IN-SITU DETECTOR AIDA – ADVANCE, RECENT AND FUTURE DEVELOPMENTS

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ABSTRACT

In-situ detection of space debris and meteoroid particles is a method which was applied to gain knowledge of non-trackable small objects since the early days of spaceflight. Although the instruments in most cases only allow the measurement of particles in the size range of some micrometers due to size restrictions of the sensors, the available – but sparse – results are insightful: The small-particle population can be seen as a tracer to the population of larger non-trackable objects, and it was possible to confirm the correctness of model assumptions for solid rocket motor firing clouds. Moreover, recent events have shown that impacts of very small particles on sensitive surfaces and instruments of a spacecraft cannot be neglected.

Existing in-situ detectors for micro-sized particles in the Earth's environment do not operate satisfactorily due to incompatibilities of the measurement principles with the space environment. For this reason the development of the Advanced Impact Detector Assembly – AIDA – was initiated to overcome the shortcomings of these instruments [1]. Breadboard models have proven the high sensitivity of the measurement principles [3, 6, 7], which are also expected to be less susceptible to environmental influences.

Based on these results, the establishment of a development model has been initiated. Details of the sensor layout, the manufacturing process and the test results are presented. Some suggestions for the deployment of AIDA and future developments to obtain a fully operational instrument are outlined.

1. INTRODUCTION

A proper shielding or possible adjustments of a satellite's orbit are appropriate methods to cope with the potential hazards to a spacecraft by sub-millimetre sized particles. For the calculation of the mission specific risks caused by small particles, statistical methods are used. These methods are based on models of the particular Earth environment such as MASTER (Meteoroid and Space Debris Environment Reference Model) [9]. But MASTER and similar models are compromised by the incomplete knowledge about very small space debris particles. This can also be seen in Fig. 6. Depending on the used measurement methods, the flux rates differ by more than an order of magnitude.

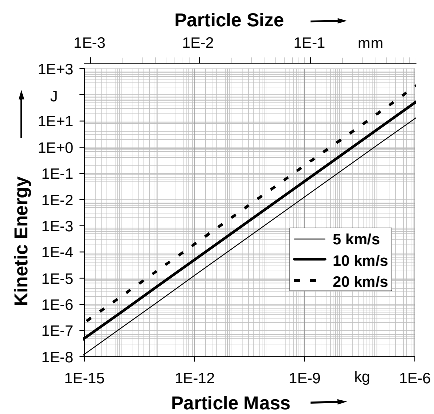

Figure 1. Kinetic energy vs. mass and size (Al sphere assumed) for three impact velocities [8].

Furthermore the first damages probably caused by such small particles have been observed [4]. The possible damage mainly depends on the kinetic energy of the impacting object, i.e. it depends on the two parameters mass m and velocity v according to the equation:

$$E_{kin} = \frac{1}{2} \cdot m \cdot v^2 \qquad (1)$$

The kinetic energy is proportional to the square of the impact velocity, thus even very small impactors can reach dangerous impact energies, if their velocity is

Proc. '5th European Conference on Space Debris', Darmstadt, Germany
30 March – 2 April 2009, (ESA SP-672, July 2009)

sufficiently high. Note that velocities of micro meteoroids can reach up to 72 km/s. In general, it is desirable to have a sensor capable of distinguishing between micro meteoroids and space debris in order to improve the models of micro-sized particles in the environment of the Earth. Furthermore, an object's mass, which is a linear function of its volume, is a cubic function of its diameter regardless of its shape. The equation for the volume of a sphere is shown here as an example for this relation:

$$V = \frac{\pi}{6} \cdot d^3 \qquad (2)$$

Therefore the kinetic energy of an impacting particle is a cubic function of its diameter. The energy range of impacting space debris particles with typical impact velocities in the order of 10 km/s is illustrated in Fig. 1 in dependence of the parameters impact velocity and particle size, assuming the density of aluminium and spherical shape. The particle diameter can be obtained from the upper abscissa. The three magnitudes of size, which range from 1 μm up to 1 mm, result in a kinetic energy range of more than 10 decades, from about 10^{-8} J to 10^{2} J.

The number of small space debris objects with a diameter larger then 1 mm is estimated to be about 100 million objects [11], where smaller particles are even more numerous. Such micrometer-sized particles are for example residues from rocket engines, paint flakes, small fragments from explosions and natural micro meteoroids. This list is incomplete due to the limited knowledge about micrometer sized space debris. This is caused by the fact that none of the measurement principles in use for the detection of micrometer sized particles yields complete information about a detected particle.

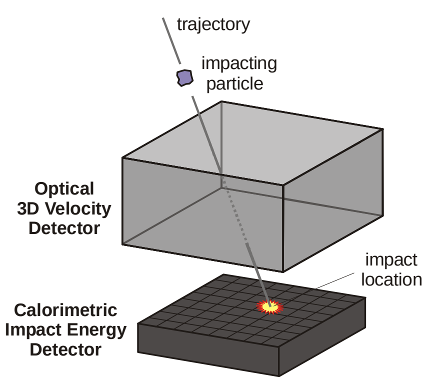

Figure 2. Principle of the fully integrated AIDA [8]

The analysis of retrieved space hardware provides only a mean value of impact rates over the mission, which is often a period of time of years. So the impact rates can neither be assigned to an orbital location nor to a specific time. At least this is the only method offering the chance for a chemical analysis of the particles chemical composition.

The in-situ detectors GORID [5] and DEBIE [10] log the impact's point in time, which allows the determination of the spacecraft's location, when the impact occurred. But detailed analyses of the results revealed these detectors' susceptibility to the space environment, i.e. effects of the Earth's radiation environment interfere with the sensors. Therefore a more robust measurement principle is strongly advisable.

For this reason the development of AIDA has been initiated. The fully developed AIDA sensor consists of an optical velocity detector and a calorimetric impact energy detector (Fig. 2). Both measuring principles are more appropriate for the space environment: The rapid changes in temperature used in the calorimetric impact stage have a much higher frequency than the expected temperature changes due to other effects, e.g. the spacecraft's cycle through sunlight and Earth's shadow. And for the optical velocity measurement, one important characteristic of laser light is its very small frequency bandwidth. This allows very effective filtering of possible interfering signals.

2. VELOCITY MEASUREMENT STAGE

Fig. 3 illustrates the principle of AIDA's velocity measuring stage which is based on a time-of-flight measurement.

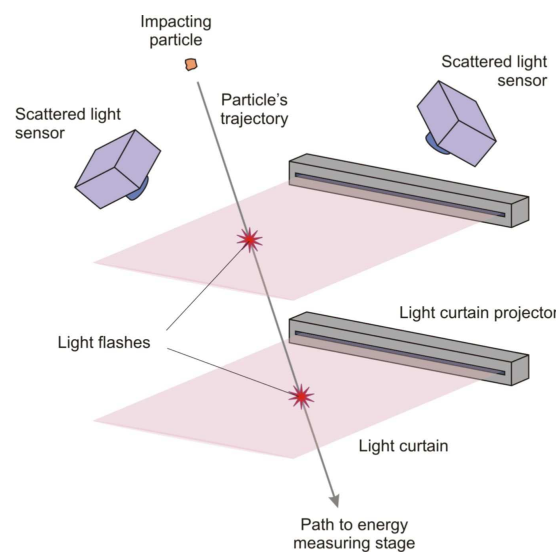

Figure 3. Principle of AIDA's velocity measurement [1]

The most important components are two laser light curtains formed by special optics. The resulting sheets of light have a thickness of approximately 1 mm. A particle passing through such a light curtain causes a flash of scattered light, which will be detectable by an arrangement of optical sensors. The position of the scattered

light flash will be determined by the principle of triangulation.
By measuring the time-of-flight needed to traverse both curtains as well as the positions of the two light flashes, the particle's speed vector and thus its orbital trajectory can be determined.

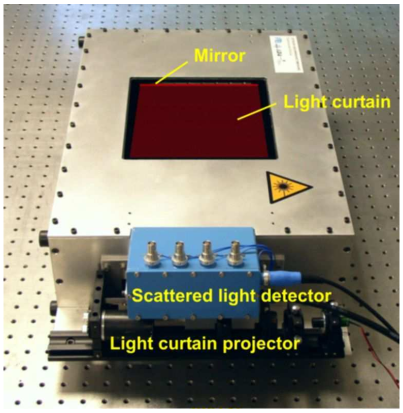

Figure 4. *Breadboard model of AIDA's velocity measurement stage*

The functionality of this measurement principle has been proven with a breadboard model depicted in Fig. 4. With this breadboard model, particles at 5.7 km/s were detected as well as particles with a diameter of 20 µm. Examinations of the measuring results revealed a theoretical capability of detecting particles with a diameter of 20 µm at 10 km/s.

3. CALORIMETRIC IMPACT DETECTOR

So far the development of AIDA's calorimetric impact detector is more advanced than the development of the velocity measuring stage. For the sake of simplification, AIDA's calorimetric detector will be referred just as AIDA in the following.

3.1. Measurement Principle

A sensor element consists mainly of an absorber sheet and a thermopile sensor (Fig. 5). The absorber sheet is made of gold and its precise geometric dimensions give a well defined thermal capacity. Each absorber is glued to a thermopile which is capable of measuring rapid temperature changes.

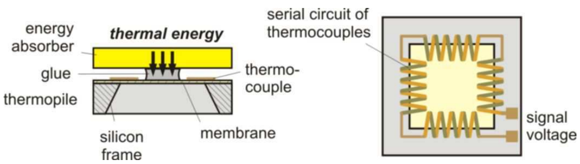

Figure 5. Principle of an AIDA sensor element

The kinetic energy of an impacting particle is transformed into a proportional rise of the temperature, which is measured by the thermopile.

A thermopile is a ring of thermocouples, which are placed on a silicon wafer by means of micro structuring technologies. They are serially connected to increase the ratio of temperature and voltage to a value of 13 mV/K [6]. A thermopile has a dimension of 3.6 x 3.6 mm^2. This size determines the theoretical spatial resolution of the impact detection.

3.2. System Design

The operability of the impact detector has been proven – also under space environment conditions – by a breadboard model [6]. Subsequently, a development model was successfully established [3, 8]. This development model provided important insights with respect to the necessary manufacturing processes. Parts of it will be reused in the development of further AIDA models, which also includes a qualified protoflight model. The most important aspects of the system design will be outlined in the following. The design has been established in two major steps:

1. Specification of the major design parameters, which are given by the requirements. This leads to the sensor's detection area, sensitivity, electrical parameters and the requirements for the housing design.
2. Design of the whole system, following the design parameters found in the first step. In this step the layout of AIDA's components (sensor module, housing, electronic board et cetera) is taken into consideration.

3.3. AIDA Major Design Parameter

AIDA is basically intended to be used as a piggyback experiment. This way it has the chance to be flown on many different missions and therefore to collect a lot of data to improve the knowledge about micro-sized particles. This intention gives the first limits for AIDA's design:

- Mass < 3 kg
- Power consumption < 5 W
- Sensitive area ~ 200 x 200 mm^2

AIDA's measurement principle still has to be verified on orbit. This is because the devices available for hyper velocity impact tests are not able to accelerate small particles to kinetic energies comparable to the kinetic energies expected in the space environment. So the calibration tests have been performed using laser pulses [6].

To verify the measurement principle in space, it is desirable to encounter as many impacts as possible. For this purpose, a high sensitivity of the detector is preferred, because the particle population increases rapidly with smaller particle size as depicted in Fig. 6.

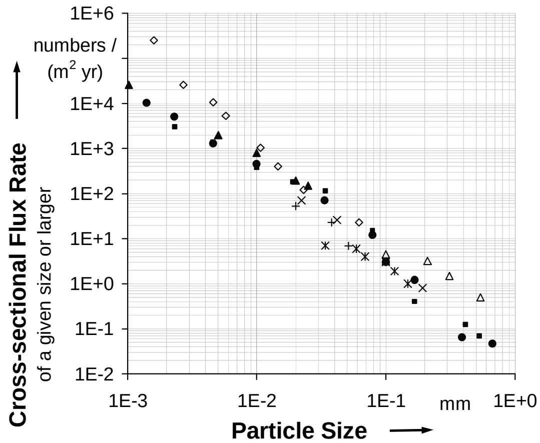

Figure 6. Particle population as a function of particle size in LEO, derived from various measurement data as indicated by the symbols [11]

But it is not advisable to design the sensor as sensitive as possible. The sensor's measurement range is given by two margins. The thermal noise of a series connection of thermopiles is

$$U_{eff} = \sqrt{4 \cdot k \cdot n \cdot R \cdot T \cdot B}\,. \qquad (3)$$

In this equation k denotes Boltzmann's constant (1.38 10^{-23} J/K), n the number of sensors in series, R the electrical resistance of a single thermopile sensor, T the temperature and B the noise bandwidth. This inevitable effect limits the detection sensitivity, i.e. the smallest detectable impact heat. A signal generated by an impact has to be clearly distinguishable from the thermal noise which scales with the sensor's temperature. Due to the given size of the absorber sheet squares, the sensitivity can only be adjusted by the thickness of the absorbers, i.e. the thinner the absorbers, the more sensitive the sensor is.

The thickness of the absorber sheet also determines the upper margin for detectable particles. Particles with a diameter exceeding approximately a third of the absorber thickness will probably perforate the absorber sheet. For a given absorber element area, the upper energy margin grows with the third power of the absorber sheet's thickness while the lower margin is proportional to this thickness. This means that the resulting measurement range increases with the thickness of the absorber sheet, while concurrently the sensitivity decreases. On the other hand, the measurement range becomes zero at some point, when perforation already occurs at the detection threshold. Fig. 7 shows these relations for the AIDA breadboard model design.

Taking this into account, there is no ideal solution for the thickness of the absorber sheet. Eventually a thickness of 20 μm has been chosen, because the on-orbit verification of the measurement principle has been prevailed.

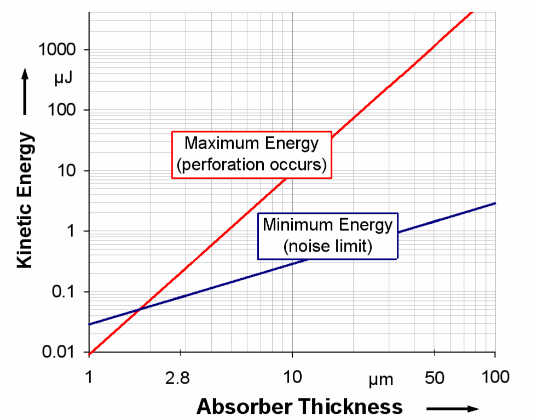

Figure 7. Sensitivity and measurement range depending of the absorber sheet thickness

3.4. AIDA Component Design

The AIDA component design is mainly determined by the fundamental design parameters outlined in the previous section. When not mentioned, the following sections describe the design parameters of the AIDA protoflight model whose development has been recently started.

3.4.1. Housing

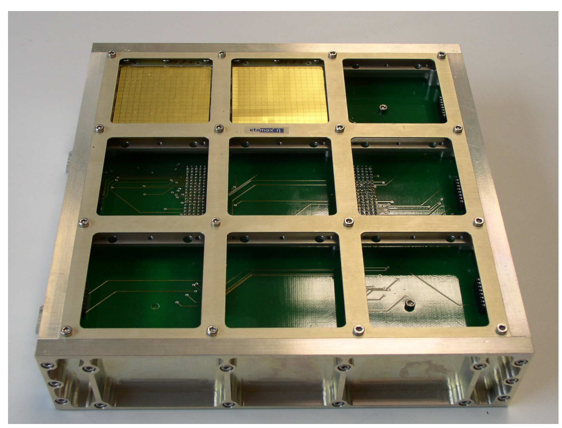

Figure 8. The AIDA DM with the ready to test housing

The housing shown in Fig. 8 has been designed for the development model (DM) of AIDA [8]. Following the model philosophy of the AIDA projects, it already has the final design intended to be used for the future protoflight model. This housing will be used for some pre-qualification testing and later for the STM (structural thermal model) and LM (laboratory model) as well. It has already passed first thermal analyses, which were performed to ensure the housing's applicability for the scheduled pre-qualification tests.

3.4.2. Thermopile Array

The applied thermopile array is based on the standard thermopile TS 100 by IPHT Jena. For the AIDA detector, the heating elements have been removed from the design. Several thermopile sensors have been already connected in series on the thermopile array chip in order to limit the number of channels. This serial connection and its consequences will be discussed in section 3.4.5.

3.4.3. Absorber Sheet

The absorber sheet will be manufactured from commercially available foils of gold. It is cut into small squares with an edge length of 3.6 mm to fit the structure given by the thermopile array (Fig. 9).

For better handling especially during the manufacturing of the sensor modules, these cuts are not complete and the absorber plates are kept connected at their very edges. This results in some cross talk between adjacent sensor elements. This effect will be used for plausibility checks of the detected impacts, i.e. an impact signal of certain attenuation must also be recorded by the neighboring sensor elements.

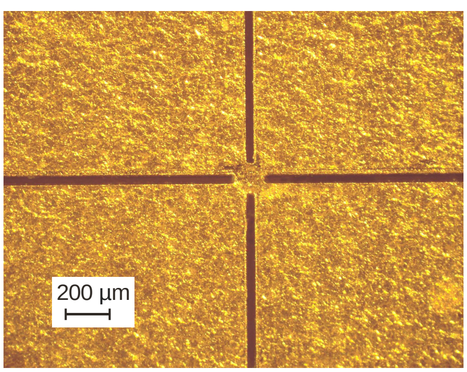

Figure 9. Microphotography of the structured absorber sheet [8]

3.4.4. Sensor Manufacturing

The manufacturing of the sensor modules, namely the adhesion of the absorber sheet onto the thermopile array, is still a challenge for three reasons:

1. The absorber sheet and the thermopile array, which consists mainly of silicon, have different coefficients of thermal expansion.
2. The thermopiles are very fragile at the area where the adhesion is applied. For a desirably low thermal capacitance, the thickness of the thermopile's membrane is only 3 µm.
3. The manufacturing process of the thermopile arrays inheres a deflection of about 50 µm. This is a result of the etching of material off the back side of the wafer. The deflection is in the order of the desired spacing between the absorber sheet and the thermopile array and requires special consideration in the joining process.

3.4.5. Electronic Design

Each thermopile array carries 256 single thermopiles. Thus, the 9 sensor modules of a fully equipped AIDA result in 2304 single thermopiles. A sensor with such a high number of measuring channels, each equipped with a dedicated amplifier, would be far beyond the margin of 5 W for the power consumption of the sensor. On the other hand, a spatial resolution of 3.6 x 3.6 mm^2 is not required. Therefore 32 single sensors are serially connected. To double the spatial resolution, the polarity of the thermopiles changes after every 16 elements. This circuit design, which is done directly on the thermopile array, allows the distinction of an impact location inside a measuring channel based on the sign of the signal. Concluding, a measuring channel consists of 32 single sensor elements and allows a spatial resolution of the impact location equivalent to 4 x 4 sensor elements corresponding to an area of 14.4 x 14.4 mm^2.

This design approach results in a source resistance of a measuring channel which is 16 times higher than the one of the first (breadboard model) design. The thermal noise, which is given by equation 3, therefore increases by a factor of 4, i.e. the detection threshold of this design is considerably higher than in the first AIDA version. However, this effect has been considered in the major design of AIDA (section 3.3).

3.4.6. Software

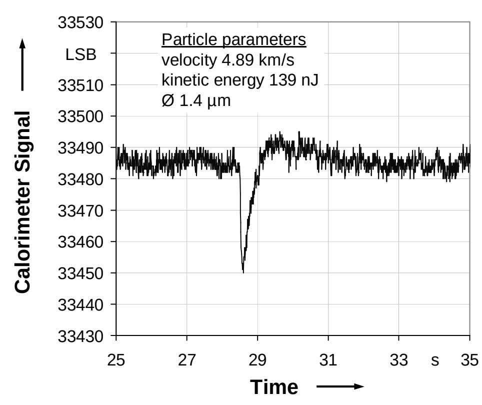

Figure 10. Impact signal [7]

The on-board software has a significant influence onto the data delivered by the detector for three reasons:

1. The decision whether an event is recorded or not has to be done by the on-board software.
2. The design of the other AIDA components is mostly determined by the major requirements. E.g. the maximum power consumption and the desired detector area result in the discussed number of measuring channels along with the discussed spatial resolution.
3. The on-board software is the only AIDA component, which can be adjusted or changed during a mission.

As a first result of the considerations regarding the software design, AIDA will record the full raw data (Fig. 10) of all measuring channels in case of an impact. This is possible due to the relatively small amount of data (approximately 15 kB) needed to record an impact. Furthermore it allows to check for reliability of the data as discussed in section 3.4.3.

The on-board calculation of the impact's energy is only foreseen as a fallback solution for situations, where the number of impacts either exceeds AIDA's memory capabilities or the bandwidth available for communication.

4. CONCLUSION AND OUTLOOK

The ongoing project has the goal to develop a protoflight model of the AIDA calorimetric detector stage. The next step would be the on-orbit verification of this novel measurement principle. This has to be followed by the same steps for the AIDA velocity measurement stage. Eventually a fully integrated AIDA shall be built which is ready to fly on various missions with the aim to contribute to the improvement of the models of micrometer-sized particles in the Earth's environment.

5. ACKNOLEDGEMENTS

The work described in this paper was conducted in the frame of the ESA GSTP programme with support from Germany and different former contracts.

Parts of the work described in this paper was funded by the German Ministry of Economics through the German Space Agency DLR, Support Code 50RM0702.

All mentioned contributions and the ones by the study teams are gratefully acknowledged.

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