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CALIBRATION OF THE DUST FLUX MONITOR INSTRUMENT (DFMI) FOR THE *STARDUST* MISSION TO COMET WILD-2

A.J. Tuzzolino[1], R.B. McKibben[1], J.A. Simpson[1], J.A.M. McDonnell[2], M.J. Burchell[2], S.F. Green[2], N. McBride[2], B.A. Vaughan[2], J.C. Zarnecki[2], P. Tsou[3], M.S. Hanner[3], B.C. Clark[4] and D.E. Brownlee[5]

[1] Laboratory for Astrophysics and Space Research, Enrico Fermi Institute, The University of Chicago, Chicago, IL 60637, USA
[2] Unit for Space Sciences and Astrophysics, School of Physical Sciences, University of Kent, Canterbury, Kent CT2 7NR, U.K.
[3] NASA, Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91109, USA
[4] Lockheed Martin Associates, P.O. Box 179, Denver, CO 80201, USA
[5] Department of Astronomy, University of Washington, Seattle, WA 98125, USA

THE DUST FLUX MONITOR INSTRUMENT (DFMI)

THE DUST FLUX MONITOR INSTRUMENT (DFMI) is part of the STARDUST instrument payload. The prime goal of the DFMI is to measure the particle flux, intensity profile and mass distribution during passage through the coma of Comet Wild-2 in 2004. This information is valuable for assessment of spacecraft risk and health, and also for interpretation of the laboratory analysis of dust captured by the Aerogel dust collectors and returned to Earth. At the encounter speed of 6.1 km/s, the DFMI measurements will extend over the particle mass range of 8 decades, from 10^{-11} to > 10^{-3} g.

The DFMI consists of two different dust detector systems — a polyvinylidene fluoride (PVDF) DUST SENSOR UNIT (SU), which measures particles with mass < ~ 10^{-4} g, and a DUAL ACOUSTIC SENSOR SYSTEM (DASS), which utilizes two quartz piezoelectric accelerometers mounted on and behind the spacecraft Whipple dust shield to measure the flux of particles with mass > 10^{-4} g. The large Whipple shield structures provide the large effective sensitive area required for detection of the low fluxes of high-mass particles.

A detailed description of the DFMI has been published (Tuzzolino et al., 2000). Here, we summarize the main portions of the instrument which consists of a PVDF dust SENSOR UNIT, two acoustic sensors (A1 and A2) and an ELECTRONICS BOX (EB), as shown in **Figure 1.**

The SU is mounted on the front of the first layer of the dust shield, which is a composite honeycomb structure known as the Bumper Shield. Detector A1 is mounted on the back of the Bumper Shield in the location shown. Detector A2 is mounted on the front of the second shield, a NEXTEL fabric layer to which is attached a thin carbon-fiber composite sheet, called the Acoustic Plate. The various mounting positions of the sensors and EB are shown in **Figure 2**.

We also present here a description of the calibration parameters for the dust SENSOR UNIT that permit determination of the particle flux and mass distribution from the data obtained from the DFMI during flight. Calibration parameters for the DASS sensor system will be submitted by the group at the University of Kent, Canterbury, the U.K., at a later date.

1. OBJECTIVES OF THE DFMI

The prime scientific objective of the DFMI is to carry out quantitative measurements with the DFMI PVDF sensors of particle impact rate and particle mass distribution throughout the flyby of Comet

WILD-2. The DFMI data are fundamental for establishing the physical processes of dust emission from the nucleus, their propagation to form a coma, and the behavior of dust jets. The particle mass range covered by the PVDF sensors at the 6.1 km/s impact velocity at comet encounter ranges from 10^{-11} - 10^{-4} g for differential and cumulative flux measurements and > 10^{-4} g for cumulative flux measurements.

The acoustic sensors mounted on the spacecraft shield are intended to provide particle flux data for larger mass particles which, given the relatively small sensitive area (220 cm^2 total) of the PVDF sensors, would have fluxes too low to expect impacts on these detectors. By mounting the acoustic sensors to the much larger area Bumper panel (~ 0.7 m^2) and Acoustic plate (~ 0.5 m^2), the area factor for detection of the larger particles is greatly increased. One acoustic sensor (A1) will detect large particles that impact the Bumper panel. The other acoustic sensor (A2) will detect only those particles with sufficiently higher mass to penetrate the Bumper panel and impact the Acoustic plate (see **Figure 1**). While the sensitive area for these detectors is essentially the area of the shield panels -- and thus much larger than the PVDF area -- because of the uncertainty of the impact location with respect to the DASS sensors, the information concerning particle mass available from the DASS sensors will be much less accurate than that for smaller particles from the PVDF sensors.

2. DFMI ELECTRONICS, DIGITAL DATA AND COMMANDS

Figure 3 shows a block diagram of the principal electronic functions of the DFMI, showing the two independent dust sensor systems — the PVDF DUST SENSOR UNIT (SU), and the DUAL ACOUSTIC SENSOR SYSTEM (DASS).

The DFMI linear electronics for the PVDF sensors consists of charge sensitive preamplifiers (CSA), shaping amplifiers (SHAPER) and threshold discriminators. Each SHAPER provides single integration - single differentiation RC shaping with a shaping time constant of 2µs. A particle impact on either the large or small PVDF sensor will result in output signals (**Figures 4b - 4e**) from the shapers which may trigger the M1, M2, M3, M4 thresholds for the large PVDF sensor, or the m1, m2, m3, m4 thresholds for the small PVDF sensor. As a contingency, the m1-m4 electronic thresholds may be increased by a fixed factor (~ factor 10) by ground command, which would activate a mass THRESHOLD SWITCH for the small sensor.

The DFMI linear electronics for each of the acoustic sensors consists of a wide-band amplifier which increases the output signal from the acoustic sensor internal amplifier by a factor 20. This amplified signal feeds discriminators set at 0.1 volts and 1.0 volts, respectively. Each of the discriminators feed a ONE SHOT having a time width of 0.5 ms (T1) and 0.2 ms (T_2), respectively.

Each of the PVDF sensor discriminator outputs M1-M4, m1-m4, will increment a 16 bit counter, and each acoustic sensor ONE SHOT outputs, A1a, A1b, A2a, and A2b, will increment 8-bit counters. The basic DFMI data packet consists of 12-16 bit words as listed in **Table 1.** To this basic DFMI data packet, the spacecraft shall append the S/C clock, SC attitude, position and velocity and DFMI EB and SU temperatures.

Table 1

16 BIT WORD	BYTE NUMBER LSB MSB
SYST	Byte 1 and 2
CLK	Byte 3 and 4
Acoustic Sensor Counting Rate Channels	
A1a, A1b	Byte 5 and 6
A2a, A2b	Byte 7 and 8
Dust Sensor Counting Rate Channels	
M1 (mass ≥ 8.5×10^{-8} g)	Byte 9 and 10
M2 (mass ≥ 1.7×10^{-6} g)	Byte 11 and 12
M3 (mass ≥ 1.4×10^{-5} g)	Byte 13 and 14
M4 (mass ≥ 1.5×10^{-4} g)	Byte 15 and 16
m1 (mass ≥ 9.8×10^{-12} g)	Byte 17 and 18
m2 (mass ≥ 1.2×10^{-10} g)	Byte 19 and 20
m3 (mass ≥ 4.3×10^{-9} g)	Byte 21 and 22
m4 (mass ≥ 6.3×10^{-7} g)	Byte 23 and 24

SYST: Byte 1 contains the DFMI status and Byte 2 is the fixed DFMI sync pattern (A5 hex = 165 decimal)
CLK: Bytes 3 and 4 contain the 16 bit roll over seconds DFMI counter
A1a,A1b: Bytes 5 and 6 contain the two 8 bit counters for the two thresholds for the BUMPER acoustic sensor. Byte 5 is the lowest threshold
A2a, A2b: Bytes 7 and 8 contain the two 8 bit counters for the two thresholds for the NEXTEL (Acoustic Plate) acoustic sensor. Byte 7 is the lowest threshold
M1: Bytes 9 and 10 contain the running sum of the 16 bit counter for the 1st (lowest) large sensor threshold M1.
M2: Bytes 11 and 12 contain the running sum of the 16 bit counter for the 2nd large sensor threshold M2.
M3: Bytes 13 and 14 contain the running sum of the 16 bit counter for the 3rd large sensor threshold M3.
M4: Bytes 15 and 16 contain the running sum of the 16 bit counter for the 4th large sensor threshold M4
m1: Bytes 17 and 18 contain the running sum of the 16 bit counter for the 1st (lowest) small sensor threshold m1.
m2: Bytes 19 and 20 contain the running sum of the 16 bit counter for the 2nd small sensor threshold m2.
m3: Bytes 21 and 22 contain the running sum of the 16 bit counter for the 3rd small sensor threshold m3.
m4: Bytes 23 and 24 contain the running sum of the 16 bit counter for the 4th small sensor threshold m4.

The basic calibration for the DFMI PVDF sensor and electronics consisted of determining the electronic thresholds required which would correspond to our choice for the particle mass thresholds M1-M4, m1-m4. The particle mass thresholds we have chosen are listed in **Table 1**, and in **Table 3** we show the required electronic thresholds corresponding to our chosen mass thresholds.

3. DUST PARTICLE CALIBRATION

Particle calibrations of DFMI-type PVDF sensors (28µm and 6µm thick) were carried out by the University of Chicago group at the Heidelberg and Munich dust accelerator facilities, as summarized in **Table 2** (Simpson and Tuzzolino, 1985; Simpson, Rabinowitch and Tuzzolino, 1989). The characteristics of the Heidelberg and Munich accelerators are such that the highest particle mass we could measure at the Heidelberg facility was ~ 1.8 x 10^{-10} g, and the lowest particles mass we could measure from the Munich facility was ~ 4 x 10^{-9} g. Thus, we have no calibration data for particles in the mass range between ~ 1.8 x 10^{-10} g and ~ 4 x 10^{-9} g for either the 6µm thick or the 28µm thick PVDF sensors.

Table 2

Summary of PVDF Dust Sensor Calibrations

Heidelberg:	August 1983	June 1984	January 1994
Munich:	October 1987	April 1989	January 1994

	6 µm	28 µm
1. MPI-K Heidelberg (Fe Particles)		
a) Velocity Range (km/s)	1.0 - 12.0	1.7 - 11.4
b) Mass Range (g)	3.8 x 10^{-13} - 1.7 x 10^{-10}	2.8 x 10^{-13} - 1.9 x 10^{-10}
c) Diameter Range (µm)	0.45 - 3.3	0.40 - 3.4
2. Munich/Garching (Glass Particles)		
a) Velocity Range (km/s)	1.8 - 15.9	2.0 - 11.4
b) Mass Range (g)	2.4 x 10^{-9} - 2.0 x 10^{-6}	5.4 x 10^{-9} - 3.0 10^{-6}
c) Diameter Range (µm)	12 - 115	16 - 130
3. Range of Measured Sensor Signal Amplitudes (In Units of Number of electron charges, e)		
a) Smallest	8.3 x 10^{4} e (Fe)	2.7 x 10^{4} e (Fe)
b) Largest	8.5 x 10^{9} e (Glass)	4.2 x 10^{10} e (Glass)

Particle calibrations of the DFMI consist of experimentally determining the amplitude of the output signal from the sensor linear electronics as a function of particle mass and impact velocity, as illustrated in **Figure 4**. In **Figures 5** and **6**, we show the mass/velocity ranges for the particles used during our calibrations and in **Figures 7** and **8** we show selected examples of the measurement details involved during the Heidelberg and Munich dust accelerator runs.

Over the mass intervals where we have calibration data, fits to the calibration data have been obtained which show that the PVDF sensor signal amplitude is proportional to $\mathbf{m^a v^b}$, where **m** and **v** are particle mass and velocity, and **a** and **b** are exponents derived from the calibration data (**Equations** [**1**] - [**4**]). In **Figure 9**, we show calculated PVDF sensor output signal vs impacting particle mass, **m(g)**, for impacts at the WILD-2 flyby encounter velocity of 6.1 km/s, based on our calibration data. From these data, and our selected electronic thresholds for the PVDF sensors, we obtain the particle mass thresholds given in **Table 3**.

Table 3

Dust Flux Monitor Instrument (DFMI) **Flight Unit**

(Electronic Thresholds and Corresponding Particle Mass Thresholds for 6.1 km/s Impact Velocity)

PVDF Sensor #1
Area = 200 cm^2
Thickness = 28 µm

Threshold	Electronic Threshold +	Particle Mass Threshold	Particle Diameter*
M1	1.76×10^{9} e	8.5×10^{-8} g	55 µm
M2	2.67×10^{10} e	1.7×10^{-6} g	148 µm
M3	2.67×10^{11} e	1.4×10^{-5} g	299 µm
M4	2.0×10^{12} e	1.5×10^{-4} g	659 µm

PVDF Sensor #2
Area = 20 cm^2
Thickness = 6 µm

Threshold	Electronic Threshold	Particle Mass Threshold	Particle Diameter*
m1	3.77×10^{6} e	9.8×10^{-12} g	27 µm
m2	7.13×10^{7} e	$1.2 \ 10^{-10}$ g	6.1 µm
m3	1.8×10^{8} e	4.3×10^{-9} g	20.2 µm
m4	6.0×10^{9} e	6.3×10^{-7} g	106 µm
Threshold	**Ground Command Electronic Threshold**	**Ground Command Particle Mass Threshold**	**Ground Command Particle Diameter**
m1	4.6×10^{7} e	7.0×10^{-11} g	5.1 µm
m2	8.7×10^{8} e	2.6×10^{-8} g	36.8 µm
m3	2.2×10^{9} e	1.2×10^{-7} g	61 µm
m4	7.3×10^{10} e	1.7×10^{-5} g	319 µm

* Assuming impacting particle with density 1.0 g/cm^3
\+ Electronic thresholds in units of number of electron charges (e)

The relationship between the output signal from DFMI PVDF sensors as a function of particle mass and velocity obtained from our calibrations are

$$\frac{N(e)}{6\mu m} = 3.6 \times 10^{18} \, m^{1.3} \, v^{3.0} \quad \text{(Heidelberg)}, \qquad \textbf{(1)}$$

$$\frac{N(e)}{6\mu m} = 1.36 \times 10^{13} \, m^{0.7} \, v^{1.3} \quad \text{(Munich)}, \qquad \textbf{(2)}$$

$$\frac{N(e)}{28\mu m} = 3.8 \times 10^{17} \, m^{1.3} \, v^{3.0} \quad \text{(Heidelberg)}, \qquad \textbf{(3)}$$

$$\frac{N(e)}{28\mu m} = 6.94 \times 10^{14} \, m^{0.9} \, v^{1.05} \quad \text{(Munich)}, \qquad \textbf{(4)}$$

The expressions (1) - (4) are valid over the particle mass/velocity ranges used during the calibration runs (**Figures 5** and **6**). Extrapolations of these data to other ranges of velocity and mass should be carried out with caution.

4. WILD-2 FLYBY DATA

Included in the DFMI WILD-2 flyby data will be:

1) the time at which impact data was obtained (measured by the DFMI and S/C clocks);

2) Instrument status;

3) SENSOR UNIT and ELECTRONICS BOX temperatures;

4) SENSOR UNIT heater power;

5) EB power;

6) S/C position and velocity with respect to the SUN, S/C position with respect to WILD-2, and finally, the accumulated number of impacts recorded by each of the 10 counting rate channels given in **Table 1**.

To illustrate the procedure for determining particle flux and mass distribution for the WILD-2 flyby data we expect to obtain, we choose a set of counts for hypothetical impacts which we list in **Table 4**. The counts from actual impacts during flight would be obtained directly from 3 lines of DFMI data.

Table 4

16 BIT WORD	1	2	3
SYST	STAT SYNC	STAT SYNC	STAT SYNC
CLK	2175	2195	2200
A1a, A1b	350, 275	398, 325	400, 328
A2a, A2b	780,448	800, 500	810, 516
M 1	5	10	82
M 2	7	9	12
M 3	3	4	8
M 4	0	0	1
m 1	700	850	980
m 2	400	500	750
m 3	150	155	220
m 4	10	11	18

For the last ten 16 bit words, the entries give the total counts accumulated for each of the listed entries from a given start time (t = o) and a time T_1 = 2175 seconds, 2195 seconds, and 2200 seconds, respectively. Differences between the entries in columns “2” and “1” give the differential counts accumulated between 2195 seconds and 2175 seconds (a time interval of 20 seconds) and differences between the entries in columns “3” and “2”, give the differential counts accumulated between 2200 seconds and 2195 seconds (a time interval of 5 seconds).

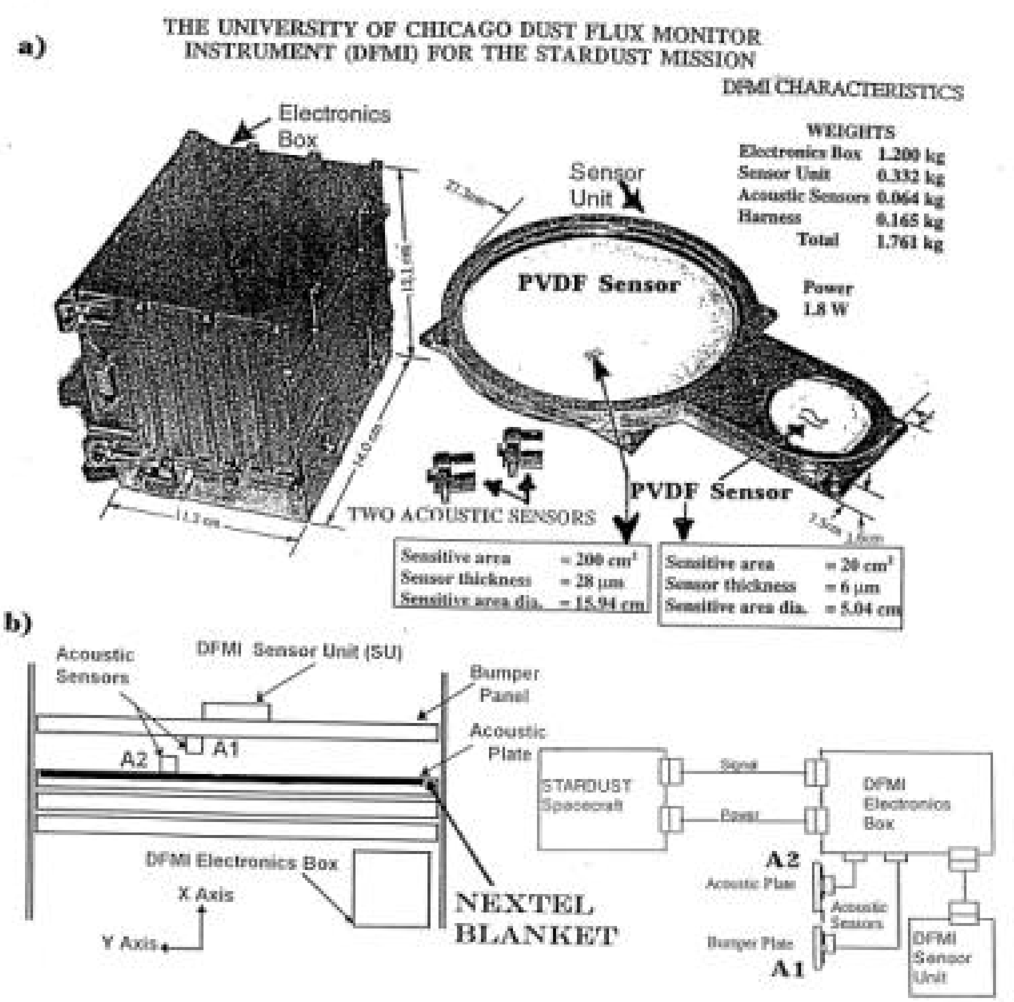
The last eight 16 bit words correspond to counts corresponding to all particles with masses ≥ to those listed in **Tables 1** and **3**. Particle flux (impacts/[cm^2-s]) and fluence (impacts/cm^2) corresponding to the data given in **Table 4** are immediately obtained by dividing the entries by the sensitive area corresponding to the large DFMI PVDF sensor (200 cm^2) and small DFMI PVDF sensor (20 cm^2).

5. REFERENCES

1. Tuzzolino, A.J., McKibben, R.B., Simpson, J.A., McDonnell, J.A.M., Burchell, M.J., Vaughan, B., Tsou, P., Hanner, M.S., Clarke, B.C. and Brownlee, D.E., “The Dust Flux Monitor Instrument (DFMI) for the Stardust Mission to Comet Wild-2” to be submitted to JGR-Planets, 2000.

2. Simpson, J.A. and Tuzzolino, A.J.: 1985, “Polarized Polymer Films as Electronic Pulse Detectors of Cosmic Dust Particles, *Nucl. Instr. and Meths.* **A236**, 187.

3. Simpson, J.A, A.J. Tuzzolino, 1989, “Cosmic Dust Investigations: II, PVDF Detector Signal Dependence on Mass and Velocity for Penetrating Particles”, *Nucl. Instr. and Meths.* **A279**, 625.

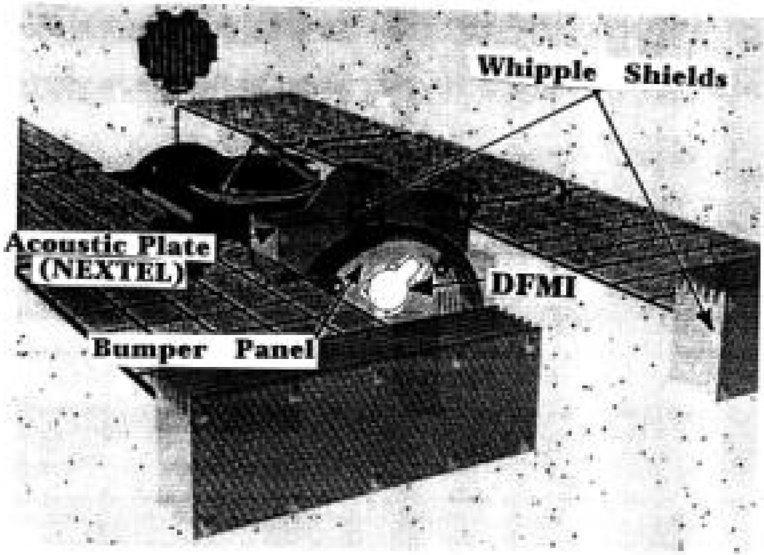


DFMI CHARACTERISTICS

PVDF Sensors:	200 cm^2, 28µm thick; 20 cm^2, 6µm.
Acoustic Sensors:	Two identical Quartz piezoelectric accelerometers.
Thresholds:	Each PVDF sensor has four mass thresholds and each acoustic sensor has two mass thresholds.
Particle Mass:	For PVDF sensors at 6.1 km/s impact velocity, differential and integral flux ~ 10^{-11} g to 10^{-4} g; integral flux > 10^{-4} g.
Counting Rates:	(PVDF SENSORS): Up to 10^4 s^{-1}, < 5% corrections; 10^4 to 10^5 s^{-1}, known correction

Figure 1. a) Photograph of the DFMI;
b) Schematic layout of the DFMI SU, EB and acoustic sensors on the spacecraft.

a)



b)

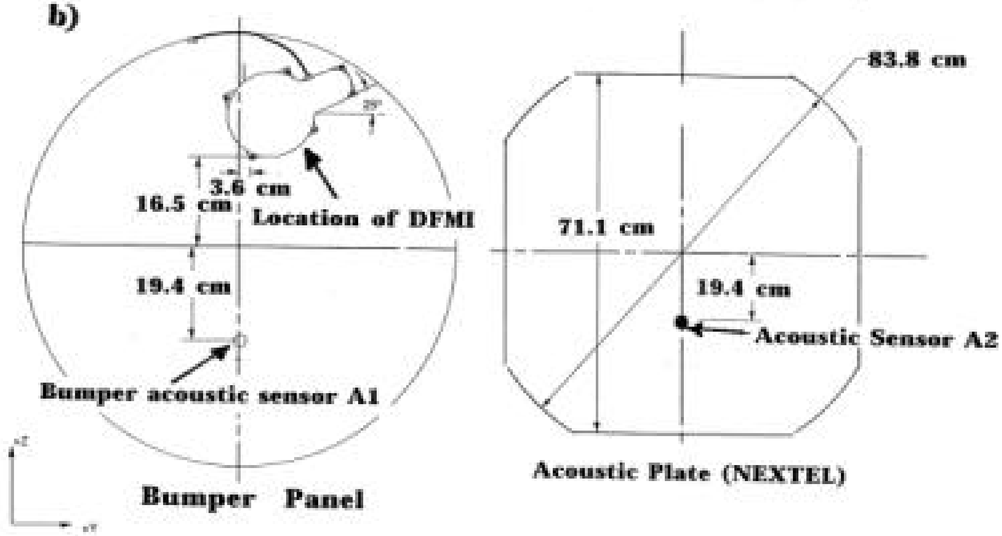


Figure 2. a) Schematic of the *Stardust* spacecraft showing the location of the PVDF DUST SENSOR UNIT (SU);
b) Location of the DFMI SU and acoustic sensor A1 on the Bumper panel. Acoustic sensor A1 is mounted to the underside of the Bumper panel;
c) Location of acoustic sensor A2 on the Acoustic (NEXTEL) plate.

a)

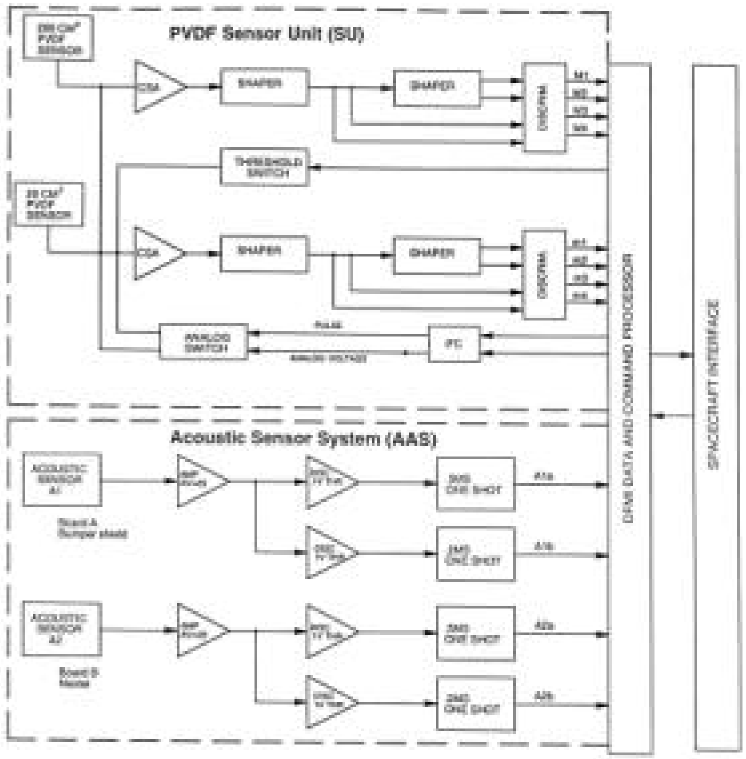


Figure 3. Block diagram of the principal electronic functions of the DFMI

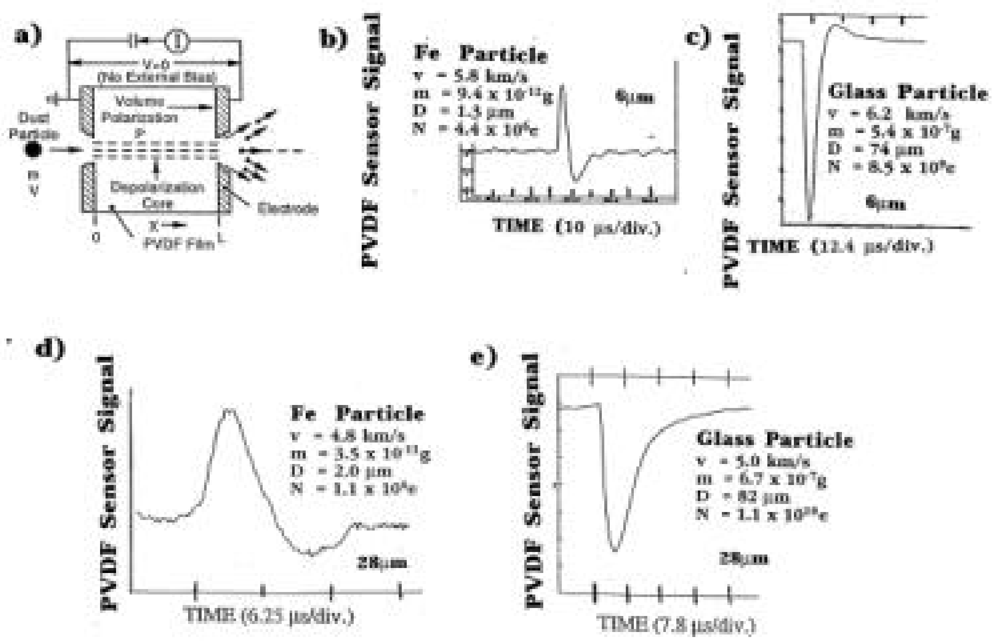


Figure 4. **a)** Schematic of a polarized PVDF sample with conducting contact electrodes. An incident particle of mass **m** and velocity **v** penetrates (or stops within) the PVDF sample resulting in complete local depolarization along its track. The signal output from the sensor depends on both particle mass and velocity. Calibration of the sensor requires measurement of the sensor signal as a function of particle mass and velocity; **b)** and **c)** Examples of output signals from a 6m thick PVDF sensor; **d)** and **e)** Examples of output signals from a 28μm thick PVDF sensor. For panels "b)-e)", listed are particle velocity, mass, diameter, and output signal amplitude expressed in units of number of electron charges;

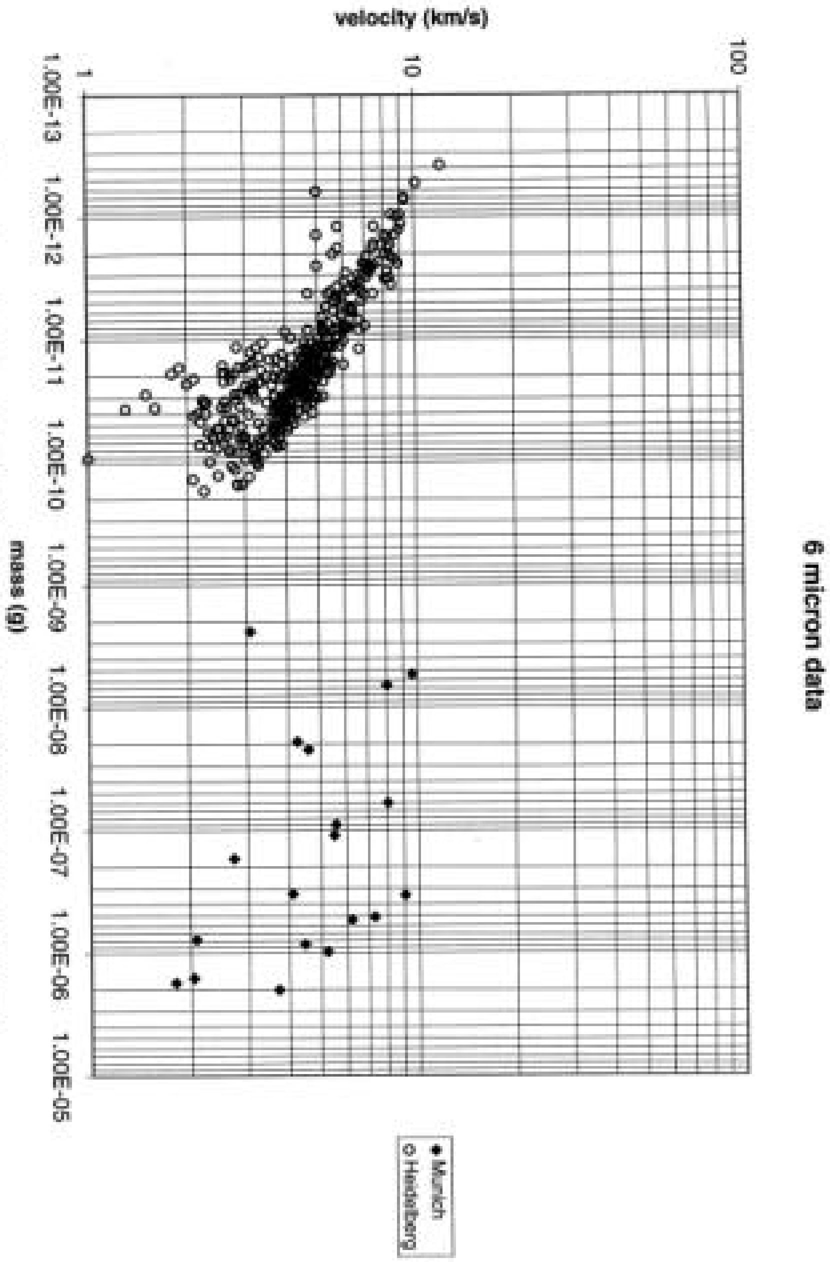


Figure 5. The Data points show the particle mass and velocity for each particle used during the accelerator calibrations at Munich and Heidelberg for 6µm thick DFMI sensors.

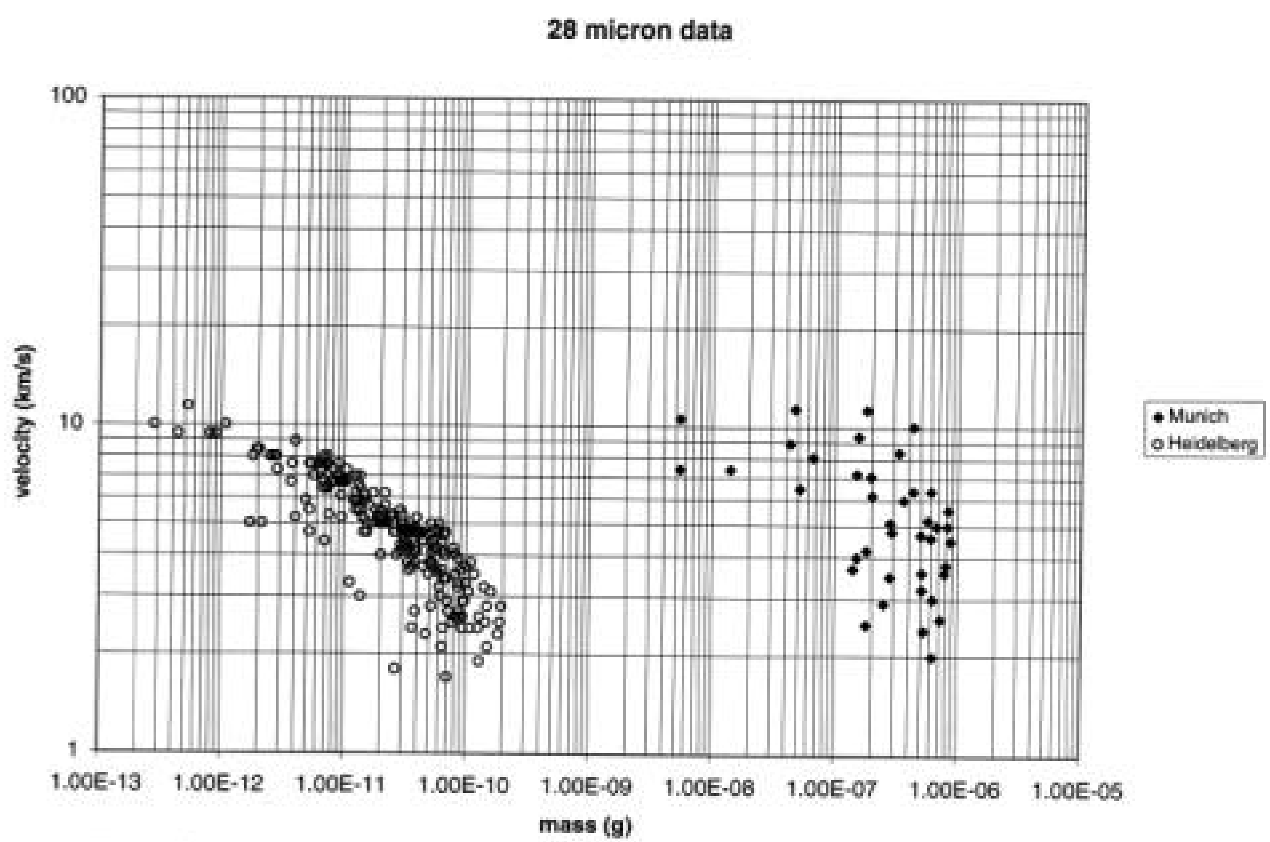


Figure 6. The data points show the mass and velocity for each particle used during the accelerator calibrations at Munich and Heidelberg for 28µm thick DFMI sensors.

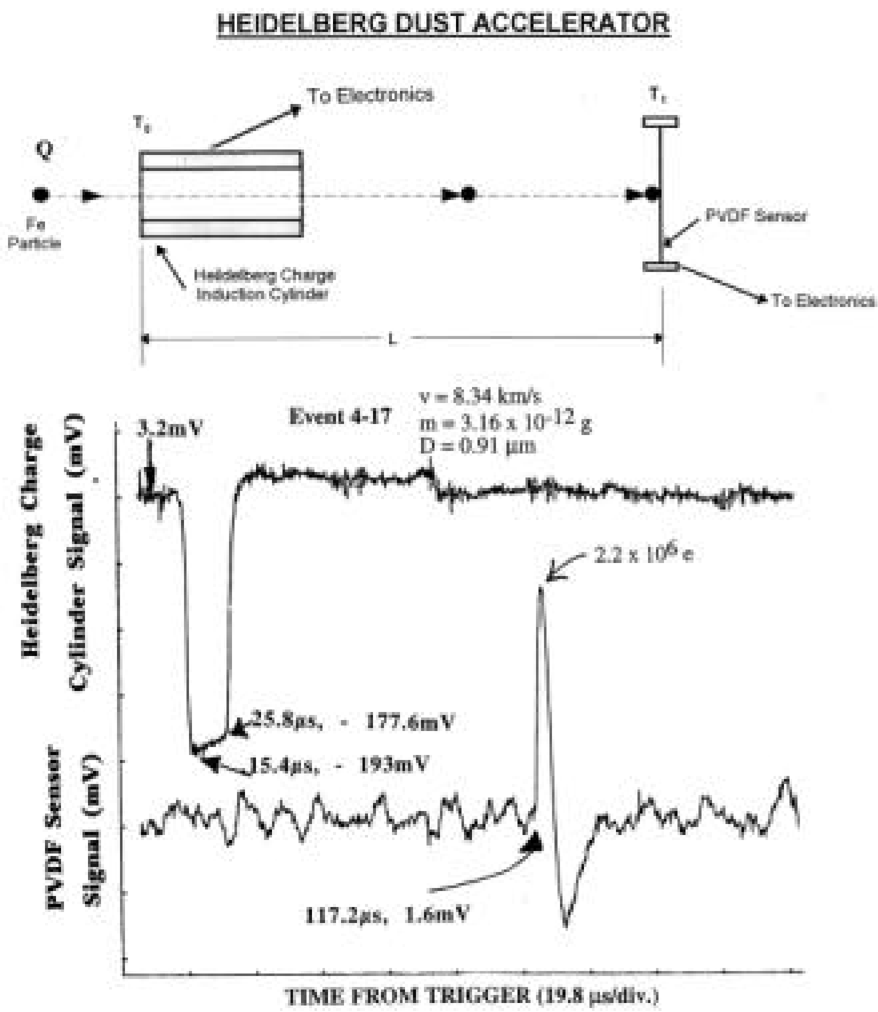


Figure 7. Example of the parameters measured during a PVDF sensor calibration run carried out at the Heidelberg dust accelerator facility. This facility provided accelerated iron particles over the mass range ~ 10^{-16}-10^{-9} g. Briefly, an iron particle is given a positive charge Q and is then accelerated through a potential difference U. The relation between its final kinetic energy and initial potential energy is $\frac{1}{2}mv^2 = QU$, where m is the mass of the Fe particle and U is the accelerating voltage, which is set at 2 MV. The particle then enters the Heidelberg charge induction cylinder at the trigger time T_0, and then travels on to impact the PVDF sensor after a travel distance L at time T_1. During the measurements, Q and v are measured, and then m is calculated from the energy relation. Finally, the measured signal amplitude from the PVDF sensor provides the calibration for this mass and velocity. The lower panel shows actual parameter values obtained for a selected Heidelberg run.

MUNICH DUST ACCELERATOR

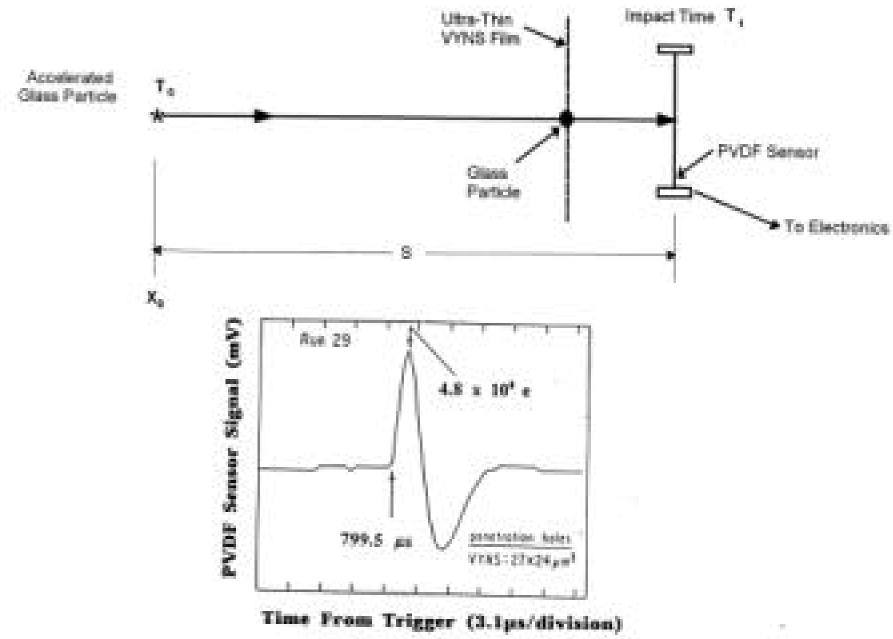


Figure 8. Example of the parameters measured during a PVDF sensor calibration run carried out at the Munich/Garching dust accelerator facility. For this accelerator, glass particles are exposed to an intense impulsive plasma flow and drag-accelerated for a short time interval at a point x_o at the trigger time T_o to a velocity v. Following this, the particle travels (at constant velocity v) a distance S and impacts a thin (< 0.1µm) nitro-cellulose film which is referred to as the VYNS film. This VYNS film is placed immediately in front of the PVDF sensor to be calibrated, and is used to determine the particle mass after disassembly of the setup. During the run, the times T_o, T_i and signal from the PVDF sensor are measured. Since ablation of the glass particle occurs during the short particle acceleration phase, the mass of the particle must be determined just before it impacts the PVDF sensor. All incident-particle mass determinations were carried out by making use of the VYNS film. Since the thickness of this film (< 0.1 µm) is less than 0.01 times the particle dimensions (> ~ 20 µm), it can be assumed that each penetration hole in the VYNS film is equal in size to that of the impacting particle — i.e., for a spherical particle, the diameter of the VYNS film hole equals the diameter of the particle. However, in many cases, the impact holes in the Munich film were noncircular and were either approximately elliptical, or had complex geometry (i.e., long, narrow slits, dumbbell-shaped, etc.). For those cases where the film hole could be approximated by an ellipse having major and minor axes of length d_a and d_b, respectively, the mass of the impacting particle producing the hole was taken to be $m = \frac{\pi}{6}(\bar{d})^3\rho$, where $\bar{d}$ is the hole's geometrical mean diameter, $\bar{d} = (d_a d_b)^{1/2}$, and ρ is the density of the glass particles ($\rho = 2.5$ g/cm^3). Thus, measurements of the glass particle mass and velocity, combined with the measured PVDF sensor signal amplitude provides the sensor calibration for this impacting mass and velocity.

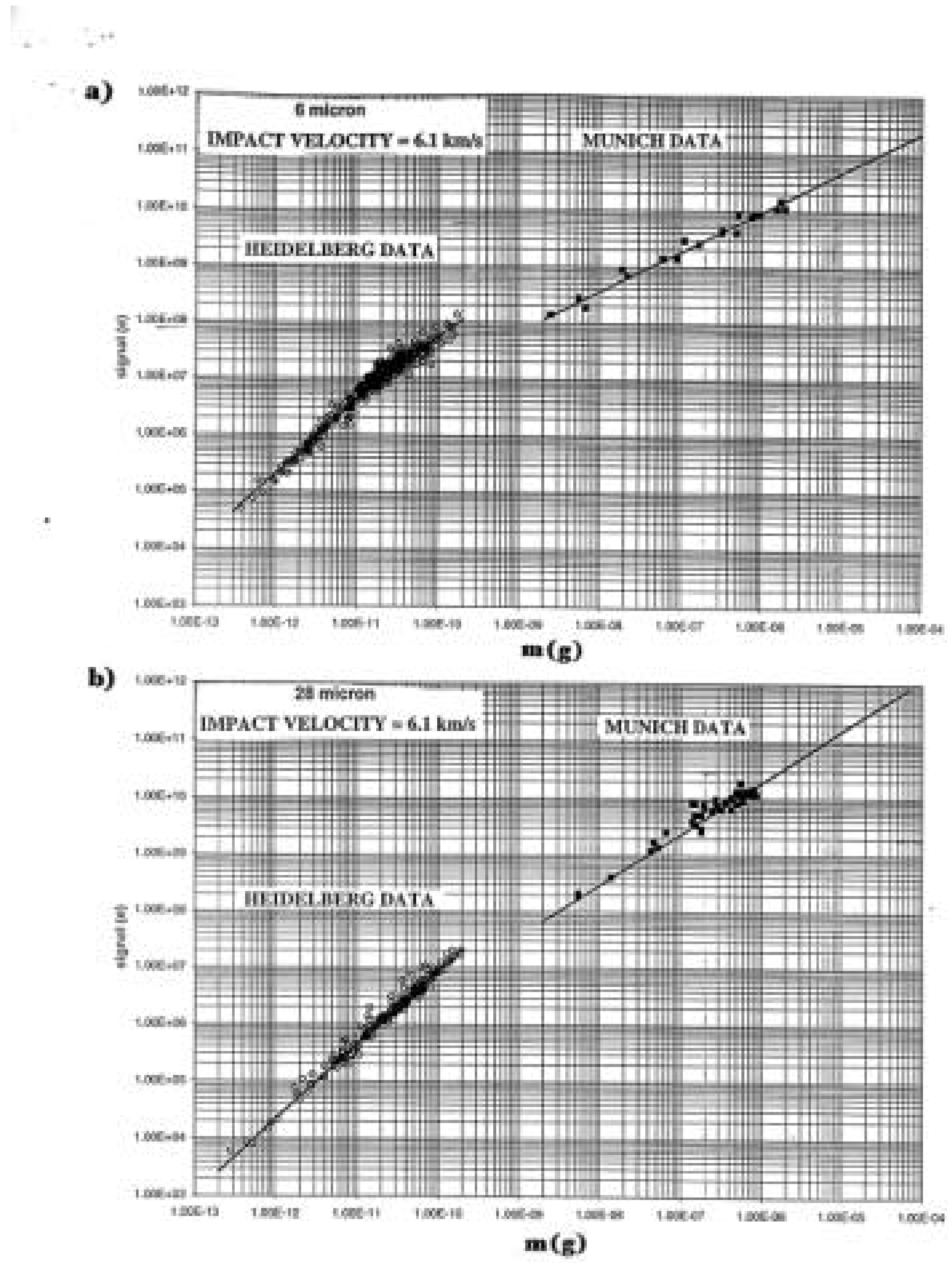


Figure 9. a) PVDF sensor output signal vs particle mass m(g) for a 6 μm thick sensor impacted by particles with impact velocity = 6.1 km/s;
b) PVDF sensor output signal vs particle mass m(g) for a 28 μm thick sensor impacted by particles with impact velocity 6.1 km/s.