MDD3 - EMI'S UPCOMING METEOROID AND SPACE DEBRIS DETECTOR EXPERIMENT ONBOARD RUSSIAN SPEKTR-R SATELLITE

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ABSTRACT

The Ernst-Mach-Institut (EMI) is currently developing its next meteoroid and space debris detector experiment, referred to as MDD3, which will be integrated onboard the Russian Spektr-R satellite. Taking this flight opportunity supported by the German Aerospace Center, MDD3 will be operated in a highly elliptical orbit, allowing for in-situ measurements of impact events in various Earth orbit particle environments. The detector system is equipped with several sensors, thus contributing to both the on-orbit verification of a robust impact detection system and the enhancement of knowledge about micrometeoroid and space debris populations. This paper addresses scientific and technical aspects of the MDD3 mission in a general overview. The status of MDD3 implementation, as well as facts on the Spektr-R mission and orbit environment are outlined for background information.

1. INTRODUCTION

Impact detection systems are used for measurements of cosmic dust particles also referred to as micrometeoroids (MM), and sub-centimetre sized space debris (SD) objects. The objective of cosmic dust measurements is to study the composition and distribution of the impacting micro-meteoroids, which mostly originate from comets and asteroids and can provide valuable knowledge for Solar system science. By contrast, the origin of space debris as a result of anthropogenic activities in space is well known, and impact detection systems in the near-Earth environment are applied to characterise the micrometeoroid and space debris populations.

Hypervelocity impacts of MM/SD on space systems can result in failures ranging from degradation of system performance to the loss of a mission. To assess the risk and to define appropriate protective measures, a monitoring of the orbit particle environment is needed. As the detection and tracking of MM/SD using ground-based sensor systems is limited to objects in the centimetre range or larger, the more numerous smaller particles can only be monitored using impact detection systems. For both applications several experiments provided information on sub-millimetre particle impacts on interplanetary missions (e.g. [1], [2], [3]) and in near-Earth environment (e.g. [4], [5], [6]). In addition, the inspection of impact damages on spacecraft structures retrieved after exposure in Low Earth Orbit (LEO) environment (e.g. [7], [8]) allows to draw conclusions about particle populations. Such passive detection methods complement the obtained data of active in-situ detection systems.

In-situ measurements of impacting fluxes are needed to model the varying MM/SD environment against the background of the threat of hypervelocity impacts to space missions. A further aspect of impact detection is due to the implications of particle impact on space operations. Active detectors integrated on space systems can be used as diagnostic sensors to identify impact damages on crewed spacecraft and to root the cause of satellite anomalies to impact effects.

The development of meteoroid and space debris detection systems at Ernst-Mach-Institute aims at both the implementation of instruments for scientific monitoring of space debris fluxes and the engineering of robust sensor systems to detect impacts on spacecrafts. The Meteoroid and Space Debris Detector (MDD3) is EMI's upcoming impact monitoring experiment.

2. MISSION DESCRIPTION

The MDD3 experiment is based on and continues the detector development started with MDD1 [6], which was flown on a Cosmos upper stage. The MDD3 experiment combines different impact detection methodologies, measuring electromagnetic emissions of the generated plasma and the acoustic noise caused by hypervelocity impacts. The detection system will be integrated as scientific payload on the Russian Spektr-R spacecraft built by Lavochkin. This flight opportunity is supported by the German Aerospace Center (DLR) within its On-Orbit Verification (OOV) programme.

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The Spektr-R spacecraft is aimed at astrophysical studies in various ranges of electromagnetic radiation. The main scientific objective of this mission is the research of structure and dynamics of space sources of radio-wave radiation. An angular resolution up to few millionth fractions of an angular second is achieved by combined operation of the Spektr-R radio telescope and a global network of Earth-based radio telescopes.

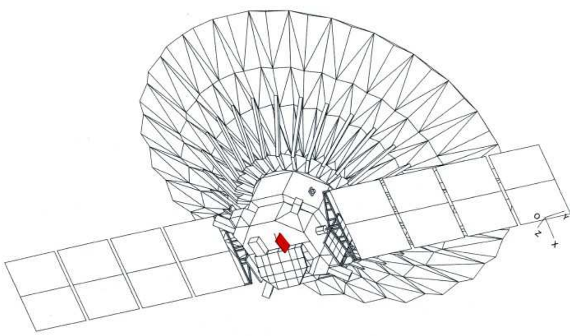

Figure 1. Spektr-R illustration with MDD3 identified (red marking) on the spacecraft radiator side

The Spektr-R spacecraft consists of the scientific payloads carried by a Navigator bus platform. The Lavochkin built Navigator platform is a unified module for spacecrafts for various applications and Earth orbit regions. The scientific payload includes:

- A Space Radio Telescope, which is the space-based part within a system of ground-space interferometer of the Radioastron project. The 10 m diameter parabolic antenna is the main payload intended for astrophysical studies and provided by the Russian Academy of Sciences.
- Plasma-F, a suite of Russian instrument to measure plasma of solar wind, interplanetary magnetic fields and energy particles flows.
- MDD3, EMI's detector system experiment.
- Corner reflectors of a Russian experiment.

Spektr-R will be launched into a high-apogee orbit. The spacecraft is oriented in an inertial reference frame to a given direction by employing reaction wheels and a hydrazine thruster system. MDD3 will be externally mounted on a thermally stabilised spacecraft panel, which is equipped with heat pipes and radiators (Figure 1). MDD3 is oriented normal to this panel by means of a mounting interface manufactured by Lavochkin (Figure 2). The electrical interfaces to Spektr-R spacecraft comprise four connections for data transfer with satellite's telemetry system and scientific payload computer and power supply using connectors, which are standard in use for Russian space systems.

3. MDD3 REQUIRMENTS

The MDD3 instrument is an in-house development of the Ernst-Mach-Institute. The primary objective is the on-orbit verification of a robust impact detection system to be applied for the monitoring of micrometeoroid and space debris fluxes. To achieve the MDD3 mission objective, the following basic scientific and technical requirements have to be satisfied:

- Autonomous and continuous detection of impacts of sub-millimetre particles
- Determination of impact characteristics (mass and velocity)
- Coincidence verification of impacts by using different sensor types in order to distinguish impacts events from noise events, to which the sensors may respond.
- Recalibration of sensor systems and verification of impact sensor functions during operation in order to identify malfunctions.
- Compliance to technical requirements defined for integration and operation on Spektr-R.
- Compliance to the spacecraft environment during launch and in orbit.

4. INSTRUMENT DESCRIPTION

The MDD3 is designed as an autonomous sub-system, which comprises all sensor and data processing elements in one unit. The complete box-shaped detector has lateral dimensions of 490 x 250 mm and a height of 36 mm as illustrated in Figure 2.

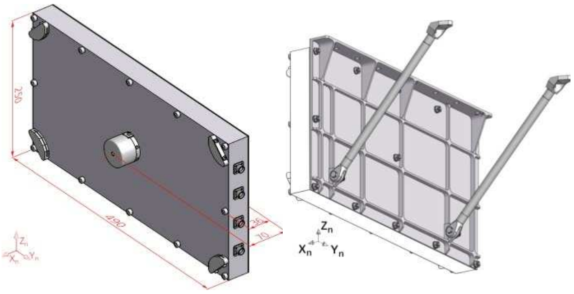

Figure 2. MDD3 mechanical configuration (left) and mounting interface (right)

The active detection surface is an integrative part of the structure, as the space-facing cover serves as the detector plate on which hypervelocity impacts of particles are measured. The detector surface is a thin aluminium plate providing approximately 0.12 m^2 detection area.

4.1 Impact Detection Methodology

MDD3 combines detection methodologies based on the measurements of different physical phenomena associated to hypervelocity impact: the generation of impact plasma and the momentum transfer to the impacted structure.

Three independent sensor systems are utilized on-board MDD3, each corresponding to a different physical signature, which is generated during hypervelocity impacts on the detector plate:

- Acoustic waves, which are excited by the shock transfer and propagate within the detector plate.
- Light emission from the short-lived plasma, commonly referred to as impact flash.
- Transient magnetic fields arising from the impact plasma.

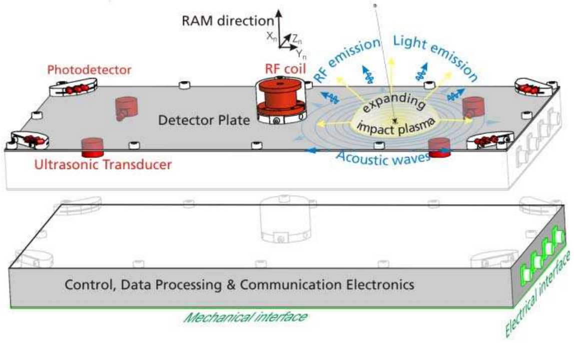

Figure 3. MDD3 configuration, measurable impact effects (blue), sensor techniques (red) and interfaces to spacecraft (green)

The coincident measurement of three independent sensor techniques measuring different impact effects ensures both the clear distinction between detected impact events and noise sources (e.g. thermal cracking or stray-light) and the characterisation of impact parameters, i.e. impactor mass and velocity.

4.1.1 Acoustic Emission Detection

The measurement of acoustic noise emissions was the first direct dust impact detection methodology numerously applied on rockets, satellites and space probes [9]. Acoustic emissions are induced by the transmitted shockwaves by the particle causing a local deformation on the impacted structure. As a result, elastic stress waves in the range of ultrasound are excited and propagate from the impact point. These surface fluctuations can be recorded by piezo-electric sensors, which are coupled to the impacted structure.

Acoustic emission inside the detector plate is measured by four broad-band ultrasonic transducers which are mounted on its rear face inside the detector. The transducers are commercial systems having a frequency range of 100-450 kHz. The suitability of these sensors to monitor hypervelocity impact induced acoustic waves has been proved during MDD1 operation. The characteristics of this sensor system include high sensitivity, robustness and the capability to utilize a large sensitive detection area by a limited number of sensors [10].

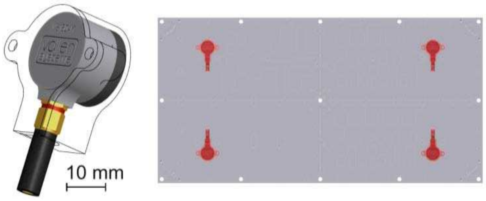

Figure 4. Ultrasonic transducer positioning

The recorded waveforms can be analysed and interpreted to characterize the detected impact event. Most important parameter of the ultrasonic signal is the peak amplitude, which can be correlated to the momentum transferred by the impacted particle. The arrival time differences between the four individual sensors can be used to determine the impact location. However, acoustic emission systems are susceptible to noise events, which exceed the trigger threshold defined for the weak impact signals. The MDD1 experienced unwanted noise signals, which probably originate from thermal expansion effects of the test platform, as clusters of triggered events occurred during eclipse line transitions. Other potential false trigger sources may be generated by the spacecraft attitude control system. To discriminate such non-impact signals on-board MDD3, a verification of impact triggers demands for existence of coincident triggering signals of a distinct sensor system.

4.1.2 Optical Detection

The measurement of impact generated plasma effects for detection of impacts was first drafted in [11]. During a hypervelocity impact a fraction of impactor and impacted structure is ionized. This electrical charge formation is associated with complex processes with regard to shockwaves and intense transient temperatures and pressures. Light is emitted from the expanding plasma cloud induced by collision reactions and recombination of free electrons and ions. This so-called impact flash can be measured to identify an impact event and to obtain information on impact parameters.

Twelve photodiodes are used for measurement of impact flash intensity. Three of each photo detectors are placed in special housings on the edges of the sensor plate external side. The housings define an aperture perpendicular to the detection area and provide a baffle to reduce stray-light susceptibility of the sensor system. The accommodation of three photodiodes connected in parallel per housing ensures high sensor redundancy and a field of view, which almost completely covers the detector plate surface.

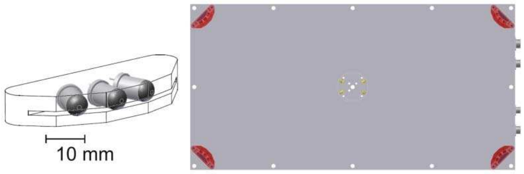

Figure 5. Photodiode (red) and LED life monitor (yellow) positioning

The silicon based photodiodes selected have a rise time of 1 nanosecond and a wavelength detection capability between 400 and 1000 nanometers, with maximum sensitivity at 800 nm. The recorded signals of plasma light emissions give information about the velocity of the impacted particle, as duration and intensity of the impact flash can be attributed to velocity and material composition of impactor and detector plate [12]. The analysis of impact flash signals correlated to impact velocity combined with coincident measured acoustic emission signals correlated to impact momentum exchange allows obtaining information on velocity and mass of impacted particle.

4.1.3 Electro-Magnetic Emission Detection

Transient magnetic fields can be observed within impact generated plasma. The experimentally observed radio emissions may be attributed to diverse processes, e.g. magnetic field generation from charge separation and different transport due to initial momentums of products of the quasi-neutral plasma [13]. Such electro-magnetic emissions in the microwave range can be exploited to monitor hypervelocity impacts.

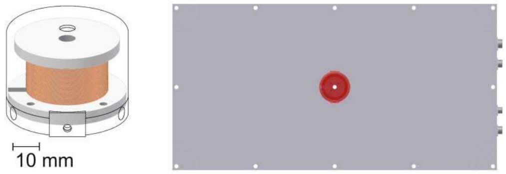

Figure 6. RF coil positioning

A radio frequency pick-up coil is accommodated in centre of the external face of the detector plate in order to measure transient electro-magnetic radiation. The coil consists of several turns of copper wire wound helically on a plastic support.

Though the signals recorded with the RF coil do not contribute to the triggering of sensor measurements, but are drawn in the coincident verification onboard MDD3. As the phenomenon of radiowave emission during hypervelocity impact has not been investigated extensively yet, the coverage and sensitivity of the RF coil will be subject of further investigations. In principle, the signals recorded by this supplemental sensor system can be correlated to plasma generation and thus to impactor velocity and material composition.

4.2 Mechanical Design

The main characteristics of the MDD3 structure and surface finish were early frozen by reason of conformity to satellite requirements. The MDD3 will be mounted on Spektr-R spacecraft radiator side by means of a mounting adapter (Figure 2). The detector plate is oriented vertically to the radiator panel in order to occupy a minimum of its emission surface.

The mounting adapter is the thermal interface to the satellite system, by which the thermal conditions are dictated. Detector's accommodation on Spektr-R radiator panel is beneficial for both, nominal pointing direction without Sun illumination and moderate temperature gradients. Heat generated by MDD3 components (and heat loads inputted from the S/C radiator via the mounting adapter) is dissipated by the structure and radiated to free space, thus providing passive thermal control.

The structure was designed to optimise component accommodation and to provide radiation protection on spacecraft's high-apogee orbit. The additional radiation shielding involved the use of structural elements made from magnesium besides aluminium alloy in order to comply with the total mass requirement.

4.3 Functional Architecture

The MDD3 functional architecture is optimised for scientific performance and interaction with Spektr-R spacecraft. According to the MDD3 functional architecture scheme shown in Figure 7, the units and components can be assigned to the following subsystems:

- Sensor systems belonging to the three independent sensing techniques,
- Life monitor / housekeeping system,
- Communication system,
- Power supply & conditioning system.

4.3.1 Sensor Subsystems

The sensor systems are composed of the scientific sensors and their control and signal processing electronics populated on two printed circuit boards labelled as sample boards. The analogue sensor signals are amplified, filtered and transmitted to the telemetric system of Spektr-R using the associated analogue data interface, on the one hand. On the other hand the analogue sensor signals are converted to digital signals, which are transmitted to the communication system via an internal I^2C bus. Programmable sensor and signal control is realised by the adjustment of:

- The trigger level values of each sensor channel,
- The amplification factor of each sensor channel,
- The sampling rate of the analogue-to-digital conversion on each sampling board.

The sensor channels are similar in principle assembly. This also applies for the design of the sample boards.

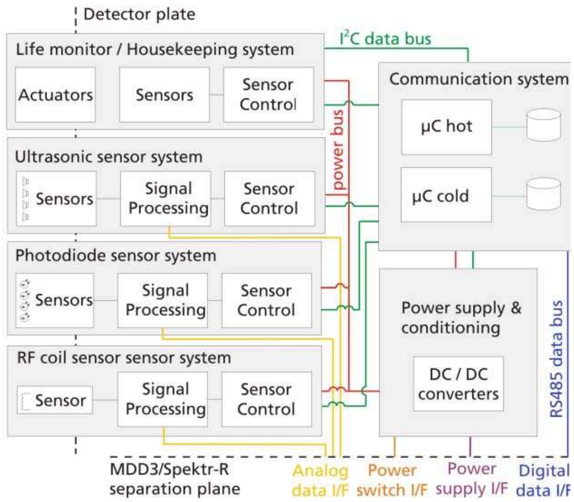

Figure 7. MDD3 block diagram showing sensor, communication and power systems, as well as power and data interconnection lines.

4.3.2 Life Monitor / Housekeeping

Life monitor and housekeeping elements are integrated in the MDD3 in order to check the functionality of the scientific sensor systems and to monitor performance parameter during detector operation. The life monitor system is composed of:

- A piezoelectric actuator and
- Four light emitting diodes (LED).

The piezoelectric actuator is glued to the detector plate, on which vibrations are induced in case this life monitor is triggered. The responses of the acoustic noise detection system indicate the status of its functionality in orbit.

The diodes are mounted in the housing of the RF-coil on detector plate's centre (see Figure 5). This positioning allows for an illumination and triggering of all photodiodes of the optical detection system to identify potential sensor malfunctions.

The housekeeping system uses digital sensors to measure MDD3 temperatures, which give information on the detector health and performance status.

4.3.3 Communication System

The digital telemetry data, containing scientific sensor signals and housekeeping data, are transmitted to the communication system via an internal I^2C bus. The communication system controls the internal telemetry and telecommand data transfer. The communication board also provides the communication link interface to the Spektr-R on-board computer for scientific experiments via a serial RS485 bus, which provides the digital data interface.

Cold redundant microprocessors and several RAM mass memory units are implemented in the communication system to make allowance for suitable MDD3 fault tolerance and control.

The on-board software provides the following tasks:

- Executing of telecommands for sensor control (e.g. activation of life monitors, change of trigger voltage level, amplification factor and sampling rate) and detector control (e.g. switching of detector functions, change of transmission mode).
- Monitoring the health status of the detector (e.g. housekeeping sensor data and unit supply voltages).
- Data acquisition of scientific sensor systems including impact event verification and data storage.
- Data transfer to the spacecraft.

4.3.4 Power Supply and Conditioning

The functions of the power system are conditioning and distribution of the power to detector units. The 27 V DC power supply interface to MDD3 is without galvanic connection to common ground of the spacecraft. Both data interfaces to Spektr-R S/C are galvanically decoupled from the Spektr-R system using optocouplers as well. Control of MDD3 is realised by the power switch interface, which provides switching of MDD3 power supply using control relays commands.

4.4 MDD3 Specifications

The specified characteristics of MDD3 instruments can be summarised to the following main facts:

- Continuous MM/SD impact detection using acoustic, optical and microwave sensor systems.
- Onboard coincident verification of impact events.
- Active detection area: 0.12 m^2
- Sensitivity: sizes in the order of 10 µm (TBD)
- Dimensions: 250 x 490 x 40 mm
- Mass: ca 3 kg
    - 1 kg sensors & electronics
    - 2 kg structure (incl. radiation shielding)
- Power consumption (maximum): 10 W
- Interfaces to Spektr-R spacecraft
    - Power supply & power switch
    - Digital RS485 & analogue

5. VERIFICATION AND CALIBRATION

Testing is the preferred method of verification of MDD3 functionality. The verification necessities are covered by a model philosophy that is strongly influenced by both a short-time implementation phase and an adequate test program. An engineering qualification model (EQM) was designed and integrated to evaluate the detector functionality and system performance. This model will also be used for environmental qualification. Potential design changes to the flight configurations will be documented and coordinated in order to validate the representativeness of the qualification test results and to finally meet the qualification objective. The flight model (FM) is manufactured in agreement with the qualified EQM design. Besides formal function tests environmental tests are to be performed for qualification on EQM and acceptance on FM:

- Static load tests
- Random vibration tests
- Shock tests
- EMC
- Thermal-Vacuum

Apart from the detector verification, tests are needed to calibrate MDD3 and to determine its detection sensitivity. This includes tests using the EQM and EMI's hypervelocity impact test facilities and instrumentation. Optional, a dedicated HVI test campaign on the EQM will be performed after Spektr-R commissioning for ground support. This will allow for analysis of gathered scientific MDD3 FM data, e.g. the evaluation of impact characteristics.

6. PARTICLE ENVIRONMENT

The MDD3 will be integrated on the Russian Spektr-R satellite to be launched into a highly elliptical orbit with 500 km perigee altitude and 330,000 km apogee altitude, on which it is exposed to various Earth orbit environments. The initial Spektr-R orbit parameters are:

- Altitude: 500 x 330,000 km
- Inclination: 51.6°
- Period: 7-10 days
- Mission duration: 3 – 5 years

Due to this orbit, the MDD3 experiment will detect space debris impacts in cross sections of Low Earth Orbit (LEO) and Geostationary Orbit (GEO) regions, as well as impacts of the natural meteoroid background.

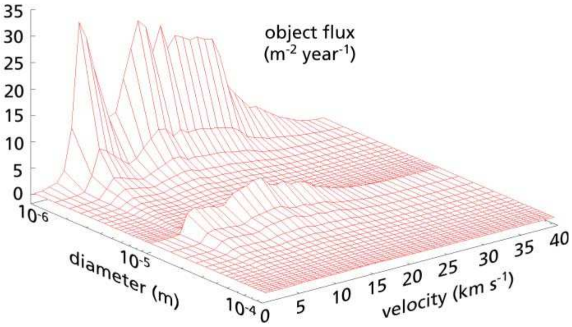

Figure 8. Particle flux vs. diameter and velocity in MDD3 orbit as predicted by the MASTER model

Figure 8 shows the predicted object fluxes in MDD3 orbit calculated using the ESA MASTER model [14]. Impact rates are visualised versus particle size and velocity distribution, both variables of the incident particle momentum.

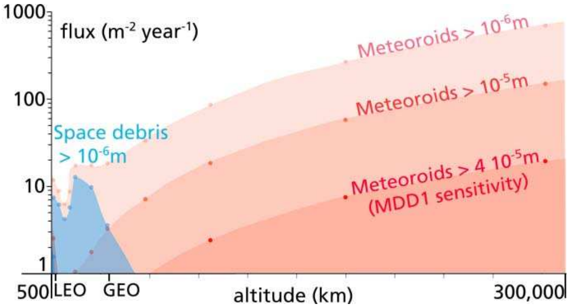

Figure 9. Particle flux vs. Altitude considering different detector sensitivities

The object fluxes are predominated by the micrometeoroid environment. Space debris flux predictions can only be validated during crossing of regions densely populated with man-made objects. In near-Earth regimes space debris accounts for the higher number of impacts, but only 2 % of Spektr-R orbital period are below GEO altitude. Therefore, the MDD3 experiment will primarily contribute to the verification of models predicting particles of natural origin. Figure 9 illustrates this fact. The meteoroid flux predictions are based on the model developed by Divine and Staubach [15], which is implemented in MASTER.

As MDD3 sensitivity is currently undetermined, the cumulative number of impacts to be recorded by the detector is undefined. Referring the sensitivity achieved with MDD1, the minimum number of measurable impact events is 10 during nominal mission duration. Considering a sensitivity increase due to technical improvements in the recent detector design, we expect a detection rate of several impacts a week.

The recorded impact data will be post-processed with respect to Spektr-R satellite operational parameters in order to characterise MDD3 position and orientation. As a result, the following parameters of an impact event detected by MDD3 can be obtained for scientific exploitation:

- Transferred impact momentum,
- Impact flash intensity,
- Time of impact,
- Orbital position,
- Detector attitude.

7. MISSION STATUS

At present the MDD3 mission is near of completion of the detector implementation phase. Fit checks and electrical interface checks were currently conducted in Moscow using the MDD3 engineering qualification model.

Figure 10. Current implementation status: view on MDD3 EQM without rear plate

Functional tests at system level and minor design modifications are to be applied before the characterisation of the sensor performance

will be initiated soon. For this purpose calibration tests will be performed using EMI's hypervelocity impact test facilities in order to control system functionality and to evaluate the detection sensitivity.

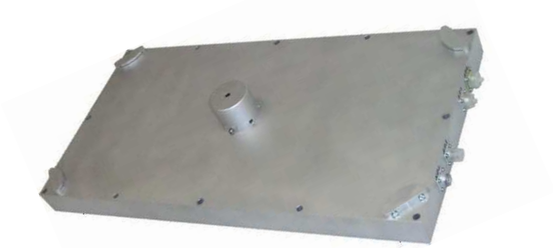

Figure 11. Current implementation status: view on MDD3 EQM detection plate

The MDD3 flight model will be integrated in parallel to these activities to allow for sufficient time for formal verification testing. The begin of MDD3 FM on-orbit verification is scheduled for end of 2009, the scheduled time of Spektr-R launch.

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