IN-SITU TRAJECTORY MEASUREMENT OF SMALL PARTICLES

Bunte, K.D.[1], Fichna, T.[2], Herbst, C.[1], Lippmann, U.[3], Drolshagen, G.[4]

[1] *etamax space GmbH, Frankfurter Str. 3D, 38122 Braunschweig, Germany, Email: k.bunte@etamax.de*
[2] *IDA, TU Braunschweig, Has-Sommer-Str. 66, 38106 Braunschweig, Germany, Email: Fichna@ida.ing.tu-bs.de*
[3] *Fraunhofer IOF, Albert-Einstein-Str. 7, 07745 Jena, Germany, Email: Uwe.Lippmann@iof.fraunhofer.de*
[4] *ESA/ESTEC, Keplerlaan 1, 2200 AG Noordwijk ZH, The Netherlands, Email: Gerhard.Drolshagen@esa.int*

ABSTRACT

Models of the Earth's space debris and meteoroid environment need to be validated against measurement data such as the particle size, velocity and impact angle distributions. In particular the characteristics of the micron-sized particle regime is fairly unknown.

Based on the requirement to measure the trajectory of fast micron-sized particles in space, a highly sensitive breadboard model of a particle trajectory analyser was developed.

Basic requirements and considerations are outlined and the overall system design is described, which is based on the results of a numerical simulation of different configurations of the instrument. Some details of the optical, mechanical and electrical design of the instrument are given.

A description of the test method is provided, which was developed for the characterisation of the breadboard model's performance. The general performance and calibration testing approach is outlined.

1 INTRODUCTION

The validation of space environment models such as ESA's MASTER model is performed against measurement data, in particular in the small particles domain (less than 1 mm in diameter). As these particles cannot be detected by means of ground-based radar or optical observations, the most common method is the investigation of hardware retrieved from space such as the Hubble Space Telescope's solar arrays. Consequently, the available data is restricted to certain low altitudes and limited declination ranges, and there is no possibility to derive the exact location and time of an impact.

If deployed in an adequate number of suitable orbits, in-situ detectors might provide measurement data to fill the above mentioned data gap. In particular, the impact velocity vector will, in combination with the impact location, allow the determination of the trajectory of the impacting particle, which then easily would enable the discrimination between man-made particles and natural meteoroids.

The measurement of the velocity vector of such small particles however is a rather demanding task, and different approaches were discussed in the past. One suitable idea is to measure the impact velocity vector by means of an optical method as implemented for the GIADA experiment onboard the Rosetta spacecraft [1] [2] [3]. Also the AIDA (Advanced Impact Detector Assembly) development has considered an optical measurement method based on laser light curtains and scattered light detection [4] [5].

2 TOP-LEVEL REQUIRMENTS AND BASIC CONSIDERATIONS

The basic requirement for the development of a breadboard model of the trajectory analyser is the detection of very small particles down to a size of some microns in diameter by means of light curtains, where the measurement principle is the detection of the scattered light flashes generated by a particle passing the light curtains as schematically shown in Fig. 1.

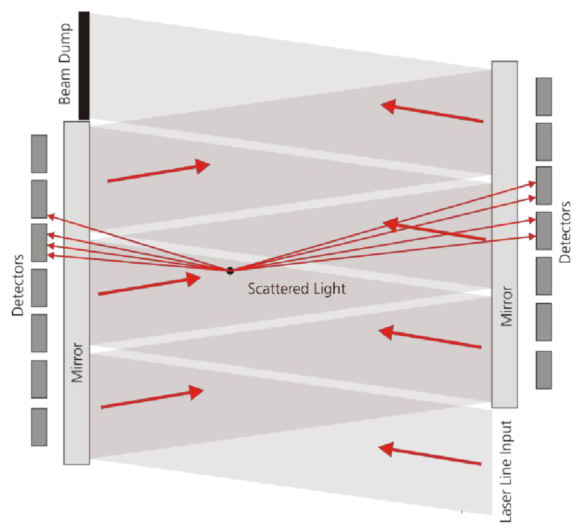

Figure 1. Schematic diagram of the detection principle

Two light curtain planes are needed for a time-of-flight measurement, and two light beam directions and detector arrays in each light curtain are required to resolve the coordinates of the particle's piercing points.

For the breadboard model development, the focus was put on the instrument's sensitivity rather than optimis-

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ing its mass and power consumption.

As no mechanical means exist to test the full measurement range of the breadboard model, an appropriate test method was developed as part of the breadboard model development.

3 SYSTEM DESIGN

As a first step, several aspects such as

- the intensity profile in the light curtains,
- the width of the light curtains,
- the beam arrangement including the number of reflections, transmission and beam shaping,
- the operational wavelength,
- the selection of the light detectors

were investigated in detail. Following the decision on the main system design, a numerical simulator was developed to assess the signals to be expected with different instrument layouts.

The numerical simulator uses the Mie-theory, which describes the diffraction of electro-magnetic rays by spherical objects with diameters in the range of the wavelength, to calculate the intensity field of the scattered light. Due to diffraction effects the maximum of intensity is in light direction (see Fig. 2, $\vartheta = 0$ deg).

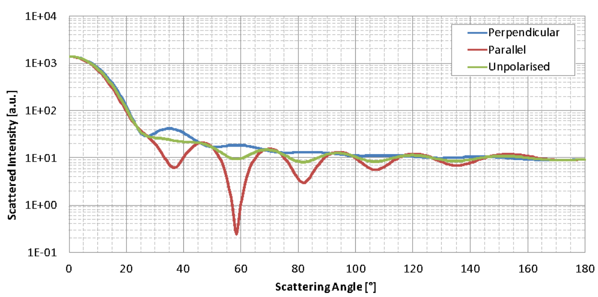

Figure 2. Scattered light intensity calculated with the Mie theory; maximum intensity in forward direction (particle size: 2 µm; different polarisation)

Consequently, the light detectors need to be placed accordingly to obtain maximum sensitivity.

The simulator also takes into account the following parameters:

- Number and position of the light detectors.
- Wavelength and light intensity of the light curtain.
- Piercing point of the particle.
- Amplification by means of electronics and collecting lenses.

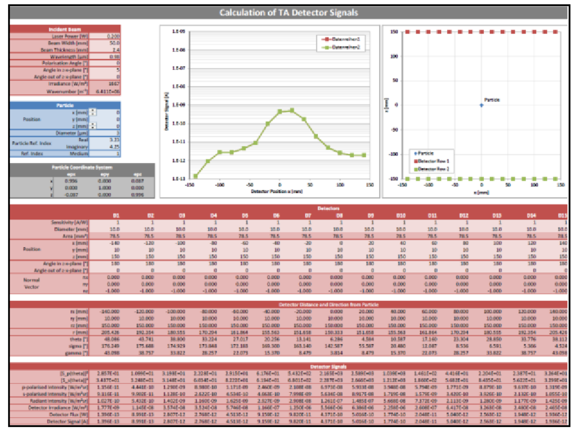

Figure 3. Calculation of the sensor signals using the simulation program

Based on the findings of the performed simulations, the system design of the instrument was detailed by means of the specification of the basic instrument parameters:

- Effective detection area: (300 mm)^2
- Laser light wavelength: 810 nm
- Light curtain thickness: 3.5 mm
- Distance between the light curtains: 160 mm
- Number of light sensors: 12 per sensor array

The first step of the design phase has to be the optical layout, as all dimensions depend on it, followed by the design of the instrument housing including all required baffles, mountings and adjustment devices.

The electronics design can be performed partly in parallel to the optical layout. The layout of the boards however has to consider the spatial constraints given by the optical and housing design.

4 OPTICAL DESIGN

The optical design was developed in the order, which follows the order of use:

1. Laser beams are shaped for the use in the light curtains.
2. These Laser beams are directed into the light curtains.
3. Particles passing the light curtains cause scattered light flashes, which will be detected by the light detectors.

4.1 Optical Design of the Light Sources

A laser beam usually features a Gaussian intensity profile. For the use in the light curtains one direction has to be shaped into a rectangular intensity profile, a so called “top hat” profile. A commercially available laser line module originally designed for the use in measurement applications, which evaluate the image of the laser line on the measurement object’s surface, generates the desired intensity profile.

A collimation optic consisting of two mirrors and a baffles shapes the laser beam for the use in the light curtain (see Fig. 4).

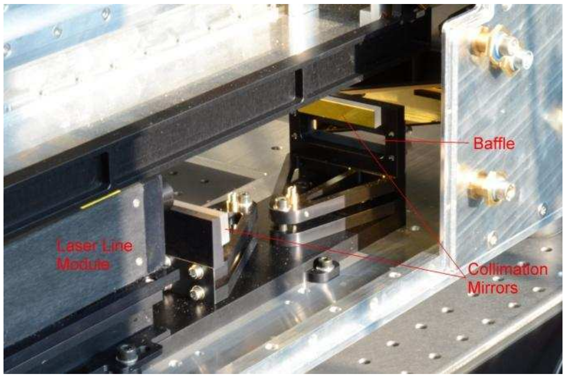

Figure 4. Laser line module with the collimation optic

When leaving the collimation optic the laser beam has a width of 50 mm, a top hat profile in this direction and a thickness of 3.5 mm ($1/e^2$). Since the light detectors have their sensitivity maximum at a wavelength of 900 nm, the wavelength of the laser line modules were chosen to be 810 nm. This value is the closest available and the light detector still feature 95% of their maximum sensitivity.

4.2 Optical Design of the Laser Light Curtains

To establish the light curtains out of the laser beams they are reflected into a zigzag pattern (see Fig. 1). This minimises the use of energy because one light source is sufficient for each light direction. However, this method brings up some design challenges:

1. For the highest possible reflectivity the mirrors are gold plated and do not feature an extra protection layer.
2. Due to the multiple reflections the mirror adjustment has to be very precise, i.e. 20 arc seconds.
3. The zigzag angle has to be taken into account for the determination for the piercing point.

The calculations by the simulation program showed the intensity of the light scattered by the light curtain mirrors is two magnitudes of order higher than the intensity of the particle's scattered light flashes. Because an interfering signal of this level cannot be suppressed by means of filters, it has to be eliminated by a baffle, i.e. the light curtain mirrors must not be visible at the detector's position (Fig. 5).

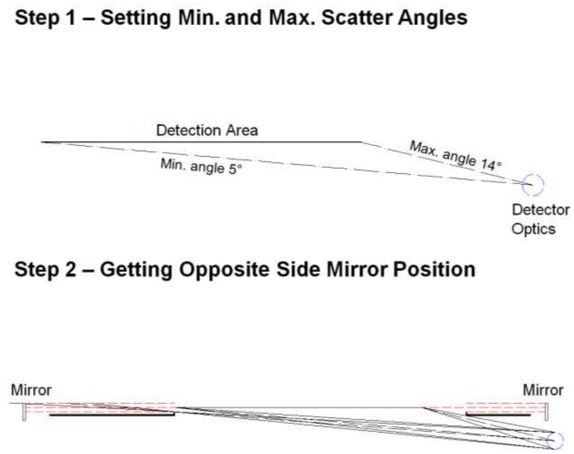

Figure 5. Design of the Main Baffles

Under the assumption that the detector optics shall view the scattered light flash under a minimum angle of 5 deg and a maximum angle of 14 deg, the positions of the main baffles are derived.

4.3 Optical Design of the APD Modules

To use the space beneath the required main baffles the light sensors are placed there. The scattered light flashes are reflected to them by passive reflectors. A further reduction of the instrument's size is achieved by an upside-down placement.

The optical components of the APD modules are (see Fig. 6):

1. An avalanche photo diode (APD), one of the most sensitive light detectors available. Compared to other sensitive light detectors it features mechanical and electrical characteristics best suited for the future use in space.
2. An optical filter. Only light with the lasers wavelength can pass it. It is required because a baffle design, which suppresses all external light, is not feasible.
3. A collecting lens for optical amplification of the scattered light flashes. An increasing diameter increases the amplification but decreases the APD module's field of view. For this reason the selected lenses are the result of an optimisation.

5 ELECTRICAL DESIGN

Particles passing the light curtains with a velocity in the range of some km/s cause electrical signals in the frequency range of some MHz, which requires digital electronics running with a frequency twice as high due to the sampling theorem. A fully equipped trajectory analyser consists of 48 APD modules and thus, processing of the resulting amount of digital measurement data would be a too demanding task for on single digital processing unit (DPU).

To cope with this, each of the APD modules (see Figure 6 6) consist beside its optical components (section 4.3) also of all electronic components required for the measurement signal processing:

1. Analogue amplifier and filter.
2. Analogue to Digital Converter (ADC).
3. A low level DPU which communicates via a digital bus with the central computer of the instrument.

By this design most of the signal processing is done by the APD modules, which deliver the digital signals of the detected scattered light flashes to the instruments central computer.

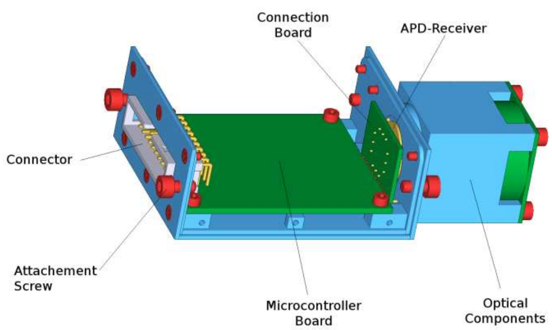

Figure 6. CAD drawing of the APD module

The central computer calculates the particle's velocity vector using the digital signals from the APD modules.

6 MECHANICAL DESIGN

The mechanical design should consider the trajectory analyser's applicability for future space use, i.e. it should be proven that using a limited mass the mechanical rigidity required for the space use could be achieved. For the trajectory analyser breadboard model, emphasis of the design was given to:

1. A flexible arrangement of the available APD modules, since 13 APD modules were manufactured for the breadboard model only. Nevertheless all of the required testing can be performed using certain test specific arrangements of the APD modules.
2. Easy access to the APD modules which supports the discussed flexibility.
3. Robust design for optical stability for effortless conduction of the test campaigns.
4. All optical components adjustable to provide the designed optical path.

Fig. 7 shows the breadboard model during its integration.

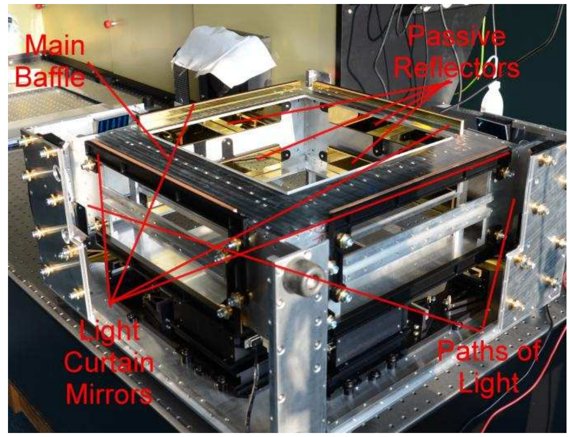

Figure 7. Integration of the Trajectory Analyser

It can be seen that an inner frame carries the main baffles and further optical components such as the passive reflectors and the light curtain mirrors. Other optical components (e.g. those forming the light paths) are mounted directly on certain outer housing panels.

7 BREADBOARD MODEL TESTING

7.1 Non-HVI Test Method

The reference speed of 10 km/s for small particles in the Earth's space environment is not available by means of mechanical experiments/assemblies:

1. A linear movement can be achieved only by hyper velocity impact (HVI) tests. However, existing HVI test facilities do not provide particles in the required mass and velocity ranges [4] [5].
2. A rotational movement would result in centrifugal forces some orders of magnitudes higher than tolerable by any known construction material.

Consequently, a test method without mechanical means has been developed.

The test device emits laser flashes. The profile of these laser flashes approximates the central maximum of scattered light flashes caused by particles passing the light curtain (see Fig. 8). The outer maxima of the scattered light flashes can be neglected, because their intensity is well below the detection threshold.

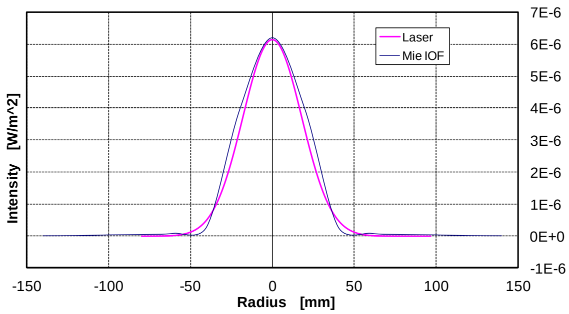

Figure 8. Intensity profiles of the test device and a scattered light flash (Mie-theory)

The dynamic of the light flashes emitted by the test device can easily be controlled by means of electronic laboratory equipment. By this means the test device is capable to stimulate the APD modules with light flashes equivalent to the scattered light flashes caused by particles passing the light curtain (see Fig. 9).

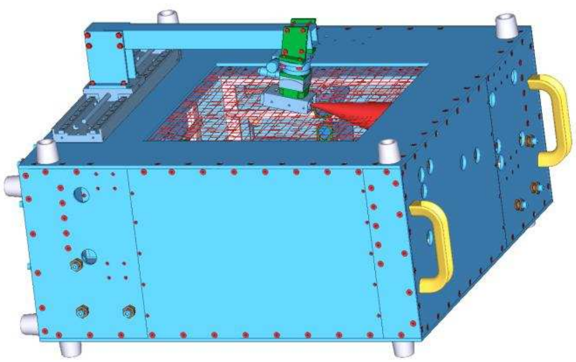

Figure 9. CAD drawing of the test device mounted on the operating TA

7.2 Calibration Testing

For these tests steel spheres with a diameter of 4 mm and a velocity of 120 m/s are used as test objects. This velocity is greater than the lower required detection threshold of 100 m/s.

The diameter of the test objects is above the aspired measurement range, but it is much easier to accelerate objects at this size to such velocities than particles with the size of some microns [4]. The measurement results obtained this way are used to calibrate the non-HVI test method by comparison.

Despite the limitations named above, HVI testing is a valuable method to calibrate in-situ detectors. Thus, it is planned to perform HVI calibration tests with micron-sized particles, if the non-HVI tests will show that the trajectory analyser breadboard model will be able to detect such small particles.

7.3 Performance Analyses

In order to determine the coordinates of the particle's piercing point on the laser light curtain, an evaluation of the available APD detector signals is required. Based on the simulator software (cp. chapter 3), an algorithm was developed, which allows the computation of the piercing point coordinates from those APD signals, which are above the detection threshold.

Once the calibration of the trajectory analyser will be completed, the resulting data will be used for the coordinate determination.

The simulator will allow to analyse in depth the performance of the trajectory analyser breadboard model with respect to the particle size and velocity ranges.

8 SUMMARY AND CONCLUSIONS

A breadboard model of a particle trajectory analyser based on an optical detection method was developed with the aim to analyse the possibilities and limits of the in-situ measurement of the impact velocity vector of very small particles. Thus, the design focus was put on a high sensitivity of the instrument rather than on the volume, mass and power minimisation.

To fully characterise the instrument's behaviour and performance, a test method was developed, which is based on light flashes simulating the scattered light flash of a particle, which passes a laser light curtain.

The result of the development is a highly sophisticated instrument, which will allow to answer the question about the performance and the resource requirements of the in-situ particle trajectory measurement by means of light curtains and scattered light flash detection.

Comprehensive testing of the breadboard model is ongoing and will be followed by the identification of improvement areas and by the optimisation of the volume, mass and power consumption. Based on these findings, a flight model design for the particle trajectory analyser will be proposed.

To establish a full in-situ detector for small particles, the trajectory analyser will have to be combined with an appropriate impact stage, which measures the particle's energy or momentum. A possible candidate would be the AIDA impact stage, which determines the particle's kinetic energy by means of a calorimetric measurement principle [5].

9 ACKNOWLEDGEMENTS

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