A Hand-held Near Infra-Red Slit Spectrograph for Earth Observations

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ABSTRACT

We describe the optical and mechanical design of a simple hand-held near infra-red spectrograph constructed to produce observations of the spectrum of scrambled light from the Earth from aboard the International Space Station. Observing the Earth in this manner simulates the changing perspective on an extra-solar terrestrial planet observed as a point source by the Terrestrial Planet Finder. A Sensors Unlimited, Inc. SU320-M InGaAs($0.86 - 1.72\mu$m) camera detects the dispersed spectrum and outputs NTSC video to be recorded and also permits frame grabbing. One of the three copies of the instrument is currently aboard the International Space Station. The optical and mechanical design was conceived and executed by graduate and undergraduate students at the University of Virginia.

Keywords: Earthshine, Spectrograph, InGaAs

1. INTRODUCTION

Dr. Gregory Olsen's private flight to the International Space Station (ISS) in 2005 October provided an opportunity for scientific work during his seven day stay. Dr. Olsen suggested that the Instrumentation Laboratory of the Astronomy Department at the University of Virginia devise an experiment for the mission that would take advantage of a Sensors Unlimited SU320-M focal plane array camera. Astronomical studies were a research possibility, however the Earth's atmosphere is largely transparent in the 0.86-1.72μm spectral response range of the focal plane and the entire sky has been surveyed from the ground to significant depth ($\sim$ 15 mag / 1milliJansky) with good spatial resolution ($\sim$3 arcsec) at near-infrared wavelengths. Opportunities for original near-infrared astronomical research from the ISS are thus quite limited, particularly if restricted to hand-held equipment. One astronomical object, uniquely accessible from space and infrequently imaged by astronomers is the Earth itself. At present, the infrared spectrum of the Earth is of great interest due to its applicability in interpreting the spectra of yet-to-be-discovered terrestrial-mass planets orbiting nearby stars. Although an armada of satellites orbit the Earth carrying extensive spectral analysis capabababilites, few can produce integrated light spectra that mimic the view of an extraterrestrial"Earth" rotating in the gaze of a powerful space-based interferometer/spectrograph such as TPF-I. To date some of the best representations of the integrated light spectral signature of Earth come from Earth-based observations of the earthshine illuminated Moon at crescent phase(Woolf et al.(2002),[1] Tinetti et al.(2006)[2]).

The ISS provides a vantage point approximately 350 kilometers above the Earth's surface. Although not a hemispheric view of the Earth, the instantaneous view from the ISS typically encompasses a mixture of terrains and cloud types while orbital motion continuously changes the mix. The 0.86-1.72um spectral region is rich in "biomarkers"(Des Marais et al.(2002)[3]) containing molecular features of water/ice, methane, oxygen, carbon dioxide, and carbon monoxide. Given the natural match between potential Earth spectroscopic science and the capabilities of a hand-held spectrograph on the ISS the Virginia Astronomical Instrumentation Laboratory embarked on a project to supply Dr. Olsen with a hand-held near infrared spectrograph that could couple trivially to an SU320-M infrared camera. The small scope of the project lent itself to undergradate and graduate student involvement and, from the beginning, the project was pursued by a mix of faculty/undergraduate/graduate

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students. As with any space project, mass and volume were primary constraints. Dr. Olsen requested that the mass of the spectrograph not exceed 1500 grams (independent of the camera) and that the instrument fit in a volume 30x20x15cm.

This paper describes the design, fabrication, and performance of three copies of a spectrograph with a mass of 547 grams which disperses light between 0.86 and 1.72μm onto a 320x240 InGaAs focal plane. One of these copies was flown to the ISS aboard Progress M-54 (ISS 19P) in advance of Dr. Olsen's visit to the Space Station between 4 and 11 October 2005. The spectrograph was designed to both scramble the light from a 25° cone onto the entrance slit as well as reimage a scene at infinity onto the slit enabling spatially resolved long slit spectroscopy. All the optics were ordered from commercial catalogs. Most of the machining of custom parts was done in the Astronomy Department at the University of Virginia.

2. SCIENTIFIC MOTIVATIONS AND DESIGN DRIVERS

The SU320-M standard InGaAs 320x240 focal plane provided the basic constraint for defining the science program. The InGaAs array is sensitive to light with wavelengths from 0.86 to 1.72μm. Conveniently, this sensitivity spans one octave of wavelength, making first-order grating spectroscopy a natural implementation. Furthermore, analysis of terrestrial spectra show the 0.86μm to 1.72μm spetrum to be rich in molecular signatures with methane bands, a biomarker of keen interest, at 0.89μm and 1.69μm spanning the entire range. Most of the molecular features in this spectral range are well resolved for spectral resolutions R>100. These facts combine to suggest a natural configuration which disperses a first-order spectrum spanning the wavelength response of the InGaAs camera across the entire array. Given 320 pixels in the dispersion direction, this configuration leads to a spectral resolving power of 240.

With the spectral properties of the instrument naturally defined, the spatial properties derive from the desire to observe the spectrum of scrambled/integrated Earth light. Although a small aperture/slit would prove sufficient for this task, the availability of 240 pixels on the area array perpendicular to the dispersion direction motivated the inclusion of a "long-slit" in the configuration. Dispersing a slit spanning 100 pixels provided the opportunity to:

1. have redundant wavelength coverage at many spatial positions on the array permitting both the replacement of data falling on bad pixels as well as summing of spectra from different slit positions to improve signal-to-noise.
2. enable a second mode of operation in which the front-end diffuser is replaced by a lens which reimages the scene onto the slit permitting spatially resolved long-slit spectroscopy of a swath of the Earth's surface as it sweeps by below.

Three copies of the spectrograph had to be built quickly (one for flight, one for space qualification analysis, and one spare). These units had to be lightweight, strong, and compact, with accurate and repeatable positioning of all optical components in a manner able to sustain intense vibrations and shocks as required for space qualification. Materials choices were limited to those approved for human space flight. The timescale for the project further limited major components such as optics, grating, slit, and diffuser to standard in-stock commercial items. While the spectrograph had to be light-tight, it could not be air-tight, and had to be able to retain light-tightness upon its interfacing with the InGaAs camera.

The integration of the spectrograph with the SU320-M camera had to be simple, quick and without the need for any tools while at the same time maintaining the focus and alignment through multiple cycles of assembly with the camera. Active control of the camera integration time on orbit would add too much complexity (and mass) to the experiment. Instead, the design throughput had to be engineered to produce unsaturated spectra with useful signal-to-noise ratio under daylight illumination conditions. Also, due to mass constraints, data acquisition was limited to direct recording of NTSC output by a digital video recorder at video frame rate.

3. OPTICAL DESIGN

The need to fabricate the spectrographs on a short timescale restricted the optical design to readily available components. Optical elements had to be mechanically strong and easy to procure at modest cost. As a result, the design was based entirely around commercially available BK7 lenses. Although BK7 is rarely used in infrared applications, the material does have good transmissive properties out to the longest wavelengths of interest (1.72μm) and the behavior of its refractive index are well understood in the infrared. A blazed reflection grating provides the dispersion. The final design consists of a $3mm \times 100\mu m$ slit, a single lens collimator, a 150g/mm bare gold plated grating, and a doublet reimager. None of the transmissive optical elements were anti-reflection coated as the Fresnel reflections were minimal and daylight illumination provides for abundant flux.

Optical design for the instrument was carried out using ZEMAX. The monochromatic reimaged slit size was set to span two pixels (xx microns) at the focal plane. The design goal was that the optics relay a monochromatic point source to the focal plane with an RMS spot size no greater than one pixel. Since the targets for this instrument are quite bright the beam diameter was limited to 6mm at the entrance to the collimator. The effective monochromatic focal ratio of the system was xxx. Given the high f/number, good image quality was assured. ZEMAX predicts a monochromatic spot radius of $10\mu m$, comfortably smaller than the $40\mu m \times 40\mu m$ pixels of the detector. Given the minimal blur introduced by the optics the slit is Nyquist sampled with two pixels per resolution element.

Light can be focused onto the slit by using a lens in front of the slit so as to provide a spatially differentiated long-slit spectrum. If a diffuser is used instead in front of the slit, the light from a cone of diffusion is scrambled, and a spatially unresolved spectrum of a large solid-angle can be obtained. A stock holographic diffuser from Edmund Scientific was selected over a ground glass alternative because of the better overall "transmission" of diffused light through the element. When observing through the earth-observation window on the ISS from an altitude of 340 km, the telescopic lens long-slit configuration maps a $30km \times 1km$ swath of terrain on Earth onto the slit. At the same altitude the diffuser will fill the slit with scrambled light from an area of $10,000km^2$.

Table 1. Prescription for the optical design(in mm)

Surf	Surface Title	Radius[a]	Thickness[b]	Glass	Catalog Item No.
01	Telescopic Lens[c]	35.09	6.60	BK7	Edmund NT45-161
02		-35.09	33.58		
03	Slit	Infinity	74.00	Stainless Steel	Melles-Griot 04PSM006
04	Collimator	76.66	3.50	BK7	Edmund NT32-626
05		-76.66	70.00		
06	Grating	Infinity	45.00[d]	Grating-BK7	Spectra-Physics 53004B402-500R
07	Reimager 1	Infinity	3.50	BK7	Edmund NT32-863
08		77.55	2.00		
09	Reimager 2	Infinity	3.50	BK7	Edmund NT32-863
10		77.55	59.90		
11	Camera Entrance	Infinity	-17.50[e]		
Ima	Image	Infinity		Detector	SU 320-M

a: Positive radii are convex and negative radii are concave surfaces.
b: All optics are 25.4mm in diameter.
c: The telescopic lens can be replaced by a 25° diffuser from Edmund - NT53-869.
d: The grating has a tilt of $\alpha = 22^\circ$ and $\beta = -10.4^\circ$ for order $m = 1$
e: The camera is shifted by 5.3mm orthogonal to the optical axis in the plane of dispersion, and is tilted by 20°. See Fig.1.

The use of only BK7 glass in the optical design produces a dramatic chromatic shift in the depth of focus at the array focal plane. The effect is nearly linear with position for the low dispersion and small wavelength range in question and was effectively countered by a 20° tilt of the focal plane(i.e; the camera). This tilt has had a

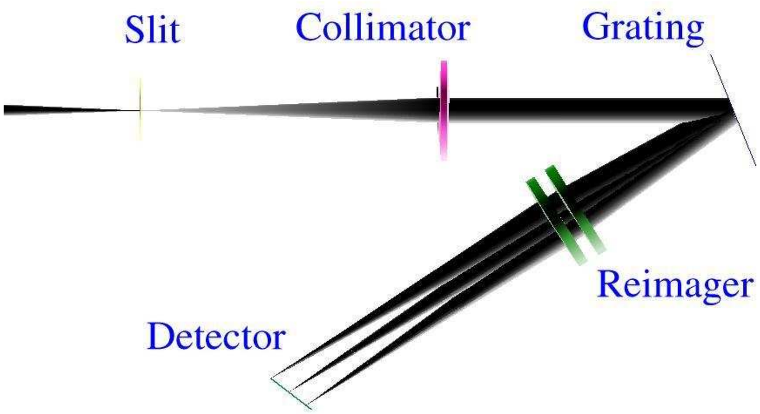

Figure 1. The design relied on only one optical material for the lenses, resulting in a strong chromatic focal shift, resulting in a 20° tilt of the focal plane. The optional diffuser and telescopic lens located in front of the slit are not shown here.

further affect on the optical design, wherein the small entrance of the InGaAs camera blocks part of the detector from the reimager. Spectral resolution of the design was decreased to compensate for this loss of pixels. The final design uses about 85% of the array along its length to provide a resolution of R $\sim$ 207. The slit occupies approximately a third of the array in the spatial direction on the array and is centered on this axis. The optical design is shown in Fig.1 and its prescription is presented in Table 1.

4. MECHANICAL DESIGN

The mechanical design of the spectrograph is based on a 'workbench' concept wherein all the parts are mounted accurately on one precisely machined plate, analogous to a workbench in a lab setup. Thus all the optical mounts are attached to the workbench directly, making all the parts small and less of a concern for strength and repeatability. On the other hand, considerable care needs to be taken in the design and fabrication of the workbench itself.

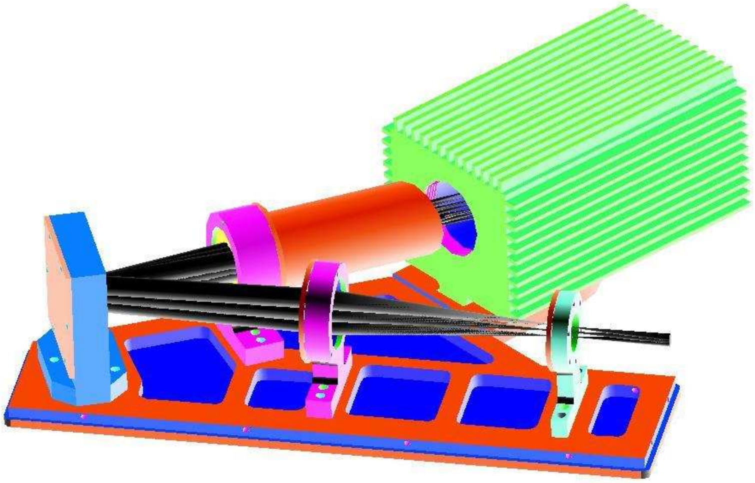

Figure 2. The mechanical design was concerned with weight, rigidity and volume. To reduce weight, metal was milled out over large parts of the optical bench. The camera sits in a tightly toleranced channel on the shoulder, thus making the assembly very repeatable.

Within each optical mount, the clearances for the optic held are designed to within the tolerance allowed by the optical design, eliminating any need for additional devices to position the optic. For convinience of machining, all mounts are orthogonal barrels, and where needed, a thin wedged ring spacer is used to modify the barrel to support a curved optic surface. All optical surfaces are cushioned from the adjecent metallic surfaces by 5μm thick nylon buffers. This mounting method has allowed us to position optics within a mount repeatably. All the mounts are positioned on the workbench using dowel pins. A view of the mechanical design is shown in Fig.2.

As the optics are mounted individually and not as connected barrels, there is a significant threat from stray light which is augmented by the observing conditions - daylight. The large acceptance angle of the diffuser, as well as for the unbaffled telescopic lense means that the front of the instrument is flooded with daylight. The slit is mounted in a plate which substantially blocks the intrusion of this light into the main body of the instrument. The use of black paint was avoided in the design to eliminate potential disqualification for space flight due to volatiles from the paint . Instead, a cylindrical baffle was added to the reimager doublet lens that restricts the detector to seeing the reimager alone. Fig.3 shows a picture of the spectrograph with the baffles in place.

Figure 3. The baffles for the reimager at the top and the slit at the bottom of the image are to minimize stray light. This is especially important because the diffuser/lens in front of the slit floods the enclosure with light.

To reduce the cost and time needed for fabrication, and to reduce the weight of the spectrograph, the instrument cover was made of sheet metal. A single sheet was cut to shape, bent up, and welded. The cover was then sand-blasted to decrease specular reflectance. The cover rests on a step all along the edge of the workbench, and is firmly held to the side of the workbench by ten screws torqued to recommended tolerance for space qualification. This configuration gives the spectrograph cover great resistance against flexure while significantly reducing stray light.

In order to achieve two easily interchangable operating modes, the telescopic lens and the diffuser are housed in identical threaded modules that can screw in to the front of the spectrograph. The lens module mounts first, and the diffuser screws in over it. To switch from the diffused to spatially resolved mode, only the diffuser module has to be removed. When the spectrograph is not in use, a brass cap screws over the diffuser module to satisfy human spaceflight requirements and retain any components shattered during launch within the instrument. For the smae reason, since the camera and the spectrograph were to fly seperately, a “dummy” cover took the place of the camera for the flight configuration of the spectrograph. To keep the design lightweight all of these components were machined from aluminum which introduced the risk of locking the parts together if the threads galled. The retaining cap was made of brass to ensure that galling of the cap would not disable the primary design function of the instrument (the scrambled light mode). In addition to the lens and diffuser, three thin disks with different aperture sizes are also included which can be inserted behind the diffuser/lens modules to control the illumination on the detector. This aperture is particularly useful when trying to observe very bright targets like clouds at high solar phase angle.

5. FABRICATION AND SPACE QUALIFICATION

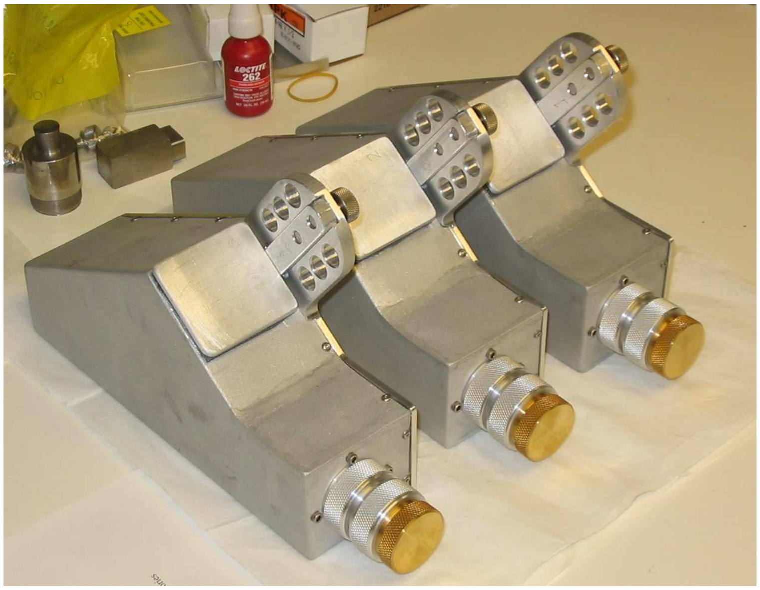

Figure 4. Three copies of the spectrograph were made, one intended for testing, the second as the payload, and the third as a backup. The backup has been retained at UVa. The three knurled modules screwed in a the front are s telescopic lens to use in the spatially resolved mode, the diffuser for the scrambled light mode and the lens cap to satisfy space qualification requirements.

After an extensive survey of the regulations and payload requirements [*], concerns focused on the three broad categories of materials, shapes and survival. The bulk aluminum structures, optical materials, and screws used in the design are all benign components. Of particular concern for materials were the toxicity and flamability requirements for the foam and epoxy used to create a light shield at the interface of the camera and the spectrograph.

Similarly, in the category of shapes, care had to be taken to avoid sharp corners and edges and protrusions. Meeting this requirement included belt sanding benign radii into the body of the SU320-M camera iteself. The mechanical stress and vibration resistance requirements on the assembly was also restrictive on our choices for fasteners and assembly techniques. Where possible, aircraft screws were used otherwise screws were torqued to levels acceptable for space qualified assembly. Both the toxicity and strength requirements ruled out many types of welding for fabricating the spectrograph cover.

In the flight configuration, shown in Fig.4, each of the three copies of the spectrograph weigh within a gram of 575g and fit in a volume of $6in \times 3in \times 10in$. The logistics for testing and qualification of the spectrograph by the RSA was undertaken by Space Adventures, Inc. The spectrograph was space-qualified and a copy of the spectrograph arrived at the ISS onboard Progress M-54.

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[*] For an extensive list of payload-safety related documents, refer to *http://psrp-pub.jsc.nasa.gov/*

6. OPERABILITY AND DATA ACQUISITION

All three copies of the spectrograph were tested on ground and found to be identical in performance, ease of assembly and repeatability. The SU-320M camera can be controlled by ascii commands given on the serial port, and the automatic gain selection on the camera can be inhibited or controlled as needed. When observing onboard the ISS, it would not be feasible to disable the automatic gain feature of the camera, and the illumination of the camera has to be controlled using the aperture disks provided to avoid saturating the spectrum for bright targets. The camera provides NTSC video output and also allows frame grabbing. The video was recorded using a Sony PD-150 camcorder onto a $2in$ DDS-2 format tape and converted to lossless tiff format using the sortware **iMovie** on Mac OS X. The tiff images were then converted to fits format using **convert** in the **ImageMagick** package. In spite of the numerous conversions involved in this process, the resulting fits images were found to be remarkably consistent. The observing setup is shown in Fig.5.

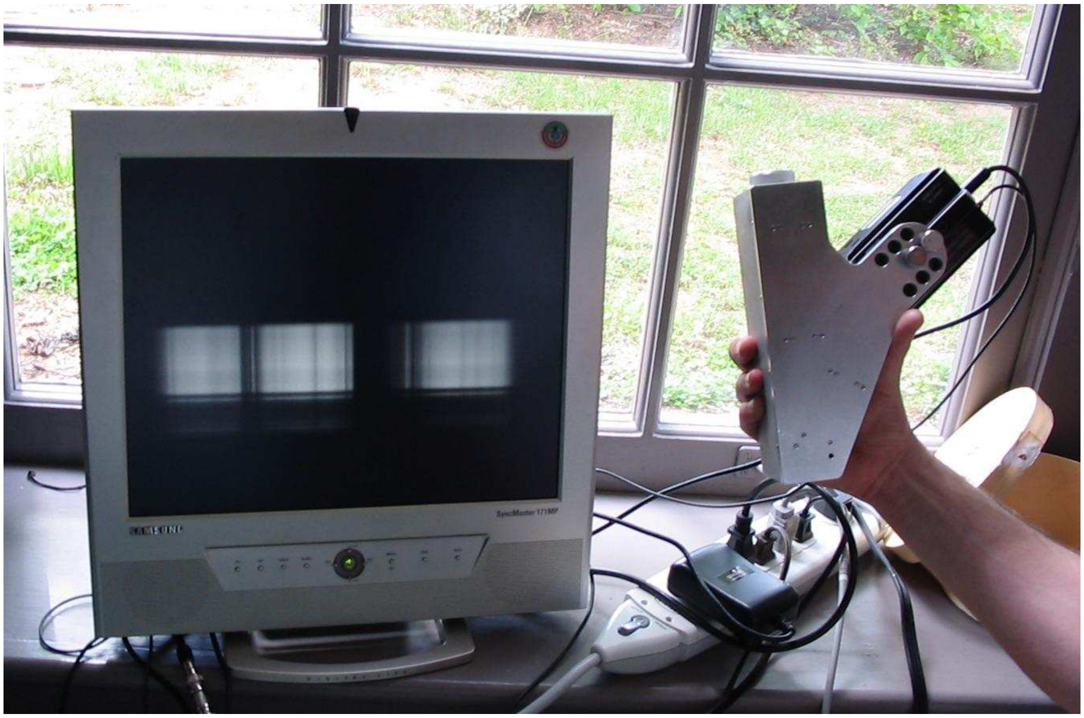

Figure 5. The spectrograph is shown acquiring data in its spacially resolved mode. The output has been diverted to a video screen for illustration. Spatial variations can be seen along the slit. Actual observing is undertaken outdoors.

7. SAMPLE RESULTS AND CONCLUSION

A series of observations of various objects in reflected sunlight was carried out near noon on 29 June 2005. The targets were Asphalt, a tree close by, a tree at mid-distance, a white car, a white sheet of paper, blue sky, a Tungsten-filament lamp, a florescent white lamp and an Argon lamp. For each target, 100 frames were extracted from the video recording, amounting to about 1.7s of exposure time. The data was stacked and background was subtracted using a swath of unused dark pixels on either side of the illuminated part of the array. Wavelength calibration was carried out using the Argon lamp spectrum, as comparision of which is shown in the top panel of Fig.6. The calculated plate-scale of $3.1765nm/pixel$ provides R=206.6, which is a good match to the design value of 207. A cleaned sample of a spectrum image is shown above a plot of all the spectra from this test. The resolution calculated using the emission lines in the Argon lamp spectrum and the florescent lamp on spectrum provides a slightly undersampled line width of 1.8 pixels, leaving the Nyquist limit as the operational limiting factor on achievable resolution.

In the end, export restrictions on the SU-320M camera prevented it from leaving the United States, so that . Dr. Olsen could not carry the camera to the ISS on his Soyuz flight. Although observations could not be obtained from orbit, we still plan to carry out a version of the experiment from aircraft.

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Desperately need references.

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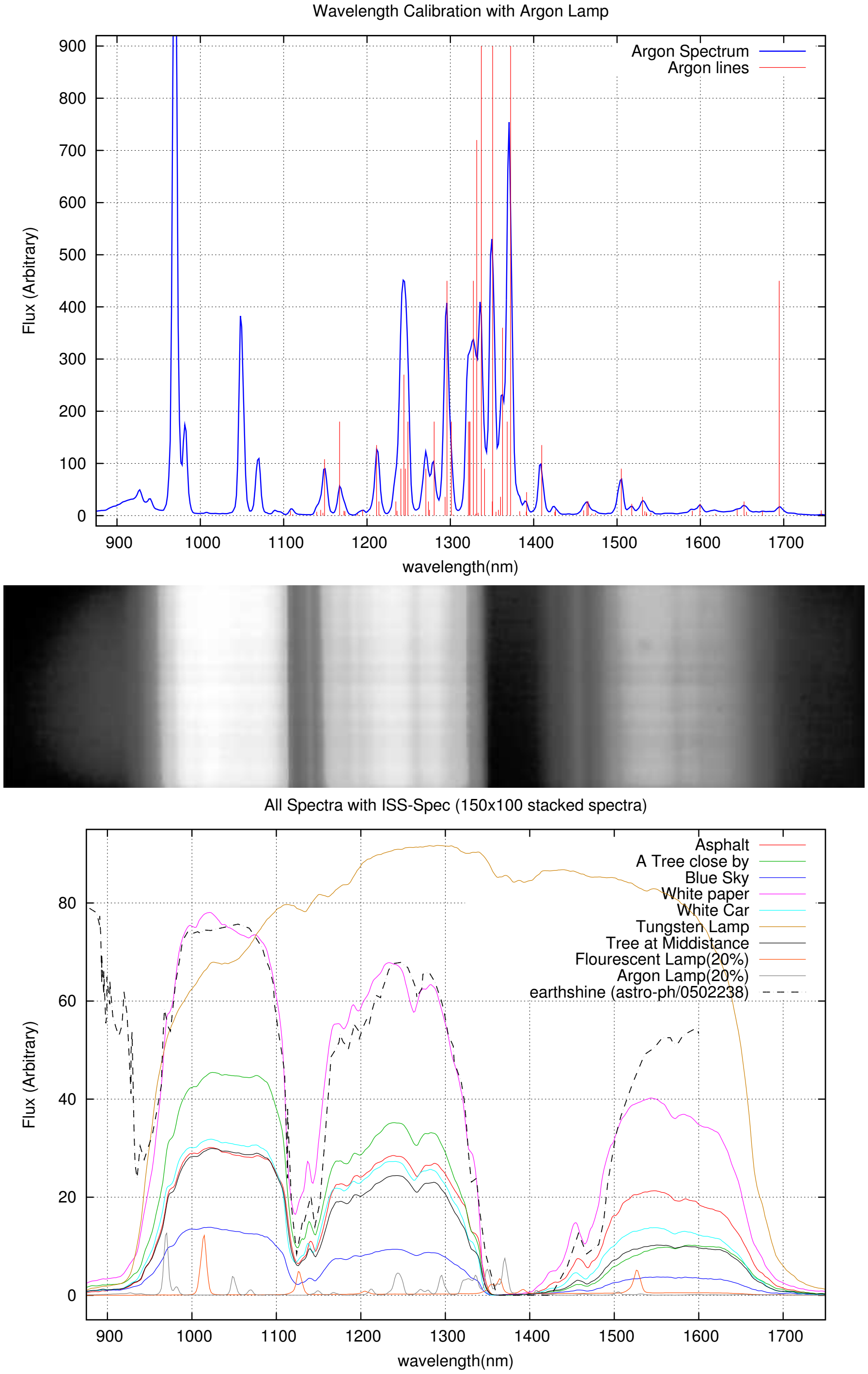

Figure 6. The top panel is a wavelength calibration using an argon gas lamp. The middle panel is a background corrected stacked image of 100 frames, or about 5 seconds of data. The bottom panel is a set of representative spectra. A spectrum from (Tinetti et al.(2006)^2) has been included(the dashed black line) for comparision.