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THE HIGH EFFICIENCY HYPERSPECTRAL IMAGER – A NEW INSTRUMENT FOR MEASUREMENTS OF THE ARCTIC SURFACE

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1 INTRODUCTION

Throughout the Polar Regions the surface heat budget is dominated by the radiative terms; this is the case not only where the surface is frozen (Persson et al., 2002) but also for summertime conditions over open water, such as polynyas and leads (Minnett, 1995). The variability of the net longwave flux component (conventionally defined as spanning the spectral range of wavelengths from ~3 to ~50 µm) at the surface is small in comparison to that in the shortwave (~0.3 to ~3 µm), which in turn is dominated by uncertainties in the surface reflectivity. This can exhibit great variations on small spatial scales and short time intervals, especially during the melt season. Further limitations on our understanding of the surface radiation budget result from uncertainties in specifying the influence of clouds.

The influence of clouds in the global climate system can be couched in terms of feedback mechanisms that amplify or moderate the initial perturbations: the cooling of the Arctic in summer by clouds is a negative feedback as the increasing cloudiness attendant on a warmer, moister atmosphere leads to a reduction in the surface insolation. The reduced rate of ice melting also has a negative feedback on the surface absorption of the insolation by reducing the rate at which a low albedo surface replaces the high albedo snow and ice during the melt season. The high surface albedo over snow and ice leads to a positive cloud forcing, sometimes referred to as the radiation paradox. However, uncertainties in the surface reflectivity render even the sign of the net cloud radiative forcing unknown over much of the summertime Arctic (e.g. Intrieri et al., 2002).

The High Efficiency HyperSpectral Imager (HEHSI) uses a simple and elegant method of providing measurements of the spectra of surface reflectivity in the pixels of an image. The Sagnac interferometer consists of a beam splitter and two mirrors forming a triangular light path, with the spatial displacement required to generate the interference patterns being provided by an offset of one of the mirrors from the position of symmetry. The interferometer is mounted in front of a camera with a single 2-D detector array. The instrument is lightweight and robust, and has been used on the Canadian research icebreaker *Amundsen* in the Arctic Ocean in the summer of 2004 to make measurements of the bidirectional reflectivity of sea ice and snow during the melt season. This type of instrument can make a significant contribution to studies of the surface reflectivity during the IPY.

2 INSTRUMENT DESIGN

The heart of the HEHSI design is a Sagnac interferometer. This is a two-beam, common-triangular-path interferometer (Figure 1) in which one beam transits the interferometer in a clockwise direction, while the other transits the same path in a counter-clockwise direction. If the two mirrors were placed symmetrically with respect to the beam splitter, then the two rays would exit the interferometer in the same direction and at the same position. If one mirror is placed offset from a symmetric position, however, then the two rays exit in the same direction, but at positions symmetrically offset from the optical axis. The path-difference through the interferometer is a function of the angle of the ray entering the interferometer, but does not vary with the position of entry.

The interferogram (fringe pattern) is localized at infinity, so a lens (referred to as the Fourier lens) is used to image the fringes onto the detector array as shown in Figure 1. The modulus of the Fourier transform of this interferogram gives the spectrum of the source. This arrangement provides the variation in path-difference across the detector array, with stationary mirrors, so there is no need for a scan mechanism. Unlike a Michelson Fourier Transform Interferometer which produces an interferogram in the time domain, a Sagnac interferometer produces the interferogram in the spatial domain.

The interference pattern is thus superimposed on the image. The motion of the platform scans the image across the interference pattern, and a Fourier transform is applied during processing to produce a spatial-spectral data set. The focal length of the lens can be selected for the desired field of view. The HEHSI instrument includes a selection of four lenses providing full FOVs ranging from 10° to 38°, each of which are designed to cover both the visible and near-infrared wavelengths.

Given that there are no moving parts, the Sagnac interferometer can be constructed out of solid glass in the shape of a 5-sided regular prism with integral mirrors and an embedded beam splitter. Such a monolithic design is extremely rugged but does not allow the spectral resolution to be adjusted, since the

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mirror offset is fixed. The HEHSI design therefore uses a *semi-monolithic* Sagnac in which the prism incorporates the embedded beamsplitter and one of the mirrors while the second mirror is a separate part to allow for adjustment of the spectral resolution. This flexibility provides the option to optimize the trade-off between spectral resolution and radiometric resolution (signal-to-noise ratio) for a particular observation. This semi-monolithic design is sufficiently rugged for deployment on a ship, while still allowing flexibility in performance.

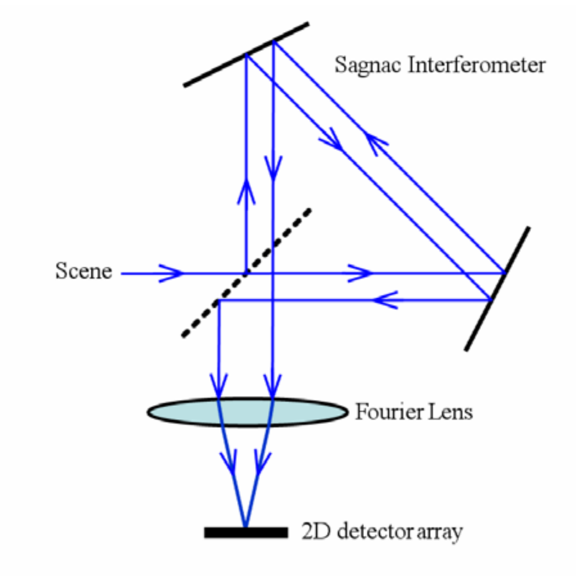

Figure 1. Schematic of the HEHSI

2.1 HEHSI Measurements

As successive frames are acquired, the movement of the instrument causes the image to scroll through the field-of-view. The fringe pattern, however, is defined by the path difference induced by the interferometer, which is fixed with respect to the field. As each point in the object moves across the field, it is modulated by the interferogram pattern. The Fourier transform of this modulation yields the spectrum of that point.

The camera used in HEHSI is a DALSA 1M30 with a 1024 x1024 element focal plane. The signal collected by each pixel is digitized to 12-bit resolution (0-4095). The operation of the camera is programmable in terms of integration times, frame rates, and which subset of the pixels are to be read out. This gives a wide range of flexibility to match the performance of the HEHSI to available lighting, required speed of operation, and desired field of view. Additional adaptability to changing levels of illumination is provided by an iris in the Fourier lens. The iris was never adjusted during measurement sequences, but when necessary to accommodate changes in the level of illumination, it was adjusted between sequences. Then the entire HEHSI was recalibrated (see below). Over the course of the field deployment reported here, the iris was operated over its full range. Frame rates were set at between 30 and 54 per second, and integration times from between 3 and 31.2 ms. These adjustments were necessary to provide good dynamic ranges in the FOV when illumination ranged from bright, direct sunlight at local noon, to dull, overcast skies at local midnight.

The HEHSI control and data system is based on an Acme Sax rugged portable computer capable of running on either 120 V AC or 28 V DC power, incorporating the camera interface card and the camera control and data acquisition software.

2.2 HEHSI Field Calibration

There are significant difficulties in attaining good levels of absolute radiometry in the visible part of the electromagnetic spectrum in the field. These result from the cumbersome size of integrating spheres and the durability and reliability of standard lamps. Thus, it was decided that the HEHSI calibration should be done in terms of reflectance, which is achieved by bracketing each set of measurements of the scene with measurements of a well-characterized calibration target. This was a 20 cm square slab of sintered Teflon on a metal substrate. The target has a nominal reflectivity of 0.98 but was characterized at 1 nm intervals from 250 to 2500 nm with a precision of 0.0005 and an uncertainty of 0.0045 at 500 and 750 nm, per ASTM Practice E259-98. The detector bias was determined by covering the HEHSI with a light-tight shroud. The dark current was found to be equivalent to 3 digital units on the 12-bit scale and to be invariant over the period of the field deployment.

The spectral characteristics of the HEHSI, in terms of matching the band number in the output data set to wavelength, are dependent on the displacement of the adjustable mirror. Before deploying the HEHSI outside, the offset and alignment of the mirror was reset using a diffused HeNe laser, with wavelength 633 nm. Although the position of the mirror was fixed for any particular set of measurements, the HEHSI was not in a constant temperature environment; in fact it was subjected to large temperature changes when deployed on an icebreaking research vessel in the Arctic. Consequently, thermally induced changes in the spectral behavior of the interferometer could not be ruled out. To monitor this possibility, and to provide the data for correcting any such effects, measurements of “Labsphere” wavelength calibration standards were done episodically between the measurement sequences. The wavelength calibration standards are a diffusely–reflecting polymer mixed with rare-earth oxides which have several absorption features at known, calibrated wavelengths.

2.3 Data Processing

The data were processed from the raw data-cube of digital units as a function of row, column, and frame number to a reflectance cube of reflectance as a function of cross-track position, along-track position, and wavelength. There were five major steps in this process:

1) Determination of the actual motion of the FOV across the scene, i.e. the spatial displacements between successive frames.
2) Resampling from coordinates of row, column, and frame number into coordinates of cross-track position, along-track position, and interferometric path-difference.
3) Fourier transform from path-difference into spectral band number.
4) Calibration from digital units to reflectance.
5) Calibration from band number to wavelength.

The calibration steps are accomplished by using measurements of known calibration targets in the field, as described above.

3 CASES CRUISE OF THE *AMUNDSEN*

The first deployment of the HEHSI was on the Canadian research icebreaker *Amundsen* on the 8th leg of a year-long expedition to the southeastern Beaufort Sea as part of the Canadian Arctic Shelf Exchange Study (CASES). The leg began on June 23, 2004, and ended August 4, with the exchange of scientists and crew taking place off Cape Parry, Northwest Territories, Canada. The ship had overwintered in fast ice in Franklin Bay and had broken out in mid June to begin multi-disciplinary research in the Cape Bathurst Polynya (Carmack and MacDonald, 2002). The ice conditions in the area of operations during Leg 8 were highly varied ranging from fast ice with many melt ponds in the south, to the Arctic ice pack to the northwest. Much melting had already taken place so there were stretches of days at a time when the ship was working in open water, and there was no ice to be measured.

The HEHSI was assembled on board and mounted on a pan/tilt head attached to the forward corner of the portside railing above the bridge. This allowed for a view of more than 270^{o} around the ship, with the remaining sector blocked by the main mast and smokestack. Other minor obstructions were caused by antennas, search lights and guy-wires. More than 180^{o} on the port side of the ship was unobstructed. The mounting arrangement is shown in Figure 2.

HEHSI measurements were taken in 87 panoramas, each bracketed by reflectance calibration measurements. Several wavelength calibrations were taken during each measurement set. Illumination conditions ranged from bright sunlight to dull overcast. The azimuth reference for the HEHSI motorized pan head was set each time by aligning the field of view along a line parallel to the center-line of the ship.

For most scans the pan/tilt head of the HEHSI was set horizontal (to within ±0.2^{o} as determined by an electronic inclinometer; the ship was extremely stable), but several were taken with the head tilted downwards to increase the range of measured view angles.

In addition to the latitude and longitude, the ship's heading from the gyrocompass, required for the determination of the relative azimuth angle between the sun and the measurement, was logged at 1 second intervals. Also a full suite of meteorological sensors was mounted on a mast erected on the foredeck. Included in this was an Eppley Labs Precision Spectral Pyranometer (PSP) which was used to provide a record of the hemispheric illumination during each scan, and thereby bridge changes in illumination between the reflectance calibrations.

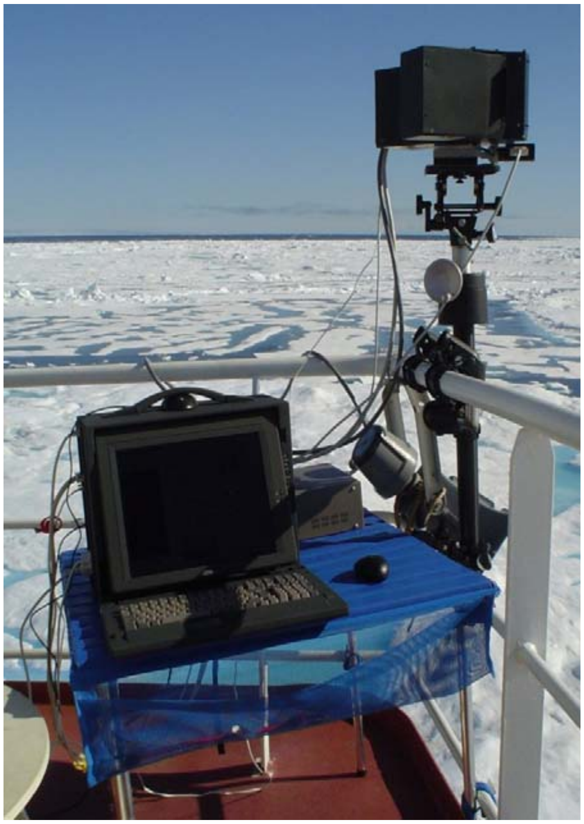

Figure 2. The HEHSI mounted on the forward, portside railing of the Top Bridge of the NGCC *Amundsen.* The control computer is on the small table, and the camera power supply behind. (The downwards pointing horn beneath the HEHSI is a loudspeaker, and not part of the scientific equipment.)

An all-sky camera was mounted close to the HEHSI to provide a record of the cloud conditions throughout the cruise. This consists of a downward-looking video camera mounted above a hemispheric mirror. The images were recorded by a time-lapse video recorder every 17s.

3.1 Examples of data

Nearly 40 hours of data were taken with the HEHSI during the *Amundsen* CASES Leg 8 cruise. Frame rates were between 30 and 54 frames per second, and this produced over 4.6 million frames that require about 1.6 TB of computer disk storage. Only a small fraction of this has been processed with prototype algorithms, but the results demonstrate that the measurement concept and processing schemes are sound.

Included in the data collected during the CASES Leg 8 cruise is a series of panoramas taken in landfast ice in Summer Harbour (70.127°N, 125.081°W) and off Cape Parry (70.085°N, 124.775°W). Separated by a distance of less than 7 miles, the fast ice was continuous between the two places (and beyond) and had the same characteristics. The data taken at the two sites span a ~25 hour period and therefore encompass a diurnal heating cycle. An example of the frames taken at Summer Harbour is shown in Figure 3. It contains 256 x 786 12-bit pixels, and belongs to a sequence of 129000 frames, spanning about 270° of azimuth. The HEHSI was rotated about a vertical axis. For the sake of clarity here, the image has been histogram equalized. The ice was covered in melt ponds, many of which had merged to form an elongated tracery over the ice. Between the melt ponds, the snow on the ice was bright. Some melt ponds had eroded the ice beneath and were connected to the sea below. The interferogram fringes are apparent as bright and dark vertical modulations of the image. Both frames were taken during the polar night, under overcast conditions so the illumination was very low. The left-hand frame was taken approximately orthogonal to the lighting, the sun was to the right, and the right hand frame was almost in the direction of the sun, which was behind the clouds visible in the sky above the bright band of more clear conditions just above the horizon. In the left hand frame, the snow is bright and the melt ponds dark, but when looking towards the sun, even when it is obscured, the specular reflection in the still surface waters renders these areas brighter than the snow.

For some sequences, the pan head of the HEHSI mount was tilted, to direct the center of the field of view below the horizon. This provides a different range of reflection angles than the horizontal mount, and also generates images with better spatial resolution.

The prototype data processing that was undertaken on board the *Amundsen* consisted of applying all of the operations outlined above to a small subset of the measurements. For ease and speed of processing, the frames were binned down by a factor of two in each spatial dimension, and processed to a spectral resolution of 41 bands. Wavelength and reflectance calibrations were applied as described above. An example of the output is shown in Figure 4. The pseudo-color image is a part of a panorama taken south of Banks Island (70.951°N, 123.448°W) on July 31, 2004, starting at 03:07 UTC, and is rendered by assigning red, green and blue to channels in those parts of the spectrum. In this example, red is assigned to spectral band 14 at a wavelength of 630.9 nm, green to band 19 at 545.8 nm and blue to band 26 at 459.1 nm. Given the relative narrowness of the spectral bands, it should not be expected that this would portray accurately what is perceived by the human eye. The pseudo-color rendition does, however, provide a sufficiently realistic representation to allow for the identification of different surface types.

4 CONCLUSIONS

The main conclusion of the first field deployment of this type of imaging, interferometric spectroradiometer is that it works in the harsh Arctic environment in the

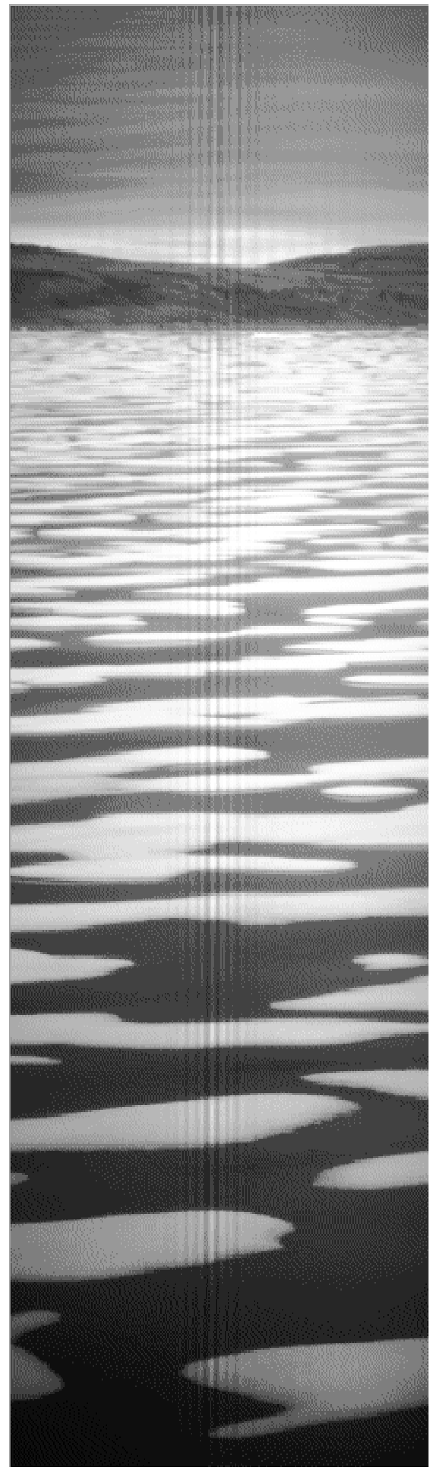

Figure 3. An example of HEHSI data from the ship in land-fast ice at Summer Harbour (70.127°N, 125.081°W) on 15 July 2004. The land in the background is Booth Island to the west of Cape Parry. The interference fringes are the vertical bright and dark vertical modulations of the scene. The frame is 256 pixels wide and 786 pixels high. Each pixel is digitized to 12 bits. The image has been histogram equalized for this figure.

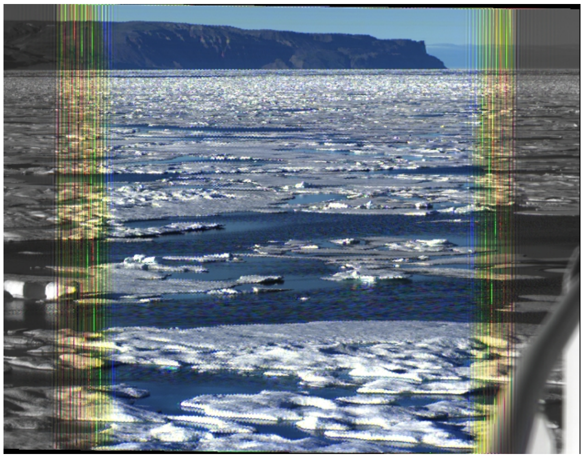

Figure 4. Pseudo-color rendering of a part of a panorama taken off Banks Island on July 31, 2004, starting at 03:07 UTC. The ship's position was 70.951^{o}N, 123.448^{o}W. Red is assigned to spectral band 14 at a wavelength of 630.9 nm, green to band 19 at 545.8 nm and blue to band 26 at 459.1 nm. The loss of color at the sides of the image are "edge effects" resulting from processing only a segment of the panorama, and are a consequence of the relevant columns of pixels not passing through the entire horizontal frame, and therefore having truncated interferograms.

demanding situation of an ice-breaking research vessel. The data are of good quality and it is anticipated that the scientific objectives of the project, to measure accurately the bi-directional reflectivity of the snow and ice surface during the melt season, will be met. Thus, the concept of the instrument design is correct and justified.

The advantages of an imaging spectroradiometer over those that provide only a point measurement are several. Not the least of which is the efficiency of the measurement; a whole panorama encompassing over 270^o azimuth range, can be acquired in just over an hour. Furthermore, the spectral measurements can be analyzed in context, as the spectra are obtained from an image. Additionally, the spatial distribution of reflectivity can be derived from the images and this is especially important when the horizontal heterogeneities are large, as is the case in the transition periods from the dry frozen surface through the melt season. The ability to generate maps of the spatial distributions of the surface reflectivity also facilitates the study azimuthal dependencies of the different surface types. The knowledge of the spatial distributions of surface types and their properties is particularly relevant to the validation of satellite-derived fields, as much of the heterogeneities are on scales below the horizontal resolution of most earth-observing imaging radiometers.

5 ACKNOWLEDGEMENTS

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