EUNIS: a Solar EUV Normal-Incidence Spectrometer

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ABSTRACT

GSFC is in the process of assembling a solar EUV Normal-Incidence Spectrometer called EUNIS, to be flown as a sounding rocket payload. This instrument builds on the many technical innovations pioneered by our highly successful SERTS experiment over its past ten flights. The new design has improved spatial and spectral resolutions, as well as 100 times greater sensitivity, permitting EUV spectroscopy with a temporal resolution near 1 second for the first time ever. To achieve such high time cadence, a novel Active-Pixel-Sensor detector is being developed as a key component of our design. The high sensitivity of EUNIS allows entirely new studies of transient coronal phenomena, such as the rapid loop dynamics seen by TRACE, and searches for non-thermal motions indicative of magnetic reconnection or wave heating. The increased sensitivity also permits useful EUV spectra at heights of 2-3 solar radii above the limb, where the transition between the static corona and the solar wind might occur. In addition, the new design features two independent optical systems, more than doubling the spectral bandwidth covered on each flight. Its 300-370Å bandpass includes He II 304Å and strong lines from Fe XI-XVI, extending the current SERTS range of 300-355Å to further improve our ongoing series of calibration under-flights for SOHO/CDS and EIT. The second bandpass of 170-205Å has a sequence of very strong Fe IX-XIII lines, and allows under-flight support for two more channels on SOHO/EIT, two channels on TRACE, one on Solar-B/EIS, and all four channels on the STEREO/EUVI instrument. First flight of the new EUNIS payload is presently scheduled for 2002 October.

Keywords: Solar, corona, EUV, spectrometer

1. INTRODUCTION

Around 1980, the Solar Physics Branch of NASA's Goddard Space Flight Center under the leadership of Werner M. Neupert began developing a sounding rocket payload, called SERTS, to provide imaged spectra of the sun's corona[1]. It has now been flown a total of ten times to date, producing some of the best quality, highest resolution data ever obtained in this wavelength range[2-5]. It has also proved valuable as a test-bed for a large number of new instrument developments, some of which have subsequently been incorporated into major satellite missions such as SOHO and Solar-B. Over its 20-year history, the SERTS program has pioneered space-flight validation of technologies that include computer-polished grazing-incidence telescopes[6], multilayer coatings on EUV gratings[7-8], photo-etched entrance slits, MCP-intensified EUV array detectors, and onboard hard-drive data recording. Each SERTS flight has involved at least one improved optical, mechanical, or electronic component, so that we have now tested a variety of telescopes, entrance slits, gratings, multilayer coatings, detectors, slit-jaw cameras, and onboard recorders, among other things.

We have recently begun to develop a next-generation solar EUV Normal-Incidence Spectrometer, called EUNIS, in order to make full use of the many technical innovations that SERTS has pioneered. EUNIS is 100 times more sensitive than SERTS, with 1-arcsec spatial (pixel) resolution, and 1-second time resolution. This powerful instrument can pave the way for entirely new studies of the corona using high cadence spectra at a single location, rapid rastering over large two-dimensional areas of the solar surface, or deep exposures on intrinsically faint coronal features. The instrument is currently designed to be flown as a sounding rocket payload, but could easily be adapted for use on satellite missions. This paper describes the new instrumental configuration, compares its capabilities with past and future experiments, and briefly discusses a few of the scientific research areas that it now opens for exploration.

2. OPTICAL DESIGN AND PERFORMANCE

The optical design of EUNIS is directly based on that of SERTS, which uses a telescope to form a real image of the sun on the spectrometer entrance aperture. A slit then selects a portion of the solar image, passing its light onto a near-normal incidence toroidal grating, which stigmatically re-images the spectrally dispersed radiation onto an array detector as shown schematically in Figure 1. The full spectral bandpass and one-dimensional spatial field are recorded all at one

time with no scanning of the detector or grating. The new EUNIS design features two independent optical systems in order to double the spectral bandwidth covered on each flight. These are mounted on opposite sides of the plane running down the middle of the instrument payload (Figure 2). For both channels, the optical design of telescope, entrance slit, toroidal grating, and detector are identical. The two different spectral bands are optimized by using slight differences in the grating operating angle and relative position of the detector focal plane, while the telescope and grating in each optical train are coated with matched multilayers tuned to the appropriate bandpass for that channel.

The two spectral ranges to be covered by initial flights of EUNIS are 170-205Å (Channel A, observed in second order) and 300-370Å (Channel B, observed in first order). Table 1 summarizes the main optical parameters for this baseline EUNIS design, which is described in more detail below.

2.1 Telescopes

The telescopes are both single parabolic segments, 110 mm in diameter and 100 mm off-axis (vertex to center), which provide imaging better than 1 arcsec over a full field of view of 960 arcsec, or 1.0 solar radius, with only one reflecting surface. They are to be made of low expansion material, such as special grade Zerodur, and super-polished to minimize unwanted scattered light. Their focal length of 1250 mm gives a spatial plate scale of 6.1 µm/arcsec at the entrance slit of each spectrometer.

2.2 Slits

The slits are fabricated from single crystal Silicon wafers using a precision lithography technique developed at GSFC for the SERTS program. There are several advantages to this process. The slits are extremely uniform because they are etched parallel to the crystal planes in the Silicon lattice. The process is extremely adaptable, so that slits can be made in essentially any configuration. In addition, since multiple slits are made from a single mask, the process is highly reproducible. A slit of this type was flown first on SERTS-97, and on each SERTS flight thereafter. For the initial EUNIS design, the slits are 8 µm wide and 5.8 mm long (1.3 x 960 arcsec), with an Aluminum coating to reduce thermal stress on the thin silicon substrates. Future EUNIS flights may use a combination of narrow and wide openings along the slit length, as was done in SERTS, or multiple offset slits in the telescope's image plane. This new slit fabrication technology should be generally applicable, and, for example, is now planned for use in the Solar-B/EIS spectrometer.

2.3 Gratings

The two gratings in the baseline EUNIS design are identical toroids (Rs = 767.12 mm, Rt = 772.23 mm) with the same uniform ruling density (3600 groove/mm), so that only one master grating is required. Each grating is placed 625 mm behind its respective slit, with focus at a distance of approximately 1000 mm, for a spectrometer magnification of 1.6. Optimized imaging is achieved by using different fixed grating tilts in the two different wavelength channels (5.710º in Channel A, 5.908º in Channel B), and by separately matching the flat focal surfaces of each detector.

As part of the SERTS program, we have been supporting work toward improving the control of groove profiles in mechanically ruled toroidal gratings. Test gratings procured for that purpose in 1998 from Hyperfine, Inc., did have a much more accurate blaze-angle than our original set (3.5º vs. 4.8º, while 3.3º ± 0.1 was specified), and laboratory EUV measurements indicated that their groove-efficiency in the SERTS bandpass was as much as a factor of 2.5 better than the best previously flown grating. In addition, we plan to investigate new capabilities of vendors to provide holographically ruled concave gratings that are then blazed by ion-etching. If that technology could be demonstrated, it would combine the high efficiency of mechanical rulings with the superb regularity and low scattering characteristic of holographic gratings. Later EUNIS flights may also take advantage of recent design developments, such as spherical variable line-space (SVLS) gratings, a novel concept that we have been investigating in collaboration with Japanese partners. In fact, an SVLS design or one with similar optical performance will be necessary before the ultimate capabilities of the EUNIS instrument can be fully utilized.

2.4 Detectors

Both of the two detector units include a microchannel-plate intensifier section with a spatial resolution of 50 lp/mm, a performance that has already been obtained on SERTS. In the baseline EUNIS design, each MCP intensifier section is then coupled via fine-pore fiber-optic blocks to a set of three detector arrays with 1024 x 1024 pixels of 9 x 9-µm size, giving a total flat active focal area of 27.65 x 9.22 mm for each unit (Figure 3).

Since the new instrument will have the sensitivity to produce useful data in exposures of one second or less, extremely fast readout is required to make most efficient use of the limited observing time on a sounding rocket flight. Therefore, the EUNIS detectors use recently developed Active Pixel Sensor (APS) technology that supports readout speeds well in excess of 2 Mpix/s. This permits an effective observing cadence on the order of one second, which is unprecedented for high-quality imaged EUV spectroscopy of the solar corona. Another advantage of the very short exposure times is that active cooling of the CCD should not be needed for the first few flights of EUNIS. However, we do plan to add cooling later, in order to provide longer exposure observations of intrinsically faint coronal features that could not be adequately measured in the past. In addition, we are investigating new developments in EUV/UV detectors that use semiconducting diamond or nitrides as photosensitive surfaces on CMOS imagers, which could be tested on later flights of EUNIS.

2.5 Data storage

At an observing cadence of one exposure per second per channel, the EUNIS instrument generates nearly 100 Mb/s of data, far more than can be handled by normal telemetry downlink rates. Large amounts of persistent on-board storage are needed for this experiment. Therefore, the detector output data are written directly onto two redundant hard drives packaged in a hermetically sealed case within the payload, one pair for each of the three APS arrays in each of the two detector units. Such dual hard drives were successfully flown on the previous two SERTS flights. In addition, a telemetry buffer allows for the transmission of part of the image data in real-time during flight. This downlink of a selected portion of the data provides rapid feedback for payload performance and offers some additional data redundancy to the experiment.

2.6 Focal plane performance

The final focal surface of each channel has a spatial plate scale of 9.70 µm/arcsec and an average spectral dispersion of 2.78 Å/mm in first order (1.39 Å/mm in second). With a pixel size of 9 µm, these values correspond to 0.9 arcsec/pix and 25 mÅ/pix in first order (12.5 mÅ/pix in second). Figure 4 plots the results of ray-trace studies demonstrating that the design, initially stopped down to f/16, provides on-axis point-source imaging spots of about 8 µm (RMS full-width) in the spatial dimension and 12 µm in the spectral dimension for both wavelength channels when recorded on a flat focal surface. Taking into account expected blurring from the telescope, and affects of the entrance-slit width and detector pixel size, this gives a Nyquist (2-pixel) instrumental resolution of 2.3 arcsec spatial and 70 mÅ spectral in first order (35 mÅ in second order). Furthermore, even at the extremes of the instrument's spatial FOV and spectral bandpasses, those full resolution values degrade by less than 9% because of the total-field optimization of the design.

3. PERFORMANCE COMPARISONS

Table 2 summarizes the optical performance of the baseline EUNIS design, and compares it to two previous SERTS configurations and to the planned EUV Imaging Spectrometer (EIS) now being built for the upcoming Solar-B satellite mission. As mentioned earlier, each of the two optical trains in EUNIS is coated with matched multilayers tuned to the appropriate bandpass for that channel. Both of the required multiplayer designs have already been flown on prior SERTS payloads, the shortwave one in 1995 and the longwave one on several flights including that in 1999. Now, however, EUNIS will observe both of these spectral regions at the same time, vastly increasing the scientific value of the collected data. Furthermore, by more effective coverage of the available detector surface area, the EUNIS longwave channel has been extended to 370 Å, well beyond the SERTS limit (since 1996) of 355 Å. This allows measurement of many additional spectral lines, most prominently the very strong lines of Fe XVI at 361 Å and Mg IX at 368 Å.

The EUNIS spectral resolutions in each of its two channels are substantial improvements over the values achieved by SERTS at similar wavelengths. For the shortwave channel, which covers nearly the same wavelengths as on the corresponding Solar-B/EIS channel, the spectral resolution is even better than that to be obtained by EIS. In terms of spatial resolution, the 2-arcsec imaging of EUNIS is comparable to that on EIS, and is again a significant improvement over what had been accomplished on any prior SERTS flight.

Another advantage of EUNIS is the very large spatial FOV over which high-resolution spectra can be obtained on a single observation, up to 960 arcsec, or 1.0 solar radius. This is three times greater than the largest instantaneous field that was ever recorded by SERTS, and twice as large as the nominal field of the EIS instrument. Combined with its broader total bandwidth, EUNIS provides a considerable increase in both spectral and spatial coverage on each of its data exposures compared to these other instruments.

In addition, EUNIS offers a very high photometric sensitivity unmatched by any previous solar EUV spectrometer. As shown in Table 3, its total effective area of 77 mm^2 is more than 100 times greater than that of prior SERTS configurations, and is nearly 40% higher than that planned for Solar-B/EIS. This increase is due to a number of improvements, listed in Table 4. By having a telescope with only one normal-incidence reflection, EUNIS immediately gains a factor of 5 over the two-mirror telescope in SERTS-99, each surface of which had a reflectance of 0.2 at the peak of its multilayer response. As described above, improved control of shallow blaze angles in the ruling of concave EUV gratings should provide another factor of 3 through higher average groove efficiency at the operating wavelengths. The microchannel plate in each EUNIS detector unit is coated with Potassium Bromide, which increases quantum efficiency in the EUV by a factor of 3 over the bare plates used in SERTS. And finally, the new K-Br photocathode is also solar blind, which means that EUNIS does not need the thin Aluminum blocking filter required on SERTS, gaining yet another factor of 2.5 in EUV throughput.

4. NEW SCIENCE CAPABILITIES

The observing power of the new EUNIS instrument is better than that achieved by our previous SERTS experiment primarily in terms of faster readout, much higher sensitivity, and significantly broader spectral coverage (Table 5). Furthermore, these three major advances are accompanied by appreciable improvements in spectral and spatial resolutions as well. The unprecedented capabilities of EUNIS open the way for entirely new studies of the corona using high time-cadence spectra at a single location, rapid rastering over a two dimensional patch of the solar surface, or deep exposures on intrinsically faint sources. Some scientific studies that now become feasible are briefly mentioned here.

4.1 Faster readout

The most recent SERTS flights produced high signal-to-noise EUV spectra of bright solar features using exposure times in the range 30 - 90 seconds. Similar exposure times are required for the CDS spectrometer on SOHO. EUNIS, with its high sensitivity and ultra-fast readout, can obtain comparable data for the first time ever at a cadence near one second.

Relatively high cadence images from EIT and Yohkoh show coronal evolution on time scales shorter than ten minutes. Such behavior had long been known for explosive phenomena, such as flares, but now it is becoming clear that non-flaring active region loops, and even structures in the so-called quiet sun, undergo rapid changes as well. Indeed, one of the great advances of TRACE has been to show how dynamic and transient the general corona can be on time scales much less than a minute. These instruments are all imagers, however. EUNIS can further explore the dynamics of bright coronal features by providing detailed EUV spectroscopy with temporal and spatial resolutions approaching or exceeding those of current imagers. The 1-second time cadence of EUNIS also permits searches for non-thermal motions indicative of magnetic reconnection or wave heating, which can severely test a number of proposed mechanisms for the classic problem of heating the solar corona.

4.2 Higher sensitivity

A surprising result from SOHO/UVCS has been the discovery of extremely broad spectral lines of oxygen in the high corona. Their widths, if due to thermal effects, imply a temperature over 10 times hotter than that observed in the underlying static corona. The most likely current interpretation is that these observations demonstrate the effectiveness of cyclotron wave heating of at least the heavy ions in the solar wind; some have even suggested that cyclotron heating might supply all of the energy necessary to accelerate the solar wind. However, UVCS has a narrow spectral bandpass, so only a few ions are observed. The improved sensitivity of EUNIS allows useful observations for the first time of many different ions over the full height range from the solar disk out to as far as 2-3 solar radii above the limb, just the region where the transition between the static corona and the solar wind is thought to occur. Such measurements will provide additional observational evidence to help with the identification of energy deposition mechanisms in the corona.

Coronal holes are important solar features, as the source of the high-speed wind, for example. But their intrinsic faintness makes it difficult to measure characteristics such as temperature, density, or flow velocity with much accuracy. The very high sensitivity of EUNIS provides a major advance for the detailed EUV spectral study of these features.

Using intensity ratios of selected emission lines with theoretically known density or temperature responses has long been a promising way to determine the physical condition of any type of emitting solar plasma. In practice, however, this technique is often limited by the accuracy to which individual EUV line intensities can actually be measured. With its higher sensitivity, EUNIS provides measurements with significantly improved signal-to-noise, and thus smaller error

bars on the observed line ratios, giving much more precise determinations of diagnostic values for the plasma parameters. Additional lines that had previously been too weak to measure are also now available through EUNIS for this technique.

4.3 Broader spectral coverage

Line ratio techniques for plasma diagnostics are even further enhanced by the much broader spectral coverage afforded by EUNIS, allowing reliable measurements over a greater range of densities and temperatures. For similar reasons, substantial improvements are expected in the quality of differential-emission-measure (DEM) analyses that can be carried out with a full set of EUNIS data. Density-*insensitive* line ratios can provide very useful checks on an instrument's relative photometric response, as well as on the atomic physics calculations used to model EUV spectra. EUNIS allows such tests over a much larger wavelength range than was possible with SERTS.

Each of the three SERTS flights since 1997 provided under-flight calibrations for both CDS and EIT instruments onboard the SOHO spacecraft. EUNIS not only continues this essential service, it significantly extends the spectral range that can be cross-calibrated in this way. For example, overlap with CDS-NIS is increased from 310 – 355 Å to 310 – 370 Å, adding the important strong lines of Fe XVI at 361 Å and Mg IX at 368 Å. And the EIT channels of 171 Å and 195 Å can now be directly calibrated, along with the 304 Å channel previously covered by SERTS. The EUNIS shortwave channel also allows such under-flight calibrations to be applied to two of the TRACE observing channels for the first time. It will further be available to provide similar calibration support for one of the bandpasses on Solar-B/EIS now scheduled for launch in 2005, and for all 4 channels of both EUVI instruments to be flown on the STEREO mission.

5. SUMMARY

Thus, EUNIS provides unrivaled capabilities in terms of high spectral, spatial, and temporal resolution EUV spectra to address many fundamental problems in the physics of the solar corona. In addition, it should prove an invaluable ongoing calibration resource for numerous present and planned solar EUV missions well into the future. First flight of the new EUNIS payload is presently scheduled for 2002 October from White Sands Missile Range in New Mexico.

ACKNOWLEDGMENT

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Table 1: EUNIS Optical Specifications (for each spectral channel)

Telescopes:

Type	Single off-axis paraboloid, circular segment
Diameter	110 mm
Offset Distance	100 mm
Focal Length	1250 mm
Plate Scale	6.1 μm/arcsec
Coating	Multilayer tuned to spectral bandpass

Slits:

Type	Photo-etched silicon wafer
Width	8.0 μm (1.3 arcsec)
Length	5.8 mm (960 arcsec)
Coating	Aluminum

Gratings:

Type	Toroidal
Object Distance	625 mm
Image Distance	1000 mm
Radii	767.12 mm (Vertical), 772.23 mm (Horizontal)
Ruling Density	3600 groove/mm
Alpha Angle	5.710° (Shortwave), 5.908° (Longwave)
Spectral Bandpass	2*170-205Å (Shortwave), 300-370Å (Longwave)
Coating	Multilayer tuned to spectral bandpass

Focal Planes:

Type	Flat MCP surface → Fiber optics → APS detectors
Spectral Dispersion	2.78 Å/mm (1st order), 1.39 Å/mm (2nd order)
Spatial Plate Scale	9.70 μm/arcsec

Table 2: Performance Comparison of EUNIS to SERTS and Solar B / EIS

Characteristic	Units	EUNIS	SERTS-99	SERTS-95	Solar B / EIS
Spectral Bandpass	Å	170-205* 300-370	--- 300-355	170-220* ---	170-215 244-290
Spectral Resolution	mÅ	35* 70	--- 100	60* ---	55 55
Spatial Resolution	arcsec	2	3	7	2
Full Spectral FOV	arcsec	960	334	288	480
Total Bandwidth	Å	105	55	50	91

*Observed in second spectral order

Table 3: Throughput Comparison of EUNIS to SERTS and Solar B / EIS

Characteristic	Units	EUNIS	SERTS-99	SERTS-95	Solar B / EIS
Geometric Area	cm^2	95	94	22	88
Telescope Efficiency	-	0.20	0.04	0.25	0.20
Grating Efficiency	-	0.09	0.03	0.04	0.08
Filter Transmission	-	1.00	0.40	0.60	0.50
Detector QE	-	0.45	0.15	0.05	0.80
Effective Area	mm^2	77.	0.68	0.66	56.

Table 4: EUNIS Sensitivity Improvements

Component	EUNIS	SERTS-99	Efficiency Ratio
Telescope	Off-axis parabola 1 reflection	Ritchey-Chretien 2 reflection	x 5
Grating Blaze Avg. Groove Efficiency	0.45	0.15	x 3
Detector MCP Photocathode	K Br	Bare	x 3
Blocking Filter	None needed, detector is solar blind	Thin Aluminum	x 2.5
		Total	x 112

Table 5: New Science Capabilities

Parameter	Capability	New Science
Faster Readout	Full spectra at ~ 1 sec cadence	♦ Studies of transient coronal phenomena. ♦ Observations of rapid loop dynamics. ♦ Searches for evidence of magnetic reconnection or wave heating.
Higher Sensitivity	Useful measurements of faint sources	♦ Detailed spectra of coronal holes. ♦ Measurements up to 3 R above the limb, at base of the solar wind. ♦ Improved density- and temperature-sensitive ratios.
Broader Spectral Bandpasses	Additional wavelength coverage	♦ Better DEM analysis. ♦ More diagnostic line ratios. ♦ Extended underflight calibrations of SOHO/ CDS and EIT. ♦ New underflight calibrations of TRACE, Solar-B/EIS, STEREO/ EUVI, and Solar Orbiter (?).

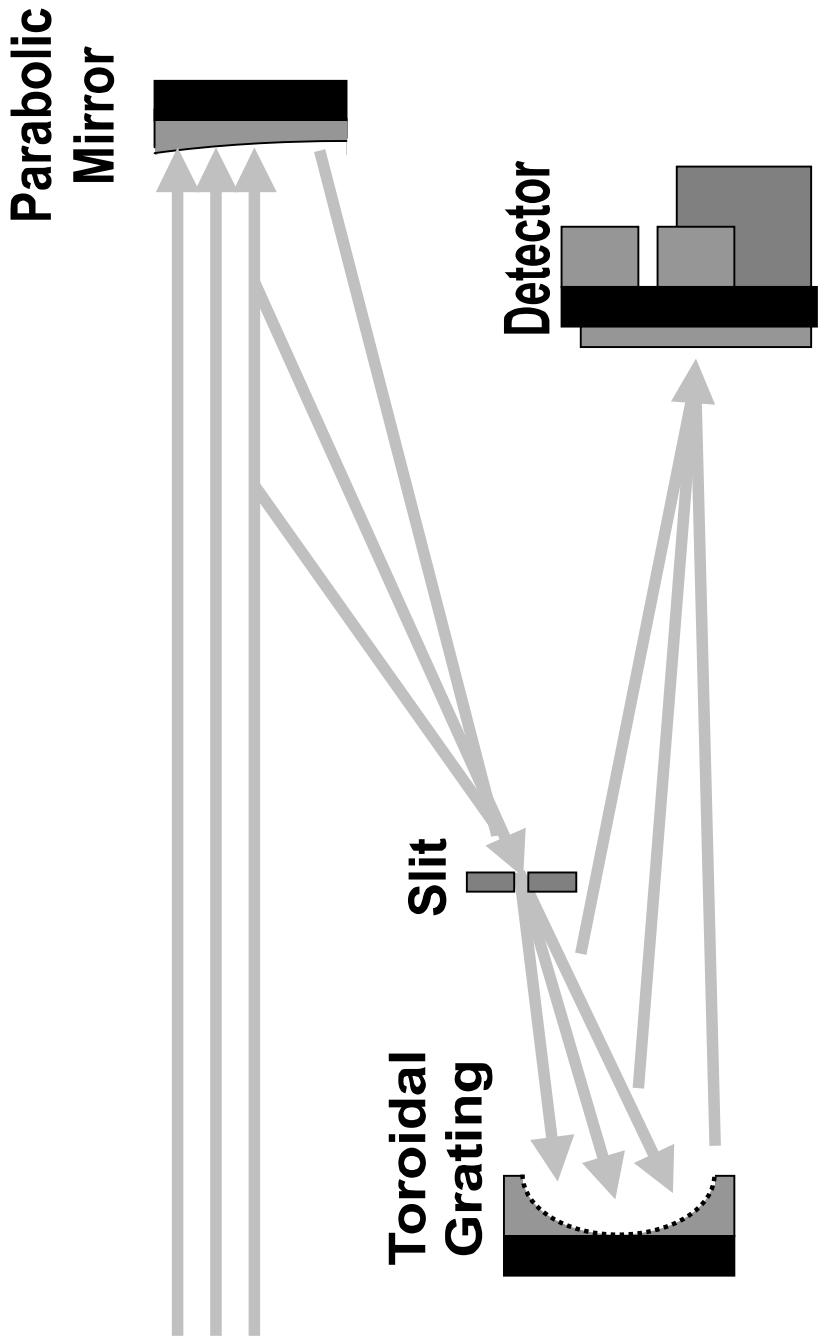

Figure 1. Schematic of the baseline EUNIS optical layout.

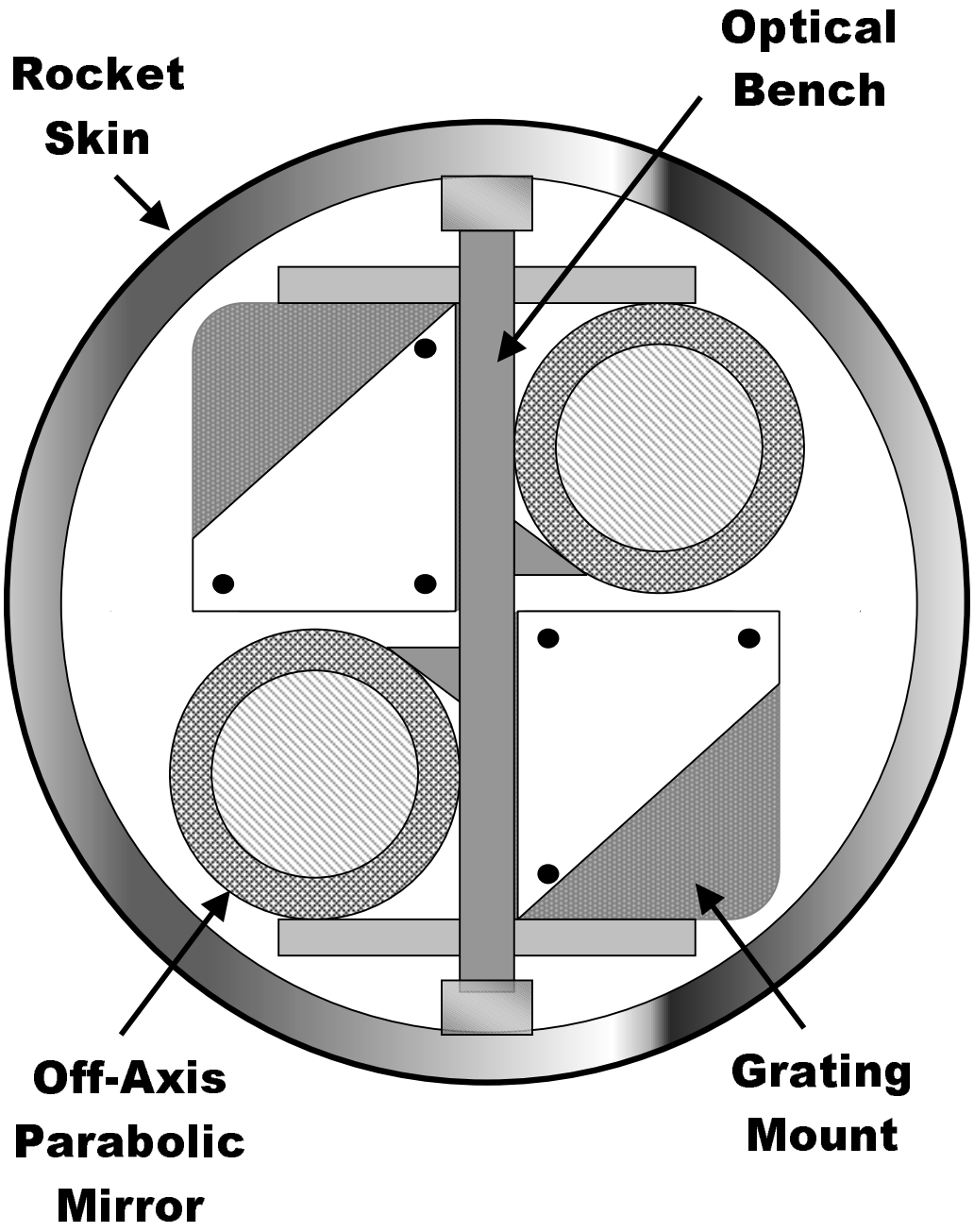

Figure 2. EUNIS front view, showing how the two optical channels are mounted on either side of the central optical bench running the length of the rocket payload.

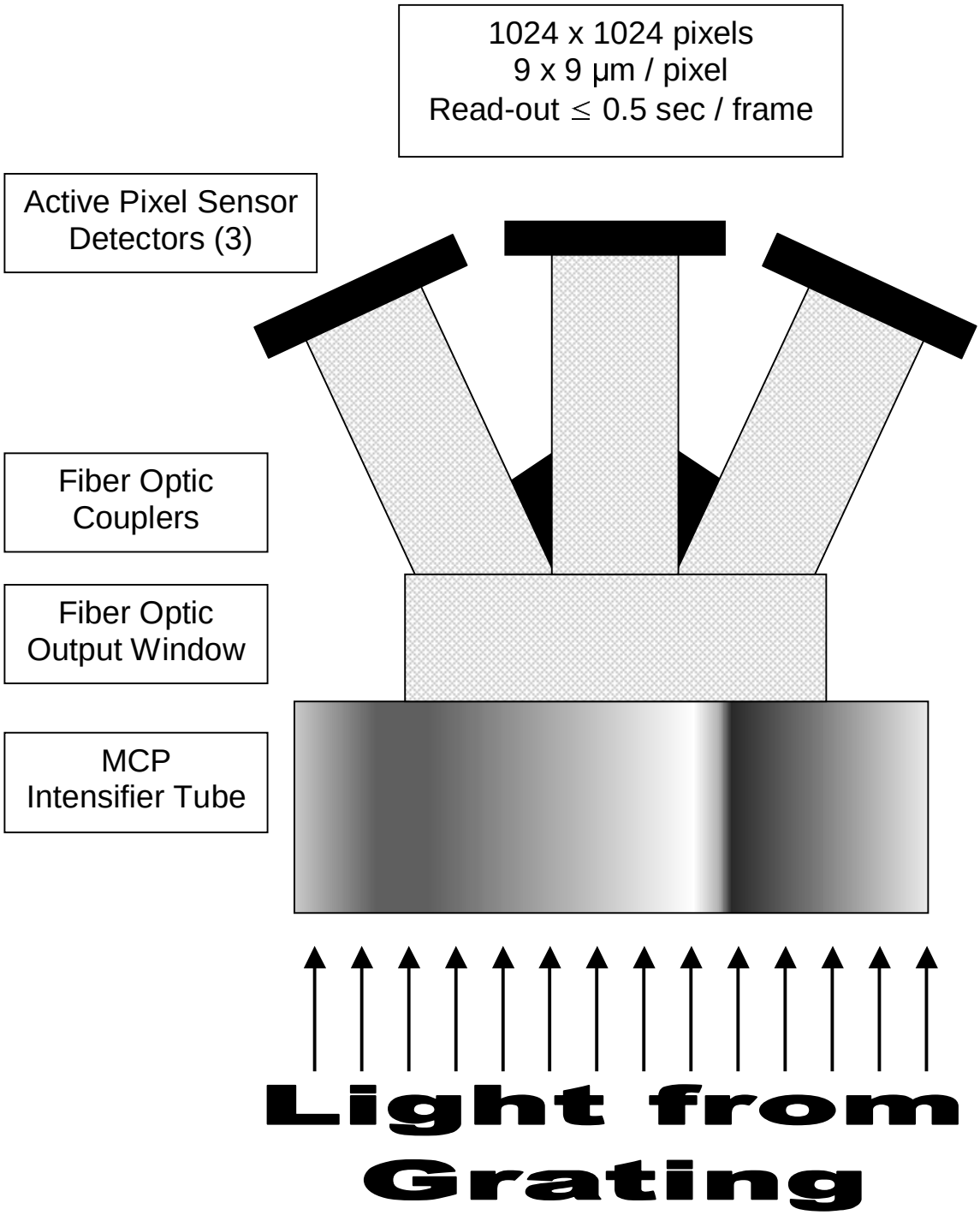

Figure 3. Schematic configuration of each detector unit for the EUNIS instrument.

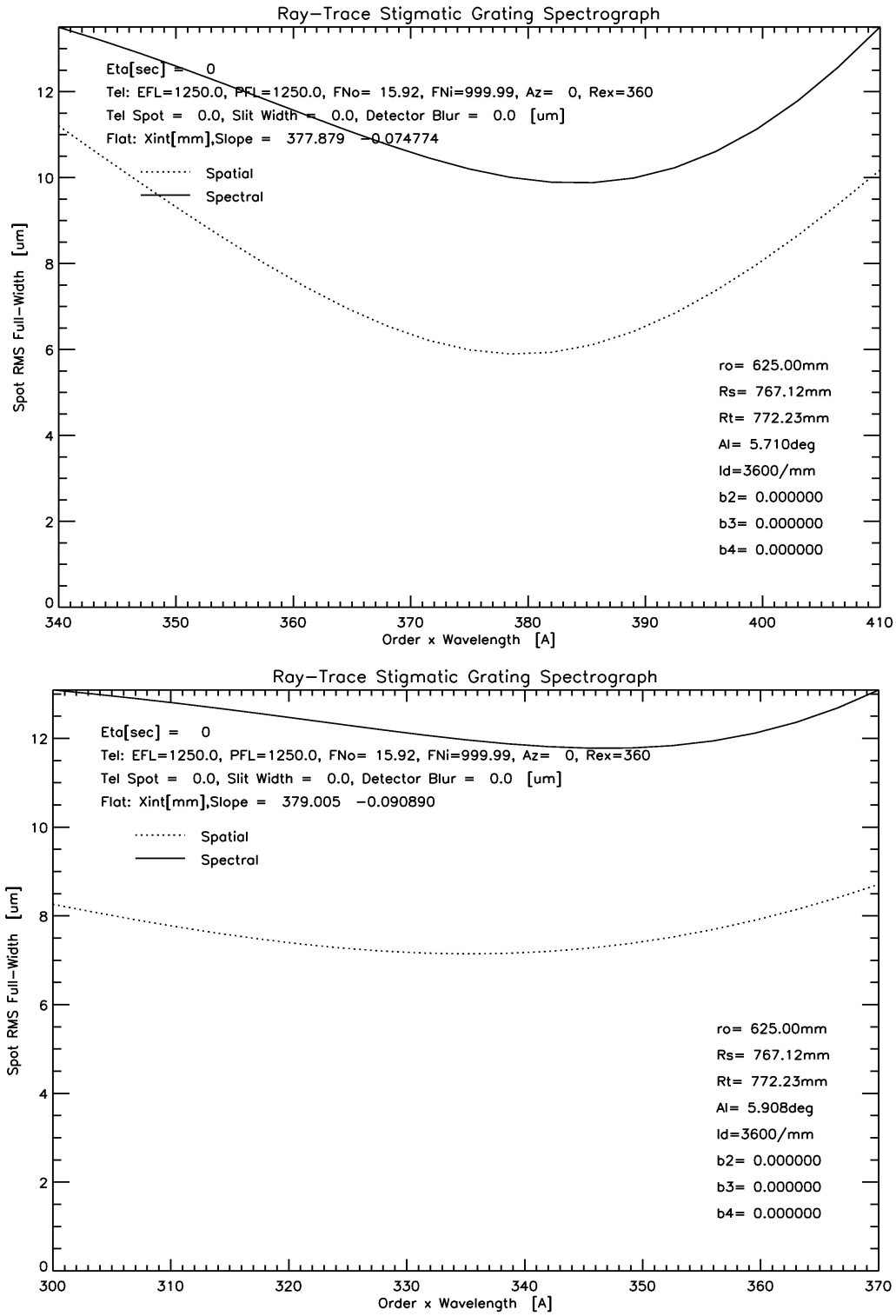

Figure 4. Ray–trace analysis of baseline EUNIS design for an on-axis point source. Upper panel shows the shortwave channel observed in 2nd order; lower panel is the longwave channel in 1st order. Both spatial and spectral widths are indicated.