INVESTIGATION OF THIN FILM ALUMINUM FILTER CONTAMINATION BY MONOMETHYLHYDRAZINE (MMH)–NITROGEN TETROXIDE (NTO) PLUMES

by

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To the memory of my uncle Professor Kanhaiya Lal (K.L) Gupta (University of Alberta)
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Abstract

Thin-film aluminum filters degrade in space with significant reduction of their Extreme Ultraviolet (EUV) transmission. This degradation was observed on the EUV Spectrophotometer (ESP), onboard the Solar Dynamics Observatory’s EUV Variability Experiment and the Solar EUV Monitor (SEM), onboard the Solar and Heliospheric Observatory. One of the possible causes for deterioration of such filters over time is contamination of their surfaces from plumes coming from periodic firing of their satellite’s Monomethylhydrazine (MMH) – Nitrogen Tetroxide (NTO) thrusters. When adsorbed by the filters, the contaminant molecules are exposed to solar irradiance and could lead to two possible compositions. First, they could get polymerized leading to a permanent hydrocarbon layer buildup on the filter’s surface. Second, they could accelerate and increase the depth of oxidation into filter’s bulk aluminum material. To study the phenomena we experimentally replicate contamination of such filters in a simulated environment by MMH-NTO plumes. We apply, techniques like Scanning Electron Microscopy and X-Ray photoelectron spectroscopy to characterize the physical and the chemical changes on these contaminated sample filter surfaces. In addition, we present our first analysis of the effects of additional protective layer coatings based on self-assembled carbon monolayers for aluminum filters. This coverage is expected to significantly decrease their susceptibility to contamination and reduce the overall degradation of filter-based EUV instruments over their useful mission life.
Preface

Using thin film aluminum (Al) foil filters is a standard technique used for spectral filtration of solar radiation. They transmit soft X-ray (SXR) and Extreme Ultraviolet (EUV) and eliminate the solar visible and near UV spectrum. Over the years, several satellite-based instruments have used these aluminum based filters for observing the Sun in the SXR (0.1-7 nm) and the EUV (17-57 nm) wavelength regions. Mechanically these aluminum filters remain in service for decades but their EUV transmission starts reducing almost immediately after launch. However, the rate of loss of their EUV transmission is not constant. It gradually slows with time and eventually plateaus in about a few years. This loss in filter transmission directly leads to an attenuated flux at the detectors which then affects the overall sensitivity of the measurements.

Together with our experiences with EUV Spectrophotometer (ESP) and Multiple EUV rating Spectrograph (MEGS) on NASA’s Solar Dynamics Observatory (SDO), Solar Extreme Ultraviolet Monitor (SEM) on Solar and Heliospheric Observatory (SOHO) and other previous aluminum filter-based EUV instruments, it has become recognized that the aluminum filters are considerably more susceptible to performance degradation in outer space, especially when compared to other EUV filter types like carbon coated zirconium. The reasons for such a difference in performance over time between two filter types, even when placed on the same instrument, next to each other, are not yet clearly understood and needs further investigation. Our experiments here, are designed as a “proof of concept” to reproduce one such contamination possibility of aluminum filters by their satellite’s Monomethylhydrazine-Nitogentetioxide (MMH-NTO) based attitude control thruster exhaust plumes under solar UV radiation environment, in a laboratory setup. This experiment will also help us in developing a methodology to measure the effectiveness of a
protective coating that is designed with the goal of shielding these aluminum filters from molecular contamination in outer space environment.

This thesis work is divided into four major sections. Section one gives the background and a brief overview of the science objectives, instrumentation and various EUV filters. This section includes three chapters. Chapter 1 briefly discusses the Sun and its variability in extreme ultraviolet wavelength region. This solar variability necessitates that we have high resolution solar EUV measurements that are long term, stable and accurate. Chapter 2 describes some of the major design principles and features of University of Southern California’s Space Sciences Center’s (SSC) EUV spectrophotometers, SOHO/CELIAS/SEM (1995) and SDO/EVE/ESP (2010). Chapter 3 presents some of the most common thin film metal foil filters that are used for EUV bandpass and are found suitable for such space based applications. Here we also discuss the ageing effects due to moisture and air on aluminum filters at standard atmospheric conditions.

Section two describes the problem statement i.e. degradation of EUV aluminum filters in space. This section includes two chapters, Chapter 4 and Chapter 5. Chapter 4 broadly covers some of processes associated with molecular contamination in space, with attitude thruster exhaust plumes as one of the major recurring sources. This is followed by Chapter 5 which describes the degradation problem associated with aluminum filters on both SOHO/CELIAS/SEM, SDO/EVE/ESP and other instruments using similar filters.

Based on our analysis in Chapter 5, we developed some thin monolayer coatings for aluminum filters which would act as a protective layer, shielding underlying aluminum filters from any direct contact/chemical reaction with plume/contaminants. These coatings are created with the goal of minimizing filter degradation on both ground and in outer space (environment).
Section three describes our methods (chapter 6-9), i.e., the contamination experiment and various characterization techniques. In Chapter 6, we explain our experiment with the objective of investigating aluminum filter contamination by a satellite’s thruster plumes. This contamination is done with and without ultraviolet (UV) light exposure, to specifically investigate solar UV radiation effects on the MMH-NTO reaction and its (products) subsequent interactions with various filter surfaces. This is followed by chapter 7-9 where we give a brief overview of characterization techniques, their respective measurements (data) and a brief analysis limited to the results obtained through a particular technique. The techniques discussed are FT-IR (chapter 7), XPS (chapter 8) and SEM/EDS (chapter 9).

Finally, in Section 4 (Chapter 10-11) we present our results in chapter 10 by taking a combined view (and more) of all measurements from various techniques in Section 3. This is followed by conclusion and future work in Chapter 11.
Section I

Background and Overview

The Sun and its EUV
Chapter 1. Sun and its EUV Variability

1.0 Introduction

Sun is the primary energy source for the earth’s atmosphere system and measurements during the last few decades have shown that any changes in solar output can have an observable impact on Earth’s atmospheric composition and structure. The effects of any solar variability on Earth’s climate not only requires fundamental knowledge of the processes that drive the atmospheric circulation, but also understanding of how these processes change in response to both external (solar) and internal factors over a wide range of time scales. Also, the exact mechanisms behind this solar variability (inside the sun) are complex and not yet fully understood. Therefore, any study investigating dynamic solar behavior or its impact on Sun-Earth system requires, absolute, long term and spectrally resolved solar irradiance measurements in multiple wavelength bands, across complete solar spectrum.

Figure 1.1 shows the solar spectrum from EUV to infrared spectral range (10-100,000 nm), its spectral variability ((max-min)/min) during an eleven year solar cycle, and the spectral component that ultimately penetrates earth’s atmosphere to reach at sea level. This solar spectrum broadly resembles to that of a blackbody at ~5770 K, whose emissions are overwhelmingly dominated by the visible and IR regions, with irradiances in EUV (and SXR) region, about only 10 ppm (parts per million) of the total solar energy output(Woods and Rottman 2002). However, solar irradiances in EUV and SXR wavelength regions has many characteristic emission lines of source elements inside the sun (like Fe 28.4 nm, He 30.4 nm) which suggest that they are emitted from regions that have much higher temperature than ~5770 K (Klimchuk 2006).
Figure 1.1. Solar irradiance vs Wavelength (nm). The spectrum of solar radiation from 10-100,000 nm (dark blue), its variability between Solar Maximum and Solar Minimum (green) and the relative transparency of Earth's atmosphere at sea level (light blue). At wavelengths shorter than about 300 nm, there is a relatively large variation in the Sun's extreme UV and x-ray output (greater than 1%), but the Earth's atmosphere is nearly opaque at those wavelengths (Lean 2011).

Based on these observations (emission lines), a temperature profile of various layers of solar atmosphere has been suggested (Yang et al. 2009). Figure 1.2 shows the link between various EUV emission lines and the region of solar atmosphere they are associated. Most of these emission lines, short ward of 50 nm, are either from transition region where temperatures are well above 15000 K or solar corona (temperature > 5 million K).

Although, solar EUV-SXR irradiance is just a small fraction (1ppm) of the total solar output, it is highly variable (green plot in Figure 1.1) with time compared to other regions of the solar spectrum. Moreover, solar EUV is the main source of energy and ionization of earth’s upper atmospheric regions and responsible for driving some of the major processes associated with overall earth-space weather
there. Therefore high resolution measurements of solar EUV-SXR emissions is extremely important, not only from the point of view of understanding the sun and its dynamicity, but also its effects on Sun-earth system. However, this energy (EUV) never directly penetrates to the surface of the earth and almost completely gets absorbed by earth’s upper atmosphere(s), therefore, any absolute or direct measurements in this region requires use of satellite based or rocket borne instrumentation.

1.1 History of Solar Measurements

The first early records in modern history, pointing to solar variability began with the discovery of the sunspots by Galileo in the early 17th century. By the mid-19th century, an 11 year variation trend was recognized in these sunspot numbers. Modern era of solar variability started when ground based measurements of solar F10.7 cm radio flux also successfully detected an eleven year cycle variation in sun’s radiative output. This solar radio flux at 10.7 cm (microwave) wavelength, i.e. F10.7 index, was later found to correlate well with various wavelengths within the solar EUV-SXR emissions and the conditions in earth’s upper atmospheric system that depend on solar EUV and SXR emissions (Tobiska 1988). This was followed by continuous Mg II core to wing ratio (279.9 nm) measurements from space. This index is based on correlation of changes in the spectral shape of the Mg-II absorption feature (~280 nm) with EUV and SXR irradiance (Viereck et al. 2004). Together, Sunspot number R, F10.7 and Mg-II core to wing ratio were commonly used as solar EUV proxies. Figure 1.2 shows the link between various solar proxy indices and the location in solar atmosphere where they are formed. These indices were used as input for various solar models and earth’s upper atmospheric models/applications, until absolute EUV-SXR measurements became feasible.
Figure 1.2. The location in the solar atmosphere where the six daily average proxies are formed, along with the time periods when each proxy was measured and available to use (Chamberlin, Woods, and Eparvier 2007).

Figure 1.3 shows several proxy time series of various indices from 1978-2001. Absolute solar UV, EUV and XUV measurements from space only began by latter half of 20th century, which for most part remained sparse, and were available for short durations. The first continuous (long term) absolute solar measurements in EUV began with the launch of Solar and Heliosphere observatory (SOHO) (Harrison et al. 1995). This was followed by several other missions like SDO, TIMED (Woods and Eparvier 2006), SORCE (Woods, Rottman, and Vest 2005), ISS (Nikutowski et al. 2011), PROBA2 (Dominique et al. 2013), and GOES (Evans et al. 2010) giving us several overlapping measurements in EUV-SXR of solar radiative variation measured from multiple different vantage points in space.
Figure 1.3. Proxy time series between 1978 and 2001 for the composite total solar irradiance (upper), NSO/KP magnetic flux, composite Mg II index, He I index, 10.7 cm radio flux, and the sunspot number (Fox 2003)
Today, by combining this data from several of the above missions, a complete picture of the Sun over an entire 22-year magnetic cycle could be constructed for the first time. Figure 1.4 shows one example of such absolute photon flux measurements (in 26-34 nm) time series (1995-2014) constructed using data from SOHO/CELIAS/SEM (Sun-Earth Lagrange point L1) and SDO/EVE/ESP (geosynchronous orbit) (Wieman 2015). Figure 1.4 shows the composite total solar irradiance measured by various space borne instruments from 1975-2012. Note (on Figure 1.5) that the variation in TSI correlates with changes in monthly sunspot number.

![Figure 1.4](image)

**Figure 1.4.** Measurements in Solar EUV photon flux vs time from 26-34nm, using data from SOHO/CELIAS/SEM and SDO/EVE/ESP from 1995-2014 (Wieman 2015).
1.2 Solar EUV- SXR Variability

The solar variability occurs on many time scales and is actually both long term (years to decades) as well as short term (seconds to days). This variability is related to solar dynamo and associated with constantly changing structure of its magnetic field, within (inside) the sun and beyond its surface. The long term solar EUV variability (Figure 1.5) is primarily identified with 11 year sunspots cycle, which is understood to be associated with the 22 year solar magnetic cycle. The number of sunspots can vary from around \(\sim 0\), at solar minimum to as high as \(\sim 200\), at solar maximum during this eleven year period. The period of two consecutive solar minimum demarcates beginning and end of 11 year. This 11 year periodicity is seen in several measurements related to solar behavior like solar irradiance, particle emissions and polar magnetic fields.

Figure 1.5 shows the absolute total solar irradiance time series constructed from several space borne instruments over the years. Over an 11 year sunspot cycle, TSI generally varies about just .01%, whereas within the EUV region, the solar irradiance varies by at least by a factor of 1 (100%) (Green curve in Fig 1.1), with certain prominent emission lines showing variability few orders of magnitude or greater.

Meanwhile, the short term variability and its periodicity is usually associated with 27 day solar rotation cycle where solar EUV flux, when integrated from 0-120 nm can vary by around 30-40%. Figure 1.6 shows the time series of absolute irradiance in 26-34 nm region measured by SOHO/CELIAS/SEM for the rise of solar cycle24. The 27 day variability in solar irradiance by about 30-50% due to solar rotation can be clearly seen during this period. In addition, sudden events such as solar flares can cause a surge in solar EUV irradiance.
Figure 1.5 Total solar irradiance vs time (in years) using Space-borne measurements. Total solar irradiance (TSI) show ~0.1 percent variations with solar activity on 11-year and shorter timescales. Note that the TSI variability matches (shape) to (below) 11 year sun-spot cycle (Kopp 2014).

Figure 1.6. SOHO/CELIAS/SEM 26-34 nm irradiance time series for the rise of Solar Cycle 24. Strong short term 27 day solar rotation variability is evident, starting on Julian Day 2456100 (Wieman 2015).
These flares usually last from about a few seconds to hours, and can anytime trigger a fractional increase in solar EUV and SXR irradiance by up to 50%. The flares related events show no periodicity (in time or energy emissions) and are characterized by two separate phases i.e. impulsive phase and a gradual phase. The timing as well as flare related irradiance for each phase of a given flare varies across EUV and SXR wavelengths. Figure 1.7 shows one such example of EUV and SXR irradiances observed during a X6.9 class flare. The red line shows 26-34 nm channel, which is dominated by the He-II transition region line (30.4 nm) and shows an impulsive phase time profile. The emissions in impulsive phase usually tend to rise rapidly, peak early and decay quickly. The blue line (in Figure 1.7) shows the 0.1-50 nm channel which includes the contributions from both the transition region emissions as well as coronal SXR emissions and shows an early slow rise and gradual decay characteristic of gradual phase flaring superimposed on a fast rising and falling impulsive phase peak. The gradual phase emissions generally start earlier, rise slowly and last much longer than the impulsive phase.

![Figure 1.7. Irradiance vs time for EUV and SXR irradiances observed during X6.9 class flare. The 26-34 nm channel exhibits impulsive phase (that lasts for seconds) variability while the 0.1-50 nm signal (SOHO/CELIAS/SEM detector saturates at ~.02 W/m²) includes both much sharper impulsive phase and gradual phase after the saturation ended (Wieman 2015).](image-url)
1.3 EUV-SXR Irradiance and the Geospace Environment

The photochemistry and heating of the earth’s atmosphere varies with altitude and is strongly dependent on the wavelength of incident Solar EUV/UV radiation. The incident solar EUV and SXR photons are almost completely absorbed by Earth’s upper atmosphere (altitudes above ~90 km), mainly through photoionization, along with other processes like photoelectron heating and driving ozone and nitrogen cycle. These interactions of solar EUV-SXR photons with other constituents present in upper atmospheric region produces earth’s Ionosphere and is mainly responsible for processes that heat neutral species in the Thermosphere (Chamberlain and Hunten 1987). Therefore, any changes in EUV flux can give rise to large changes in thermal and compositional structure of Thermosphere and Ionosphere (see Figure 1.8.) directly affecting space weather conditions such as temperature, neutral and electron density profiles (Tobiska 1988).

**Figure 1.8.** Schematic of the major processes within the thermosphere that establish its global mean structure (Fuller-Rowell et al. 2003)
These changes in earth’s upper atmospheric regions significantly affect satellite operations (drag on low earth orbiting spacecraft), communications (propagation of HF radio signals) and navigation (accuracy of GPS signals). This makes absolute solar EUV irradiance measurements extremely important in modelling earth’s ionosphere and thermosphere in models like GAIM, CTIEPe, NRLMSIS and JB2006/JB2008. These models are highly useful in applications that require accurate space weather predictions. Furthermore, such high resolution measurements from instruments like SDO/EVE will improve solar irradiance models like NRLEUV, FISM and SIP and advance our understanding of solar irradiance modulation and its connection with solar (and its surface) magnetic flux variations.
Chapter 2. Instrumentation-EUV Spectrophotometers

This chapter gives the instrument overview of SOHO/CELIAS/SEM (1995) and SDO/EVE/ESP (2010). Both of these are transmission grating based EUV photo spectrometers that were designed and built at University of Southern California’s Space Sciences Center. The instruments take continuous measurements of solar irradiance in various band passes between 0.1-50 nm. This data is important for scientific investigations of the Sun and its variability and various atmospheric models.

2.1 SOHO/CELIAS/SEM

The Solar EUV Monitor (SEM), is a highly stable transmission grating based solar extreme Ultraviolet (EUV) spectrometer that is integrated into the Charge, Element, and Isotope Analysis System (CELIAS) instrument onboard the Solar and Heliospheric Observatory (SOHO), launched in 1995 (Hovestadt et al. 1995). SOHO/CELIAS/SEM (Figure 2.1-2.2), designed and built at the University of Southern California’s Space Sciences Center, measures the full disk absolute solar flux in two bandpasses, 26-34 nm (first order) and 0.1-50 nm (zeroth order). The 26-34 nm bandpass channel is centered at important He II Lyman-α 30.4 nm emission line. (Judge et al. 1998) which corresponds to the transition region between the Chromosphere and the Corona of the Sun.

SOHO/CELIAS/SEM is fitted with a EUV bandpass aluminum filter at (next to) its entrance aperture that blocks the visible portion of incident solar radiation and transmits the EUV-XUV. The filtered light (in EUV) the gets diffracted using a high density, free standing transmission grating (5000 bars per mm) (Schattenburg, Anderson, and Smith 1990) which is detected by three aluminum coated radiation
Figure 2.1. SOHO/CELIAS/SEM Schematic showing its working mechanism (Judge et al. 1998)

Figure 2.2. Opto-mechanical layout of the SOHO/CELIAS/SEM (Judge et al. 1998). (Top right) Actual flight instrument.
hard silicon photodiodes that are located at about a distance of ~200 mm, at one zeroth-order and two ±30.4 nm first-order positions (channels). The first order detectors measure the irradiance within an 8nm bandpass centered about 30.4 nm solar He II emission line, whereas the zeroth order detector measures the solar irradiance within the nominal aluminum bandpass between (0.1-77nm) to effectively 0.1-50 nm. Low-current electrometers at each photodiode are used to measure the analog photocurrent signals, which are thereby converted to digital frequencies with a linear voltage-to-frequency convertor. These output frequencies are then counted with a 0.25 second gate time and averaged over 15 seconds before being transmitted through telemetry to the ground station (earth).

The absolute response function of the SOHO/CELIAS/SEM instrument was measured using a calibrated light source at NIST SURFIII on beam-line 9 with 1 nm resolution over a spectral range from about 15 to 49 nm. The response function of the zeroth-order channel for soft x-ray wavelengths shorter than 15 nm was modeled based on photo absorption and transmission values for the relevant materials found in (Henke, Gullikson, and Davis 1993a). Figures 2.3-2.4 show examples of short term and long term solar measurements by SOHO/CELIAS/SEM. These resolution and cadence of SOHO/CELIAS/SEM measurements, have since helped in tracking of minute variations in irradiances during various phases of solar activity (Wieman 2015).

‘More than 13 years of EUV measurements have shown that the SOHO/CELIAS/SEM is a highly accurate and stable EUV spectrometer that has suffered only minor degradation mainly related to deposition of carbon on the SEM aluminum filters” (Didkovsky et al. 2012).
Figure 2.3. Spectral irradiance vs Wavelength (nm) coverage for SOHO/CELIAS/SEM zeroth order channel (in pink) from 0.1-50 nm band and two first order channels from 26-34 (in orange).

Figure 2.4. Temperature (K) vs Height (km) profile in solar atmosphere. The peak emission lines includes He II 30.4 nm (304 Å) at the transition region. (Yang et al. 2009)
SOHO/CELIAS/SEM has been periodically calibrated by launching sounding rocket under flights with an SEM clone along with other spectrometers like RGIC absolute detector as payloads. Multiple such calibrations over time, had shown that the sensitivity of SOHO/CELIAS/SEM was decreasing, primarily due to degradation of its primary Aluminum filter which led to reduced transmission (increased opacity) (Figure 2.5) in its EUV bandpass. Although, neither does the exact source nor the processes involved with contamination could be determined with certainty, this degradation has been attributed to molecular contamination by hydrocarbons, which are thought to be polymerizing under solar UV radiation exposure on Al filter surface. This hydrocarbon deposition is currently modelled like a Carbon/CH based contaminant layer that grows in thickness $\tau$ with time according to:

$$\tau(t) = a + b \cdot e^{-t/c}$$  \hspace{1cm} (2.1)

where $t$ is time from the beginning of the mission and $a$, $b$, and $c$ are parameters that are determined to minimize discrepancies between sounding rocket and corresponding on-orbit measurements. (Wieman 2015). Figure 2.5 shows this modeled contaminant layer growth (red curve) based on above calculations using solar reference spectra, SOLERS22. A newer contaminant growth curve by (Wieman 2015) using FISM reference spectra will be discussed in later chapters. In (Judge et al. 2002), a degradation factor was introduced into SOHO/CELIAS/SEM’s main data processing algorithm to account for this filter transmission loss (and instrument sensitivity) in SOHO/CELIAS/SEM’s absolute measurements (raw data). The degradation factor is applied as a wavelength dependent transmission value between 0 and 1 determined from carbon photo absorption cross-sections, $\sigma_C(\lambda)$, as:

$$\lambda(t) = \exp(-\sigma_C \cdot \tau)$$  \hspace{1cm} (2.2)
2.2 SDO/EVE

The *Extreme ultraviolet Variability Experiment* (EVE) (Woods et al. 2012) was launched (Feb, 2010) onboard NASA’s *Solar Dynamics Observatory* (SDO) (Pesnell 2015) into earth’s geosynchronous orbit. Following SOHO/CELIAS/SEM and Times/SEE instruments, EVE data extends the record of continuous solar EUV, SXR irradiance measurements from 0.1 to 105 nm with unprecedented spectral resolution (0.1 nm), temporal cadence, and accuracy.

The EVE instrument suite (Figure 2.6) consists of the following five irradiance channels (sub instruments). Due to a power supply failure on 26th May, 2014, only three (MEGS-B, ESP, MEGS-P) of the below five channels remain currently (as of Aug 2015) operational.
• **The MEGS-B channel** was a normal-incidence, dual-pass spectrograph that provides the solar EUV irradiance in the 35 to 105 nm range with 0.1-nm resolution.

• **The EUV Spectrophotometer (ESP)** channel provides the solar EUV irradiance in broadband between 0.1 and 39 nm.

• **MEGS-Photometer channel** provides the irradiance measurements of Sun’s bright hydrogen emission at Lyman-α (121.6 nm).

• **The Multiple EUV Grating Spectrographs (MEGS)-A** was a grazing incidence spectrograph that provides the solar EUV irradiance in the 5 to 37 nm range with a 0.1-nm resolution (*non-operational since May, 2014*).

• **The Solar Aspect Monitor (SAM) instrument** is a filtered pinhole camera, within the MEGA-A housing, that provided alignment information of EVE in the visible light along with low resolution images of the sun in the 0.1-7 nm SXR spectral range through detecting individual X-ray photon events using a photon counting technique (*non-operational since May, 2014*).

Table 2.1 briefly lists specifications for all above channels on EVE instrument suite. MEGS-A and ESP are discussed in more detail below (Woods et al. 2012).

![Image](image-url)

**Figure 2.6.** The EVE instrument suite, shown with entrance door mechanism for ESP and various MEGS channels. (Woods et al. 2012)
Table 2.1. EVE solar irradiance instruments. $\Delta \lambda$ is the spectral resolution, $\Delta t$ is the normal operations integration time (cadence). $R$ is the grating radius of curvature, $d$ is the grating line spacing, $\alpha$ is the grating incidence angle, $\beta$ is the grating diffraction angle, 1 and 2 for MEGS-B refer to its two different gratings. 2nd is the filter used for second- and higher-order sorting calibrations. BI is Back-Illuminated (back-thinned) for the CCD type, AXUV is XUV grade (n-on-p) Si photodiodes from IRD.

<table>
<thead>
<tr>
<th>Instrument (slit, mm²)</th>
<th>$\lambda$ Range (nm)</th>
<th>$\Delta \lambda$ (nm)</th>
<th>$\Delta t$ (sec)</th>
<th>Filters</th>
<th>Grating</th>
<th>Detector</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEGS-A</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slit A1 (0.02 × 2)</td>
<td>5–18</td>
<td>0.1</td>
<td>10</td>
<td>Zr/C</td>
<td>$R = 600 \text{ nm}$</td>
<td>$d = 1304 \text{ nm}$</td>
<td>1024 × 2048</td>
</tr>
<tr>
<td>Slit A2 (0.02 × 2)</td>
<td>17–37</td>
<td>0.1</td>
<td>10</td>
<td>Al/Ge/C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MEGS-B (0.035 × 3.5)</td>
<td>35–105</td>
<td>0.1</td>
<td>10</td>
<td>None</td>
<td>$R_1 = 200 \text{ nm}$</td>
<td>$d_1 = 1111 \text{ nm}$</td>
<td>1024 × 2048</td>
</tr>
<tr>
<td>(26 µm Dia.)</td>
<td>250</td>
<td>80</td>
<td>10</td>
<td>Acton 250W</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MEGS-SAM</td>
<td>1–7</td>
<td>1</td>
<td>10</td>
<td>Al/Ti/C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Table 1 (Continued)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Instrument (slit, mm²)</td>
<td>$\lambda$ Range (nm)</td>
<td>$\Delta \lambda$ (nm)</td>
<td>$\Delta t$ (sec)</td>
<td>Filters</td>
<td>Grating</td>
<td>Detector</td>
<td>Description</td>
</tr>
<tr>
<td>MEGS-P (0.035 × 3.5)</td>
<td>121.6</td>
<td>10</td>
<td>0.25</td>
<td>Acton 122XN</td>
<td>MEGS-B1</td>
<td>AXUV-100</td>
<td>HI Lyman-α Photometer. Uses MEGS-B Slit and Grating.</td>
</tr>
<tr>
<td>ESP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Normal Incidence, Transmission Grating Spectrograph. Entrance Slit, Al Filter, and Grating shared with all ESP channels. Quad Diode (QD) is at 0th order, other channels are at ±1st order.</td>
</tr>
<tr>
<td>(1 × 10) Ch 1:</td>
<td>36.6</td>
<td>4.7</td>
<td>0.25</td>
<td>Al</td>
<td></td>
<td>AXUV-SP2</td>
<td></td>
</tr>
<tr>
<td>Ch 2:</td>
<td>25.7</td>
<td>4.5</td>
<td>0.25</td>
<td>Al</td>
<td></td>
<td>(6 × 16 mm²)</td>
<td></td>
</tr>
<tr>
<td>Ch 3:</td>
<td>Dark</td>
<td>N/A</td>
<td>0.25</td>
<td>Thick Ta</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ch 8:</td>
<td>18.2</td>
<td>3.6</td>
<td>0.25</td>
<td>Al</td>
<td></td>
<td>AXUV-PS5</td>
<td></td>
</tr>
<tr>
<td>Ch 9:</td>
<td>30.4</td>
<td>3.8</td>
<td>0.25</td>
<td>Al</td>
<td></td>
<td>(6 × 16 mm²)</td>
<td></td>
</tr>
<tr>
<td>Ch 4–7 QD:</td>
<td>0.1–7</td>
<td>6</td>
<td>0.25</td>
<td>Al + Ti/C</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2.2.1 SDO/EVE/MEGS-A

MEGS-A channel (Figure 2.7) is an 80° grazing-incidence, off-Rowland circle spectrograph with a CCD detector that measures the solar spectrum between 5-37 nm (~0.1 nm spectral resolution). It uses a spherical holographic grating with a radius of curvature of 600 mm, platinum coating, and 767 grooves mm⁻¹ with a laminar groove profile to suppress even orders. The detector for MEGS-A is a back-thinned, back-illuminated, split-frame transfer CCD with 1024×2048 pixels. More details on MEGS can be found in (Crotser et al. 2004).

It has two entrance slits (slit 1 and slit 2), that correspond to channels MEGS-A1 and MEGS-A2 respectively. In front of each slits, there is a filter wheel mechanism that contains different bandpass filters at various positions. Table 2.1 lists some of the main specifications for MEGS-A.

**MEGS-A1**

Slit 1 (MEGS-A1) channel primarily isolates 5-18 nm using a Zr (280 nm)/C (20nm) filter with another Zr (230 nm) / Si (120 nm) / C (20 nm) filter (on wheel) occasionally providing measurements between 13-18 nm. A blanked-off position on each filter wheel provides dark measurements.

**MEGS-A2**

Similarly, Slit 2 (MEGS-A2) primarily isolates 17-37 nm wavelength region using an Al (200 nm) / Ge (20 nm) / C (20 nm) filter. It also has an Al (180 nm) / Mg (300 nm) filter with a bandpass from 25 to 37 nm.
Figure 2.7. Opto mechanical layout for one of the MEGS A channel (Crotser et al. 2007)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>λ Range</td>
<td>0.1 - 7 nm</td>
</tr>
<tr>
<td>Λ Resolution</td>
<td>0.01 - 1 nm</td>
</tr>
<tr>
<td>Time Cadence</td>
<td>10 sec</td>
</tr>
<tr>
<td>Field of View</td>
<td>± 2°</td>
</tr>
<tr>
<td>Aperture Door</td>
<td>One-shot</td>
</tr>
<tr>
<td>Filter Wheel</td>
<td>5 positions (A1 and A2)</td>
</tr>
</tbody>
</table>
2.2.2. SDO/EVE/ESP

The Extreme Ultraviolet Spectrometer (ESP) (Didkovsky et al. 2012) is one of the five channels of the Extreme Ultraviolet Variability Experiment (EVE) onboard the NASA Solar Dynamics Observatory (SDO), and is an advanced/extended version of SOHO/CELIAS/SEM (Judge et al. 1998). ESP’s (Figure 2.8) design is based on similar type of free standing transmission grating (200 nm period) that is shared by all of its wavelength bands. Compared (Table 2.3) to SOHO/CELIAS/SEM’s three channels, SDO/EVE/ESP measures solar irradiance at four first order EUV wavelength bands that are centered at 18.2, 25.7, 30.4 (overlaps with SOHO/CELIAS/SEM) and 36.6 nm (non-operational), each with ~4nm bandpass at FWHM, and one zeroth order soft X-ray band (01.-7nm). Each first order wavelength band corresponds to a measurement channel that has a silicon photodiode as detector. The detector in case of zeroth order band is a silicon quadrant photodiode, (each quadrant is separate channel) that helps detect location of flares on solar disk.

Therefore, in total, ESP has nine measurement channels, four first order and four zeroth order (Quad band) along with dark band channel. Nine digital electrometers convert diode currents into count rates using Voltage-to-Frequency Converters (VFC). ESP is also more sensitive to changes in detector temperature and each band’s gain change by having an on board compensation mechanism for signal correction.

Table 2.3. List of some of the major differences in design features between SOHO/CELIAS/SEM and SDO/EVE (Didkovsky et al. 2012).

<table>
<thead>
<tr>
<th>Design Feature</th>
<th>SEM</th>
<th>ESP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Bands</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>Channels</td>
<td>26-34 nm</td>
<td>19,24,30,36 with 4nm spectral</td>
</tr>
<tr>
<td>Quad Diode bands</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Dark Band</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Dark mode for all bands</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Gain Reference Mode</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Figure 2.8-2.9 shows the SDO/EVE/ESP’s design and mechanical layout, along with its specifications (table 2.4) respectively. To restrict the bandpass of incident solar radiation, ESP, like SOHO/CELIAS/SEM also uses thin film metal foil filters. However, instead of one fixed primary Al filter (on SOHO/CELIAS/SEM) in front of its entrance slit, ESP uses a filter wheel mechanism. And at its zeroth order, it has an additional filter thin foil Titanium (300 nm) / Carbon (40 nm) filter, that is fixed inside the instrument to restrict the bandpass to SXR (0.1-7 nm). The filter wheel has total of five positions, of which three include aluminum (150 nm) EUV bandpass filters, one primary and two extra, along with a fused silicon window and blank position(dark filter). The fused silica filter is used to determine incident visible light which needs to be subtracted from EUV band signals and the dark filter helps measure dark currents on each band directly.

Figure 2.8. Design Layout of ESP while undergoing preflight calibration at NIST (BL-9). The instrument has filter wheel mechanism at its entrance slit followed by four first order channels and zeroth order (quad band) channels. The zeroth order has additional titanium filter fixed inside the instrument (Didkovsky et al. 2012).
Having multiple aluminum filters on filter wheel not only provides redundancy incase the primary filter gets damaged, but it also gives ESP an inflight filter degradation monitoring capability. By periodically rotating the filter wheel, the instrument uses the secondary filter for about one minute every day and the tertiary filter once every week. Therefore, by measuring the ratio of the detected
signal between using the primary and the secondary filters for multiple wavelength band channels, the primary Al filter’s transmission w.r.t to secondary filter can be measured on daily basis. Figure 2.10 shows such daily calibration measurements (Ratio of signal at detectors between using Secondary/Primary Al filters) from 2010-2014 for ESP’s multiple wavelength channels. These capabilities in ESP are a considerable improvement over SOHO/CELIAS/SEM, where, the primary Al filter transmission due to degradation could only be calibrated using sounding rocket calibration under flights with an SOHO/CELIAS/SEM instrument clone, which was could/usually be done, around once every couple of years. (Didkovsky et al. 2012).

![ESP Filter Degradation](image)

**Figure 2.10.** Daily onboard secondary/primary filter (transmission) calibration ratio vs time since launch (2010- 2014) for ESP. The four curves shows the ratio of the signal at all broadband channels (detectors) between using the secondary filter and primary filter on filter wheel (Didkovsky 2015).
Chapter 3. EUV Filters

This chapter gives a general overview of thin film metal foil EUV filters, their transmission characteristics and suitability for space based EUV measurements. This is followed by a discussion on degradation of various aluminum filters under standard atmospheric conditions, and pre-flight calibration results of SDO/EVE/ESP filters.

3.1 Henke’s Filter Transmission Model

Henke’s filter transmission model analytically calculates transmittance $T$, ratio of transmitted energy to incident energy of a filter at a particular wavelength by the relationship

$$T = \exp(\mu \chi)$$

where $\chi = \tau \delta$

where $\mu$ is the linear absorption coefficient at the chosen wavelength and $\chi$ is the thickness of the material. $\chi$ is usually calculated by multiplying $\tau$, the mass absorption coefficient with density of the material. Using optical models, theoretical predictions of filter transmission are generally reasonable except for occasional anomalies near absorption edges (Henke, Gullikson, and Davis 1993b).

For composite multiple layer filters, overall transmission can be computed as a combined product of the predicted transmittance for each layer. For compounds, each elements is taken in proportion to its percentage of weight and its transmittance is then determined separately. Then all such separate transmittances of elements present are multiplied to get the composite transmission of the original filter. However, this process ignores any interactions of properties exhibited by compound molecules in difference to just individual atoms of elements and the results may not always be reliable. Nevertheless, in a given wavelength range these calculations give a general idea of the filter behavior.
which have usually shown to be in close agreement with the transmission data derived experimentally. (Powell et al. 1990). Figure 3.1 to 3.6, later in this chapter, show some examples of transmission curves of common EUV filters derived using Henke’s Model. An online version for this model for common EUV materials can be accessed at CXRL LBNL.

3.2 Filter History and Development

The total solar intensity for wavelength greater than 1000Å (100nm) is a million times greater than total short ward of this wavelength. Hence it becomes necessary to select a filter with a band pass such that it eliminates the long wavelength region completely in order to present EUV (<120nm) portion of the spectrum from being swamped by stray light. In EUV and SXR bandpass of particular interest are filters with high transmittance that enable imaging solar disk between 0.1-50 nm, especially at some prominent solar emission lines at Fe IX 17.1 nm, He II 30.4 nm, 25.7 nm, Fe XV 28.4 nm and other nearby wavelengths.

The first measurements of the XUV transmittance of a thin metal film were made by (Tomboulian and Pell 1951) who measured aluminum, supported on Zapon, from 80 nm to 32 nm. Since then similar measurements from 13-75 nm have been reported for many different metal foils like Tin (Sn), Indium (In), Germanium (Ge), Silicon (Si), Magnesium (Mg), Manganese (Mn), Boron (B) and Beryllium (Be) along with their many foil combinations. Table 3.1 below lists some of the standard configurations of various filter materials along with Figure 3.1 with modelled transmission curves (% vs wavelength) for some standard EUV filters.

The genesis of current state of the art film filters for XUV bandpass can be traced to the Extreme Ultraviolet Explorer EUVE (92’) mission by the Space Sciences Laboratory (SSL) at the University of California, Berkeley and Luxel Corporation in the 1980’s (Vallerga, Vedder, and Siegmund 1993).
where twenty separate thin film filters were launched after almost a decade of filter development that included perfecting optimization processes, calibration techniques and profiling material behavior best suited for space based EUV instrumentation.

**Table 3.1.** Some standard EUV bandpass filter configurations (Luxel).

<table>
<thead>
<tr>
<th>COMPOSITION</th>
<th>THICKNESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>1500Å</td>
</tr>
<tr>
<td>Indium</td>
<td>1600Å</td>
</tr>
<tr>
<td>Al / Carbon Overcoat</td>
<td>1500Å / 270Å</td>
</tr>
<tr>
<td>Tin: 3% Germanium</td>
<td>1600Å</td>
</tr>
<tr>
<td>Al / Titanium Overcoat</td>
<td>1500Å / 270Å</td>
</tr>
<tr>
<td>Carbon</td>
<td>1200Å</td>
</tr>
<tr>
<td>Lexan (polycarbonate)</td>
<td>1300Å</td>
</tr>
<tr>
<td>Boron</td>
<td>1200Å</td>
</tr>
<tr>
<td>Silicon</td>
<td>1200Å</td>
</tr>
<tr>
<td>Polyimide</td>
<td>1100Å</td>
</tr>
<tr>
<td>Palladium</td>
<td>1500Å</td>
</tr>
<tr>
<td>Titanium</td>
<td>2000Å</td>
</tr>
<tr>
<td>Zirconium</td>
<td>1500Å</td>
</tr>
</tbody>
</table>

Aluminum, since then, has proved to be one of the best and most frequently used filter materials. It was not only found relatively durable and easier to process than many other materials but also had a wide band pass (from 17 nm to about 80nm, see Figure 3.2), with excellent visible light rejection.(Powell et al. 1990).

Figures 3.2-3.6 shows the transmission vs wavelength profiles for some of the standard filters configurations of elements that are of particular interest in EUV region. Many other materials like Beryllium (Be) and Silicon (Si) (see Figure 3.3), despite having good transmission characteristics within certain wavelength bands of EUV, are usually not found suitable for space based applications. For Be, the issue is mainly related to extreme difficulty in handling its thin films and Si /Ge are highly brittle and susceptible to vibrations. Still, both are widely used on ground in a laboratory setup.
Similarly, Boron (B) and Carbon (Figure 3.4) are found suitable for applications that require filters with a bandpass in shorter wavelengths, but then, they do not provide much visible light rejection. The other problem with Boron was that despite having good bandpass in 10-40 nm, it is extremely difficult to evaporate and produce good films. Meanwhile instead of free standing Carbon filters, polyimide was found as a good replacement. Polyimide has a EUV bandpass similar to carbon but offered greater mechanical strength. It is widely used for very large filters, especially those used to support pressure differentials, but then it is highly susceptible to degradation due to long term EUV/UV exposure and is extremely reactive with atomic oxygen. This made Polyimide also unsuitable for any long duration space based instrumentation.

Magnesium also has relatively high transmission but it could not be floated from a substrate onto water surface as it rapidly oxidized to magnesium oxide with completely different bandpass characteristics. These materials since have mainly been used for order sorting rather than standalone film filters in combination with more durable materials like aluminum, Titanium, Lexan or Zirconium (Zr). For example, Figure 3.5 shows transmission characteristics of a commonly used carbon coated standard Aluminum filter (150/270Å) on a nickel mesh. Another recent example is a composite filter (Figure 3.6) of the Hi-C Radiometry instrument which has an 1150 Å thick Silicon layer on top of a 1500 Å standard Aluminum filter, also supported on a Nickel (Ni) mesh.
Figure 3.1. Transmittance (%) of each filter material vs Wavelength. The standard filter configurations are shown in (Green) and custom filters (blue) (By Luxel).
Figure 3.2. Transmission (%) vs Wavelength (Å) for a standard 1500Å thick Aluminum filter. (Inset above right) is the absorption coefficient of pure Al and inset (second from above) is absorption coefficient of Alumina. Aluminum eliminates visible and near UV light, High band pass >80% transmission 20-80 nm and easy to fabricate.
Figure 3.3. (Above) Transmission vs Wavelength (0-1200 Å) of a Silicon (120 nm thick) filter. (Below) EUV Transmission vs Wavelength (0-160 Å) of a standard Silicon (120 nm thick) filter. Silicon is brittle, doesn’t evaporate so difficult to fabricate and is brittle, doesn’t evaporate so difficult to fabricate and is primarily used in order sorting.
Figure 3.4. (Above) Transmission (%) vs Wavelength (0-1200 Å) of a standard carbon (120 nm) Luxel filter. (Below) EUV Transmission vs Wavelength (0-160 Å) of standard carbon (120 nm) Luxel filter.
Figure 3.5. (Above) Transmission (%) vs Wavelength (0-1200 Å) of Aluminum/Carbon (27 nm) filter. (Below) EUV Transmission vs Wavelength (0-160 Å) of Aluminum/Carbon (27 nm) filter.
Figure 3.6. Transmission (%) vs Wavelength (Å) curve for a Hi-C Radiometry filter that uses a composite combination of silicon on top of Aluminum, supported on a Nickel mesh. The line shows the complete transmission curve derived using Henke’s model against the measure values (data points) at some designated wavelengths.

3.3 Aging Effects on Aluminum Filters

Filter degradation can be divided into two major categories – On ground and in space. The on ground degradation is usually associated with affects primarily due to filter oxidation. Whereas, the in space degradation is more complicated and can depend on several factors such as a spacecraft’s operating
space environment, altitude conditions and spacecraft configuration itself. In-space filter contamination and degradation will be discussed from Chapter 4 onwards.

### 3.3.1 Aluminum Filter Degradation at Standard Atmospheric Conditions

All filters age to varying degrees, and this becomes one of the most common causes for any filter degradation. The effects of aging are usually reduced transmittance or physical degradation like weaker mechanical strength. *At standard conditions, the problem is usually moisture or oxygen, particularly in presence of moisture (Powell et al. 1990)*. To understand filter oxidation Stanford’s Center for Space Studies carried a comparative study of filters collected from multiple sources/projects that were in use or procured over a period of time, completely unrelated, and were aging in widely varying conditions. The study (Figure 3.7) found out that the bulk aluminum material of an Al filter gets slowly oxidized to alumina (aluminum oxide) with time. This oxidation process is understood to be initially starting from filter’s outer surface, and then layer by layer, grows with time, i.e. from few tens of angstrom deep to as much as 150-200 angstroms depending upon the storage conditions and time. (Powell et al. 1990). For a new Al filter, the nominal oxidation depth is usually accepted to be around 18Å. This oxidation is almost immediate as it happens while fabrication and cannot be completely avoided. Whereas, for filters aged a year or more, about 50-100 Å equivalent of total aluminum oxidation depth should be expected. The study also suggested that there is a natural limit to this oxide growth, at about 150 Å at standard atmospheric conditions. The evaluation further concluded that a filter’s EUV transmission loss was proportional to incident EUV wavelength i.e. the transmission loss was greater at longer wavelengths. This was in agreement (curve shape) with analytical calculations using Henke’s model at varying degrees of oxidation (depth) using absorption coefficients and thickness (es) of Aluminum and Alumina. Henke Model at CXRL (LBNL) has since
proved to be a useful tool for calibrating/estimating a filter’s transmission (loss) with time (on ground). By experimentally measuring a filter’s EUV transmission, we can now factor oxidation within reasonable limits and estimate if they would show further degradation or are stable enough before being launched. The section below discusses the pre-flight calibration results of SDO/ESP aluminum filters.

![Graph](image)

**Figure 3.7.** Transmittance vs Wavelength comparison of several standard aluminum filters (1500 Å thick). These filters were analyzed for varying degrees of oxidation with time, due to aging under standard atmospheric conditions (Powell et al. 1990).

### 3.3.2 Pre-Flight Calibration of SDO/EVE/ESP Filters

EUV Spectrophotometer (ESP) is one of the five channels (along with MEGS A, MEGS B, SAM and MEGS P) of the Extreme Ultraviolet variability Experiment (EVE) on Solar Dynamics Observatory. It measures the absolute solar EUV irradiance in multiple broadbands within the spectral range from...
about 0.1 to 32 nm with excellent absolute photometric accuracy to complement the high spectral resolution of EVE/MEGS channels. The aluminum filters for any space mission like SDO/ESP are usually procured 5-7 years before their launch. These filters, as in case of ESP then periodically undergo calibration for determining their absolute transmission in EUV at a synchrotron facility such as NIST. The Figure 3.8 shows the preflight calibrations of the primary and secondary aluminum filters on ESP, done at BL-9 at NIST in 2008, that was due launch in 2010. The pre-flight value of absolute filter transmission at 30.4 nm channel was around 33%. Figure 3.9 shows the analytical model for this filters transmission that factors equivalent aluminum oxidation depth that leads to loss in transmission to its preflight calibrated value (along with nickel mesh ~85% transmission). The blue curve (in Figure 3.9) shows the absolute transmission of a new aluminum filter that is assumed to have about 18 Å of alumina layer (Powell et al. 1990). The grey curve is analytically calculated to align with the experimentally (Figure 3.8) derived pre-flight transmission calibration (curve) of ESP’s primary and secondary aluminum filters. The modelling estimates that the ESP filters were oxidized by equivalent to 125 Å of Alumina layer in 4-5 years after being manufactured. This 125 Å oxidation is also in close agreement with the Stanford study (Powell et al. 1990) (see Figure 3.7). Since this was the last pre-flight calibration of the filters, based on experience, the aluminum filters were considered relatively stable or matured (i.e. not going to considerably oxidize further) in 2008 for the planned SDO launch that was scheduled a couple of years later in 2010.
**Figure 3.8.** Preflight calibration (transmission vs Wavelength) of ESP’s primary and Secondary Aluminum filters at NIST (Didkovsky et al. 2012).

**Figure 3.9.** Transmission vs Wavelength curve modelled using Henke’s (CXRL) for SDO/EVE/ESP preflight calibration results. The model points to a total of 125 Å of oxidation depth on the filter.
Section II

Aluminum Filter Degradation in Space
Chapter 4. EUV Filter Degradation in Space

“Solar Absorbance can be degraded by a number of environmental factors such as radiation, micrometeoroid/orbital debris impact, arcing, sputtering or the solar UV but the contamination is usually the largest concern.” Alan C Tribble

4.0 Molecular Contamination

A great care is taken to ensure that a spacecraft is clean when launched but often this spacecraft itself may become a source of contamination during its orbit operations through a process called outgassing. Outgassing is responsible for the familiar odor of plastics and rubber. All materials contain some fractional amount of volatile chemicals dispersed throughout the satellite materials and structures, for example vacuum seals, conformal coatings, adhesives-tapes and epoxies. These volatile molecules over time, migrate to surface and escape into the atmosphere and may get deposited to other surfaces. If the effected surface is sensitive optics like EUV filters or detectors, this buildup of outgassed molecules may severely degrade its optical properties like transmission or sensitivity. The exact mechanism of outgassing is complicated and not very well understood. But in order to minimize outgassing the processes that control the generation, transportation and deposition of such molecular contamination were carefully studied, so that they could be controlled. During SOHO, a first of such a detailed and a rigorous program was initiated to eliminate residuals at every step of fabrication that might later cause contamination by outgassing. Guidelines and standards were developed which set the benchmarks for all future missions to minimize susceptibility to any molecular degradation.

Material outgassing can be classified into three main types of processes. First is desorption, which is release of surface molecules that are held by electrical and chemical forces and it usually varies
exponentially with time. Second, is diffusion, where contaminants having enough thermal energy inside bulk of material simply escape to the surface and evaporate into the space environment. Diffusion usually varies inversely as power of time. And finally, outgassing can be due to decomposition of chemical compounds on/with the spacecraft which can then either diffuse or outgas by desorption. Decomposition is usually independent of time.

For molecular contamination it is not necessary that the sensitive surface should be in direct line of sight form the source, the outgassed contaminants from opposite or far surfaces can also get deflected from intermediate surfaces or absorbed and later re-outgas, reaching opposite sides of satellites. In addition, backflow of thruster plumes, either during launch or recurring attitude control/station keeping maneuvers can also pose serious threat to sensitive materials. Once away from spacecraft, some contaminants can always be scattered back to spacecraft due to collisions with other molecules in space environment and significantly affect extremely sensitive surfaces like EUV filters. This is usually of greater concern in low earth orbit (LEO) than geostationary (GEO) where the ambient space environment is a lot denser. Also, one other phenomena to note is, outgassed contaminants/ exhaust plumes can get ionized (see Figure 4.1), due to solar UV radiation and then dribble with spacecraft for prolonged periods sometimes reaching completely unexpected directions because of electrostatic retraction due to spacecraft charging. This can be a major concern in higher altitude orbits (geosynchronous and beyond) than LEO where spacecraft charging (negatively) to high voltages is common. This is one of the many possibilities that might explain contamination of both SOHO/CELIAS/SEM and SDO/EVE filters, as they both the spacecraft’s are positioned beyond low earth orbits, where charging effects on spacecraft as well as he filters themselves can be quite significant.
Therefore, of the many possibilities that exist, contaminants due to either or combined effects of above mechanisms can reach filter surfaces and get deposited. This build up can get thick (up to few layers) over time, especially when the rate of contaminants arrival on target surface is higher than departure. The deposited contaminants not only change the surface topography of filters, but they can also trigger chemical changes, such as their own polymerization (aluminum bed acts as catalyst) forming layers or clumps (Figure 4.2) that interfere with the filters optical properties (like transmission).

Furthermore, contaminants can also alter the chemical profile of their underlying substrate, like triggering enhanced oxidation of bulk Al materials to alumina, which has significantly lower transmission in EUV. Therefore, the effects of molecular contamination can best be controlled by minimizing the amount of contamination that is generated, transported, and deposited on a surface (Schuehle 2003).
4.1 Thruster Plume Contamination

Thrusters are known to scatter a very small fraction of ejected mass at angles greater than 90 degrees off the thruster axis. Typically it’s around one part in million for the backflow region but depends on specific thruster design. No matter however small, the plume can still play a role in contamination of optical sensitive surfaces like EUV aluminum filters. Both SDO and SOHO use a bipropellant thrusters with Monomethylhydrazine (MMH CH₃NHNH₂) and nitrogen tetroxide. Studies have shown that the products of incomplete combustion of nitrogen tetroxide (NTO, N₂O₄) and amine fuels when the ACS is cold started or used in pulse firing mode are rich with Monomethylhydrazine nitrate (MMH-HNO₃), fuel nitrates along with water vapors and carbon dioxide. This MMH-HNO₃ and hydrocarbon rich mixture is then known to form a thick yellow condensate (Figure 4.3) on surfaces at room temperature. This condensate is extremely hygroscopic and can further absorb more such incident contaminant molecules, which can then later get polymerized (similar to Figure 4.2) and deposited permanently in reaction with underlying aluminum substrate under solar UV radiation.
exposure. (Jenkins, Ciucci, and Cochran 1994; Fote and Hall 1982, 95-101; Tribble 2003). A study by (Liu and Glassford 1981) further investigated contamination of aluminum surfaces by MMH-NTO plumes. They reported that the plume product condensed on aluminum surfaces. This condensate was found stable at room temperature, which is also nearly equivalent to the operating temperatures of SDO and SOHO satellites in orbit. The study also further explored this contamination exercise in UV radiation environment and found that this condensate when exposed to UV, not only shrunk and lost mass, but was no longer hygroscopic.

![Figure 4.3](image)

**Figure 4.3.** The MMH-NTO forms a hygroscopic condensate at room temperature

Figure 4.4 shows the SDO spacecraft design with eight attitude control thrusters (5 lbf each) placed in four pairs at the aft corners of the vehicle to provide attitude control. All the thrusters are canted 10 degrees from the Z axis. The main engine, provides deltaV only in x direction and is located at center of the ACS (thrusters), on the side opposite to filter windows.
By placing all thrusters on one side, and all highly sensitive optics on SDO instruments on the opposite side, designers ensured that any plume contamination will be bare minimum as back plume angle is greater than 180 degrees for any single thruster pair. In fact there are no other thrusters on any other axis (Figure 4.5-4.6). The thrusters are fired at least once per month (DeltaH mode) for about 15-20 seconds, performing spacecraft’s momentum unload maneuver. This (extra) momentum develops on the spacecraft due to frequent use of reaction wheels for various station keeping requirements like balancing disturbance torques generated due to pointing requirements of various instruments on
board. Hence the possibility of few contaminants reaching the filter surfaces over time (after firing) cannot be completely ruled out.

**Figure 4.5.** Basic plume structure of a nozzle exhaust (Jenkins, Ciucci, and Cochran 1994).

**Figure 4.6.** Thruster plume off axis scattering (mass flux vs angle off plume axis).
4.3 Space Environment Affecting Filter Surfaces

For purposes of this study, we can broadly classify satellites taking solar observations in EUV into two broad categories based on their space environment i.e. Low earth Orbit (LEO) based, and outer space based i.e. geosynchronous orbit and beyond (GEO).

4.3.1 Degradation of Filters Due to Low Earth Space Environment Factors

An altitude of up to 1000 km is considered as near Earth space environment where combined effects due to presence of neutral particles, charged particles (Plasma), solar radiation and micrometeoroid/orbital debris, in varying degrees, have to be considered on a spacecraft. The dominant effects on Aluminum filters here to take note of are surface charging, physical sputtering, atomic oxygen attack and retraction of contaminants.

Compared to GEO environment, the Low Earth Orbit environment is a much denser space environment. Figure 4.7 shows the MSIS atmospheric model with concentration of various molecular species up to 1000 km altitude. A spacecraft’s moving with ~ 8km/s in LEO has significant interactions with various neutral atmospheric species here. The collisional kinetic energy due to the orbital motion of spacecraft is 5 eV as compared to a thermal energy of 0.3 eV. The impact of atoms at such high speeds not only gives rise to aerodynamic drag but may also physically sputter material from some of the satellite’s surfaces. This impact energy leads to a chemical (not mechanical) degradation of certain susceptible materials, especially those which have volatile oxides, like carbon and plastics, and those with unstable oxides, like silver. This degradation is usually expressed as thickness lost for a given particle fluence and is known for many materials.
Figure 4.7. Altitude dependence (in km) of density (g/cm$^3$) of atmospheric components in Low Earth Orbit (LEO) using MSIS E-90 Atmosphere model –NASA. The model shows atomic oxygen as dominant species from almost 200 km to up to 1000 km in space.

The photo absorption of solar UV-EUV rays by various ambient molecular constituents in LEO can make operating temperature in regions like Thermosphere (200-1000 km) as hot as 2000k (1000K at ~200km), upsetting the whole thermal equilibrium of the spacecraft (and its surfaces like optical windows). Depending on the orbit, there are a variety of other mechanisms that may contribute to filter degradation, such as the solar ultraviolet radiation, atomic oxygen, nuclear radiation, and micrometeoroids/orbital debris impact. Any small amount of molecular contamination (in film or clumps) on filter surfaces here could significantly alter the thermal and optical properties like
increased solar absorptance, scattering and opaqueness in transmission. Usually such contaminants are absorptive in EUV/UV than IR. (Tribble 2003). Figure 4.8 shows the example of thermal control coating degradation (change in solar absorptance vs time in orbit) of various satellites. Much of this degradation is associated with photochemical deposition of contaminants.

Neutral atomic oxygen is the dominant atmospheric constituent at ~500 km altitude. This atomic oxygen is highly reactive and can chemically erode certain spacecraft surfaces or give rise to a visible glow. Aluminum surfaces, in general are naturally oxidized to Alumina in varying degrees, and this Alumina layer on its outer surfaces acts as a protective shield preventing further oxidation, deep inside the bulk aluminum material. Studies have shown that Alumina is one of the least reactive materials to a direct atomic oxygen attack under standard conditions. Other materials like Gold, Platinum, and Silicon Dioxide are also quite resistant to oxidation and not appreciably affected in LEO environment.
(Vallerga, Vedder, and Siegmund 1993; Peters, Gregory, and Swann 1986). However, in LEO space environment, a combined attack of ambient atomic oxygen in presence of solar UV radiation, could lead to enhanced oxidation of an already oxidized or termed ‘stable’ aluminum surface. If this is the case, this might explain increased opacity (loss in transmission) in EUV for aluminum filters at LEO orbits. Furthermore, the plasma environment in LEO can also develop spacecraft charging which could enhance sputtering. This can lead to retraction of some of the contaminants back to a spacecraft. This can significantly increase molecular contamination and affect EUV filters. The following section discusses two of such solar missions, PROBA-2 (LYRA) and Hinode (EIS), which are based in such LEO environment and have Al filter based EUV instrumentation (Tribble 2003; BenMoussa et al. 2013).

4.3.1 EUV Filter Degradation on LYRA on PROBA-2

Lyman Alpha Radiometer LYRA on PROBA-2 is a solar UV radiometer that was launched in a sun synchronous low earth orbit (~725 km) in November, 2009. It has Aluminium filter channel (17-50 nm) that includes He II 30.4 nm line, and a Zirconium filter channel (1-20nm). As (Del Zanna 2013, A47) quotes “Degradation in LYRA is due to molecular contamination on the first optical surface.”

Figure 4.9 shows the adjusted signal loss (counts per ms) factored with filter degradation. The estimated loss in 23-27 nm bandpass was around 20% in just first two years of operation, whereas no such signal loss/degradation was seen in zirconium filter based channel from 3 -5 nm. A study* later by Jones in 2013 compared LYRA data with TIMED SEE data to understand this degradation. Their analysis suggested silicone RTV566 and Epoxy AV 138 /HV 998, both used in front door mechanism as the possible contaminants mainly responsible for this LYRA’s degradation.
4.3.2 Filter Degradation on HINODE EIS

“Out-gassing and contamination of the entrance filter could partly be responsible for the observed degradation in the EIS LW. Deposition of carbon compounds would cause an enhanced degradation in the LW channel, compared to the SW one, as observed in the SDO EVE MEGS-A2.” (Del Zanna 2013)

The Hinode (JAXA) EUV imaging Spectrometer (EIS) was launched in September 2006 in a sun synchronous low earth orbit (~600 km). The EIS instrument uses a multilayer toroidal gratings to disperse and measure the solar irradiance onto two detectors covering 17-21 nm and 25-29 nm
broadband respectively. Of the known issues related to overall EIS instrument degradation, one is the radiation damage of its CCD detectors. After around five years of operations, EIS shows considerable signal attenuation of its longer wavelength (LW) channel compared (Figure 4.10) to short wavelength (SW). By December 2006 (within 2 months) the ratio of LW/SW signal was further lowered by 20-30% than what was measured at launch. This ratio continued to decrease significantly till 2010 when radiances in LW became underestimated by a factor of 2.

Figure 4.10. Ratio of longer wavelength/shorter wavelength channel’s signal sensitivity with time for EIS on HINODE. Observed Fe xiv 274.2 / 211.3 Å ratio, divided by its theoretical value. The full line is the fit, while the other lines are previous suggestions. The signal loss is higher at longer wavelength compared to shorter one with time. (Del Zanna 2013)
4.4 Space Environment in Outer Orbits- GEO Missions

GEO based missions, where altitude is around 36000 km or higher, have a near ultra-high space vacuum environment. The solar continuum received here is almost unobstructed and the dominant species are protons (from sun) and energetic electrons (if near outer radiation belts). At GEO, Figure 4.11 shows the only dominant species are protons from solar radiation (and lower radiation belts) and energetic electrons in the trapped radiation belts (outer). Any neutral species, as found in near earth space environment like atomic oxygen or nitrogen, both diatomic and atomic, for all practical purposes is considered negligible here i.e. order of 5-6 less than that found in upper earth atmospheres. Some stray gas molecules are found, but their density is so low that they can be thought of as practically nonexistent. Degradation effects observed in neutral environment (LEO – 800 km) because of chemical effects due to atomic oxygen attack or spacecraft glow are not observed here. Neither do spacecraft’s experience any mechanical effects like aerodynamic drag and physical sputtering.

Figure 4.11. The trapped radiation belts (flux vs distance from earth in earth radii) (Tribble 2003).
Both SOHO at Lagrange point 1 and SDO at geosynchronous orbit are deployed in such outer earth space environment. The dominant effects on filters here to be carefully observed are pressure differentials, filter surface charging, solar UV enhanced degradation and molecular contamination. (Tribble 2003). Both SOHO/CELIAS/SEM and SDO/ESP have a high voltage grid (1000 V) to deflect some of the low energy charged particles from reaching inside the instrument. However, the possibility of higher energetic charged/neutral particles reaching the aluminum filters cannot be ruled out. The following chapter (5) will discuss in detail, degradation of EUV filters in outer space environment, especially on SOHO/CELIAS/SEM and SDO/EVE.
Chapter 5. Aluminum Filter Degradation on SOHO/CELIAS/SEM and SDO/EVE/ESP

5.0 Introduction

Using thin film aluminum (Al) foil filters is a standard technique used for spectral filtration of solar radiation. They transmit soft X-ray and Extreme Ultraviolet (EUV) and eliminate the solar visible and near UV spectrum. Over the years, several satellite-based instruments have used these aluminum based filters for observing the sun in X-ray (0.1-7 nm) and EUV (17-57 nm) wavelength regions. Mechanically these aluminum filters remain in service for decades but their EUV transmission starts reducing almost immediately after launch. However, the rate of loss of their EUV transmission is not constant. It gradually slows with time and eventually plateaus in about a few years. This loss in filter transmission directly leads to an attenuated flux at the detectors which then affects the overall sensitivity of the measurements.

Together with our experiences with EUV Spectrophotometer (ESP) and Multiple EUV rating Spectrograph (MEGS) on NASA's Solar Dynamics Observatory (SDO), Solar Extreme Ultraviolet Monitor (SEM) on Solar and Heliospheric Observatory (SOHO) and other previous aluminum filter-based EUV instruments, it has become recognized that the aluminum filters are considerably more susceptible to performance degradation in outer space, especially when compared to other EUV filter types like carbon coated zirconium. The reasons for such a difference in performance over time between two filter types, even when placed on same instrument are not yet clearly understood and needs further investigation.
5.1 EUV Filters on SOHO/CELIAS/SEM and SDO/EVE/ESP

SDO/EVE/ESP is one of the five channels of the Extreme Ultraviolet Variability Experiment (EVE) onboard SDO, launched in Feb, 2010 into geosynchronous orbit. The ESP channel design is based on a highly stable diffraction transmission grating and is an advanced version of SOHO/CELIAS/SEM, which is onboard SOHO, that has been successfully observing solar irradiance from the Sun - Earth’s Lagrange point 1(L1), since December 1995. Using a thin film aluminum filter that rejects the visible light and transmits the soft X-ray (0.1-7 nm) and EUV (17-57 nm), SEM measures the full disk absolute solar flux in two band passes (26-34 nm) (first order channels) and 0.1-50 nm (zeroth order channel) whereas SDO/EVE/ESP measures the solar EUV irradiance in four first order bands of the diffraction grating centered around 19 nm, 25 nm, 30 nm and 36 nm (non-operational), and in a soft-X ray band from 0.1 to 7 nm (zeroth order of the grating). SOHO/CELIAS/SEM has its main EUV bandpass aluminum filter fixed at its entrance aperture, whereas the next generation SDO/EVE/ESP uses a rotating filter wheel that has three such aluminum filters, one primary and two spare (secondary and tertiary) along with a visible light and a dark filter (in total five). Having spare filters on SDO/EVE/ESP not only provides redundancy in case the primary filter gets damaged but also enables monitoring of filter degradation. By periodically rotating the filter wheel, the instrument uses the secondary filter for about one minute every day and the tertiary filter once every week. This mechanism therefore provides a daily onboard filter calibration procedure by measuring the ratio of the detected signal between using the primary and the secondary filters for multiple wavelength band channels (see Figure 5.1 later).
5.2 Aluminum Flight Filters

The filters used on both SDO/EVE/ESP and SOHO/CELIAS/SEM is a standard, most commonly used 1500-Å thick aluminum filter on a Nickel (Ni) mesh. Although these aluminum filters are considered very stable, aging still affects their transmission performance at standard atmospheric conditions. This gradual increase in EUV opacity over time can be attributed to a 50-150 Å layer equivalent of oxidation depth of aluminum to aluminum oxide (Alumina) in about the first two to three years after manufacturing (refer section 3.3 for details). Once naturally “anodized” these filters further get oxidized only negligibly and can be said to become extremely stable. In one such study in 1990’s, Powell at Luxel Corp. experimentally tested multiple filters, some more than a decade old stored at atmospheric pressure, not in any controlled environment. The study revealed that for filters aged a year or more 50-100 Å of oxidation should be expected. It further suggested that at standard conditions, there is a natural limit to this oxide growth at about 150 Å oxidation. They also experimentally determined that the transmission loss was greater for longer wavelengths for aged/oxidized aluminum filters. This observation is consistent with analytically calculated transmission values across wavelength bands using Henke’s model (see section 3.1), where the transmittance, $T$, ratio of transmitted energy to incident energy of a filter at a particular wavelength is determined by the relationship

$$T= \exp (\mu \chi) \quad (5.1)$$

where $\mu$ is the linear absorption coefficient at the chosen wavelength and $\chi$ is the thickness of the material. The value of $\chi$ is usually calculated by multiplying the mass absorption coefficient with density of the material. Using optical models, theoretical predictions of filter transmission are generally reasonable except for the occasional anomalies near absorption edges. For composite
multiple layer filters overall transmission can be computed as combined product of the predicted transmittance of each layer. The preflight calibration data (see Section 3.4) for SDO/EVE/ESP filter when modelled using the above approach points to 125 Å equivalent of aluminum oxidation depth.

5.3 Aluminum Filter Degradation on SOHO/CELIAS/SEM and SDO/EVE

For SDO/EVE/ESP, within months after launch, the daily inflight calibration data (Figure 5.1.) when compared across multiple wavelength channels showed varying levels of transmission loss. The higher wavelength channels were affected considerably more by filter degradation than shorter wavelengths. From Figure 5.1, it can be clearly seen that by the end of four years the 30.4 nm channel showed almost 75% signal loss (25% of prelaunch value) using the primary filter when compared to the secondary filter. The difference was just over 60% for 25.6 nm, 40% in the case of 17.1 nm wavelength channel and less than 10% for soft X ray (0.1-7 nm) band channels. This loss was initially very rapid but gradually slowed with time.

A similar phenomenon was observed on another wavelength band on the EVE instrument, MEGS-A2 (Figure 5.2) which also uses an aluminum composite filter (Al/Ge/C) for its multiple wavelength channels from 17.1 nm to 36.8 nm. Figure 5.2 shows the data from inflight calibrations of MEGS-A2. At 30.4 nm overlapping wavelength band, both MEGS-A2 and SDO/EVE/ESP (see Figure.5.3) have an almost identical rate of performance degradation from 2010 until 2013. Figure 5.4 shows similar observations were made earlier on SOHO/CELIAS/SEM as well, where over a course of five years, using multiple calibration under flights, the sensitivity at 30.4 nm channel detectors was found reduced to just 40% of its preflight calibrated value.
Figure 5.1. Dependence of SDO/EVE/ESP filter degradation (primary/secondary) ratio with time as determined by daily onboard calibrations (Didkovsky 2015).

Figure 5.2. MEGS A2 (Al/Ge/C) filter degradation ratio with time for multiple wavelength channels (BenMoussa et al. 2013).
Figure 5.3. Comparison of Transmission (%) vs time (since launch) for SDO/EVE/ESP (upper line) and MEGS A2 (below line) aluminum filters at overlapping 30.4 nm. (A. Jones, 2012).

Figure 5.4. SOHO/CELIAS/SEM (Al) filter degradation (fraction of preflight calibration value with time). The red curve shows the modelled thickness (growth) of carbon/hydrocarbon contaminant layer on the filter surface (BenMoussa et al. 2013).
Like MEGS-A2 and SDO/EVE/ESP, another SDO/EVE channel, MEGS-A1, also measures solar irradiance at 17.1 nm, but it instead uses a carbon/zirconium/carbon (C/Zr/C) composite filter for its EUV bandpass. Figure 5.5 shows that in two years of operation (2010-12) at 17.1 nm wavelength, this carbon coated zirconium filter experienced a transmission loss of just around 10% compared to 40% (in Figure 5.2 earlier) for the aluminum filters of MEGS-A2 and SDO/EVE/ESP. Based on the data from Figure 5.5, it was evident that the MEGS-A1’s C/Zr/C filter had shown significantly less susceptibility to degradation in similar conditions compared to aluminum based filters on SDO/EVE/ESP and SDO/EVE/MEGS-A2. Moreover, this C/Zr/C filter had shown almost all of its transmission losses (see 17.1 nm data points in Figure 5.5) during the first 1-2 years after launch, but then it stabilized (A. Jones, 2012). Whereas, the primary aluminum filters on both MEGS-A2 and SDO/EVE/ESP still, even after more than four years of operations, continue to degrade, though the rate of their EUV transmission loss (on MEGS A2 and ESP) is slowing with time.

Figure 5.5. MEGS A1 C/Zr/C filter degradation (fraction of preflight calibration value vs time). Unlike aluminum filters on MEGS A2 and SDO/EVE/ESP, the primary filter here shows almost negligible loss in transmission compared to secondary filter (BenMoussa et al. 2013).
Now what exactly makes these C/Zr/C filters of MEGS-A1 far more resilient to degradation compared to aluminum filters of SDO/EVE/ESP, MEGS-A2 and SOHO/CELIAS/SEM under similar operating conditions is not well understood. Another question is, whether if it is this carbon coating that is primarily responsible for improved performance of zirconium filers. If this is the case, then it would be interesting to see if coating aluminum filters with carbon also reduces their susceptibility to degradation.

5.4 Propellant Plumes as a Possible Source of Filter Contamination

Of the possible modes of degradation for these filters in space, contamination seems to be one of the most plausible. This is because in general, erosion of the aluminum as a filter material is not a concern in space beyond Low Earth Orbit (LEO) environment. Had this been the case, the filters would have shown increased transmittance. This means that either the aluminum is undergoing some chemical transformation like enhanced oxidation or there is some sort of contaminant buildup on its surface which makes the overall filter more opaque. Or it could be a combination of both i.e. contaminant build up which leads to UV enhanced oxidation due to “passivation”. In either of the discussed possibilities, overall filter degradation slows with time and eventually plateaus. But given that in either instrument contamination continues for years, it only shows that the contaminant source is also long lasting or recurring. It is unlikely that the ambient high vacuum space environment is a significant source of moisture, oxygen, or carbon, but it is plausible that these contaminants could be coming from the spacecraft itself. (See section 4.1 for details)

One potential source of contamination, which is recurring and can last for years could be the plumes from the spacecraft's attitude control thrusters. Both SOHO and SDO use similar bipropellant attitude control thrusters using Monomethylhydrazine (MMH) fuel and Nitrogen Tetroxide (NTO) oxidizer
that are fired at least once every month. The principal products of MMH/NTO incomplete combustion in the Pulse firing mode of thrusters when the engine is cold are rich in CHNO, dominantly CH₃NHNH₂·2HNO₃ (MMH.2HNO₃) and also (CH₃ONO₂, CH₃N₃, HN₃, H₂O, N₂O), and small amounts of NO, NO₂, Methane (CH₄) and Carbon dioxide (CO₂). Studies have shown that MMH.2HNO₃ is highly hygroscopic and forms a yellow condensate on surfaces at room temperature, which is also about the same temperature environment for both SOHO and SDO. To make sure that instruments (filter windows) are not affected by any plumes, thrusters are mounted on the opposite side of the spacecraft. In spite of these precautions, it is possible that some plume contaminants may reach the filters (refer section 4.1).

Moreover, aluminum as a filter material is not entirely inert to such MMH/NTO based contaminants. This is because Alumina (Al₂O₃) is also the Ziegler-Natta catalyst to polymerize alkene or olefins. So, a combination of hydrocarbon and moisture rich plume contaminants on these aluminum filter surfaces (which are Alumina) in solar radiation (UV and below) environment can facilitate many possible reactions. Our approach is to reproduce above set of conditions in the lab to see the effect it has on aluminum thin film filters.

5.5 Analytical Models

The thickness of this contamination layer buildup can be analytically calculated using Henke’s filter transmission model. Figures 5.6-5.7 show the growth profile of a carbon/hydrocarbon (C/CH) buildup on SDO/EVE/ESP and SOHO/CELIAS/SEM since their launch. For SDO/EVE/ESP, in three years using measurements from 30.4 nm channel, the calculated thickness of this deposition is equivalent to about 35 nm (Figure 5.6). Whereas for SOHO/CELIAS/SEM (Figure 5.7), this thickness is around 30nm in about nineteen years. The growth of this hydrocarbon buildup on SOHO/CELIAS/SEM,
Figure 5.6. Carbon/hydrocarbon(C/CH) contaminant layer growth (thickness in nm) with time (since launch) using Henke’s model. For SDO/EVE/ESP 30.4 nm channel (Didkovsky 2015).

Figure 5.7. Carbon/hydrocarbon(C/CH) contaminant layer growth (thickness in nm) with time (since launch) using Henke’s model. For SOHO/CELIAS/SEM 30.4nm channel using sounding rocket measurements. The two curves show measurements processed with different reference spectrum but point to layer thickness of around 25-30 nm.(Wieman 2015).
more or less started plateauing after about seven eight years. For SDO/EVE/ESP, this rate of growth (slope) seems to be slowing down as well, but has not yet (in 2015) plateaued. So if the contaminant source is recurring, then why does the filter degradation slows with time and eventually plateaus, is still not well understood.

A problem with using Henke’s model to identify contaminants is that it can similarly be used to demonstrate this performance loss due to 300 Å of equivalent increased filter oxidation or 350 Å of moisture deposition (see Figure 5.8). This is because most common elements like carbon, oxygen and nitrogen have a decreasing transmission profile of almost similar shape in the EUV region (17-60 nm). Also by using this model it is not feasible to identify any specific molecular species or mixture ratios of carbon, oxygen or nitrogen (CNO) of a contaminant that may directly hint at their potential source. This is because each of the CNO has a decreasing transmission profile of almost similar shape in the EUV region (17-60 nm).

![Image](image.png)

**Figure 5.8.** Degradation in SDO/EVE/ESP filter transmission for all channels since launch. The plot shows Absolute filter transmission vs Wavelength (nm) using Henke’s Model. Analytical calculations reveal that the EUV transmission loss could be due to either oxidation, moisture on filter or just carbon/hydrocarbon deposition.
Therefore, to improve our understanding on filter degradation in space, we would try an experimental approach. We would replicate aluminum filter contamination with MMH-NTO thruster plumes under laboratory conditions and then characterize both the physical and chemical changes of our contaminated filter samples. We hope that our investigation will provide us valuable clues/insights in highlighting the processes that are responsible for degradation in Al filter EUV transmission. This knowledge would then be helpful in further developing solutions (like coatings) that could reduce the overall susceptibility of aluminum filters to space based contamination, giving improved transmission performance over a mission’s lifetime.
Section III

Methods

Contamination and Characterization Techniques
Chapter 6. The Contamination Experiment

6.0 Objective

The following experiment is designed as a “proof of concept” to reproduce contamination of aluminum filters, in a laboratory setup. This experiment will help in improving our understanding about contamination related degradation of aluminum filters in outer space (as witnessed on SDO/EVE/ESP and SOHO/CELIAS/SEM) and test/develop the effectiveness of our carbon-based monolayer protective coatings that are designed with the goal of shielding the underlying aluminum filter substrate from reacting with MMH-NTO based plume contaminants.

6.1 Introduction

The experiment will synthesize satellite’s attitude control thruster plumes (MMH-NTO), in a UV radiation environment at standard atmospheric conditions. Also, to broadly understand the effects of radiation (UV specifically) on overall contamination processes i.e. on both combustion products, as well as their subsequent interactions with filter surfaces, a second run of the above contamination exercise was performed on new set of filter samples, except without any UV radiation exposure. Later in Section 8 we would explain our methods and techniques for physical and chemical characterization of these filter before/after the contamination. The above experiment will help us develop a methodology to measure the effectiveness of some protective coatings on these filters.

The combustion products of MMH-RFNA reaction in both the cases, i.e. with UV exposure and without UV exposure will be analyzed using FTIR. Any broad differences in these scans will help us in determining if the above reaction is sensitive to UV radiation i.e. if the UV radiation significantly
alters the chemical structure or composition of the final products and their subsequent interactions with various filter samples. Besides, direct analysis by looking at visible images, we would measure the chemical changes on/inside Al filter samples by taking secondary electron images by Energy Dispersive Spectroscopy (EDS), using a Scanning Electron Microscope. Although EDS is not a surface analysis technique, but a relative comparison between before and after contamination versions of various samples should prove useful in identifying major chemical differences and physical formations due to above contamination exercise. These SEM images will also help us in validating performance of our protective carbon based monolayer coatings. These coatings are expected to act as a protective layer by shielding/isolating underlying surface from moisture and hydrocarbon rich contaminant attacks.

For surface analysis (3-10 Å depth), using X-Ray Photoelectron Spectroscopy (XPS) measurements along with technique developed by (Strohmeier 1990), we would be able to detect any significant change in the ratio of aluminum to aluminum oxide on filter surfaces before and after the experiments. This will help us verify one of the postulated theories that the UV radiation could have enhanced aluminum filter oxidation of our onboard filters in space. XPS also became the quality verification technique for our coatings (process). Since these coatings are just a monolayer thick, faster and cheaper techniques like Raman spectroscopy detected no characteristic fingerprint signature that could confirm their deposition. Whereas, XPS proved extremely sensitive in identifying some of the “signature” elements in our coatings. The identification confirmed that the monolayer coatings were chemically bonded to the filter substrate.
6.2 Setup

The Experimental Setup (see Figure 6.1) has four main components-

- Photochemical Quartz Reactor for propellant reaction in UV light
- Propellants
- Aluminum filter Samples
- UV radiation source

**Figure 6.1.** Experimental setup for UV based filter contamination.
6.2.1 Photochemical Quartz Reactor

A long cylindrical 3 mouth reaction chamber made of quartz, since quartz is UV transparent, was designed for a controlled fuel and oxidizer combustion. An 8 inch long Teflon cylindrical shell (1 mm thick) structure lines the inside wall of this chamber and acts as a mounting assembly for the filter samples. At its very top, four slots are cut that hold one sample each. Helium, as a carrier gas is used to extract plumes away from the reactor towards a liquid Nitrogen based cold trap.

Figure 6.2. Photochemical quartz reactor with Teflon mounting stand (in white) for filter samples inside.
6.2.2. Propellants

The pair of Monomethylhydrazine (MMH, CH₃NHNH₂) and Nitrogen Tetroxide (NTO, N₂O₄) is a well-known hypergolic propellant for rockets and spacecraft. A hypergolic propellant is a pair of fuel and oxidizer in which ignition occurs almost spontaneously upon contact between the two, thereby eliminating the need for a complex ignition system. Both SOHO and SDO use MMH-NTO based attitude control thrusters.

For safety reasons and ease of handling, we decided to use liquefied versions of above fuel and oxidizer. 100 grams of 98% MMH was directly purchased from Sigma Aldrich. This was equivalent to 24.8 millimoles of MMH per ml (mmol/ml) of solution. Instead of using gaseous NTO we used Red Fuming Nitric Acid (RFNA). We synthesized this RFNA (Figure 6.3) by dissolving 22.372 grams of NTO to 150 ml (211.95 grams) of Concentrate Nitric acid (1.4g/ml) at room temperature. This is done until the clear nitric acid liquid turns saturated (dark red) and produces flumes. The final oxidizer consisted of around 10% NTO.

![Before](before.png) ![After](after.png)

**Figure 6.3.** RFNA being synthesized from NTO and Nitric Acid.
6.2.3 Samples

One square inch of 1500 Å thick aluminum layer was deposited on a microscopic glass substrate (Figure 6.4). These samples are manufactured by Lebow Corp. using the same standard thermal vapor deposition processes by which the SOHO/CELIAS/SEM and SDO/EVE filters were produced. The flight version of filters are made by extracting these exact thin films from this underlying glass substrate, adhering a nickel mesh support and then mounting them on a metal frame. Glass substrate based samples, are extremely sturdy compared to fragile mesh mounted versions. This also eased handling and mounting while performing characterization techniques like Electron Microscopy and XPS.

Figure 6.4. Each filter sample is 1 square inch in size, 1500 Å thick Aluminum coating on a glass substrate

6.2.4 UV Radiation

A Hanovia high pressure quartz mercury vapor arc lamp was used to provide a concentrated source of ultraviolet radiation from a distance of about 20 inches from the reactor. As per the specifications of the lamp from Hanovia Ltd., the complete spectrum (see Figure 6.5) transmitted is 184.9-280 nm (far), 280-320 nm (middle) and 320-400 nm (Near UV). The overall intensity of radiation (313 nm and shorter), measured at 20 inches distance, is over 250 microwatts per square centimeter (μW/cm²). The total solar irradiance (TSI) at 1AU is around 136 μW/cm² of which roughly 10% (or less) is
ultraviolet light i.e. 14 μW/cm². Therefore, for the purposes of this experiment, we can assume that the incident UV radiation flux on our samples is greater than the actual incident solar UV flux on the inflight filters by an order of magnitude or more.

**Figure 6.5.** Spectral distribution (Normalized Power vs Wavelength in nm) of Hanovia UV lamp.

### 6.3 Measurements

All the filter samples were pre-characterized for their physical and chemical properties using EDS and XPS. A single experiment run inside the photochemical reactor consisted of four samples, two original uncoated aluminum samples and two aluminum samples with a mono-layer of carbon fluoride coating under test as a preventive measure against contamination. Having more than one of each
sample types in a single run, provided both redundancy and consistency in our observations. In total, two batch runs were conducted (see Figure 6.6 for sample distribution) with four filter samples each, one without any UV radiation exposure and one with.

![Image](image.png)

**Figure 6.6.** Filter sample distribution diagram. Number of (in bracket) coated/uncoated filter samples in UV and non-UV based contamination runs.

The reactor was purged with pure nitrogen prior to all the runs. The reaction (oxidizer rich combustion) inside the chamber was triggered by first pouring 5 ml of liquid RFNA into the reactor followed by slowly introducing 1 ml of MMH at standard room temperature and atmospheric pressure. After five minutes Helium (as carrier gas) was switched on to collect the plumes inside the reactor towards the cold trap for FTIR analysis. For the experiment run involving UV radiation exposure, the reactor (and filters inside) was UV exposed for a total of about 90 minutes, of which an hour was in combination with the combustion plumes. The following chapter will present the measurements and data from above experiment. We would begin my presenting a brief analysis of FTIR results of plumes in UV and non-UV runs, followed by an overview and discussion on XPS and SEM techniques.
Chapter 7. FT-IR Spectroscopy

7.0 FT-IR Overview

FT-IR stands for Fourier Transform Infrared Spectroscopy where IR radiation is passed through a sample (see Figure 7.1), in our case MMH-RFNA combustion plumes. Some of this infrared radiation is then absorbed by the sample and some of it is passed through (transmitted). The resulting spectrum represents the molecular absorption and transmission, creating a molecular fingerprint of the sample, where every individual molecular species/structures produces a unique spectrum. FT-IR can not only help identify unknown materials but can also determine the quality or consistency of a sample. Moreover, it can also help estimating the amount of components in a mixture.

![Figure 7.1. Measurement principle of FT-IR spectrometer.](image)

7.1 Procedure - FT-IR Data for MMH-RFNA Plumes

For our measurements, the FT-IR spectrometer was a Bruker Alpha instrument with a spectral resolution of 2 cm\(^{-1}\). The processing software used was Opus 7.0. For purposes of this study, it is...
neither intended nor feasible to identify individual chemical species/structures in plumes from various experiment run scenarios. Therefore, this analysis will be restricted to highlighting the broad differences in scans due to chemical composition (both qualitatively and quantitatively) of products of MMH-RFNA combustion with and without UV light exposure. This relative comparison helps us in understanding if the UV light significantly alters the MMH-RFNA reaction (and its products), which later (in inside photo reactor) contaminate our aluminum filter samples.

For both the contamination run scenarios, i.e., first, MMH-RFNA reaction in UV exposure, and second, MMH-RFNA reaction without any UV radiation exposure, exactly same reactants mixture (10 ml RFNA with 1 ml MMH) was used at standard atmospheric conditions. Therefore the FTIR scans below, for either case can be considered standardized. The plumes were collected away from the photo reactor using Helium (as carrier gas) and then condensed using a liquid nitrogen cold trap. Figure 7.2 shows the condensed plumes. The blue stripe on top right shows presence of Nitric Oxide (NO) in the condensed (frozen) combustion products.

![Figure 7.2](image)

**Figure 7.2.** The condensed MMH-RFNA plumes at the cold trap. The blue stripe on top right shows presence of Nitrogen Oxide (NO) in the mixture.
For each experiment run, the FTIR analysis was carried out for four successive gas condensates. This means, that the cold trapped plumes from each run were first brought back to gaseous state (in vacuum lines), and then each time a fixed amount (equivalent to quarter of initial pressure) was extracted to be analyzed (for FTIR). This was performed four times until the vacuum lines had no plumes left. Therefore, total two such experiment runs, one with UV exposure and one without were performed with four FTIR scans per each run (total eight).

### 7.2 FTIR Data and Results

Figure 7.3 shows the average of four FTIR scans of MMH-RFNA combustion products under UV radiation followed by MMH-RFNA combustion products without any UV radiation exposure. For comparison, below (third-III from top) we have the average FTIR scans from a similar reaction from a previous study. The Figure at bottom (IV) shows the scan when nitric acid and water is substracted from the background. For both UV based and non-UV (Figure 7.4) based products (spectrums), there is a major difference in terms of the overall absorption depth (transmission) in both the curves, but on a closer look, most of the peaks in either case are at almost the same wavenumbers. This shows that in both runs, a good portion of molecules that were easily identified were the same (Nitric Acid, Water, N₂O, CO₂). However, the curve depth between the two scans tells that the percentage of these molecules in either of two runs is significantly different. The concentration of Nitric acid in non UV run (products) was found much higher (by almost a factor of 2-3) compared to UV based combustion (MMH-RFNA combustion). High concentration of nitric acid in our experiments (non UV) is in close agreement with results (Figure 7.5) from another study that also conducted MMH-RFNA combustion under similar conditions, without any UV exposure (Wang and Thynell 2013). The comparison of FTIR spectrums between their non-UV based products and our UV based products also suggests that
there are many common overlapping molecular species, but also many distinct or characteristic products (peaks). Therefore, we can say that the MMH-RFNA combustion reaction is a UV photosensitive process, i.e., the transient states and reactions in each scenario (UV and non UV) has both overlapping and distinct sub-reactions (and components). This means that any further interactions of either kind of plumes with an aluminum filter surface will be different and will be effected by UV light exposure.

A similar experiment by was carried out by (Liu and Glassford 1981), where an aluminum surface was contaminated by MMH-NTO exhaust plumes at standard atmospheric conditions under non UV environment. They reported that the when a contaminated aluminum surface that had developed a thick yellow condensate (MMH-NTO), was later exposed to UV radiation, the condensate’s visibility shrunk both in size and mass. They further suggested that this change in mass and texture of the condensate was because of some chemical changes that might have occurred due to UV exposure. However, this observation (in their study) was not further investigated.
Figure 7.3. FT-IR (Transmittance vs Wavenumber) spectra for four condensates of MMH-RFNA plumes in UV. A greater than 1 transmittance in scan IV is due to a calibration error (noise) but can be ignored.
Figure 7.4. FT-IR (Transmittance vs Wavenumber) spectra for each of four condensates of MMH-RFNA plumes without UV (top to bottom – first to fourth).
**Figure 7.5.** Average of four FT-IR spectra in Figure 7.4 (top) and Figure 7.5 (2nd from top). The third (from top) is an FTIR scan from similar reaction that was done under non UV conditions. The last spectra is subtracts water and nitric acid from previous (III) scan (Wang and Thynell 2013).
Chapter 8. X-Ray Photoelectron Spectroscopy (XPS)

8.0 Introduction

X-ray photoelectron spectroscopy (XPS) is a technique for analyzing the surface chemistry of a material by measuring the elemental composition, empirical formula, chemical state and electronic state of the elements within a material. XPS spectra are obtained by irradiating a solid surface with a beam of X-rays while simultaneously measuring the kinetic energy and electrons (counts) that are emitted from the top 1-10 nm of the material being analyzed (see Figure 8.1). Since the top few surface layers of any material are in a different state (boundary layers/interface) than the bulk of the underlying material, therefore to avoid any surface reactions and contamination effects XPS requires high vacuum ($P \sim 10^{-8}$ mill bar) or ultra-high vacuum (UHV; $P < 10^{-9}$ military) conditions.

By measuring the kinetic energy of the emitted electrons, it is possible to determine which elements are near a material’s surface, their chemical states and the binding energy of the electron. The binding energy depends upon a number of factors, including the following:

- The element from which the electron is emitted.
- The orbital from which the electron is ejected
- The chemical environment of the atom from which the electron was emitted.

Peaks appear in the spectrum from atoms emitting electrons of a particular characteristic energy.
Figure 8.1. XPS measurement principle. An x-ray source emits a photon which is absorbed by an atom in a sample, leading to ionization and the emission of a core (inner shell) electron. Each element produces a characteristic set of XPS peaks at characteristic binding energy values that directly identify each element that exists in or on the surface of the material being analyzed. Typical XPS spectrum is a plot of the number of electrons detected (sometimes per unit time) (Y-axis, ordinate) versus the binding energy of the electrons.

The XPS spectrum plots intensities of photoelectrons (in counts per second) emitted versus binding energy (in eV). When an atom or molecule absorbs an X-ray photon, an electron can be ejected. These electrons leaving the sample are detected by an electron spectrometer according to their kinetic energy. The kinetic energy (KE) of this ejected electron depends upon the photon energy (hv), the binding energy (BE) of the electron (i.e., the energy required to remove the electron from the surface) and the spectrometer work function $\phi_s$. The binding energy is regarded as the difference between the initial and the final states after photoelectron has left the atom. Because each element has a unique set of binding energies, XPS can help in identifying as well as determining the concentration of elements on a sample surface.
8.1 XPS Sampling Depth

The sampling depth of any XPS measurement is defined as the depth from which 95% of all the photoelectrons are scattered by the time they reach the surface. For an electron of intensity $I_0$ emitted at a depth $d$ below the surface, the intensity is attenuated according to the Beer-Lambert law. So, the intensity $I_s$ of the same electron as it reaches the surface is

$$I_s = I_0 e^{-d/\lambda}.$$  

Where $\lambda$ is the inelastic mean free path of an electron in solid. Therefore with path length of one $\lambda$, 63% of electron are scattered in a material. This depth is equal to about 3 times when 95% of all photoelectrons are scattered by the time they reach the surface.

The $\lambda$ for Al$_{k\alpha}$ is in the range of 1-3.5 nm for . Therefore the sampling depth for our aluminum filter samples (150 nm thick) under these conditions can be assumed to be around 3-10 nm. This is equivalent to about 10-30 monolayers depth inside Aluminum filter sample.

8.2 Estimation of Aluminum Oxide Thickness

The high resolution scans for Al (2p) spectrum (Figure 8.2) of an aluminum surface can be used to determine the oxide thickness on an aluminum surface (Strohmeier 1990). The binding energies of an oxide (alumina) and the metallic species (aluminum) are separated by a few electron volts. Thus, when the oxide is thin ($< 9$nm), it is possible to distinguish the contribution from both oxide and metal photoelectrons in the sample. For aluminum, this oxide thickness ($d$) is determined by

$$d \text{ (nm)} = 2.8 \ln ((1.4(I_o/I_m)) +1) \quad (8.1)$$

where $I_o$ and $I_m$ are the intensities (peak areas) of the oxide and metal photoelectron peaks respectively.
8.3 Measurement Objectives

Following are the main objectives of using XPS for this study-

- To verify the deposition of our monolayer coatings on aluminum filter samples
- To evaluate aluminum oxidation (depth) of filter samples before and after contamination.
- To measure relative change in intensity ratios of various sub molecular species in a sample (before and after contamination)

For the purposes of this study, our XPS analysis will be more qualitative and restricted to understanding broad differences between various sample states (before and after contamination), rather than determining any absolute quantification of various elemental/molecular species.
Each complete XPS scan for a filter sample consists of total six sub scans. The first of these is a broad scan survey from 100-1200 eV binding energy to get/identify the elements present. Rest five scans are specific high resolution measurements for the following elements:

- Florine (1s, 675-695 eV),
- Oxygen (1s, 524-544 eV),
- Nitrogen (1s, 390-410 eV),
- Carbon (1s, 276-300 eV) and
- Aluminum (2p, 66-86 eV).

Following are the XPS spectra for above five elements. Each spectra includes an example of a survey scan that shows characteristic peaks associated with a particular element. This is followed by high resolution spectra of most useful photoelectron peaks acquired using the same (monochromatic Al) photoelectron source as the survey spectra.

8.4 Spectra of the Filter Samples and Analysis

The following section includes the survey spectra and high resolution spectra using a monochromatic Al x-ray source using a Physical electronics Model 10-360 SCA Omni-focus lens (Moulder, Chastain, and King 1992). Table 8.1 shows the binding energy spectral range for some common molecular species in high resolution Al2p and Oxygen2s scans. For example, the change of ratio of total counts between the aluminum and aluminum oxide, between two samples can help estimate if there was any significant change in surface oxidation between two materials. However, this analysis is not sufficient and accurate by itself to derive any absolute values, such as oxide thicknesses or ratios of various species on a given surface by itself. Though, the technique described in the section 8.2 can help determine the thickness of aluminum oxide on aluminum, this method is only suggested if a clear
peak of aluminum oxide is detected in the high resolution aluminum scans. In the XPS scans of our samples (Figures 8.2- 8.11), no such aluminum oxide peak was clearly detected.

**Table 8.1.** Binding energy spectral range (in eV) in high resolution XPS scans for some common molecular species in Al\(_2p\) (top) scan and Oxygen\(_{2s}\) (bottom) scan.

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<th>Compound Type</th>
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For a non-coated control aluminum filter sample, Figure 8.3 shows the XPS survey scan, followed by high resolution XPS scans of Carbon (8.4), Aluminum (8.5) and Oxygen (8.6) in the same sample. Similarly, Figure 8.7 shows complete XPS spectra of a control coated filter sample. The survey scan (top, Figure 8.7) of a coated sample shows an additional peak (on left) compared to a non-coated sample. This detection of additional peak was the clear indication of our monolayer coatings which were about 1-2 nm thick, and otherwise could not be detected using techniques like Raman, FTIR or SEM. This made XPS as our primary verification technique to assess the yield of our coatings on an aluminum substrate (samples) and confirmed that these coatings chemically adhered to aluminum and stayed months after deposition.

Figures 8.8 and 8.9 show the XPS spectra of sample A and coated sample C (refer to Figure 6.6) that were contaminated under UV exposure. It can still be clearly seen that compared to high resolution aluminum scan on original control uncoated or uncoated surfaces(Figures 8.5, 8.7), where a twin peak due to different aluminum spin states was detected, no such separate (peaks) spin state were detected once filters were contaminated. The exact reason for this are not well understood but the data
suggests that any change in surface due to contamination, on either coated or uncoated samples, attenuates or suppresses the one (~69 eV) of the two separate characteristic Aluminum metal signals. Figure 8.10 (uncoated) and Figure 8.11(coated) show the XPS spectra of samples B and sample D after they were contaminated under non-UV conditions. No immediate major difference could be derived from their XPS scans. This complements the visual inspection/optical images (Figure 10.1-10.2) had clearly shown that both filters types has a reasonably thick surface deposition by the condensate of MMH-NTO plumes. We expect that it’s the condensate that overwhelms their spectra, overshadowing the underlying aluminum sample surface.

Also a comparison of XPS spectra of uncoated sample A and sample B (Figure 6.6) shows no clear remarkable difference that might suggest changes in surface chemistry due to UV and non-UV based contamination. The optical images (later in Figure 10.1-10.2) however show that effects of contamination on aluminum sample was extremely different under UV and non-UV conditions. Therefore, we can say that the immediate surface chemistry that was in XPS detection depth (range) was similar under either conditions, but there effects on underlying aluminum bulk material were remarkably different. Similarly for coated samples C and sample D (Figure 6.6) the XPS spectra comparison (Figures 8.9 and 8.11) also does not highlight any major differences that could be identified with UV or non-UV based conditions, although the visual images prove otherwise. The sample D had a thick condensate deposition on its surface, the sample C had a very transparent oil like film. XPS spectra suggests that both the condensate and the film (on sample C) then had a very similar chemical profile that resulted in similar characteristic detection (signals) in either of the samples.
Based on above data (XPS), we thereby would like to conclude that XPS by itself is not conclusive or sufficient to understand the change in chemical differences such as surface oxidation or effects of UV vs non-UV exposure on chemical composition on coated/uncoated surfaces. However, this technique was helpful in verification of our monolayer thick coatings on aluminum substrate.

Figure 8.3. Survey XPS scan (Intensity in CPS vs Binding energy (eV)) of a control aluminum filter sample (control)
Figure 8.4. High resolution Carbon spectrum (Intensity in CPS vs Binding energy (eV)) of Ctrl Aluminum Sample
**Figure 8.5.** High resolution Al spectrum (Intensity in CPS vs Binding energy (eV)) for control (uncoated) Aluminum filter sample.
Figure 8.6. High resolution Oxygen spectra ((Intensity in CPS vs Binding energy (eV)) of control aluminum filter sample
Figure 8.7. XPS spectra (Intensity in CPS vs Binding energy (eV)) for a control coated aluminum sample. The top row shows the survey spectra, middle row (L to R) high resolution spectra of Florine (1s), Oxygen (1s) and N (1s), bottom row (L to R) – high resolution spectra for Carbon (1s) and Al (2p)
Figure 8.8. XPS spectra (Intensity in CPS vs Binding energy (eV)) for regular aluminum sample A contaminated under UV exposure. The top row shows the survey spectra, middle row (L to R) high resolution spectra of Oxygen (1s) and N (1s), bottom row (L to R) – high resolution spectra for Carbon (1s) and Al (2p)
Figure 8.9. XPS spectra (CPS vs Binding energy (eV)) for a coated aluminum sample C contaminated under UV exposure. The top row shows the survey spectra, middle row (L to R) high resolution spectra of Fluorine (1s), Oxygen (1s) and N (1s), bottom row (L to R) – high resolution spectra for Carbon (1s) and Al (2p)
Figure 8.10. XPS spectra (CPS vs Binding energy (eV)) for uncoated aluminum filter sample B contaminated without UV exposure. The top row shows the survey spectra, middle row (L to R) high resolution spectra of Florine (1s), Oxygen (1s) and N (1s), bottom row (L to R) – high resolution spectra for Carbon (1s) and Al (2p).
Figure 8.11 XPS spectra (CPS vs Binding energy (eV)) for coated aluminum filter sample D contaminated without UV exposure. The top row shows the survey spectra, middle row (L to R) high resolution spectra of Florine (1s), Oxygen (1s) and N (1s), bottom row (L to R) – high resolution spectra for Carbon (1s) and Al (2p).
Chapter 9. Scanning Electron Microscopy and EDS

9.0 SEM/EDS Overview

X-ray microanalysis is routinely used for both qualitative and quantitative analysis of microstructures. When an X-ray analysis with an electron beam instrument like Scanning Electron Microscope (SEM) is combined with digital image analysis, this technique can help in understanding the composition and structure of materials.

In this technique (see Figure 9.1) a solid specimen is bombarded with high energy electrons, which produces characteristic X-rays that are then detected, in our case, by an Energy Dispersive Spectrometer (EDS), which is a solid state device that discriminates among various X-ray energies. EDS allows us to identify a particular element in the scanned area and its relative proportions. The X-ray spectrum from the scan area of the sample shows the counts (Y axis) (number of X rays received and processed by the detector) vs the energy level of those counts (X axis). The post processing software then associates the energy level of these detected X-rays with the elements and the shell level that generates them.

Secondary and Backscattered electron images in the SEM display compositional contrast that results from different atomic number elements and their distribution. The units of spatial resolution of these images is usually in microns -- not nanometers. This is due to the fact that both X-rays and backscattered electrons are generated from deep in the interaction volume. The size of the interaction volume increases with accelerating voltage. That is why EDS is not considered as a surface analysis technique. However, in comparison to backscattered electrons, secondary electrons are still generated
much nearer to the surface (inside), but it’s the Auger electrons that are favored for surface analysis for low atomic elements (Goldstein and others 2012; Friel 1995).

**Figure 9.0** Sample distribution for various experiment run scenarios (from Figure 6.6).

**Figure 9.1.** Interaction of electrons with a specimen can be divided into two ways i.e. elastic and inelastic scattering of electrons. Elastic scattering is change in trajectory of electrons without loss of energy, such as Back-scattering of electrons. When an electron loses some energy without any loss in direction (trajectory), this refers as inelastic scattering. The production of secondary electrons, X-rays (characteristic and continuum) and Auger electron are such events. (Goldstein and others 2012)
9.1 SEM/EDS Measurements

For our purposes in this study, a relative comparison of Secondary electron images of two different samples (coated/uncoated aluminum filters) can reveal if they were affected any differently, chemically (inside or on surface) in similar various contamination scenarios, as described in chapter 6 (UV, non UV based MMH-RFNA combustion).

Our instrument at USC’s Center for electron Microscopy and Microanalysis (CEMMA) was a JSM-7001F-LV, which is an analytical field emission scanning electron microscope equipped with imaging detectors for secondary and backscattered electrons. It has analytical detectors for electron backscatter diffraction (EBSD) and energy dispersive X-ray spectrometer (EDS). The processing software is EDAX Genesis.

Figure 9.2-9.10 show the secondary electron images along with their X-ray spectrum for various aluminum filter samples. Figure 9.2-9.3 show the SEM/EDS measurements for both coated and uncoated aluminum filter samples prior to any contamination. The SEM images of both coated and uncoated filters looks almost identical, with no noticeable differences, either visibly or in their X-ray spectra. The silicon peaks on each sample spectra is due to underlying glass substrate on which aluminum is deposited, and the sodium (Na) signature can be attributed to the handling i.e. “contamination” due to air/moisture at standard atmospheric conditions. Both the samples show clear oxygen peaks, which most reasonably point to surface oxidation of aluminum to aluminum oxide on either of samples or from the underlying glass substrate (Silicon dioxide).
Figure 9.2. (Top) SEM image and EDS (x ray spectra Intensity vs binding energy in KeV) for a control filter (uncoated Al) before contamination.
Figure 9.3. (Top) SEM image and EDS (x ray spectra Intensity vs binding energy KeV) for a control (carbon based monolayer coated Al) sample before contamination
Figure 9.4-9.5 shows the EDS scans for both sample types when contaminated with MMH-RFNA plumes under UV light exposure. Figure 9.3 shows sample A (Figure 9.0 for sample nomenclature), which shows a completely different picture from Figure 9.2. Here, the material looks heavily altered with white “curls” of sort on the base image, which shows that filter material heavily reacted with the plumes that changed its chemical as well as physical profile. Its X spectra although reveals no specific new element was introduced due to this contamination, that also got detected by EDS. The curls and bright formations could either just be thick contaminant depositions on the surface, which radiate the major SEM signature (hiding the underlying aluminum surface) or it could be some sort of “etching” inside the bulk aluminum material because of plume deposition on surface. In either of the possibilities, it is certain that the bulk aluminum material reacted with contaminates altering the filters physical and chemical characteristics.

Figure 9.5 show the EDS scans for coated Sample C (refer Figure 9.0) that was also contaminated in the same experiment run as the above sample. Here also the XPS spectra is almost unchanged as before (Figure 9.3) any contamination. No bright white peels or fragments are seen deposited or etched here like Sample A. Although, the SEM image for Sample C shows large cracks, which either could be “fractures” starting from top surface, to all the way through filter material. The “fissures” or cracks seems to be originating/ fragmenting around the circular point of impacts, which could be interaction zones of contaminant particles with the filter surface. Since most of the surface look unscathed, it suggests that the monolayer coatings were successfully able to isolate aluminum from any most of any direct impact from the contaminant molecules, and also shielded them from reacting chemically “deep inside”.
Figure 9.4. (Top) SEM image and (bottom) EDS (X ray spectra Intensity vs Binding energy keV) for a (uncoated Al) Sample A after contamination
**Figure 9.5.** (Top) SEM image and (bottom) EDS (x ray spectra with Intensity vs binding energy in eV) for a (carbon based monolayer coated Al) **Sample C** after contamination.
Figure 9.6. High resolution (focused on impact zone) SEM image (top) and (bottom) EDS spectra for a (carbon based monolayer coated Al) Sample C after contamination.
Figures 9.7 and 9.8 shows similar EDS scans for samples both uncoated Sample B (Figure 9.1) and coated Sample D (Figure 9.0) that were contaminated with MMH-RFNA plumes without UV radiation exposure, under standard atmospheric conditions. For sample type B and D, no significant change in X-ray spectra was observed, either in comparison to their previous self (Figures 9.2 and 9.3) or in comparison to each other. But SEM images of these reveals that the plumes interacted and left a “symmetric rain shower” like pattern on sample B. These distinct individual interactions or marks are stretched and elongated and most likely to be impact points of plume particles on the surface and their subsequent interaction zones with the underlying aluminum. These zones are most likely some sort of an etching or passivation from top aluminum surface.

Similar to Sample B, SEM images of coated sample D when contaminated without UV radiation also shows similar individual marks. Now at first look, both coated and uncoated in these run are affected in a similar way i.e. rain shower like impact on the sample surface with contained interaction zones. But on a closer look, compared to sample B, no such symmetric “rain shower” like spread of such interaction zones is seen on sample D. with interaction zones that are either stretched or elongated as on sample B. One of the possible explanations for this difference in interactions might be surface tension effect. The coatings on sample D interacts with plumes, rather than alumina/aluminum surface directly, as on sample B. Now, it is already known to us that our coatings were developed with material properties that are extremely hydrophobic, compared to alumina surface which is hydrophilic. This probably might explain why the plumes molecules are far circular and confined and not spread like a shower. These interactions of plume particles with coated surface is similar in way to rain droplets on a waxed car surface.

*please refer to Figure 9.0 or Figure 6.6 for filter nomenclature
Figure 9.7. (Top) SEM image and (bottom) EDS (x ray spectra) for a (carbon based monolayer coated Al) Sample B after non UV contamination.
Figure 9.8. (Top) SEM image along with (bottom) EDS (x ray spectra) for a (carbon based monolayer coated Al) Sample D after contamination (non UV).
Section IV

Results and Conclusions
Chapter 10. Results and Analysis

The main engineering objective of our study was to develop a monolayer coating which acts as a protective layer, shielding the aluminum filters (surfaces) from a direct contaminant attack, such as of MMH-NTO plumes under UV radiation. This protective coating is expected to reduce the susceptibility of aluminum filters to degradation that directly affects (reduction) in their EUV transmission. Our contamination setup, hence thereof, provided a “proof of concept” procedure to test the effectiveness of these coatings under laboratory setup at standard atmospheric conditions. In addition, we also tried to understand if UV radiation significantly affects the normal course of interactions between exhaust plumes and aluminum filter surfaces.

Our FT-IR measurements (Figure 7.5) in Chapter 7 of MMH-RFNA products, clearly suggest that UV light effects, both qualitatively and quantitatively (stoichiometric ratios) products of this combustion reaction. Both UV based and non-UV based reaction products had many overlapping/common molecular species, mainly Nitric Acid, Water and Carbon Dioxide, but they were present in significantly different stoichiometric ratios. The non UV based combustion products were clearly far more concentrated in Nitric Acid. Moreover, (non–UV) left a clear wax like white condensate (Figure 10.2) on the walls of the chamber as well as on the aluminum filter sample surfaces. For UV exposed MMH-RFNA combustion, no such condensate was seen deposited (Figure 10.1). This observation is in agreement with some previous studies (Liu and Glassford 1981) that noted that the MMH-HNO₃ rich condensate when exposed to UV radiation, shrunk and lost mass. In our case, the reaction was conducted while being under direct UV exposure, only an oil like glossy deposition was left on either of surfaces. No wax like solid formation was seen, neither on the walls of the photo reactor nor on the filter surfaces.
This proves, that the overall, products of combustion for either of the above cases were clearly different (with common species as well). Therefore, the MMH-RFNA combustion, its transient reactions (and molecular species) and final products are extremely UV photosensitive. Identifying individual molecular species and their absolute stoichiometric ratio’s in each combustion type is beyond the scope of this work.

Figure 10.0 Sample Distribution Map (from Figure 6.6) and Nomenclature

Figure 10.1 shows the uncoated sample A and coated sample C (please refer Figure 10.0 for filter sample nomenclature), exposed to plumes under UV radiation at standard atmospheric conditions. Clearly, the sample A seems to have undergone extensive physical and chemical “damage” by this contaminant attack, whereas coated sample C looks almost unscathed, with just a thin oil like film deposition. The extensive visible damage on sample A could be due to presence of nitric acid (MMH-HNO₃) in plumes. It is known that nitric acid readily/immediately dissolves aluminum, but interestingly, the coated sample C was completely untouched by any acid attack from the same plumes. This clearly suggests that our monolayer coatings, just ~1-2 nm thick, were able to successfully shield underlying aluminum metal from any direct contact with nitric acid rich plumes.
Secondary electron images of both coated (sample C, D) and uncoated filter sample (A, B), show no visible difference (Figure 10.3) prior to the experiment. However, after the contamination (under UV exposure) Figure 10.4. SEM images are in close agreement with our assessment of optical/visible pictures (Figures 10.1 and 10.2). Clearly, sample A (10.4 left) has undergone significant changes inside (a few layers deep), reacting heavily with plume particles under UV exposure. Its majority of aluminum film looks fragmented/shattered. Whereas, coated sample C (10.4 right), like its visible image looks largely intact, with a few contained/localized circular zones of interactions with plume particles. The majority of aluminum material here is clean, with much larger cracks compared to “shattered” condition of aluminum film on sample A. This proves that the coatings were highly effective in shielding the bulk aluminum material from reacting from highly acidic plumes. Also a few particles that did manage to penetrate, were contained at the point of impact.

Now, when the sample types (B and D) are exposed to plumes under non UV run scenario, things seem to go differently. As seen in their pictures earlier (in Figure 10.2), there was this “whitish” wax like deposition on both coated and uncoated samples, which is primarily MMH-HNO₃ (Liu and Glassford 1981, 306-311) rich hygroscopic condensate of MMH-RFNA combustion. However, SEM images of both sample (B) and sample D show that on the uncoated sample, these interactions zones of plume particles were stretched and elongated. There was this rain shower like symmetry of plumes’ running” all over the aluminum/alumina bare surface of sample B. whereas, on coated sample D, number of interaction zones or plume particles were confined (circular) with no “symmetry” in hower/ spread of particles. This direction of the stretch of plumes on uncoated samples can be attributed to gravity.
Figure 10.1 (Left) uncoated Sample A* and (Right) monolayer coated Sample C* when contaminated under UV light. The uncoated sample (A) showed visible surface erosion and developed a shiny gloss. The coated sample C was largely intact with just an oil like film on its surface.

*please refer to Figure 6.6 or previous page for filter nomenclature

Figure 10.2. (Left) Uncoated Sample B* and (Right) coated Sample D* when contaminated without UV light. The plumes left a residual wax like condensate on both surfaces with bulk Al surface almost intact. No surface erosion was seen on either of the samples in non-UV based contamination.
Before Contamination

(a) (Al) **Sample A***. No visible traces could be seen.  

(b) Coated (Al) **Sample C***. No visible traces could be seen.

After Contamination with UV exposure

(a) Contaminated **Sample A** shows “peeling” curling of top layers (bright spots)  
(Inset): Underlying Aluminum surface shows heavy fragmentation with much smaller individual pieces

(b) Contaminated **Sample C** shows a combination of Al surface “fragmentation” and plume particle impact zones  
(Inset): 10 micron resolution image of particle impact areas which are contained (circular) zones.

*please refer to Figure 6.6 for filter nomenclature
Figure 10.5. SEM images of Sample B (L) and coated Sample D (R) when contaminated in non UV conditions. The plumes particles are elongated and stretched with spread like a “rain shower” on uncoated Sample B. In Coated sample D, each interaction(zone) is more circular and contained.

One possible explanation, based on studies related to development of such carbon based coatings is that they were designed to be extremely hydrophobic in nature, compared to the alumina surface, which is hydrophilic. Therefore, moisture/water vapors find difficult to “stick” and react on such a coated Sample D. This might also explain that if contaminants under UV exposure are unable to “stick” and react with coated filter surface, they would have later evaporated under UV exposure.

Whereas for a non-coated filter surface (sample A), the UV radiation triggers condensate interactions with aluminum surface (alumina), which otherwise would have just rested ‘dormant’ like a wax deposition (as in case of sample B).

Based on above observations at standard atmospheric conditions, it is expected that our coatings can effectively protect the underlying bulk aluminum filter material from a similar direct contaminant attack in an ultra-high vacuum space environment (geosynchronous orbit and beyond). This can
significantly enhance the overall performance of aluminum filters (transmission) over a mission lifetime (and beyond) that usually can last up to a decade and more. The Figure 10.6 shows the analytical model that projects the performance improvement in aluminum filter transmission (for SDO/EVE/ESP primary filter as example). For instruments like SDO/EVE/ESP, at 30.4 nm wavelength, our analytical calculations show that after four years of exposure (operations in orbit), transmission for an aluminum filter protected with our carbon monolayer coatings can remain as much as three times higher than an uncoated filter, i.e. projected performance improvement of up to 200%. If these coatings, as expected, can also slow down or prevent filter degradation due to aging at standard atmospheric conditions, this improvement can be as high as 400%. However, the actual effectiveness of such coatings in slowing or preventing aluminum filter oxidation on ground is yet to be experimentally tested or proven.

Figure 10.6. Transmission (%) vs Wavelength (nm) curve using Henke’s model for various stages of SDO/EVE/ESP’s primary aluminum filter. The green curve shows the expected transmission profile of a new aluminum filter (blue) just coated with carbon monolayer coating. The curve (grey) in preflight calibration results of ~5 year old filter. The curve in red shows Nov 2013 EUV transmission by SDO/EVE/ESP primary filter.

Coating can decrease oxidation of Al filter on ground and shield from contaminants in space
Chapter 11. Conclusions and Future Work

11.0 Conclusions

This study described an experimental approach to improve our understanding on thin film aluminum filter degradation in outer space, specifically with reference to SOHO/CELIAS/SEM and SDO/EVE primary aluminum filters. We here, investigated one of the hypothesis that states that deterioration of these filters over time is because of contamination of their surfaces from plumes of their satellites Monomethylhydrazine (MMH) – Nitrogen Tetroxide (NTO) thrusters, in solar radiation environment. The conditions under which the samples in this study were contaminated were not ideal, mainly because it was conducted at standard atmospheric conditions and we used a liquid oxidizer, Red Fuming Nitric Acid (RFNA), instead of gaseous NTO. Using RFNA directly increased the concentration of Nitric acid during contamination, which explains surface erosion under UV exposure on our uncoated aluminum filter samples (Figure 10.1). Moreover, it is expected that the atmospheric conditions, mainly constituents (air) and pressure (operating temperature is almost similar on ground and in orbit) also would have significantly interfered with the overall reactions of MMH-RFNA and the subsequent interactions of their plumes with filter surfaces. However, for the purposes of this study, our objectives were restricted to understanding relative differences in the performance/behavior of coated and uncoated filters (with plumes). This “proof of concept” demonstration of relative comparison at standard atmospheric conditions is complementary and in addition to our observations on different filter (material) types on SDO/EVE (chapter 5) in geosynchronous orbital conditions (high vacuum and solar radiation exposure).

Our FTIR results (Figure 7.5) demonstrate that the MMH-RFNA (13% NTO) combustion reaction is
extremely UV photosensitive, i.e. the products of MMH-RFNA combustion (in standard atmospheric conditions) under UV exposure, significantly differ in composition, both qualitatively (molecular species) and quantitatively (stoichiometric ratio’s) from a non-UV based MMH-RFNA combustion. Both of the above reaction types produce many common molecular species, mainly nitric acid, water and carbon dioxide. However, the non UV based combustion produced/left far higher concentration of Nitric acid in its plumes, by almost a factor of 2-3 times greater than UV based reaction, and left a “wax” like solid condensate on filter surfaces. The UV based reaction produced no such condensate. This observation was in agreement with one of the earlier study (Liu and Glassford 1981; Tribble 2003) that also found MMH-RFNA plumes to condense on aluminum surfaces but then later shrink and lose mass/density when exposed to UV radiation.

The visual inspection (Figures 10.1-10.2) of our filter samples also demonstrated differences in interactions of UV and non-UV based plumes with aluminum filter surfaces. In addition to the aforementioned differences related to the ‘wax’ like deposition (visible to naked eye) the uncoated filter under UV based contamination developed a shiny gloss on its surface with visible surface erosion (of aluminum), whereas the coated filter remained almost intact. This erosion (on uncoated filter) is most likely due to nitric acid (in plumes). Although non-UV based plumes had far higher concentration of nitric acid, they triggered no such surface erosion. This proves that the UV radiation plays a significant role by providing necessary activation energy that not only triggered the nitric acid that was present in plumes to directly react with aluminum surface, but also liberate the acid molecule that was bound/contained in other plume product species, mainly MMH-HNO3.

Based on above observations, we suspect that both the primary aluminum filters degradation on MEGS A2 and SDO/EVE/ESP channels (chapter 5) of SDO/EVE is not just due to continuous
deposition (increased thickness over time) of thruster based plume contaminates, but because of chemical changes (like increased oxidation) induced on their surfaces (and deeper inside) with time. The secondary filters on either channel of SDO/EVE, that mostly remain in shade, away from direct solar exposure, meanwhile are almost intact. Together, our observations in above experiments and experience with onboard flight filters suggests that the solar UV radiation is the vital factor in combination with hydrocarbon rich outgassing contaminants (and plumes) in facilitating both the physical and chemical changes that leads to degradation of the aluminum filter’s EUV transmission. Our carbon based monolayer coatings (1-2 nm thick) that were developed to act as a protective layer for aluminum filters, proved highly effective. The comparison of the visible images (Figure 10.1) of contaminated filters also clearly show that the coated surface was almost intact whereas the uncoated filter had a visible shiny gloss, with significant physical changes on its surface (erosion and rough spots). The coated filter samples exhibited no surface erosion or degradation compared to regular filter samples under UV based contamination. SEM (Figure 10.4) results (chapter 9, 10) revealed that these coatings were able to successfully shield the underlying aluminum from any direct contact with plume particles. They also prevented buildup of plume products on the filter surface with the exception of a few isolated spots, and while some deterioration of the filter is evident at these locations, they account for a very small fraction of the filter surface. The total affected surface area (Figure 10.4) on a coated filter surface (~ 4-5%) was almost an order of magnitude smaller than on an uncoated filter (50% area affected). SEM images (Figure 10.2) of non-UV based contamination further demonstrated that these coatings increased the surface tension (i.e. increased contact angles) on filter surfaces. The interaction area of individual plume particles, with a coated surface was circular and contained, compared to a non-coated surface
were each plume-surface interaction zone was stretched and elongated. This behavior is in agreement with the known properties exhibited by these coatings, which were primarily developed with the goal of being extremely hydrophobic, compared to a regular aluminum (alumina) surface that is hydrophilic.

For instruments like SDO/EVE/ESP, at 30.4 nm wavelength, our analytical calculations (Figure 10.6) project that after four years of exposure, transmission for an aluminum filter protected with our carbon monolayer coatings can exhibit EUV transmission improvement, anywhere between existing transmission levels up to three times higher than current (uncoated) filters, i.e. performance improvement (margin) of around 200%. If these coatings, as expected, can also slow down or prevent filter degradation due to aging at standard atmospheric conditions (during preflight), this improvement can be as high as up to 400%. However, the actual effectiveness of such coatings in slowing or preventing aluminum filter oxidation on ground is yet to be experimentally tested or proven. Furthermore, the deposition thickness of our coatings can be manipulated at nanoscale, in increments of 1-2 nm. This precise control of deposition thickness allows us to design newer filters with varying degrees of protective coatings (on either surfaces). The thickness of the coatings can be optimized based on the performance requirements/benefits like reduced susceptibility to degradation in various environments (on ground and in geo-space) versus tradeoff in absolute EUV transmission for a new filter.

11.1 Future Work

As a next step, we would like to improve upon our existing methodology by synthesizing contamination of actual mesh mounted aluminum filter samples in conditions that are much closer to actual space environment (high vacuum) inside our laboratory. This includes a vacuum chamber setup
for both contamination and UV radiation exposure. Instead of using a highly acidic oxidizer, RFNA, the reaction will be carried out in gaseous state of MMH/NTO, just like on board attitude control thrusters on SOHO and SDO. Also to better understand the chemical composition of plumes, our setup will be designed to take FTIR scans inside the reaction chamber, in real time under UV radiation exposure.

Post contamination, the filter samples would be characterized using a monochromatic EUV light source (like 58.4 nm setup at USC Space Sciences Center). This would not only help us in measuring the transmission performance of these filters but also measure the effectiveness of our protective coatings in a quantifiable way. Also, to observe and characterize long term (duration) effects (chemical and physical) of radiation on filter surfaces, we would like to conduct this study over a period of few months.
References


