A sounding rocket mission concept to acquire high-resolution radiometric spectra spanning the 9 nm - 31 nm wavelength range

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Abstract -- When studying Solar Extreme Ultraviolet (EUV) emissions, both single-wavelength, two-dimensional (2D) spectroheliograms and multi-wavelength, one-dimensional (1D) line spectra are important, especially for a thorough understanding of the complex processes in the solar magnetized plasma from the base of the chromosphere through the corona. 2D image data are required for a detailed study of spatial structures, whereas radiometric (*i.e*., spectral) data provide information on relevant atomic excitation/ionization state densities (and thus temperature). Using both imaging and radiometric techniques, several satellite missions presently study solar dynamics in the EUV, including the Solar Dyamics Observatory (SDO), Hinode, and the Solar-Terrestrial Relations Observatory (STEREO). The EUV wavelengths of interest typically span 9 nm to 31 nm, with the shorter wavelengths being associated with the hottest features (*e.g*., intense flares and bright points) and the longer wavelengths associated with cooler features (*e.g*., coronal holes and filaments). Because the optical components of satellite instruments degrade over time, it is not uncommon to conduct sounding rocket underflights for calibration purposes. The authors have designed a radiometric sounding rocket payload that could serve as both a calibration underflight for and a complementary scientific mission to the upcoming Solar Ultraviolet Imager (SUVI) mission aboard the GOES-R satellite (scheduled for a 2015 launch). The challenge to provide quality radiometric line spectra over the 9-31 nm range covered by SUVI was driven by the multilayer coatings required to make the optical components, including mirrors and gratings, reflective over the entire range. Typically, these multilayers provide useful EUV reflectances over bandwidths of a few nm. Our solution to this problem was to employ a three-telescope system in which the optical components were coated with multilayers that spanned three wavelength ranges to cover the three pairs of SUVI bands. The complete system was designed to fit within the Black Brandt-IX 22”-diameter payload skin envelope. The basic optical path is that of a simple parabolic telescope in which EUV light is focused onto a slit and shutter assembly and imaged onto a normal-incidence diffraction grating, which then disperses the light onto a 2048 $\times$ 2048 CCD sensor. The CCD thus records 1D spatial information along one axis and spectral information along the other. The slit spans 40 arc-minutes in length, thus covering a solar diameter out to +/- 1.3 solar radii. Our operations concept includes imaging at three distinct positions: the north-south meridian, the northeast-southwest diagonal, and real-time pointing at an active region. Six 10-second images will be obtained at each position. Fine pointing is provided by the SPARCS-VII attitude control system typically employed on Black Brandt solar missions. Both before and after launch, all three telescopes will be calibrated with the EUV line emission source and monochromater system at NASA's Stray Light Facility at Marshall Spaceflight Center. Details of the payload design, operations concept, and data application will be presented.

A sounding rocket mission concept to acquire high-resolution radiometric spectra spanning the 9 nm - 31 nm wavelength range

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Abstract – Abstract - When studying complex processes in the solar atmosphere, observations in the extreme ultraviolet (EUV) are important. Two forms of observations include single-wavelength two-dimensional (2D) spectroheliograms and multi-wavelength one-dimensional (1D) line spectra. 2D image data facilitate a detailed study of spatial structures, whereas radiometric (i.e., spectral) data provide information on relevant atomic excitation/ionization state densities (and thus temperatures). The EUV wavelengths of interest typically span 9 nm to 31 nm, with the shorter wavelengths being associated with the hottest features (e.g., intense flares and bright points) and the longer wavelengths associated with cooler features (e.g., coronal holes and filaments). Because the optical components of satellite instruments degrade over time, it is not uncommon to conduct sounding rocket underflights for calibration purposes. The authors have designed a radiometric sounding rocket payload that could serve as both a calibration underflight for and a complementary scientific mission to the upcoming Solar Ultraviolet Imager (SUVI) mission aboard the GOES-R satellite. The challenge to provide quality radiometric line spectra over the 9-31 nm range was driven by the relatively narrow passbands of the multilayer coatings used to make the optical components reflective in EUV. This motivated a three-telescope system in which the optical components were coated with multilayers that spanned three wavelength ranges to cover the three pairs of SUVI bands. The basic optical path is that of a simple parabolic telescope where EUV light is focused onto a slit and shutter assembly and projected onto a normal-incidence diffraction grating. The dispersed light is imaged by a four megapixel CCD sensor, recording 1D spatial information along one axis and spectral information along the other. With this study, we discuss both operational and scientific benefits from such a proposed rocket flight. Technical challenges are also addressed. Suggestions for mission objectives from the SHINE community are welcome..

BACKGROUND: The SUVI Mission on the GOES-R Satellite

As one of six GOES-R operational instruments, SUVI will observe the solar disk and atmosphere out to 1.3 solar radii and record 2D images in six narrow-wavelength passbands in the Extreme UltraViolet (EUV) spectrum centered about the following emission lines: 9.4, 13.1, 17.1, 19.5, 28.4, and 30.4 nm. Each 2D image is recorded as a band-specific spectroheliogram illustrating the emissions within the solar atmosphere, beginning at the chromosphere, spanning the transition region, and extending through the corona out to 1.3 Solar Radii. Table 1 shows the relevance of each passband to the different regions of interest, also represented visually in Figure 1 using a thematic map based on SDO data.

Wavelength Log (Te)	94 Å 6.8	131 Å 7.0,7.2	171 Å 5.8	195 Å 6.1,7.3	284 Å 6.3	304 Å 4.7
Filaments						
Coronal Holes						
Active Region Complexity						
CMEs (e.g. dimming)						
Flare Location and Morphology						
Quiet Regions						

Table 1. Summary of SUVI passband wavelengths and their utility for observing solar features.

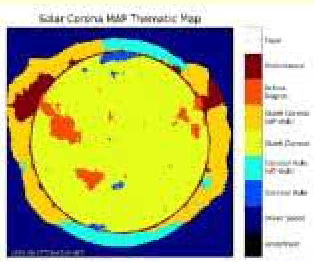

Figure 1. Thematic maps identify distinct solar regions including flares, prominences, coronal holes, active regions and corona. This image displays proxy data from the NASA Solar Dynamics Observatory's Atmospheric Imaging Assembly.

SUVI's design is based on a Ritchey–Chrétien telescope, a version of the Cassegrain telescope with both primary and secondary mirrors as hyperboloids. Multilayer coatings are used to provide optimal reflectance for the six passbands. Details of the configuration parameters appear in Table 2. A photo and CAD model of the SUVI assembly appear in Figure 2.

Quantity	Value
Telescope type	Generalized Cassegrain
Primary mirror radius	138.62 cm
Secondary mirror radius	-91.10 cm
Effective focal length	173.2 cm
Physical pixel size	21 x 21 microns
Angular pixel size	2.5 x 2.5 arc sec
Min Field of View (FOV)	44 x 44 arcmin
Image array size	1056 x 1056 pixels

Table 2. Some key parameters of the SUVI Telescope Configuration

Figure 2. Photo and CAD model of SUVI Telescope Assembly.

Space Weather Products will be developed from GOES-R data, and an overview of these products appears in Figure 3.

SUVI's data will contribute to eight of these products, three of which offer a new capability to heliophysics researchers, spacecraft operators, space weather forecasters, and other space professionals.

The need for a precise radiometric calibration will assure that the SUVI data represent the most accurate and precise solar emission data to be used in these products.

Precise requirements are outlined and explained in the next section of this poster.

Figure 3. A Summary slide of the GOES-R Space Weather Products under development by NOAA's Space Weather Prediction Center (SWPC)

Feasibility Study Objectives

PURPOSE: Outline and identify key elements for a viable SUVI sounding rocket underflight calibration program.

Key questions to address include:

What GOES-R mission requirements can be fulfilled with a SUVI underflight program?
What alternatives are there, and why is the underflight program the best alternative?

- What systems and teams are in place to realize the underflight program? Are there any systems or teams which need to be developed?
- What is the optimal payload configuration for the underflight program?
- What is the operations concept? How often do we need to launch and under what solar conditions? What simultaneous observations from SUVI do we require?
- How will the data be processed, archived, and distributed?
- How much will this program cost in terms of time, manpower, and dollars?

Initial Approach

Examination of SUVI performance requirements, research of possible degradation effects due to long-term exposure to the Geosynchronous Earth Orbit (GEO) space environment, and assessment of present on-orbit calibration plans have prompted us to consider an imaging spectrograph (e.g., a 1D slit image focused onto a diffraction grating with photons being recorded by a 2D CCD, sized to provide 1 arc-sec spatial and 0.01 nm spectral resolutions.

SUVI Performance Requirements

Solar X-ray/EUV Imager Observational Requirements Table

	Observational Parameter	Requirement
SUVIRQ1	Spatial coverage	0 - 1.3 solar radii
SUVIRQ2	Spatial/Angular resolution	See "Point Response Requirement in Terms of Ensquared Energy" Table (MRD4106)
SUVIRQ3	Pointing/"Mapping" accuracy	Pointing accuracy during 24 hours: 3.0 arcmin (N-S, E-W) (3 sigma), Pointing accuracy during 60 seconds: 2.0 arc seconds (E-W, N-S) (1 sigma), 6.0 arcsec (E-W, N-S) (3 sigma)
SUVIRQ4	Pointing Knowledge/ Mapping uncertainty	± 2.5 arcsec
SUVIRQ5	Measurement range	Radiance: 0.3 - 10^{6} photons s^{-1} cm^{-2} $arcsec^{-2}$ Temperature: 1 - 10 MK
SUVIRQ6	Measurement resolution	Radiance: 0.1%
SUVIRQ7	Measurement accuracy	40% in radiance
SUVIRQ8	Refresh rate Product latency Long-term stability	Threshold: Imaging: < 2 min, Temperature: < 6 min < 1 min 30%
SUVIRQ9	Reliability/Continuity	No gaps > 2 min

SUVI Calibration Underflight Requirements Derived from SUVI Requirements

SUVIREQ ID	CUF Derived Objective	CUF Method/ Approach	NOTES
1	Image out to 1.3 solar radii	Slew 1D slit image target radially out to 1.3 solar radii along each of four cardinal limbs	Alternative plan is to target 2 of the cardinal limbs and two of the "corner" limbs to seek artifacts that may be introduced by the CCD
2	Image high-contrast features on solar disk. CUF spectral resolution of 0.01 nm.	Target in real-time (during flight) coronal hole and/or planetary occultation. Compare co-registered 1D images with SUVI.	Feature selection method will depend on targets of opportunity for any given launch.
3	CUF Spatial resolution of 1 arcsec	To avoid aliasing in the spatial dimension, will employ CCD with at least 2x the pixel resolution (spatial axis) of the SUVI telescope. Will compare co-registered images.	1. Requires commensurate pointing knowledge of rocket. 2. Only partially addresses this SUVIREQ since flight is ~ 5 min.
4	Spatial resolution of 1 arcsec	To avoid aliasing in the spatial dimension, will employ CCD with at least 2x the pixel resolution of the SUVI telescope	Requires commensurate pointing knowledge of rocket
5	Image wide range of features, including active regions, bright points, coronal holes, and limbs	Slew 1D slit image to regions with a wide variety of luminosity values in real-time during the rocket flight.	Success in this area depends on targets of opportunity during flight.
6	Match SUVI's radiance precision req't.	Employ pre- and post-flight absolute calibration of underflight rocket payload using MSFC calibration facilities	Previous underflight studies have reported changes in absolute radiance calibration during flight, thus motivating our pre- and post-flight cal.
7	Match SUVI's absolute radiance req't.	Employ pre- and post-flight absolute calibration of underflight rocket payload using MSFC calibration facilities	Previous underflight studies have reported changes in absolute radiance calibration during flight, thus motivating our pre- and post-flight cal.
8	Match SUVI's absolute radiance req't.	Perform absolute radiometric calibration and compare with historical data from previous flights.	Can only address long-term stability issue; requires one flight every 12-18 months for duration of operational life
9	N/A	N/A	N/A

Conceptual configuration

Examination of SUVI performance requirements, research of possible degradation effects due to long-term exposure to the Geosynchronous Earth Orbit (GEO) space environment, and assessment of present on-orbit calibration plans have prompted us to consider an imaging spectrograph: a 1D slit image focused onto a diffraction grating with photons being recorded by a 2D CCD, sized to provide 1 arc-sec spatial and 0.01 nm spectral resolutions. To maximize throughput, we are investigating the use of four 8" telescopes with reflective optics optimized to the SUVI passbands: 9.4 nm, 13.1 nm, 17.1/19.5 nm combo, and 28.4/30.4 nm combo. These will be arranged into a 22" cylindrical payload envelope with a 3" guide telescope at the center (Figure 4). Each telescope would incorporate a standard imaging spectrograph design with a normal-incidence grating. The SUMER instrument aboard SOHO is one example of such a configuration (Figure 5.)

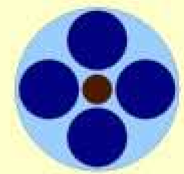

Figure 4. Possible arrangement of 4-8" telescopes (dark blue) into a 22" Black Brandt Rocket Payload Envelope (light blue). The central 3" telescope (burgundy) is used as a guide telescope to allow the operator to control the target real time during the rocket flight.

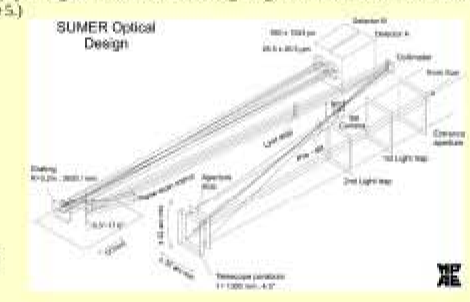

Figure 5. Schematic of the SUMER imaging spectrograph aboard SOHO

EUV Reflectance: Multilayer Coatings

Approach: Employ multilayer coatings on both parabolic mirror and normal-incidence diffraction gratings to maximize reflectivity for each telescope

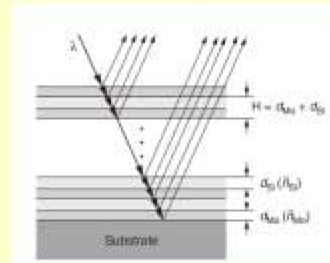

Fig. 6. Alternating layers of silicon and molybdenum in a multilayer structure

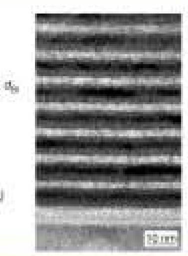

Fig. 7. TEM image of multilayer coating with a period: H = dMo + dSi = 7.0 nm

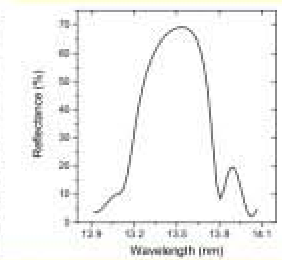

Fig. 8. Measured reflectance versus wavelength for a Mo/Si multilayer mirror consisting of 50 periods [9]

Pre- and Post-flight calibration

Test facilities at NASA/MSFC consist of: a small vacuum chamber to mount the detectors and test optics, the broadband AIXUV source with Luxel thin metal EUV filters to isolate different wavelength bands, a custom EUV transmission grating to monitor the source and a custom EUV monochromator that is mounted between the source beam and the test facilities (NSSTC, XRCF and SLF). This system provides the narrow wavelength bands to provide the absolute radiometric calibration of the SUVI underflight payload.

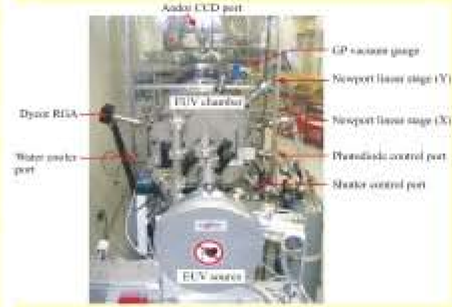

Figure 9. The EUV source is an AIXUV, consisting of the discharge head comprised of the following components: the discharge body containing capacitor bank, discharge electrodes, the turbo pump and gas flow controllers to control the gas in the lamp, and the pressure gauges and temperature sensors to monitor the status of the lamp. The discharge head has an online beam that is matched to the test chamber and two additional beams that can be used to monitor the source.

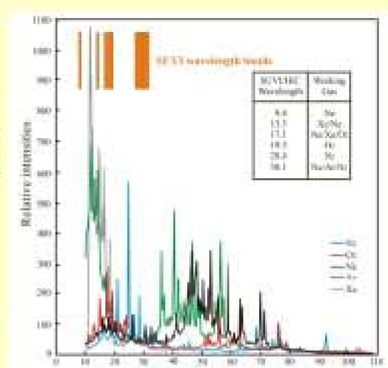

Figure 10. SUVI wavelength bands (orange boxes at top, III-C is at 19.5 nm) with the working gases that will be used to produce "broadband" emission (BB: Xe, Ne, Ar) and emission lines (EL: N2, O2) in our wavelength range.