OPTICAL DESIGN AND PERFORMANCE OF THE ODIN UV/VISIBLE SPECTROGRAPH AND INFRARED IMAGER INSTRUMENT

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ABSTRACT

Sweden's Odin international scientific small satellite is planned for launch into a sun synchronous low earth orbit in 1998. Odin's mission will be both astronomy and atmospheric science (aeronomy). Its principle aeronomy payload is a high performance, lightweight (12 kilograms) ultraviolet/visible imaging spectrograph and infrared imager, that will point at the limb of the earth's upper atmosphere and measure molecular species associated with ozone chemistry, detect aerosols and tomographically measure and map ozone. The Canadian Space Agency is funding this payload, which has the acronym "OSIRIS", and Routes Inc. is currently building the flight model. OSIRIS is effectively two optical instruments mounted in a common optical housing and supported by common electronics. The first instrument consists of three infrared telescopes, each with an Indium Gallium Arsenide (InGaAs) linear detector. The second part is a high precision imaging spectrograph with a wavelength range of 280 to 800 nanometers, which uses a UV-enhanced CCD. The imaging spectrograph uses compact reflective optics and an aspheric reflective ruled grating, and provides excellent spectral imaging performance and stray-light rejection. This paper first briefly describes the overall instrument and then describes the optical design and the Development Model optical and sky test performance results. This paper includes a brief description of how OSIRIS will obtain valuable new environmental information on the upper atmosphere, and the requirements this places on the instrument's optical design.

I. INTRODUCTION AND MISSION DESCRIPTION

Osiris n.[Lat< Gk; of Egypt origin] *Myth. an ancient Egyptian god, brother and husband to Isis, whose annual death and rebirth symbolized the self renewing fertility of nature.* [Webster's II].

In our context, the acronym OSIRIS spells out Optical Spectrograph and Infra-Red Imaging System. Routes Incorporated is building this space science instrument for the Canadian Space Agency (CSA). OSIRIS will continue the upper atmospheric studies (aeronomy) done in part by the ultraviolet imaging cameras on Sweden's Viking[1] and Freja[2] satellites, and the Wind Imaging Interferometer (WINDII) on NASA's UARS satellite.[3,4]

The Odin Satellite

OSIRIS will fly on Sweden's Odin satellite, scheduled for launch in 1998. Odin is a 235 kg, 260 Watt, 3 - axis stabilized satellite, with a height of 1.1 m and a span of 1.8 m with the solar arrays deployed. A Russian Start-1 launch vehicle will place Odin in a circular sun-synchronous dawn/dusk orbit at approximately 600 kilometers altitude with an ascending node at 18:00. The planned mission duration is two years. A more complete summary of the Odin mission and the electronics portion of OSIRIS can be found in Payne et al.[5]

Odin's scientific objectives are:

- Astronomy in the sub-millimeter wavelengths.
- Aeronomy in the sub-millimeter, ultraviolet (UV), visible and infrared (IR) wavelengths.

Odin will be maneuvered in different ways for aeronomy and astronomy: For aeronomy, the spacecraft will point the instruments to follow the Earth's limb, scanning the atmosphere up and down between 15 to 120 km altitudes at a rate of up to 40 scans per orbit. The nominal view direction will be in the orbit plane, but it can be directed anywhere within ±32 degrees out-of-plane. For astronomy, Odin will be inertially stabilized to point towards a celestial object for up to 60 minutes, after which the Earth blocks the view to the object until it appears on the other side of the earth. Odin's astronomy instrument is a Submillimeter Radiometer (SMR), which will also be operated along with OSIRIS during the aeronomy phase of the mission. Figure 1 illustrates the Odin satellite in orbit.

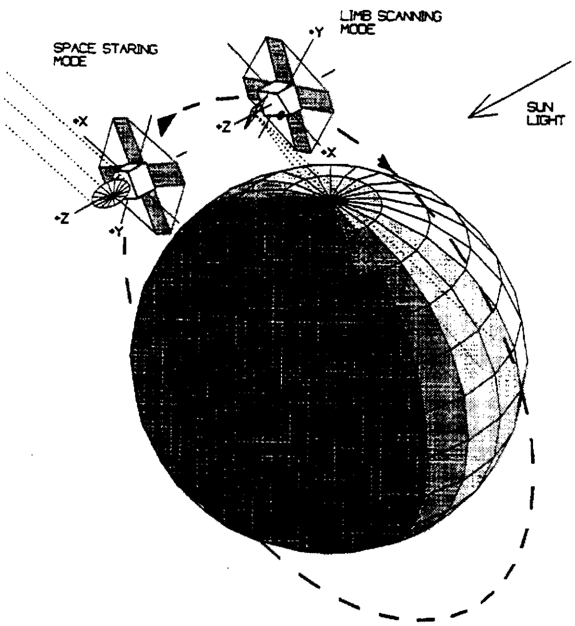

Figure 1. Odin Satellite in Orbit

The Swedish Space Corporation is building the Odin satellite and is responsible for the mission. Sweden has developed a successful model for low-cost scientific satellites: it entails international cooperation, where experimenters from each participating nation provide their respective instruments and related equipment. For most nations, funding for the instruments comes from their national space agencies.

The Canadian Space Agency is funding OSIRIS (plus some other participation in Odin). The OSIRIS science team includes members from Canada, Sweden, Finland, and France. Dr. E. (Ted) Llewellyn of the University of Saskatchewan is the Principle Investigator for the aeronomy portion of the mission.

The OSIRIS instrument project includes a development model (DM) and a proto-flight model (PFM). The DM is used for proof-of-performance, whereas the PFM will be subjected to full environmental qualification testing as well as performance demonstration prior to flight. Both versions of the instrument will be characterized in a calibration test facility at the University of Calgary. At the present time, the DM is under test and the PFM is being built.

Odin Aeronomy Objectives

OSIRIS and the Submillimeter Radiometer (SMR) will provide complementary data to meet the overall aeronomy objective, which is observation of radiation from the earth's limb for the study of middle atmosphere processes, particularly to increase our understanding of ozone depletion at the earth's poles and middle latitudes. More detailed information on the aeronomy measurements, and other aspects of OSIRIS, can be found on Routes Web site [6].

OSIRIS will measure NO_2, BrO, OClO, NO_3, O_3 and possibly ClO, all of which are species of critical importance in understanding ozone. Other important species, *e.g.* H_2O and HNO_3, will be measured by the SMR, which will also measure CO, ClO, N_2O and NO_2. The near infrared portion of OSIRIS will measure oxygen singlet delta emissions at 1.27 microns, which is a direct indicator of ozone. Combined with dynamical input from weather forecast and climate models, this will allow an assessment of the contribution of dynamics and chemistry to the ozone budget in polar regions. The techniques developed can also be applied to understanding the decrease of ozone at mid-latitudes.

Another objective is to better define the chemical conditions of the Arctic vortex and to estimate the extent of the winter and spring time depletion of ozone due to the chemical processing by aerosols and Polar Stratospheric Clouds (PSC's). This is not a simple matter because it is difficult to separate dynamical effects. It is currently believed that the most intense period of processing on PSC's is during December through March, with the peak times being January and February, although this can be quite variable.

The vortex in the Antarctic is stronger, cooler and lasts longer than in the Arctic, and Odin will have the opportunity to obtain useful measurements as it forms and cools. In the southern hemisphere the vortex is sufficiently extensive that the edge will be in sunlight and, based on the UARS observations, we can expect to see large abundances of ClO, $ClNO_3$ and depleted amounts of HCl and water. This will provide extremely interesting observations from June through early November, when the vortex breaks up. That will be analysed to provide information on both the dynamics and ozone depletion in this region.

The ODIN aeronomy mission presents a unique opportunity to obtain new and timely data on environmental parameters that are of vital importance to many nations, not only those directly involved in the mission. Together with the TOMS-EP instrument recently launched (July '96); UARS, GOME and Odin will provide important contributions to stratospheric ozone research.

The scientific analysis of the potentially rich database that the OSIRIS (and SMR) observations offer will be done by international collaboration. The project has brought together experts in instrumentation, data analysis, atmospheric radiation and chemical and dynamic modeling. The Odin mission is also providing an excellent opportunity to train young scientists.

Synopsis of OSIRIS Payload

OSIRIS will provide simultaneous aeronomy observations from two components; a UV/Visible spectrograph with 1nm resolution over the nominal passband from 280 to 800 nm, and a vertical near infrared (IR) imager with three narrow passband channels centered at 1.263, 1.273 and 1.520 microns.

The near infrared (IR) component of OSIRIS will provide measurements of the mesosphere and upper stratosphere. The three IR channels use linear InGaAs array detectors, aligned perpendicular to the Earth limb. Each IR image contains information from 90 different tangent altitudes. This permits a 2-D recovery of mesospheric ozone concentrations from tomographically inverted 1-D measured oxygen singlet delta (1.270 micron emission) limb brightness profiles. The spatial recovery using tomographic techiques significantly shortens the scale size of measureable structures as compared with conventional inversion techniques.

The IR imager will also be used to determine other fundamentally important characteristics from the mesosphere and stratosphere such as temperature and aerosol information including particle size, shape, composition and number density.

The 280-800 nm optical spectrograph component of OSIRIS will provide ozone related specieis measurements in the altitude range from 15 to 80 km. This will be done through measurement of atmospheric airglow as well as utilization of a modified DOAS 9Differential Optical Absorption Spectroscopy) techique on scattered and subsequently absorbed sun or moon light.

In regions of the spectrograph wavelength passband, where the atmosphere does not contribute to the signal through airglow emissions or attenuate the signal through absorption, the spectrograph will provide interesting information about the scattering sources present in the atmosphere. This information includes atmospheric pressure that can be related to temperature, as well as information to determine aerosols, PSC and PMC information, and properties such as particle number density, size, shape and composition.

II. Optical Performance Requirements

The scientific objectives of the aeronomy mission lead to the detailed performance requirements for OSIRIS's optical design. These design specifications for the UV/Visible and the IR parts of OSIRIS are listed in the next two boxes. The rationale (design drivers) is then described.

UV/Visible Spectrograph:

- Wavelength	300 nm to 800 nm (down to 280 nm with degraded performance)
- slit orientation	perpendicular to the orbit plane (horizontal)
- minimum sensitivity	12 kR/Angstrom/pixel
- dynamic range	greater than 3000
- wavelength resolution	1 nm from 300 to 450 nm, less than 2 nm from 450 to 800 nm
- vertical fov	nominally 1 km for the slit
- horizontal fov	nominally 40 km
- spatial resolution	1 km at the limb
- pointing direction	aligned with SMR boresight
- detector temperature	-20° C or less
- temperature stability during exposure	+/- 0.1° C
- readout noise	25 electrons rms or less
- A/D converter	14 bits (meets dynamic range requirements)

IR Imager:	
- detector orientation	in the orbit plane (vertical)
- bandpass filter center wavelengths	1.263, 1.273, 1.520 microns
- bandwidth (FWHM)	10 nm for 1.263 and 1.273 micron filters, 40 nm for 1.520 micron filter
- vertical fov	90 km, with degraded performance near high altitude end of FOV
- horizontal fov	2 km
- spatial resolution	1 km in the vertical direction (1 km per pixel)
- minimum sensitivity	50 kR/band/pixel (in each of the three bands)
- detector temperature	-40° C or less
- temperature stability during exposure	+/- 0.1° C

UV/Vis Spectrograph Optical Design Drivers

A. The wavelength range of 300 to 800 nm is required to provide coverage of the large number of ozone related species. These include:

> O_3 - from broadband absorption in the 300 to 330 nm region (Hartley-Huggins band) and around 550 nm (Chappuis band).
>
> NO_2 - broadband absorption in the region near 400 nm
>
> BrO - absorption from 300 to 370 nm
>
> OclO - absorption from 300 to 450 nm
>
> O_2 - emission and absorption around 687 and 762 nm

The spectrograph's wavelength range was extended down to 280 nm when it was realized that this could be done with essentially no change to the optics. This will allow for extended measurements of spectra, associated with aerosols at higher altitudes.

B. The slit is oriented perpendicular to the orbit plane (horizontally) for a number of reasons: With one km spatial resolution along the slit, spectral structures whether they are species concentration structures, aerosol formations, PSC's or PMC's can be detected. The horizontal extent of these structures is important in polar ozone chemistry. When structures are not present, the signal in the spatial dimension all comes from basically the same tangent point and can be considered to be homogeneous. This allows for binning of several pixels with similar signals to improve the signal to noise ratio. (A vertical slit, was originally specified, but it had two problems: the dynamic range of a single exposure is increased from 10^{-3} to 10^{-5} due to the exponential decay of molecular scatterers with increase in altitude, and the downlink data rate for the Odin satellite is insufficient to transmit two dimensional images of altitude and wavelength.)

C. A minimum sensitivity of (12/kR/A/pixel) was chosen to allow detection of nightglow features in the limb.

D. A dynamic range requirement of 3000 was chosen to cover the expected dynamic range of modeled signals at the lower extent of the tangent altitude nod range. Ozone absorption, attenuation through Rayleigh scattering, the shape of the instrument throughput curve, the solar spectrum shape and the shape of the Rayleigh scattering cross sections significantly decrease the signal in both the red and the blue ends, resulting in a dynamic range, over one exposure, of about 3 orders of magnitude. Added to this, the range of two orders of magnitude of the exposure times, accompanied with different binning factors, gives enough dynamic range to cover the signal dynamic range of between 5 and 6 orders of magnitude from the lower tangent altitudes to the highest tangent altitude.

E. A vertical field of view (FOV) of nominally one km was chosen to allow for recovery of species profiles on a one km grid.

F. A horizontal FOV of 40 km was selected to provide a large signal to noise (S/N) ratio through binning, without altitude smearing due to large integration times, for nightglow.

G. For spatial resolution, pixels subtending one km in the spatial direction provide the required resolution for edge detection and other scientific needs.

H. Regarding pointing direction, the spectrograph is co-aligned with the SMR boresight to give simultaneous measurements of sometimes redundant and other times complementary species related to ozone chemistry. The goal is for OSIRIS to measure in the same place and at the same time as the SMR, to make the extraction of scientific results easier.

I. The detector temperature of -20° C maximum, and temperature stability during a given exposure of +/- 0.1° C, and readout noise of 25 electrons rms or less, were chosen to meet the minimum sensitivity requirement.

J. A 14 bit A/D converter meets the dynamic range requirements.

IR Imager Optical Design Drivers:

A. Each InGaAs detector is oriented vertically necessary for tomographic recovery, to simultaneously image multiple tangent heights. Even the 1.520 micron channel, which will not be used for tomographic recovery at low altitudes, benefits from multiple tangent altitude images because the vertical extent of structures such as PSC'S and waves can be determined with the vertically oriented detector.

B. The 1.263 and 1.273 micron filters are at the singlet delta oxygen emission bands. Two measurements of the same emission located on different parts of the band allow for correction and correlation. They may also be useful in determining atmospheric temperature as well as color information of aerosols that scatter solar light.

The third band at 1.520 microns was chosen to be outside the singlet delta emissions, so that a background signal of scattered sunlight could be determined. This band contains no absorption features so it is dominated by scattered sunlight, and moonlight during periods of high lunar illumination. The 1.520 band also contains some OH emissions which will be visible at night and from these it is expected that O and H concentrations can be determined.

C. Modeling of the singlet delta emissions and absorptions indicate that Gaussian filters with ten nanometer (nm) half widths at the above locations best meet the needs of the tomography. Gaussian shaped filters allow the bandpass to drift slightly without large effects on the measured signal. Square filters that drift are not appropriate for measuring emission lines because a slight drift can cause very narrow strong lines to either be fully included or excluded from the measurements without confirming knowledge. This can significantly effect the results.

The filter at 1.520 microns is square shaped because as much light as possible is required from this filter. It is as wide as possible, bounded by water absorption lines on both sides.

D. A nominal vertical FOV of 40 km was selected. The tomography requires as many altitudes as possible to be sampled at the same time. The IR detectors have 128 pixels available (minus masked pixels used to measure dark current), so an extended FOV of 90 km could be accommodated without changing the optics. However, a consequence is that the optical performance is degraded on the outer bounds of the extra altitude elements (outside the 40 km FOV), due to vignetting.

E. A one km spatial resolution in the vertical direction was chosen in order to resolve all significant features in the vertical singlet delta emission profile. The original tomographic algorithms were tested using one km resolution and they functioned adequately.

F. A minimum sensitivity of 50/kR/pixel was chosen to provide excellent signal to noise in the singlet delta measurements even for the relatively weak night time emissions that will be measured. (The 1.520 micron filter was not part of the design when this sensitivity specification was defined).

G. The detector temperature of -40° C maximum and temperature stability during a given exposure of +/- 0.1°C were chosen to meet the minimum sensitivity requirements.

III. OSIRIS OPTICAL DESIGN OVERVIEW

OSIRIS is a good example of a high performance science payload for a small satellite. In a single compact, low mass and low power package, OSIRIS provides the capabilities of two distinct space science instruments, the wideband UV/Visible spectrograph and 3 channel IR imager. A single electronics/power subsystem is provided for the two OSIRIS optical subsystems. An exploded view of OSIRIS on the Odin satellite is shown in Figure 2.

The OSIRIS total mass is 12 Kg, and its electrical power demand is 15 to 20 Watts (depending on operating mode). The overall dimensions of OSIRIS are 200 mm x 426 mm x 485 mm. OSIRIS is functionally divided into three main parts: an optics unit, an electronics unit, and a power unit. Figure 3 is a photograph of the assembled DM packaging, and Figure 4 is a rendering of the integrated flight model. Figure 5 is a photo of the milled aluminum enclosure and cover parts. The electronics unit and the power unit are packaged in a common enclosure. The units are bolted together to form an assembly which is mounted to the satellite's honeycomb panel. Two penetrations through this panel provide paths for cooling straps to connect to the radiator on the exterior of the spacecraft that rejects heat from OSIRIS's thermo-electric coolers.

The fields- of-view of the UV/Vis and the IR channels are aligned to produce simultaneous measurements of the atmosphere at varying altitudes above the surface of the earth. OSIRIS will be mounted on Odin so that its optical axis is aligned with the calibrated axis of the SMR, permitting collaborative measurements of atmospheric constituents that are significant to the understanding of ozone depletion as discussed previously.

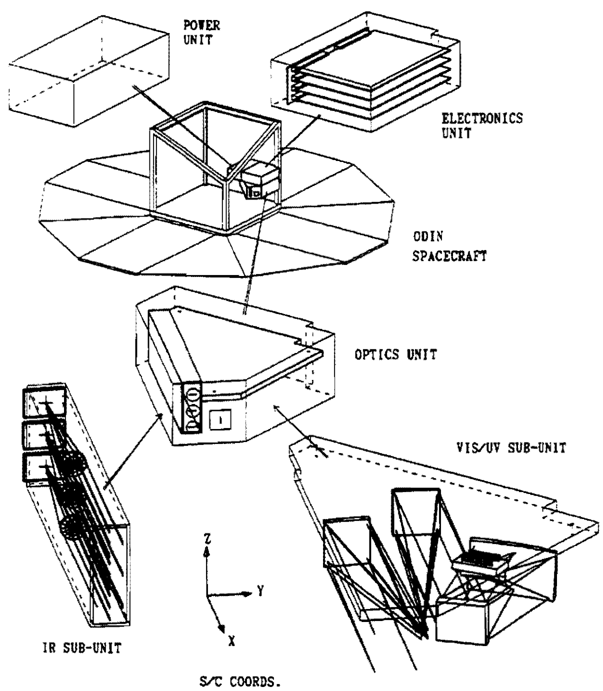

Figure 2. Exploded View of OSIRIS on the Odin Satellite

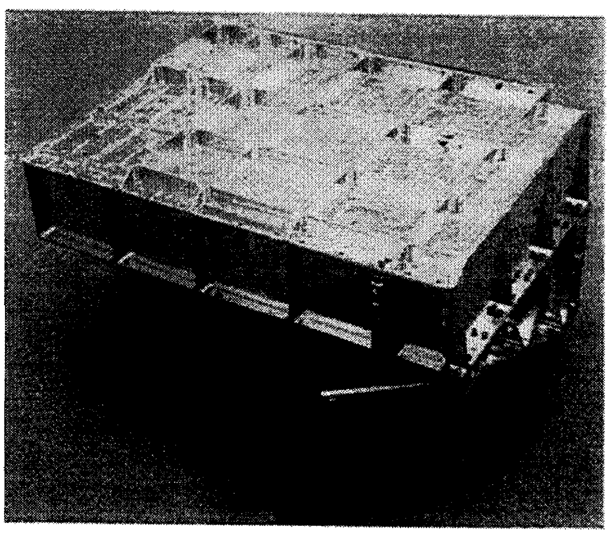

Figure 3. OSIRIS DM Instrument Packaging

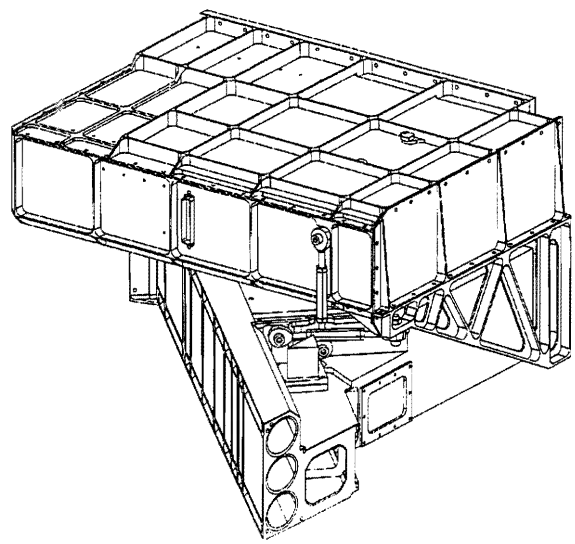

Figure 4. Rendering of Integrated OSIRIS Instrument

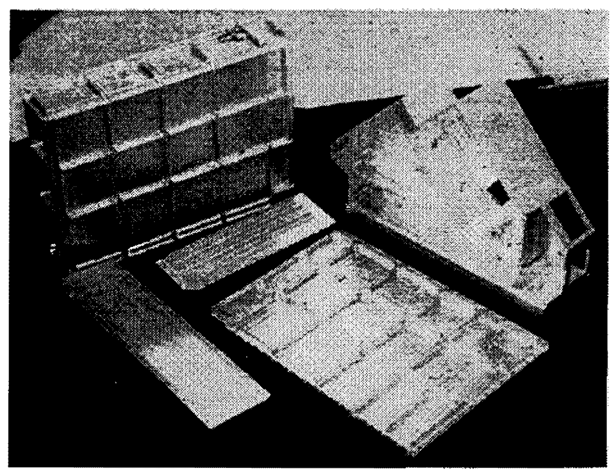

Figure 5. OSIRIS Enclosure and Cover Parts

The optics unit is packaged in a light-tight housing which contains the optical elements, detectors and supporting electronics for the Ultraviolet/Visible (UV/Vis) and IR parts of OSIRIS. All optics elements are mounted to the optical bench using precision machined brackets; other components directly attach to the housing. The optics unit is mounted to the rest of OSIRIS by adjustable kinematic mounts so that the entire optics unit can be adjusted to comply with alignment needed with respect to the SMR. The optics unit is designed to have ±0.5° of adjustment of its optical axis in all 3 axes for this purpose. Figure 6 is a view of the optics unit with the covers removed. Figure 7 is a cross-sectional view of the optics unit, showing both the UV/Vis and IR optics.

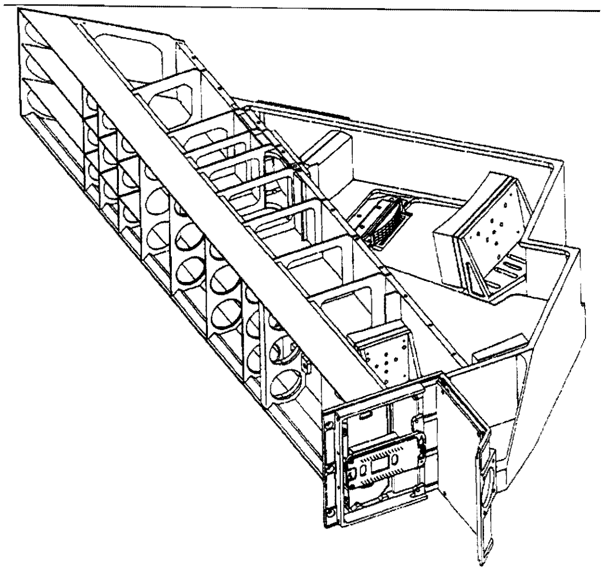

Figure 6. Cross - Section of Optics Unit

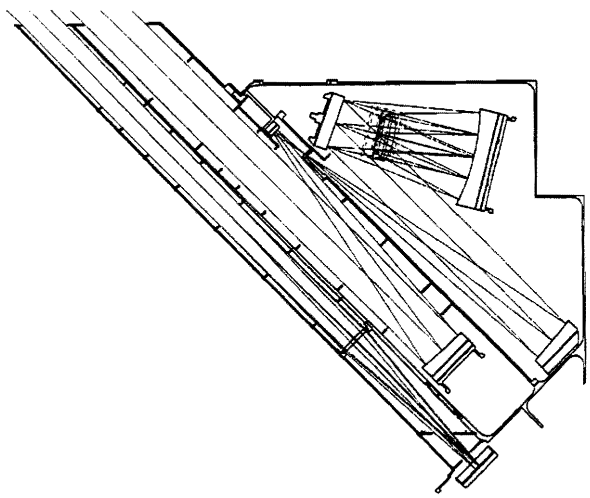

Figure 7. Rendering of Optics Unit with Covers Removed

The slit of the UV/Vis spectrograph is oriented horizontally (perpendicular to the orbit plane). As the satellite nods, spectral images will be captured of atmospheric sources at various altitudes above the surface of the earth. The IR imager uses narrowband filters to provide wavelength separation, while height information is obtained through the vertically oriented InGaAs linear detector array. The UV/Vis spectrograph boresight is coincident with that of the SMR. The boresights of each of the three IR Imager channels are parallel and at an angle of approximately 0.4 degrees above the SMR boresight. Figure 8 shows the OSIRIS fields of view.

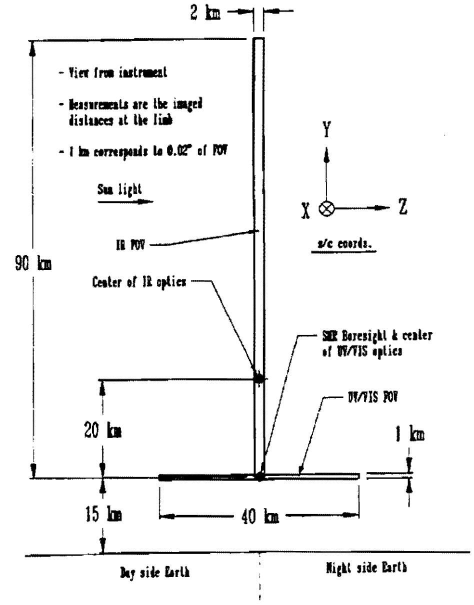

Figure 8. OSIRIS Fields-of-View

The spectral response of the CCD ultimately determines the overall passband of UV/visible part of OSIRIS. An EEV (Chelmsford, England) Model CCD26 is being used. The CCD26 is similar to the CCD being used for the Global Ozone Monitoring by Occultation of Stars (GOMOS) instrument for ESA's Envisat-1 satellite, currently scheduled for launch in 1999. The CCD26 is back thinned, rear illuminated and Multiple Pinned Phase (MPP) mode, selected for relatively uniform quantum efficiency across the passband. It is UV-enhanced with a proprietary UV anti-reflection (AR) coating, giving relatively high quantum efficiency at the UV end of the spectrum.

The IR imager uses InGaAs linear photodiode arrays from Sensors Unlimited (Princeton, New Jersey). As previously described these arrays have hybrid multiplexers. The passbands of the three IR channels are determined by narrowband interference filters and both the CCD and IR detectors must be operated at temperatures lower than the ambient optics unit temperature to give adequate signal-to-noise ratios. Thermoelectric coolers (TEC's), and cooling straps connected to the external space-facing radiator provide this additional cooling of the detectors.

To maintain stability of the detector temperatures during conditions when the spacecraft temperature is below normal or during transient thermal conditions, heaters are provided on the detectors. If needed, these heaters will be powered using thermostat-type on/off control about a selected set-point for each of the detectors.

The UV/Vis spectrograph uses compact folded optics, with off-axis parabolic mirrors. One major benefit of the design is that there are no obscurations in the optical path, and this reduces internal stray light. Reflective optical elements are used almost exclusively since they are achromatic and also tend to introduce less stray light than refractive elements. The only refractive element is the Field-flattener/Order sorter/Prism (FOP) assembly. An aspheric reflective grating supplied by Instruments SA/Jobin-Yvon (Longjumeau, France) provides the spectral dispersion.

The IR imager has a simple optical design, with a ZnSe lens, filter and detector for each of the three channels. The narrow bandpass interference filters are mounted on each of the three IR detectors. AR coatings are also used on the lenses and filters.

Baffles and vanes form part of the optics, and are used to reduce both internal and external stray light. Internal stray light arises from the scattering of unwanted light inside the optics unit (e.g. cross talk between light wavelengths which are separated in the spectrograph) and external stray light is unwanted light from outside the instrument FOV (e.g.. from the bright limb of the earth surface). The specification for stray light rejection is attenuation by a minimum of 10^{-4} compared to the desired incident light for both internal scattering and external (off-axis) stray light. OSIRIS's optical baffles extend out to the folded position of the ODIN solar arrays.

Dr. Harvey Richardson of Victoria B.C. did the system level and conceptual optical design for Routes Inc.
Ms. Donna Lee Desaulniers did many aspects of the detailed design, and Lumonics Optical Group of Ottawa built most of the optical elements.

IV. Details of UV/Vis Spectrograph Optics Design

The UV/Vis spectrograph is an off-axis system with no obscuration. It is an elegant and "clean" folded design. The aperture is 36 x 36 mm square, with truncated corners. Light enters the UV/VIS spectrograph's entrance port, goes through a set of baffles and vanes, and then is reflected by an off-axis parabolic objective mirror onto a flat folding mirror (refer to Figure 9). The light then passes through the slit located at the mirror focus and falls on a second off-axis parabolic mirror which collimates the light and illuminates a blazed aspheric reflective grating. The first order light reflected off the grating is directed out of the plane of the rest of the optics by a spherical camera mirror to a combination field-flattener, order-sorter and prism element (FOP), and then the dispersed light is imaged onto the CCD. The slit is imaged onto the CCD such that the vertical (columns) correspond to the horizontal FOV direction and the horizontal (rows) correspond to the light dispersed in wavelength. The dispersion is a nominal 2.55 pixels per nanometer at the short wavelength end of the spectrograph bandpass and 2.5 pixels/nm at the long wavelength end. The FOP's order sorting filter is placed just in front of the CCD so that the spectrum is not corrupted by light from the second order spectrum from the grating. Note that the CCD is installed without a cover glass on its package. While this introduces additional instrument handling and cleanliness requirements, it also provides better optical performance.

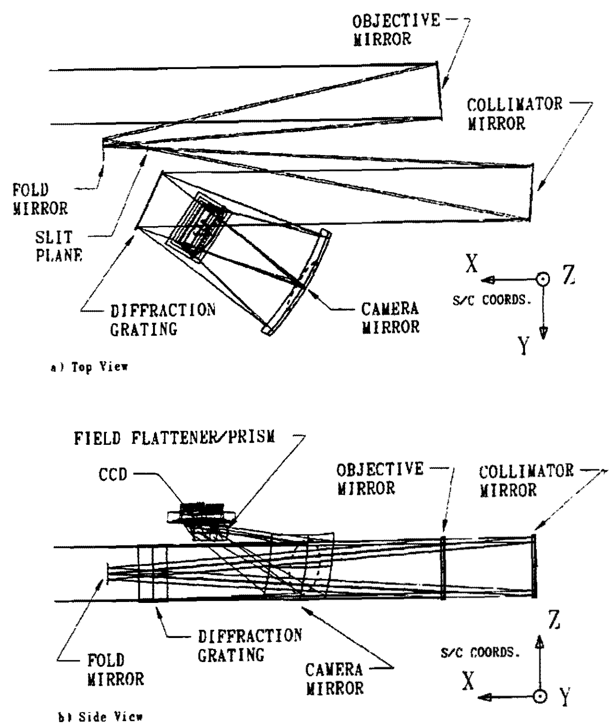

Figure 9. UV/Vis Spectrograph Optical Design

Several measures were taken to minimize the effect of scatter: The number of optical surfaces was minimized; diamond-turned surfaces were avoided because of their poor scattering performance in the ultraviolet; optical coatings are used. The coatings were selected so that the scatter introduced by the coatings was minimized in the 300-425nm region, and the transmission enhanced, in relation to the longer wavelengths.

Mirrors

The objective and collimator mirrors are a matched set of off-axis paraboloids supplied by Space Optics Research Laboratories (SORL), Chelmsford, Massachusetts. The mirrors are decentered 35 cm along the direction parallel to the dispersion of the grating. The optical specifications for the paraboloids and other mirrors are:

Mirror	Radius of Curvature (mm)	Dimensions (mm)
Parabolic	508.0	43 x 43
Fold	flat	10 x 12
Camera	187.45	80 x 46

Aspherized Grating

The diffraction grating is an order 1, ruled blazed reflection replica which has been aspherized using the elastic deformation technique developed about 15 years ago, by Dr. G. Lemaitre of the University of Marseilles. This technique results in an aspheric and achromatic grating.

To make the grating, a plane grating is replicated onto a special thin blank of variable thickness. This replica is called the active master. The blank is then bent by suction such that its shape determines the relative values of the aspheric coefficients. The amount of suction determines the total amount of asphericity. Then another replica is made from this deformed submaster. The submaster is designed to bend in the opposite direction required, thus yielding a final replica with the required aspherization. The grating resin takes up the aspherization and, unlike Schmidt plates, does not introduce wavelength-dependant aberrations. The grating specifications are as follows:

Order:	1
Density:	600 lines/mm
Blaze:	400 nm
Wavelength range:	280 to 800 nm (nominal)
Clear Area:	40 by 36 mm (36 mm parallel to rulings)
Asphericity:	"Lemaitre ratio" of 3.63 (gives the degree of aspherization from the submaster)
Conic Constant:	-1 (parabolic)
Radius of curvature:	2331.55 mm
Decentration:	27.925 +- 0.2 mm

Field-Flattener/Order Sorter/Prism (FOP)

The field-flattener/order sorter/prism is a combination of four elements: two plano-spherical lenses, an order sorter, and a right angle, total internal reflection prism. Except for the order sorter, all the elements are made of Ultran 30 (high UV transmission) glass, although the flight model OSIRIS instrument will use fused silica.

The reflection grating operates in the positive first order. Consequently, the light from the positive second order (400 nm and shorter) overlaps the first order and would be imaged onto the detector if it is not blocked. To block the unwanted orders of light, an absorptive color glass filter (GG455) is incorporated into the FOP assembly, between the prism and exit lens. This filter glass blocks light longer than 455 nm wavelength, and is positioned starting at the location of 480 nm dispersed light.

Coatings

The four fused silica mirrors are coated with protected, unenhanced aluminum. The design of the anti-reflection (AR) coatings for the field flattener/prism is difficult because of the wide spectral range and the range of incident angles. The transmission of the AR coatings in the 300 to 425 nm region should be enhanced with respect to the 425 to 800 nm region. The DM instrument uses a 16 layer thin film wideband coating, giving a maximum measured reflectivity within the 320 to 800 nm band of approximately 1% (rising to about 4% at 300 nm).

Geometric Optical Performance

The raytrace packages CODE-V and Zemax-EE were used to estimate the encircled energy diameters. The analyses show that the UV/Vis spectrograph generates 50% encircled energies that are just over one pixel in diameter, for the CCD pixel dimensions of 20 x 27 μm.

CCD Detector

The detector CCD measures 1353 by 143 pixels (active imaging area). The pixel size is 20 x 27μm (with the 20 μm being along the 1353 pixel direction). The slit is projected onto the CCD as a rectangle of 1353 by 44 pixels. There are several imaging modes which can be selected (various windows and on-chip binning for the image data). There are sufficient pixels in the dispersion dimension to sample at more than 2.4 times the required spectral resolution. Cooling of the CCD to -20°C prevents dark current from integrating to a significant level after a maximum exposure time of 10 seconds.

The CCD detector is mounted on an adjustable kinematic mount in such a way that it can be moved for the purposes of alignment, both within the image plane (for image positioning) and out of the image plane (for focussing).

UV/VIS Shutter Design

The CCD operates with integration times selectable in the range from 0.1 to 10.0 seconds with a resolution of 0.05 seconds. To minimize smearing as the image is clocked out, the system has a shutter for the slit. A voice-coil activated mechanism is used. The shutter opens or closes within approximately 100 milliseconds, and defaults to the open position when power is removed. The shutter is also used to cut off all light to the CCD, to permit dark current measurements. When energized (held closed), the shutter consumes less than 150 mW.

On-orbit UV/VIS Calibration

For the UV/Vis portion of the instrument, on-orbit spectral calibration will be done by observing artificial sources emanating from the earth, such as discrete lines produced by mercury and sodium street lights. Radiometric calibration is not provided internally.

V. Details of IR Imager Optics Design

The IR Imager, as depicted previously in Figures 2, 6 and 7, consists of three separate telescopes; one for each passband, and each with a separate aperture (23 mm diameter), Zinc Selenide (ZnSe) lens, and InGaAs detector array. Each has a convex-plano lens and narrowband filter. The three channels are mounted so as to maximize the length of the front-end baffles. The f-number is 2.3. The system is telecentric. The boresights of the three channels are parallel and tilted with respect to that of the SMR by 0.405 degrees in the altitude direction. The filter is mounted directly to the IR detector, acting as a window for the detector. The area after the lenses and before the filter/detector contains a shutter mechanism that has the dual role of being the shutter and diffuser/mirror for the calibration source light input.

The impact of the environment on the passband of the filters was considered. The filters must be stabilized and able to operate within specification at a low temperature. To reduce ghosting and increase transmission, the reflectivity of the AR coatings is as low as possible. A long wavelength blocker is the last element before the detector. It is placed as close to the detector as possible.

Lenses

The Zinc Selenide lenses have a diameter of 26 mm, a central thickness of 3 mm and a radius of curvature of 210.4 mm.

Filters

The definitions of the filter passbands are as follows:

Channel	filter center wavelength	bandwidth (FWHM)
1	1.263 μm	10 nm, Gaussian passband
2	1.273 μm	10 nm, Gaussian passband
3	1.520 μm	40 nm, Square passband

The required minimum out-of-band rejection is 10^{-4}.

Geometric Optical Performance

The 50% encircled energy diameters are approximately 10 to 11 μm. This is well within the detector pixel size of 50 x 100 μm.

IR Detectors

Each InGaAs detector has 128 pixels, with 10 pixels masked on each end for a dark reference on each image. The pixel dimensions are 50 x 100 μm (with the 50 μm dimension being the pitch between pixels along the array).

The detectors are composed of two basic parts; the array of photo-diodes and a self-scanning multiplexer. A detector diode acts as a current source, where the current is proportional to the light level plus dark current. Cooling to -40°C prevents dark current from integrating to a significant level after a maximum exposure time of 10 seconds.

Each pixel is read out sequentially through the multiplexer, and if the shutter is closed, the value is the dark current for that pixel. A monitor of the dark current for each scan is provided by the values from the masked pixels.

The detectors are mounted in such a way that they can be moved for the purposes of alignment, both within the image plane (for image positioning) and out of the image plane (for focussing). No other alignment adjustment is required for the IR imager.

Shutter for IR telescopes

A shutter is required for dark current measurement and on-orbit calibration. The design consists of a single door for all three IR bands. It pivots through 45° and is driven by means of a brushless DC limited angle torque motor. This shutter defaults to the open position when power is removed. A shutter control signal is provided by the electronics unit. When energized, this shutter consumes approximately 1.5 W.

On-Orbit Calibration Source

The IR shutter assembly contains a built-in incandescent lamp source which is operated with a constant current source to provide an absolute radiometric calibration signal. There are two lamps for redundancy. Calibration is performed by commanding the shutter closed, then commanding the calibration source ON. The source then illuminates the back side of the shutter and a baffle vane, and reflects light onto the IR detectors. Spectral calibration is not provided internally.

VI. DEVELOPMENT MODEL TEST RESULTS

The optical performance of the DM OSIRIS instrument has been tested by capturing images from various light sources, including views of the sky. The sections below provide a summary of these tests. Most of the imaging tests were performed with cooled detectors. The tests were done at Routes Inc.

A special test enclosure was built to provide a clean and dry environment for the OSIRIS instrument during testing. This test enclosure has provisions for dry gas purging, and a removable port with interchangeable windows for the aperture of the instrument to view the test light sources. Dry ice was used as a heat sink for the detector cooling straps.

UV/Vis spectrograph Optical Performance Tests

Mercury and sodium lamps were used as light sources to provide line spectra. The preliminary test results using these line spectra sources indicate that the actual instrument wavelength coverage is from 273 to 819 nm, based on straight line fits to map the CCD pixel columns to wavelength, (fits provided by Dr. R. King of the University of Calgary). This meets the wavelength range requirement.

Figure 10 shows a plot of the mercury lamp spectrum captured by the spectrograph. Of particular interest is the line doublet at 577 and 579 nm. This doublet with a 2 nm separation is easily resolved by the OSIRIS spectrograph, as shown in detail in Figure 11. Therefore, the requirement of 2 nm spectral resolution above 450 nm is shown to be satisfied.

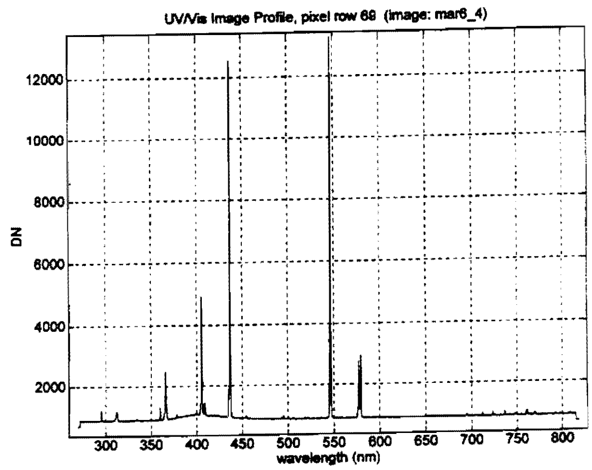

Figure 10. Profile of CCD Image for Mercury Lamp Spectrum

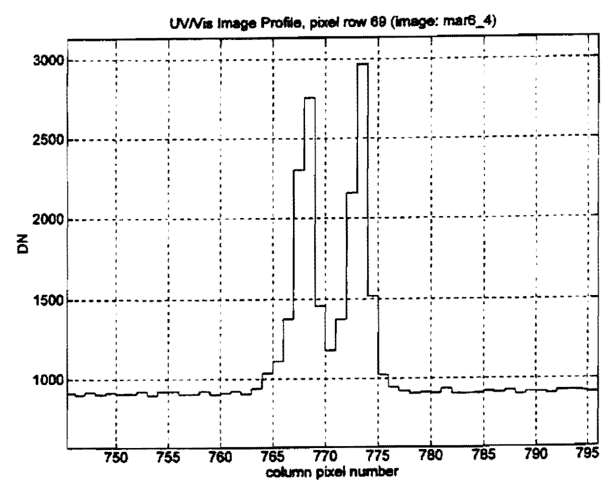

Figure 11. Detail of CCD Image Profile -- 577/579 nm Lines of Mercury Spectrum

A HeNe laser (633 nm) was used as a point source to generate a spot on the CCD spectral image. This spot image is illustrated as a 3D mesh plot in Figure 12. Most of the energy falls within the centre two pixels in the spectral direction. This indicates that to resolve two monochromatic lines they must have their centers separated by at least three pixels. Three pixels on the CCD is roughly 1 nm. This data is therefore a good indication that close to 1 nm resolution has been achieved.

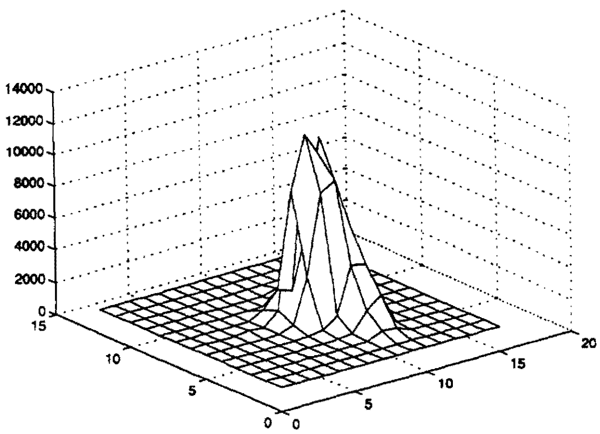

Figure 12. 3D Mesh Plot of Spot Image on CCD from HeNe Laser Point Source

At the request of Dr. Wayne Evans (an OSIRIS science team member from Trent University, Peterborough, Ontario), his research assistant Greg Marshall performed optical tests to evaluate the extent of spectral cross-talk present in the OSIRIS spectrograph, and thereby obtain one indicator of the extent of the spectrograph internal stray light. Spectral cross-talk refers to the amount of dispersed light of a specific wavelength that scatters within the spectrograph and shows up as scattered light on portions of the CCD that should correspond to dispersed light with other wavelengths. The test used the light from a Quartz Halogen lamp, transmitted through sharp cut-off filters (which pass long wavelengths only) and reflected off a diffuse screen (smoked with Magnesium Oxide) into the spectrograph aperture. Figures 13 and 14 show the profile of a CCD image for a cut-off filter at 665 nm. This data does not show any significant cross-talk scattered light (above the detector noise floor) and thus is an excellent indication that the internal scattered light requirements have been met, and that internally scattered light resulting in spectral contamination does not appear to be a problem.

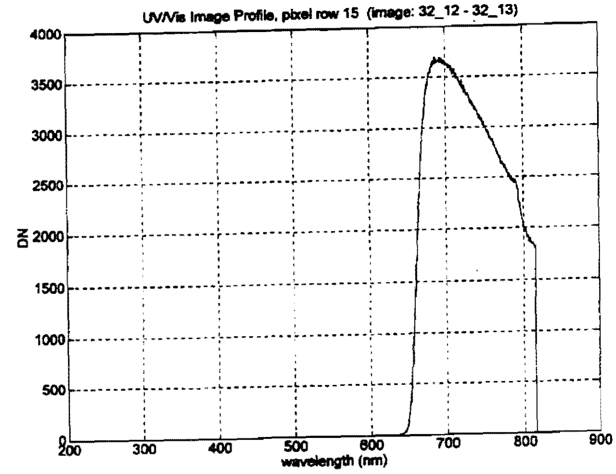

Figure 13. Profile of CCD Image from Specral Cross-Talk Test

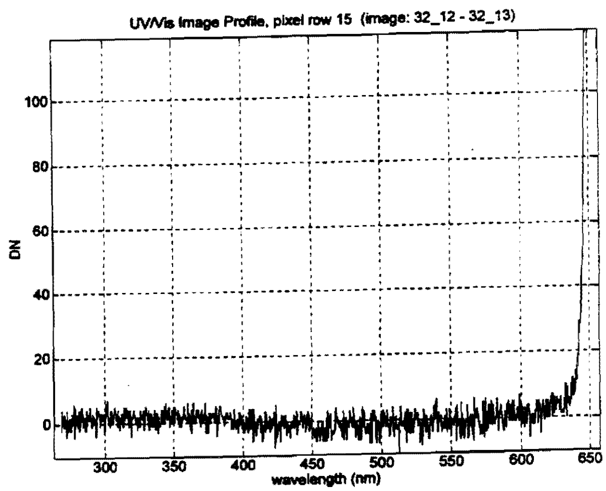

Figure 14. Detail of Profile of CCD Image from Spectral Cross-Talk Test

IR imager Optical Performance Tests

A Quartz Halogen lamp and pin-hole were used to generate a broadband point source of light for the IR imager. After alignment, the spot image captured by the detector showed an illumination of one pixel plus small shoulders on the two adjacent pixels, as shown in Figure 15. This is consistent with the theoretical spot size of 1.5 pixels for the point source used. Therefore, this indicates that the spatial resolution requirement will be met.

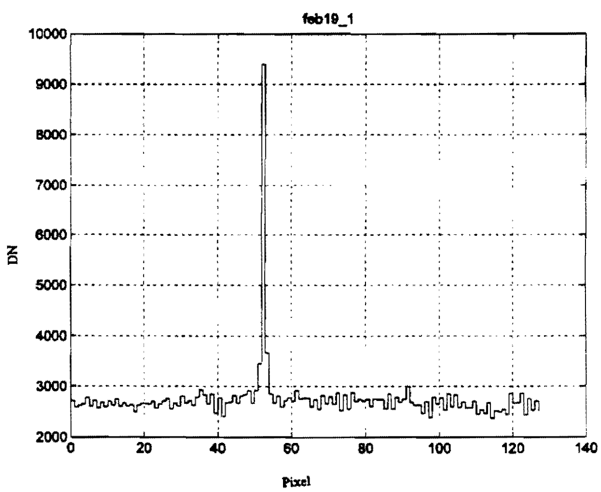

Figure 15 IR Detector Readout for Quartz Halogen Point Source

Sky Image Tests

The DM OSIRIS was used to acquire images of the sky. There were three reasons for capturing the sky images:

a. Sky imaging was a good way to confirm the systems level integration and operation of the DM instrument and its Ground Support Equipment (GSE);

b. The zenith sky serves as a wideband and well characterized light source, for evaluating the optical performance of the DM OSIRIS (eg. spectral resolution, spectral cross-talk, radiometric sensitivity);

c. The zenith sky at twilight as viewed from the ground is in some respects representative of the view of the earth's limb to obtained in orbit by the FM OSIRIS instrument, and so gives an early indication of the data that is expected to be obtained in flight.

The sky was viewed from a roof hatch in a stair well inside the Routes Inc. building. This provided an unobstructed view of the sky centred on approximately 9 degrees South-East of the zenith. Images of the blue sky were acquired at midday, and throughout the dusk twilight period.

Figure 16 is an example of a UV/Vis spectrograph image of the zenith sky, taken on March 30 '96 at the time of local sunset. A profile of the spectrum taken through the centre of this image is shown in Figure 17. This spectral image shows a number of features that indicate that the OSIRIS spectrograph will provide the required scientific data in flight. It does not completely prove that the specifications have been met but it does provide confidence that the desired scientific results can be obtained from the spectrograph. No faults are evident in the acquired data and the overall data quality is excellent.

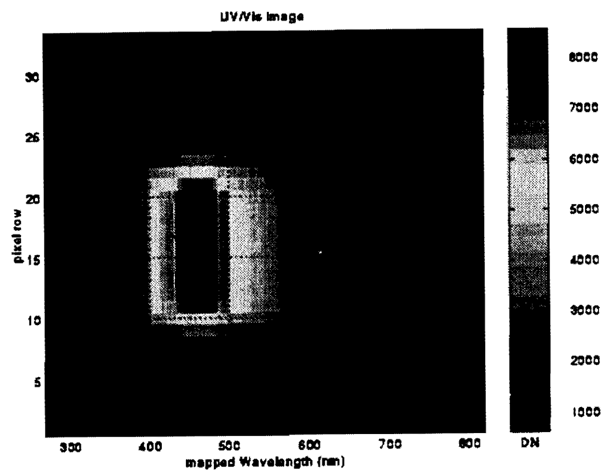

Figure 16 CCD Image of Zenith Sky at Twilight

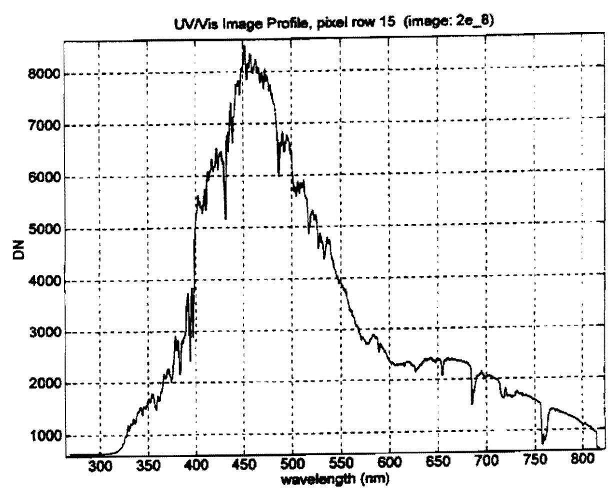

Figure 17 Spectrum of Zenith Sky at Twilight from CCD Image

The following are some observations from the data shown in Figure 17:

a. Ozone absorption can be clearly seen in the 280 to 330 nm region. Below 330 nm the spectrum starts to lose intensity at a higher rate and has an intensity very close to zero for wavelengths shorter than 300 nm; this is as expected.

b. There are clearly defined Fraunhoffer lines, particularly the deep lines at around 430 and 485 nm, as expected.

c. There is visible ozone absorption in the 500 to 700 nm region. This is indicated by the shallow curve in the spectrum through this region. The absorption band there is weaker than the 280 to 330 nm band so the signal is not completely attenuated. Other twilight pictures (specifically ones taken when the horizon was being viewed instead of the zenith) show a deeper absorption feature. This gives confidence in the ability of OSIRIS to obtain ozone results from this wavelength region.

d. There also exist two visible molecular oxygen absorption features in the spectrum around 687 and 762 nm. It once again gives confidence that two branches, the separation in the features, can be seen in each of these absorption bands. Also seen sandwiched in between these two oxygen absorption bands is a water absorption feature.

e. With respect to internally scattered light: the lack of signal in the very shortest wavelengths in the sky tests indicates that spectral cross-talk is minimal, since there should be no signal there.

VII. CONCLUSIONS

The DM OSIRIS instrument has been successfully integrated and performance tested. The analysis of image data derived from various test sources and sky viewing has shown that the DM OSIRIS optical performance is excellent. Indications are that the spectral and spatial resolution of the UV/VIS spectrograph and spatial resolution of the IR imager are within specification. The level of internal scattering is low. Particularly noteworthy is that the optical performance is good in spite of several known deficiencies of the as-tested DM instrument versus the FM to be built, namely:

- Grating aspherization error: The aspherized grating currently installed in the DM instrument was manufactured with an estimated overaspherization of 18%. This was compensated for somewhat in the DM, using camera mirror alignment adjustments.

- General use of grit-blasted aluminum with black anodize, instead of high-performance optical black coatings for baffles, walls and vanes -- the FM design includes the use of Martin Black and EAS Orlando Black coatings for a number of critical surfaces;

- Slit plate without a high performance optical black coating, such as EAS Orlando Black;

- Missing baffles/vanes: the DM UV/Vis spectrograph does not have the inner vanes specified for the FM design in place.

Routes Inc. is now building the OSIRIS flight model. It will undergo extensive performance and environmental tests.

The Odin aeronomy science team is now refining their models, analysis techniques and instrument observation plans to take advantage of the data to be generated by OSIRIS once the mission begins. OSIRIS is expected to provide significant new results and contribute to the understanding of the earth's upper atmosphere and, in particular ozone depletion.

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AUTHOR BIOGRAPHIES

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Gabriel Warshaw received a Bachelor of Science in Mechanical Engineering from the Massachusetts Institute of Technology, Cambridge, Massachusetts, in 1981. He received his Masters and Ph.D in Electrical Engineering from the Systems and Computer Engineering Department of Carleton University, Ottawa, Ontario, in 1990 and 1994 respectively. His doctoral research topic was the adaptive control of robotic manipulators. Dr. Warshaw has been with Routes Incorporated since 1994, and is currently Mechanical, Thermal and Optics Manager for the OSIRIS project. Previously, he worked for CAL Corporation on a range of space hardware projects (including the Canadian Mobile Servicing System for the space station program, the Viking space science satellite ultraviolet imaging cameras, and the High Purity Germanium micro-gravity materials processing furnace) in the capacities of technical and project manager, and systems engineer. Dr. Warshaw has authored 10 papers in the fields of robotics and materials science. He is a member of the IEEE.

Donna-Lee Desaulniers

Donna-Lee Desaulniers is a graduate of McGill University (B Sc.in Physics) and Queen's University (M. Sc. in Electrical Engineering). Her masters thesis was in the field of imaging speckle interferometry. From 1977 to 1981, she was a Defence Scientist at the Defence Research Establishment Ottawa (DREO), involved in research in optical signal processing. During her time at DREO, she participated in the SeaSat project. From 1981 to 1985, she was a Research Analyst at MacDonald Dettwiler & Associates in Richmond, B.C., working on various image processing projects. In 1985 she joined CAL Corporation as a Senior Optical Engineer. She was subsequently the lead optical engineer on several space optics projects. In particular, she was the lead optical engineer at CAL Corporation for the WINDII Project; Canada's contribution to the UARS Observatory. Since 1991, she has been a consultant in space optics. Her contribution to OSIRIS has been mainly in optical system engineering and baffle design. Ms. Desaulniers is a member of SPIE and O.C.A.

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Mr. Degenstein graduated from the University of Saskatchewan with a B.Sc. in Computer Science, and a B.E. in Engineering Physics. He is currently completing his Ph.D in Engineering Physics at the University of Saskatchewan. This program has included a two year on-site stay with Routes Inc., the prime contractor for OSIRIS, where he has provided expert liaison between the Odin/OSIRIS Aeronomy Science Team and Routes Inc. For his Ph.D research, Mr. Degenstein is developing advanced tomographic algorithms that will be used to recover two dimensional mesospheric ozone concentration profiles from data collected with the infrared imager component of OSIRIS.