Environmental Dosimetry with the Pille TL Space Dosimetry System During the BEXUS-12 Stratospheric Balloon Flight

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Due to significant spatial and temporal changes in the cosmic radiation field, radiation measurements with advanced dosimetric instruments on board spacecrafts, aircrafts and balloons are very important. The Hungarian CoCoRAD Team was selected to take part in the BEXUS (Balloon Experiment for University Students) project. In the frame of the BEXUS programme Hungarian students from the Budapest University of Technology and Economics carried out a radiation experiment on a research balloon, which was launched from Northern Sweden in September 2011.

The objective of the CoCoRAD experiment was to measure the effects of the cosmic radiation at lower altitudes where measurements with orbiting spacecrafts are not possible due to the strong atmospheric drag. The experiment included measurements with the Pille thermoluminescent (TL) space dosimetry system to measure the absorbed dose during the BEXUS-12 stratospheric balloon flight with the Pille TL dosimeters. One of the main goals of the experiment was to prove the usability of the Pille passive TL dosimeter system during stratospheric balloon flights for environmental dosimetry monitoring purposes.

The BEXUS-12 balloon flew at an altitude of 27.6 km and a latitude of N68° for more than 2 hours. Ten Pille dosimeters were on board to measure the absorbed dose during the BEXUS-12 mission. This paper presents the scientific background of the cosmic particles for the altitude range of the stratospheric balloons, the expected doses in case of the minimum and the maximum of the solar activity, the results of the Pille measurements during the BEXUS-12 stratospheric balloon flight and conclusions about the usability of the Pille TL system on board stratospheric balloons.

Keywords: radiation monitoring, thermoluminescent detectors, stratosphere, space dosimetry

1 The BEXUS programme and the CoCoRAD student experiment

Among many other student projects ESA Education Office announced a call for proposals for the REXUS 11/12 and the BEXUS 12/13 flights for university students in 2010. The REXUS/BEXUS programme allows students from universities and higher education colleges across Europe to carry out scientific and technological experiments on research rockets and balloons. Each year two balloons capable of lifting their payloads to a maximum altitude of 35 km, depending on total experiment mass (40-100 kg) are launched from Northern Sweden, carrying experiments designed and built by student teams.

A Hungarian student team were selected for the first time to take part in the BEXUS 12/13 project of the European Space Agency Educational Office. The name of the experiment was CoCoRAD, an abbreviation for Combined TriTel/Pille Cosmic RADiation and Dosimetric Measurements. The experiment flew on board the BEXUS-12 stratospheric balloon on the 27th of September 2011 from ESRANGE Space Center. The CoCoRAD experiment used the TriTel three dimensional silicon detector telescope for active monitoring and several Pille thermoluminescent dosimeters in order to study the usability of the Pille passive dosimeter system during stratospheric balloon flights. Both the Pille and the TriTel space dosimeter system has been developed in the former KFKI Atomic Energy Research Institute (MTA Centre for Energy Research from 1 of January 2012). The present paper addresses the usability of the Pille system for dosimetry measurements on board stratospheric balloons.

2 The Pille TL Space Dosimetry System

The development of the Pille Thermoluminescent Dosimeter System started in the KFKI AEKI in the 1970s. The aim of the development was to invent a small, compact, space qualified TL reader device suitable for on-board evaluation of TL dosimeters. The Pille TL dosimeter contains $CaSO_4$:Dy TL material produced by the Budapest University of Technology and Economics. The TL material is laminated to the surface of a resistive, electrically heated metal plate inside a vacuum bulb made of glass. The dosimeter also contains a memory chip that holds identification data and individual calibration parameters of the device such as TL sensitivity, TL glow curve integration parameters or the time of the last read-out.

The Pille TL Reader (Figure 1) is designed for spacecraft: it is a small, light-weight device with a low energy consumption. The reader is capable of heating the dosimeters, measuring the emitted light during the read-out, performing preliminary data evaluation, storing and displaying the results. The measurement results are stored on a removable flash memory card which can store up to 8000 data blocks consisting of the TL glow curve, the time of the last read-out, the results of the background and sensitivity measurement (performed in the beginning of each read-out) and all derived data such as the absorbed dose [1].

One of the main advantages of the Pille TL system is the possibility of the onsite data acquisition and evaluation, which means no transport dose in the calculations.

Figure 1 The Pille TL dosimeter system in its transporting case (reader and ten dosimeters)

3 The scientific background of the cosmic particles in the stratosphere

Since the typical altitude range for stratospheric research balloons is between 20 and 40 km it is important to give a short introduction to the cosmic particles of this region. The primary cosmic radiation interacts with the magnetosphere and the atmosphere of the Earth. The particle intensities change with the magnetic and geographic latitude and with the solar activity too. The galactic cosmic rays determine the components of the radiation field in the atmosphere. It consists of about 85% protons, 12% helium ions, 1% heavier ions and 2% electrons [2].

The penetrating ability of particles into the geomagnetic field is determined by the magnetic rigidity (kinetic energy divided by the charge). For each point and each direction of incidence there exists a threshold value of magnetic rigidity, called the geomagnetic cut-off. Below this cut-off value no charged particle can reach the specified point from the given direction [3].

The solar cosmic radiation is relevant during the maximum of the solar activity through the solar flares (sporadic eruptions of the chromosphere of the sun). They develop in minutes and the released energies range between 10^{22} to 10^{25} J [2] [4].

The main interaction of a charged particles coming from space with the atmosphere is the ionisation of atoms and molecules. Protons are most likely responsible for the production of secondary particles. Figure 2 shows an example for secondary particles production.

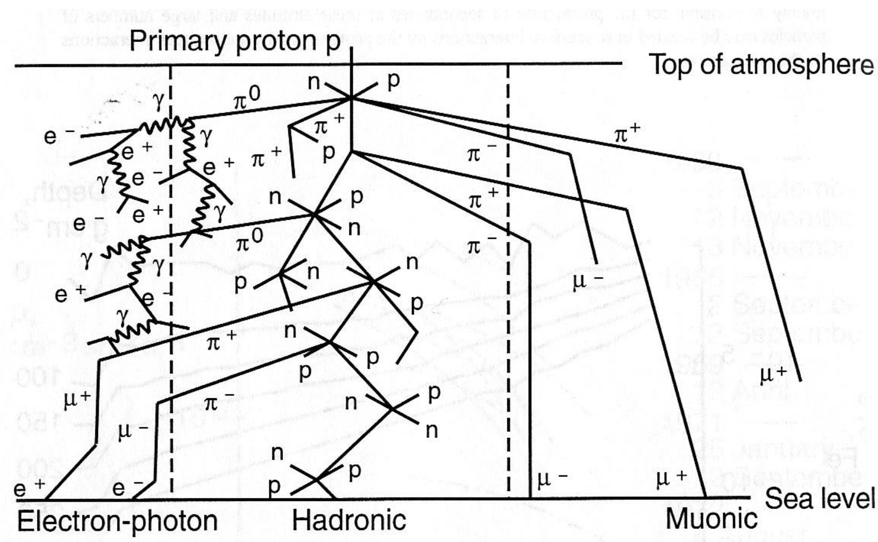

Figure 2 Schematic representation of the particle production in the atmosphere [2] [5]

The most important reactions are the production of secondary neutrons, protons and the pion triplet. The charged pions decay to muons and neutrinos. Most of the muons easily reach see level through the atmosphere and some of them decay to electrons and neutrinos. The neutral pions decay into gamma rays. At an altitude of about 20 km a local maximum can be found, called Pfotzer-maximum [2].

Neutrons are produced in two different ways in the atmosphere. At energies below 10 MeV neutrons are evaporated from highly excited nuclei. Above 10 MeV neutrons are produced in collisions from high energy protons by means of charge exchange reactions.

4 The expected doses measured during a typical BEXUS stratospheric balloon flight using Pille TL dosimeters

$CaSO_4$:Dy is used as TL material in the CoCoRAD experiment. The measured dose range of the system is ~3 µGy to 10 Gy (at accuracy level of <10%), the accuracy of measurements above 10 µGy is < 5%, using a ^{137}Cs calibration source.

Earlier measurements performed on board Concorde have shown that the average total dose equivalent rate in the period between 1976 and 1983 was 11.2 µSvh^{-1} for altitudes of about 18 km [6]. There are Russian supersonic measurements available in the literature, too ranging from 10 to 12 µSvh^{-1} [7]. Figure 3 shows the typical values of total dose equivalent rates in the supersonic flight altitude range.

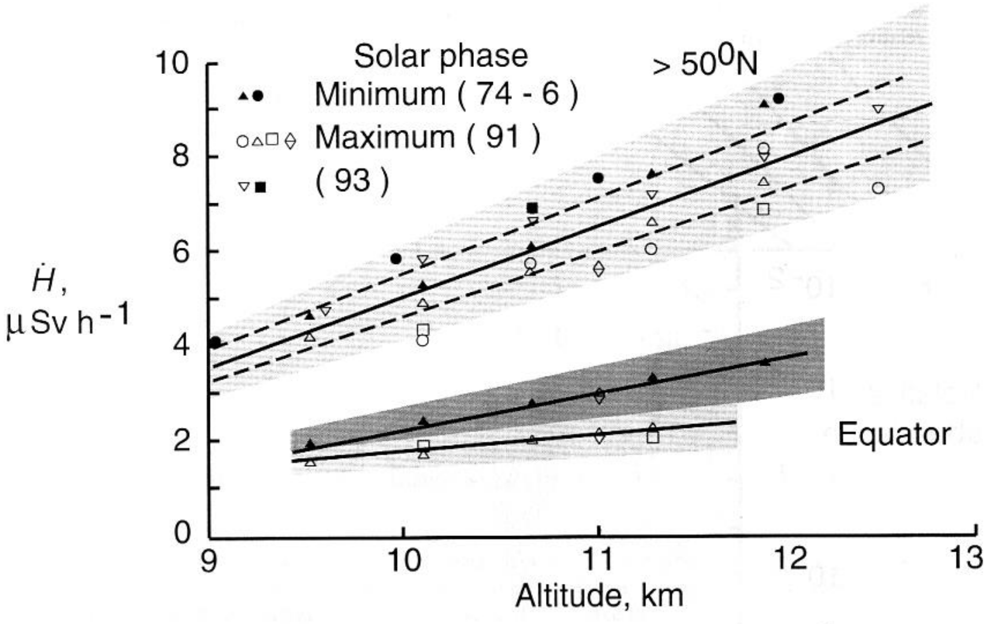

Figure 3 The typical values of total dose equivalent rates in the supersonic flight altitude range

At altitudes higher than 15 km the chance of higher dose equivalent rates is higher too [6].

According to the BEXUS User Manual [8]: "The nominal ascent speed is 5m/s. Depending on float altitude and variations in speed, this phase can take up to 2 hours." The landing phase takes a much shorter time (maximum 1 hour) due to the thin atmosphere. Due to the parachute system of the balloon an impact speed of about 8 m/s is reached. According to Figure 3 the total dose equivalent rate expected is between 3-10 µSvh^{-1} with an average of about 5 µSvh^{-1} during the BEXUS ascent and landing phase. In case of the BEXUS-12 flight the time of the ascent and descent phase together was about 2.5 hours. It means about 7.5-25 µSv with an average of 12.5 µSv expected total equivalent dose.

Based on earlier experimental and theoretical data [9] it has been shown that the dose equivalent rate decreases by 40% during solar maximum compared to solar minimum periods. The maximum and the minimum galactic dose equivalent rates as a function of the geomagnetic latitude can be seen in Figure 4.

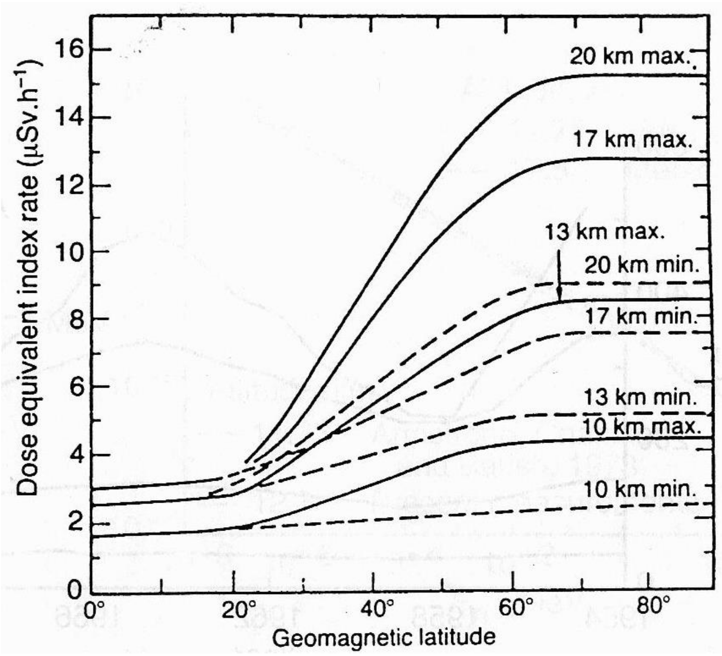

Figure 41 The maximum and minimum galactic dose equivalent rates as a function of the geomagnetic latitude for different altitudes. Note: minimum indicates solar maximum conditions, and vica versa [2] [10]

Based on NASA's experimental results we expected medium solar activity during the BEXUS-12 flight (http://www.swpc.noaa.gov/SolarCycle/), which can be seen in Figure 5 below.

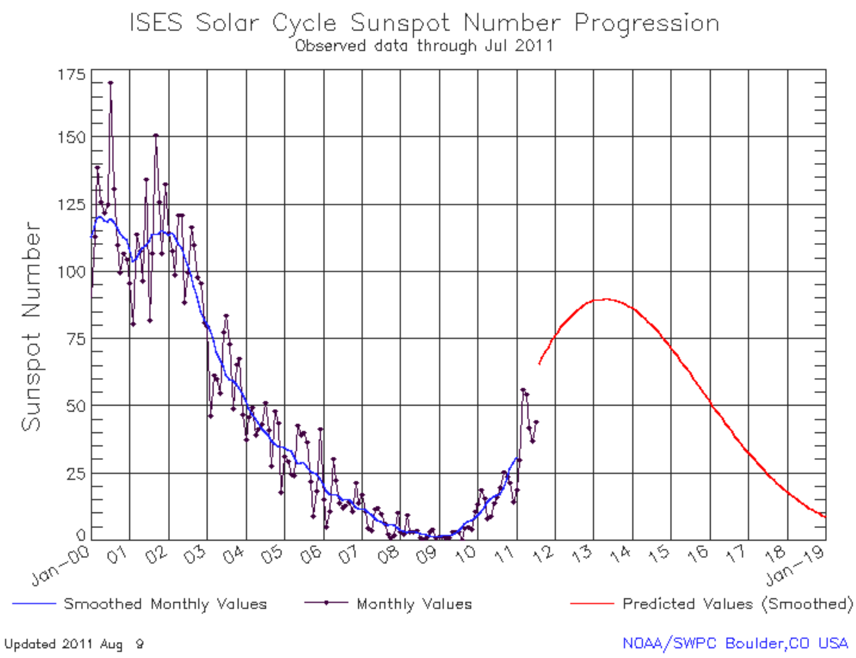

Figure 5 International Solar Energy Society (ISES) Solar Cycle Sunspot Number Progression

The nominal flight time (float phase) is one to four hours [8]. In case of the BEXUS-12 the flight time was about 2 hours and the floating altitude was about 27.6 km. According to Figure 4 the minimum total dose equivalent rate expected will be in the range 9-16 μSvh^{-1} during the BEXUS float phase. It means 9-32 µSv minimum expected total equivalent dose during the BEXUS-12 flight.

$CaSO_4$:Dy has a realtively poor sensitivity for the neutron component of the radiation. At the altitude of the BEXUS balloons about 40% of the expected dose equivalent comes from neutrons [11], which will not be measured. It means an expected total equivalent dose of about 10-35 µSv during the BEXUS-12 mission. This value is above the minimal sensitivity of the Pille dosimeters.

In the case of solar flare events the upper limit of the dose equivalent rate can be 30 $mSvh^{-1}$ at an altitude of 20 km [11]. Measuring extremely high doses with the Pille dosimeters might indicate a solar flare event during the mission time. The measurement results can be verified with on-ground measurements at the same time.

5 The results of the Pille measurements during the BEXUS-12 stratospheric balloon flight

The CoCoRAD experiment flew on board BEXUS-12 on the 27^{th} of September 2011 from ESRANGE Space Center located in Northern Sweden close to the city of Kiruna (latitude of N68°). The floating altitude was about 27.6 km for two hours long. The geographical latitude indicates a very low cut-off rigidity which results more particles in the altitude range of the balloon [13]. In the experiment eight Pille bulbs were used for flight and two were used as reference bulbs (Figure 7). The reference dosimeters remained on ground at the ESRANGE base during the entire mission of the BEXUS-12 (Figure 6).

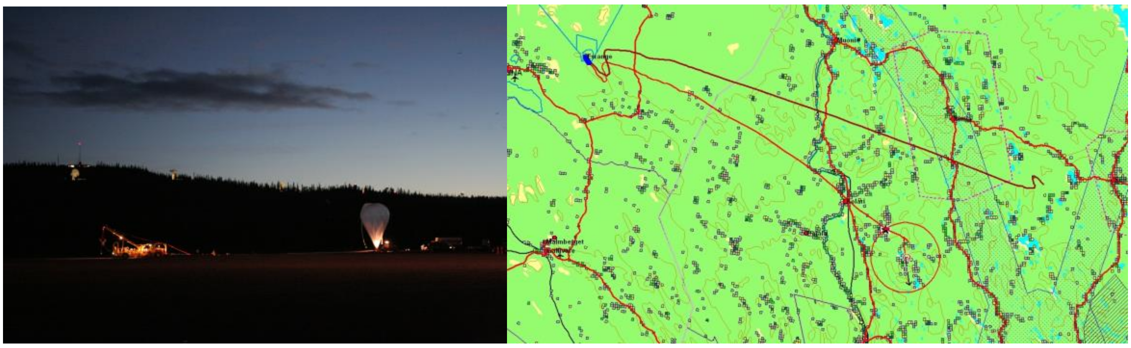

Figure 2 The launch of the BEXUS-12 (left) and the BEXUS-12 flight trajectory (right: the dark red line indicates the predicted trajectory and the light red line indicates the real flight trajectory, Swedish Space Corporation)

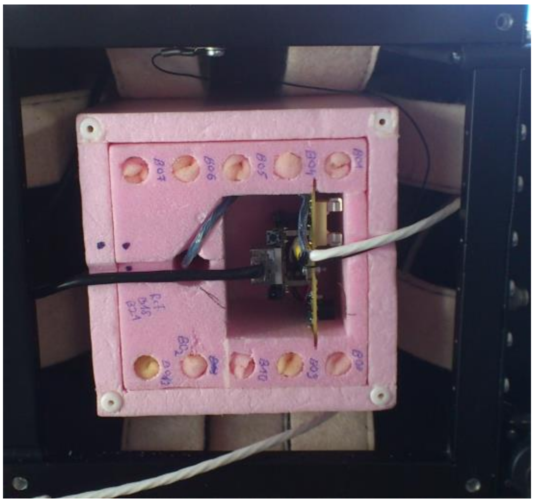

Figure 7 The measurement geometry in the CoCoRAD experiment (in the holes with numbers indicated where the Pille bulbs can be found inside the thermal insulation and a mechanical protection aluminium box)

Table 1 shows the results of the Pille read-outs after the recovery. In the fourth column can be found the second read-out results from the calibration of the dosimeters. These values indicates the background level of the chosen Pille bulbs. In its last column the measured doses corrected with the background level of each bulb are listed.

ID	Type	Measured absorbed dose (µGy)	Second read-out (µGy)	Corrected dose with the background level (µGy)
B01	flight	20.7	1.5	19.2
B02	flight	22.7	2.3	20.4
B03	flight	23.0	2.0	21.0
B04	flight	24.0	1.1	22.9
B05	flight	21.6	1.6	19.9
B06	flight	21.1	1.0	20.0
B07	flight	20.1	0.8	20.13
B08	flight	21.4	0.7	20.68
B09	flight	22.7	0.9	21.87
B10	flight	23.4	1.6	21.74
B18	ref	6.7	1.2	5.44
B21	ref	6.3	1.0	5.3

Table 1 Pille read-out results after the recovery

The results of the Pille measurements of the BEXUS-12 flight are summarized in Table 2.

Condition	Value
The average background level of the choosen bulbs	1.4 ± 0.5 µGy
The mission time	4.3 ± 0.2 h
The time between the read-outs	70 ± 0.5 h
The measured average absorbed dose (flight bulbs)	20.8 ± 1.1 µGy
The measured average absorbed dose (reference bulbs)	5.4 ± 0.1 µGy
The measured average dose rate at the surface (in ESRANGE)	77.7 ± 1.5 nGy/h
The excess absorbed dose of the BEXUS-12 flight	15.6 ± 1.1 µGy
The estimated error of the measurements	~ 7-10 %

Table 2 The results of the measurements with Pille in the BEXUS-12 flight

The reference dosimeters were stored on ground in ESRANGE during the mission while the flight dosimeters landed close to the city of Kolari in Finland. Based on the radiation monitoring data at the station close to Kolari the background radiation where the flight dosimeters landed was about 100±10 nGy/h. It is a little more than what was measured in ESRANGE with the reference dosimeters. The difference is about +30-40 nGy/h. For the 70-hour-long measurement the total difference is about 2.1-2.8 µGy. The corrected measured result from the flight dosimeters is 13.1±1.5 µGy. This result is in the expected dose range of 10-35 µSv. Since the Pille TL system provides onsite data acquisition and evaluation we do not need to calculate with the transport dose.

6 Conlcusions about the usability of the Pille TL system on board stratospheric balloons

The Pille TL dosimeters flew as a part of the CoCoRAD experiment on board the BEXUS-12 stratospheric balloon. The experiment included flight and reference TL dosimeters. The measured excess absorbed dose of the BEXUS-12 flight was 13.1±1.5 µGy which is in good agreement with the values estimated before the mission (10-35 µSv).

One of the main lessons learned from the CoCoRAD experiment is that the Pille TL system is capable of performing environmental monitoring measurements on board stratospheric balloon flights. For the best measurement efficiency it is highly recommended to select dosimeters with the lowest noise level available. An important advantage of the Pille TL system is the possibility of the onsite data acquisition and data evaluation without the need of calculating the transport dose.

7 Acknowledgements

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8 References

[1] Fehér, I., Deme, S., Szabó, B., Vágvölgyi, J., Szabó, P.P., Csőke, A., Ránky, M., Akatov, Yu.A., **A new thermoluminescent dosimeter system for space research**, Advances in Space Research, 1, pp. 61-66, 1981

[2] EURADOS, radiation protection 85. In: McAulay, I., et al. (Eds.), **Exposure of air crew to cosmic radiation**. EURADOS Report 1996-01, Luxembourg, 1–77, 1996

[3] Lemaître, G., Vallarta, M. S., **On Compton's Latitude Effect of Cosmic Radiation**, Phys. Rev., 43, 87, 1933

[4] Stassinopoulos, E.G., **The Earth's trapped and transient space radiation environment.** NATO ASI Series A: Life Sciences, 154, 5-35, 1988.

[5] Allkofer, O.C. and Grieder, P.K.F., **Cosmic rays on Earth**. Physics Data 25-1, ISSN 0344-8401, 1984

[6] Davies, D.M., 1993: "**Cosmic Radiation in Concorde Operations and the Impact of New ICRP Recommendations on Commercial Aviation**". Radiat. Prot. Dosim. 48, pp121-124 (1993)

[7] Akatov, Yu.A., 1993: "**Some Results of Dose Measurements Along Civil Airways in the USSR**". Radiat. Prot. Dosim. 48, pp59-64 (1993)

[8] EuroLaunch: **BEXUS User Manual** (2010), **REXUS User Manual** (2010)

[9] Advisory Committee for Radiation Biology Aspects of the SST, Final Report., 1975: "**Cosmic radiation exposure in supersonic and subsonic flight**". Aviat. Space Environ. Med. 46, pp1170-1185 (1975)

[10] Advisory Committee for Radiation Biology Aspects of the SST, Final Report, **Cosmic radiation exposure in supersonic and subsonic flight**. Aviat. Space Environ.Med. 53, 808-

817, 1982

[11] McAulay, I.R., Bartlett, D.T., Dietze, G., Menzel, H.G., Schnuer, K., and Schrewe, U.J., 1996: "**Radiation Protection 85, Exposure of air crew to cosmic radiation**", EURADOS report 1996-01

[12] Foelsche, T., Mendell, R.B., Wilson, J.W., and Adams, R.R., 1974: "**Measured and Calculated Neutron Spectra and Dose Equivalent Rates at High Altitudes; Relevance to SST Operations and Space Research**". NASA TN D-7715, Washington DC, (1974)

[13] Zábori, B., Hirn, A., Bencze, P., **The relationship between plasma effects and cosmic radiation studied with TriTel-LMP measurements during the ESEO mission**, Adv. Space Res 48 (2011) 240-253