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Space weather and its effects on spacecraft charging

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Abstract.

In the current work we describe the Langmuir Probe (LP) and its operation on board the International Space Station. This instrument is a part of the scientific complex "Ostonovka". The main goal of the complex is to establish, on one hand how such big body as the International Space Station affects the ambient plasma and on the other how Space Weather factors influence the Station. The LP was designed and developed at BAS–SRTI.

Keywords: *Space weather; spacecraft charging*.

1. Studies on spacecraft charging

Studies on the spacecraft charging began after several occasions of anomalous behavior of satellites in the early 1970s, and especially after the loss of the US military satellite DSCS-9431 in 1973 [Bedingfield et al., 1996]. A large program was jointly conducted by NASA and the U.S. Air Force to investigate the problem. The USAF P78-2 Spacecraft Charging at High Altitudes (SCATHA) satellite operating between March 1979 and June 1980 was specially designed to obtain environmental and engineering data to allow the creation of design criteria, materials, techniques, tests and analytical methods to control charging of spacecraft surfaces [Mullen and Gussenhoven, 1983]. Its orbit was close to geostationary (apogee 43 240 km, perigee 27 550 km, inclination 7,9°). The satellite had a mass of 227 kg, diameter of 1.3 m, length of 1.5 m. There were several booms for instruments' sensors. The scientific tasks included the determination of the electric potential at the surface of different materials widely used for spaceborne instrumentation, measurement and analysis of electrostatic disturbances caused by electrical discharges on the surface, study of the degradation of the outer surface of the satellite and evaluation of the surface pollution by the vehicle's own atmosphere. The electron gun with 3 KV maximum accelerating voltage and 6 mA current allowed to induce charging of the satellite with respect to the surrounding plasma, similar to the charging in active experiments. During the operation of the electron gun, electrical discharges were registered and even failures in two of the instruments, coinciding in time with the most intense discharges. This was a direct confirmation of the possibility of instrument failures due to electrical discharges on the satellite's surface. The first year of SCATHA operation showed a high level of elecrtization. For example, in the morning of 24 April 1979, even when the satellite was sunlit, the surface charged up to -340 V. When the satellite was in the shade for a short time on this same day, a surface potential of -8 V was registered.

Later experimental evidence has shown that electric potential differences as severe as -680 volts can develop between Defense Meteorological Satellite Program (DMSP) polar-orbiting (840 kilometers) spacecraft and their high-latitude environment, an analysis was performed using DMSP F6, F7, F8, and F9 satellite precipitating particle and ambient plasma measurements taken during the winters of 1986-87 (solar minimum) and 1989-90 (solar maximum) to explore space vehicle charging in this region. Solar cycle dependence was found with charging occurring more frequently and with greater severity during the period of solar minimum [Frooninckx, 1991]. The joint Air Force/NASA Combined Release and Radiation Effects Spacecraft (CRRES) which was launched in July 1990 into a geosynchronous transfer orbit further investigated the effects on microelectronic elements of space radiation.

Data for the time distribution of anomalies and failures of the payload of geostationary satellites, as well as results of direct measurements of the satellite surface potential show that disturbances in the instrument operation due to charging to high negative potentials occur mainly at nighttime and in the morning hours. Moreover, a correlation is found with the level of geomagnetic activity.

2. Space weather and its effects on spacecraft charging

What mainly determines the spacecraft charging and therefore the safe operation of the electronic devices in space is the space weather. “Space weather” is usually understood as the conditions and processes occurring in space which have the potential to affect the near Earth environment. Space weather processes can include changes in the interplanetary magnetic field, interplanetary plasma parameters like plasma speed, density and temperature, and disturbances in the Earth's magnetic field. All these changes have their origin in processes occurring on the Sun. Space weather is very similar in context to atmospheric weather. Atmospheric weather is a set of phenomena occurring in the terrestrial atmosphere. Space weather is the set of phenomena occurring in the solar atmosphere. The Earth, together with the whole Solar system, is inside the atmosphere of the Sun. Sun is a variable star, and the varying solar radiation, magnetic fields and charged particles interact with the Earth and result in variations in geomagnetic activity, weather and climate, telecommunications, space flight and air flight security, power supply stability, down to seismic activity and human physiological state. The best known manifestation of solar variability is the ~11-year cycle of the number of sunspots (Fig.1). Actually, sunspots themselves are not “geoeffective” – they have no effect on the Earth, but they are the manifestation of the evolution of the solar magnetic field. Related to this magnetic field are solar total and spectral irradiance which vary in the 11-year solar cycle together with the number of sunspots (Fig.2).

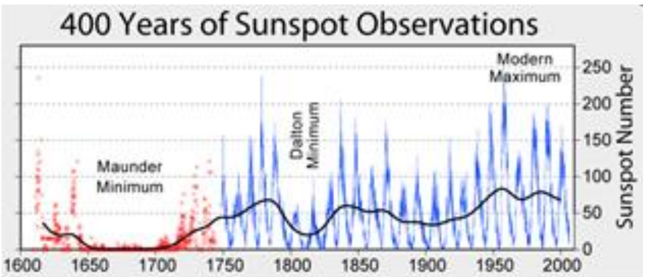

Figure 1. *Yearly number of sunspots showing a ~11-year cycle superposed on longer-term secular variability. A figure borrowed from Wikipedia.*

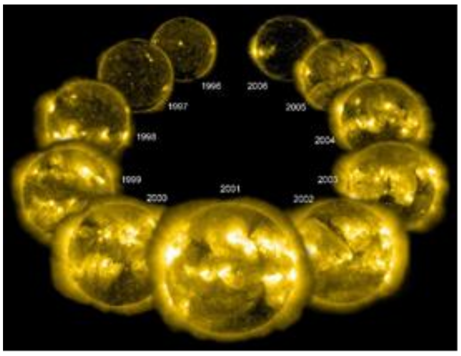

Figure 2. *An image in the 284 Angstrom wavelength of extreme UV light from each year of nearly an entire 11-year solar cycle. Courtesy: EIT instrument, Solar and Heliospheric Observatory (SOHO) http://sohowww. nascom.nasa.gov/.*

Also related to sunspots are the Coronal Mass Ejections (CMEs) – powerful explosions sending into space huge bubbles of gas threaded with magnetic field (Fig.3). The number and intensity of CMEs are greatest during periods with maximum number of sunspots.

Apart from this sunspot-related solar activity, another manifestation of solar activity are high speed streams of charged particles (the so called solar wind) emanating from solar coronal holes - areas of open magnetic field lines where the Sun's corona is colder, and has lower-density plasma than average, so they look darker in X-ray images (Fig.4). The number and intensity of high speed solar wind streams are greatest on the declining phase of the sunspot cycle.

Variations in total and spectral solar radiation are important for the chemistry and dynamics of various atmospheric regions, and are related to climate change. Coronal mass ejections and high speed solar wind streams both lead to geomagnetic disturbances which may disrupt telecommunications and power supply and damage space-borne and air-borne instrumentation. But their effects are not the same. CMEs cause the strongest geomagnetic storms during all phases of the sunspot cycle, but they are relatively rare and short-lasting.

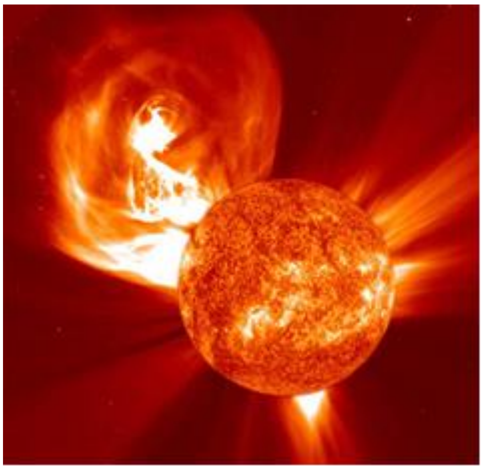

Figure 3. *An EIT image of the Sun in extreme UV light, taken on January 4, 2002, enlarged and superimposed on LASCO C2 coronagraph image. Courtesy: EIT and LASCO C2 instruments, Solar and Heliospheric Observatory (SOHO) http://sohowww.nascom.nasa.gov/.*

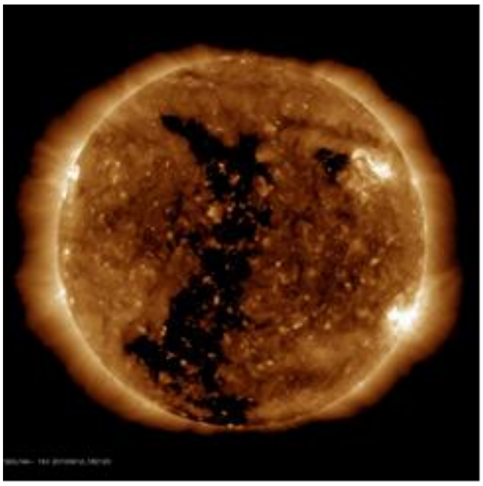

Figure 4. *An X-rat image of the Sun showing a big solar coronal hole (the dark ares). Credit: SDO/AIA.*

Storms caused by high speed solar wind streams are as a rule weaker but longer lasting, and because they are related to long-lived solar structures (coronal holes), they are recurrent – reoccurring every about 27 days, the period of solar rotation, when their parent coronal holes rotate to face the Earth. The spacecraft charging that occurs during storms driven by high speed solar wind streams is evaluated to be more severe than it is for CME-driven storms: the voltages attained are higher, the region of local time over which the severe charging occurs is wider, and the high voltages persist longer (days) [Borovsky and Denton, 2006]. This conclusion, however, is made on the basis of a limited number of events: 78 CMEs and 32 high speed solar wind streams.

3. Spacecraft effects on plasma

Not only surrounding plasma affects a body immersed into it. The body also disturbs the plasma, creating a sheath – a region surrounding the body - with a thickness proportional to the Debye length $\lambda_D = (\varepsilon_0 KT_e/e^2n)^{1/2}$ where (ε_0 is the permittivity of free space, K the Boltzmann’s constant, T_e, e and n the electron temperature, charge and density, in which the plasma is perturbed by the presence of the body. Besides, a moving body the piles plasma in front of it creating a wake with depleted plasma. Of particular interest is the case when the body’s velocity is intermediate between the electron and ion thermal velocities, characteristic for the low orbiting vehicles like manned spacecraft. This has been first confirmed by an experiment aboard AE-C satellite.

All earlier studies have been conducted for 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 floating potential reaches tens of volts which causes serious problems: On the one hand, the interpretation of the results from the scientific instruments measuring plasma parameters, electric and magnetic fields, becomes practically impossible. On the other hand, the most dangerous effect of the spacecraft charging is the electrostatic discharge during which very strong currents may flow in a short time. As many instruments measure currents of the order 10^{-7} – 10^{-11} A, a much stronger current will lead to the breakdown of the device’s input. Of course, each device is protected against such overload, but the problem is the time reaction of the protection circuit. Such current impulses can create false signals in the logical schemes and to lead to the failure of the instrument. For example, twice during the docking of the Shuttle to the ISS, a whole group of computers failed. The possible explanation is a current impulse as a result of the different potentials of the Shuttle and the ISS. Several times there were difficulties during the undocking of the Soyuz spacecraft from the ISS, and one of the hypotheses is the electrostatic charging. To mitigate these problems, a special device - Plasma Contactor Unit (PCU) - has been constructed by NASA to keep the potential under 40 volts. While the PCU limits the space station potential, it neither measures the space station’s floating potential, nor characterizes the plasma environment. A Floating Potential Probe is designed for the American module of ISS to monitor the station structure's electrical potential with respect to its local plasma environment and assess the effectiveness of the PCU, and to measure the local plasma parameters. However, the station is a very complex construction which moreover is not fully metalized, so both the surface charging and the ambient disturbed plasma parameters are different in different points, and their special distribution is not known.

Nevertheless, it is important to acknowledge that the inherent nonlinearity [Damgov and Trenchev, 2001; Damgov and Trenchev, 2003; Damgov and Trenchev, 2004] resulting from diverse factors and uncertainties adds a layer of complexity to most processes, challenging our ability to accurately model and comprehend their behaviors using conventional linear frameworks.

4. “Obstanovka” experiment onboard ISS

The goal of the Plasma Wave Complex (PWC) (“Obstanovka” experiment) for wave and plasma parameters measurements in the ISS environment planned onboard 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 [Klimov and Korepanov, 2004]. PWC is composed of multiple units, which are integrated into two measuring blocks with nearly identical sensors installed outside ISS and the third one inside ISS:

- two combined wave sensors
- two flux gate magnetometers
- two Langmuir probes
- two spacecraft potential monitors
- a plasma discharge stimulator
- a correlating electron spectrograph (10eV – 10KeV)
- a radio frequency analyzer
- a signal analyzer and sampler
- two data acquisition and control units
- a block of storage of telemetry information
- grounding support equipment

During the first stage of the experiment ("Obstanovka-1"), a database of electromagnetic fields and of plasma-wave processes occurring in the ISS near-surface zone will be compiled to account for the influences of the plasma component factors of near-Earth space, including influence of artificial origin. The results will be used in the field of applied geophysics, ecology, space weather monitoring, and also for the updating of operational requirements used in space engineering and technology.

5. Deriving the spacecraft charging with a Langmuir probe

The Langmuir probe is one of the classical instruments for plasma diagnostics [Mott-Smith and Langmuir, 1926] 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 [Brace, 1998], at other planets [Krehbiel et al. 1980] and comets [Grard et al., 1998].

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.5). The plasma parameters are derived from the form and amplitude of this volt-ampere curve. When the probe potential is negative enough to repel all the electrons (region A in Fig.5), 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 (region B in Fig.5), the more energetic electrons overcome it, and produce an electron current, exponentially increasing when the voltage is further decreased. The net current is a sum of the ion and electron currents, and when the ion current is extracted based on extrapolation of region A, 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.

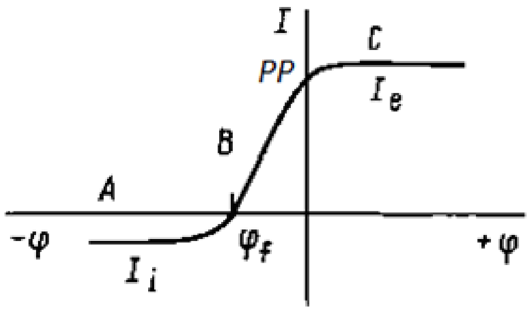

Figure 5. *A typical volt-ampere characteristic from the cylindrical Langmuir probe.*

The point marked PP in Fig.5 is an inflection point in the volt-ampere curve. It corresponds to the plasma potential with respect to the spacecraft, or the spacecraft potential with respect to the plasma. The determination of this potential is equivalent to measuring the electrization of the spacecraft, which is actually our goal.

But the detection of PP, at least as an initial task, is quite difficult. For this reason, instead of the detection of the structure's potential with respect to the plasma, as an initial task the instrument's algorithm is aimed at the detection of the floating potential φ_f - the potential at which the currents due to positively and negatively charged particles to the structure are equal, so the net current is zero. Practically, we apply a sweep voltage to the probe and determine, with accuracy better than 3 mV, φ_f - the voltage at which the current changes sign from positive to negative. For the expected temperature range at the altitudes where the International Space Station operates, the difference between the floating potential φ_f and the station's potential with respect to the plasma PP does not exceed 1.5 V. Further, we apply to the probe a sweep voltage in the range φ_f -$U1$ to φ_f +$U2$, with $U1$ and $U2$ being functions of the slope of the probe characteristic dI/dU in the electron retardation region - that is, in the voltage range between φ_f and PP where the current *I* is an exponential function of the applied voltage *U*. At low plasma temperatures the voltage difference between φ_f and PP is too small, and if the data points are uniformly distributed in the measured range, very few points will be derived in the electron retardation region, and the electron temperature will not be correctly determined. To be sure we will have enough data points in the electron retardation region so that we could correctly derive the electron temperature, we divide each of the ranges from φ_f -PP to φ_f (the ion acceleration region), from φ_f to $U2$ (the electron retardation region), and from $U2$ to $U2$+$U3$ (the electron acceleration region) into 20 equidistant points, and measure the probe current in each of these voltage values.

The foreseen modes of operation and the adaptive sweep voltage algorithm may not be enough to account for all different situations that can occur due to the station's charging and the disturbances introduced by the structure itself and by the operation of the numerous systems and instruments into the plasma in the near-surface zone of the station. For this reason, a possibility is foreseen for remote upgrading of the mode of operation of the Langmuir probe, which can be used for remote upgrading of any space-borne instrument in order to maintain the scientific experiments in real time. The communication between the station and the Earth is realized through the telemetry information channels based on radio-frequency connection. Apart from scientific data from the instruments, these channels will be also used for transmitting of commands from the Earth (about the instruments' modes of operation), as well as information blocks (containing object code) for changing the processing and control programs. It allows combining several functions:

- deriving data (in real time) for the observed physical parameters and saving the measured parameters to the onboard computer;

- maintaining an information channel between the ground-based stations and the onboard computer;
- providing access to the derived information and adjusting the specialized software of the orbital scientific instruments using a virtual network (in Internet).

Each scientific program is realised as a state machine and is controlled in real time by its state variables and by the values of the measured parameters.

5. Effect of shading

The ion concentration Ni measured by LP1 on 23.04.2013 does not exceed 4.1010 m-3 (Fig. 6) while the concentration obtained by ground-based data and measured by NLP instrument [Barjatya et al., 2009] at the same time is around 1.1012 m^{-3}.

The difference is due to the fact that NLP is located in the front part of the station and all measurements are performed in undisturbed plasma. On the other hand, LP1 is located on "Zvezda" module in the backside of the station, and just in front of LP1 along the velocity vector is the MLM module, which actually leads to a significant decrease of the plasma density in the vicinity of LP1. Such a decrease of the plasma density in the shadow of a space vehicle was shown in 1965 [Brace et al., 1965].

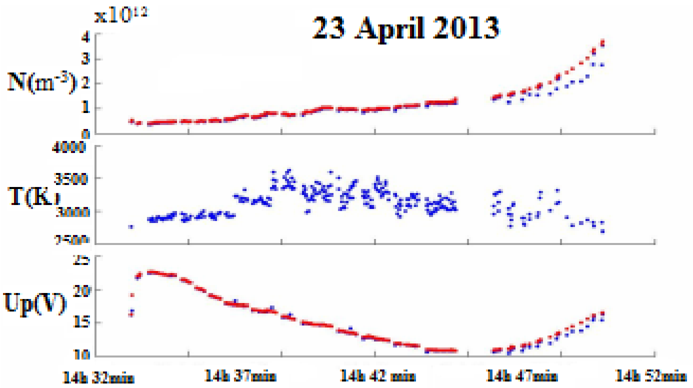

Figure 6. *Ion concentration Ni – upper panel, electron temperature Te – middle panel, and flowing potential Up – bottom panel measured on 23 April 2013 by LP1.*

6. Effect of eclipse exit

When the ISS crosses the eclipse, the observations show a jump of the floating potential. In the case shown in Fig. 3 the potential Up(V) (third panel in Fig. 7) suddenly changed from 10 to 25V (i.e. the floating potential of the station became -25V). According to our American colleges [Mott-Smith and Langmuir, 1926] such a jump is caused by "charging due to additional electron collection on the exposed edges of solar cells".

7. Effect of the Equator crossing

Over the Equator area there are regions with high plasma concentration. One example is shown in Fig. 8. Here the station crosses the Equator at 14:25. The station enters a region of high concentration (upper panel in Fig. 8) which leads to a sharp drop in the flowing potential.

7. Variation of the Flowing potential during a geomagnetic storm

On 23.04.2013, a high speed solar wind stream (HSS) reaches the Earth and causes a geomagnetic storm. Kp starts to increase in the early hours of 23.04.2013 (Fig. 9), while Dst increases a couple of hours later. At the same time the flowing potential jumps from -10 to -15V (Fig. 10). Dst drops around 21:00 UT.

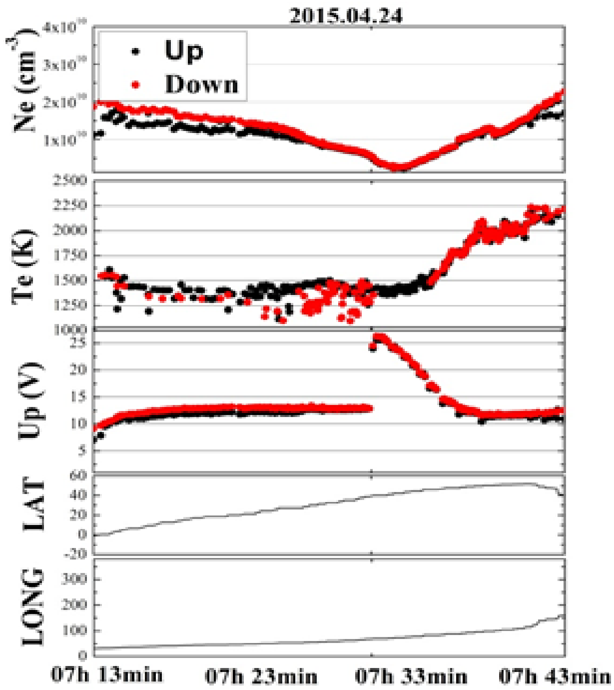

***Figure 7**. Ne (cm^{-3}) – upper panel; Te (K) second panel; Up (V) – third panel; orbital parameters – bottom two panels.*

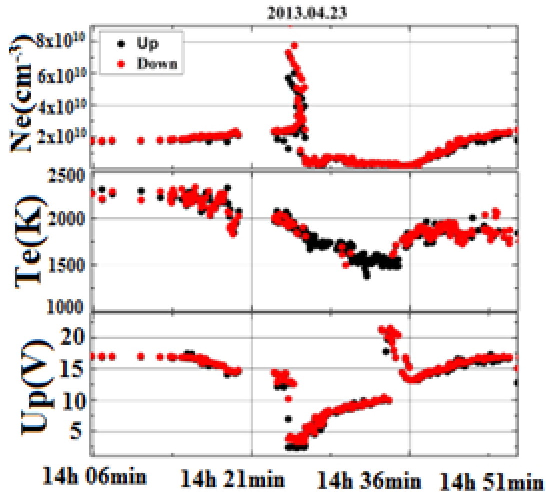

***Figure 8.** Plasma concentration (upper panel), electron temperature (middle panel), and flowing potential (bottom panel) during the Equator crossing.*

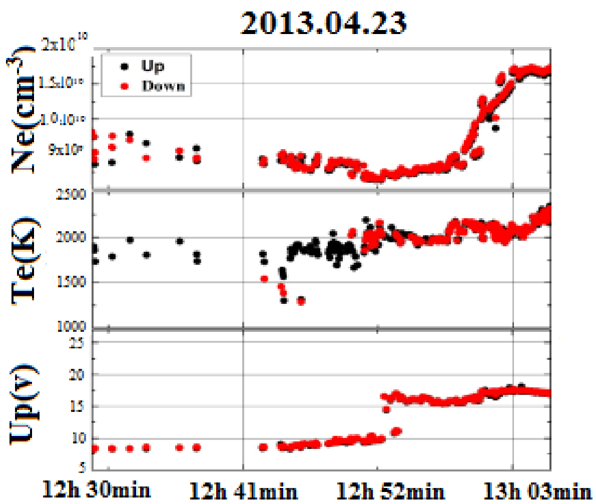

***Figure 9**. Variations of the plasma parameters and spacecraft potential around noon UT on 23.04.2013: Ne (upper panel), Te (middle panel), Up (bottom panel).*

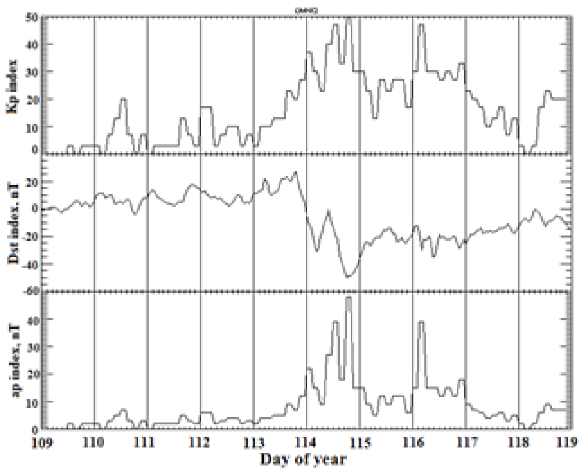

***Figure 10**. The geomagnetic storm on 23.04.2013: Kp-index (upper panel), Dst-index (middle panel), Ap-index (bottom panel).*

Conclusions

Because of the big size of the International Space Station and its complex shape, the plasma density in its vicinity can differ by as much as two orders of magnitude.

In spite of the differences in the plasma density in different locations, their variations are similar.

The spacecraft potential is always negative with respect to the plasma and varies between 0 and -25 V.

The spacecraft potential can change sharply during passages of the eclipse and the equatorial anomaly, and at the beginning of geomagnetic storms.

Acknowledgements

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