LAP at the comet will be to detect and map early cometary activity, which it can do by high sensitivity in situ measurements of plasma density structures. This capability was examplified with data from the Martian magnetosheath and bow shock, and we expect that similar data gathered close to the comet will provide good spatial resolution of the structure of the cometary outgassing through its ionized components.

Closer to comet perihelion, we expect a much denser plasma environment, at least as dense as at the terrestrial plasmasphere encounters shown here. Different biasing modes (current and voltage bias, respectively) will be optimal in these two plasma regimes, and LAP has the capacity to cover both at high resolution.

Acknowledgements We are greatly indebted to all people participating and helping in the development of LAP and RPC. We wish to particularly emphasize the excellent collaboration within RPC, where the efforts of the PIU team at Imperial College deserve special praise, and with the project teams at ESTEC and ESOC. We thank Rickard Lundin for density comparison data from the Mars Express ASPERA-3 instrument. The development of LAP was supported by the Swedish National Space Board and by the Research Council of Norway.

References

1. C. Carr, E. Cupido, C.G.Y. Lee, A. Balogh, T. Beek, J.L. Burch, C.N. Dunford, A.I. Eriksson, R. Gill, K.H. Glassmeier, R. Goldstein, D. Lagoutte, R. Lundin, K. Lundin, B. Lybekk, J.L. Michau, G. Musmann, H. Nilsson, C. Pollock, I. Richter, J.G. Trotignon, Space Sci. Rev. **128**, 629 (2007)
2. A.I. Eriksson, R. Boström, R. Gill, L. Åhlén, S.E. Jansson, J.E. Wahlund, M. André, A. Mälkki, J.A. Holtet, B. Lybekk, A. Pedersen, L.G. Blomberg, the LAP team, Space Sci. Rev. **128**, 729 (2007)
3. R. Grard, H. Laakso, A. Pedersen, J.G. Trotignon, Y. Michailov, Ann. Geophysicae **7**, 141 (1989)
4. J.E. Wahlund, R. Boström, G. Gustafsson, D.A. Gurnett, W.S. Kurth, A. Pedersen, T. Averkamp, G.B. Hospodarsky, A.M. Persoon, P. Canu, F.M. Neubauer, M.K. Dougherty, A.I. Eriksson, M.W. Morooka, R. Gill, M. André, L. Eliasson, I. Müller-Wodarg, Science **308**, 986 (2005)
5. K.C. Hansen, T. Bagdonat, U. Motschmann, C. Alexander, M.R. Combi, T.E. Cravens, T.I. Gombosi, Y.D. Jia, I.P. Robertson, Space Sci. Rev. pp. doi:10.1007/s11,214–006–9142–6 (2007)
6. L.H. Brace, W.R. Hoegy, R.F. Theis, J. Geophys. Res. **93**, 7282 (1988)
7. A.I. Eriksson, R. Boström, in *Measurement Techniques in Space Plasmas: Fields (AGU Geophysical Monograph 103)*, ed. by J. Borovsky, R. Pfaff, D. Young (American Geophysical Union, 1998), pp. 147–153
8. G. Holmgren, P.M. Kintner, J. Geophys. Res. **95**, 6015 (1990)
9. A. Pedersen, R. Grard, J.G. Trotignon, C. Beghin, Y. Mikhailov, M. Mogilevsky, Astron. Astrophys. **187**, 297 (1987). F.
10. A. Pedersen, F. Mozer, G. Gustafsson, in *Measurement Techniques in Space Plasmas: Fields (AGU Geophysical Monograph 103)*, ed. by J. Borovsky, R. Pfaff, D. Young (American Geophysical Union, 1998), pp. 1–12
11. J.G. Trotignon, J.L. Michau, D. Lagoutte, M. Chabassière, G. Chalumeau, F. Colin, P.M.E. Décréau, J. Geiswiller, P. Gille, R. Grard, T. Hachemi, M. Hamelin, A. Eriksson, H. Laakso, J.P. Lebreton, C. Mazelle, O. Randriamboarison, W. Schmidt, A. Smit, U. Telljohann, P. Zamora, Space Sci. Rev. **128**, 713 (2007)
12. C. Cully, R.E. Ergun, A.I. Eriksson, J. Geophys. Res. **112**, A09211, doi:10.1029/2007JA012269 (2007)
13. S. Barabash et al., Space Science Reviews **126**, 113 (2006). DOI 10.1007/s11214-006-9124-8
14. M.K. Wahlström, E. Johansson, E. Veszelei, P. Bennich, M. Olsson, S. Hogmark, Thin Solid Films **220**, 315 (1992)
15. D.A. Gurnett, W.S. Kurth, D.L. Kirchner, G.B. Hospodarsky, T.F. Averkamp, P. Zarka, A. Lecacheux, R. Manning, A. Roux, P. Canu, N. Cornilleau-Wehrlin, P. Galopeau, A. Meyer, R. Boström, G. Gustafsson, J.E. Wahlund, L. Åhlen, H.O. Rucker, H.P. Ladreiter, W. Macher, L.J.C. Woolliscroft, H. Alleyne, M.L. Kaiser, M.D. Desch, W.M. Farrell, C.C. Harvey, P. Louarn, P.J. Kellogg, K. Goetz, A. Pedersen, Space Science Reviews **114**, 395 (2004). DOI 10.1007/s11214-004-1434-0
16. J.E. Wahlund, R. Boström, G. Gustafsson, D.A. Gurnett, W.S. Kurth, T. Averkamp, G.B. Hospodarsky, A.M. Persoon, P. Canu, A. Pedersen, M.D. Desch, A.I. Eriksson, R. Gill, M.W. Morooka, M. André, Geophys. Res. Lett. **32**, doi:10.1029/2005GL022699 (2005)
17. L.H. Brace, in *Measurement Techniques in Space Plasmas: Particles (AGU Geophysical Monograph 102)*, ed. by J. Borovsky, R. Pfaff, D. Young (American Geophysical Union, 1998), pp. 23–35