

**Development of an Electrostatic Energy Analyzer (ESA)
for the EQUARS Scientific Satellite**

R. S. Dallaqua, I. H. Tan, M. V. Alves, E. del Bosco

Abstract

We present in this report the development of an electrostatic energy analyzer to be launched onboard the EQUARS Scientific Satellite. The instrument will be capable to detect electron beams with energies in the 0.1 – 40 keV range. This document concerns mainly with the scientific objectives and the mass and power requirements of the instrument

MISSION

- 1. Name of scientific instrument:** **ESA: Electrostatic Energy Analyzer**

- 2. Physical parameters to be measured:** **Electron Energy Spectrum (0.1-40) keV**

- 3. Physical parameters to be studied:** **Electron Precipitation in Equatorial Region**

4. Scientific objectives

Electron beams with energies below 50 keV are a common occurrence in either near earth distances (ionosphere), intermediate distances (magnetosphere) or interplanetary regions. These beams participate in several phenomena in these plasmas, with the aurora borealis being perhaps the most outstanding one. The electrostatic energy analyzer (ESA) has been part of several scientific satellite payloads, detecting charged particle beams with energies below 50 keV [1]. Most of the data available in the literature is related to the auroral, magnetospheric or interplanetary regions, the equatorial region having received less attention in the past. The launching of the EQUARS satellite seems therefore a good opportunity to study electron beams in the equatorial region with energies below 50 keV with an electrostatic energy analyzer. Two main scientific objectives are aimed, which will be described below.

The first objective is related to the electron precipitation in the South Atlantic Magnetic Anomaly (SAMA). This region is characterized by a global minimum in the Earth's total magnetic field intensity, providing a permanent sink for the inner belt quasi-trapped particles which, during their longitudinal drift, dip down to low levels in the atmosphere over the anomaly region. It is technologically difficult to operate satellites below 300km altitudes. Rockets and balloons provide extremely limited temporal and spatial coverage, and the altitude (<100km) provides formidable challenges to the instrument designer because of the high ambient pressure and consequent breakdown and corona problems facing instrumentation that contains high voltages. Therefore, the study of charged particle precipitation has been made by indirect measurements such as X-ray detectors and radio wave techniques. Unlike the auroral region, charged particle precipitation in low/medium latitude regions produce low optical emission, limiting the photometric techniques. Fluxes of precipitating electrons are sufficiently strong to produce localized enhancements of ionization in the D and lower E regions of the ionosphere at the SAMA. It has also been inferred from

the studies of electromagnetic wave propagation that precipitating particles are important contributors to the maintenance of the mid-latitude ionospheric D and E regions at night on a global scale [2]. Direct measurements of electron beams at the SAMA with energies below 50 keV have been made by the Atmosphere Explorer –C satellite [3]. The electron beam was detected by a cylindrical ESA, similar to the one proposed for EQUARS. The analyzer onboard AE-C was projected for studies in the auroral region, where charge particles fluxes are 10^2 - 10^4 times larger than in the SAMA. Data were obtained for orbits in which the AE-C passed in the anomaly, and the analysis was very complex owing to the low signal to noise ratio [3,4].

Electron precipitation at the SAMA and its ionizing effect in the D and E layers has been extensively studied by Abdu et al, using VLF techniques [5-7]. An electron flux of $8 \times 10^5 \text{ cm}^{-2} \text{ sec}^{-1}$ at 20 keV is expected as being the ionizing source for the D and E layers at SAMA, according to these studies. Furthermore, measurements with X-ray detectors in stratospheric balloons have indicated the occurrence of 16 keV electron beams in the SAMA region [8]. More recently, the use of an imaging riometer (IRIS) has lead to more evidences of a 20 keV beam precipitation in the SAMA region [9]. A direct measurement of the electron beam by a ESA on board EQUARS could corroborate the indirect evidences obtained by the CEA/INPE group for the presence of a ~ 20 keV electron beam at the SAMA region.

Another scientific contribution of the electrostatic energy analyzer would be the detection of electron beams in plasma bubbles. This is a controversial issue in the literature. A citation of an occurrence have been made, but due to lack of further in loco observations, there are doubts about such occurrences in plasma bubbles. The presence of electron beams in these regions would be an indication of a complex wave-particle interaction in the equatorial ionosphere [2].

The second scientific objective is related with the work developed in the plasma experiment called Quiescent Plasma (PQUI) of the Associated Plasma Laboratory (LAP/INPE). Figure 1 shows the schematics of the experiment, where an electron beam with energies below 0.5 keV originated in the plasma source is injected in the target plasma. The beam excited an electrostatic wave with frequency $\omega_0 \approx \omega_{pe} = kv_b$, where v_b is the beam velocity, ω_{pe} is the plasma frequency. Depending on the value of n_b/n_0 (n_b is the beam's density, n_0 is the plasma density) and w_0/n_0T_e ($w_0 = E_0^2/8\pi$ is the wave energy density, n_0T_e is the energy density of the plasma), the instabilities excited in the target plasma can be described by a quasi-linear or non-linear theory. As a result of a wave-particle interaction,

electrons in the plasma are heated [10,11]. Heating of electrons in the equatorial plasma (plasma bubbles) and also at the SAMA has been detected by scientific satellites, the heating mechanism being still unknown [12, 13]. Instabilities triggered by the propagation of an electron (ion) beam in space plasmas and the wave-particle interactions involved, are commonly detected by instruments onboard scientific satellites [14-18]. However, due to the complexity of these interactions, there are controversies concerning the interpretation of the observed phenomena [19,20]. A joint project of the proposed analyzer (measurement of electron energies) with the Langmuir probe (IONEX, fluctuation measurements) could be relevant for the study of the electron beam interaction with the plasma in the equatorial region.

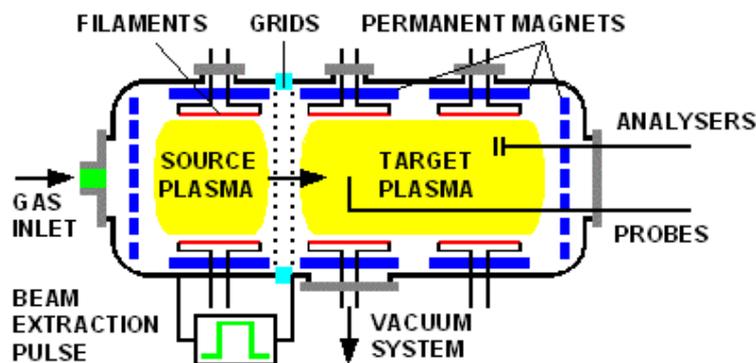


Figure 1: Schematics of the Quiescent Plasma (PQUI) Experiment

During the 2004-2006 period, an upgrade is planned for the PQUI experiment. The electron beam energy will be increased to a few keV and a magnetic field will be added ($< 10\text{G}$) to better simulate space plasma conditions. Plasma diagnostics are made with an electrostatic probe (n_0 , T_e and fluctuations), and the energy distribution function of the beam will be measured by a Retarding Potential Analyzer (RPA) ($E < 0.5\text{ keV}$), and an ESA ($E > 0.5\text{ keV}$). This experiment will be used for the calibration of the proposed analyzer.

Two analyzers should be launched onboard EQUARS, with fields of view parallel and perpendicular to the Earth's magnetic field as shown in figure 2.

The analyzers developed in this project would also be useful in future INPE scientific missions such as the Spatial Climate Monitor. The calibration equipment to be developed could also be utilized in other instrument tests like Langmuir probes.

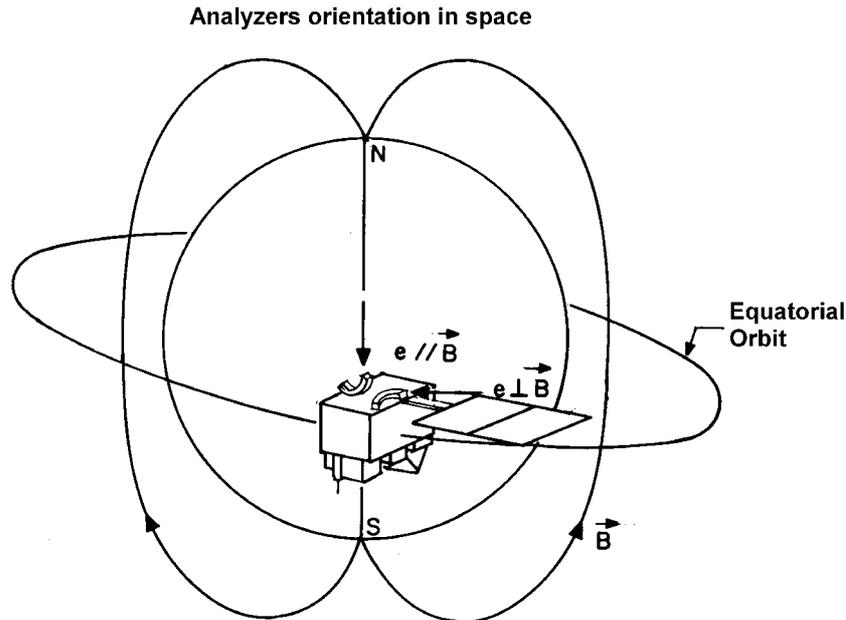


Figure 2: Orientation of the two analyzers: one parallel and one perpendicular to the Earth's magnetic field

5. Scientific final goal: Measurement of Ionizing Sources of E and F Layers at SAMA

6. Data processing facility you need: No data processing onboard

7. Data distribution policy: As defined by EQUARS committee

8. Social and educational return of your project:

Graduate, undergraduate, and technical high school students may develop scientific and technical projects during the construction of the equipment and after launching

9. Participants:

- Dr. Renato Sergio Dallaqua (INPE-LAP)
- Dra. Ing Hwie Tan (INPE-LAP)
- Dra. Maria Virginia Alves (INPE-LAP)
- Dr. Edson del Bosco (INPE-LAP)
- Dr. M. A. Abdu (INPE-CEA)
- Dr. P. Muralikrishna (INPE-CEA)

INSTRUMENT

10. Physical design and block diagram of PI

10.1 Geometry

The geometry chosen for the analyzer is cylindrical due to its construction simplicity. Besides AE-C, this type of analyzer was used in the sixties by Mariner 2 [21], for the study of solar wind particles, and in the OGO3 satellite [22] in the study of magnetospheric electrons at distances of 8 to 20 R_e . More recently, cylindrical analyzers have been used in the DMSP/F2 [23-25], DMSP/F10 and DMSP/F12 [26] satellites (Defense Meteorological Satellites Program of the US Air Force) for the studies of electron precipitation in the auroral region.

The electric field between two cylindrical concentric plates with radii r_{ext} and r_{int} , with potential difference V , will deflect circularly the trajectory of a charged particle with energy E and charge q according to the relation

$$E = qV/[2\ln(r_{ext}/r_{int})]$$

Figure 3 shows the voltages necessary as a function of energy for several values of r_{ext}/r_{int} .

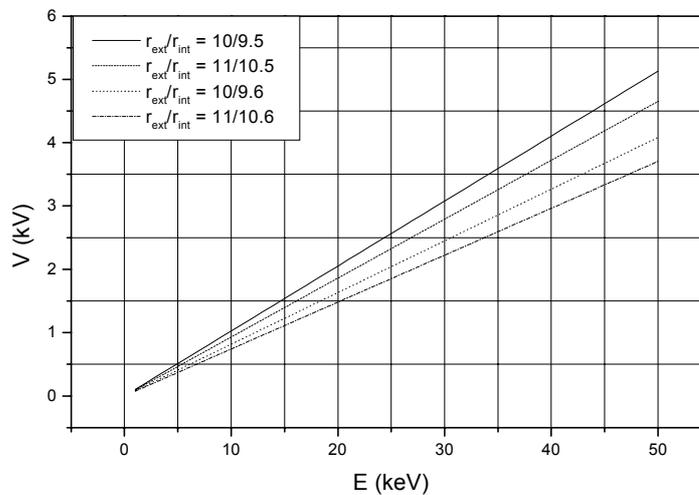


Figure 3: Voltage necessary to deflect electrons with energy E for several values of r_{ext}/r_{int} .

For the analyzer proposed in this project the values $r_{\text{ext}} = 11\text{cm}$ and $r_{\text{int}} = 10,6\text{cm}$, were chosen, which allows the detection of electrons of up to **40 keV** with a power source of **4 kV**.

The cylindrical plates will have angular extension of 127° , which is the configuration of optimal focus. This means that two electrons with the same velocity entering at different angles $\pm \Delta\alpha$ relative to the tangent, will meet again after an angular sector of $\phi = [\pi/(2)]^{1/2} = 127^\circ 7'$.

It should be noted that for cylindrical sectors with angles smaller than 127° the condition for focalization is given by:

$$\ell = \frac{r_0 [1 + \cos(\sqrt{2}\phi)]}{2 \sin(\sqrt{2}\phi)}$$

where ℓ is the distance between the entrance slit and the plates (see figure 4) and r_0 is the mean radius of the plates. It can be seen that for $\phi = [\pi/(2)]^{1/2} = 127^\circ 7'$, $\ell = 0$.

The resolution of the analyzer is given by

$$\frac{\Delta E}{E} = \frac{d}{r_0} + \frac{2}{3}(\Delta\alpha)^2 + \frac{1}{2}(\Delta\beta)^2$$

where β is the entrance angle in the plane perpendicular to α , and d is the slit's width. For $d = 2\text{mm}$, $r_0 = 108\text{mm}$, $\Delta\alpha = 5^\circ$ (0,0872 rad) and $\Delta\beta = 10^\circ$ (0,174 rad), $\Delta E/E = 0,0185 + 0,0051 + 0,0152 \cong 0,039$. The angle α and β are defined by slits placed at adequate distances from the entrance.

The plates height will be approximately 15mm.

In order to avoid contamination by ultra-violet radiation, the plates inner surfaces should be darkened (with "gold black" or platinum).

Figure 5 shows the deflecting electrodes in the analyzer box (without cover). The analyzer box is grounded and isolated from the electrodes by Macor pieces.

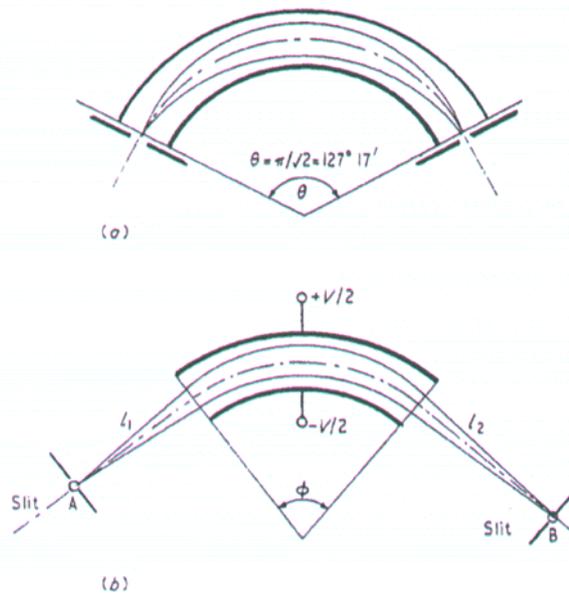


Figure 4: (a) a 127° cylindrical analyzer and (b) a generic cylindrical analyzer with angular sector ϕ .

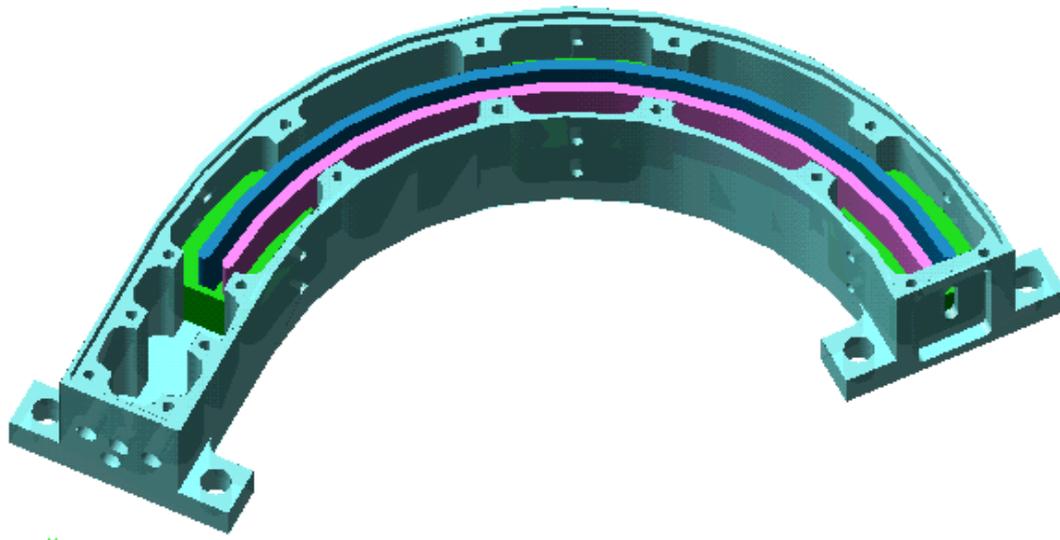


Figure 5: Analyzer box with deflecting electrodes

10.2 Detectors

Electrons selected by each analyzer are collected by channel electron multipliers (CEM) or channeltrons. These detectors should be purchased from Sjuts Optotechnik GmbH in Germany, who builds them with space specifications, and have already supplied detectors for other missions like Ulysses, Cassini etc. The model chosen is the KBL510, at the cost of US\$1100 each, and whose specifications are described in the enclosed invoice.

The electron flux expected is $8 \times 10^5 / \text{cm}^2 \text{s}$ at 20 keV [5]. With a 2mmx2mm entrance slit and 10^6 gain in the channeltrons a current of approximately 5 nA is generated.

10.3 High Voltage Source and Electronics

Both the channeltrons and the deflecting plates have to be biased to high voltages.

For the channeltrons, a source of $2,5 \text{ kV} \pm 20\text{V}$, with maximum current of $150 \mu\text{A}$ can be purchased with space specification from WMT – Elektronik GmbH in Germany at the price of US\$9.200,00, with full documentation.

The same high voltage source can be used to bias the deflecting plates with inverse polarities in order to reach a voltage difference of 4 kV. The two analyzers can share high voltage sources. Voltage sweeps are made in 32 steps (16 or 64 steps are also possible) with the circuit shown in figure 6.

Channeltron gains are dependent on energy but can reach values of up to 10^8 . For each input electron, the channeltron produces an electron cloud of about 100 million electrons, which can be detected using a discriminator, a preamplifier and a counter. The output pulse is amplified by a pulse amplifier when it remains above the discriminator level. The preamplifier transforms the negative pulse into a standard rectangular pulse that is fed into a counter. Amptek's model A111 preamplifier is a possible choice, with a cost of approximately US\$500.

Figure 7 shows the analyzer and a possible mounting scheme in the satellite. Detailed drawings of the analyzer components are shown in the appendix.

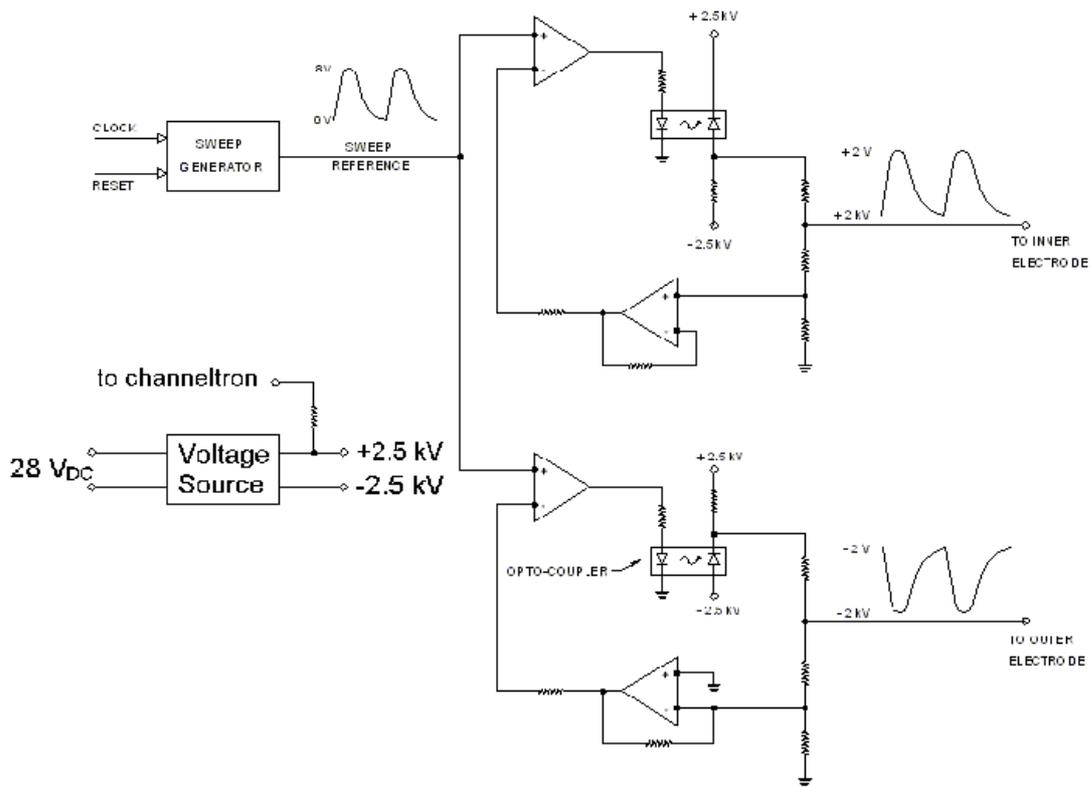


Figure 6: Electronic circuit for the analyzer plates voltage sweeps and channeltron biasing.

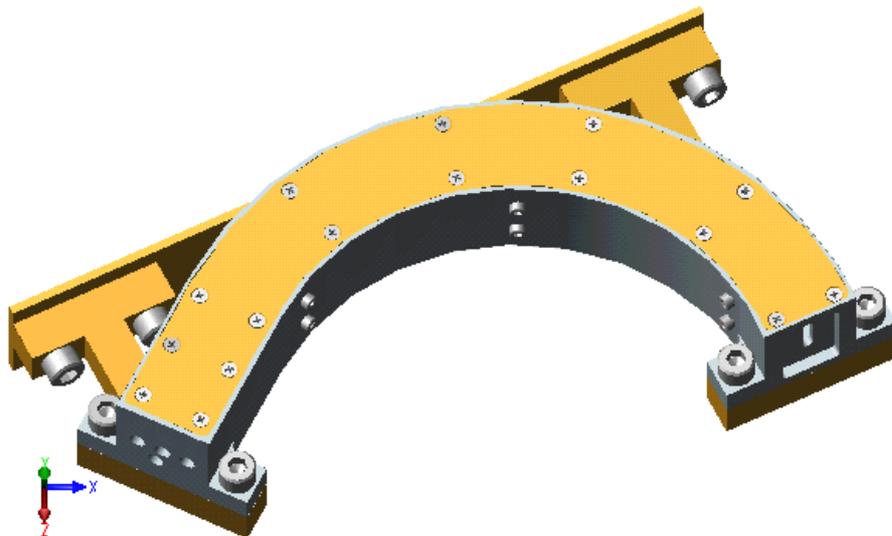


Figure 7: Possible mounting scheme of the electrostatic energy analyzer in EQUARS

11. Total Mass: < 6 kg

The analyzer will be made of aluminum 6061-T651 (density 2.75 g/cm³) and pieces of Macor (density 2.52 g/cm) for high voltage electrical insulation. The mass distribution among the various components is shown in table 1.

To fix the cover on the box, and the analyzer box to the satellite, the following 304 stainless steel components will be used: 1) screws: 4 M8x25, 4 M10x25, 51 M3x25, 2) nuts: 4 M10, 4 M8, 3) washers: 8 M10, 8 M8, totaling **334g**.

The mechanical part of the two analyzers will therefore have a total mass of **2700g**.

The electronic circuits (high voltage source, cables, shielding, telemetry etc) can be shared by the two analyzers and has a mass of approximately **2500g**.

Therefore, to board two electrostatic analyzers on EQUARS require about **5200g** of payload. Assuming a 15% tolerance, we estimate that the mass will be less than **6 kg**.

Table 1: Mass of mechanical components of the electrostatic energy analyzer

Component	Mass (g)
Box	403
Cover	78
Inner electrode	48
Outer electrode	51
Macor D	72
Macor E	72
Macor C	67
Support 1	128
Support 2	97
Total	1016

12. Dimensions:

Each analyzer will occupy a rectangular volume of 30cmx17cmx5cm or 2500 cm³. The electronic box will occupy a rectangular volume of 18cmx12cmx10cm or 2120 cm³, totaling a volume of **7120 cm³**.

- 13. Power consumption:** < 5W
- 14. Operation scheme (sequence) in orbit:** continuous with periodic calibrations
- 15. Data sampling rate:** < 21 kbits/sec

The following data should be monitored continuously:

High voltage on the analyzer plates: since the plates are biased with opposite polarities of the same voltage source, and voltage sweeps are made in 32 steps, a 5 bit number identifying the step number in the sweep is sufficient to know the plates voltage. In case the sweep is made in 64 steps, a 6 bit number is necessary. Allowing another 2 bits for information of the sweeping mode (16, 32 or 64 steps), an 8 bit number per step should be allocated for this information. For 32 step sweeps, $8 \times 32 = 256$ bits per sweep, and for 64 step sweeps, **512 bits per sweep** are necessary.

Channeltron outputs: the number of counts for each channeltron should be stored in 8 bit numbers. Channeltron gain (which should be controlled by the high voltage bias), and other information like mode of operation (calibration or continuous) should occupy another 8 bit number. For 32 step sweeps, $3 \times 8 \times 32 = 768$ bits per sweep, and for 64 step sweeps, $3 \times 8 \times 64 = 1536$ bits per sweep are necessary.

For continuous operation and with **10 voltage sweeps per second** we have:

$(256 + 768) \times 10 = 10240$ bits per second, in 32 step sweeps or

$(512 + 1536) \times 10 = 20480$ bits per second, in 64 step sweeps.

In addition to continuous operation, some measurements should be made periodically to make sure that the analyzer is functioning properly. The parameters to be checked are:

1) voltage on the four deflecting plates during a voltage sweep, 2) bias voltages on the two channeltrons, 3) noise level of the two channeltron outputs with no voltage on deflecting plates.

Some parameters to be provided by the satellite's onboard database are also necessary: the time in which each data point was taken, and the corresponding values of local magnetic field direction and intensity (if available).

16. Data storage volume:

If data are stored continuously the storage volume would be 885Mbits/day (in 32 step sweeps) or 1770Mbits/day (in 64 step sweeps), which is above the capacity of the onboard computer (800 Mbits/day). The satellite will complete about 16 orbits per day (one orbit in 90 minutes), from which only 12 can be monitored. The analyzers can be turned on only in the SAMA region, or about $\frac{1}{4}$ of an orbit. This will reduce the storage volume to $(90\text{min} \times 60\text{sec} \times 12\text{orbits} \times 21\text{kbits}) \div 4 = \mathbf{340,2 \text{ Mbits/day}}$ in 64step sweeps or $(90\text{min} \times 60\text{sec} \times 12\text{orbits} \times 10.3\text{kbits}) \div 4 = \mathbf{167 \text{ Mbits/day}}$ in 32 step sweeps

Another option would be to reduce the number of sweeps to one per second, which will reduce the storage volume to 1/10 of the above numbers or **34 Mbits/day** in 64 step sweeps and **17 Mbits/day** in 32 step sweeps.

17 Field of view: **5x10 degrees along and perpendicular to B**

18 Satellite pointing type: **to Earth**

19. Pointing accuracy: **< 5 degrees**

20. Pointing information accuracy:

21. Attitude control for your instrument: **No**

22. Orbit: **Equatorial**

23. Altitude: **(600-800) km**

24. Inclination: **20 degrees**

25. Any maneuver you need? **Desirable if possible.**

26. Any attitude maneuver in orbit: **No**

- 27. On board command necessary?** **No**
- 28. Command from ground station necessary?** **Yes**
- 29. Real time data transmission and reading necessary?** **No**
- 30. How many ground stations you need?** **One**
- 31. Estimated time for construction:** **30 months**

32. Financial support you request:

Due to the difficulties in importing space qualified components via INPE, a financial support of US\$80.000,00 – US\$100.000,00 should be asked to FAPESP.

A prototype of the analyzer (without space qualification) will be constructed with funding from the PPA, from the FISPLA project already in progress. The 2004/2007 PPA's budget includes funding for the purchase of space qualified components of the electrostatic analyzer. However, these funds are often subject to contingencies or are often released with delay making any time schedule unpredictable. Therefore the development of the project depends on financial support from FAPESP.

33. Financial time schedule / 34. Time schedule for construction and integration:

a) INPE PPA 2000-2003

During the period from June 2003 to March 2004, a prototype should be constructed using commercial electronic components and ordinary aluminum. This will allow adjustments in the mechanical project, find any difficulties in machining the components, and begin the development of the electronic circuit. This prototype will be tested in the PQUI experiment as a diagnostic of the (0-0.5) keV electron beam. Vibration and thermal transient tests will also be made in this prototype. About R\$25.000,00 should be used from the PPA already in progress.

b) FAPESP US\$80.000,00 – US\$100.000,00

Date	Task
August 2003	Submission of project proposal to FAPESP with detailed description of space qualified components to be imported.
November 2003	Begin import process (after approval by FAPESP)
February 2004	Beginning of the arrival of imported components
June 2004	Construction of analyzers with space qualified components Vibration and thermal transient tests Calibration with electron beams with energies up to 40 keV
June 2005	Mounting and calibration of analyzers to be mounted in EQUARS Instrument documentation
June 2006	Launching

35. Final Comment

In addition to the approval of financial support from FAPESP, the development of this project will also require the hiring of a researcher with experience in development of plasma experiments and instrumentation.

36. Appendix

Technical drawings of the mechanical components of the analyzer are enclosed.

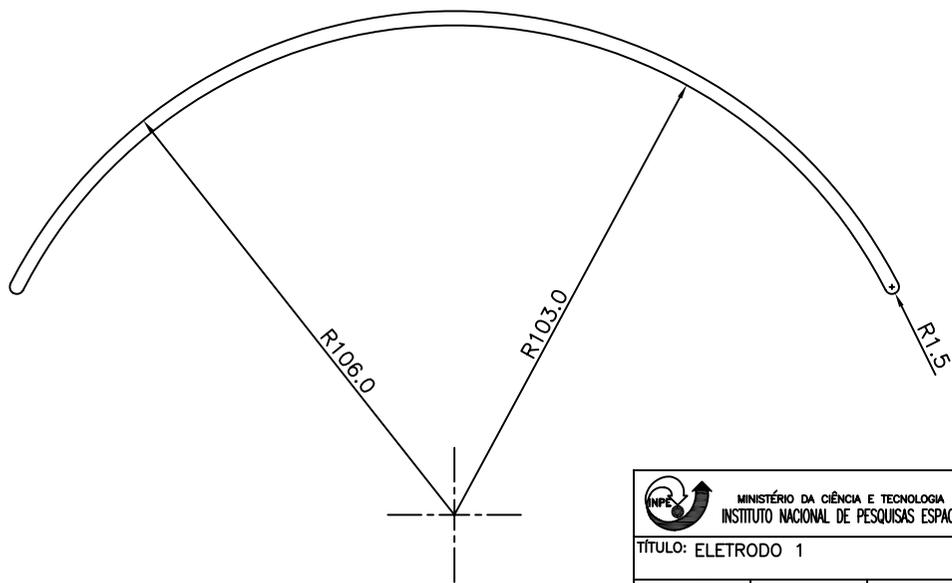
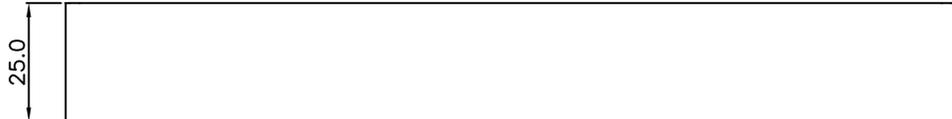
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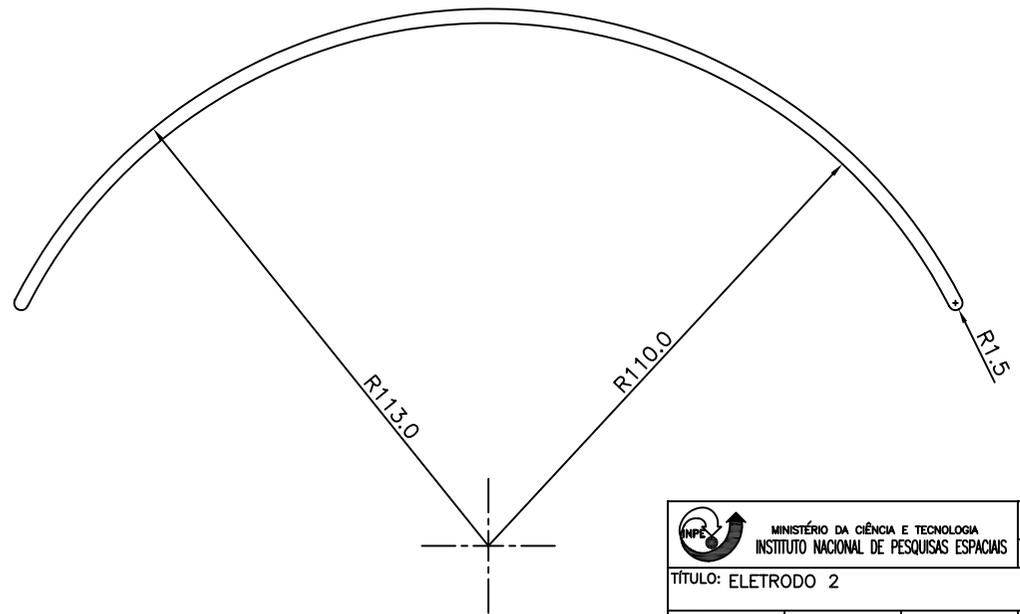


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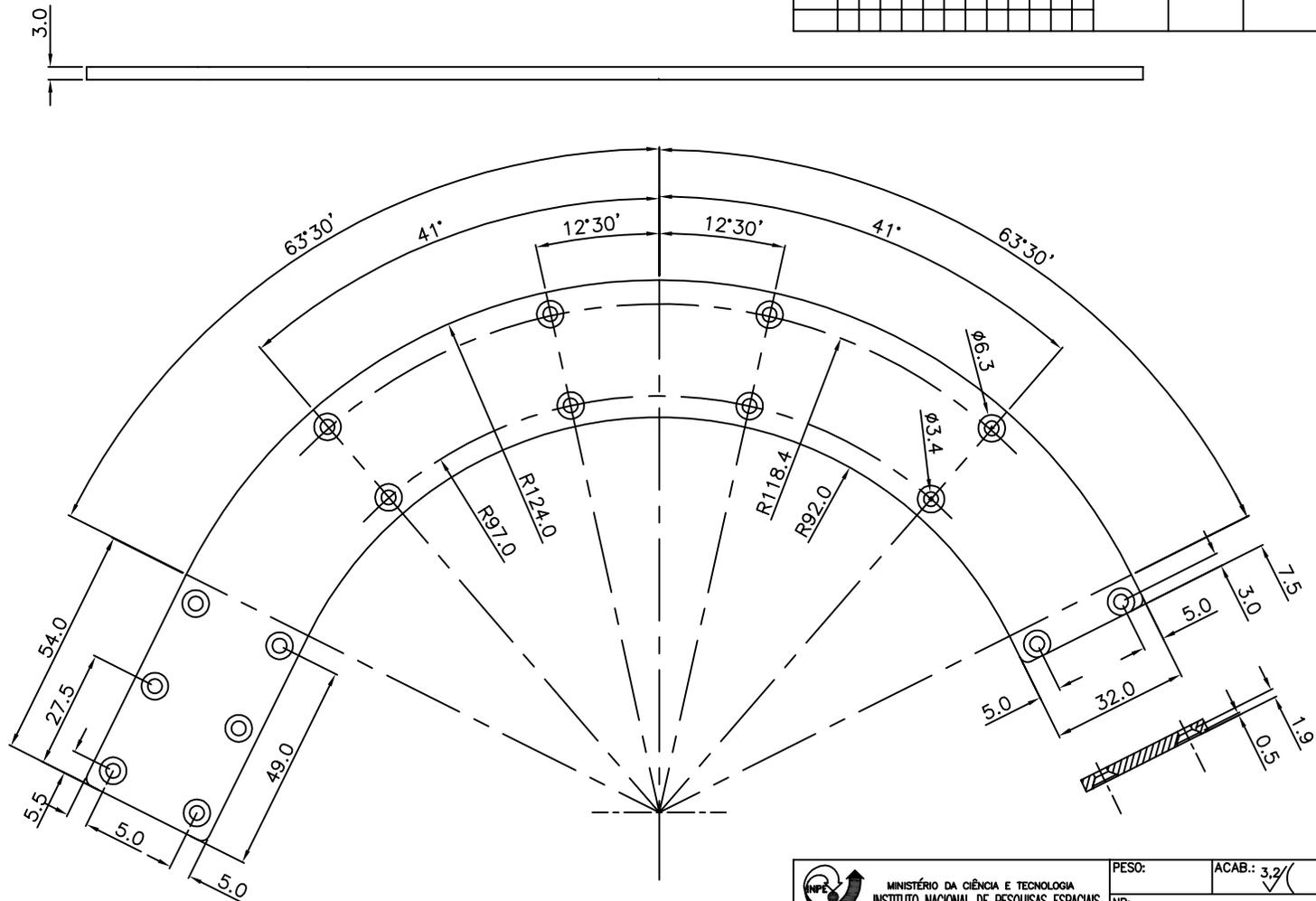


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 TERCEIROS SEM A PRÉVIA AUTORIZAÇÃO DO INPE.

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 MINISTÉRIO DA CIÊNCIA E TECNOLOGIA INSTITUTO NACIONAL DE PESQUISAS ESPACIAIS	PESO:	ACAB.: 3,2/()	TOLERÂNCIA GERAL			
	NP:		LINEAR	ANGULAR		
TÍTULO: ELETRODO 2			MATERIAL/DIMENSÕES: ALUMINIO 6061			
DESENHISTA: JOSE VITOR 30/01/03	REVISOR:	PROJETISTA:	Nº	QUANT.	FOLHA	ESCALA
				01	1 DE 1	1:1
REVISÕES DA FOLHA						

Nº DESENHO:										APROVAÇÃO DAS REVISÕES									
VERSÃO																			
FOLHA	CONTROLE DE REVISÕES																		

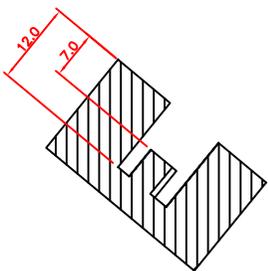
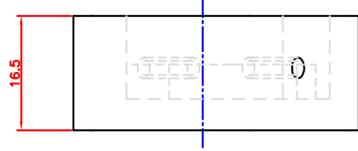


ESTE DOCUMENTO PERTENCE AO INPE, E NÃO PODE SER REPRODUZIDO OU COMUNICADO A TERCEIROS SEM A PREVIA AUTORIZAÇÃO DO INPE.

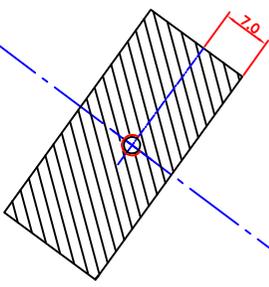
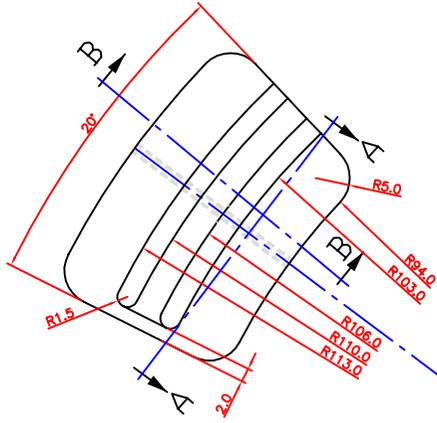
REV.: 13/07/95

 MINISTÉRIO DA CIÊNCIA E TECNOLOGIA INSTITUTO NACIONAL DE PESQUISAS ESPACIAIS	PESO:	ACAB.: 3,2 ()	TOLERÂNCIA GERAL			
	NP:		LINEAR	ANGULAR		
TÍTULO: TAMPA DA CAIXA			MATERIAL/DIMENSÕES: CHAPA ALUMINIO 6061			
DESENHISTA: JOSE VITOR	REVISOR:	PROJETISTA:	Nº	QUANT.	FOLHA	ESCALA
30/01/03				01	1 DE 1	1:1
REVISÕES DA FOLHA						

Nº DESENHO:		APROVAÇÃO DAS REVISÕES												
VERSÃO	FOLHA	CONTROLE DE REVISÕES												



CORTE B-B



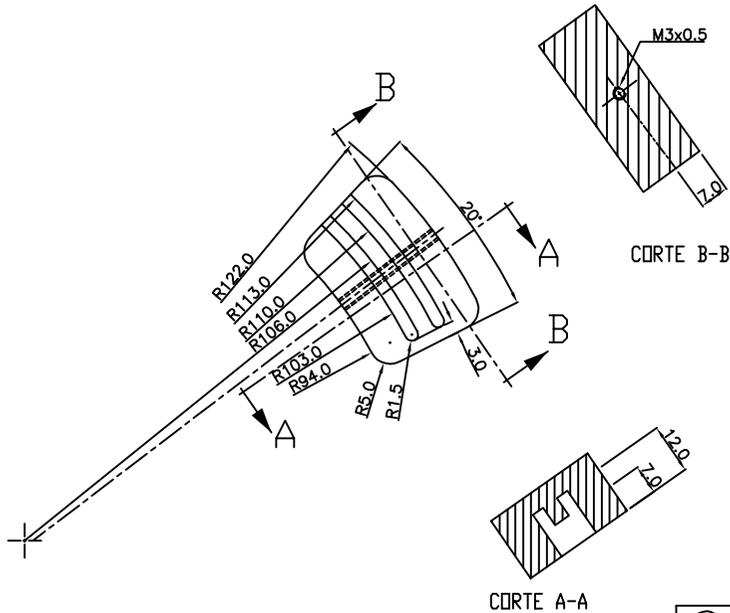
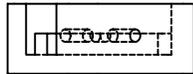
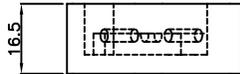
CORTE A-A

ESTE DOCUMENTO PERTENCE AO INPE E NÃO PODE SER REPRODUZIDO OU COMUNICADO A TERCEIROS SEM A PRÉVIA AUTORIZAÇÃO DO INPE.

REV: 13/07/98

INSTITUTO NACIONAL DE PESQUISAS ESPaciais DEPARTAMENTO DE PESQUISA E DESENVOLVIMENTO	PESO:	ACAB.: 3.2	TOLERÂNCIA GERAL	
	NP:		LINEAR	ANGULAR
TÍTULO: SUPORTE ESQUERDO	MATERIAL/DIMENSÕES: MAKOR		± 0,1	±
DESENHISTA: JOSE VITOR 29/01/03	REVISOR:	PROJETISTA:	QUANT.: 01	FOLHA: 1 DE 1
REVISÕES DA FOLHA			ESCALA: 1:1	

Nº DESENHO:		APROVAÇÃO DAS REVISÕES					
VERSÃO							
FOLHA	CONTROLE DE REVISÕES						

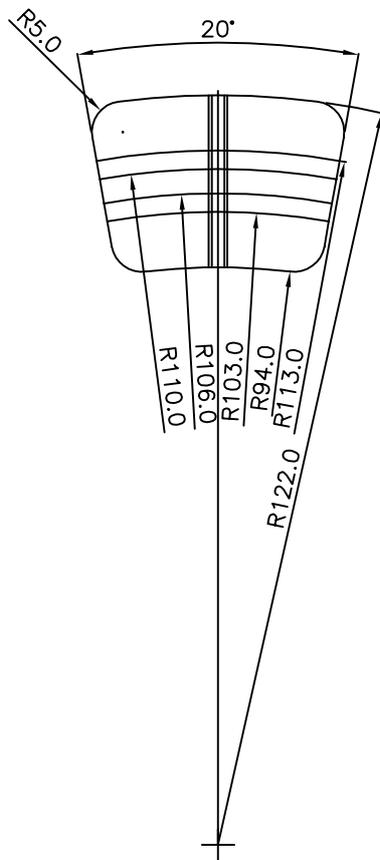
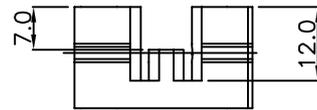
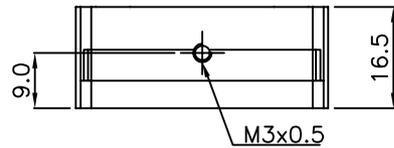


ESTE DOCUMENTO PERTENCE AO INPE. E NÃO
 PODE SER REPRODUZIDO OU COMUNICADO A
 TERCEIROS SEM A PRÉVIA AUTORIZAÇÃO DO INPE.

REV: 13/07/95

MINISTÉRIO DA CIÊNCIA E TECNOLOGIA INSTITUTO NACIONAL DE PESQUISAS ESPACIAIS	PESO:	ACAB.: 3,2/ ()	TOLERÂNCIA GERAL			
	NP:		LINEAR	ANGULAR		
TÍTULO: SUPOORTE DIREITO		MATERIAL/DIMENSÕES: MAKOR				
DESENHISTA: JOSE VITOR	REVISOR:	PROJETISTA:	Nº	QUANT.	FOLHA	ESCALA
29/01/03				01	1 DE 1	1:2
REVISÕES DA FOLHA						

Nº DESENHO:										APROVAÇÃO DAS REVISÕES									
VERSÃO																			
FOLHA										CONTROLE DE REVISÕES									



ESTE DOCUMENTO PERTENCE AO INPE, E NÃO PODE SER REPRODUZIDO OU COMUNICADO A TERCEIROS SEM A PRÉVIA AUTORIZAÇÃO DO INPE.



MINISTÉRIO DA CIÊNCIA E TECNOLOGIA
INSTITUTO NACIONAL DE PESQUISAS ESPACIAIS

PESO:

ACAB.: 3,2/ ()

TOLERÂNCIA GERAL

LINEAR ANGULAR

NP:

± 0,1

±

TÍTULO: SUPORTE CENTRAL

MATERIAL/DIMENSÕES: MAKOR

DESENHISTA:
JOSE VITOR

REVISOR:

PROJETISTA:

Nº

QUANT.

FOLHA

ESCALA

29/01/03

REVISÕES DA FOLHA

01

1 DE 1

1:2

REV.: 13/07/95

