Final Report

by

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Summary

This report summarizes work performed under DURIP grant No F49620-02-1-0258, awarded to the Space Dynamics Laboratory, Utah State University Research Foundation (USURF) for the design and development of a novel infrared imager for mapping mesospheric temperature and its variability at high-latitudes. This instrument concept was proposed by Dr. M. Taylor and Dr. W.R. Pendleton Jr., and utilized state-of -the-art system components to achieve a new capability in wide-field (120°) narrow band (~2 nm) measurements of the mesospheric OH Meinel nightglow emissions (altitude ~ 87 km) to study atmospheric radiance and temperature changes with high spatial and temporal precision. Furthermore, the system was designed to be able to make detailed measurements of mesospheric temperature even in the presence of substantial auroral precipitation (up to IBC III conditions). During the course of this grant the original instrument design has undergone several major changes, driven primarily by manufacturing needs and material limitations, resulting in substantial delays in its planned development. However, these delays have also enabled us to significantly enhance the capabilities of this novel imager, which is now expected to exceed our original design goals.

Three no-cost extensions have been approved (5/31/2003-11/30/2003; 11/30/2003 – 5/31/2004, and 5/31/2004-11/30/2004) to accommodate the difficulties we have experienced in dealing with manufacturing design changes and subsequent delays in placing orders and receiving component delivery. As the instrument is composed of several key parts, these changes have often had a compound effect. This said, the manufacture of the key system parts is now almost complete and we anticipate system assembly and integration to begin shortly (Summer 2005) with extensive laboratory and field testing at our Bear Lake Observatory, UT during the fall/winter 2005. Thereafter the imager will be deployed at the ALOMAR Arctic Observatory, Norway (69.3°N, 16.0°), for coordinated measurements alongside several powerful lidar and radar systems to quantify atmospheric variability and IR background signatures (around 1.6 μm) in unprecedented detail (as outlined in our original proposal). Throughout this extended development period we have maintained good relations with ALOMAR scientists and staff and they are keen to assist us in the instrument deployment and operation once at ALOMAR. The following text details the development of the key components and the changes (and improvements) that have been made during the full 2.5 year grant period.

Background

The Advanced Mesospheric Temperature Mapper (AMTM) design was based on our experience gained with the development of a CCD based imaging system that has proven to be most capable of accurate, long-term, unattended measurements of mesospheric temperature (<1-2 K in 3-min). This instrument utilized a high quantum efficiency, bare CCD (>50% at NIR wavelengths) to obtain high quality images of selected emission lines in the NIR OH Meinel (6,2) band around 840 nm and selected portions of the $O_2(0,1)$ band near 866 nm. These two naturally occurring nightglow layers originate at mean heights of ~87 km and 94 km respectively, with typical half-widths of 8-10 km. The Mesospheric Temperature Mapper (MTM) was developed during 1996/7 with funding from the National Science Foundation CEDAR Phase III program aimed at developing new instrument capabilities for the 21^{st} century. The imager utilized a (then) state-of-the-art, high resolution (1024 x 1024 x 24 μm pixel) back-thinned CCD array, with very low noise (~0.1/e-/pix/sec) and low readout noise (~15 e- RMS). The CCD imager was operated at –50°C using a combined of two-stage Peltier unit with recycled refrigerated coolant.

In operation, sequential relative intensity measurements of selected emission lines (e.g. the $P_1(2)$ and $P_1(4)$ rotational-vibrational lines in the OH (6,2) band), together with a background sample were made using a filter wheel. Absolute determinations of mesospheric temperature (height weighted over the emission layer depth) were then obtained using the well-established "ratio method", using the emission line data. Typical measurement precisions for the data are ~1% (in 1 min) for intensity, and > 1-2 K (in 3-min) for temperature. The MTM was successfully field tested alongside the Colorado State University Na-temperature lidar system at Ft. Collins, CO (1977/8) and the University of Illinois Na-wind-temperature lidar operated at the Starfire Optical Range (SOR), NM (1998-2000). These measurements yielded an absolute uncertainty of ± 5 K when referenced to the nominal emission height of 87 km as measured by lidar. Subsequently, the MTM has participated in the jointly sponsored AFOSR/NSF Maui-MALT program where it has operated unattended at the USAF AEOS facility, at the summit of Haleakala Crater, Maui, HI, for the past 3 years (Nov 2001- to date) with only limited servicing. Over 650 nights of high-quality data have been obtained during this period enabling an unprecedented coordinated study of the mesospheric temperature and its variability at low latitudes on time scales ranging from ~10's min to many months.

The AMTM design utilizes the same basic technique of using relative intensity field observations of the OH nightglow emission to derive absolute temperature with high precision, but applied to the high-latitude environment where strong auroral events often occur. Our existing MTM measures sub-micron airglow emissions to study the mesospheric dynamics which are usually much weaker than auroral emissions in the

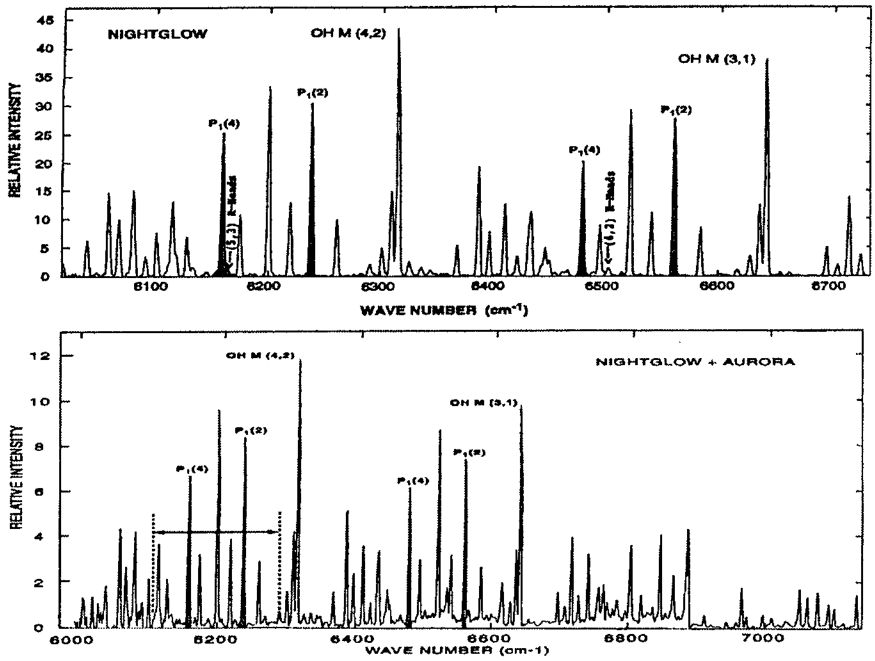

Figure 1. (top) Infrared spectrum of the high-latitude night sky showing prominent OH(4,2) and (3,1) bands, and (bottom) same spectral region during a strong IBC III auroral display.

same spectral range and can be strongly influenced, even during relatively weak precipitation events. The AMTM was therefore designed to measure the longer wavelength OH M band emissions that occur in the 1.5-1.65 μm range that are not significantly affected by auroral contamination. Specifically, the OH(4,2), and the OH(3,1) bands were selected for this new imaging capability. This is illustrated in Figure 1 which shows two spectra of the night sky taken at high latitudes using a Utah State University (USU) Michelson Interferometer. The upper plot shows the prominent OH(3,1) and (4,2) nightglow spectrum. The emission lines to be measured by the AMTM are indicated in red. In comparison, the lower plot was recorded in the presence of a strong auroral (IBC III) display. Note the additional auroral emissions structure in this plot. However, of key importance to our instrument design is the absence of any auroral emissions at or close to the $P_1(2)$ and $P_1(4)$ lines of the OH(4,2) band making it ideal for high-latitude temperature studies. The OH(3,1) band is also well placed but there is some evidence of a small contamination of this band under strong auroral forcing. As the OH (3,1) band emission has been extensively studied using interoferometric techniques, the AMTM is designed to also measure this band to permit detailed cross-calibration with existing instrumentation. Finally, as both of these band emissions are substantially stronger than the OH(6,2) band (used in the MTM) this provides for a significant improvement on the temporal resolution of the AMTM imager, assuming similar sensitivities for both systems. Higher temporal resolution for the new temperature mapper is most desirable as our current measurements at mid- and low-latitudes indicate a preponderance for short-period (~5 min) waves that are not currently resolvable in temperature using the MTM, yet clearly represent a significant amplitude, high frequency component to the observed wave spectrum.

AMTM Design

Figure 2 shows a sketch of the AMTM instrument. The camera design has undergone several revisions resulting in a significant increase in the size and complexity of the fore optics. In the final design the instrument is ~2 m long and will be mounted vertically on a base plate (as shown). The system consists of four basic parts:

- Wide angle telecentric optics and mount
- Warm and cold filter assemblies
- Rockewll HgCdTe IR detector
- Dewar housing for detector and clod filters operating at 77 K

The development of each of these key parts is described below.

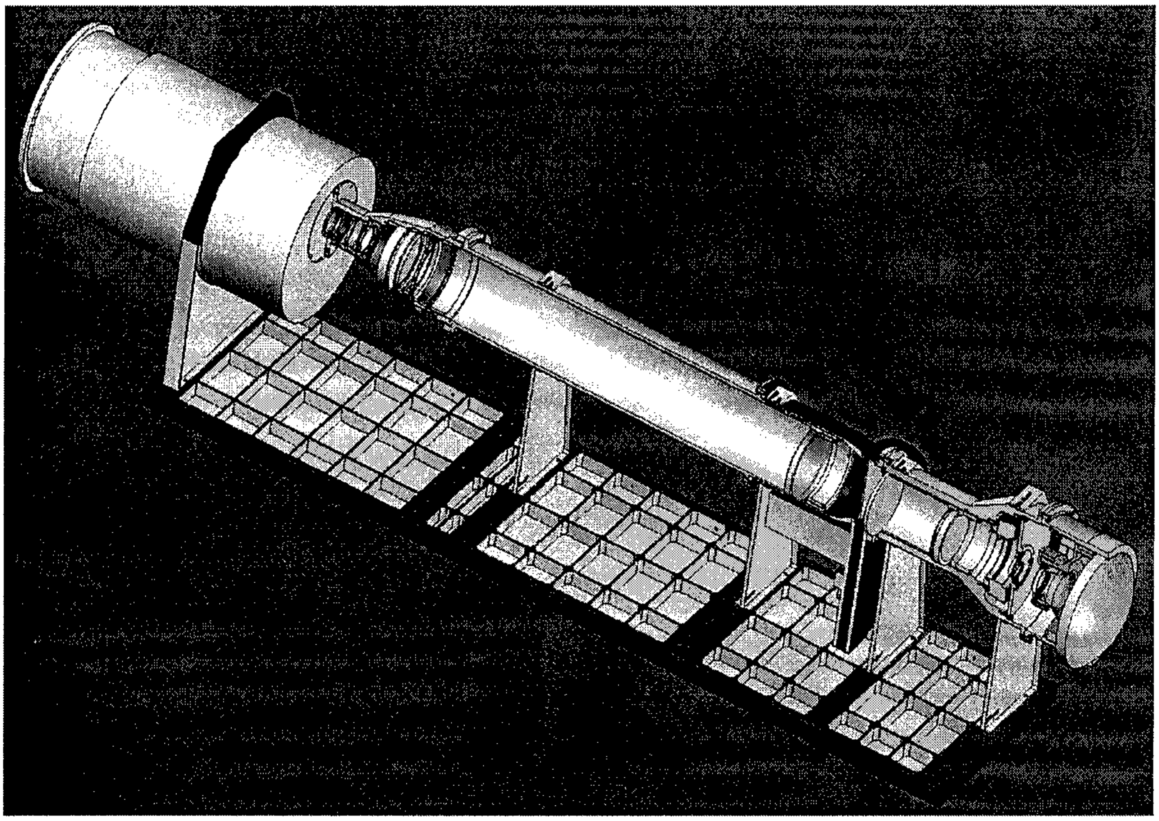

Figure 2. Solid body drawing of the AMTM instrument showing the optical housing with warm filter wheel and the dewar containing the IR detector and the cold filters.

Telecentric Optics

Our original camera design called for a similar optical arrangement as that employed in the MTM design. This utilized a commercially available telecentric lens arrangement (manufactured by Keo Consultants) that enables wide field measurements (~90°) using narrow band interference filters (~1 nm) to isolate the $P_1(2)$ and $P_1(4)$ rotational lines in the OH (6,2) band emission needed for the temperature determination. However, as the AMTM is to be operated at IR wavelengths it was necessary to develop our own lens design. To enhance the capability of the new imager it was decided to increase the field of view to 120°. This is illustrated in Figure 3 which shows a ray diagram for the wide angle lens system. Over 20 lens elements are used in this design, each of which is specially coated to minimize transmission losses and resulting in an expected optical system transmission of ~50%. This design differs significantly from that presented in our proposal and was developed at the Space Dynamics Laboratory (SDL) specifically for this program. The system is exceptionally fast (f/1), employing large optics to maximize the signal thruput to the sensor array, necessary for rapid temperature determinations (> 2 per min). Careful optical design has also minimized distortion of the wide-field permitting very high quality imaging. The optical mount was also designed in-house at SDL and comprises three main sections to permit easy assembly and transportation. Where necessary Invar steel was used to minimize thermal expansion problems. All the parts were manufactured to high tolerances at the SDL workshop. The telecentric optical components were manufactured to precise tolerances by Harold Johnson Optical Laboratories and are currently being installed in the optical mount.

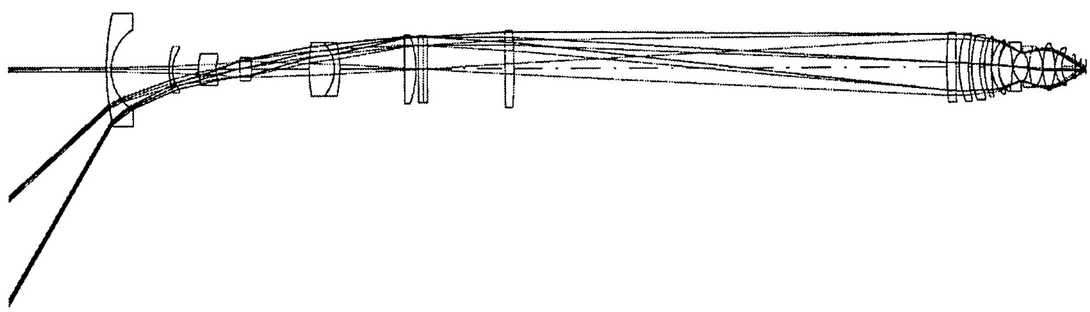

Figure 3. Optical layout and ray diagram for the 120° telecentric lens system. The warm filter(s) are placed at the focus of the rays in between the two large lens elements.

Filters

The original optical design used a set of warm filters housed in a filter wheel assembly at the focus of the telecentric optics (see Figure 3 for placement) to isolate the spectral emission lines followed by a single cold filter housed in the dewar to limit long wavelength (thermal) radiation onto the detector. The use of warm (room temperature) narrow band filters greatly simplifies the instrument design. Figure 4 shows an example of one 4 inch diameter interference filter (centered at 1600.0 nm) as manufactured by

Barr Associates, who are world experts in specialized filter designs. Important for our measurements is a narrow bandwidth (~2.32 nm) and high filter transmission (~95%). Each filter also has excellent out of band rejection (~10^{-6}) over the pass band of the cold filter to minimize background signal contamination.

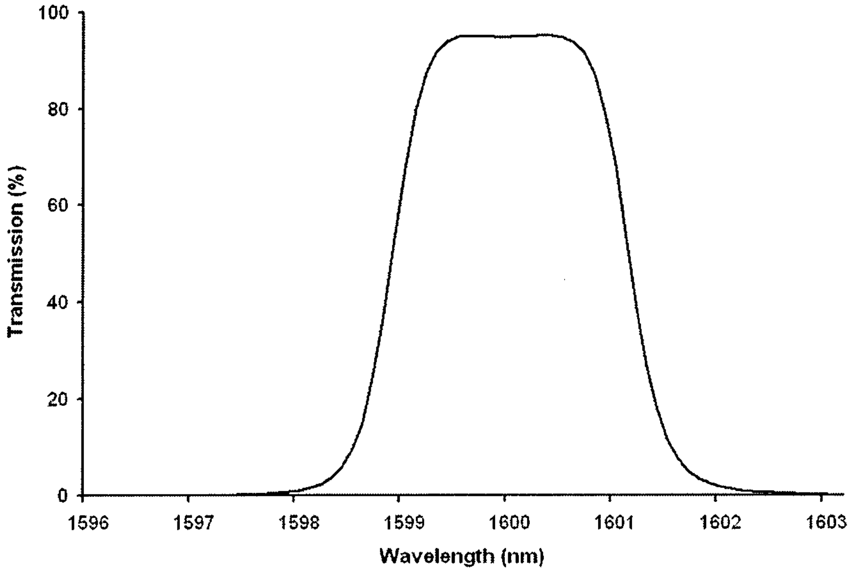

Figure 4. Spectral response of the OH (4,2) Meinel band at 1600.0 nm warm interference filter manufactured by Barr Associates.

Following many discussions with Barr Associates it was decided to make two cold filters to separately isolate the OH(4,2) band lines and the OH (3,1) band lines. This was done to simplify filter manufacturing tolerances and to further minimize background (thermal) signal that would be present in a single wide band cold filter that encompassed both spectral bands. This decision impacted the dewar design (see below) as it required the placement of a filter wheel inside the dewar to house two cold filters. It has also impacted our software design which now needed to be able to control two filter wheels for synchronous isolation of the OH(4,2) and the OH(3,1) band emission lines. Figure 5 shows the broad spectral response for the OH (3, 1) cold filter (nominal bandwidth ~ 55 nm) centered at 1,535 nm as developed by Barr Associates. The multiple curves show the spectral response for different angles of incidence (up to 32°) and different polarizations, and again illustrate the high filter transmission (~70 %). This filter together with the OH (1,608 nm) cold filter will be mounted in a small filter wheel inside the dewar for operation at 77 K. Filter design and manufacture has taken a long time, but, with the exception of one cold filter, all 5 warm filters have now been manufactured, tested and delivered. The final cold filter (1,608 nm) is currently being made and is expected to be delivered by end of May, 2005.

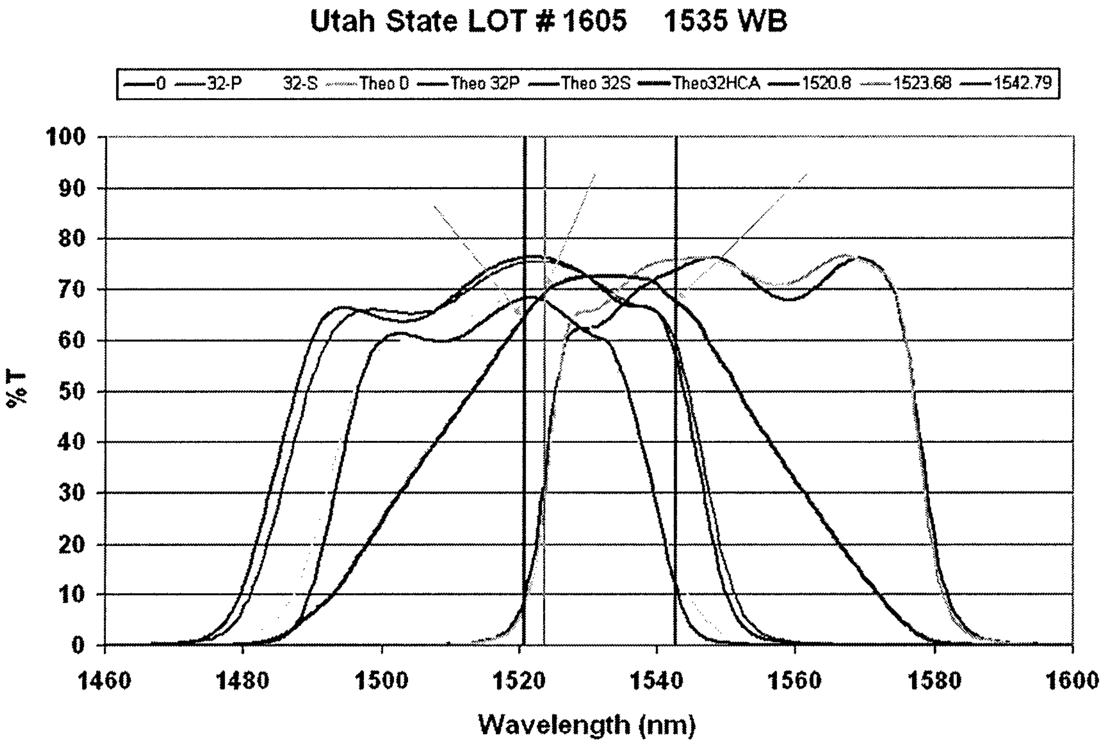

Figure 5. Spectral response of the OH (3,1) cold filter manufactures by Barr Associates.

IR detector

The heart of the AMTM is an HgCdTe IR detector. This device is manufactured by Rockwell Scientific Inc., and comes in several different pixel formats. We have chosen the 256 x 256 x 40 μm PICNIC array for the AMTM which has a well proven capability for infrared measurements over the spectral range ~1-2.5 mm. This device has been used on several astronomical telescopes, including the Hubble Space Telescope and represents the state-of-the-art for commercially available devices. The 256 x 256 pixel format gives a four fold enhancement in spatial resolution over our existing MTM (which is binned to 128 x 128 superpixels to enhance the signal-to-noise-ratio) and also offers flexibility for even higher temporal resolution using 2 x 2 binning. For our measurements we are interested in the quantum efficiency of the detector over the ~1.5-1.65 μm region which is exceptionally high, at typically 70-80 %. However, as part of our discussions with Rockwell it was decided to include a specilaized anti-reflection (AR) coating on the device to limit the effects of "etaloning" on the measurements. This is a well known effect using high quality CCD detectors that results in a interference pattern superimposed on the data due to multiple reflections inside the detector when exposed to monochromatic light. Our narrow band measurements are therefore prone to etaloning and the addition of the AR coating (which was not anticipated in our original proposal) was deemed essential.

The discussions with Rockwell on the device manufacture and the design of the AR coating took much longer than anticipated and a critical problem arose at the time of the placement of the order. As Rockwell manufactures the PICNIC array on a fixed cost "best effort" basis it was suddenly determined by USURF administration that the device could not be purchased in the normal way where the required specifications are given as criteria for product acceptance. Due to the complex processes involved with the PICNIC array manufacturing Rockwell advertise delivery of the best possible device available. Following considerable negotiations between USURF and Rockwell the solution to this problem was to place a fixed price sub-contract with Rockwell for the device manufacture. This was finally placed just over a year ago.

Rockwell produce PICNIC arrays in batches and the first device that they made that met our desired specifications was available in the fall 2004. However, the new AR coating applied to this device failed. This resulted in the re-design of the AR coating. The latest device was manufactured in March 2005 and has now been successfully tested with the new AR coating. This device meets our design specifications for high quantum efficiency ~ 80 % (at 1.6 μm) and low noise (0.1 e-/sec; 15.9 e- read out) operations at 77K and is currently undergoing final testing at Rockwell. It is expected to be delivered to USU shortly.

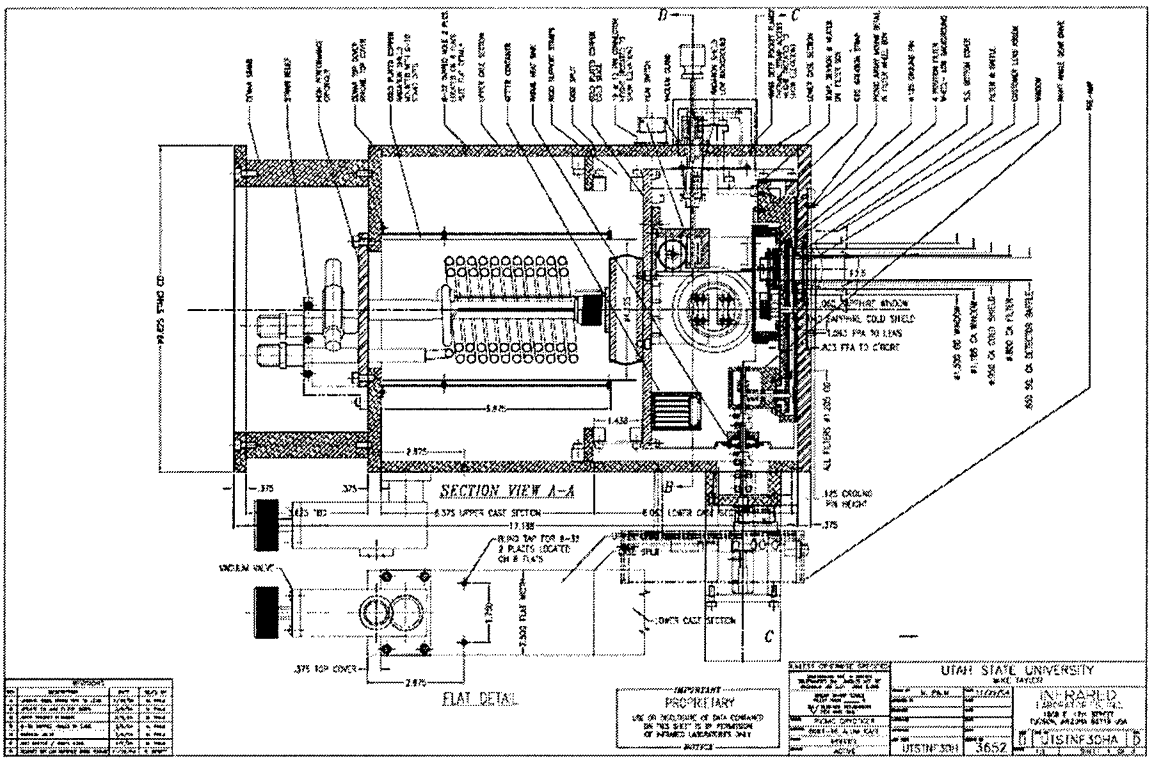

Figure 6. Cross section of the dewar design currently under manufacture by IR Labs.

Dewar

The dewar is a specialized system designed to house the HgCdTe detector and the cold filters for operation at 77K. This unit is being manufactured by IR Laboratories who have considerable expertise in the design and construction of dewars using Rockwell IR sensors. For the AMTM several modifications were made to an existing (basic) design.

This is illustrated in Figure 6 which shows a cross-section though the dewar. The primary design changes involved the placement of the cold filter wheel in between the dewar window and the detector. This was challenging due to the constraints imposed by the fast re-imaging optics and many discussions were held with IR Labs to determine the best configuration for the components. The final dewar design was fixed over a year ago but the device has yet to be completed. This is because Kirby Hnat (the designer of our system) left the company several months ago. We were not made aware of this problem until December, 2004. Subsequently, IR labs have requested several minor changes in the design that have now been approved and the dewar is currently under construction with an expected delivery date within 2 months. The dewar will be cooled using a closed cycle "cryotiger" system that has a proven heritage for long term, unattended operations.

Concluding Remarks

A number of unexpected delays have occurred during the design and development of the AMTM resulting in a much longer construction time than originally planned. The problems have now been overcome and many of the key system components have been successfully manufactured and delivered to USU where they are now being integrated. The remaining parts are very close to completion. We anticipate complete assembly and testing of the optical system during the summer of 2005. This will be followed by the integration of the PICNIC array and dewar to complete the AMTM system. Laboratory tests will be followed by detailed field measurements using our facilities at Bear Lake Observatory (BLO), UT. We anticipate making cross-calibration measurements using a Bomen Michelson spectrometer observing the same spectral bands as the AMTM. Finally, the software for controlling the AMTM has been developed in-house at USU and is based on the successful operation of the MTM. This will permit remote, unattended operation of the imager using a set sequence for the measurements, as well as daily internet access to the system for health monitoring and remote data downloading for timely data analysis. The software has been tested in the lab, but has yet to be tested on the integrated system.

We apologize for the delay in the development of this novel IR imaging system, the performance of which is expected to be exceptional. Once the laboratory and field tests at BLO have been successfully completed, a further supplemental report will be submitted to quantify the system performance.

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14. ABSTRACT
This report summarizes work performed under DURIP grant No F49620-02-1-0258, awarded to the Space Dynamics Laboratory, Utah State University Research Foundation (USURF) for the design and development of a novel infrared imager for mapping mesospheric temperature and its variability at high-latitudes. This instrument concept was proposed by Dr. M. Taylor and Dr. W.R. Pendleton Jr., and utilized state-of -the-art system components to achieve a new capability in wide-field (120°) narrow band (~2 nm) measurements of the mesospheric OH Meinel nightglow emissions (altitude ~ 87 km) to study atmospheric radiance and temperature changes with high spatial and temporal precision. Furthermore, the system was designed to be able to make detailed measurements of mesospheric temperature even in the presence of substantial auroral precipitation (up to IBC III conditions). During the course of this grant the original instrument design has undergone several major changes, driven primarily by manufacturing needs and material limitations, resulting in substantial delays in its planned development. However, these delays have also enabled us to significantly enhance the capabilities of this novel imager, which is now expected to exceed our original design goals. Three no-cost extensions have been to accommodate the difficulties we have experienced in dealing with manufacturing design changes and subsequent delays in placing orders. The manufacture of the key system parts is now almost complete and we anticipate system assembly and integration to begin shortly (Summer 2005) with extensive laboratory and field testing at Bear Lake Observatory, UT during the fall/winter 2005.

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