Zone plate EUV Solar Irradiance Monitor

James C. Bremer, Research Support Instruments, Inc.;
John F. Seely, Naval Research Laboratory;
Glenn E. Holland, Global Strategies Group North America, Inc.;
Yan Feng, Xradia, Inc.;
Benjawan Kjornrattanawanich, Artep, Inc.;
Leonid Goray, Russian Academy of Sciences

EUV Workshop, LASP, October 25-27, 2011
This work was supported by NASA project NNH09AK121
"Ultra-Stable Extreme Ultraviolet Solar Monitor Using Zone Plates"

Overview

- Solar EUV spectrum & upper atmospheric interaction
- EUV measurement requirements & techniques
- Zone plate (ZP) optical properties
- ZP-based solar EUV irradiance monitor architecture
- Advantages of ZP-based solar irradiance monitor
- EUV monitor development goals & spectral band selection
- ZP solar irradiance monitor design parameters
- EUV channel parameters & predicted performance
- EUV monitor development status
- Atmospheric sounding with an EUV sensor
- Conclusions & recommendations

Solar Extreme Ultraviolet (EUV) Spectrum & Upper Atmospheric Interaction

Solar EUV Spectrum

Much lower irradiance than NIR/visible/NUV

Dominated by bright emission lines from transition region, corona, flares, CME's

Highly variable: solar max/min ≅ 10x; major flare/quiet Sun > 1000x at some λ's

Upper Atmospheric Absorption (λ < 100 nm, altitude 100 - 200 km)

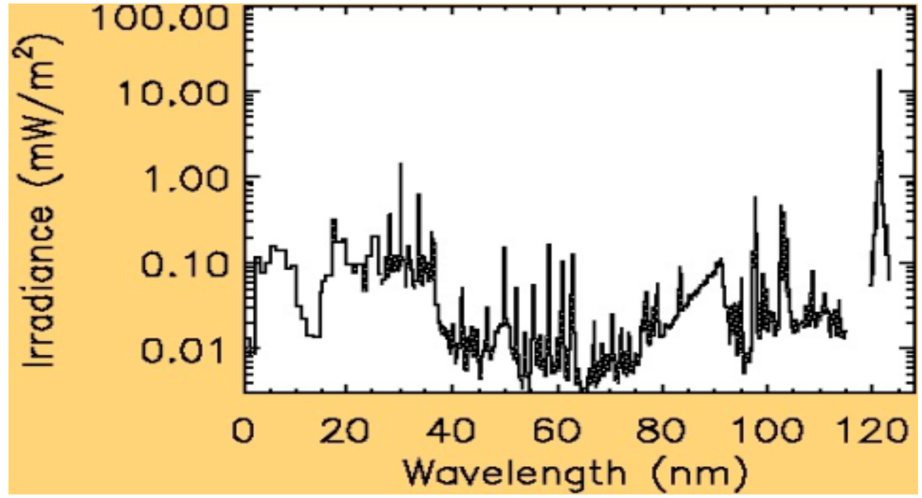
Produces ionosphere

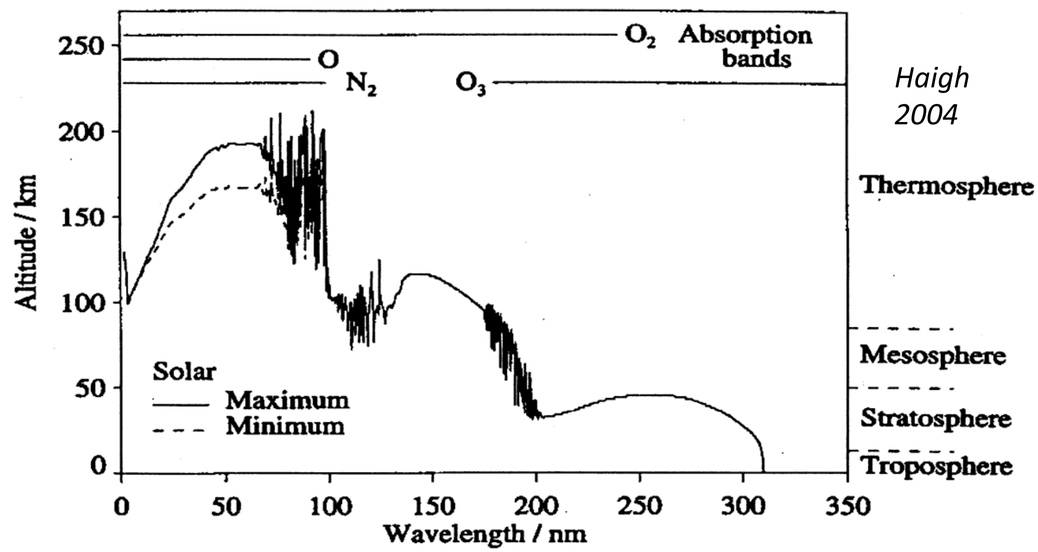
Drives thermosphere's variation

Effects

Disrupts RF & microwave communication & navigation

Increases drag on satellites in low-Earth orbits





Haigh 2004

EUV Measurement Requirements & Techniques

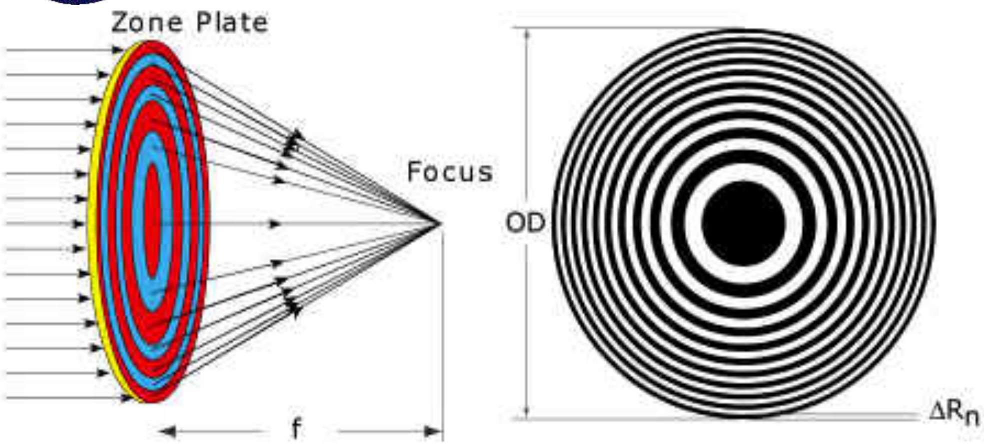
Requirements

- Measure total solar irradiance in several narrow EUV spectral bands
- Typical threshold sensitivities: 10^{-6} - 10^{-4} W/m^2
- Extremely good long-λ (NIR/visible/NUV) rejection
  - total solar irradiance = 1366 W/m^2
- Long term stability in very contamination-sensitive spectral region
- Operational solar EUV monitoring on GOES-R satellites
  - 10% absolute accuracy
  - 10-yr operation after 5-yr on-orbit storage
  - Calibration with periodic sounding rocket flights

Techniques

- Thin (50-500 nm) metal film on mesh substrate and/or detector
  - Reflects/absorbs long-λ radiation
  - Semi-transparent in material-specific EUV band
  - Spectral selectivity often inadequate
  - Materials problems
- Linear transmission gratings (+ thin film filter)
  - Detector area > grating area
  - Passband varies with angle in dispersion direction across ~0.5^o solar disk
  - Polarization sensitive
- Reflection gratings (+ thin film filter)
  - Specialized coatings for some EUV bands
  - Can focus radiation (Also used for telescopes)
  - Coatings extremely contamination & oxidation sensitive
  - Passband varies with angle in dispersion direction across ~0.5^o solar disk
  - Polarization sensitive

Zone Plate (ZP) Optical Properties



Alternating opaque & transparent zones

Annular zones with radius α (zone #)$^{1/2}$

Focal length $f(\lambda,m) = (OD)(\Delta R_n) / m\lambda$

- λ = wavelength
- m = diffraction order
- OD = ZP's diameter
- ΔR_n = outer zone width

Fresnel ZP (FZP) transmission $\tau(m)$

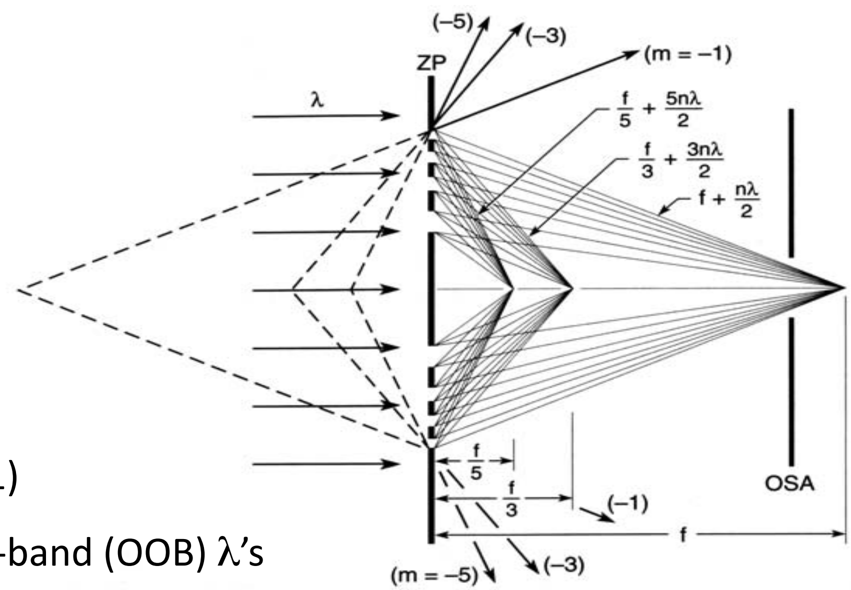
- $\tau(0) = 0.25$
- $\tau(m) = 1/(m\pi)^2$ $m = \pm1, \pm3, \pm5$, --
- $\tau(m) = 0$ $m = \pm2, \pm4, \pm6$, --

High-efficiency zone plate (HEZP)

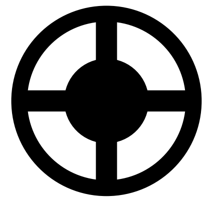
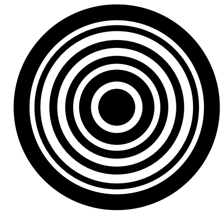
- semi-transparent zones shift phase ~ 180°
- $\tau(+1) > 0.30$ at some λ's
- $\tau(0) << 0.25$

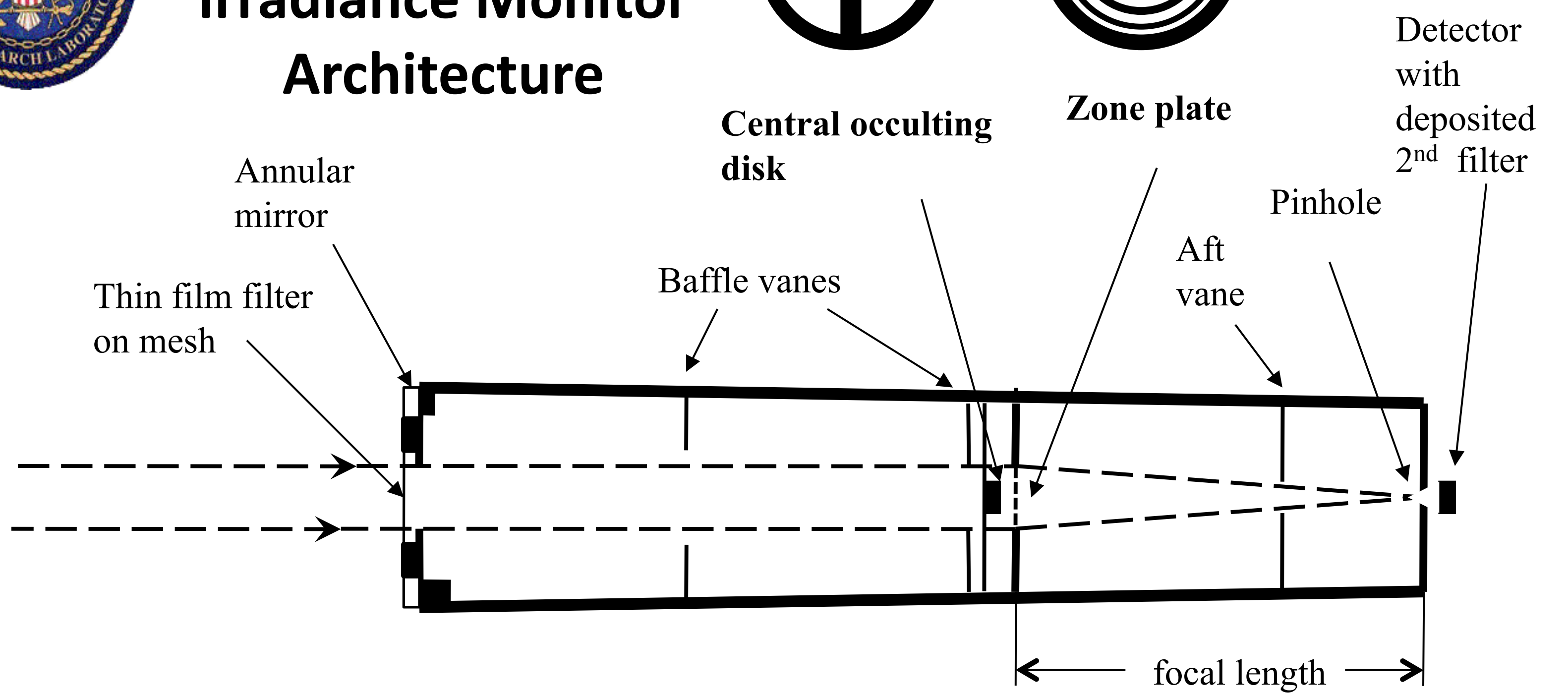
Pinhole order-sorting aperture (OSA) at $f(\lambda, +1)$

Central occulting disk blocks 0-order & out-of-band (OOB) λ's



ZP-Based EUV Solar Irradiance Monitor Architecture



Compo-nent	Thin film on mesh	Occulting disk	ZP on mesh or membrane	Pinhole aperture	Detector w/ filter	Annular mirror
Function	Reflects & absorbs long-λ's & restricts EUV λ's	Blocks 0-order & OOB λ 's from pinhole	Disperses EUV radiation, focusing desired λ's into pinhole	Passes in-band λ & blocks most long-λ & OOB EUV λ's	Blocks long-λ's, including fluorescence & restricts EUV λ's	Boresight reference for S/C alignment

Advantages of a ZP-Based EUV Solar Irradiance Monitor

- Spectrally selectivity
  - ZP's dispersion augments thin film filters to improve OOB-λ rejection
- In-band focusing into small pinhole
  - Permits small detector with low dark current
  - Blocks most OOB-λ radiation from reaching detector (especially long-λ radiation)
  - Blocks most contamination from reaching detector
- Circular symmetry
  - Spectral response ~ constant over 1^{o} FOV
  - Polarization insensitive
- Two thin film filters
  - 1^{st} filter heats rapidly to ~200 ^{o}C in full sunlight, but creates benign internal thermal environment (relatively contamination insensitive due to high T & dT/dt)
  - 2^{nd} filter on detector blocks long-λ radiation due to fluorescence
  - Dual filters allow use of incompatible materials & decrease degradation due to filter flaws
- No reflective optics
  - Less sensitive to contamination & oxidation than reflective EUV gratings & telescopes
- Compact
  - Much smaller volume & lower mass than grating-based monitor with equivalent performance

EUV Monitor Development Goals & Spectral Band Selection

Develop stable, compact, space-qualified solar EUV irradiance monitors
Calibrate present & future solar EUV instruments on-orbit
Strong emission lines coinciding with those used by imaging EUV telescopes
Develop ZP on mesh substrate for use in 20-90 nm spectral region

Custom ZP's, 4 mm diameter, produced by Xradia, Inc.

- Fe IX-XII band (17.1-19.5 nm):
  - Includes numerous strong coronal emission lines ($T \cong 0.5\times10^6$ K - 2.0×10^6 K)
  - HEZP with Mo zones on Si_3N_4 membrane substrate ($\lambda_{max} \cong 19.5$ nm)
  - Al filters determine short-λ cut-off ($\lambda_{min} = 17.1$ nm)
- He II band (30.4 nm)
  - Dominant solar EUV spectral line, emitted by transition region ($T \cong 60{,}000$ K)
  - Si_3N_4 zones on open mesh substrate (no membrane)
  - Broadband Al filters ($\lambda_{min} = 17.1$ nm to $\lambda_{max} > 40$ nm)
  - ZP's dispersion and pinhole aperture define spectral band

R·S·I Research Support Instruments

ZP Solar Irradiance Monitor Design Parameters

R·S·I RESEARCH SUPPORT INSTRUMENTS

- Focal length, f_{LC}, and diameter, δ_{LC}, of circle of least confusion for a finite bandwidth λ_{min} to λ_{max} = focal length at $\lambda_0 = (\lambda_{min} + \lambda_{max})/2$:

  $$f_{LC} = 2(OD)(\Delta R_n) / (\lambda_{min} + \lambda_{max})$$

  $$\delta_{LC} = OD[(\lambda_{min} - \lambda_{max}) / (\lambda_{min} + \lambda_{max})]$$

- Diameter, δ_{FOV}, of FOV, θ, in focal plane:

  $$\delta_{FOV} = f_{LC}\theta = 2(OD)(\Delta R_n)\theta / (\lambda_{min} + \lambda_{max})$$

- Diameter of pinhole, δ, required to capture all radiation within FOV from λ_{min} to λ_{max}:

  $$\delta = OD[(\lambda_{min} - \lambda_{max}) + 2(\Delta R_n)\theta] / (\lambda_{min} + \lambda_{max})$$

- Minimum occulting disk diameter, d, to block m = 0 radiation from pinhole:

  $$d > \delta + 2(OD)(\Delta R_n)\theta / (\lambda_{min} + \lambda_{max}) = OD[(\lambda_{min} - \lambda_{max}) + 4(\Delta R_n)\theta] / (\lambda_{min} + \lambda_{max})$$

- FWHM wavelengths, λ_+, λ_- (in absence of spectral filtering by thin films):

  $$\lambda_+, \lambda_- = \lambda_0\{1 \pm \delta / [2/(OD^2 + d^2]^{1/2}\}$$

FOV: $\theta = 0.01745$ (1^o) includes photosphere & transition region (~0.6^o) & tolerance ($\pm 0.2^o$)

D = 4 mm, d = 2 mm, spider leg width = 0.3 mm for both channels:

Unocculted area = $\pi/4(4^2 - 2^2) - 4(1)(0.3) = 8.22$ mm^2

Effective area, Aeff, = (8.22 mm^2)$*\tau_1*\tau_Z(+1)*\tau_2$

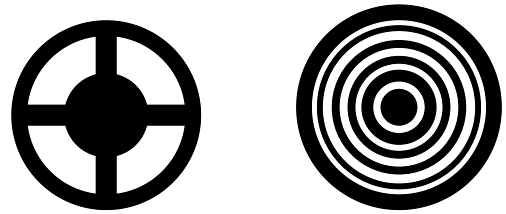
where τ_1, τ_2 = filter transmissions, $\tau_Z(+1)$ = ZP efficiency @ m = +1 (w/substrate)

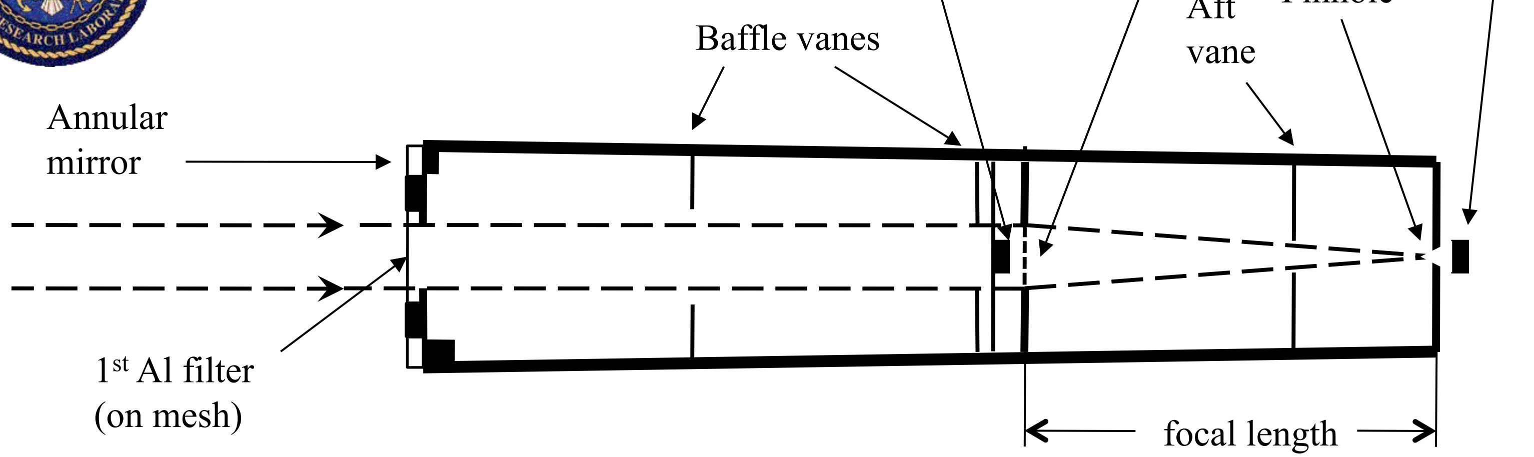
EUV Channel Parameters & Predicted Performance

Flux from GOES-R SIS PORD

Quiet Sun (F_{min}),

Major flare (F_{max})





Channel	λ_o (nm)	ΔR_n (nm)	f (mm)	δ (mm)	FWHM (nm)	A_{eff} (mm^2)	Res (A/W)	F_{min} (W/m^2)	I_{min} (pA)	F_{max} (W/m^2)	I_{max} (pA)
Fe IX-XII	18.3	100	21.85	0.64	17.1-19.5	0.23	0.25	3.0E-5	1.7	1.3E-2	730
He II	30.4	190	25.00	0.44	26.2-34.6	0.40	0.22	1.1E-4	9.7	2.4E-2	2110

J. Bremer, J. Seely, G. Holland, & Y. Feng, "Zone plate EUV Solar Irradiance Monitor", *Proc. SPIE,* **7438**, 743810-1-8, (2009).

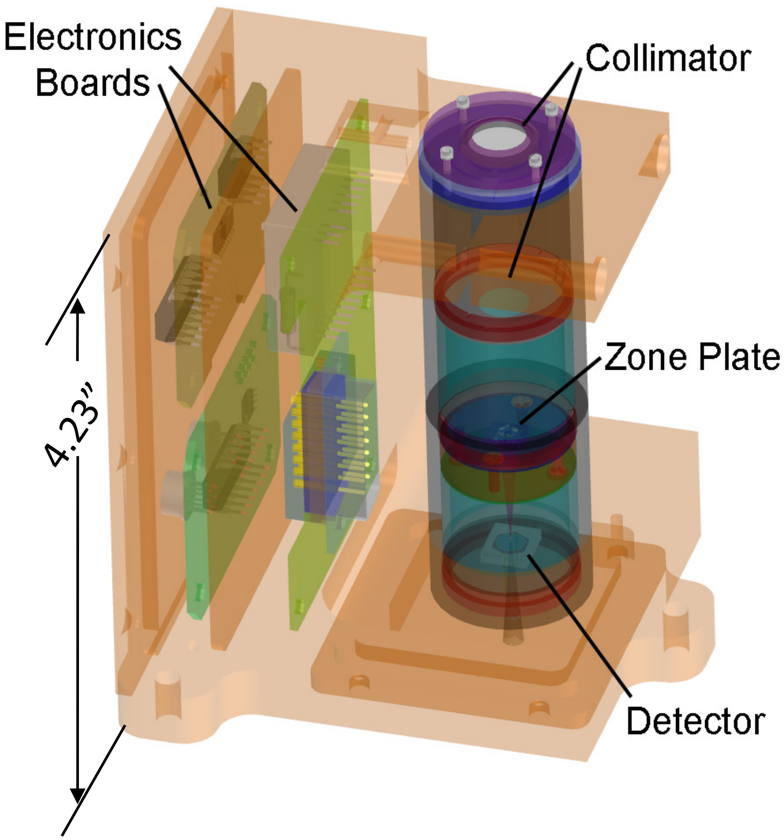
ZP Radiometer Module

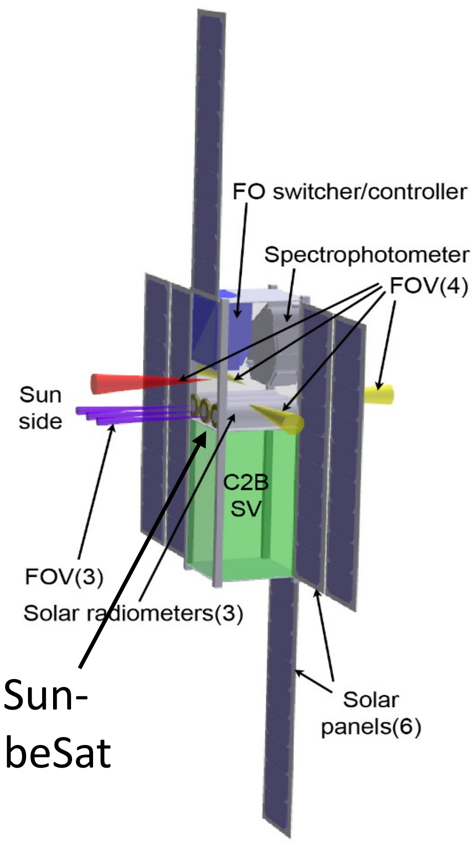
Potential Platforms

Sounding rockets
- VERIS (NRL, C. Korendyke)
- EUNIS (GSFC, D. Rabin)

CubeSats

Solar Array Drives
(*e.g.*, GOES solar payloads)





3 modules on the Sun-facing side of a CubeSat

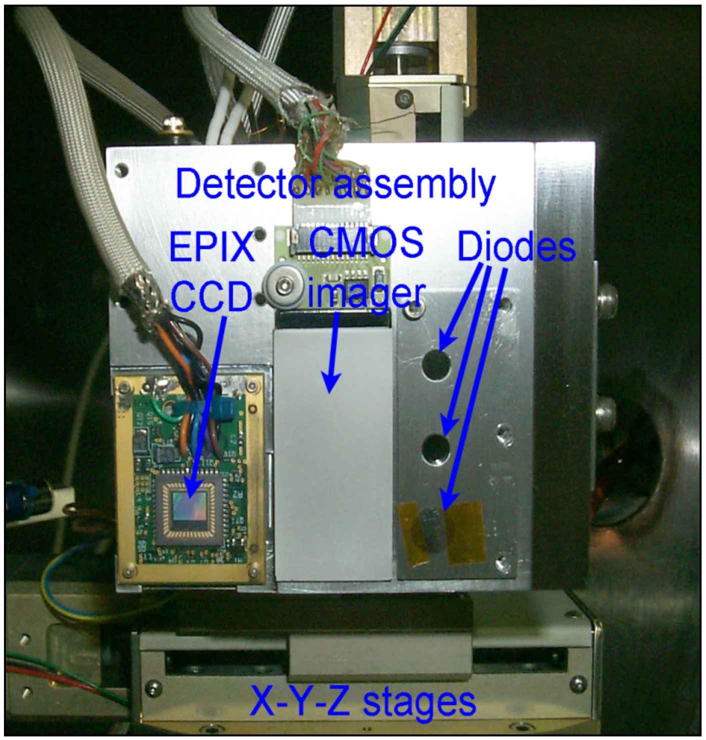
EUV Monitor Development Status

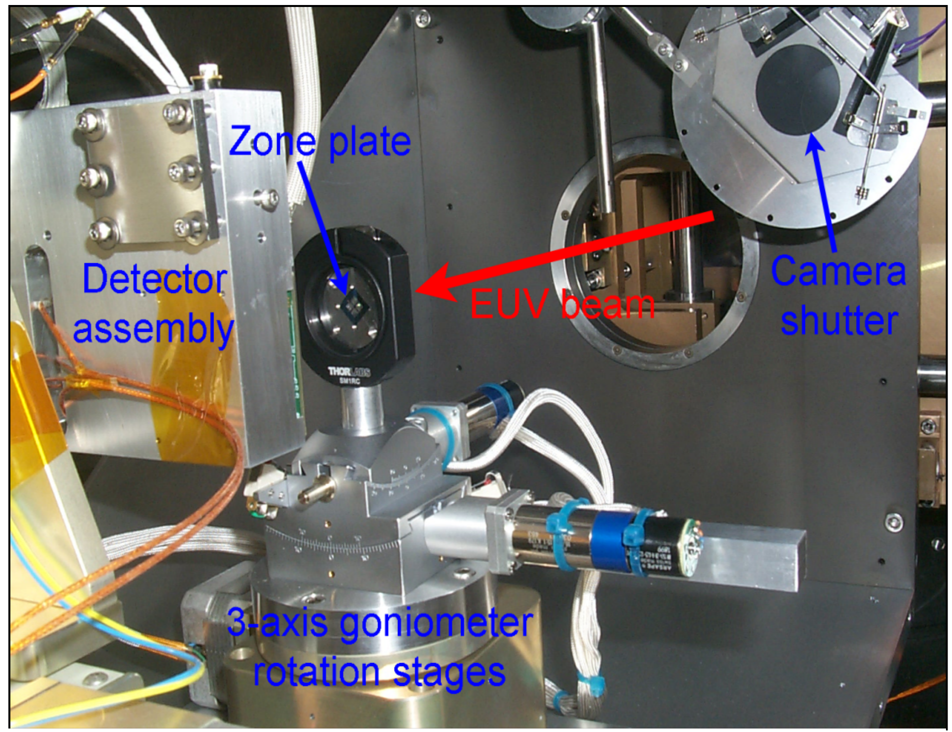
- Thin film Al filters, both on mesh supports and directly deposited on EUV detectors, have extensive space flight heritage.
- Custom Fe IX-XII and He II channel ZP's have been fabricated, mounted & integrated with occulting disks by Xradia, Inc., delivered to NRL, and tested.
- Measurements of ZP's at the National Synchrotron Light Source have verified their optical properties.
- The ZP with Mo zones on a Si_3N_4 substrate has passed a vibration test that indicates it can survive launch loads
- We plan to fly the Fe IX-XII channel solar irradiance monitor (and possibly also the He II channel) as a secondary payload on the NRL's VERIS sounding rocket.

Measurement apparatus in calibration chamber at X24C Beamline

Detector assembly

ZP assembly on 3-axis mount





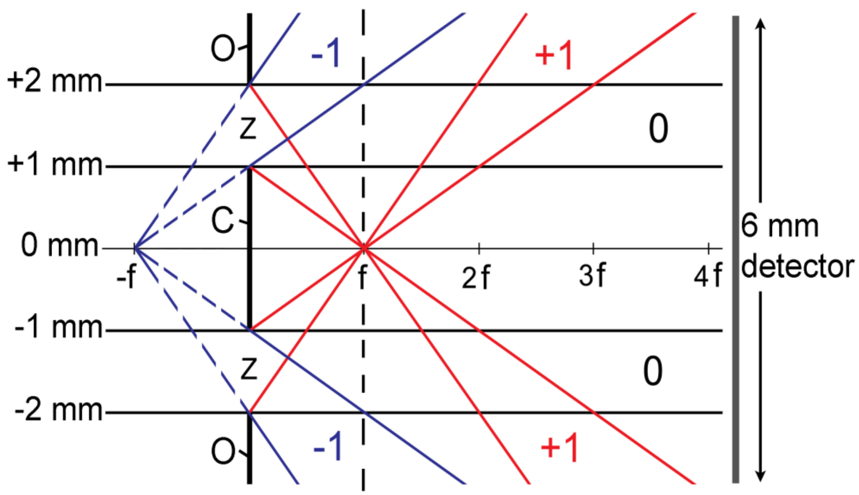
J. Seely, B. Kjornrattanawanich, L. Goray, Y. Feng, & J. Bremer, "Characterization of zone plate properties using monochromatic synchrotron radiation in the 2 to 20 nm wavelength range, *Applied Optics,* **Vol. 50**, No.18, pp 3015-3020, (20 June, 2011).

Measurements at Beamline X24C

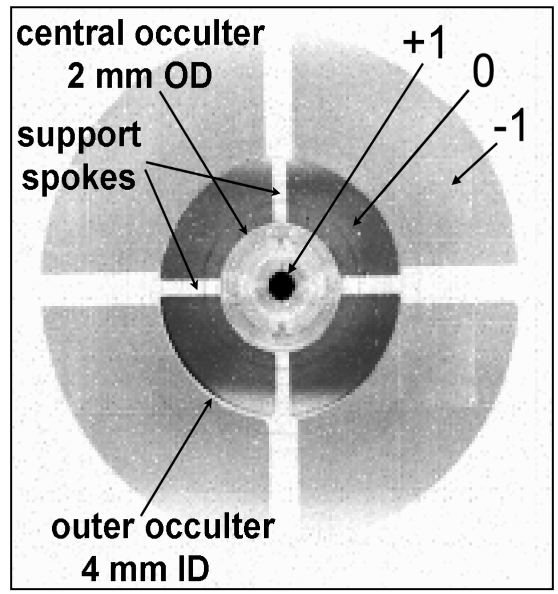
4 mm ZP with 2 mm occulting disk

Mo zones on Si_3N_4 membrane (Fe IX-XII)

+1 (converging) & -1 (diverging) orders



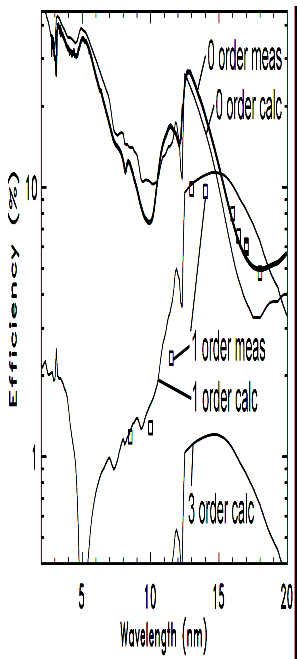
Diffraction pattern image
in +1 order focal plane

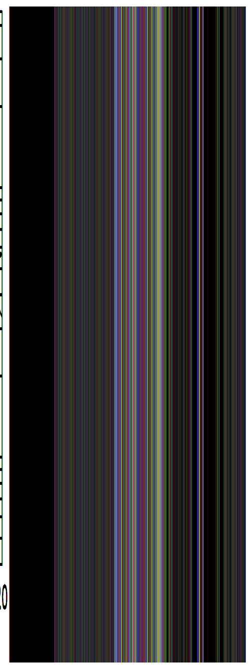


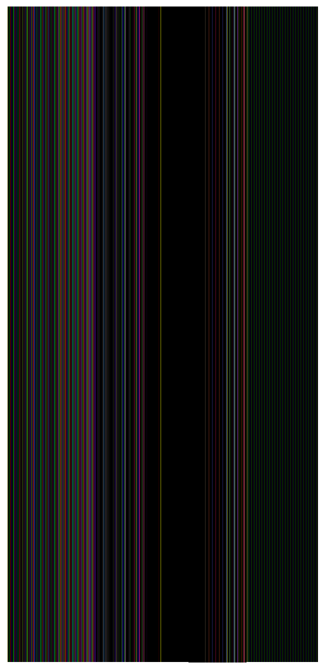
Measured and Calculated Efficiencies of Mo zones on Si_3N_4 membrane as functions of wavelength & field angle

Calculations with PCGRATE code

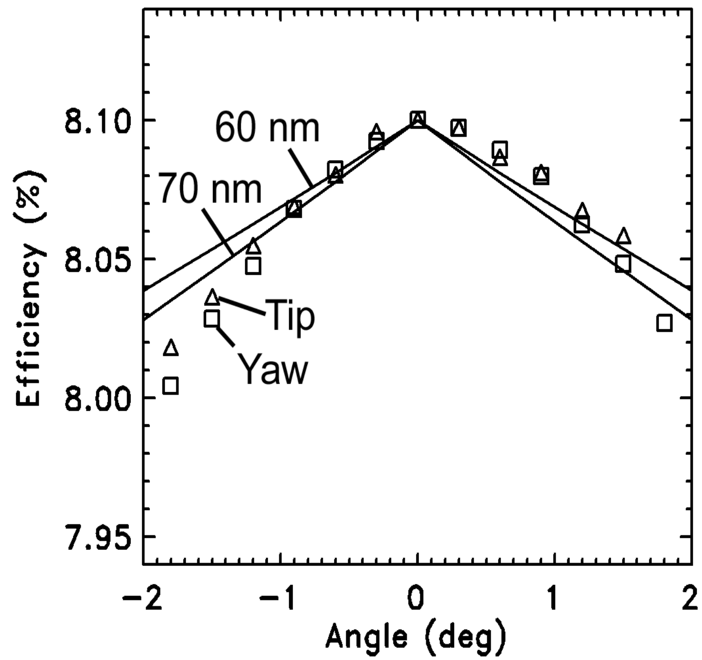
0 (—) & +1 (□) orders measured vs. λ







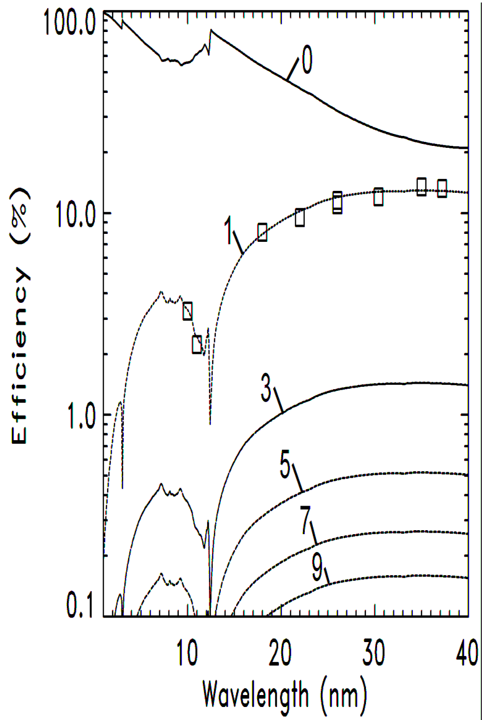
Efficiency vs. field angle

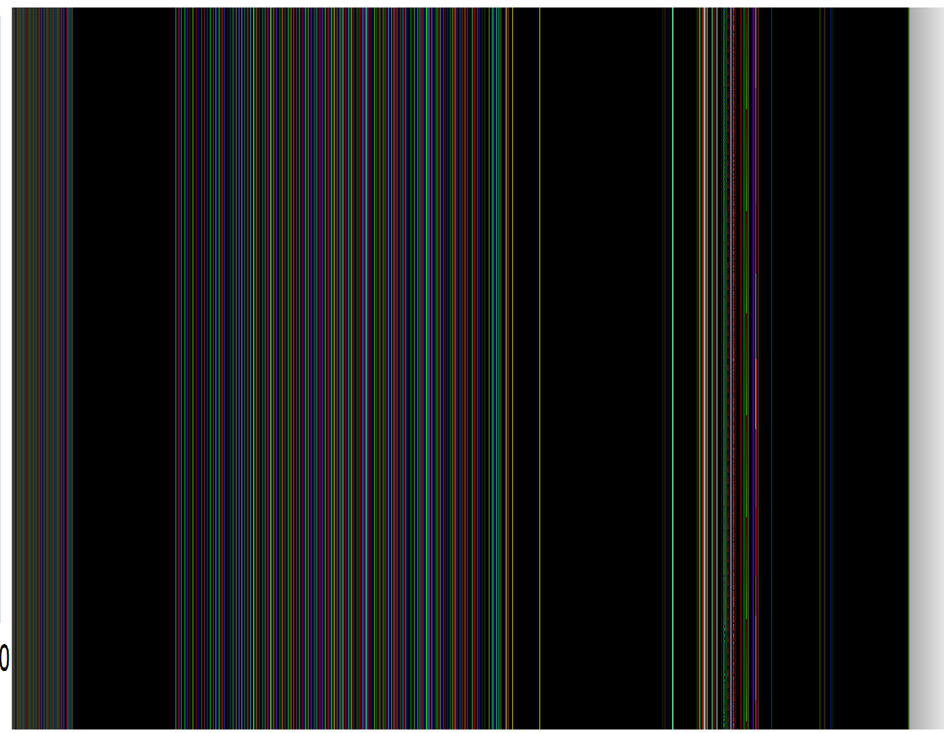


Measured and Calculated Efficiencies of Si_3N_4 zones on mesh substrate (He II) as functions of wavelength & field angle

RESEARCH SUPPORT INSTRUMENTS

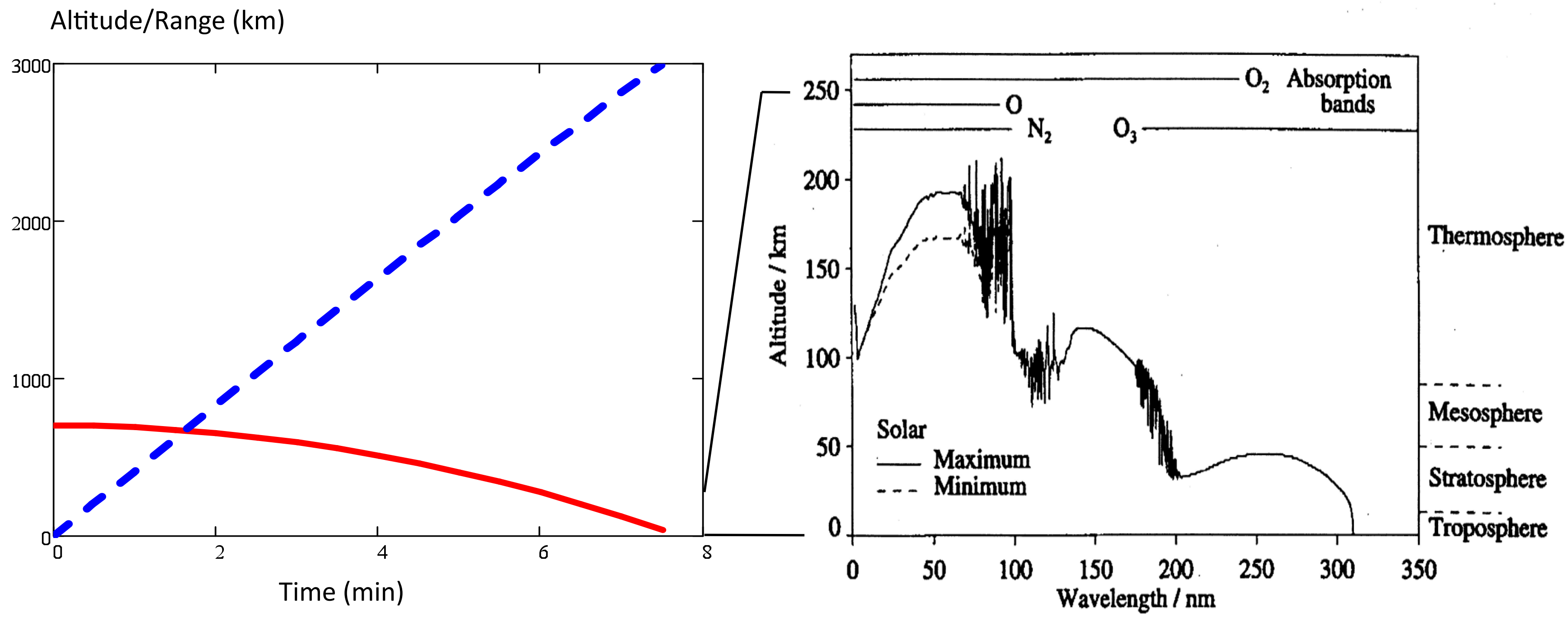
1st demonstration of a ZP with a mesh substrate





Atmospheric Limb Sounding with an EUV Sensor

Tangent altitude (red solid line) and range to tangent (blue dashed line) as functions of time during local sunset for a 705 km / 1:30 orbit



Solar disk subtends ~28 km altitude at limb

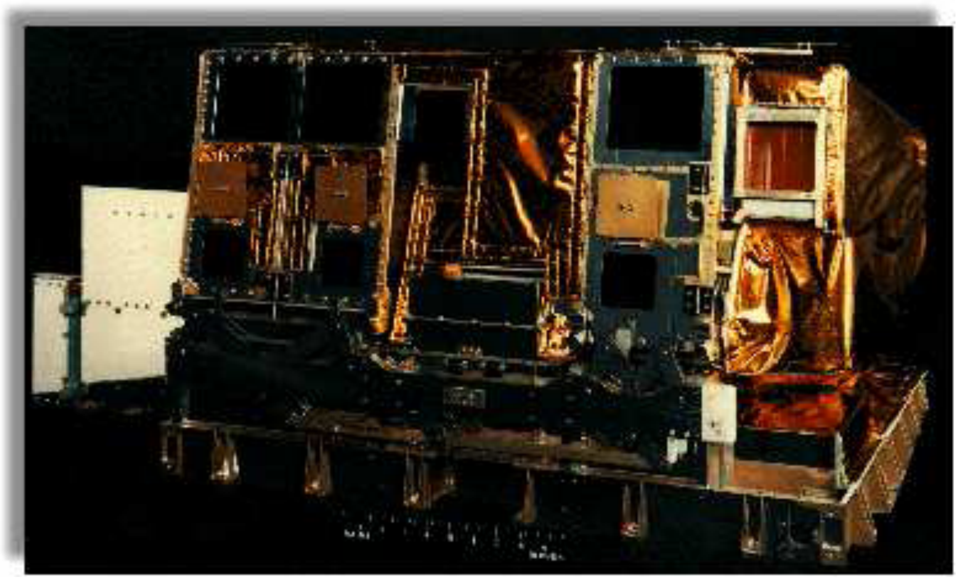
Limb extinction of EUV while transmitting longer- λ's measures sensor's response to out-of-band background radiation

Extinction vs. tangent altitude measures themosphere

During sunrise, outer filter is heated by visible light before exposure to vacuum UV

Remote Atmospheric and Ionospheric Detection System (RAIDS)

- Scientific measurement objectives
  - Temperature of lower thermosphere (100-200 km)
  - Composition and chemistry of lower thermosphere & ionosphere
  - Initial excitation source of OII 83.4 nm emission
- Suite of 3 photometers, 3 spectrometers, 2 spectrographs
  - Measures airglow from Earth's limb: 90-350 km tangent altitude
  - 50-874 nm spectral range
- Collaborative effort of NRL Space Science Division, Aerospace Corp., & RSI
- Now deployed on the ISS



R·S·I RESEARCH SUPPORT INSTRUMENTS

Conclusions & Recommendations

R·S·I
RESEARCH SUPPORT INSTRUMENTS

- Total solar EUV irradiance monitors based on ZP's have important performance advantages over alternatives: EUV spectral selectivity, long-λ rejection, circular symmetry, long-term stability
- They are easy to accommodate on spacecraft: low mass, compact envelope, low power, low data rate, relaxed pointing requirements
- Potential satellite platforms
  - Secondary payloads on solar-pointing missions or on solar array drives (like GOES SIS)
  - NanoSats like CubeSats (max. envelope = 10x10x34 cm)
- In low-Earth orbit, measurements during eclipse improve long-λ background subtraction & provide limb-extinction profiles
- All components except the ZP's have substantial space flight heritage
- The ZP's optical properties have been verified by measurements at the NSLS & the mechanical properties of the Fe IX-XII channel ZP have been verified by vibration test
- We plan to space qualify the ZP's and to fly one or two ZP EUV irradiance monitors as a secondary payload on the VERIS sounding rocket mission in the near future
- ZP-based monitors with channels at 17.1 nm, 19.5 nm, 30.4 nm, etc. can calibrate EUV instruments with the same spectral bands, including the SUVI and EUVS on GOES-R
- Mesh supported ZP's can be used in conjunction with appropriate thin film filters to measure the solar irradiance in the 20-90 nm spectral range

Acknowledgements

- This work was sponsored by NASA grant NNH09AK121.
- James C. Bremer was employed by Alliant Techsystems, Inc. when this work was initiated.
- Glenn E. Holland is now at the Center for Nanoscale Science and Technology, National Institute of Standards and Technology.
- We would like to thank Dr. Clarence Korendyke of the Naval Research Laboratory for providing us with an opportunity to fly a ZP-based sensor as a secondary payload on the VERIS sounding rocket.
- We would like to thank the following people for their assistance:
  - Dr. Charles Brown, NRL
  - Dr. Uri Feldman, NRL
  - Dr. Michael Kowalski, NRL
  - Dr. Michael Fesser, Xradia, Inc.
  - Mr. Alan Lyon, Xradia, Inc.