Carnegie Mellon

REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE 30 Oct 03	3. REPORT TYPE AND DATES COVERED Final 1 Apr 01 – 30 Sep 03
4. TITLE AND SUBTITLE High Performance Cameras for Hyperspectral and Polarimetric Imaging Research		5. FUNDING NUMBERS C-DAAD19-01-1-0430 PR-E-41736-EL-RIP-01037-1
6. AUTHOR(S) Louis J. Denes, Ph.D.		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Carnegie Mellon University 5000 Forbes Avenue Pittsburgh PA 15213-3890		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) U. S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211		10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12 a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited.	12 b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

The high-performance cameras and accessories obtained through this DURIP grant provide important state-of-the-art instrumentation to the **Spectral Visualization Laboratory** at the Robotics Institute of Carnegie Mellon University. This research-grade instrumentation supports programs sponsored by the Army and other government agencies in hyperspectral imaging. CMU's hyperspectral imaging technology is based on the acousto-optic tunable filter (AOTF), a technology that optimally exploits remote sensing in the hyperspectral domain. Our research initiatives cover from the visible-near infrared (0.4 -1 µm) spectral domain to the mid-IR (1 - 5 µm) and far-IR (8 – 12 µm) regions. Advantages of infrared hyperspectral imaging are greater signature differentiation, emissive (heat) signatures and superior aerosol penetration that will considerably enhance numerous DoD sponsored initiatives in automated target recognition (ATR). Examples include: better penetration through cloud cover, extended vision over sea water, and target ID under extreme ground terrain/camouflage and battlefield smoke scenarios.

14. SUBJECT TERMS Cameras, high performance, broadband, visible through infrared, research instrumentation, transportable			15. NUMBER OF PAGES 30
			16. PRICE CODE
17. SECURITY CLASSIFICATION OR REPORT **UNCLASSIFIED**	18. SECURITY CLASSIFICATION ON THIS PAGE **UNCLASSIFIED**	19. SECURITY CLASSIFICATION OF ABSTRACT **UNCLASSIFIED**	20. LIMITATION OF ABSTRACT **UL**

NSN 7540-01-280-5500

Standard Form 298 (Rev.2-89)
Prescribed by ANSI Std. 239-18
298-102

Carnegie Mellon

High Performance Cameras
for Hyperspectral and Polarimetric Imaging Research

To Support Advanced DoD Imaging Technology Initiatives

Final Report

Contract: DAAD19-01-1-0430
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

Defense University Research Instrumentation Program
for acquiring equipment critical for continuing research
at Carnegie Mellon University
in the area of infrared hyperspectral imaging

October 30, 2003

Point of Contact: Dr. Louis Denes
Senior Scientist
Tele: 412-268-3647
Fax: 412-268-7759
E-mail: ld2s@andrew.cmu.edu

Table of Contents

High Performance Cameras

1.0 Abstract

The high-performance cameras and accessories obtained through this DURIP grant provide important state-of-the-art instrumentation to the **Spectral Visualization Laboratory** at the Robotics Institute of Carnegie Mellon University. This research-grade instrumentation supports programs sponsored by the Army and other government agencies in hyperspectral imaging. CMU's hyperspectral imaging technology is based on the acousto-optic tunable filter (AOTF), a technology that optimally exploits remote sensing in the hyperspectral domain. Our research initiatives cover from the visible-near infrared (0.4 -1 μm) spectral domain to the mid-IR (1 - 5 μm) and far-IR (8 – 12 μm) regions. Advantages of infrared hyperspectral imaging are greater signature differentiation, emissive (heat) signatures and superior aerosol penetration that will considerably enhance numerous DoD sponsored initiatives in automated target recognition (ATR). Examples include: better penetration through cloud cover, extended vision over sea water, target ID under extreme ground terrain/camouflage and battlefield smoke scenarios.

The **Spectral Visualization Laboratory** serves two primary objectives within the university environment:

1) As a Test bed facility for Army/DoD research activities involving hyperspectral/spectro-polarimetric initiatives.

2) As a learning electro-optics/robotics laboratory for teaching and training undergraduate and graduate students at CMU.

We used considerable thought in using the following criteria in the selection of the high-performance equipment purchased under this grant.

- The equipment must be readily hand-transportable for both laboratory and field-trial deployment. Flexible usage has high value.

- Cameras, controllers and processors power from a single readily available source (110 AC or 12/24 DC).

- Cooling (when required) must be thermo-electric. No consumables (e.g. liquid N_2).

4) Data transfer through a fast computer interface (i.e. IEEE 1394 - 'Firewire').

5) All controller and processing functions obtained through a notebook host computer.

The camera ensemble that we purchased provides, in three steps, continuous coverage over the spectral range from 0.4 to ~11 μm. These cameras will allow test and evaluation of new hardware, the building of comprehensive spectral database for characterizing target signatures, and a means to create new image processing algorithms.

2.0 Background

Infrared hyperspectral imaging systems have been deemed critical to various mission scenarios by all branches of the military. Carnegie Mellon has been developing hyperspectral imagers based on AOTF technology with primary support coming from the Navy (ONR) under a MURI program (POC Tom McKenna, Ph. 703-696-4503), and more recently, from an Army FEDLAB program, entitled Multi-Domain Spectral Sensors (POC Herb Pollehn, Ph. 301-394-4616 and Neelam Gupta 301 304 2451). Previous interactions have shown strong interest at DARPA/ETO (Elias Towe, Ph. 703-696-0045), BMD (Mike Lee, Ph. 256-955-2692) and Air Force/Wright Laboratory (Pat Gardner, Ph. 937-255-4039) for spectral technology in conjunction with their various programmatic initiatives.

The AOTF uniquely images the entire scene in a single spectral band, and the bands are then electronically scanned, which eliminates the need for push broom scanning. This not only simplifies the process as the scene does not have to be assembled from individual line images, but there are also additional advantages, such as higher optical throughput and the ability to select specific bands without having to gather all the spectral bands before assembling the spectral image. The AOTF has the advantages of throughput, speed, flexibility, and compactness compared to other spectrometers. Its most outstanding characteristic is that the center wavelength is electronically tunable over a wide spectral range by simply changing the frequency of the acoustic wave. Interference filters, diffraction gratings, birefringent filters, and etalons are all mechanically tuned. Since the AOTF is polarization sensitive, it can analyze the polarization state of a scene, a feature of notable importance in classifying objects within a spectral scene.

Some results from an Army application are shown in **Figure 1**. Here our AOTF-based hyperspectral imager detected a military truck hidden by camouflage netting. This device, which operates in the visible and near infrared range of the spectrum, underwent successful field trials

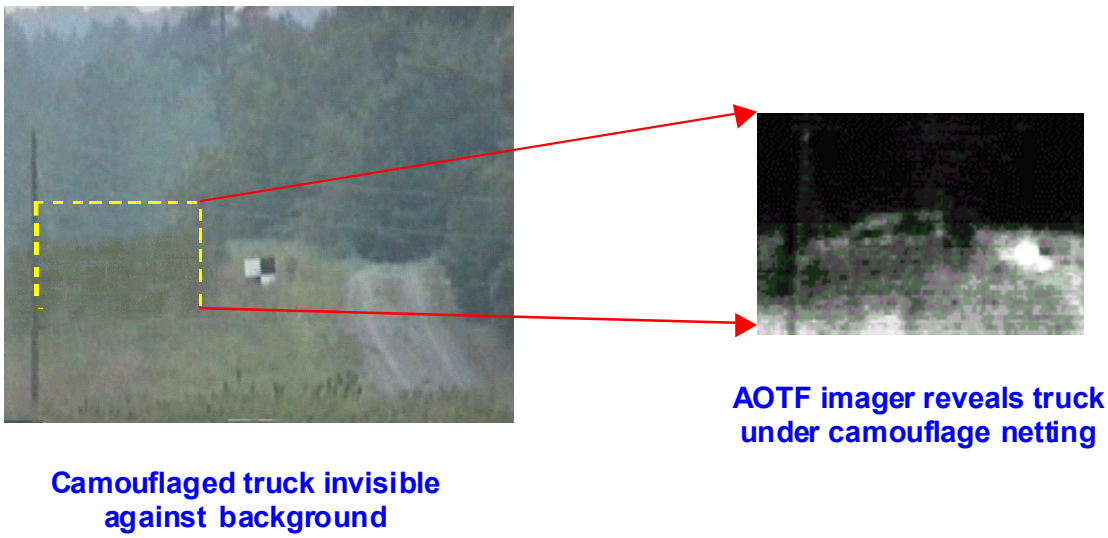


Figure 1 - Carnegie Mellon's spectro-polarimetric imager locating targets in background, such as trucks covered with camouflage netting.

under battlefield conditions at Fort A. P. Hill, VA in 1998.

The capabilities of this hyperspectral imager can be greatly improved by extending its range into the mid and far infrared, as indicated by the example shown in **Figure 2**. In particular, the ability to penetrate smoke and fog increases with increasing wavelength; this will enhance the usefulness of the *polarization difference imaging method*, which we have demonstrated in the laboratory to be capable of enhancing visibility by up to 100x. Such capabilities are needed in several theaters of operation, where air superiority has been degraded by bad weather conditions. We know that there are unique spectral and polarization target signatures seen in emission, rather than reflection, requiring infrared sensor systems. These will be particularly useful for typical battlefield conditions encountered by all of the armed services. Advancement of this technology depends upon the availability of high quality IR crystals.

2.1 Present Programs

Figure 2 - Target imagery under smoke-screen conditions: M113 armored personnel carrier at 1192 m (right vehicle in each image), and M2 Bradley at 3209 m (left vehicle in each image): broadband visible CCD image is obscured (left), 3-5 μm LM InSb camera image shows M2 and parts of M113; 8-12 μm QWIP camera provides ATR-quality imagery (right). Data taken by Sanders-Lockheed Martin at fort A.P. Hill, September 1998.

DoD support for the AOTF based programs at CMRI is provided by two agencies, an ONR-sponsored MURI program on Automated Vision, and an ARL-sponsored FEDLAB program on Multi-Domain Spectral Sensors. CMU's contributions to both of these are directed at target recognition through the use of hyperspectral and polarization imaging. Hyperspectral discrimination is emerging as a high payoff component of the Army's 21st century digital battlefield, and CMRI has pioneered the development of AOTF hyperspectral imagers over the last decade. **Figure 3** presents a prototype system imager being tested under Army, Navy and DARPA programs. Our hyperspectral imager utilizes an AOTF capable of obtaining spectral measurements for an entire scene at 30 microseconds per spectral band. Designed for operation as a field-portable device in demanding outdoor environments, the device is rugged,

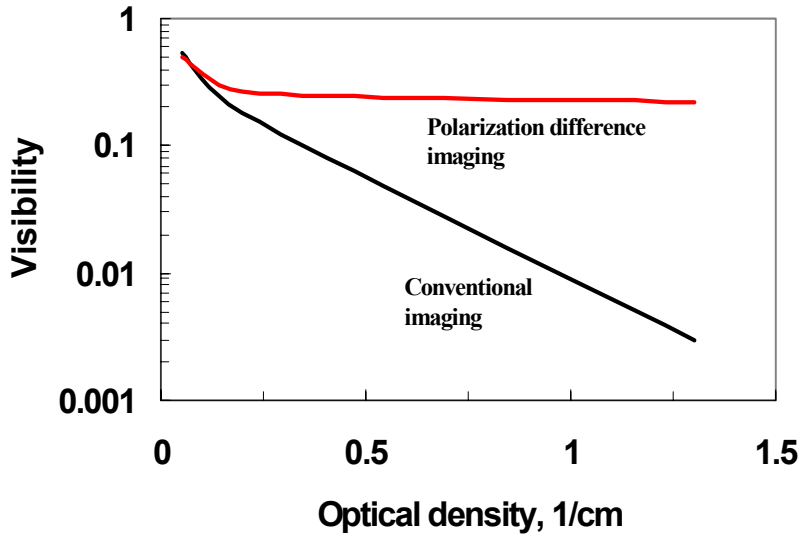
compact and modular. Its design offers unprecedented flexibility and permits microscopic to telescopic imaging in a wide range of configurations under open sky or laboratory conditions.

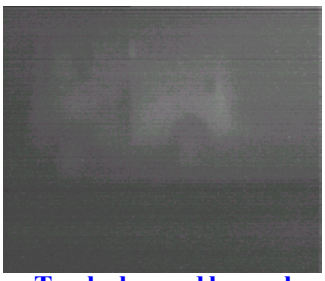
Specifications

AO material	TeO_2
Spectral range	450-1100 nm
Resolution	10 nm @600nm
AO efficiency	>80%
RF range	25-70 MHz
Retarder range	400-1800 nm
IFOV	~7deg (Optics Adjustable)
RF power	<1 W
AOTF aperture	15 x 15 mm
AO Interaction	15 mm
Crystal length	26.5 mm
Min. Illumination	CCD Camera dependent

Figure 3 - Prototype AOTF spectro-polarimetric imager.

$$\text{Visibility} = \frac{I_{target} - I_{background}}{I_{target} + I_{background}}$$





Truck obscured by smoke

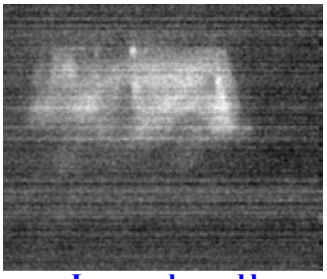


Image enhanced by polarization difference

Figure 4 - Polarization difference imaging enhances target visibility through smoke and fog.

The system has polarization discrimination capability, and is a complete spectro-polarimetric imager. For instance, a scene might be examined at specific wavelengths and polarizations, and scene subtraction used to enhance features in the scene. We are presently investigating this technique for the Army to detect hidden and camouflaged targets, along with extending the visibility range of imaging systems. This is especially useful to the military in seeing through clouds and fog, as depicted in **Figure 4**, where the visibility remains constant with polarization difference imaging, while it greatly drops off under increasing obscuration with conventional imaging. This technology applies to other military and commercial applications, such as mineral exploration, land management, and crop assessment.

One of the initial projects being considered for our newly acquired thermal imaging systems is in medical diagnostics. Thermal imaging is being considered in the diagnosis of Rheuma in children. The goal is to provide localized temperature monitor over the affected areas that can be remotely monitored by the treating physician. The CMU Robotics group through Dr. Andreas Nowatzyk is in contact with Dr. Raphi Hirsch of the Children's Hospital of the University of Pittsburgh Medical Center (UPMC) to pursue this initiative.

3.0 Acquired Equipment

The image-processing laboratory serves to train, to design, to implement advanced imaging systems, and to acquire and to analyze spectropolarimetric data that ultimately leads to new algorithms for target recognition. The following camera-based equipment serves to provide this functionality.

0.4 – 1.1 μm High–Performance Camera

Qimaging **Retiga 1350 EX Digital Camera** **Cost: $ 12,600**
Supplier: I-Cube
Crofton, MD 21114

Camera Features:

- Super-high sensitivity Exview CCD technology
- Peltier cooled for low light imaging
- 1660 x 1036 resolution
- Up to 100 frames per second
- 12-bit digitization
- Programmable gain and offset
- Compact size
- Programmable exposure - 15 μsec to 15 minutes
- All features programmable through host computer
- Compatible with a laptop (notebook computer)

Retiga 1350 EX Digital Camera

Figure 5 pictures the Retiga 1350 EX digital camera incorporated into the second-generation spectro-polarimetric imager system. Included in the hardware is a high performance notebook computer, seen in the foreground that provides the imager's control interface and display. The General User Interface (GUI) has been coded. We are now embarking on detailed coding to obtain the intended functionality and data processing algorithms.

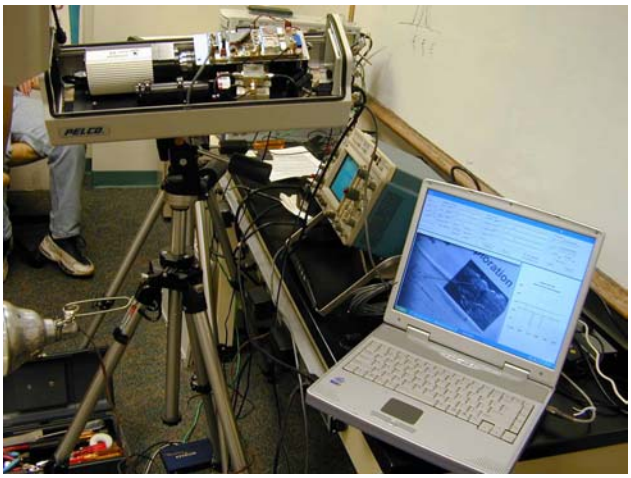
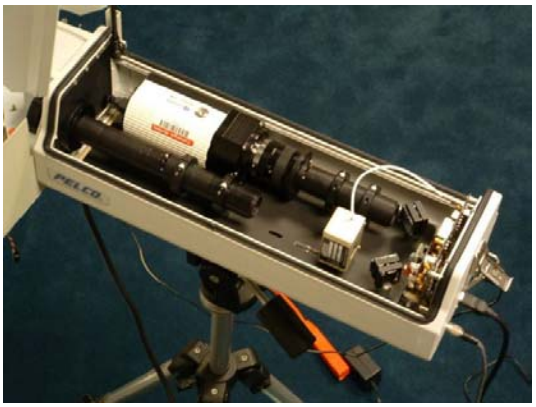


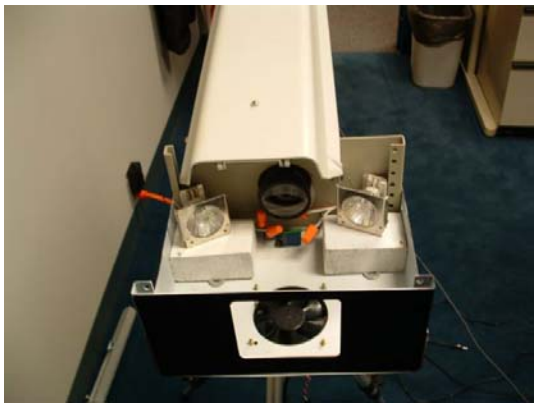
Figure 5. Gen 2 Spectropolarimetric imager utilizing the Retiga 1350 EX digital camera

The Retiga EX camera in the past year has had two major updates. The first update occurred during November 2002 which converted its features from an 'A' model to a 'B' model. This upgrade basically permits multi-threading camera control making it possible to perform camera operations simultaneously. The second update that occurred very recently (May 2003) change the camera to a EXi model. This camera has three times the sensitivity of the older model.

The updated EXi CCD camera has been installed into the Gen 2 Spectropolarimetric imager that has been adapted for the commencement of clinical testing with patients with diagnosed or suspected cancerous moles (nevi). Pictured is our hardware in its current state of implementation: The EXi CCD camera is shown in the left photograph. The right photograph pictures the two illumination lamps that are installed to the face plate of the Gen 2 Spectropolarimetric imager.

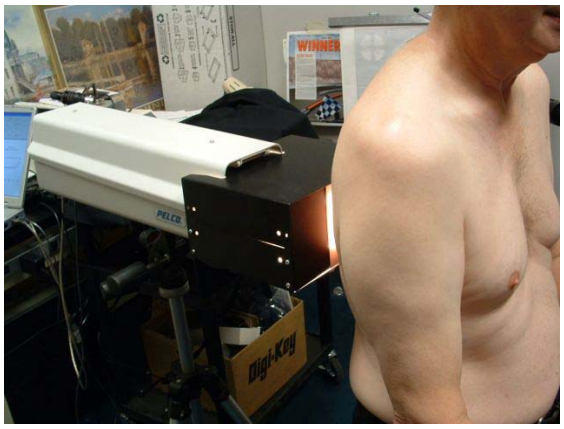


Diagnostic spectropolarimetric camera - illumination housing is partially shown at the left.

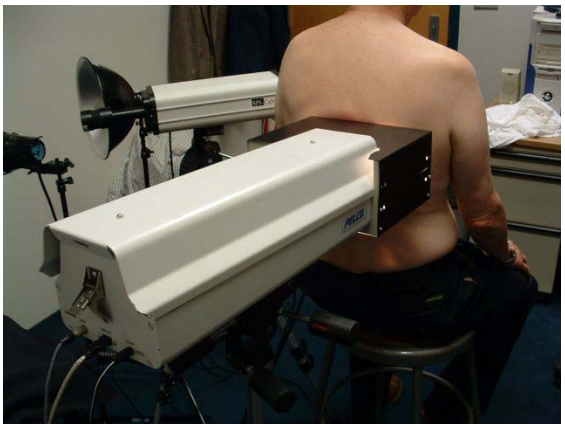


Front end of the Diagnostic spectro-polarimetric camera showing the Illumination lamps and imaging window.

The clinical scenario is shown below. The patient places the skin area under surveillance at this plane as pictured in the second and third photographs. The forth and fifth photographs give displays of the back of the hand, and an area of the stomach adjacent to the 'belly button'.

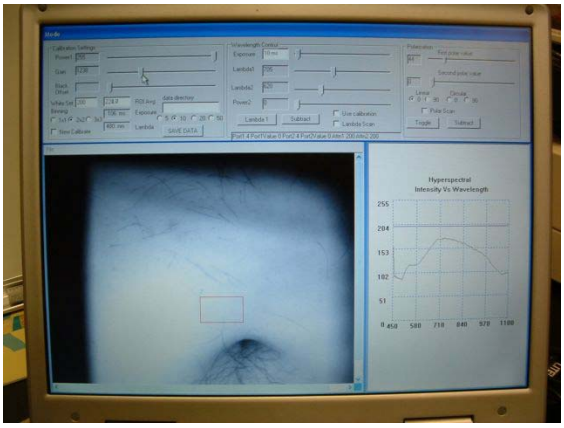


Frontal view of test subject under examination.



Rear view of same test subject under examination.


Notebook display of test subject's hand.


Notebook display of test subject's stomach area.

Broad band infrared polarizers

Broad band infrared polarizers are components that allow polarimetric calibration throughout the infrared. Our selection focused to the BaF_2 polarizers that can cover the spectral range from the visible to about 10 μm with high transmission without the need anti reflection coatings. Descriptive details and comparative features are displayed below. The best-option supplier was Optometrics USA, Inc. of Ayer MA.

Two polarizers were acquired:

Part number 5-8221 BaF2 2400 G/MM Holo polarizer, 50 mm diameter, 34 mm clear aperture, mounted. Total cost is $2600.

Optometrics LLC

HOLOGRAPHIC WIRE GRID POLARIZERS… for Infrared Applications

Highlights

- 2400 Grooves per mm
- On Calcium Fluoride (CaF_2), Barium Fluoride (BaF_2), Zinc Selenide (ZnSe) and KRS-5
- For improved short wave-length performance
- For performance beyond 30 microns (KRS-5)
- Extended infrared range
- High transmission
- High extinction ratios
- Customize for higher transmission or higher extinction ratios

Working with experts in the field, Optometrics has developed a special holographic technique to produce Infrared Polarizers with a sub-micron grid spacing.

In the Company's holographic laboratory, an interferometrically generated interference fringe pattern is produced from monochromatic light and exposed onto a photo-resist coated substrate. Once developed, the resist has a regular sinusoidal profile which is vacuum aluminized at an oblique angle to create the array of parallel conductors.

Optometrics LLC
Nemco Way
Ayer, MA 01432 USA
Tel: (978) 772-1700
Fax: (978) 772-0017
E-Mail: sales@optometrics.com
www.optometrics.com

HOLOGRAPHIC POLARIZERS……

Compliments Optometrics' existing line of ruled wire grid polarizers on CaF_2 and ZnSe.

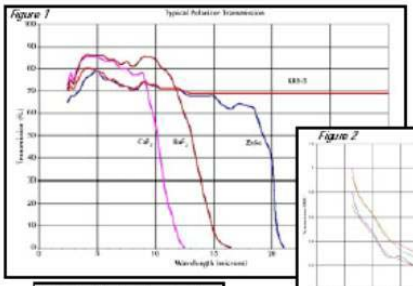
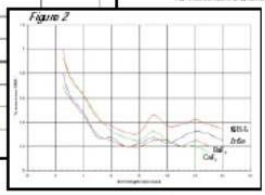


Figure 1 - Typical transmission in linear polarized light with wire grid polarizers oriented for maximum transmission.

Figure 2 - Typical transmission in linear polarized light with wire grid polarizers oriented for minimum transmission.



Material	Wavelength (microns)	Typical Extinction Ratio
CaF_2	3 8	100 250
BaF_2	3 10	100 300
ZnSe	3 10	100 300
KRS-5	3 15	100 200

CAUTION

The surface of a wire grid polarizer, like any diffraction grating, is extremely delicate. Nothing should ever be allowed to touch the surface of the polarizer. Handling, when necessary, should be by the edge only and with protected fingers. Careful removal of dust by gentle air flow is the only cleaning procedure recommended by Optometrics. Particular care should be used when handling KRS-5.

Overcoatings

Calcium Fluoride and Barium Fluoride have low refractive index (high Tx) values and do not require anti-reflective (AR) coatings.

Zinc Selenide has a high refractive index and transmission at specific wavelength regions which can be enhanced by AR coating on one or both sides. Zinc Selenide is usually optimized for transmission at specific laser lines, typically from 9 to 11 microns.

KRS-5 is not normally AR coated, because this would limit its broad transmission range, which is its primary advantage.

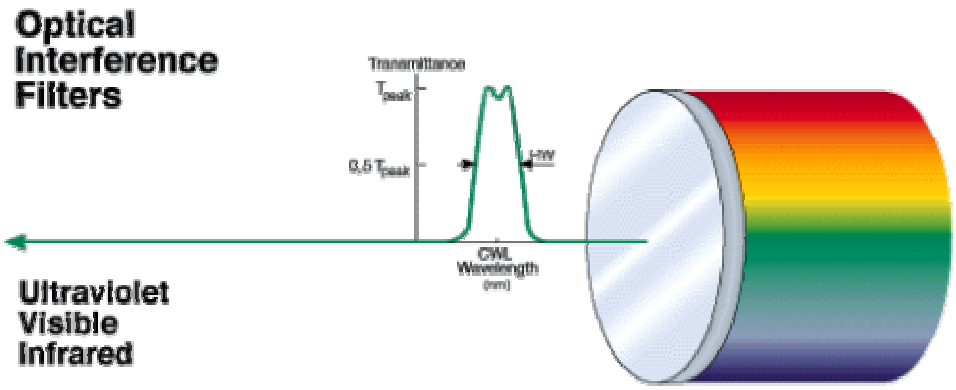
Standard Sizes and Options

All polarizers are available unmounted, mounted in a protective ring or mounted in a bench mountable stage which allows 360° rotation, in several standard sizes. If your application requires a different size or shape, please contact us for price and delivery. OEM inquires are welcome.

Our process allows us to tailor extinction ratios or transmission to suit your application needs. Call Optometrics for details.

Infrared filters

SPECTROGON US, INC. Parsippany, N.J. was selected for the IR filters based on price, expected quality and of-the shelf availability. Nine Filters, described below, were purchased covering the spectral range from 980 nm to a 10000 nm (10 µm) longwave-pass filter at a total cost of $3000.



Bandpass filters

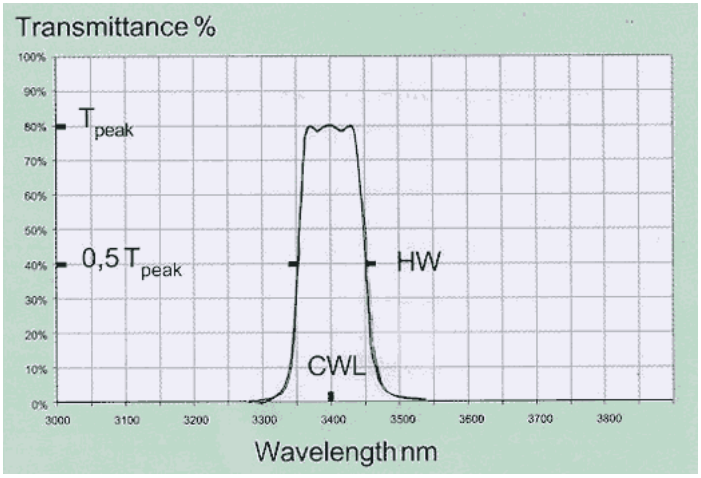
General Specifications:

Diameter: 25.4 mm +0/-0.2 mm

Transmittance: > 50 %

Blocking: Average < 0.1 % from UV to:
A: 1200 nm B: 3500 nm C: 6500 nm
D: Far IR E:10500 nm F:16500 nm
(Other blocking available upon request)

Transmission curve:
Supplied with each filter type



Catalogue no	CWL nm	Tol± nm	HW nm	Tol± nm	Unit price
BP-0980-055-A	980	10	55	10	$175
NB-1064-020-A	1064	3	20	3	$175
BP-1300-090-B	1300	20	90	20	$225
BP-1535-080-B	1535	10	80	10	$225

Broad-bandpass filters

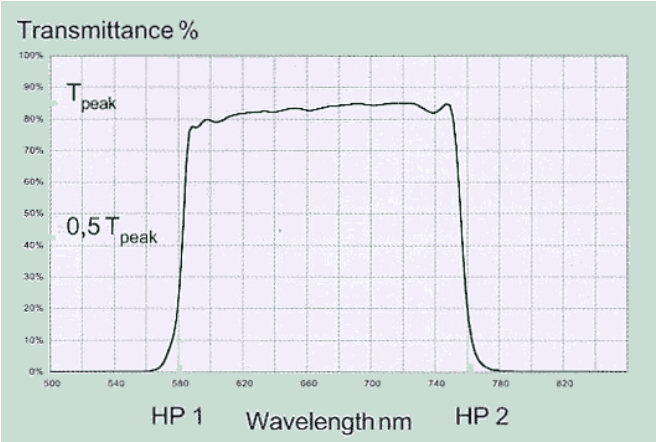
General Specifications:

Diameter: 25.4 mm +0/-0.2 mm

Transmittance: > 50%

Blocking: Average < 0.1 % from UV to:
A: 1200 nm B: 3500 nm C: 6500 nm
D: Far IR E:10500 nm F:16500 nm

(Other blocking available upon request)



Transmission curve:
Supplied with each filter type

Catalogue no	HP1 nm	Tol± nm	HP2 nm	Tol± nm	
BBP-2115-2550-D	2115	100	2550	125	$370
BBP-3000-5000-D	3000	75	5000	75	$475
BBP-4150-4620-D	4150	100	4620	100	$475

Shortwave-pass filters

General Specifications:

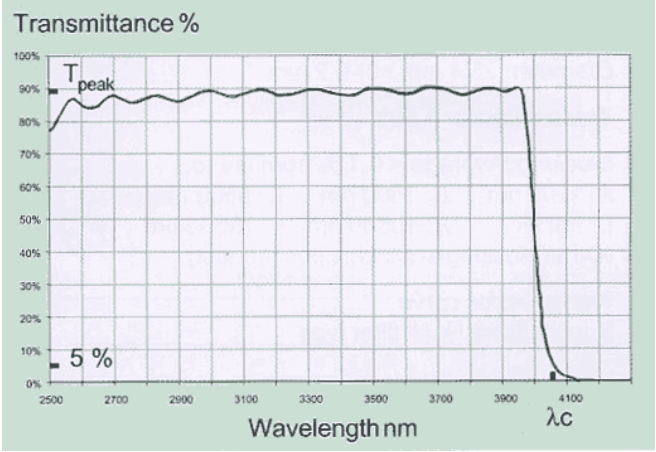
Diameter: 25.4 mm +0/-0.2 mm

Transmittance: Average > 60 % from T-range through last peak

Blocking: Average < 0,1 % above passband through blocked region

Slope: < 5 % defined as

$$\%Slope = \frac{\lambda(80\% \text{ of Tpeak}) - \lambda c}{\lambda c} \cdot 100$$



Transmission curve:
Supplied with each filter type

Catalogue no	Cutoff nm	Tol± nm	T-range nm	Block nm	
SP-9850	9850	200	5400	18000	$440

Longwave-pass filters

General Specifications:

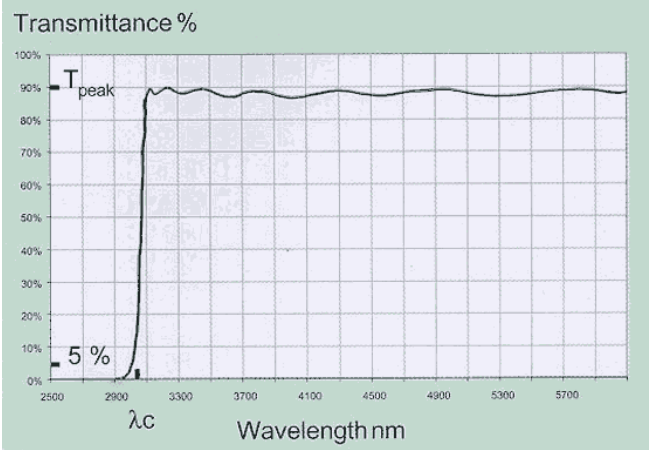
Diameter: 25.4 mm +0/-0.2 mm

Transmittance: Average > 75 % first peak through T-range

Blocking: Average < 0,1 % below passband through UV

Slope: < 5 % defined as

$$\%Slope = \frac{\lambda(80\% \text{ of Tpeak}) - \lambda c}{\lambda c} \cdot 100$$



Transmission curve:
Supplied with each filter type

Catalogue no	Cuton nm	Tol± nm	T-range nm	
LP-10000	10000	250	18000	$440
			Total cost of IR filters	**$3000**

Long-Wavelength (7.5 – 13.5 μm) microbolometer Camera

Indigo Systems **ALPHA Uncooled IR Camera** **Cost: $ 12,990**

Supplier: Ircameras Northeast
1600 Providence Highway
Walpole, MA 02081

ALPHA Uncooled IR Camera

<u>Camera Features:</u>

- 160 x 128 uncooled microbolometer focal plane array
- f/1.6 aperture
- Thermoelectric sensor stabilization
- Minimized size, weight and power
- Dimensions:1.7" H x 1.7" W x 3.0" L
- Weight: < 200 grams (< 7 oz.)
- Remote control through serial command interface
- Analog RS-170A
- Real time 12 bit corrected digital available (digital unit not purchased)
- 30 frames per second
- Camera parameters controlled by laptop (notebook computer)

The ALPHA uncooled camera system, pictured here, consists of the tripod mounted ALPHA camera, a video monitor and a notebook computer that provides the camera control interface that is displayed in the upper right hand corner of the display.

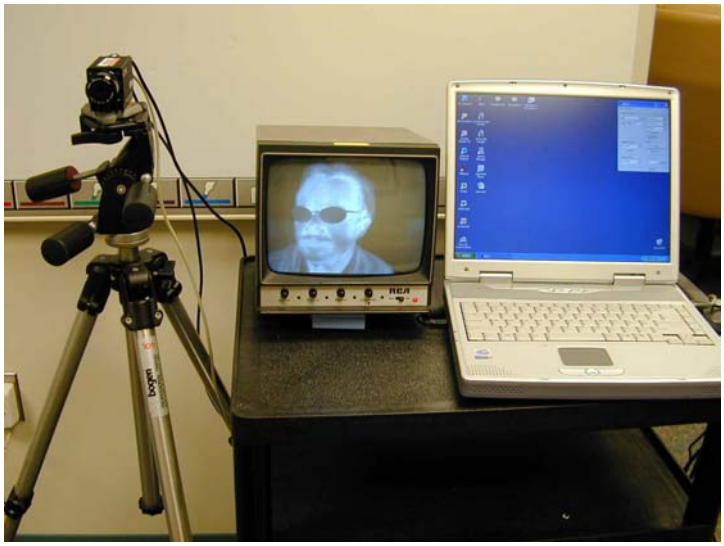


Image-processor notebook computer

M-Tech 928 notebook computer (custom configured) Cost: $2100

Supplier:
M-Tech Laptops, Inc.™
843 Richardson Rd.
Charlevoix, MI 49720

M-Tech 928 notebook computer

<u>Key notebook features:</u>

- Northwood core, 2.0 GHz CPU
- 256 KB DDR-SDRAM RAM
- 30 GB ATA 100 Hard drive
- Internal rewritable CD
- Six pin 1394 port
- 4 USB <u>2.0 ports</u>, transfer rate up to 480 Mbps
- Three year warranty

As displayed above with the various high end cameras, this customed configured notebook computer functions as a field-transportable image processor and display for utilization with newly acquired high end cameras set up in the Spectral Imaging Laboratory. This notebook computer fulfills the needs for both the Retiga and Alpha cameras for deployment in field evaluations and demonstrations. This computer has been a reliable workhorse working well with all of the cameras that were utilized to date.

Long-wave (Thermal) IR cooled (2-12 µm) Digital Camera

IDS-3100-2001 IRFPA imaging System with a CCH-05
Closed cycle Dewar Camera Head with MCT IRFPA **Cost: $80,950**

Supplier:
Talktronics, Inc.
17682 Gothard Street, Ste. 3
Huntington Beach, CA 92647

Talktronics, Inc was the only known supplier that agreed to meet our critical requirements for a versatile long-wave IRFPA Field-Portable Camera Systems at a competitive cost. Their system includes a fast (i.e. Firewire) interface and software (DTSpec Imaging Spectrometer Software) that runs on a systems integrated laptop. This longwave camera system comes with a 50-mm lens that can cover 2 to 12 micron range of operation. This system is hardware and software compatible and interchangeable with a mid-wave InSb IR camera system also developed for our equipment cadre by Talktronics (following topic).

The key performance features are the following:

1. Compact two-unit housings
2. High QE sensitivity
3. Cryogenic low noise operation
4. 2 – 12 µm functionality
5. Firewire (IEEE 1394) digital interface
6. Laptop computer control and display

Other camera vendors that we solicited marketed generic-type cameras that lack a fast interface (Firewire or USB). These cameras would be very unwieldy for field trials as frame grabbers and desktop computers are needed. Image processing software (included by Talktronics) from the other vendors is a costly additional expense.

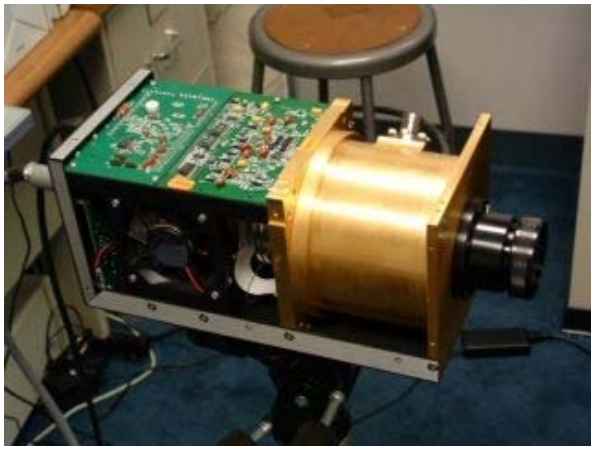
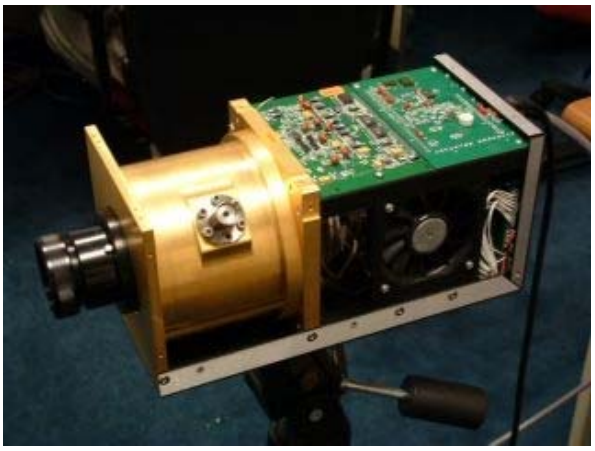
After a strong verbal commitment by Talktronics that Talktronics could meet our delivery requirements. We did not anticipate that Talktronics would be so delinquent in the delivery of both the MCT IR camera and the InSb IR camera. We have received a stream of messages from Doug Triman of Talktronics pleading for more time. As an example one of his latest messages asserts:

"I'm doing everything I can to get finished. I will be able to ship the MCT camera this week, and will make every attempt to get the InSb completed and ready for final test by end of this week. Is there any way to keep this project alive for a few more days? My schedule is finally opening up, and I will have more and more time per week to devote to the imaging business. I have been working through a very difficult situation to get to this point, and have not given up -- and have managed to keep working in spite of significant hardship. Please see if there is a way to see this through."

Our IDS3100-2001 MCT IRFPA Camera System including CCH-05 Camera Head finally arrived on 7/30/03. Below are pictures of the system.

MCT IRFPA Camera System consisting of a controller/power unit (left black box), the cryo-cooled camera head module (right black/gold box) and a laptop computer.

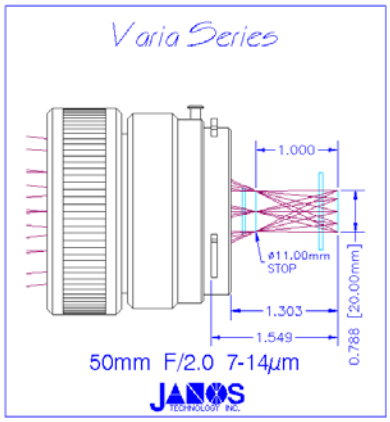
MCT IRFPA Camera System with covers removed from the controller/power unit (left) and the cryo-cooled camera head module (center)

Two views of the cryo-cooled camera module (CCH-05 Closed Cycle Dewar camera head) with its cover removed


Views of the controller/power unit (IDS-3100-2001 IRFPA Imaging System) with its cover removed.

The camera lens is a Janos Varia Series (50 mm F/2.0, 7 – 14 μm). The key dimensions are shown in the figure below. Janos has recently introduced a new lens NINOX series that covers a range from 3 to 12 μm. Focal Length available include 25 mm, 50 mm and 100 mm at F/2.3.



This camera unit overall is very professional and well built. Although not yet verified, the camera appears appropriate for field test trials in the army's programmatic initiatives.

The camera was sent back to Talktronics during the last week of September for hardware and firmware improvements. The improvements (vacuum integrity, firmware modifications, etc.) were confirmed by Talktronics while working on the Mid-wave IR cooled (1-5.4 µm) digital Camera. Further improvements will be necessary before the cameras will meet our nominal specifications. As the cameras now stand, they have implemented only a single point 'pedestal' correction for background subtraction. The images currently obtained from the camera clearly demonstrate that the individual pixels have grossly differing response. Consequently two-point correction is required to obtain a considerably improved image quality. This requires a firmware change, to reprogram the FPGAs. Talktronics estimates that it will take some time (at least weeks) to implement. We expect that Talktronics will implement the two point calibration that results in good image uniformity before the return the long-wave MCT cooled digital camera head.

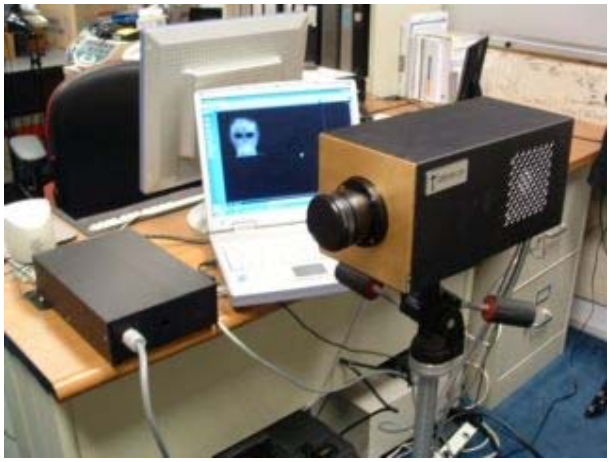
Mid-wave IR cooled (1-5.4 µm) digital Camera

IDS-3100-173 IRFPA imaging System with a CCH-05
Closed cycle Dewar Camera Head with InSb IRFPA **Cost: $58,950.00**

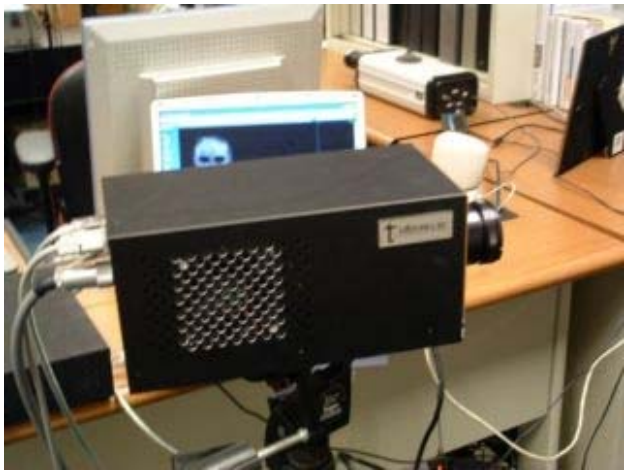
Supplier:
Talktronics, Inc.
17682 Gothard Street, Ste. 3
Huntington Beach, CA 92647

Talktronics, Inc was also the sole supplier identified that agreed to meet our critical requirements for a versatile mid-wave IRFPA Field-Portable Camera Systems at a competitive cost. Their system includes a fast (i.e. Firewire) interface and software (DTSpec Imaging Spectrometer Software) that runs on a systems integrated laptop. This midwave camera system comes with a 50-mm lens that would cover the 3 to 5 micron range of operation with some hope of extending down to 1 micron. This system, as designed and built, is hardware, software compatible and interchangeable with a MCT IR camera described above.

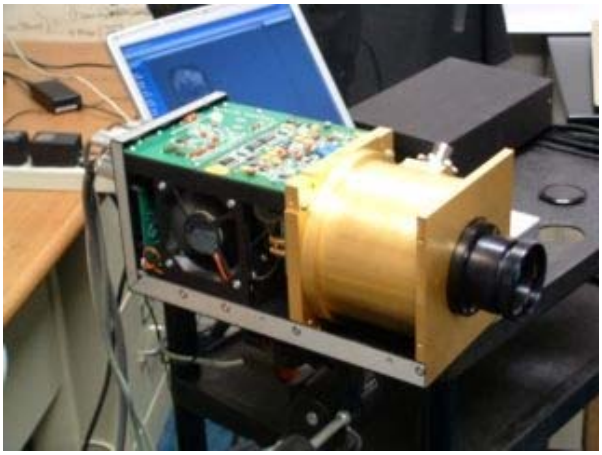
Our IDS3100-2001 InSb IRFPA Camera System including CCH-05 Camera Head finally arrived on 9/20/03. As received, the camera required to be re-evacuated so that cryo-temperature operation is possible. Using in-house facilities, we achieved the required vacuum and began check-out. Below are pictures of the system components.




InSb IRFPA Camera System consisting of a controller/power unit (left black box), the cryo-cooled camera head module (right black/gold box) and a laptop computer. A face image obtained from the camera is displayed on the laptop screen at the right picture. Note the graininess of the image. The reduced image size is caused by the 256 x 256 image being displayed on a 640 x 480 format. This is an artifact of the current Firewire interface software.

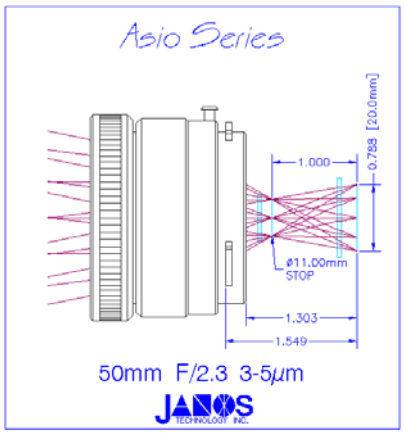
Right and left side views of the InSb cryo-cooled camera module (CCH-05 Closed Cycle Dewar camera head)

Right and left side views of the InSb cryo-cooled camera module (CCH-05 Closed Cycle Dewar camera head) with its cover removed.

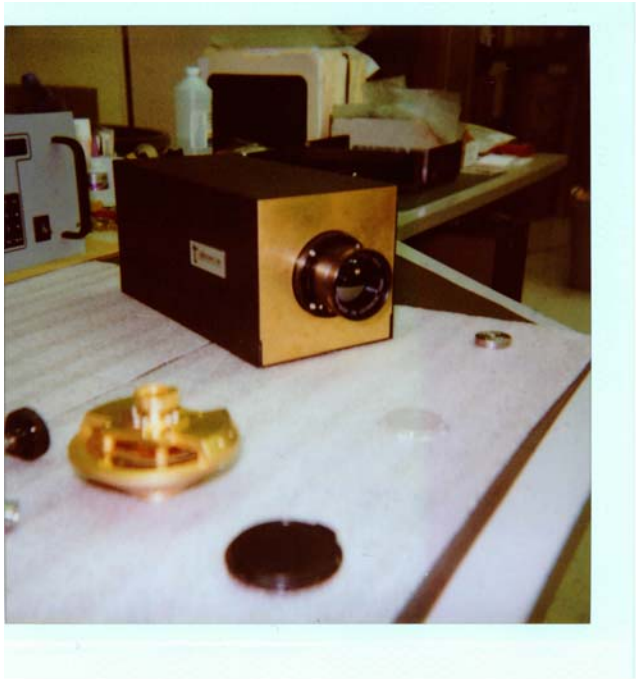

Views of the controller/power unit (IDS-3100-2001 IRFPA Imaging System) with its cover removed.

The camera lens is a Janos ASIO Series (50 mm, F/2.3, MWIR 3 – 5 μm), part # 40495-0068. The key dimensions are shown in the figure below. A separate lens will be required to extend down to the 1 μm specification.



We include photographs of the hardware-in-development that Talktronics sent on 4/16/02. This allows visualization of some of the specific internal components.

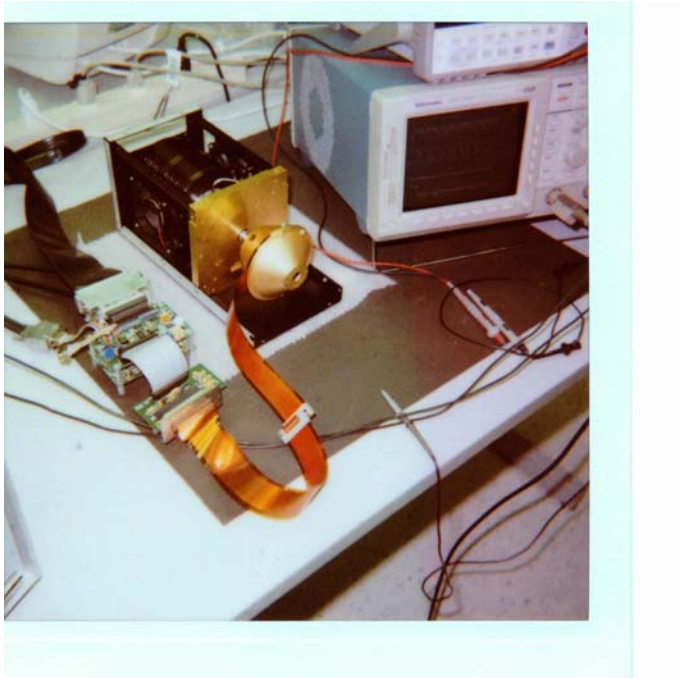
Views of the assembled IDS3100 IR Camera.



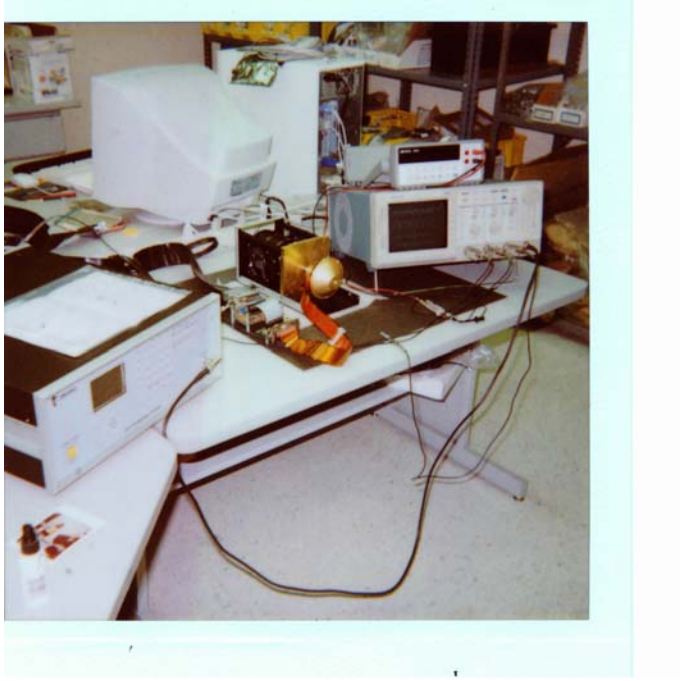
With cover removed, note vacuum pump-out port, with manual valve operator, connected to vacuum pump (not visible).

Other (circular) assembly is the FPA enclosure and radiation shield. Note the vacuum shroud "can" has square front flange, and is connected to matching base plate in rear. This is camera #2. (EOI temperature source is in background).

View below shows camera #1 attached to IDS2100 Development system. Note FPA assembly on front of cryo-cooler. Difficult to see, but the cryo-pump heat sink assembly can be seen behind the gold "base plate", with fans on either side. Test electronics is tied to flex circuit that normally is contained in the vacuum shroud.

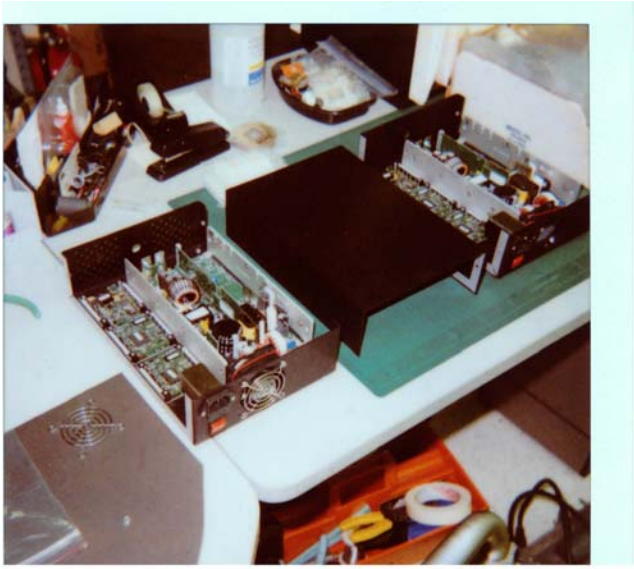


Another view of camera #1 and the development/test setup. The IDS2100 system (at left) is used to develop and test the gate array programming for the finished camera.



A view of the IDS2100 development system.

Two of the IDS3100 power supplies, and a cover.

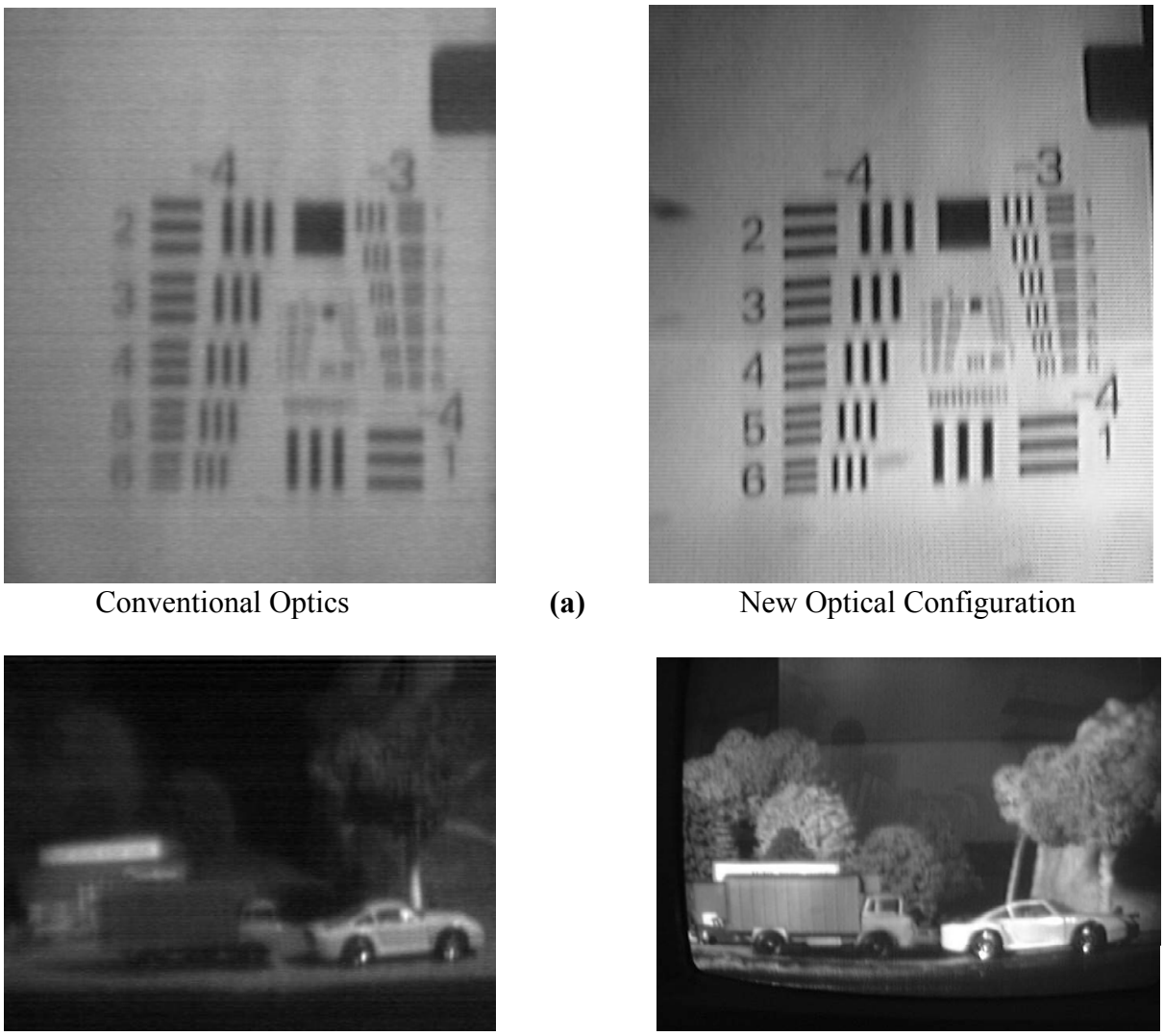


4.0 Research Benefits of the High Performance Cameras

Operation of our present electro-optical system using low-cost CCD arrays is limited to the 0.5-0.9 μm spectral range with signal to noise ratios (S/N) in the 46 to 56 dB range (broadcast quality cameras are in the 72 dB or higher range). Since our new thrust is to extend operation to broader operation, especially to the mid- and far infrared, we must expand our optical imaging capabilities to include infrared arrays and associated optical components. We were under a subcontract with Northrup Grumman (prime to ARL) to evaluate a far-infrared imaging AOTF, for which our in-house capability is restricted by the lack of an infrared camera. In addition to extending the wavelength range, another goal of our research activity has been to greatly improve the quality of the images produced by our hyperspectral systems. Typically, the spatial resolution has been severely degraded by various aberrations associated with AOTF imaging systems. Recently, new optical designs implemented at CMRI have led to order-of-magnitude improvement in the spatial resolution produced by AOTF imaging, as is shown in **Figures 5a and 5b**. We are now capable of achieving pixel-limited resolution, necessitating the incorporation of very high quality cameras to exploit these new designs.

The new high performance cameras for the image processing laboratory will contribute to our research capability in the following ways:

- Testing and evaluation of IR AOTF devices and systems.
- Acquisition of data for establishing IR target signatures.
- Conducting scenario studies for modeling infrared content.
- Creation of new algorithms and software for IR target recognition applications
- Evaluation of IR crystal quality



Conventional Optics **(a)** New Optical Configuration

Conventional Optics **(b)** New Optical Configuration

Figure 5 - Dramatically improved image quality with new optical configuration.

5.0 Interest in Materials for Infrared AOTFs

The key to developing infrared AOTF imagers is the availability of long-wave infrared (LWIR) AO materials and devices. The only highly developed LWIR AO material is germanium, a material that works well in isotropic applications such as scanners, and sold commercially for such applications as rapid scanning of CO_2 laser beams. For AOTFs and other birefringent applications, no commercialized materials exist in the LWIR, and the development of LWIR AOTF spectrometers and imagers depends upon having a consistent supply of these materials.

AO devices can generally be classified as relating either to optical processing, or spectroscopy, including spectral imaging. Optical processing is almost exclusively done in the visible, where excellent AO materials such as TeO_2 exist, whereas spectroscopy must often be done in the infrared due to the vibrational spectra of the molecules of interest. Unfortunately TeO_2 does not transmit beyond 4.5 μm, yet some of the most productive molecular spectra occur at wavelengths beyond this point. There are a number of AOTF materials transparent in the LWIR spectral region, including Hg_2Cl_2, Tl_3AsSe_3, Hg_2Br_2, Hg_2I_2, Tl_3AsS_4, and AgTlSe. Of these, Tl_3AsSe_3 (TAS) has been used the most extensively. It is efficient and can be grown in large, high quality boules. It does suffer from fragile crystal structure that makes it difficult to fabricate and easily damaged. The transmission range is 1.2-17 μm. Hg_2Cl_2 is notably similar to TeO_2, but transmits much deeper into the infrared. It is also transparent in the visible, which aids in fabrication since defects can be seen without using an IR camera. It is less efficient than TAS, but has a larger birefringence, Δn, which results in a higher resolution for a given interaction length.

Table 1 - Properties of LWIR AOTF materials.

Parameter	**TAS**	**Hg_2Cl_2**	**Hg_2Br_2**
Transmission (μm)	1.2-17	0.36-20	0.40-30
Index (n_o) at 10 μm	3.34	1.90	2.03
Δn at 10 μm	0.18	0.55	0.67
V_a (km/sec)	1.05	0.347	0.273
Max M_2 at 10 μm	2715	704	2607

(Figure of Merit relative to Silica)

Hg_2Br_2 has one of the largest transmission ranges of any optical material, which extends to 30 μm. It has efficiency similar to TAS, and a higher Δn than Hg_2Cl_2. It has been used mainly as experimental delay lines due to its extremely slow acoustic velocity, which is slower than that of sound in air. These properties are summarized in **Table 1.**

Each material has particular strengths and weaknesses for AOTF device fabrication. In general, the acoustic interaction frequency in the LWIR is comparable for all three. The interaction length L needed for a particular resolution will be about the same for both Hg_2Cl_2 and Hg_2Br_2, which is about three times less than TAS. This effect is due to the resolution scaling inversely roughly as ΔnL, a parameter of importance in developing very high resolution AOTFs.

The diffraction efficiency for a given acoustic intensity is roughly proportional to the figure of merit M_2, which is nearly identical for TAS and Hg_2Br_2, and considerably smaller for Hg_2Cl_2. This is not necessarily a problem since the acoustic power and efficiency can always be increased, provided crystal damage does not occur. With TAS, the safe operating limit is less than 0.5 W/cm^2 for uncooled devices, whereas we believe the power loading of Hg_2Cl_2 is similar to TeO_2, and can tolerate about an order of magnitude more power. With cooling, it should be possible to increase the power loading considerably for both TAS and $HgCl_2$. Very little work has been done in this area for these materials; however, one can point to commercial infrared germanium scanners, which are water cooled, and can be operated at power levels approaching 100 W/cm^2.

5.1 Advancement of Crystal Growth Facilities

CMU's collective AOTF crystal and device experience spans several decades at various companies and institutions. Over the past several years our group has grown near-optical quality Hg_2Cl_2, all under internal funding. The next step in crystal development is to expand our activities to grow larger optical quality crystals that are needed for first-generation IR hyperspectral imagers.

6.0 Benefits to Student Training

The primary mission of the university is to generate knowledge through education and scientific research. Student training is one of the core components in the process. It has been the tradition at CMRI to provide opportunities to undergraduate and graduate students, as well as interns and postdoctoral fellows. Typically, undergraduates and interns are given tasks involving software programming, materials processing and hardware assembly and data collection. Graduate students and postdoctoral fellows will become closely involved developing new materials growth methods, hyperspectral sensor system design and integration, and advanced image understanding. It is expected that these areas will lead to Ph.D. thesis level research programs. The proposed new equipment will greatly enhance the range of research opportunities opened.

7.0 Personnel

These highly qualified and experienced members of the CMU's professional and technical staff are recognized experts in their various areas of expertise. Biographies of the key people are included in the following paragraphs.

L.J. Denes, Ph.D.
Louis Denes received his Ph.D. degree from the University of Pittsburgh in Physics in 1965. Coming from Westinghouse in 1991, he has been associated with Carnegie Mellon University as a senior staff member and Electro-optics Program Manager at the Carnegie Mellon Research Institute. He has over 30 years experience in the development of numerous optical sensors / sensor systems involving acousto-optics, IR sensing, lasers, laser-based systems, vision systems, automated metrology and fiber optics. He has managed many projects leading to the development of remote sensing systems, serving as principal investigator on numerous corporate and government agency projects including those with the Air Force, Army, Navy and Bureau of Mines. Previously, he was employed at the United Technologies Research Laboratories, East Hartford, CT (1966-1970) and at the Westinghouse R&D Center, Pittsburgh, PA (1970-1991). He is the author of numerous technical papers and holds a number of patents.

M. Gottlieb, Ph.D.
Milton Gottlieb received his B.S. degree in Physics from the City College of New York in 1954, and Ph.D. in Physics from the University of Pennsylvania in 1959. He spent most of his career since 1959 with the Westinghouse Science and Technology Center from which he retired in 1993 as a Consultant Scientist in the Optical Department. At Westinghouse he worked in the areas of thermionic energy conversion, superconductivity, acousto-optics, fiber optic sensors, optical materials and optical information processing. Following retirement from Westinghouse,

he joined Rosemount Analytical, Inc. as a Senior Scientist, where he worked on development of spectroscopic analyzers. He has co-authored over 100 technical articles; six books, and is co-inventor of over 35 issued patents.

Dennis Suhre, Ph.D.
Dr. Suhre received his Ph.D. from the University of Illinois in 1976, and was employed at the Westinghouse R&D Center until 1996. He then worked at Northrop Grumman STC for two years, and is currently at the Carnegie Mellon Research Institute. He has 25 years of experience in optics and lasers, including device and prototype systems development, lasers, lidar, optical design, and image processing. He has developed tunable acousto-optic filters in the visible and IR, including 8-12 μm filters for hyperspectral imaging applications. Dr. Suhre has also been involved with nonlinear optics. He has demonstrated both the highest efficiency of 57% and highest power of 6 W ever produced in the mid-IR, using second harmonic generation of a CO_2 laser beam. Various military applications have included EOCM, FLIR design, and optical hardening. Dr. Suhre has authored more than 50 publications, and has four patents.

Z.K. Kun, Dipl. Ing.
Zoltan Kun joined CMRI as a consultant on electro-optical materials after retiring as a Consultant Scientist from the Westinghouse Systems & Technology Division in Baltimore. Prior to transferring to Baltimore in 1991, he was a Consultant Scientist at the Westinghouse Science and Technology Center. His work included the transfer of TAS crystal growth from the lab to manufacturing, and the co-invention and development of a solid-state imaging device. In both areas he received corporate "George Westinghouse" awards for his accomplishments. From its beginnings, he was the "champion" of the new imaging technology. To exploit this technology, Westinghouse formed a joint venture with a Japanese company. Eventually, the technology was sold to Hewlett Packard. Since working in the U.S., Zoltan authored/co-authored over 30 technical articles and is inventor/co-inventor of over 20 issued patents. He is a member of SID, and SIST.

MASTER COPY: PLEASE KEEP THIS "MEMORANDUM OF TRANSMITTAL" BLANK FOR REPRODUCTION PURPOSES. WHEN REPORTS ARE GENERATED UNDER THE ARO SPONSORSHIP, FORWARD A COMPLETED COPY OF THIS FORM WITH EACH REPORT SHIPMENT TO THE ARO. THIS WILL ASSURE PROPER IDENTIFICATION. NOT TO BE USED FOR INTERIM PROGRESS REPORTS; SEE PAGE 2 FOR INTERIM PROGRESS REPORT INSTRUCTIONS.

MEMORANDUM OF TRANSMITTAL

U.S. Army Research Office
ATTN: AMSRL-RO-BI (TR)
P.O. Box 12211
Research Triangle Park, NC 27709-2211

☐ Reprint (Orig + 2 copies)

☐ Technical Report (Orig + 2 copies)

☐ Manuscript (1 copy)

X - Final Progress Report (Orig + 2 copies)

☐ Related Materials, Abstracts, Theses (1 copy)

CONTRACT/GRANT NUMBER: C-DAAD19-01-1-0430

REPORT TITLE: High Performance Broadband Cameras for Hyperspectral and Polarimetric Imaging Research

is forwarded for your information.

SUBMITTED FOR PUBLICATION TO (applicable only if report is manuscript):

Sincerely,