

An Instrument for Measuring the Near-Surface Plasma Temperature and Concentration, and the Surface Charging of the International Space Station

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Accepted: 27 February 2010

Abstract The Langmuir probe is one of the classical instruments for plasma diagnostics [1] and among the first space-borne instruments. Langmuir probes have been successfully used aboard a number of rockets and satellites for in situ measurements of thermal plasma parameters in the terrestrial ionosphere [2], at other planets [3] and comets [4], and recently it is an indispensable instrument for measuring the satellite surface potential. In the present paper we discuss some theoretical and practical aspects of the application of the Langmuir probe for ionospheric measurements. We show that the spherical probe cannot be used for measurements in the ionosphere, and for the cylindrical probe the experimental Volt-Ampere curves are not described by the formula for an infinite cylinder. A formula is proposed for processing of this region. We demonstrate that in the case of two prevailing ions, their concentration can be found from the ion saturation region. Finally, we describe the two Langmuir probes designed and manufactured in Bulgaria, a part of the Plasma Wave Complex PWC (Obstanovka experiment) aboard the Russian segment of the International Space Station, whose goal is to monitor the surface charging and the noises and disturbances in the surrounding plasma induced by the station and by the experiments conducted aboard it.

Keywords: Langmuir probe, ionospheric plasma measurements, International Space Station

Introduction

In principle, a Langmuir probe can be any conducting body introduced into the plasma. Voltage is applied to the probe, changing over a certain range, and the probe current is measured. The dependence of the probe current on the voltage is usually referred to as "probe characteristic" or "Volt-Ampere curve" (Fig.1). The plasma parameters are derived from the form and amplitude of this curve. When the probe potential is negative enough to repel all the electrons, the probe current is due only to the ions which are accelerated towards the probe, and the current's amplitude is proportional to the ion concentration. When the probe potential is less negative, the more energetic electrons overcome it, and produce an electron current, exponentially increasing when the voltage is further decreased. The electron temperature is derived from the slope of the volt-ampere curve in this electron retardation region. When the probe is positive with respect to the plasma, the ion current is negligible while the electrons are accelerated, and the amplitude of the current is a function of the electrons concentration.

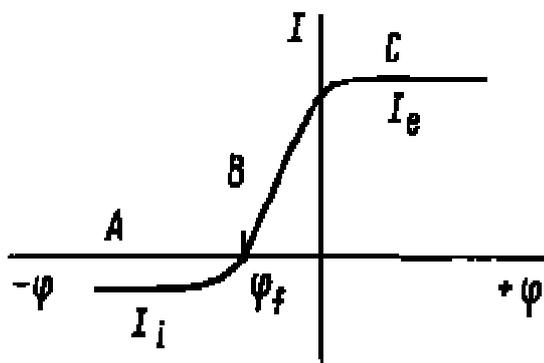


Fig.1. A typical volt-ampere characteristic from the cylindrical Langmuir probe

Langmuir probe - LP for ionospheric measurements

Choosing the probe geometry

In spite of its simple construction, the interpretation of the results from the Langmuir probe is not an easy task, further complicated in space experiments by the fact that the probe together with the spacecraft moves with respect to the plasma. The general equation of the current to a moving spherical or cylindrical probe is quite complex and has no analytical solution, so some approximation should be used. The equation can be solved in two limiting cases determined by the ratio of the sheath radius to the probe radius [5]: (1) Thin sheath (sheath area limited) approximation, $r/a \rightarrow 1$; 2) Thick sheath ("orbital motion limited") approximation, $r/a \rightarrow 0$, where r is the probe radius, and a the sheath radius. As the sheath radius is proportional to the Debye radius Дебай $\lambda_d = (ekT/Ne^2)^{1/2}$, usually the ratio r/λ_d is used instead of r/a .

Our earlier analysis [6] demonstrated that the sheath area limited approximation introduces very big errors which are practically never below 10% and quickly increase with increasing the non-dimensional potential $V = |e\phi/kT|$, where e is the electron charge, ϕ - the voltage applied to the probe in V, k - Boltzman constant, T - electron (ion) temperature, and become >100% even at V as low as 1.5 V. The orbital motion limited approximation is accurate within 2.5% for the cylindrical probe for any value of V up to 29. For $r/\lambda_d = 1$ the difference between the exact and the approximated values is 0 up to $V=20$ and 0,002% for $V=25$, and for $r/\lambda_d < 1$ it is 0 for any V . However, for the spherical probe the errors are still big, being below 10% only in a very limited region of the ionosphere, and at relatively low values of V , that is for $\phi < 2$ V, and are strongly dependent on the plasma parameters.

When the probe is used for space research, it moves together with the vehicle with respect to the surrounding plasma. This leads to big ion Mach numbers $M = (ma^2 \sin^2 \theta / 2kT)^{1/2}$ where θ is the angle between the probe axis and the velocity vector for a cylinder; for a sphere $\theta =$

$\pi/2$; ω is the probe velocity with respect to the stationary plasma, and to much smaller but not vanishing electron mach numbers. In orbital motion limited approximation the current to a moving sphere is given by [5]:

$$I_{sphere}^{oml} = \frac{\pi^{1/2}}{2} \frac{M^2 + V + 1/2}{2} \operatorname{erf}(M) + \frac{1}{2} e^{-M^2}$$

Where the current I is expressed in a normalized form $I = i/i_{random}$ with i denoting the actual current and i_{random} - the random current to a non-charged probe of area A due to particles of mass m with density n and temperature T :

$$i_{random} = (kT/2\pi m)^{1/2} N A e$$

The asymptotic formula which is often used is:

$$I_{sphere}^{oml} \approx \frac{\sqrt{\pi}}{2} M \left(1 + \frac{1}{2M^2} + \frac{V}{M^2} \right)$$

It is derived under the assumption that M is big enough, As expected, the error mainly depends on M and quickly decreases with increasing M , being always below 1% for $M > 1.8$. On the other hand, for small M the error is considerable and can exceed 1000%. For hydrogen ions at high temperatures M becomes critically small. For $T > 3000$ K the error is above 50 %, and for $T > 5000$ K - above 100 %.

For the cylindrical probe Wharton and Hoegy (1971) have derived the following formula:

$$I_{cylinder}^{oml} \left(V + M^2 + \frac{1}{2} \frac{M^2}{V + M^2} + \frac{V}{V + M^2} \right)^2 \quad (1)$$

(1) can be used in both the electron saturation region and in the ion saturation region. For electrons M is taken as 0 and (1) becomes:

$$I_{cylinder}^{oml} = \frac{2}{\sqrt{\pi}} (1+V)^{1/2} \quad (2)$$

For ions the formula used is:

$$I_{cylinder}^{oml} = \frac{2}{\sqrt{\pi}} \left(V + M^2 + \frac{1}{2} \right)^{1/2} \quad (3)$$

(3) is derived from (1) for $M > V$. However, as commented above, for lighter ions this is not always true. For $M > 2.5$ the error is below 1 % for any value of V . For $M < 0,7$ и $V < 1.3$ the error can exceed 10 % and reaches up to 10,82% for hydrogen ions at $z = 10,000$ K, when the accelerating potential is below 1 V. If the probe operates at $\varphi < 3$ V, the error is below 5 % for any temperature.

As seen from the above analysis, the accelerated particles current to both a spherical and a cylindrical probe can be approximated by the orbital motion limited approximation. This approximation introduces no errors for the cylindrical probe. For the spherical probe the errors are always above 10 % and strongly depend on the plasma parameters and on the voltage applied to the probe. Further approximations introduce errors of up to 5 % in the data from the cylindrical probe and much bigger for the spherical probe. The spherical probe is practically unusable for measuring the electron concentration, and the ion concentration data are unreliable for lighter ions at higher temperatures.

Measuring the electron concentration with a cylindrical Langmuir probe

The following equations are derived under the above approximations for the current to a cylindrical probe moving with respect to the plasma [2]:

The electron current collected at $\varphi > 0$ is given by:

$$I_e = A N_e e 2 \pi^{1/2} (k T_e / 2 \pi m_e)^{1/2} (1 + e \varphi / k T_e)^{1/2} \quad (4)$$

Where T_e is the electron temperature, N_e the electron concentration, m_e the electron mass and k the Boltzmann constant. This equation can be presented in the form:

$$I_e = (a_e \varphi + b_e)^{1/2} \quad (4')$$

If the coefficients a_e and b_e are known, it is easy to derive the concentration

$$N_e = \frac{\pi}{A} \sqrt{\frac{\alpha_e m_e}{2e}} \quad (5)$$

When studying the electron saturation region of the Langmuir probe aboard the Bulgaria-1300 satellite it was found that the coefficient a_e is a function of the potential φ which means that the current in the electron saturation region is not described by equation (4). We suppose that this is due to the fact that the probe is not an infinite cylinder and the end effects cannot be neglected. As a result the current is described by the equation

$$I_e' = I_e + I_{e1}$$

where the first term is the current given by (4), and the second term - the current due to the end effects. Assuming spherical symmetry of the end effects, $I_{e1} = a_{e1} \varphi + b_{e1}$. Other authors (Brace, private communication), assuming that the true solution of (4) should be between cylindrical and spherical symmetry, suggest for I_e an approximation of the form $I_e = (a_e \varphi + b_e)^n$

Here the coefficients a_e have b_e the same meaning as the coefficients in (4'), and the power n varies between 0,5 in the case of an ideal cylinder and 1 in the case of an ideal sphere. We have tested the Bulgaria-1300 V-A characteristics against the above equation, and have found that at low electron temperatures T_e ($\approx 1000^\circ\text{K}$), n is about 0.55. With increasing T_e , n also increases, but in all studied cases it never exceeded 0.8. The accuracy of the concentration derived with this approximation is close to the one derived by the other method

Deriving the ion concentration and the concentrations of two dominant ions with a cylindrical Langmuir probe

If negative voltage with respect to the plasma is applied to the probe, the ions are accelerated to the probe and the electrons are retarded. Therefore, the current is due to both ions and electrons with high enough energy to overcome the potential barrier. If the negative potential is large enough, the current is fully determined by the ions and is described by the following equation:

$$I_i = \sum_{j=1}^n A N_j q_j \omega_j \pi^{-1} \left(1 + k T_j / m_j \omega_j^2 + 2e \varphi / m_j \omega_j^2 \right)^{1/2} \quad (6)$$

where I_i is the ion current; A - the probe area; N_j , q_j , T_j , m_j - density, charge, temperature and mass of the j -th

ion species; ω_i - ion drift velocity in the satellite reference frame; φ - probe potential with respect to the plasma; e - electron charge; k - the Boltzmann constant. This equation can be presented in the form:

$$i_i = \sum_{j=1}^n (a_j U + b_j)^{1/2}$$

As a result of the higher energy of the ions it can be expected that the end effects in the ion saturation region will be less. Indeed, the investigation of the V-A characteristics of the Langmuir probe aboard Bulgaria-1300 satellite showed that the power is equal to 0.5 with accuracy down to the third digit.

If the plasma consists of two ion species, i.e. $n=2$, a good approximation is

$$i_i = (a_i U + b_i)^{1/2} \quad (7)$$

If we know the coefficients a_i and b_i , we can determine the ion N_i , and the effective ion mass M_i

$$N_i = \frac{\pi}{A e w} \sqrt{\frac{2be - akT}{2e}}; M_i = \frac{2be - akT}{aw^2}$$

Assuming that the two ions are O^+ and H^+ , it was found that the error in determining N_i as a result of the above approximation does not exceed 10%, and depends on the concentration of the two ions (Fig.2).

The maximum error (10%) is when the concentrations are equal, i.e. $N_1/N_2 = 1$. With increasing N_1/N_2 the error quickly decreases and for $N_1/N_2 = 100$ it is less than 1%. It is interesting to note that the results for $N(O^+) > N(H^+)$ and $N(O^+) < N(H^+)$ coincide. For two ions the following system of two equations is obtained.

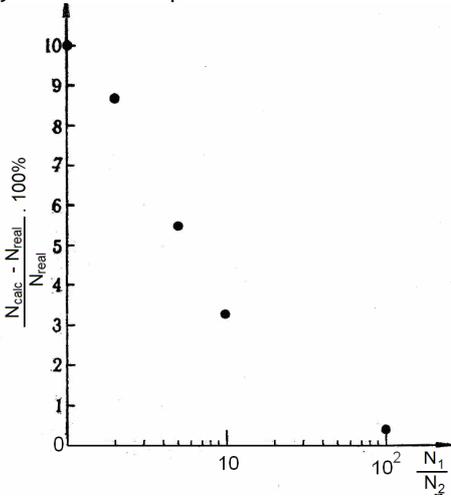


Fig.2. Errors (in %) in determining the ion concentration as a result of approximation (7)

$$N_i = N_1 + N_2$$

$$\frac{1}{M_i} = \frac{1}{N_i^2} \left(\frac{N_1^2}{m_1} + \frac{N_2^2}{m_2} \right)$$

Here m_1 and m_2 are the masses of the two ions in a.e. If m_1 and m_2 are known, the unknown in the equations are only N_1 and N_2 - the concentrations of the two ions, and they can be derived from the system. Fig.3 presents the errors in determining N_1 and N_2 as a function of N_1 and N_2 . The error in determining $N(O^+)$ is in all cases below 20%, and the calculated concentration is usually

underestimated. If $N(O^+)$ is higher than $N(H^+)$ by an order of magnitude or more, $N(H^+)$ is calculated with a big error and is always overestimated. The shaded area denotes the parameters for which the method is not applicable. In this area the ratio $N(O^+) \gg N(H^+)$ after calculations is interpreted as $N(O^+) < N(H^+)$

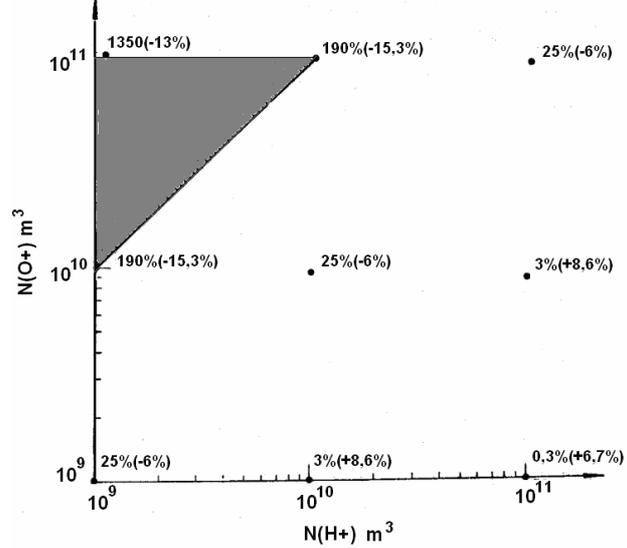


Fig.3. Errors in determining N_1 and N_2 . The numbers in brackets are about 0

Determining the electron temperature with a cylindrical Langmuir probe

When the negative potential is decreased, the growing electron current is superimposed on the ion current. The negative potential is retarding for the electrons. The current depends only on the potential across the sheath and doesn't depend on the size of the sheath. In terrestrial and planetary ionospheres the equation for the electron current at negative potential is

$$i_{ret} = AN_e e \sqrt{\frac{kT_e}{2\pi m_e}} \exp\left(-\frac{e\varphi}{kT_e}\right)$$

Which can be presented as $i_{er} = a_{er} \exp(b_{er}\varphi)$. The net current for $\varphi < 0$ is given by

$$i_{net} = i_i + i_e = (a_i\varphi + b_i)^{1/2} + a_{er} \exp(b_{er}\varphi) \quad (8)$$

In principle, there are two approaches in determining the electron temperature T_e . The first one is to approximate the ion current for $\varphi \ll 0$, i.e. in the region where the electron current can be neglected. This ion current is extrapolated for all $\varphi < 0$, and the electron current is $i_{er} = i_{net} - i_i$, i.e. the net current is corrected for the ion current. The linear dependence of the logarithm obtained after the correction on the applied voltage can be used as a criterion for the quality of the correction [7]. The electron temperature is calculated as

$$T_e = \frac{e}{k} \left(\frac{d \ln i_{ret}}{d\varphi} \right)^{-1}$$

The other approach which we apply is to approximate (8) and to determine the coefficients a_i , b_i , a_{ret} and b_{ret} , after which the temperature T_e is calculated from the

coefficient b_{ret} : $T_e = -e/kb_r$, and the ion parameters are calculated from the coefficients a_i and b_i .

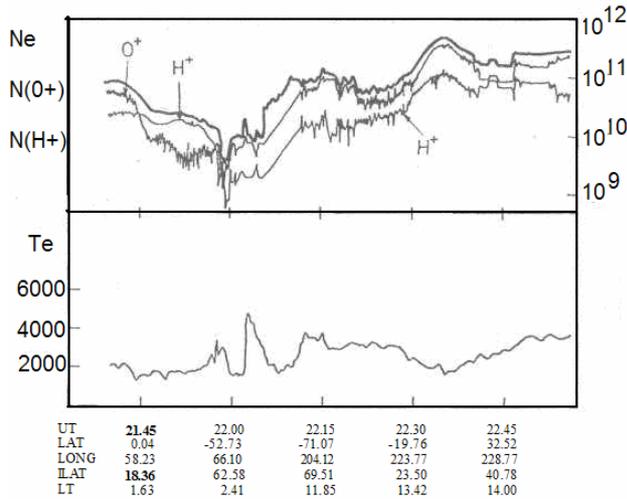


Fig.4. Plasma parameters measured by a cylindrical Langmuir probe (P7 instrument) along 175 orbit of “Intercosmos Bulgaria-1300 satellite”

Fig.4 summarizes the plasma parameters measured with the Langmuir probe: the electron concentration N_e , the concentrations of the two dominant ions $N(O^+)$ and $N(H^+)$, and the electron temperature T_e

Determining the spacecraft potential with a Langmuir probe

The zero of the voltage generator is connected to be the satellite body and all voltages are applied with respect to this “zero”. The satellite also charges electrostatically and reaches some potential φ_s , which is due to both the surrounding plasma and the solar electromagnetic radiation.

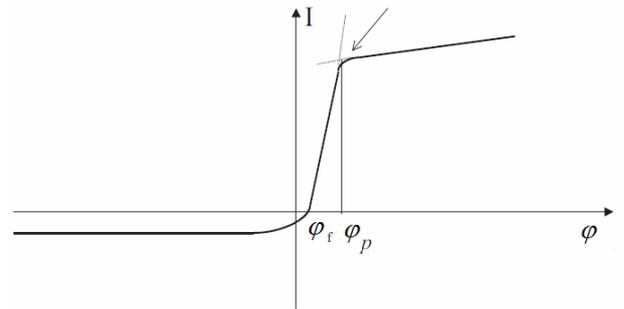


Fig.4. Floating potential and satellite body potential with respect to the plasma

The net current i_{net} to the surface of the spacecraft can be written as $i_{net} = i_e - (i_i + i_{se} + i_{bse} + i_{sp} + i_\phi)$ where: i_e - plasma electron current; i_i - plasma ion current; i_{se} - secondary electron emission current; i_{bse} - backscattered electrons current; i_{sp} - secondary electron emission due to protons; i_ϕ - photoelectron emission current. The plasma electron current i_e brings negative charge to the spacecraft surface, the other currents remove the negative charge from the surface. The resulting floating potential φ_f is determined by the dynamical equilibrium on the surface when the net current $i_{net} = 0$. On the other hand, the net current to the probe at $\varphi < 0$ is $i_{net} = i_{ret} + i_i$. Therefore, φ_f (φ at $i_{net} = 0$) depends on T_e . In the ionosphere φ_f normally will not exceed 1 V, so if we determine the floating potential, we will have a good estimation of the satellite body potential with respect to the plasma (φ_p) - Fig.4.

More accurately the satellite body potential can be determined by locating the point φ_p on the curve $dI/d\varphi$. This is the point where the extrapolated curves of the electron retarding region and of the electron acceleration region cross (Fig.4).

Table 1

Unit	Responsible Institute
Combined wave sensor - CWD-1, CWD-2	LC ISR
Flux gate magnetometer - DFM-1	IKI
Flux gate magnetometer - DFM-2	LC ISR
Langmuir probe - LP-1, LP-2	STIL BAS
Spacecraft potential monitor - DP-1, DP-2	IKI BAS
Plasma discharge stimulator - SPP	SKB
Correlating Electron Spectrograph (10eV - 10KeV) CORES	Sussex University
Radio Frequency Analyzer - RFA	SISP; SRC
Signal Analyzer and Sampler - SAS3	SRG, BLE
Data Acquisition and Control Unit - DACU-1, DACU-1	KFKI RMKI; Sheffield University
Block of Storage of Telemetry Information - BSTM (inside ISS)	KFKI RMKI; Sheffield University
Grounding support equipment - GSE	KFKI RMKI; SRC

“Obstanovka” experiment onboard ISS for space weather research

All earlier studies have been conducted aboard relatively small and homogenous spacecraft, while with the launch and gradual build-up of the International Space Station we face the problems of the interaction of a super-large structure at a low orbit with its environment. For the first time we have a structure which is not only that large but also so much energy consuming and emitting. The surface potential reaches tens of volts which can seriously endanger the payload.

The goal of the Plasma Wave Complex PWC (“Obstanovka” experiment [8] for wave and plasma parameters measurements) in the ISS environment planned aboard the Russian segment of ISS, is to monitor the surface charging and the noises and disturbances in the surrounding plasma induced by the station and by the experiments conducted on it. PWC is composed of multiple units (Table 1), which are integrated into two blocks installed outside ISS and the third one (BSTM) inside ISS.

Langmuir probes for PWC - general characteristics

The main task of the two identical cylindrical Langmuir Probes LP1 and LP2 is to measure in two points the thermal plasma in the vicinity of the ISS and the potential of the ISS structure. The measured parameters are the electron and ion concentrations N_e and N_i in the range $1 \cdot 10^9 - 1 \cdot 10^{13} \text{ m}^{-3}$, the electron temperature T_e from 1000 to 6000 K, and the space station potential U_s in the range from -100 V to +100 V. There are two main modes of operation: "full", for measuring T_e , U_s , N_e and N_i , with time resolution 1 s, and "fast" for measuring the fluctuations of the plasma concentration, with frequency 200 Hz. The presence of two identical instruments LP1 and LP2 mounted in two different points allows the determination of space variations of T_e , U_s , N_e and N_i in the near surface zone.

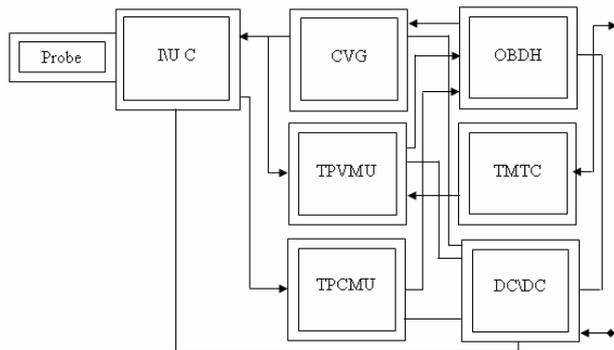


Fig.6 Functional diagram of LP unit

Each of the two probes contains an electronic block LP-VP and a measuring monoblock LP-PP. Each LP-PP is situated on a boom and consists of a sensor and a multi-range current meter. The sensors are cylindrical electrostatic probes consisting of a measurement electrode for electron or ion collection (depending on the voltage applied), a guard electrode and a connecting rod, all together forming a probe. LP-PP has 3-scales for positive currents and 3 for negative currents $\pm 5 \cdot 10^{-5} \text{ A}$, $\pm 5 \cdot 10^{-7} \text{ A}$, and $\pm 5 \cdot 10^{-9} \text{ A}$ current-to-voltage converter (I/UC), which converts the current from the measuring electrode into voltage and sends it to LP-VP.

The two LP-VP modules are situated in the Data Acquisition and Control Units DACU-1 and DACU-2. The LP-VP housing is made of aluminum (dural) and consists of: Controlled Voltage Generator (CVG), Two-polarity Current Measurement Unit (TPCMU), Two-polarity Voltage Measurement Unit (TPVMU), microcontroller for controlling and optimizing the measurement process included in On-Board Data Handling Unit (OBDH), data-processing and Telemetric Command (TMTc) and power supply (DC-DC), (Fig. 5). CVG generates the sweep voltage applied to the measuring electrode with the possibility to set the potential to any value from -100 to +100 V. The time for its tracing trough full scale (from -100 V to +100 V) is less than 20 seconds. The sweep voltage generated by CVG is controlled and commanded by the microprocessor.

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TPVMU measures the voltage applied to the measuring electrode, controls input value for potential checking and is a feedback for the software control of this potential.

TPCMU measures the current (indirectly) by taking measurements of the voltage signal produced from the LP-PP converter, proportional to the current trough the probe. There are three proportionality factors - 1, 100 and 10000. They correspond to the three scales for current measurements. The selection of the concrete factor is controlled by the microprocessor.

The above two units measuring the probe current and sweep voltage, include identical fast 16-bit ADC's, each of them interfacing with the microcontroller on its own SPI bus. TMTc is responsible for the interface between each of the LP devices and DACU. DC/DC is the power supply module generating a number of stabilized voltages.

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