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SHIMMER ON STS-112: DEVELOPMENT AND PROOF-OF-CONCEPT FLIGHT

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ABSTRACT

The Spatial Heterodyne Imager for Mesospheric Radicals (SHIMMER), which is based on a new interferometric technique called Spatial Heterodyne Spectroscopy (SHS), flew on the Space Shuttle Atlantis mission STS-112 in October 2002. SHS has the advantages of high throughput, high spectral resolution, small size, low mass, all in a rugged instrument with no moving optical components. The SHS proof-of-principal flight successfully demonstrated the suitability of SHS for spaceflight applications where high spectral resolution measurements over a relatively narrow spectral band are required. In addition, the highest spectral resolution measurement of middle atmospheric hydroxyl (OH) solar resonance fluorescence ever achieved was made by SHIMMER during this mission.

INTRODUCTION

The Spatial Heterodyne Imager for MEsospheric Radicals (SHIMMER), designed specifically for flight on the Space Shuttle middeck[1], is based on a newly developed interferometric technique called Spatial Heterodyne Spectroscopy[2,3] (SHS) developed by Roesler and Harlander at the University of Wisconsin and St. Cloud St. University, respectively. The SHS technique is similar to a Michelson interferometer or Fourier transform spectrometer (FTS), with the mirrors in the interferometer arms replaced by fixed, tilted gratings equidistant from the beamsplitter. Diffraction at the gratings results in a wavenumber-dependent tilt of the wavefronts recombining at the beamsplitter, and interference of the tilted wavefronts creates Fizeau fringes at the instrument's charge-coupled device (CCD) detector. The Fourier transform of the interferogram produced at the CCD yields the incident spectrum. When viewing the earth's limb from space, the scene can be imaged on the gratings and the gratings imaged on the CCD, with the dispersion plane parallel to the horizon. Using this technique, limb scanning can be avoided since the detector simultaneously records interferograms in each horizontal row of the CCD, corresponding to discrete altitudes in the range subtended by the field-of-view of the instrument.

Under the sponsorship of the DoD Space Test Program, SHIMMER flew on the Space Shuttle Atlantis mission STS-112 in October 2002. The 500 mm focal-length telescope (see Figure 1) was designed to image the earth's limb, over the altitude range of approximately 30 – 100 km, on the gratings. Relay optics focus the fringe localization plane at the gratings onto a UV-sensitive CCD. The CCD rows are binned on-chip resulting in thirty two 1024-element interferograms, each with approximately 2 km altitude resolution and 60 milli-Angstrom spectral resolution over the 3 nm ultraviolet passband 307 – 310 nm. This passband was chosen because it includes solar resonance flourescence from the (0,0) band of hydroxyl (OH).

The primary goal of the instrument development and flight was to assess the suitability of SHS instruments for spaceflight and to determine the performance of SHIMMER by measuring high spectral resolution solar spectra and the much dimmer superimposed ultraviolet spectrum emitted by OH molecules in the 30 – 100 km altitude range of the atmosphere. OH is one of the key radicals in middle atmospheric chemistry. It is highly reactive, historically one of the least measured atmospheric constituents, and is critical to ozone chemistry throughout the atmosphere, particularly above 50 km where it participates in the only known ozone-destroying chemical process. Its observation above 65 km can also provide an indirect measure of water vapor, which photodissociates to produce OH. Its measurement is a rigorous test of any hyperspectral imaging technology because retrieval of the OH radiance profile, entailing the removal of the bright and spectrally complex ozone-attenuated Rayleigh-scattered solar background, demands highly accurate knowledge of the instrumental line shape function, wavelength calibration, radiometric calibration, and instrumental contributions to the signal and noise.

The first global OH observations were acquired by NRL during flights of its Middle Atmosphere High Resolution Spectrograph Investigation[4] (MAHRSI) spectrometer on STS-66 and STS-85. The size and weight of conventional grating spectrometers like MAHRSI, however, are not suitable for future space missions. In contrast, the practical advantages of SHS for future space shuttle, satellite, and interplanetary

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flights are dramatic: the desktop printer-sized SHIMMER is approximately one-seventh the weight and volume of the MAHRSI spectrometer, yet has higher spectral resolution, is much more sensitive, and has no moving optical components.

A next-generation version of SHIMMER currently being developed at NRL for an upcoming satellite mission continues the trend towards even smaller and lighter SHS instruments[5].

In addition to SHS's application for basic scientific research missions, its potential military applications include new remote sensing and surveillance capabilities, and contributions to the extension of the Navy Operational Global Atmospheric Prediction Model (NOGAPS), which requires high vertical resolution atmospheric data for assimilation and verification.

PROPERTIES OF SHS INSTRUMENTS

Spatial heterodyne spectroscopy is particularly well suited to UV applications that require high resolving power and high throughput over a relatively narrow spectral band. In general, however, an SHS can be tuned to work in any spectral region with control over the tradeoff between spectral resolution and bandwidth. SHS is similar to Fourier transform spectroscopy (FTS), with three primary differences. First, SHS effectively heterodynes the interferogram about a selected reference wavelength, resulting in easily measurable low spatial frequency fringes produced by wavelengths in the passband of the instrument. Second, the SHS has no moving parts, even in the field-widened mode, and therefore is much smaller, lighter, and less complex mechanically than FTS instruments making similar measurements. Third, SHS uses an imaging detector to record a fringe pattern localized inside the interferometer; consequently phase errors resulting from optical defects can be easily corrected in the data reduction. Compared with more conventional grating spectrometers such as MAHRSI, SHS achieves orders of magnitude higher throughput at similar or higher spectral resolution in a much smaller package. As is the case with FTS instruments, zero, one, or two dimensions of spatial information can be obtained by appropriate choice of the optics prior to the interferometer.

The basic SHS concept is depicted in the Figure 1, where the image of an extended scene is collimated to form a beam incident on the beamsplitter. Diffraction gratings in each arm return the light to the beam splitter. Lenses L_2 and L_3 in the exit beam image the gratings onto a position sensitive detector. The gratings are positioned so that they are the same distance from the beamsplitter along the optical axis and are set at an angle θ_L such that rays of a certain wavelength incident on the gratings parallel to the optical axis retroreflect, returning parallel to the optical axis. At this wavelength, called the Littrow wavelength the recombining wavefronts exit the interferometer completely in phase with each other combining constructively at all points across the aperture.

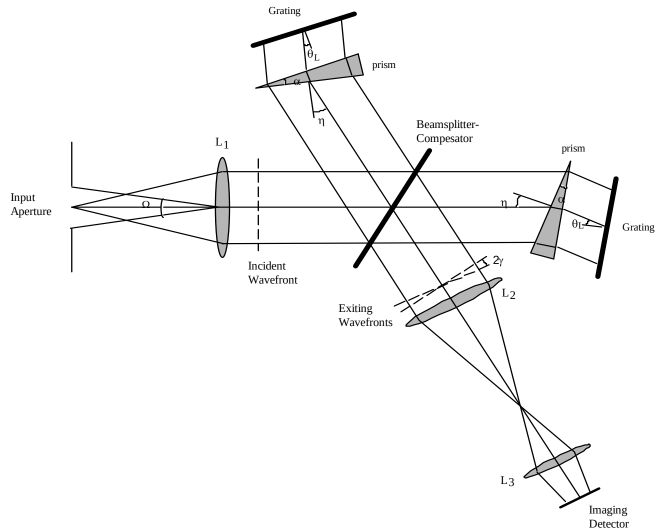

Figure 1. Conceptual diagram of a field-widened spatial heterodyne spectrometer.

For a wavelength slightly different from the Littrow wavelength, the diffracted beams return at a small angle to the optical axis, and the recombining wavefronts are crossed as depicted in the figure. In this case the phase difference between the two wavefronts changes from a maximum at one edge, to zero in the middle, and back to maximum at the other edge, resulting in a Fizeau fringe pattern whose spatial frequency is related to the angle at which the wavefronts cross. The fringe localization plane is at the gratings, and therefore the gratings are imaged directly on the detector to produce an interferogram that is then Fourier transformed to recover the input spectrum.

The non-aliased passband of the SHS is limited by the number of samples across the interferogram. If the detector has N pixels in the dispersion plane of the gratings (the plane of figure 1), N/2 non-aliased spectral resolution elements can be measured. In order to achieve this maximum bandwidth, the optics that image the gratings on the detector must adequately reproduce *N/2* fringes at the detector.

The field-of-view can be greatly increased through the use of the field widening prisms shown in Figure 1. The fixed prisms serve to rotate the images of the gratings (from a geometrical optics point of view) so that they appear to be normal to the optical axis, and the field-of-view at the gratings can be increased by an order of magnitude above the non-field-widened case. Such a large field-of-view gives SHS an enormous throughput advantage over grating spectrometers that require a narrow slit to achieve high resolving power.

THE SHIMMER-MIDDECK INSTRUMENT

Measurement Objectives

The SHIMMER instrument was specifically designed to measure OH solar resonance fluorescence while viewing the limb from low Earth orbit. As discussed above, this measurement is a rigorous test of any hyperspectral imaging technology because retrieval of the OH radiance profile requires highly accurate knowledge of the instrument's performance characteristics. In particular, the retrieval of OH spectra from limb observations entails identification and removal of the very bright and spectrally complex ozone-attenuated Rayleigh scattered solar background.

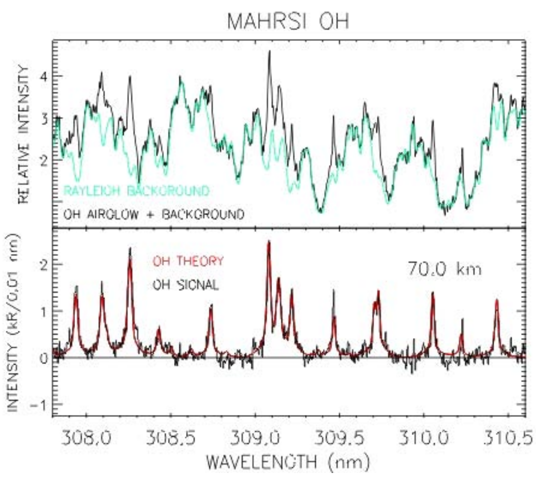

Figure 2. MAHRSI detection of OH at 70-km tangent height.

The problem is illustrated in Figure 2, where the top panel shows a MAHRSI-measured OH emission spectrum at 70 km tangent height and the underlying Rayleigh scattered solar spectrum. This is a tangent altitude for which OH is prominent against the Rayleigh scattered solar background. The lower panel shows the OH signal extracted by subtracting the Rayleigh background from the raw spectrum. Since, in effect, the curve fitting algorithm subtracts two large numbers from each other at every wavelength, leaving the residual OH spectrum, any uncharacterized and uncorrected instrumental contributions to the spectral shape will result in large errors in the retrieved OH intensity, particularly for observations of lower tangent heights where the background-to-signal ratio is large. It is the combination of high spectral resolution over an extended bandwidth covering many OH(0,0) rotational features that is essential to the accurate identification of the background spectrum contribution.

Design Specifications

The optical layout is shown schematically in Figure 3, and the design specifications for the SHIMMER instrument are summarized in Table 1. The spectral resolution, passband, field-of-view, and responsivity requirements of SHIMMER were determined by the previous successful OH measurements by the MAHRSI instrument.

The 500 mm focal length refractive telescope focuses the limb on the gratings. The telescope aperture limits the range of angles incident on the gratings while also imaging the scene at infinity on the grating localization plane. This property is used in SHIMMER to image altitude along the columns of the CCD while producing 1-D interferograms along the rows while limb viewing from space. Telescope aberrations limit the altitude resolution on the limb to 0.87 km. In practice, however, rows are co-added on the chip to give a 2.2 km (4.3 arc min) altitude resolution.

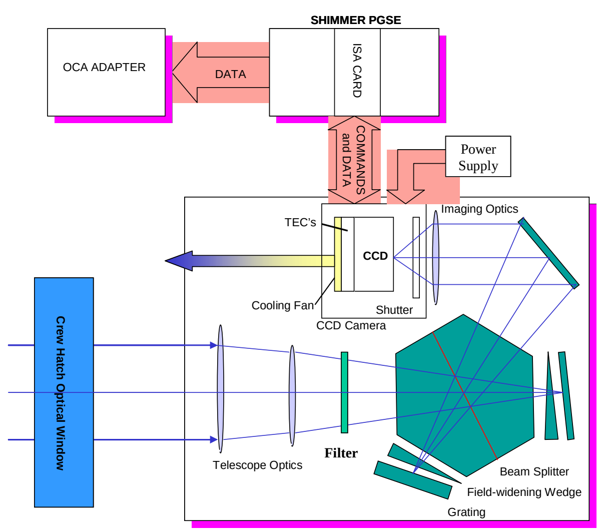

Figure 3. SHIMMER block diagram and optical layout.

Out-of-band rejection is achieved by 6.6 cm diameter interference filter between the telescope and interferometer and narrowband multilayer dielectric coatings on the three fold mirrors in the system. All transmitting elements have been AR coated for 308 nm. The interference filter has a 2.3 nm FWHM pass band centered at 308.9 nm. The interferometer uses an anti-reflection (AR) coated, non-polarizing hexagonal beamsplitter, a pair of 13.02° apex angle field-widening prisms, and a pair of 1200 l/mm, 75% efficiency gratings. A doublet field lens and a multi-element relay lens focus the plane of the gratings, which is the fringe localization plane, on the CCD. The camera used in SHIMMER utilizes a thinned back-illuminated UV anti-reflection coated CCD manufactured by SITE, Inc with approximately 58% quantum efficiency at 308 nm. The CCD format is 1024 X 1024 with 24 micron square pixels.

Table 1. SHIMMER Design Specifications

System	**Interference filter**	2.3 nm FWHM centered at 308.9 nm 307.0 nm - 310.5 nm full width
	Entrance optics	500 mm fl telescope
	Exit optics	7 element relay system
	Detector	1024 X 1024 24 μm CCD
	Gratings	
	Clear aperture	20 x 20 mm
	Groove density	1200 l/mm
	Littrow angle	10.7°
	Littrow wavelength	307.0 nm
	Field-widening prisms	
	Clear aperture	22 x 22 mm
	Wedge angle	13.02°
	Incident angle	8.73°
	Exit angle	10.7°
	Beamsplitter	
	Clear aperture	28 x 28 mm
	Field of view	
	At gratings	10°
	On sky	2.3 x 2.3°
Performance	**Resolving power**	53,500
	Spectral resolution	0.0058 nm
	Non-aliased spectral range	2.95 nm
	Achieved spectral range	Filter limited
	Sky imaging	1.7 arc min
Resources	**Mass**	22 Kg
	Volume	52 x 42 x 23 cm^3
	Power	27 W
	CCD Readout	72kB / 4 sec
	Image Rate	750 images / orbit
	Data Rate	55Mbytes / orbit

The camera also includes a shutter mechanism, thermoelectric coolers, cooling fins, and fans for convectively dispelling heat into the cabin air.

The mechanical design for SHIMMER was driven by 5 requirements: 1) locate and support to interferometric precision the optical elements of the interferometer in a manner suitable for Space Shuttle launch and landing loads, 2) locate and fasten the optical components shown in Figure 3 to assure accurate alignment, 3) constrain the mechanical envelope of the instrument to the interior dimensions of the Space Shuttle middeck lockers, 4) provide a simple, robust mating assembly to locate and fasten the instrument to the Space Shuttle crewhatch, and 5) meet all manned-flight program safety requirements.

The interferometric elements, i.e. the beamsplitter, prisms, and gratings, are mounted in a Vascomax steel structure shown in Figure 4. The beamsplitter is positioned below the triangular cap visible at the top. The design allows very precise and stable positioning of the prisms and gratings relative to the beamsplitter. The prism holders are attached to the grating holders, and a spring-loaded turret assembly holds the grating holders tightly to a three-point kinematic mount integral to the cell structure. An interior chamber encloses the CCD Camera and is walled off using light-tight bulkheads and baffle tubes.

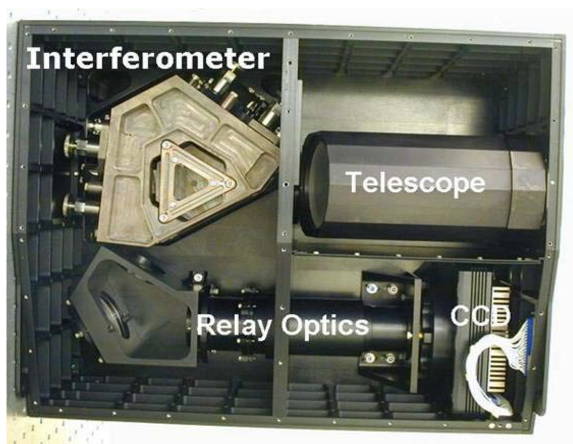

Figure 4. SHIMMER component layout.

<u>Characterization and Calibration</u>
An extensive series of laboratory tests were performed pre-flight to verify that SHIMMER met design expectations. The most basic test was to observe the interferogram produced by a monochromatic source within the instrument's spectral filter passband (T > 35% from 307.8 nm to 309.6 nm). A Zn pen-ray lamp with a single bright emission at 307.6 nm was used for optimization and testing. The spectral width of the emission is not resolved by the interferometer. The fringe pattern recorded by SHIMMER using the Zn pen-ray source is shown in Figure 5.

Note that all spectral information is in the horizontal dimension, and the vertical dimension is exclusively an image of the vertical intensity distribution of the source. When applied to the OH limb-viewing problem, the vertical dimension will be aligned perpendicular to the limb so that each row of the CCD will record the spectrum observed at distinct viewing angles corresponding to distinct tangent heights.

The interferogram is corrected for dark field and nonuniformity, then Fourier transformed to derive the instrument function, i.e. the response of the instrument to an unresolved monochromatic source.

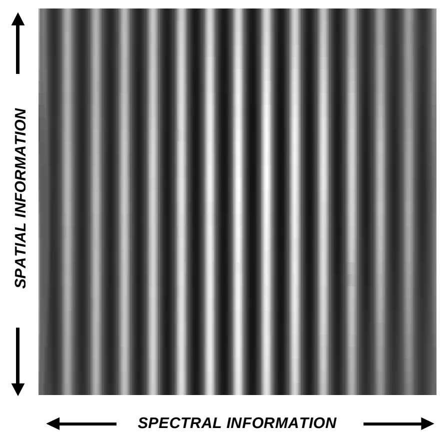

Figure 5. Interferogram recorded in the laboratory.

Polychromatic sources including a microwave-excited OH lamp, a MnNe hollow cathode lamp, a Deuterium lamp, and a calibrated Labsphere, Inc. integrating sphere fed by halogen lamps, were used to verify that the spectral resolution (0.0059 nm), bandwidth (3.02 nm), and field-of-view (2.3 deg. X 2.3 deg. on the sky, 10 deg. at the gratings) all met design specifications. The optical transmission $\overline{T}_{opt} = 0.18$, and the throughput $\overline{T}_{opt}\overline{T}_{filt}A\Omega = 4.5 \times 10^{-3}$ cm^2-sr were as expected. The spectral responsivity, calculated by dividing the instrument's spectral response to the integrating sphere by the calibrated sphere's spectral radiance curve, was lower than expected. Although the total number of electrons collected at the CCD was as predicted with the integrating sphere irradiance, the contrast of interference fringes was less than optimum. The situation was largely remedied by installing a baffle in front of the telescope that limited the aperture in the dimension parallel to the dispersion plane. This reduced the throughput by a factor of two, but ultimately increased the signal-to-noise ratio of the measurements.

STS-112 MISSION OPERATIONS

Operations Overview

As described above, SHIMMER was designed to conduct a space flight proof-of principal test of the application of the SHS technique to remote sensing of the middle atmosphere. The mission was to observe the vertical profile of OH solar resonance fluorescence by imaging the Earth's sun-illuminated horizon through the UV transmitting optical window in the Space Shuttle Orbiter crewhatch.

The primary mission of the STS-112 flight was to install a major truss section in the International Space Station (ISS). SHIMMER, as a secondary payload, was allotted a total of three orbits for observations during the mission, a checkout period prior to ISS docking, and two nominal operations periods following ISS un-docking. During each period, the crew maneuvered the orbiter to an attitude that placed the SHIMMER line-of-sight tangent to the limb at a predetermined optimal altitude while placing the window out of the sun's direct illumination. The instrument was attached to the Orbiter crewhatch using a bracket assembly that utilized threaded studs located around the optical window.

The bracket includes a hinged channel that supports the instrument and a power converter module. Projected on the limb, the 2.3 degree instrument field of view had an nominal upper boundary near 100 km altitude and a lower boundary near 30 km altitude. At a wavelength of 308nm, the vertical radiance profile of Rayleigh scattered sunlight has a well-defined maximum at about 41 km altitude, and the flight crew confirmed the pointing of the instrument by observing the placement of this radiance peak in the field-of-view displayed on the PGSC laptop computer.

The display (see Figure 6) shows an altitude intensity plot from each of the two edges of the field-of-view parallel to the limb. The first panel shows the interferogram imaged on the CCD, and the second and third panel show examples of properly aligned and misaligned fields-of-view. The absolute and relative position of the two 41 km intensity peaks on the screen indicates the orbiter roll and pitch adjustments required to properly point the SHIMMER FOV at the correct tangent point. Once aligned, the crew initiated several sequences of exposures. The data were stored on the PGSC laptop, and then downlinked to an operations control center at Johnson Space Center where the SHIMMER science team analyzed the data and provided feedback to the crew. The purpose and details of each of the observation periods is discussed below.

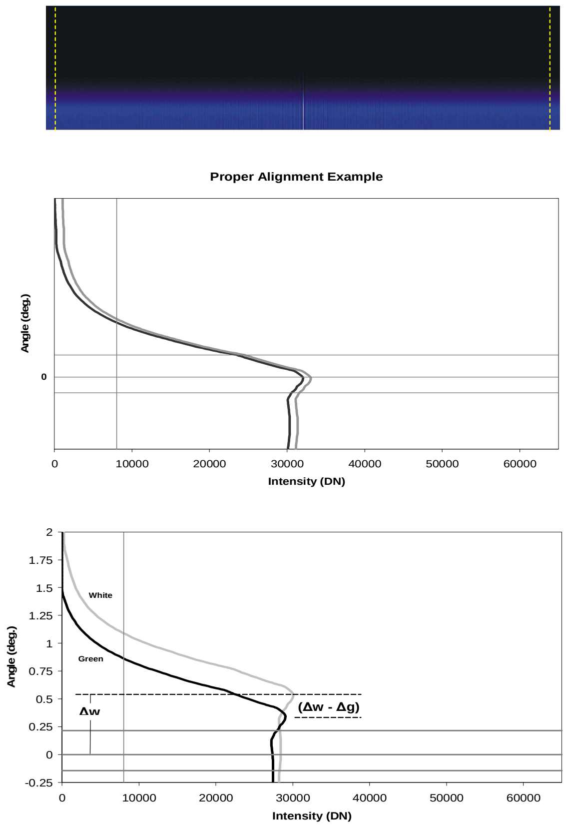

Figure 6. Interferogram recorded and PGSC altitude intensity profile display.

ISS Pre-dock Checkout

After orbit insertion and prior to ISS docking crew and orbiter time were extremely difficult to get, but the flight planners scheduled an approximately one hour period for the critical SHIMMER Checkout observations. The purpose of the Checkout was to 1) verify that the instrument was operating properly, 2) verify that the orbiter attitude could be accurately adjusted to position the SHIMMER FOV, 3) verify that the default 2 second exposure time selected based on pre-flight instrument calibration and predicted limb brightness was optimal for post-ISS undock nominal operations, 4) verify that the instrument did not exhibit any internal scattered light or out-of-FOV light sensitivity problems that would preclude accurately measuring the altitude intensity distribution across the entire altitude range of interest, and 5) to give the SHIMMER team an extended period prior to post-ISS undock operations to analyze the data, trouble shoot potential problems, and in the event of problems, develop corrective procedures. The Checkout also provided an opportunity for the crew to master the logistics of unstowing, installing, activating, data acquisition, deactivation, teardown, and re-stowage of the instrument, as well as practice with the real-time orbiter attitude adjustment procedures.

As a consequence of the short time allocated for Checkout, it was determined pre-flight that a very small set of non-optimal measurements would be made (a total of three full CCD images, 30 binned 1024 X 32 CCD images, and a single darkfield image were acquired). Importantly, there was insufficient time to cool the CCD to its nominal operating temperature of -26 ºC, since the CCD cooldown and warmup each take approximately 15 minutes. The CCD was cooled to -7 ºC, the minimum feasible cooling to guarantee adequate instrument capability to meet Checkout objectives.

The Checkout operation was successful in verifying the proper operation of the instrument and the orbiter capability to point accurately at the altitude region of interest using feedback from the PGSC laptop display. The orbiter was in a –ZLV, +XVV bias attitude prior to fine attitude adjustments, and at an altitude of 194 km. The GMT of the Checkout observations was day 281, 19:28:00, and the tangent point solar zenith angle (the angle between the Earth’s radius vector through the tangent point and the position of the Sun) was approximately 30 degrees. The tangent point latitude, longitude, and local time were 7.3N, 86.2E, and 13:44, respectively and the Beta angle (the angle between the orbit plane and the vector from the sun) was about 150 degrees. In general, OH observations are best when the solar zenith angle is low, i.e. overhead sun, because the OH concentration peaks around local noon. These viewing conditions were good, but the unfortunate ramification of running the CCD at a warm temperature was that the signal-to-noise ratio of the measurements was lower than later post-ISS undock nominal measurements. Nevertheless, the measured altitude intensity distribution and OH resonance florescence spectra (discussed below) clearly demonstrate that the instrument performance met design goals.

ISS Post-dock Operations

The first nominal observation period was GMT day 289, 16:01:00 through day 289, 16:14:00 after the orbiter undocked from the ISS. The orbiter was in a -ZLV, -XVV bias attitude prior to fine attitude adjustment, and at an altitude of about 330 km. Prior to these observations, the crew installed SHIMMER on the side-hatch window and cooled the CCD to its nominal operating temperature of -26 °C. As with all the SHIMMER measurements during the flight, the exact time of observations were determined by flight planners to not interfere with the primary mission, and were not necessarily ideal for measurement of OH underlying the bright Rayleigh scattered solar spectrum. The first three minutes of the orbit were best, but not ideal for observing OH. At this time the solar zenith angle at the tangent point was about 55 degrees. The tangent point latitude, longitude, and local time were 34.9N, 94.2E, and 09:45, respectively, and the beta angle was about 167 degrees.

Upon analysis of the data, it was found that the background intensity profile had changed dramatically since the Checkout period. The altitude intensity distribution, which had the expected shape and intensity in the Checkout data, was now quite different (see Figure 7). In particular, the 41 km intensity peak was not sharply peaked, and the overall dynamic range of intensities over the vertical field-of-view was greatly decreased.

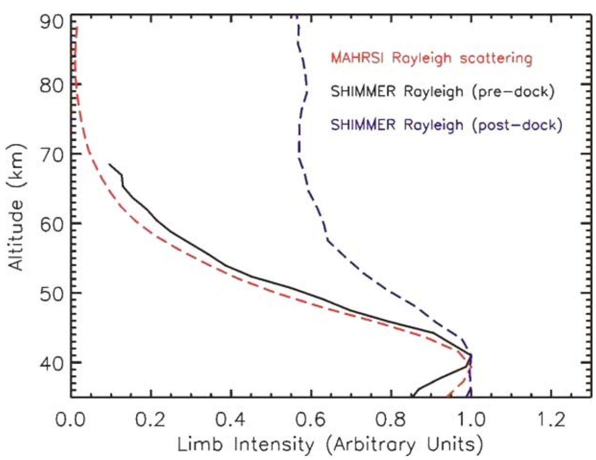

Figure 7. Altitude intensity profiles observed before and after ISS docking.

Our conclusion is that the crew-hatch window (either inside or outside) was somehow contaminated during the ISS docked period between SHIMMER's Checkout and first nominal operations. The cause of the contamination is not known, but the crew of STS-114 (launch date currently under review) is scheduled to observe the side-hatch window for any signs of contamination. We believe the contaminated window acted as a diffuser, degrading the altitude resolution of the measurements and scrambling light coming from different tangent heights and the earth's illuminated disk. The spectra measured by SHIMMER had exactly the right spectral shape (solar spectrum including Fraunhofer structure) indicating that the source of contamination was in the optical path before the interferometer, and very likely before the input aperture of the instrument (no damage to or contamination of the telescope was observed post-flight). The result of the contamination (possibly condensation of water on the inside of the window) was that light from the altitudes producing the brightest OH spectra was scattered into a large range of angles, and hence, we believe, washed out and not measurable. The solar spectrum observed and discussed in the results section below, however, has high signal-to-noise ratio and matches the known solar spectral shape.

Following the daytime portion of the orbit, the orbiter swung around to point SHIMMER's line-of-sight towards the moon to measure a reference solar spectrum uncontaminated by OH emissions. The shape of the solar spectrum reflected from the moon, when scaled to the limb observations and corrected for ozone attenuation, should provide an excellent approximation of the Rayleigh scattered sunlight which can then be subtracted to reveal the distinctive OH spectrum. A diffuser was installed in front of the SHIMMER input aperture to fill the entire field-of-view with moon light. Unfortunately, due to the window contamination, we believe that the incident moon light was almost entirely scattered out of the SHIMMER field-of-view, and hence not measurable. In lieu of the moon measurement, we used a high resolution ground-based solar spectrum convolved with the SHIMMER instrument line shape to estimate the background (see Figure 10 in the results section below). This same high-resolution solar spectrum was also used in the analysis and reduction of the MAHRSI data[4].

The second nominal observation period was GMT day 290, 11:46:00 through day 290, 12:07:00. The orbiter was in a +ZLV, +XVV bias attitude prior to fine attitude adjustment, and at an altitude of 325-334 km. Prior to these observations, the crew installed SHIMMER on the side-hatch window and cooled the CCD to its nominal operating temperature of -26 °C. The three minutes from 11:58:00 – 12:01:00 of the orbit were best for observing OH due to the lighting conditions. At this time, the tangent point latitude, longitude, and local time were 29.3N, 43.8E, and 09:06, respectively. The solar zenith angle at the tangent point was about 57.4 degrees, and the beta angle was about 154.54 degrees. As in the case of the first nominal operations period, it appears that the window was contaminated, and hence OH emissions and sunlight reflected from the moon could not be observed.

In addition to the good altitude intensity distribution and OH resonance florescence spectra measurements acquired during the Checkout period, the high quality spectra of Rayleigh scattered light measured from the Earth's limb during each of the nominal operations periods prove that the instrument performance met design goals.

Overview of Data Analysis Algorithms

Algorithms for correction and optimization of interferograms and for calibration of spectra to scientific units with error estimates were developed in preparation for the flight. Data reduction and analysis entails removing instrumental effects (such as CCD dark field and instrument fixed-pattern nonuniformities), removing noise and charged particle spikes from the interferograms, phase shifting prior to Fourier transforming to maximize signal-to-noise, shifting and stretching spectra to match the wavelength scale of the Fraunhofer structure in the Rayleigh scattered solar background, and ultimately production of calibrated spectra with error estimates.

In order to determine the OH resonance fluorescence radiance present in a limb measurement, a nonlinear least-squares curve fitting algorithm incorporating reference solar background scaling and ozone attenuation is used[4]. The curve fitting process establishes the magnitude of all non-OH components of the measured spectrum, and the OH contribution is the residual remaining after subtraction of these components.

MEASUREMENT RESULTS

Altitude Intensity Profiles

Possibly the most important observation of the mission was made during the Checkout period and is shown in Figure 8. Since SHIMMER images the entire altitude range of interest simultaneously, it is very important that off-axis scattering and internal scattering be minimized to maintain the proper dynamic range of the scene. Over the altitude range shown, the total UV signal measured by SHIMMER varies greatly (brightest at about 41km, and near zero at the top of the field-of view). Due to the low orbit altitude of 194 km during the Checkout period, the SHIMMER field-of-view subtends only about 50 km at the limb, and the triangles show two overlapped profiles, one from 25 – 70 km and the other from 40 – 85 km. The dashed line shows the profile measured by the MAHRSI instrument (obtained under similar solar illumination conditions) which had a very narrow field-of-view directed up and down on the limb using a scanning mirror. The figure demonstrates that SHIMMER succeeded in accurately measuring the altitude intensity profile, and all the profiles match well with the predicted scale height of the Rayleigh scattered solar background.

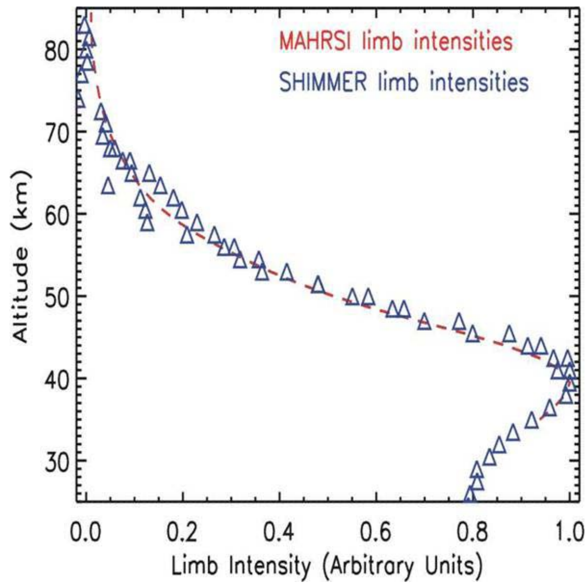

Figure 8. Altitude intensity profile measured during Checkout observation period.

Hydroxyl Spectrum Retrieval

The highest spectral resolution mesospheric OH resonance fluorescence spectra ever measured were also retrieved from the Checkout data (see Figure 9).

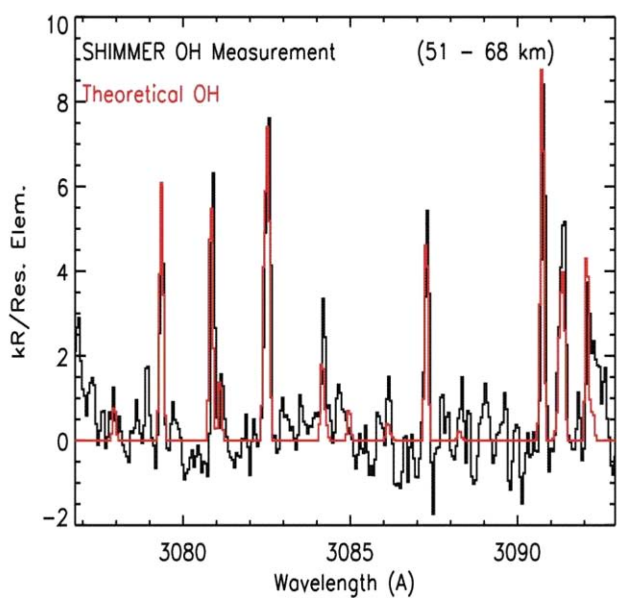

Figure 9. Hydroxyl spectrum (51 – 68 km) measured during Checkout observation.

As discussed above, it was not possible to fully cool the CCD during the Checkout period, and consequently, the signal-to-noise ratio of the retrieved OH spectrum is lower than desired. Also, due to operational constraints, the spectrum shown is the average of only

30 images, each acquired with a 1.2 second exposure time (36 seconds total exposure time). Nonetheless, this retrieval unambiguously demonstrates that SHIMMER is capable of accurately measuring the UV emission from the limb at high spectral resolution and that the OH retrieval algorithms are sufficiently mature to extract the OH spectra superimposed on the very bright and highly structured solar background. Additionally, OH spectra were measured for each of a broad range of tangent point altitudes, and the high vertical resolution mesospheric OH radiance profiles will be presented in a future report.

High Resolution Solar Spectra

Due to the window contamination problem discussed above, it was not possible to measure OH resonance fluorescence spectra during the two nominal operations periods. However, with the CCD fully cooled, the signal-to-noise ratio of measured solar spectra was very high, verifying the spectral resolution and overall performance of the instrument. Figure 10 shows the measured solar spectrum compared with the expected modeled spectrum, confirming the high spectral resolution (0.006 nm), spectral response calibration, and line shape of the instrument on orbit. The modeled spectrum was determined by correcting the ground-based observation of the solar irradiance reported by Kurucz et al.[6] for extinction by OH and ozone, normalizing to an exoatmospheric spectrum, and convolving with the laboratory-measured SHIMMER instrument function.

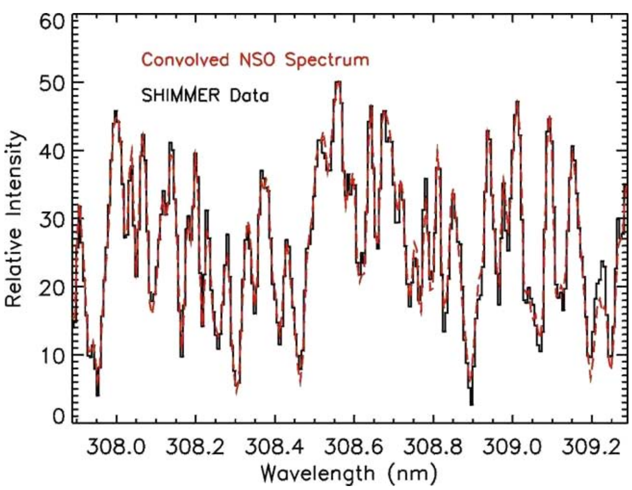

Figure 10. High resolution limb spectrum recorded during nominal operations period.

SUMMARY

The data from the STS-112 mission indicate that SHIMMER met design goals, producing high spectral resolution solar and OH spectra over a broad altitude range without the use of any moving optical components. The mission has provided a successful and invaluable proof-of-concept of the SHS technology in space-based remote sensing.

A next generation version of the SHIMMER instrument is currently being built and tested at NRL in preparation for a full one year DOD Space Test Program satellite mission scheduled for launch in 2006 which is dedicated to measuring global OH density over the altitude range 30-100 km and in the latitude range 55N – 55S. The new instrument includes the first-ever monolithic SHS interferometer which eliminates the complex mechanical fixture that held the interferometer optics in the STS-112 version of the instrument[5]. Results of the proof-of-concept flight of SHIMMER reported here have been invaluable in the ongoing development and operations planning for this upcoming mission.

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