THE D-CIXS X-RAY SPECTROMETER ON ESA’S SMART-1 MISSION TO THE MOON

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ABSTRACT

The D-CIXS (Demonstration of a Compact Imaging X-ray Spectrometer) instrument will provide high quality spectroscopic mapping of the Moon, the primary science target of the ESA SMART-1 mission. At the same time it will demonstrate a radically novel approach to building a type of instrument essential for the Mercury cornerstone mission. It consists of a high throughput spectrometer, based around the use of advanced dual microstructure collimator and Swept Charge Device X-ray detector technologies.

D-CIXS will perform spatially localised X-ray fluorescence spectroscopy. A solar monitor provides the calibration of the illumination necessary to derive absolute lunar elemental abundances. It will produce the first global map of the lunar surface in X-rays, providing absolute measurements of Fe, Mg, Al and Si under normal solar conditions and several other elements during solar flare events. These data will allow for a more detailed look at some of the fundamental questions that remain regarding the origin and evolution of the Moon.

THE D-CIXS INSTRUMENT

D-CIXS will image fluorescence X-rays emitted from the surface of the Moon. The essential concept of the instrument is that rather than a traditional X-ray telescope, we will produce a modern version of "X-ray detecting paper". In order to obtain adequate statistics for what can be very weak sources, it is essential to have a large effective area, while remaining light. The solution is to make a thin, low profile detector. With its large collecting area and angular resolution, the technology is especially suitable for the Moon where it is necessary to accumulate images quickly to avoid blurring due to the spacecraft motion over the surface. D-CIXS can derive 42km spatial resolution images of the entire lunar surface from a 300km orbiting spacecraft with a spectral resolution of 200 eV or better.

Figure 1: A schematic of the D-CIXS X-ray spectrometer.

This will provide an important elemental abundance dataset, which, in combination the IR and optical SMART-1 lunar remote sensing instruments (Nathaus, this volume; Jost, this volume), will give a greatly improved geochemical picture of the Moon.

The instrument is a new technological evolution, based around the use of advanced dual microstructure collimator and Swept Charge Device X-ray detector technologies. Swept Charge Device X-ray detectors, a novel architecture based on proven CCD technology, have the virtue of providing superior X-ray detection and spectroscopic measurement capabilities, while also operating at room temperature. Thus we avoid the need for the large passive cooling radiator that was previously required to cool large X-ray focal plane CCDs. The advanced low profile microstructure collimation and filter design builds on expertise developed at RAL in solid state and microwave technology to enable us to dramatically reduce the instrument mass. The total mass of D-CIXS, including two X-ray solar monitors is ~3.6kg.
SWEPT CHARGE DEVICE

The inclusion of the DGIXS instrument in the SMART-1 payload provides the best opportunity possible for the verification of the performance and survivability in the space environment for a new CCD-based X-ray detection system. Swept Charge Device X-ray detectors, a novel architecture based on proven CCD technology, have the virtue of providing equivalent X-ray detection and spectroscopic measurement capabilities, while also operating at near room temperature. Unlike conventional imaging CCDs with two transfer directions, the SCD has only one readout direction. This both simplifies the clocking of charge, and also enhances the effect of dark current suppression during dynamic clocking. It comprises an active collecting area of $\sim 1 \text{ cm}^2$, covered with diagonal, 3-phase polysilicon electrodes running diagonally across the array from the top right corner to the bottom left corner. N-type channels in the underlying silicon are arranged so as to funnel charge towards a conventional low-readout noise, charge detection amplifier at the bottom corner when transferred by clocking the electrodes. There are 575 3-phase electrodes, and so conceptually, the SCD can be viewed as a pseudo-linear CCD array of 575 pixels. A sequence of 575 readout clocks is required to sweep charge to the readout amplifier.

Compared to the multiple transfers in a conventional CCD, the comparably low number of readout clocks needed to read out the entire array lead to high frame rate, and hence a reduced requirement for cooling to overcome dark current. In addition, the dynamic suppression of surface-generated dark current which occurs during clocking with high substrate voltage reduces dark current still further. Thus we avoid the need for the large passive cooling radiator that was previously required to cool large X-ray focal plane CCDs.

The detailed design of the prototype SCD has been modified to a new specification better suited to X-ray detection in the space environment. All devices will be manufactured on high resistivity epitaxial silicon, with supplementary 'narrow' channels made narrower to increase radiation tolerance, and using the electrode structure developed by EEV for the Russian Spectrum X-JET-X mission.

For DGIXS, individual SCDs are to be bonded, four per group, on ceramic ladders. A total of 24 are employed, viewing in three different facets, one of 8 and 2 of 12 degrees.

In-flight calibration of the detector field of view and energy resolution using observations of well-known astronomical X-ray sources will take place over a period of a year in the cruise phase. The aim is to produce high quality lunar science.

COLLIMATOR

A key feature in the progress of the D-CIXS instrument has been the development of low profile collimators, which define the instrument field of view. Such simple optics has been the basis for many X-ray observatories. As no X-ray reflections are involved, the requirements on the properties of the surfaces are much more relaxed than flux collecting and focussing devices. The innovation in D-CIXS is to micro-fabricate the collimator using the techniques of micro engineering to produce a very low profile device, which is robust and ideally matched to the detector array placed immediately behind. By making use of micro engineering the cross section is an entirely free design choice and strong bars can be included as desired. The collimator is constructed from an electro-depositable material of sufficiently high $z$ to avoid fluorescence radiation caused by interaction of high energy cosmic rays with low $z$ wall materials.

The micro-fabrication of deep high aspect ratio structures is a fast moving field and several techniques are available. We make use of conventional ultraviolet optical lithography with the three dimensional structure being written through a two dimensional mask into a recently designed ultraviolet sensitive resist. This resist then becomes the former or pattern onto which three-dimensional structures in gold or copper etc can be plated.

Overall, the D-CIXS collimator construction requires the following micro-fabrication process steps:

- Mask design
- Mask fabrication using commercial facilities
- Resist application to suitable depth on suitable substrate
- UV exposure.
- Regions of resist exposed to UV are removed by wet chemical developing process.

Figure 5. Electron microscope photograph showing the finished product. Walls are $\sim 30\mu\text{m}$ thick.
• The wall structure is produced by electroplating copper into the gaps developed into the resist - to required depth
• Removal from substrate
• Remove resist template by chemical processing to leave the metal structure.
• Gold plate the copper structure.

As the detector is sensitive to visible light a light blocking filter is required. However, and more importantly, the filter also reduces to insignificant levels the background count from the isotropic flux of low energy solar electrons. A total thickness of 4000Å of aluminium filter reduces the electron flux to essentially zero whilst allowing the transmission of 1-10keV fluorescence X-rays. For maximum electron suppression and immunity to pinholes, the filter is implemented as two separate foils. Free standing filters of this thickness would be far too fragile to survive launch thus a suitable mesh support is required. The collimators themselves make ideal filter support structures.

X-RAY SOLAR MONITOR (XSM)

In order to obtain an absolute elemental abundance by the X-ray fluorescence technique, it is essential to continuously monitor the solar X-ray flux that excites the lunar emission. The flux of the Sun in the energy range 0.1-20 keV, is very high, and variable. The spectrum is generally soft, with most of the photons concentrated in energies below 1 keV. The variability, on the other hand, is mostly in the higher energies associated with variable high temperature active regions and flares. Even if we filter out the essentially constant low energy part of the flux below 0.8 keV, the high photon fluxes dictate a very small detector active area.

![SMART-1 X-ray Solar Monitor Efficiency](image)

*Fig 2 Predicted spectral response of XSM detector*

We find that an optimal energy passband is given by a 13 micron beryllium window. The standard design includes an aluminium contact of 500 nm thickness, and the estimated Si dead layer is 200 nm. Predicted yield is about 1 cps at solar cycle minimum, about 100 cps at solar maximum, when the SMART-1 mission will take place, and about 3000 cps during an X1 flare. A very rare class X10 flares would give a photon count rate above 10000 cps.

Two identical detector units are needed to ensure continual solar viewing. However, since they will not be measuring simultaneously, the same signal processing electronics can be used for both detectors after the preamplifier and the shaper stages. The electronics of the XSM consists of pre-amplifier stages, which are identical in the two sensor units, and an electronics board in the main D-CIXS instrument box, which includes further stages of the signal processing electronics. The required energy resolution is about 230 eV at 6 keV, sufficient for a good spectral analysis. Over the energy range of the instrument, the X-ray flux from the Sun will overwhelmingly dominate over the sky background or any other possible source simultaneously in the FOV.

X-RAY REMOTE SENSING OF THE MOON

The Apollo 15 and 16 missions carried remote X-ray detection instrumentation. An arrangement of gas proportional counters and filters enabled scientists to produce maps of the Mg/Si and Al/Si ratios for 9% of the Moon in equatorial regions. The data collected were of good spatial resolution and showed the heterogeneity of the lunar surface across different terrane, revealing differences in elemental abundances across those regions and establishing the importance of the technique. It also became clear that extrapolating these data to other regions of the Moon was not possible and that a global elemental dataset would be necessary to fully understand the distribution of materials across the Moon.

D-CIXS will provide the first global map of the Moon in X-rays. During normal solar conditions, it will be able to detect elemental Fe, Mg, Al and Si on the lunar surface while the on-board solar monitor, acting in real time, will enable the determination of absolute elemental abundances as well as the ratios produced by the Apollo missions. To date the absence of global maps of the elemental abundances of Mg, Al and Si represents a significant impediment to our understanding of the Moon. The global mapping of these elements and in particular Mg#, the magnesium number (MgO/[MgO+FeO]) therefore represents the prime goal of the D-CIXS experiment. During solar flare events, it will be possible to detect other elements such as Ca, Ti, V, Cr, Mn, Co, K, P and Na (Grande et al. 2000a), although a global survey of these elements is beyond the scope of the baseline mission.

In addition to lunar observations, the D-CIXS will carry out a number of observations during the extended cruise phase of the mission, as summarised in table 1.
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Table 1. D-CIXS Observation Regimes.

Although intrinsically capable of a spatial resolution of better than 40km, the SMART-1 orbit will result in an average resolution of >100km on the surface. Data obtained at these resolutions will allow for advances in several areas of lunar science, including:

- **Composition**: D-CIXS will make improved estimates of the bulk composition of the Moon.
- **Geochemistry**: D-CIXS will provide the first global maps of Mg, Al and Si surface elemental abundances, and hence derive a global Mg#.
- **Stratigraphic detail**: by studying large impact craters and basins, detailed observations of the lateral and vertical nature of the crust will be possible.
- **Volcanism**: chemical observations of the maria across the Moon will when coupled with other datasets provide a more complete compositional picture of maria volcanism.
- **Regolith**: monochromatic X-ray scattering background measurements combined with AMIE observations will provide a unique view of the lunar regolith.
- **Resources**: the global nature of the D-CIXS mapping will provide an important dataset for the location of important resource materials.

The D-CIXS baseline science targets will include the large-scale features such as impact basins, their mare fill, the highland regions and the elemental variation across each. In addition, some data on small-scale structures, such as the central peaks of large craters will be returned. A good example of the expected science targets of D-CIXS is the large impact basins. Impact basins are ideal candidates for observations using D-CIXS, as the instrument’s footprint will provide good coverage across features of this scale. Measurements of the elemental abundance across these features can be used to help refine estimates of the bulk composition of the lunar crust, and will result in a complimentary improvement in the evolutionary models to which this is applied. Perhaps most importantly, the data will provide us with the ability to investigate the distribution of magnesium and olivine across the Moon and with depth. Of particular interest is the South Pole-Aitken (SPA) basin. Believed to be the largest impact feature in the Solar System, it may have exposed materials from the lunar mantle (Lucey et al. 1998). D-CIXS will help us to further characterise the SPA terrane, and hence continue to improve our understanding of large-scale impact processes. The information on material excavated from depth will also contribute to models of thermal evolution, crustal differentiation and petrogenesis.

**SUMMARY**

The D-CIXS X-ray spectrometer on ESA’s SMART-1 mission represents a radical technological solution to the need to provide light, large area X-ray instrumentation for planetary exploration. The instrument is a new technological evolution, centered around a purpose-designed matrix of the newly developed Swept Charge Device (SCD) X-ray sensors mounted behind low profile copper collimators and aluminium thin film filters. The system has the virtue of providing superior X-ray detection, spectroscopic and spatial measurement capabilities, while also operating at near room temperature.

D-CIXS will provide the first global coverage of the lunar surface in X-rays, providing absolute measurements of elemental abundances. Under normal solar conditions, D-CIXS will be able to detect elemental Fe, Mg, Al, Si and several others in solar flare events. In combination with information to be obtained by the other instruments on SMART-1 and the data already provided by previous missions (i.e. Clementine and Lunar Prospector), this information will provide new insights into some of the fundamental questions that remain regarding the origin and evolution of the Moon. Further details of the D-CIXS instrument and the science objectives can be found in Grande et al. (2000) and Dunkin et al. (2000).

**REFERENCES**


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Nathaus A. et al. (2000), SIR, this volume.