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LABORATORY DEVELOPMENT OF THE MUPUS DENSITOMETER FOR THE *ROSETTA* COMET LANDER

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MUPUS

UCL

Abstract

The MUPUS physical properties experiment has been selected for the payload of the lander to be deployed to the surface of comet 46P/Wirtanen as part of the *Rosetta* mission. One of the constituent instruments of MUPUS is a densitometer. This will measure the bulk density of the surface layers of the comet nucleus to a depth of about 0.35 m.

The technique employed is a simple attenuation method using a ^{137}Cs source (662 keV photons) at the tip of the MUPUS thermal probe, to be inserted into the nucleus surface. Detectors at the surface will measure the attenuated count rate. Due to the dependence of required integration time on density and depth, an algorithm for budgeting the available operation time during the penetration process is proposed.

Laboratory experiments have been performed to examine the spectrum of ^{137}Cs emission as seen by a Cadmium Telluride (CdTe) detector through water. CdTe detector technology is being studied as an alternative to the Geiger tubes previously used in Compton backscatter densitometers on the Moon and Venus (Surkov et al., 1990).

Results show that exponential attenuation of the 662 keV radiation can be seen, together with scattered radiation at lower energies.

Rosetta and the MUPUS Experiment

ESA's cornerstone mission *Rosetta* due for launch in January 2003 provides an opportunity to perform experiments at the surface of a comet nucleus, by means of the *Rosetta Lander*. One of the experiments selected for the Lander is MUPUS (Multi-Purpose Sensors for Surface and Sub-Surface Science). This is a suite of small sensors designed to measure physical properties of the near-surface material, including temperature profile, thermal conductivity, mechanical strength and density, and the evolution of these parameters with time. Interpretation of the results will allow us to examine the energy balance across the nucleus surface and constrain models of the formation and evolution of cometary material.

The constituent measurement subsystems of MUPUS are listed in Table 1. The first four listed are incorporated into the MUPUS probe, as shown in Figure 1. The probe will be hammered gradually into the nucleus surface, performing measurements of density and mechanical strength vs. depth. Once inserted, measurements of temperature profile and thermal conductivity will be made using the line heat source technique (Seiferlin et al., 1996). Separate measurements of mechanical properties and temperature will be made using the Lander's anchor (deployed on landing), while the surface temperature will be monitored by the infrared sensors of the Thermal Mapper.

Further information and news on MUPUS is available at
http://saturn.uni-muenster.de/~seiferl/muphome.html

What will MUPUS Measure?

Experimental Subsystem	Measurements
Temperature Probe†	Sub-surface temperature profile
Thermal Conductivity Probe†	Thermal conductivity (line heat source technique)
Penetrometer	Mechanical and structural properties of surface layers
Densitometer†	Bulk density of surface layers
Thermal Mapper†	Surface temp. (IR sensors at 12-17 μm & 17-23 μm)
Anchor Penetrometer	Mechanical and structural properties of surface layers
Anchor Temperature Sensor†	Sub-surface temperature

Table 1. Post-selection MUPUS measurement subsystems. †Subsystems which measure the evolution of these parameters with time (diurnal and orbital variations).

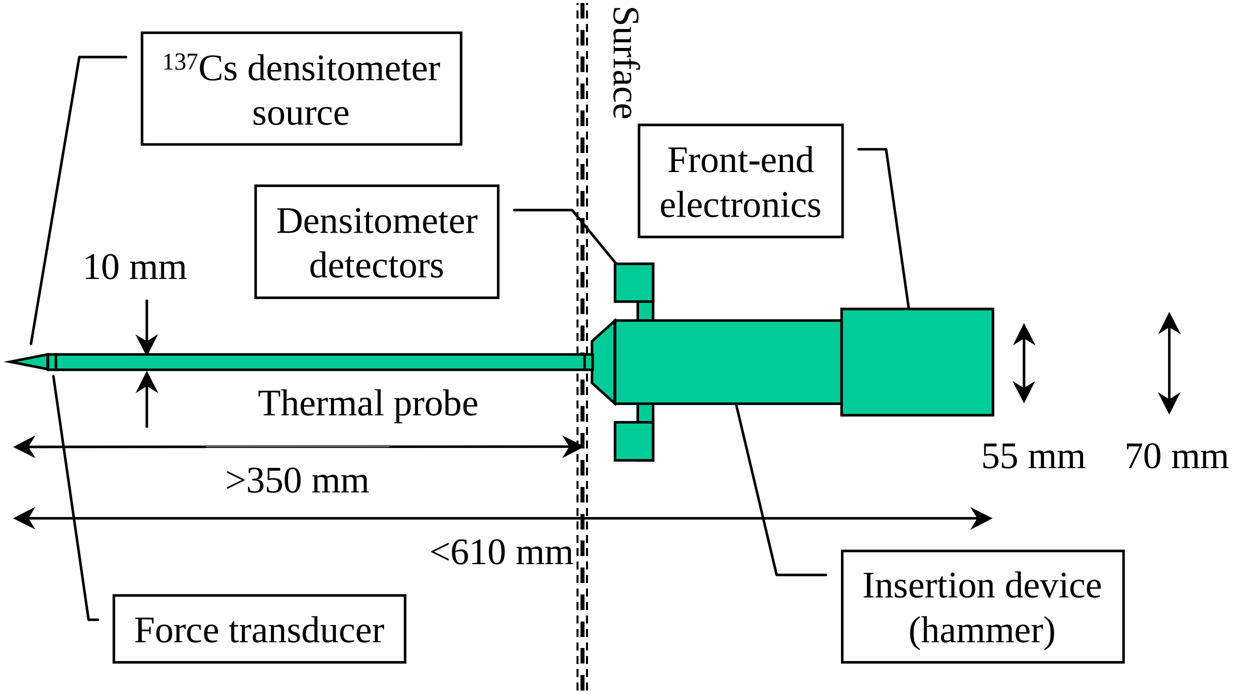


Figure 1. Diagram of the MUPUS probe after penetration of the nucleus surface, showing the sensors for measurement of density, thermal and mechanical properties. The two densitometry detectors provide two different paths through the material as well as redundancy.

Why Measure the Density of a Comet?

- The density of cometary nuclei has been a matter of much discussion (Klinger et al., 1996), but it is widely thought that densities in the range 200-1500 kgm^{-3} are reasonable.
- The measurement of both mass and volume is problematic. Unless the nucleus can be imaged, as was the case for Halley (Keller, 1990), the volume of the nucleus can only be derived less directly. This often requires an assumed albedo or activity model.
- Even for Halley, the mass had to be derived using observations of the non-gravitational perturbations, assuming a model for the activity of the nucleus (Rickman, 1989; Sagdeev et al., 1988).
- *Rosetta* will measure the bulk density of the entire nucleus using measurements of the nucleus size and gravitational influence on the Orbiter, however...
- We may expect there to be significant variations in density on a range of linear scales, as would be the case if the nucleus were a pseudo-fractal body (Hughes, 1996).
- We may expect the density at the surface to have changed relative to the undisturbed material, due to modifying processes such as the sublimation of volatiles.
- The surface density at the landing site may be extended to other parts of the surface if data from the Orbiter can demonstrate the landing site to be representative of other areas.

Factors Associated with Density

- Features affecting density:
  - Environment and collision dynamics of the grains and fluffy aggregates which form planetesimals in the primordial solar nebula (Donn, 1991; Donn and Meakin, 1989).
  - Composition
  - Collision history
  - Thermal evolution
  - Sublimation
  - Chemical evolution
  - Grain Density
  - Porosity
  - Self-gravity of comet
- Features affected by or correlated with density:
  - Thermal properties (conductivity, diffusivity, temperature profile, specific heat capacity) (Seiferlin et al., 1996).
  - Mechanical strength (penetrometry)
  - Chemical profiles
  - Seismic velocity
  - Dielectric constant
  - Balance between mantle formation and erosion (Kührt and Keller, 1994).
  - Gamma ray spectrometer measurements
  - Gravitational field of comet

How will MUPUS Measure Density?

Initially the density measurement was proposed to be performed on one of the Lander's feet, using a novel low energy Compton backscatter technique (Ball et al., 1996), however the current concept combines the density measurement with the MUPUS probe using a simple attenuation technique. On balance this is an improvement on the previous design for reasons of simplicity, improved interface requirements and the co-location of the density measurement with the other MUPUS probe measurements.

The new design involves mounting a ^{137}Cs at the tip of the probe, the 662 keV radiation from which is viewed by detectors at the surface. Thus the radiation is attenuated by any intervening cometary material. The dominant interaction at 662 keV is Compton scattering. Since the cross-section for this process is proportional to electron number density, and the ratio of mass number to atomic number is 2, or nearly so, for all elements except hydrogen, the degree of attenuation is almost independent of composition.

The gradual insertion of the MUPUS probe by the hammering mechanism provides an opportunity to measure density down to a range of depths at intervals during the insertion process. Thus the profile of density vs. depth may easily be obtained. After full insertion any long-term changes in the density or thickness of the surface layer may be monitored.

Requirements for Detection System

- A detector system is required to sense the radiation from the source.

  Spectroscopy is not necessary, but some energy-discrimination will be useful. Instrument accuracy will be improved by counting photons which have travelled directly through the material. Scattered photons and background radiation may degrade the measurement. It is therefore desirable to filter these unwanted photons using some combination of -

pulse height discrimination

- pulse shape discrimination
- physical shielding

  Coincidence or anti-coincidence triggering schemes are unlikely to be affordable within the Rosetta Lander’s physical resources.

Other general requirements of the detector system are -

- permit density measurement in a “reasonable” time.
- be compact and have low mass
- operate in the temperature range at the cometary surface
- withstand the physical environment of the mission, particularly : **vibration, thermal extremes, radiation, mission duration**

Photon-counting detector systems generally consist of -

- Detector and housing
- Shielding if necessary
- Bias voltage unit
- Preamplifier
- Pulse processing electronics [shaping, discriminator, counters]

Choice of Detector Technology

Gas Detectors

e.g. ionisation counter or proportional counter. Performance adequate except -

- ✗ Poor efficiency at 662 keV
- ✗ High volume and mass
- ✗ Gain is required for detection above electronic noise. A high voltage unit is therefore needed

Scintillators

Atoms in the material emit (visible) light when struck by photons

- ✓ Simple readout, e.g. Silicon photodiode
- ✗ Large block of scintillator
- ✗ Complex output spectrum - energy discrimination difficult

Semiconductors

usually photodiodes

- ✓ Generally do not require gain, therefore small bias voltage
- ✓ Certain materials (Ge, Si) widely available, but these ...
- ✗ Need low temperature operation to suppress leakage current
- ✗ Inefficient capture of gamma rays - need higher Z

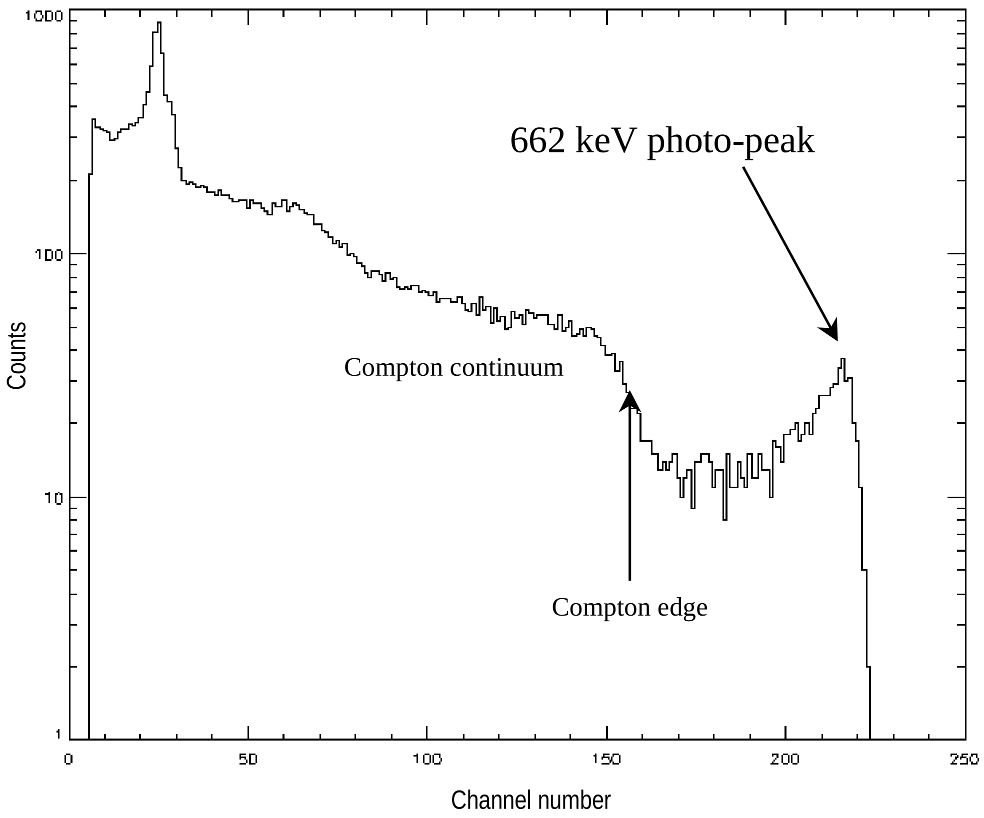
Compound semiconductors

High Z, High bandgap, e.g. CdTe and CZT.

- ✓ high bandgap = low leakage current = no need for cooling

The high-Z compound semiconductors are the most attractive. Of these, Cadmium Telluride (CdTe) and Cadmium Zinc Telluride (CZT) are the most commercially mature. Several manufacturers offer a wide range of detector types.

Spectrum of ^{137}Cs using CdTe



- Pulse-height spectrum taken with a CdTe detector in view (through 10 cm air) of a source of 662 keV photons.
- The 662 keV photo-peak (where all the photon's energy is converted to charge) is shown at left.

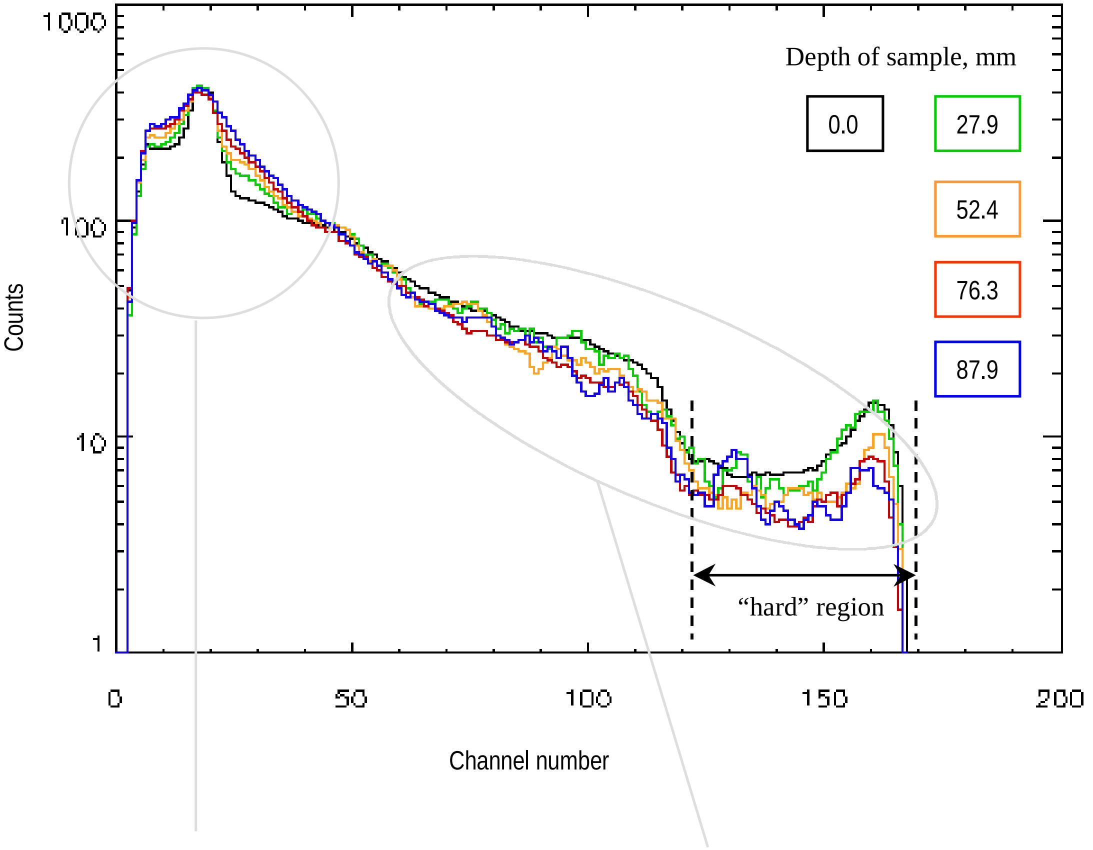
  The remainder of the spectrum is due mainly to secondary photons leaving the active detector volume.
- The detector is a planar diode
  5 x 5 x 2 mm, biased at 170 V.

  Detector supplied by Eurorad sa, Strasbourg

^{137}Cs Spectrum through H_2O

- The detector was illuminated with the ^{137}Cs source through samples of water.
- Spectra were acquired with varying depths of water. The source-detector distance was kept constant.
- The figure shows the spectra normalised by exposure time.

- As the sample depth increases, the received counts increase at the low end of the spectrum and reduce at the high end.



Increased

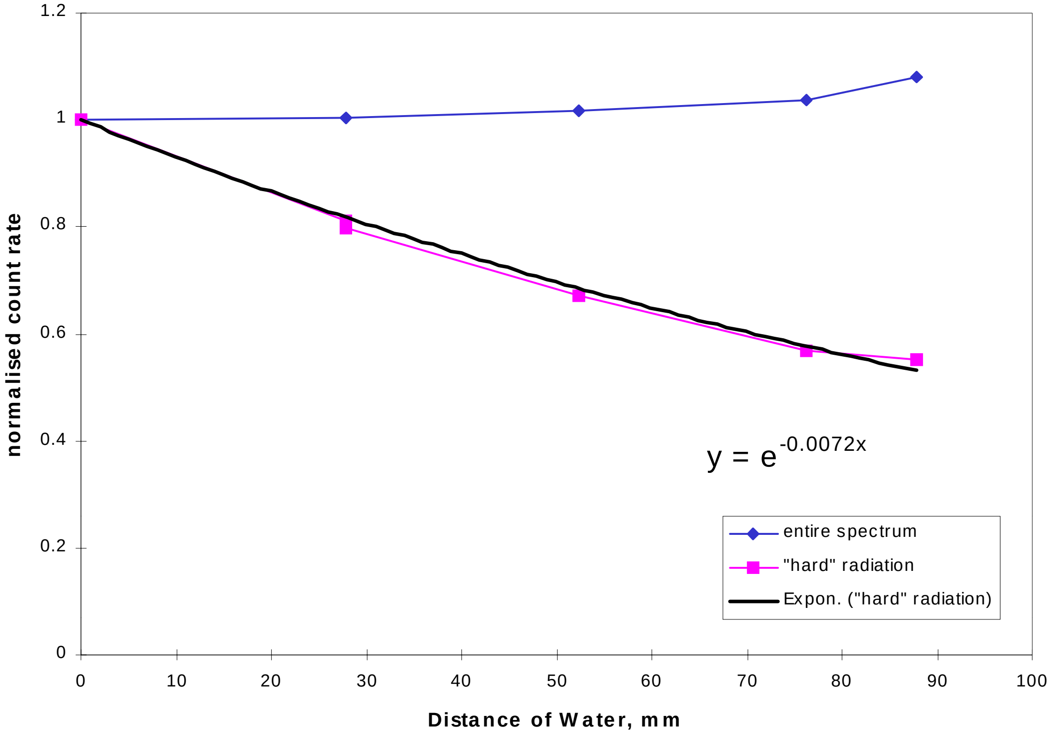
Reduced

A region near the photo-peak is defined as the “hard” region. This is used in the parameterisation of the spectra - see following material.

Analysis of Spectra

- The total transmitted flux is compared to the flux in the "hard" region

The values are normalised to the reference spectrum (air path only).



- The intensity of the entire spectrum increases with the addition of water, whereas the hard region is attenuated.
- It is apparent that the presence of the water sample causes the off-beam source photons to be Compton-scattered (losing energy) into the detector.
- The attenuation of the hard flux follows the expected exponential form but with an attenuation length of 139 mm, 11 % higher than would be the case for a collimated beam and thin target.

How will Densitometry be Combined with Probe Insertion?

The time required for the densitometer detectors to integrate a sufficient number of counts to measure density to a given accuracy varies with density as well as depth (see next page). The total time required for the measurement sequence could thus be greater or less than the time allocated.

We propose an active control system to modify the number of measurement depths chosen and the time spent counting at each depth, in order to perform the measurement in exactly the time allocated.

The instrument would obtain a calibration count at the surface and an initial density measurement at some shallow depth (5 cm), which it then uses to estimate how much time will be needed later on, assuming the density will be similar at greater depths. The algorithm allows better depth resolution (to some defined limit) if this can be achieved within the time allocated. Any further spare time is then spent on improving the accuracy of each measurement by integrating for longer at each point. If the instrument requires a longer time for each measurement it will reduce the depth resolution, the limit being that it would go straight to full penetration and integrate there for as long as possible before timeout. Having decided how far apart the data points should be, the algorithm then allows the penetrator to advance to the next point. The density measured there is then fed back into the loop for "budget reallocation". This allows for density variations and overshoot by the penetrator.

How does the Measurement Time Vary with Depth?

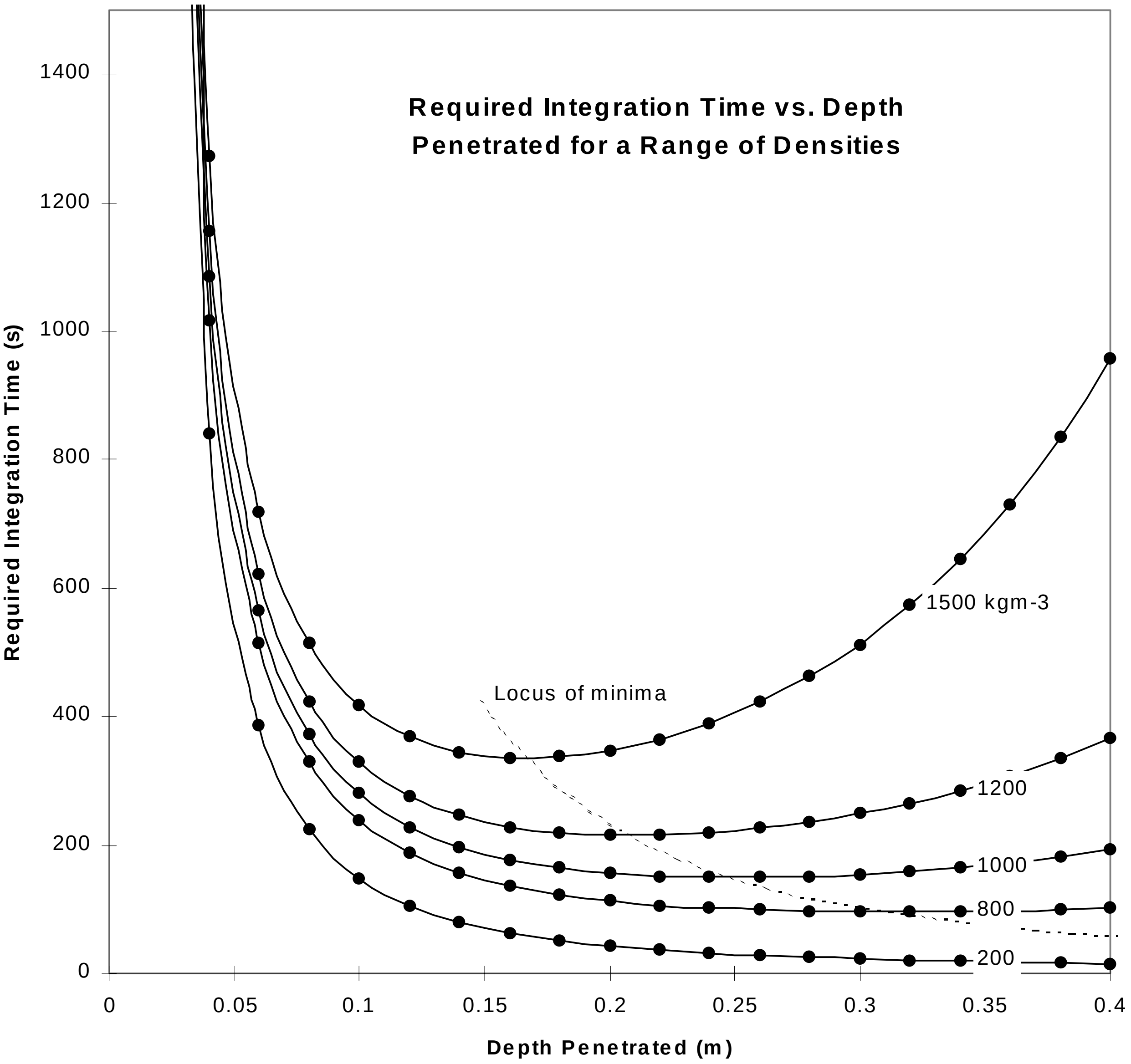
The count rate C(z) detected at penetrated depth z is given by

$$C(z) = C(0)e^{-\mu\rho z}$$

Where μ is the mass attenuation coefficient, and ρ is the density. The number of counts required to measure ρ to accuracy Δρ is equal to $(\mu\Delta\rho z)^{-2}$, therefore the integration time as a function of depth required to make a measurement to accuracy Δρ is given by

$$\tau_{\mathrm{int}}(z) = \frac{1}{C(0)} \cdot \frac{e^{\mu\rho z}}{(\mu\Delta\rho z)^2}$$

This function is shown in the graph opposite. A minimum occurs at z=2/(μρ).



- Further work required:
  - Optimisation of detection and counting system
  - Examination of temperature dependence of candidate detector technologies
  - A larger detector is required for better detection of 662 keV photons
  - Definition of interfaces with MUPUS and the Lander

- Current Status:
  - Development to date has been funded by the University of Kent Research Development Fund and by PPARC Rolling grants at the two participating institutes. This has allowed initial proving of the design, conceptually and experimentally. Design and manufacture of a fully engineered flight worthy instrument will require further funding which is currently being sought through various channels.

Conclusions

- A densitometer can be integrated into a single probe, combined with sensors for thermal and mechanical measurements.
- Attenuation of 662 keV ^{137}Cs emission through water has been measured successfully using CdTe detector technology.
- An algorithm has been developed to allow for uncertainty in the time required to make each measurement during probe insertion.

17 References

Ball, A. J., Solomon, C. J. and Zarnecki, J. C., A Compton Backscatter Densitometer for the RoLand Comet Lander-design concept and Monte Carlo simulations, *Planet. Space Sci.* **44**(3), 283-293, 1996.

Donn, B., The Accumulation and Structure of Comets. In *Comets in the Post-Halley Era* Vol. 1 (eds. Newburn, R. L. et al.), 335-359, Kluwer, 1991.

Donn, B. and Meakin, P., Collisions of Macroscopic Fluffy Aggregates in the Primordial Solar Nebula and the Formation of Planetesimals. *Proc. 19th Lunar and Planet. Sci. Conf.*, 577-580, 1989.

Hughes, D. W., The Interior of a Cometary Nucleus. *Planet. Space Sci.* **44**(7), 705-710, 1996.

Keller, H. U., Surface Features and Activity of the Nucleus of Comet Halley. In *Comet Halley: Investigations, Results, Interpretations*, Vol. 2 (ed. J. Mason), 133-145, 1990.

Klinger, J., Levasseur-Regourd, A.-C., Bouziani, N. and Enzian, A., Towards a Model of Cometary Nuclei for Engineering Studies for Future Space Missions to Comets. *Planet. Space Sci.* **44**(7), 637-653, 1996.

Kührt, E. and Keller, H. U., The Formation of Cometary Surface Crusts. *Icarus* **109,** 121-132, 1994.

Möhlmann, D., Comet 46 P/Wirtanen Nucleus Reference Model, ROL-DLR/Möh-TN, DLR, 1996.

Peale, S. J., On the Density of Halley’s Comet. *Icarus* **82**(1), 36-49, 1989.

Rickman, H., The Nucleus of Comet Halley: Surface Structure, Mean Density, Gas and Dust Production. *Adv. Space Res.* **9**(3), 59-71, 1989.

Rickman, H., The Mass of the Nucleus of Comet Halley as Estimated from Nongravitational Effects on the Orbital Motion. In *Comet Halley: Investigations, Results, Interpretations*, Vol. 2 (ed. J. Mason), 163-172, 1990.

Sagdeev, R. Z., Elyasberg, P. E., Moroz, V. I., Is the Nucleus of Comet Halley a Low Density Body? *Nature* **331,** 240-242, 1988.

Seiferlin, K., Kömle, N. I., Kargl, G. and Spohn, K., Line Heat-Source Measurements of the Thermal Conductivity of Porous H_2O Ice, CO_2 Ice and Mineral Powders under Space Conditions. *Planet. Space Sci.* **44**(7), 691-704, 1996.

Surkov, Yu. A., Kirnozov, F. F., Khristianov, V. K., Korchuganov, B. N., Glazov, V. N. and Ivanov, V. F., Density of Surface Rock on Venus from Data Obtained by the Venera 10 Automatic Interplanetary Station. *Cosmic Res.* **14**(5), 612-618, 1976.

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