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Calibration of Faraday Cups used on the Spectr-R Spacecraft for Monitoring the Solar Wind

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Abstract. The solar wind is a stream of charged particles ejected from the atmosphere of the Sun. It consists of electrons, protons, and a small amount of helium ions. This stream of particles varies in density, temperature, and speed over time. The monitoring of these parameters is a key problem of the Space Weather Program. A new unique instrument (BMSW) consisting of six Faraday cups was developed in the Department of Surface and Plasma Science in collaboration with the Space Research Institute, Moscow. We used the Simion software package for modeling of the Faraday cup for calibration of the new instrument that is used onboard the Spectr-R spacecraft. Results of the simulation are presented in this study.

Introduction

The solar wind consists of electrons, protons, a small amount of helium ions (1–3 %), and a trace amount of heavier ions expanding from the solar corona to free space. A typical velocity is between 300–750 km/s, temperature 1–30 eV, and density up to 200 cm^{-3} at 1 AU. At such speed, the solar wind travels from the Sun to the Earth 2.5–6 days. Investigations of the Solar–Terrestrial relation have shown that sudden changes of solar wind properties can significantly affect the state of the Earth's magnetosphere. For this reason spacecraft measurements of solar wind parameters with a sufficient temporal resolution and accuracy are needed. Devices composed of Faraday cups (FCs) are frequently used for such measurements e.g., Zastenker et al. [1982], Safrankova et al. [1997]. We present a new device (BMSW) with a high-temporal resolution of ion current measurements by six independent FCs for monitoring of the solar wind [Safrankova et al., 2008]. This device is placed onboard the Spectr-R spacecraft that was launched in July 18, 2011 into a highly elliptical orbit with apogee $\approx 350\,000$ km and perigee $\approx 10\,000$ km. Spectr-R is a radio telescope mission equipped with the 10 m mirror antenna and it is predominantly dedicated to investigate a structure of various objects in the Universe as black holes and quasars. Simultaneously, it presents a good platform for a solar wind monitoring because it spends ≈ 8 days out of the 9-day orbit in the solar wind. Onboard measuring solar wind system are also equipped with the AC/DC magnetometer, energetic particle detectors, and the Sun-direction sensor. In this paper, we apply the Simion software package for modeling of FCs used in BMSW with motivation to calculate the plasma parameters from measurements of the currents of FCs.

Basic principles of FCs

The FC is a metal (conductive) cup designed to collect charged particles in vacuum. It can be used in laboratories for measuring of an intensity of electron and ion beams and it is also frequently used in space exploration for monitoring of the solar wind and energetic particles. A schematics of the FC design is shown in Figure 1 (left). The FC is generally equipped with a collector (5) and four grids: ground grids cover outer and inner diaphragms (1, 3), a positive control grid (2) is placed between diaphragms, and a suppressor grid (4) lies between the inner diaphragm and the collector. The ground grids are used for elimination of an internal electric field outside FC. The positive control grid is connected to tunable HV source and thus, only the ions with the velocity sufficient to overcome the grid potential can reach the collector. The

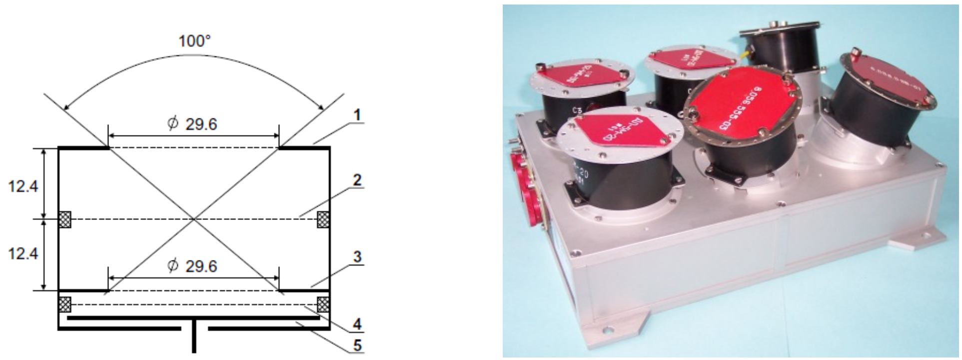

Figure 1. Left—Design of the Faraday cup: (1) and (3) are outer and inner diaphragms with ground grids, respectively; (2) a positive control grid, (4) a suppressor grid, (5) a collector. Right—BMSW instrument for monitoring of the solar wind.

suppressor grid is powered by a negative potential of ≈ 300 V and it is used for deflecting of solar wind electrons, secondary electrons emitted from other grids, and photoelectrons emitted from the collector by solar UV radiation, but the electron component of the collector current caused by photoelectrons from the suppressor grid should be subtracted from the total measured current. This current will be determined during crossings of the spacecraft through magnetospheric lobes where the photocurrent is a dominant component of the collector current.

Design of the solar wind monitor

The BMSW instrument consists of six independent FCs divided into two groups: in the first of them, three FCs are oriented toward the Sun, while three FCs of the other group are inclined at 20° from the sunward direction Figure 1 (right). Three FCs oriented toward the Sun are equipped with HV sources that supply the control grid and they are used for estimation of the temperature, velocity, and density of the solar wind (outer diaphragm diameter is 20 mm). Collector currents (I) of the FCs oriented toward the Sun depend on the solar wind density (n), velocity, ratio of thermal and bulk solar wind velocities (hereafter called temperature T), control grid voltage (U), and declination of the solar wind from FC inclination (A). The second group of inclined FCs without a voltage on the control grid are used for estimation of the solar wind direction and solar wind ion flux (in this case, the outer diaphragm diameter is same as diameter of the inner diaphragm 30 mm). Collector currents of these FCs are functions of the solar wind density (n), temperature (T), and inclination of the solar wind velocity from the FC direction (A).

Simulation using the Simion software

The Simion is a software package primarily designed to calculate electric fields and trajectories of charged particles in these fields when a configuration of electrodes with voltages and particle initial conditions are given [Manura and Dahl, 2008]. We use this software for modeling of Faraday's cups and their interaction with the solar wind. The model of real FCs includes an effect of a finite geometry and the geometry of the control grid. The effect of the finite geometry can significantly affect the shape of the electric field inside the FC. Figure 2 (left) presents equipotential levels between two grounded grids. The geometry of the control grid deforms the electric field and the potential among grid wires decreases and affects trajectories of ions as it is shown in Figure 2 (right). These effects can influence a motion of charged particles inside the FC and an estimation of solar wind parameters from collector currents.

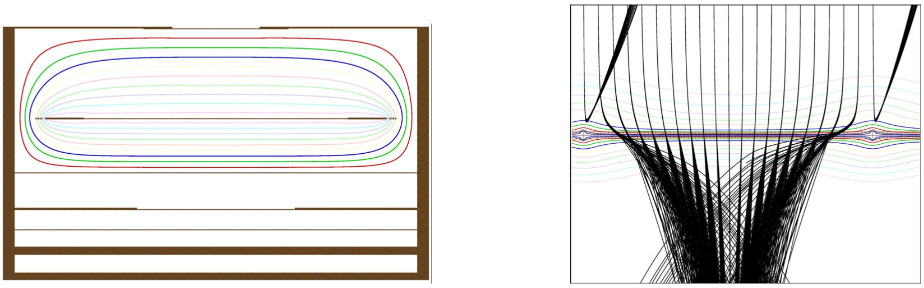

Figure 2. Letf—Model of the FC created by the Simion software includes the effect of finite geometry—with electric equipotentials. Right—A detail of the control grid—the effect of the grid geometry on trajectories of ions.

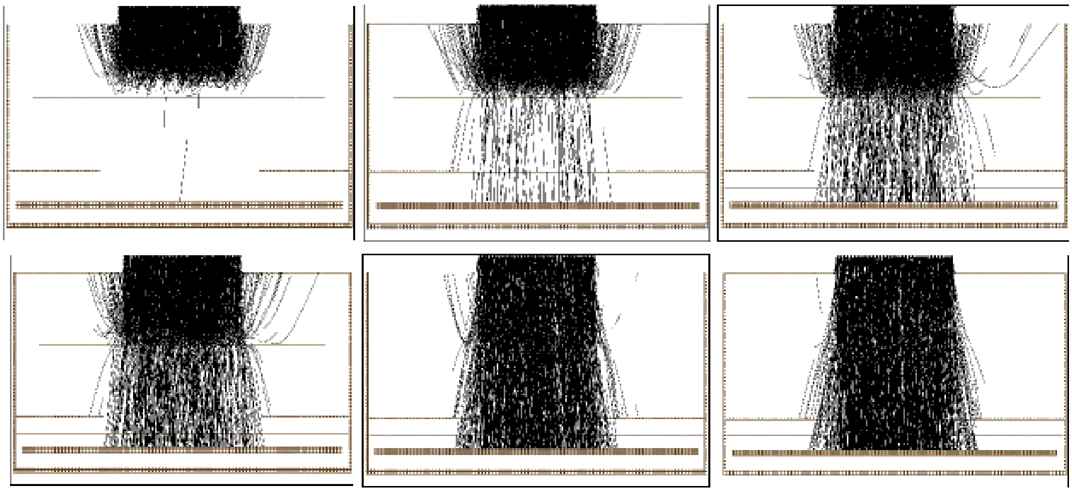

Figure 3. Interaction of the FC with the solar wind velocity of 400 km/s (≈ 1000 eV) and thermal velocity of 44 km/s. Voltages on the control grid: 1670 V, 1340 V, 1150 V, 1070 V, 770 V, and 540 V, respectively. The trajectories of ions are shown by the lines.

Results of simulation

A detailed model has been created for two types of FCs (outer diaphragm diameters of 20 mm and 30 mm, respectively). Figure 3 depicts an interaction of the solar wind of velocity of 400 km/s (≈ 1000 eV), thermal velocity of 44 km/s, and various voltages on the control grid (1670 V, 1340 V, 1150 V, 1070 V, 770 V, and 540 V). 3 % of helium ions were added to the model for a precise simulation of the real solar wind conditions. Figure 4 shows normalized collector current (I/I_0) as a function of the control grid voltage to energy of the solar wind ratio (U/E) and incident angle of the solar wind (A) for a fixed solar wind temperature (T = 10 % of the solar wind velocity) and with added 3 % of helium ions. It is important to note that I is a current that is measured by a sensor and I_0 is a value of full ion current from the ion source.

Normalized collector currents (I/I_0) for both groups of FCs without the voltage on the control grid as a function of an incident angle of the solar wind (A) and the solar wind temperature (T) are depicted in Figure 5. It is clearly seen that a dependence of the collector current for FCs oriented toward the Sun (with smaller outer diaphragm) on the incident angle of the solar wind (A) is weaker than for FCs with larger diaphragm, especialy for small angles. Normalized collector currents (I/I_0) as a function of the voltage on the control grid, incident angle of the solar wind (A), and the solar wind temperature (T) are shown in Figure 6.

It is useful to find out an analytical expression for collector currents as a function of solar wind parameters for estimation of solar wind parameters from measured currents. For this

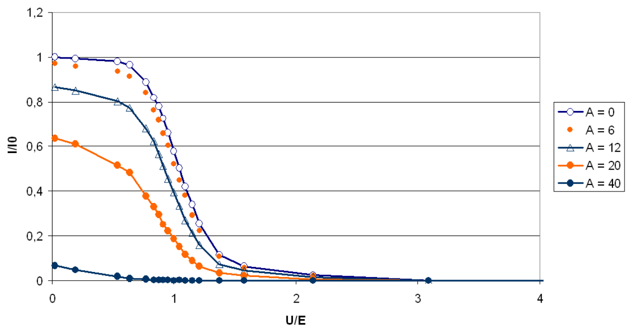

Figure 4. Normalized collector currents (I/I_0) as a function of control grid voltages to energy of the solar wind ratio (U/E) and incident angle (A) in degrees of the solar wind with added 3 % of helium ions. The temperature velocity of the solar wind is fixed to 10 % of a bulk velocity.

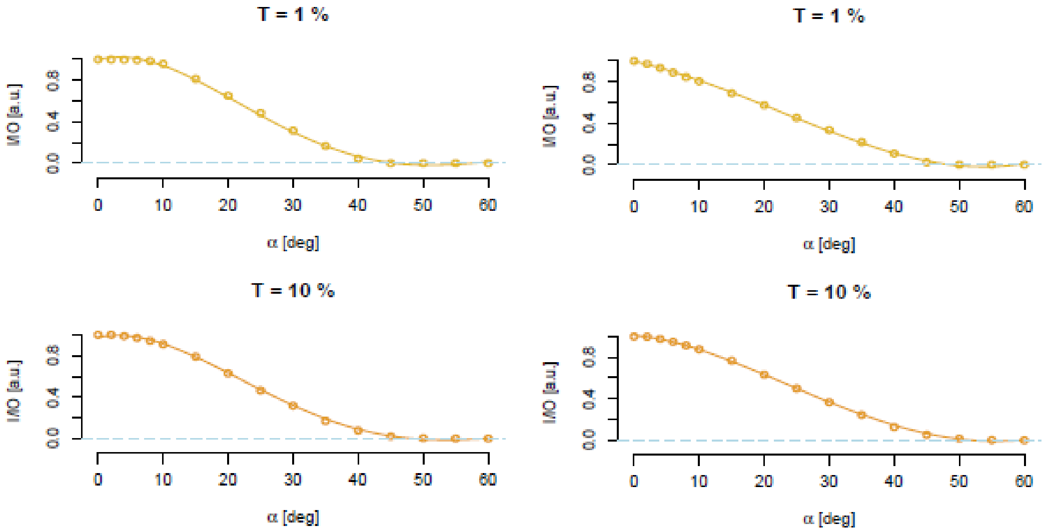

Figure 5. Normalized collector current for FC without voltage on control grid as a function of incident angle of the solar wind and the solar wind temperature. Points represents calculated data by Simion software. Lines represents fourth-order polynomial function fitted on calculated data by R software. Left—Outer diaphragm diameter 20 mm. Right—Outer diaphragm diameter 30 mm.

reason, a large set of data has been created for various solar wind parameters (incident angle of the solar wind (A) 0–40° , temperature (T) 0–50 eV, and various voltages applied on the control grid) and obtained data was fitted by an analytical function [Komarek, 2011]. The R software was used for computation of all fits [Software R, 2011]. We selected fourth-order polynomial function for a description of the angular dependence of the normalized collector current as a function of the incident angle of the solar wind (A) and the solar wind temperature (T). Examples of fitted curves are present in Figure 5. It is clearly seen that obtained curves fit well the calculated data. Two shifted functions connected in a point U/E = 1 was selected for description of the normalized collector current on the control grid voltage to energy of the solar wind ratio (U/E), incident angle of the solar wind (A), and solar wind temperature (T). Examples of fitted curves are shown in Figure 6. The blue lines represent fits for a single combination of the temperature and angle. This curve corresponds well to the calculated data but it is not appropriated for estimation of solar wind parameters. The red lines represent general fits and the green lines represent fits with a simplificated dependence for some coefficients (for a colored version see the electronic version of this article). Although the red lines represent a more complicated model than green ones, this model will be used for our estimation because of the simple model does not fit well to the calculated data in important ranges of parameters.

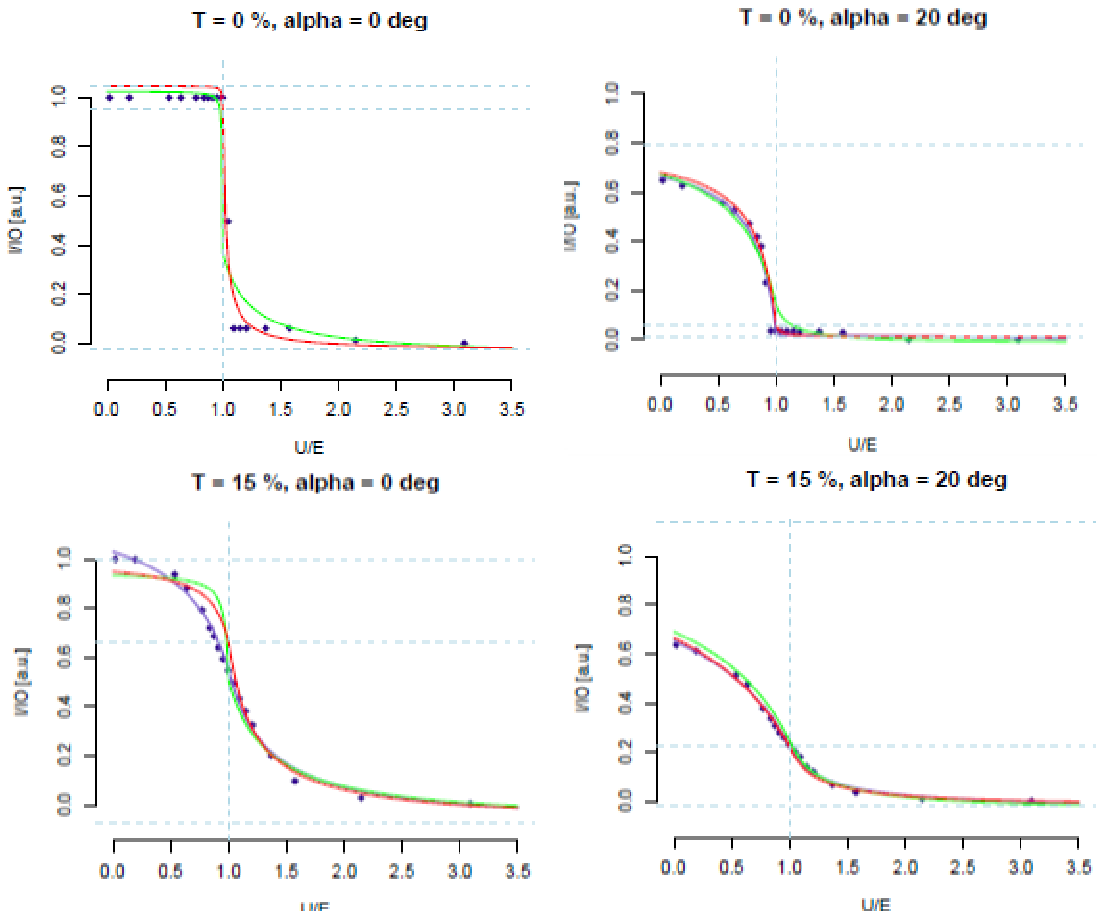

Figure 6. Normalized collector currents for the FC (outer diaphragm diameter of 20 mm) as a function of the control grid voltage, incident angle of the solar wind, and the solar wind temperature. The points represent calculated data by the Simion software. The blue lines represent fits for a single combination of the temperature and angle. The red lines represent general fits and the green lines represent fits with simplification dependence for some coefficients (for a colored version see the electronic version of this article).

The parameters of fits will be used for creating a numerical algorithm which will be used for processing of measured currents of FCs. This algorithm is now under development.

Conclusion

The detailed simulation model of Faraday cups used for the BMSW instrument onboard the Spectr-R spacecraft has been developed with a support of the Simion software and a large set of data describing the interaction between Faraday cups and the solar wind has been computed. Calculated data was fitted by analytical functions and parameters of these functions will be used for creating a numerical algorithm which will be used for processing of measured data.

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