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Flight performance of UV filters on the ALEXIS satellite

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ABSTRACT

The ALEXIS (Array of Low-Energy X-ray Imaging Sensors) mission, serving as the first dedicated all-sky monitor in the extreme UV, has been collecting data since its launch in 1993. ALEXIS operates in a 70° inclination orbit at an altitude of 800 km. The ALEXIS science mission is to observe the cosmic UV background and to study variability of EUV sources. The ALEXIS experiment is composed of six telescopes. Although the telescopes were only designed for a one-year technology verification mission, they are still functioning with much the same effectiveness as at the beginning of the mission. The telescopes comprise: 1) layered synthetic microstructure (LSM) spherical mirrors, 2) thin foil filters, and 3) microchannel plate (MCP) detectors, all enshrouded within the telescope body. The LSM mirrors select the bandpass for each telescope, while rejecting some of the HeII 304Å geocoronal radiation. The filters, constructed either from aluminum/carbon or Lexan/titanium/boron, serve to strongly reject the geocoronal radiation, as well as longer wavelength emission from bright OB stars. Each telescope detector consists of two plates, the outermost of which is curved to accurately match the spherical focal surface of the mirror. By reviewing the ground and flight histories, this paper analyzes the flight performance of the filters, including the effects of long term exposure and the formation of pinholes.

Keywords: ALEXIS; UV filters; filter performance; pinholes; pinwindows

1. INTRODUCTION TO ALEXIS

The ALEXIS satellite, launched in 1993, carried two experiments - ALEXIS (Array of Low-Energy X-ray Imaging Sensors) and BLACKBEARD, a radio frequency experiment which was a precursor to FORTE (Fast On-orbit Recording of Transient Events). The ALEXIS experiment became the first dedicated all-sky monitor in the extreme ultraviolet/ultrasoft x-ray regime (15-125eV). The science goals for ALEXIS were to detect and to monitor transient EUV sources, to look for EUV counterparts to gamma ray bursts, and to map the diffuse EUV background due to the hot interstellar medium.

The ALEXIS spacecraft flies in a low Earth orbit (LEO) with an altitude of 460 miles, an orbital period of 100 minutes, and an orbital inclination of 70°. The experiment consists of three pairs of telescopes with staggered fields of view that each subtend 33°. The satellite is spin-stabilized with a spin period of ~50 seconds, allowing the combined telescopes (>90° combined field-of-view) to sweep the entire anti-Sun hemisphere at a rate slightly higher than once per minute

The telescopes have EUV bandpasses centered around either 66eV (186Å), 72eV (172Å), or 93eV (130Å). Each pair of telescopes has a binocular configuration, such that any point viewed by the pair is simultaneously recorded in both telescopes, but with sensitivities to different photon energies. The orientation and bandpass center of each of the six telescopes are listed in Table 1. The telescopes first began opening to receive data on July 22, 1993, once operators had recovered the satellite after a launch problem [Bloch et al, 1994]. Data is taken mainly when the spacecraft is eclipsed by the Earth, and no data is taken during periods of 100% solar illumination ("hot times").

Each telescope is constructed from 1) a layered synthetic microstructure (LSM) spherical mirror, 2) a microchannel plate (MCP) detector, and 3) a thin film filter [Priedhorsky et al, 1988]. These components are all contained within the coffee-can-sized telescope body, as shown in Figure 1, and the instrumentation is protected from low-energy electrons by a magnetic broom located at the entrance aperture. The telescopes and supporting structure were built and integrated to the spacecraft bus at Los Alamos National Laboratory (LANL).

The LSM mirrors, designed at LANL and fabricated by Osmic Incorporated, are designed both to provide a high level of normal-incidence reflectivity at the desired wavelength for each telescope, and to minimize refectivitiy of the HeII 304Å component of the geocoronal background. Alternating layers of Mo and Si provide the main bandpass

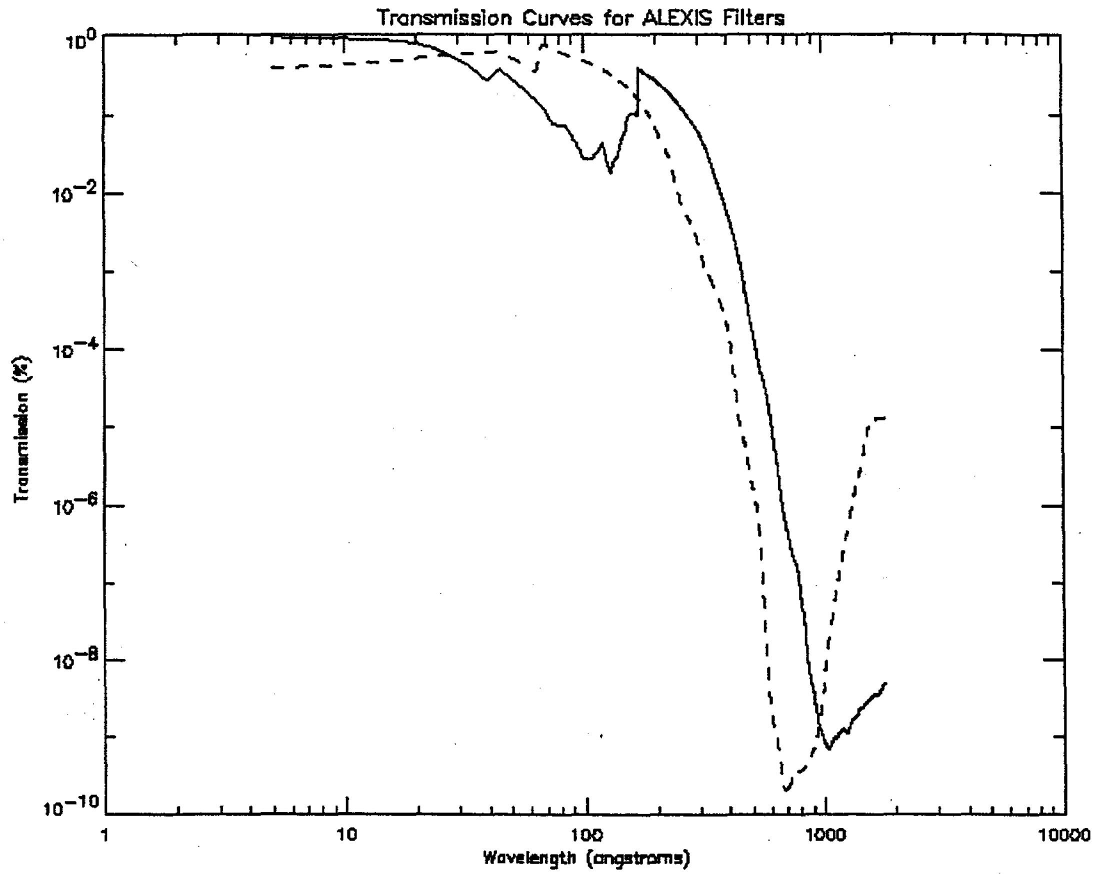

Figure 2: ALEXIS Filter Transmission Curves. The solid line corresponds to an Al:Si/C filter (2B), and the dashed line to a Lex/Ti/B filter (2A).

2. FILTER PERFORMANCE

The impetus for this study is the presence of ring-shaped signatures on the images produced from several of the telescopes. Some of the signatures have been strong in images from telescope 2A since first light; some appeared in telescope 3A in 1995 and strengthened until they noticeably diminished the performance of that telescope. Still other signatures are evanescent - only occasionally detectable, and sometimes only as a portion of a ring.

With the first observations of these signatures, it was immediately hypothesized that they were due to holes in a filter, focussing background photons in the image of the annular aperture, as in a pinhole camera. Software "masks" were developed to screen out these strong signatures, but the evanescent signals were harder to manage. Why true "holes" in the filter should only transmit occasionally was not known, and the reasons contributing to the formation of any of the point flaws creating the signatures were poorly understood. This paper represents an intensive examination of the filters in light of all that is known about the ALEXIS mission, and hopefully it can be of use to future UV filter applications.

3. FILTER LIFE HISTORIES

3.1 Fabrication

The ALEXIS filters were manufactured by Luxel Corporation between December 1989 and April 1990. Each filter consists of layers of EUV absorptive materials, formed by vacuum deposition and attached to a wire mesh substrate. The mesh is electroformed nickel, comprising a grid with a spacing of 360 μm and a transmittance of 82%.

3.3 Operation

The satellite was launched by a Pegasus rocket on April 25, 1993. During launch, the hinge bracket attaching one of the solar panels broke, resulting in a loss of attitude control and causing the spacecraft to be out of contact with the ground until June 2. The bus design should have shielded the telescopes from direct sunlight, but the post-accident attitude left the metal telescope bodies exposed to the Sun, allowing temperatures in the telescopes to increase to an estimated range of 275-300K.

Once the spacecraft was recovered and a nominal mode of operation was established, the telescope covers were opened between July 22 and August 31, 1993. ALEXIS has been in constant operation since first light. Since recovery, the nominal temperature environment for the telescopes, as measured by the telescope sensors[6], has been fairly benign. Over the course of the mission, the temperature during eclipse orbits has changed 2-3 degrees through a range of roughly 266-268K. Due to the precession of the inclined orbit, ALEXIS goes through periods of 100% solar illumination, called "hot times". These hot times are marked by increased temperatures of all spacecraft components, with the telescope sensors recording persistent temperature extremes, varying amongst hot times, of 270-275K. The hot time temperature variations - nominally 1-2 degrees per day - are even less abrupt than those observed during eclipse orbits.

4. DATA AND QUALITATIVE OBSERVATIONS

The history of the inspections, storage, and operation of the ALEXIS filters provides an important context for observations of filter transmission variability. Such variability may be over time (ie, degradation); it may also be over the surface of a single filter, causing localized variations in the telescope response (e.g., pinholes, pinwindows). Degradation, whether localized or widespread, results from filter material changes from various causes, such as stress relaxation or metal oxidation for example. Some spatial variations in transmissivity may not vary over time; for example, some nonuniformities in thickness - very small pits or bumps - might be created during manufacture yet remain invisible to inspection procedures.

4.1 System Degradation

Any significant, widespread degradation in the ALEXIS filters should have resulted in a change in observations of known sources over the satellite lifetime. Database records, however, show consistent source observations over the ALEXIS lifetime. That is, observed variations in count rates do not indicate a net change in performance as a system over the lifetime of the satellite. With no permanent change in these observations, neither the detectors, the mirrors, nor the filters must have undergone severe widespread degradation.

4.2 Localized Variations (Point Flaws)

Instead, the significant degradation experienced by ALEXIS filters seems limited to localized phenomena. These phenomena are observed as annular signatures on the detector images. An annular signature suggests either a "pinhole" or a "pinwindow". These two terms are sometimes used interchangeably, but for the purposes of this paper, they will denote two different phenomena. A pinhole is a small perforation in the filter, and a pinwindow is point of reduced opacity due to a variation in thickness or a localized chemical change, such as formation of a metal oxide or ablation of an organic by free radicals. Since the filter is positioned 2mm from the center of the spherical detector surface, the light from an otherwise filtered source passing through a small opening in the filter would fall in an elongated annulus on the detector. Because of the speculative nature of any attempts to distinguish between pinholes and pinwindows on ALEXIS, the neutral term "point flaw" will be used for any filter flaw which creates an annular signature.

The point flaws observed in the ALEXIS filters can be subdivided into two main groups: those with bright, persistent signatures, and those with dim, evanescent signatures. The bright signatures are visible as nearly complete annuli in every 12-hour data set, but the dim ones are rarely visible, and usually only as partial rings (see Figure 3). Most of the point flaws with dim signatures were first detected by summing several 12-hour images, as discussed below.

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[6] Located on the electronics boxes between each telescope pair, these sensors are thermally well coupled to the telescopes.

The image summation also confirmed that the point flaws in telescope 3A were evident in the first data collected after the Jan 1995 hot time, and that before this time there were no detectable dim point flaws at or near those positions. All of the other eleven point flaws that have been confirmed[7] appear to have been present since first light, as these eleven can all be detected in images produced just after operational voltage was achieved in their respective detectors.

To determine the sources of contamination penetrating the dim point flaws, the signatures were characterized in terms of the direction of origin of their photons and of variation in their strengths. When the photon origins for several dim annular signatures were mapped onto a grid of the sky, no point sources appeared to be responsible for the contamination. When the summed images were analyzed for a relation between orbit configuration and dim signature intensity, it was found that the dim point flaws in telescope pairs 1 and 2 appear to brighten when approaching and during dawn-dusk orbits in comparison to noon-midnight orbits. In addition, the signature brightness for all dim point flaws was observed to slightly anti-correlate with the anomalous backgrounds discussed in other ALEXIS papers [Roussel-Dupre' & Bloch, 1995]. This is probably due to increased count rates (>200 counts/sec) forcing the DPUs to stop digitizing the x-y positions of photon counts.

4.3 Recent Filter Inspections

A visual inspection of the witness filters kept at SSL, and extra flight-type (to distinguish from flight filters actually on the satellite) filters stored at LANL, was conducted at LANL in early 1999. Backlighting and oblique, reflected lighting were used for each inspection. The five witness filters were from the same batches as those used on ALEXIS, but were smaller and mounted somewhat differently from their flight counterparts. The outer 2mm of the 4.6cm-diameter flight-type filters were glued to and sandwiched between two metal rings, whereas the outer 2mm of the 1.3cm witness filters were glued on top of a hard epoxy ring with a beveled underside.

Figure 4 shows a photograph of a typical witness filter of the Al:Si/C composition. All the filters inspected appeared to be loosely attached to the supporting mesh; this presumably keeps tension in the film itself down to a minimum[8]. The witness filter for batch #03606 (Lex/Ti/B), corresponding to ALEXIS telescope 2A, had one flake or tear near the center of one of its grid squares, with a length of about 220 μm and a width of about 50 μm. The witness for batch #03639 (Lex/Ti/B), corresponding to telescope 1A, had about seven discolorations localized in one quarter of the filter, which were more visible on the boron side than on the Lexan side. The discolorations spread to diameters of 200-400 μm, and had dark, brown nuclei.

The witness for batch #03479 (Al:Si/C), corresponding to 1B and 3A, had no apparent flaws, though the foil was twice detached from the mesh wire for a length of about 350 μm. The witness for batch #03483 (Al:Si/C), corresponding to 2B and 3B, had 1 apparent hole in the carbon layer that was 0.8 mm from an edge and near the middle of a grid square. The hole was opaque to backlighting, but when observed with oblique lighting, reflected significantly more light than did the adjacent carbon film, indicating that the aluminum was exposed. The fifth witness filter, of an Al/Ti/C composition, did not correspond to any ALEXIS flight filters.

Only three of the ten extra flight-type filters inspected were of the same material composition as ALEXIS flight filters; these three were Lex/Ti/B, and revealed no pinholes. The flight-type filter from batch #03639, however, showed a patch of discoloration like those found on the witness from that batch.

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[7] Other possible flaws have been detected, but only the 14 clearly distinguishable point flaws are discussed in this paper.

[8] The Al filter composites appeared to have more variability in tautness over a single filter than did the Lexan composites.

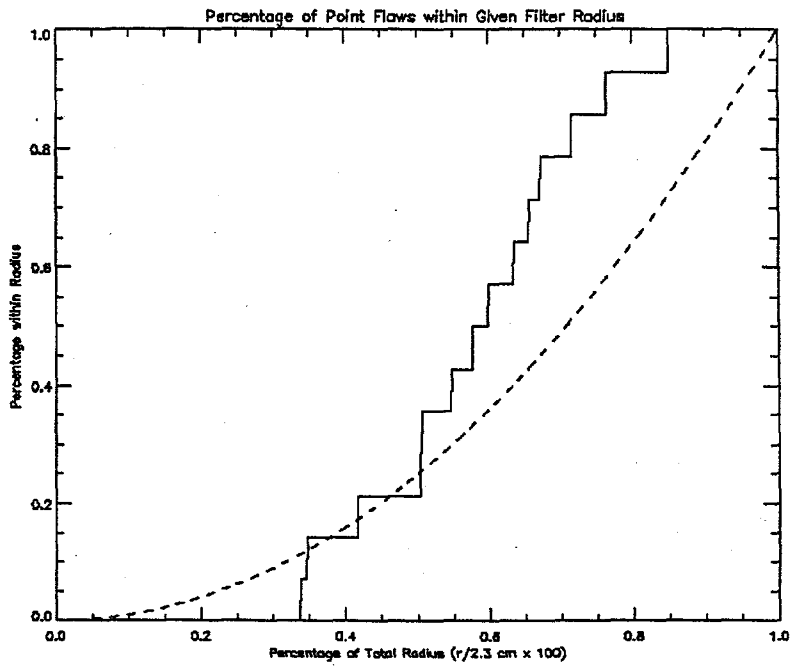

Figure 5: Percentage of point flaws within given normalized radius (solid) and percentage of filter area within radius, $f = radius/radius_{max}^2$ (dashed)

Kolmogorov-Smirnov analysis rejects ($p > 0.9$) the hypothesis that the point flaw radial coordinates belong to the area distribution (i.e., have radial coordinates that fit a random distribution over a circular area); visual inspection of the data suggests a bias for a band between about 40-80% of the total filter radius.

Similar analysis of the bright and the dim signatures as separate groups was performed. The hypothesis that the bright point flaw locations are evenly distributed is rejected ($p > 0.9$) by the test. However, the test does not significantly reject the hypothesis that the dim point flaw locations are evenly distributed on the filters, so this phenomenon probably has no preference between filter edges or centers.

6. DISCUSSION

An ideal filter is invariant in its performance - both over time and over its surface. Time variations, also described here as degradation, cause the instrument response to be uncertain. Since space missions can rarely afford to replace degraded UV filters, experiment designers must seek filters with the least potential for degradation. Filters should also be uniform over their surfaces; localized differences in transmission characteristics reduce instrument effective areas, make the interpretation of instrument data more difficult, and even reduce effective experiment on-time by increasing data count rates past the limits of the data processing units.

6.1 Degradation of UV Filters

The performance of filters similar to those used on ALEXIS has been explored by several authors. F. Powell [1989] presents a review of Luxel's UV filter technology and performance. One point of interest in his paper is aging effects, particularly the effects of oxidation on aluminum filters. The observations presented suggest that an aluminum filter will become more opaque in the range from about 200-800Å as it oxidizes. Results that might have dealt with surface variability, such as pinholing, were not discussed.

P. Vedder et al [1992] describe the EUVE filter lifetesting program in depth. No significant degradation was recorded in the filters of similar composition to those on ALEXIS, and no pinholes had been detected in the witness filters during the 2-5 years between their manufacture and 1992.

Both of these papers indicate that Lexan filters should not degrade significantly and that aluminum filters, if they degrade, become more opaque in the range from 200-800Å and change little in the ALEXIS wavelength range (130-186Å). C. M. Castelli et al [1997] point out, however, that oxidized aluminum is semi-transparent at visible and by coefficients of 10^{-9} and 10^{-6} for the Al:Si/C and Lex/Ti/B filters, respectively. Calculations for a 1500Å-thick filter suggest that points on the order of 10Å thinner could allow transmissions 10% greater, at coefficients of 10^{-6}, than the nominal filter thickness would allow. By comparing the ALEXIS filter thickness tolerances with the transmission characteristics of the filter materials used, it was found that transmission variations on the order of 10%, such as were observed in the dim point flaw signatures, in the very low transmission range of the far UV (near 1200Å) could result from filter pits in a single layer shallow enough to be well within tolerance levels (see Table 1 for tolerances). These flaws probably would not have been detected by inspections or calibrations, since no time-integrated mapping of the filter surface was done.

There are spans of time when otherwise visible dim point flaw signatures are totally indistinguishable, even when counts are summed over a week or a month. Since back illumination by point sources has been ruled out at least for some ALEXIS data sets, the only pattern that is suggested by these variations in intensity is a strengthening of signatures during dawn-dusk orbits as opposed to noon-midnight orbits. The increase in dim signature intensity during dawn-dusk orbits could further implicate the geocoronal backgrounds, because the telescopes take data in the sunlight more often during these orbits, and so view more of the geocoronal radiation from the sunlit atmosphere. Since the Al:Si/C filters block the strong Lyman-α background much more effectively than do the Lex/Ti/B filters, shallow pits of similar geometry in both types of filters would be expected to be more detrimental to the function of the Lex/Ti/B filters. Though the ALEXIS data is not well enough understood to be conclusive, the Kolmogorov-Smirnov results do show a possible preference for detecting dim point flaws in the Lex/Ti/B filters.

6.3 Ground Filter Inspections

The degradation modes observed in the witness filters may be considered as possible modes of degradation for the flight filters. In the Al:Si/C filters, a hole in the carbon layer should be noticeably more transparent to wavelengths between about 250-850Å, since Al has a transmission of ~50% [Luxel 1999] at these wavelengths. The effect of the strong 304Å geocoronal background would increase by a factor of about two, which is consistent with the character of the bright point flaws observed in 3A.

For the Lex/Ti/B filters, the "nucleated discolorations" found in the witness filter for batch #03639 may be a mode of degradation. From visual observations of only two filters, it is difficult to tell what the discolorations are, or why, in the filter containing multiple discolorations, they are located in only one quarter of the filter. This localization discredits the discolorations as the mode of failure prevalent on ALEXIS, since the distribution of the dim point flaws is relatively random. Chemical and optical analysis of these discolorations would be useful in gaining a better understanding of their importance.

The filter inspections conducted for this paper substantiate the worth of various lighting approaches in inspecting for flaws. The carbon hole would not have been detected using the backlighted inspection procedure adopted for the ALEXIS project; therefore, oblique lighting is of use. The discolorations in the Lex/Ti/B filters were nearly invisible from one side, so observing both sides was essential.

6.4 Environmental Effects

The effects of the thermal environment encountered by the ALEXIS filters are unknown. Thermal effects might be closely related to mechanical stresses in that thermal cycles of expansion and contraction of the metal rim would stress the more fragile filter materials. The appearance of pinholes just after a hot time does suggest that temperature fluctuation may be a mechanical stressor for the filters. ALEXIS underwent over 25 full hot times, though, so the uniqueness of the event indicates that such stress is probably mild.

The filter for telescope 2A at one time underwent a pressure impulse of unknown intensity. Though Lexan is very good at resisting pressure impulses, this event may be related to the density of point flaws in this filter (7 out of 14 flaws are in 2A). With only one datum, whether or not this impulse resulted in filter degradation cannot be known.

7. CONCLUSIONS

The ALEXIS experiment, designed as an EUV/soft x-ray all-sky monitor, has been in continuous operation since 1993. The UV filters used on ALEXIS showed signs of localized variations in transmission - points of decreased opacity - as soon as the telescopes reached flight voltage. ALEXIS data was analyzed in an effort to understand these variations and the performance of the filters in general.