A Microparticle Recognition Experiment for Near-Earth Space On Board the Satellite ASUSat 1

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Abstract

The Microparticle Recognition Experiment (MRE) under development for flight on the ASUSat 1 mission to measure the flux, mass, velocity, trajectory and temperature of near-Earth microparticles is discussed. A parabolic PVDF copolymer array sensor with particulate position detection capabilities is employed to distinguish between natural particles and orbital debris in low-Earth orbit. Measurements will cover the particle mass range ~ 2×10^{-12} g (2 µm diameter) to ~ 1×10^{-2} g (1mm diameter) with an expected mean error in particle trajectory ± 7 degrees. ASUSat 1 is a 10 LB class microsatellite under design and development by students at Arizona State University. Mission characteristics include a 98°, 6am-6pm sun-synchronous polar orbit at 450 km altitude. It has a mission duration of 2 years and an anticipated launch date in early 1996 by Orbital Sciences Corporation¹.

Nomenclature

Α	area of depolarization
с	volume specific heat
С	electric charge Coulomb
e	particle emissivity
Е	energy
J	Joule
Κ	temperature Kelvin
L	PVDF thickness
m	particle mass
MeV	Mega-electron volt
Ν	depolarization signal charge
p	pyroelectric coefficient
P	magnitude of volume polarization
PIN	input power
Q	pyroelectric signal charge
r	distance from center of Earth
S	particle cross section
Т	temperature
v	particle velocity
α	mass index
ß	velocity index
ε	dielectric constant
ρ_{ATM}	atmospheric density
σ	Stefan-Boltzman constant

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1. Introduction

1.1 Asteroidal Particles

One of the outstanding problems in solar system science is the source of particles that constitute the zodiacal cloud. The detection of particle trails along the paths of active comets and particle bands in the main asteroid belt suggests that both regions contribute to this structure. However, the relative proportions of the contributions from each region have not been established. In 1983 the Infrared Astronomical Satellite (IRAS) discovered circumsolar near-ecliptic bands of particles in the zodiacal $cloud^2$. Investigation of the orbital evolution of these particles revealed that the Earth might be embedded in a ring of interplanetary particles in resonant lock with our planet³. The structure of this ring (Fig. 1), produced by resonant trapping, has been estimated from numerical calculations⁴ and shows the heliocentric ring of planetary particles corotating with the Earth. Fig. 2 displays the ring at a higher resolution. On this scale the eccentricity of the Earth's orbit is apparent and the Earth's path in the corotating frame is depicted by the small 2:1 ellipse. The importance of this "leading-trailing" asymmetry of the zodiacal cloud is two-fold. First the existence of the ring strongly suggests that large (diameter $> 12\mu$ m) interplanetary particles (or particles with low orbit eccentricities) are transported to the inner solar system by drag forces^{4,5}. Secondly, most particles that are trapped in terrestrial resonance are released from their lock through close encounters with the Earth. This leads to a yearly variation in the flux ratio and a high probability of these particles encountering the Earth at certain times of the year 4,5. Both of these effects are predicted to be maximized around September to October when the Earth is closest to the trailing cloud⁴. Thus, the ring may act as a funnel through which these interplanetary particles are deposited in near-circular orbits into the Earth's upper atmosphere. Initial indications of these orbits are consistent with those of an asteroidal source⁶, a low inclination of I = 0 to 30°. Larger particles (> 12) um) from the same source are also expected to be in similar orbits. Further studies are needed to determine the true origin of these particles. Low-Earth near-exosphere orbits of low inclination should be searched for annual variations in the deposition

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1) Identify the periodic flux and particulate composition of the zodiacal cloud from low-Earth orbit interplanetary particles.

2) Determine and analyze the spatio-temporal effects of space debris in LEO.

3) Establish the orbital parameters of IDP's in low-Earth orbit and determine their source of origin.

<u>2. MRE</u>

2.1 Impact Rates

The MRE sensor has an overall depth of 12cm, a diameter of ~29cm, and a total surface detection area of ~660cm oriented in the path of the velocity vector (Fig. 3). Anticipated impact rates, based on data returned from LDEF's only active experiment $(IDE)^{15}$ and as a function of surface area, reveal a predicted mean flux of ~9 impacts per day with a peak flux of ~135 impacts per day. The MAP experiment²⁰ aboard LDEF indicated an average particle density of \sim 7.9gm/cm³ with a mean diameter of $< 20\mu m$. This compares roughly with the particle size range of silt ~2-50µm with a density similar to that of stainless steel. The sensor arrays are passive and operate independently of ground control. The MRE's continuous monitoring and low storage requirements maximize data return for its 2 year mapping and reconnaissance mission.

2.2 IR Detection

Perhaps the most unique aspect of the MRE is its microparticle classification capability which employs PVDF sensors to detect the impacting particle's thermal infrared radiation. It is now known that the Earth's atmosphere provides the dominant perturbing force on particles in LEO and creates a sink for orbital particles²¹. This aspect has been neglected in almost every paper and article dealing with microparticles or IDP's and has a rather profound impact upon previous conclusions and analyses. Orbital lifetimes depend to a considerable extent on the atmospheric density profile, and thus on solar activity, and it is only above 500 km altitude in the case of low solar activity, and 700 km for high, that particles are able to complete a significant number of orbits, or to have a significant lifetime²¹. At the mean altitude of LDEF, approximately that of ASUSat 1, a significant number of particles will have lifetimes of less than 1 day, and in a number of cases even less than 1 hour. Estimates of microparticles in Earth orbit represent only 10% of the total near-Earth microparticle population. These conclusions suggest that ~90% of the population under 500 km altitude



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are spiraling in towards the Earth with drastically shortened lifetimes. Higher velocities, and a wider dispersion of trajectories, than originally expected must now be taken into consideration for sensor design.

When this information is considered it becomes evident that determining a particle's velocity, mass, and trajectory could be insufficient to identify the particle's source of origin. Exaggerated velocities and altered orbital parameters, created by the LEO sink, could lead investigators to anomalous conclusions. For this reason the added dimension of particulate identification through thermal IR sensing may prove to be extremely useful.

Interplanetary dust particles are characterized by chondritic composition and can be divided into two principle groups, anhydrous and hydrated²². The hydrous group is dominated by lattice layer silicates: primarily Smectite, Serpentine, and Cronstedtite. The anhydrous silicates consist mostly of Pyroxene or Olivene with smaller contributions from Fassaite and Diopside. Each IDP, due to chemical composition, has its own unique emissivity value and therefore each microparticle class has its own unique temperature range particular to its composition. Through quantitative analysis, the particulate temperature data provided by the MRE should reveal basic segregated groupings separated by compositional structure, that when evaluated with the velocity, trajectory, and mass data, should provide a strong indication of the microparticle's source of origin.

3. PVDF Film Sensors

3.1 Pyroelectric Properties

The pyroelectric detection of infrared radiation (IR), with wavelengths longer than ~ 2.5 μ m, has become an important technology area over the last few years with the development of new ferroelectric materials playing a major role in improving IR device characteristics²³. The pyroelectric effect is the change in polarization with temperature which occurs in any polar material. Ferroelectrics generally exhibit the strongest pyroelectric effects and IR sensors using them offer a number of advantages over competing technologies using semiconductors. They will work at ambient temperature unlike long wavelength photon detectors using, for example, mercury cadmium telluride which needs to be cooled to 77K in order to achieve its best performance²³. Ferroelectrics are also broadband devices which need simply to absorb the energy of the radiation. This can be accomplished either intrinsically or via an

absorbing layer deposited on the surface of the detector element. The absorbed energy causes a temperature change in the element which releases a detectable electronic signal. Of particular interest are pyroelectric polymers and copolymers which detect in the IR (8 to 14 μ m) range. This covers a transmission window from ~ 200K to 400K and is therefore well suited for detecting microparticles in low-Earth orbit which reradiate their energy in exactly this wavelength range²⁴. Polyvinylidene Fluoride (PVDF) film detects changes in the temperature of the material. This effect is timedependent and it is necessary to modulate the source of energy in order to make the pyroelectric sensor work. However, this property can be used to our advantage. If an IR detector of this nature were to be used in a static scene, such as inside an enclosure, it would efficiently detect any incident radiation. Specifically, the static nature of the MRE enclosure is an ideal setting for optimizing the IR detecting properties of PVDF or the copolymer P(VDF 0.7-TRFE 0.3).

3.2 Polyvinylidene Fluoride Film

In 1969 the piezoelectric and pyroelectric properties of PVDF were discovered²⁵. Polyvinylidene Fluoride is a semi-crystalline polymer (50% crystalline, 50% amorphous) that through treatment becomes piezoelectric. This is accomplished by stretching and polarizing the material until the dipoles achieve a preferred orientation along a line perpendicular to the film and thus obtains a stable macroscopic polarization. The piezoelectric effect occurs when an external mechanical force acts upon the film. This compresses the PVDF in certain directions which induces an electric polarization (and a corresponding voltage) due to the displacement of charged atoms along the same $axis^{25}$. This voltage is directly proportional to the amount of strain. These charges are measured on the electrodes of the sensor and are transformed into a voltage signal. This development was further stimulated by the discovery that the copolymer trifluoroethylene TRFE possesses even more enhanced piezoelectric properties than PVDF. PVDF film is flexible, extremely light, and has a plastic toughness. It has a good response in temperature ranges from -50°C to 100°C. PVDF is resistant to most chemical substances, is not sensitive to radiation under 10^7 RAD's, and is unaffected by high background fluxes of nuclear charged particles. It is easy to cut (available in thicknesses of 9-800 µm) and can be shaped to produce any required geometry or laminate. Electrodes can be attached using standard methods, i.e. vacuum deposition.

4. Basic Design

4.1 Peripheral Sensor

The initial event sensor has a series of PVDF infrared (IR) thermally conductive elements configured into a segmented planar array that are employed as a peripheral intercept of the incident microparticles. This segmented network detects the particle's thermal radiation as it passes through a - 5µm thick gold foil, onward through the IR sensor, and into the MRE enclosure. The gold foil helps to maintain the static environment required in the enclosure while reducing the MRE's ambient temperature. The pyroelectric charge induced by the particle's close proximity to the PVDF sensor enables position detection for trajectory determination and also triggers a time stamp for starting "time of flight" (TOF) initiation for velocity measurements. Fig. 4 depicts the peripheral sensor with the exterior overlay of gold foil. Fig. 5 depicts the interior segmented cells with the foil removed. The PVDF IR thermally conductive grid array is configured parallel and adjacent to the exterior gold foil.

4.2 Parabolic Sensor

The secondary event sensor has a series of PVDF segmented elements which emphasize both the piezoelectric and pyroelectric effects. Subsequent to initial peripheral detection, the microparticles then impact upon the interior walls of the paraboloid. This induces both mechanical to electrical and pyro to electrical properties within the same waveform which are discriminated and channeled into post impact A hypervelocity microparticle amplification. impacting upon a PVDF sensor also creates a charge pulse due to a third property discovered by the University of Chicago referred to as depolarized induced signals²⁶⁻³⁰. The impactor creates a local depolarization which occurs rapidly throughout a volume of film approximately equal to that of the incident particle. This results in a very fast (nanosecond range) charge pulse in the external circuit and provides a relative mass determination technique. The charges induced in the parabolic sensor array also supply: position coordinates that allow for completion of trajectory determination, velocity measurements through a second time stamp indicating the end of TOF, and particulate temperature characteristics.

4.3 Acoustic Vibration Sensor

An isolated acoustic vibration detector is employed to record any acoustic impulses that the MRE sensors might encounter. This detector is protected from particle impacts and is used to help



Fig. 4 Peripheral Sensor (Exterior): Gold foil overlay maintains a static environment while reducing the ambient temperature of the enclosure.



Fig. 5 Peripheral Sensor (Interior): Infrared, thermally-conductive, open elements create a pyroelectric charge when subjected to a particle's radiation at close proximity. discriminate anomalous signals from the particulate data.

4.4 Position Detection

As previously stated the MRE is capable of trajectory determination which is accomplished through position sensing cells. Each cell segment, located in the planar open cell peripheral array and the internal parabolic closed cell array, is electronically connected in a cross grid series pattern (Fig. 6). This ultimately provides two sets of X, Y inputs into the charge sensitive culminator board (CSC). The CSC board's function is to determine which input line is carrying the charge load, output the identified grid element number, and channel the charge into the amplification network. Trajectory is then determined by a predefined Data Analysis algorithm. This equation is used after analyzing the downlinked data, with the MRE coordinates, and correlating the particle's encounter time stamp with the satellite's actual position. This position detection system exceeds the accuracy obtained by the less precise resistive array models 29 due to the absolute determination of the activated grid element. The MRE is accurate to within a $\pm 2.5\%$ instrumentation error on trajectory measurements. This value is determined worst case and is based on a 12cm flight of a microparticle between two parallel 2.5 cm² cell segments within a 360° plane.

5. Theory

5.1 Pyroelectric Theory

To demonstrate the pyroelectric and local depolarization induced signals a single PVDF cell element will be considered (Fig. 7) which will illustrate the dynamic response for the case of an incident microparticle. The pyroelectric and piezoelectric response of this sensor is a result of the dependence of P on temperature and strain²⁶⁻³⁰. An externally induced change in either (or both) of these parameters will change P, which will result in a current in the external circuit. The time integral of this current results in a signal charge ΔQ on the electrodes. If a pulse of energy ΔE is absorbed by the sensor at time t = 0, the sensor will achieve a temperature T = T₀+ T(∞) after a period of time where

$$\Delta T(\infty) = \Delta E / (cAL) \tag{1}$$

As a result of the temperature change, a signal charge $\Delta Q(\infty)$ will be detected at the circuit given by

$$Q(\infty) = [P(T_0 + T(\infty)) - P(T_0)]A$$







Fig. 7 Schematic drawing of a polarized PVDF sensor. The sensor film, of thickness L, has a volume polarization P as shown. An incident hypervelocity particle penetrates the sensor, resulting in irreversible depolarization along the particle track. The impact generates a fast current pulse in the external circuit which is analyzed for mass and orbital parameter determination. Courtesy A. Tuzzolino et al. Univ. of Chicago (1991) the interior surface of the parabolic sensor. Upon impact a second set of X, Y position coordinates, and a TOI signal, are generated along with the particle's thermal IR signature. Time of flight can then be determined by subtracting the original 1st generation TOI's from the 2nd generation TOI's. Velocity can then be calculated with a medium dampening constant to allow for velocity loss during points of impact. Trajectory, or angle of incidence, is calculated through the vector drawn by the particle between the 1st and 2nd generation grid coordinates. The particle shape is statistically insignificant in determining the orbital path due to quantitative analysis of the results. However, the entire infrastructure is optimized to reduce particle deformation and fragmentation, since qualitative data are dependent on constraining the incident angle. ASUSat 1's angle of inclination directs the MRE through a substantial number of particles at a 5-40° angle (with respect to the plane of the satellite's leading edge) to the particle's velocity vector. Investigations have shown that data received from PVDF instruments involving angles $<45^{\circ}$ (with respect to the plane of the instruments surface) becomes increasingly unreliable while the degree of particle fragmentation becomes proportionally unpredictable³⁰. In order to compensate for this asymmetry, we have designed a position sensing parabolic detector that reduces the severity of the incident particle's encounter angle. The parabola maintains a maximum surface area normal to the particle's encounter, thereby reducing fragmentation, improving reliability, and minimizing data loss.

8. Data Analysis

All information obtained by the MRE will be downlinked to a data reduction and scientific analysis center. Each waveform, and every point sampled therein, generated from an impact event can be displayed and graphed for analysis. Mass, velocity, and composition determined from these waveforms will be added to each particle's dataset. The entire dataset from the 2 year mission will be stored in an event specific database. Software designed exclusively for image simulation and data display will be used to construct a three dimensional spacetime dependent map of the entire near-Earth space exosphere. Initially a spherical distribution of the entire particle encounter history will be displayed with each impact event represented by a point superimposed over the Earth. Areas of interest can be further investigated through a second window activated by locating the cursor over the target area. This new screen will graphically display the trajectory of each particle selected with the number of particles depicted controlled by the user. The numerical values for the orbital parameters can be displayed for each particle at the user's discretion. Also, since the entire dataset is stored in a database, any correlation wishing to be explored can be examined. This is accomplished by constructing an image and numerical display based on any of 10 dataset and sorting parameters: mass, size, velocity, trajectory, temperature, coordinates, time, orbit number, multi-orbit and seasonal encounters, and chemical composition.

9. Conclusions

The MRE is capable of obtaining valuable scientific data on all three mission objectives. The data obtained will enable the determination, in part, of the flux rate, mass, velocity, and trajectory of the incident microparticles. The orbital parameters are added to the database established by the individual thermal IR signatures. Finally, the basic segregated groups, separated by compositional structure, are analyzed to establish the microparticle's source of origin. The information received from the MRE is of multidisciplinary interest, providing valuable data for those involved in meteoric, asteroidal, cometary, and debris particle research. The MRE provides a versatile means of particle detection and establishes the first comprehensive microparticle recognition experiment in near-Earth space. ASUSat 1, with the Microparticle Recognition Experiment, becomes the first 10 LB class satellite to gather both quantitative and qualitative scientific data and collectively represents a revolution in scientific instrumentation and satellite design.

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