Raytheon
Space and Airborne Systems

HYPERCUBE:
Hyperspectral Imaging Using a CUBESAT

Ian S. Robinson
Senior Engineering Fellow
Raytheon Certified Architect

Customer Success Is Our Mission

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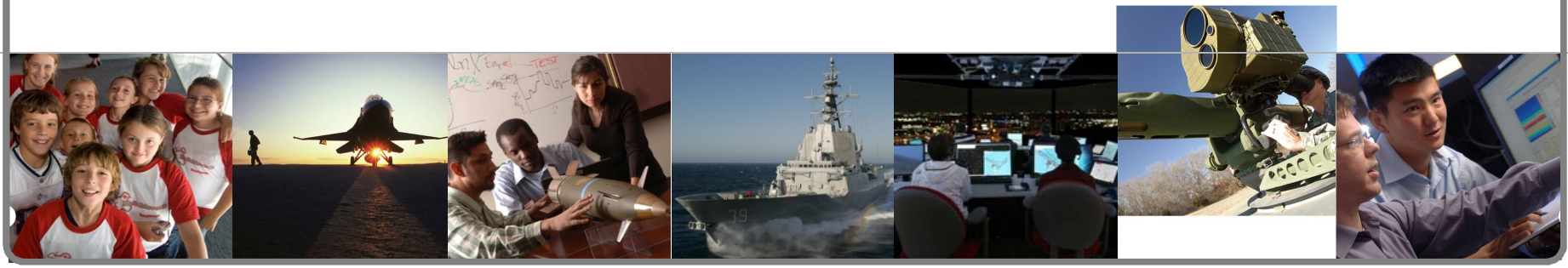

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WHO WE ARE

- A technology and innovation leader specializing in defense, homeland security and other government markets throughout the world
- 2010 net sales: $25 billion
- 72,000 employees worldwide
- Headquarters: Waltham, Massachusetts

›› A global leader in technology and innovation

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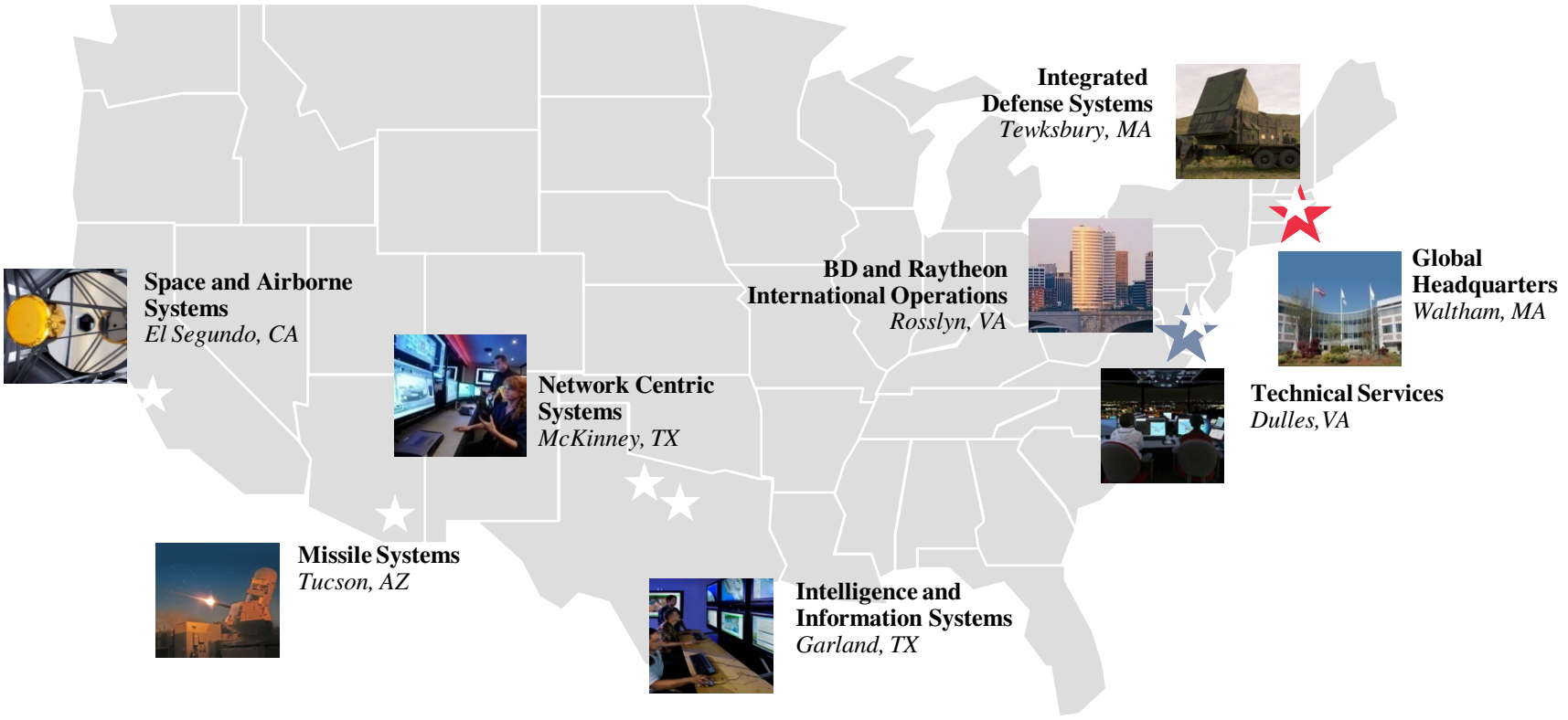
Raytheon Business Headquarters



›› 72,000 employees; 2010 net sales: $25 billion

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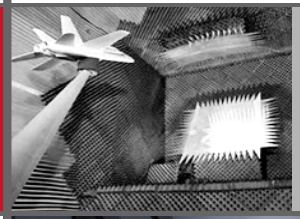
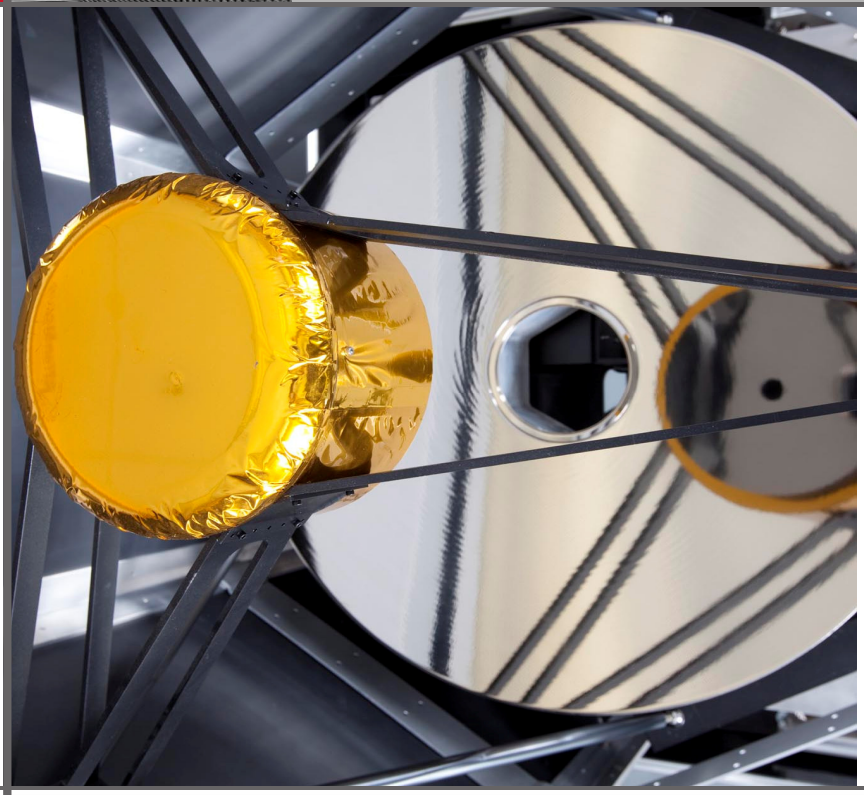


SPACE AND AIRBORNE SYSTEMS

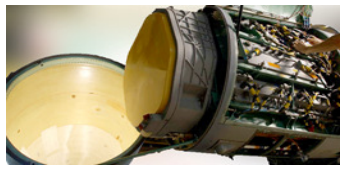
Richard R. Yuse
President

2010 Net Sales: $4.8B
Employees: 11,900
HQ: El Segundo, CA



Integrated sensing solutions for advanced applications in aviation and space technology

- Tactical Airborne Radars and Processors
- Electronic Warfare Systems
- Intelligence, Surveillance and Reconnaissance
- Integrated Aircraft Solutions
- Civil, National and Military Space Solutions



›› World leader in integrated sensor systems for space and airborne missions

Hyperspectral Imaging

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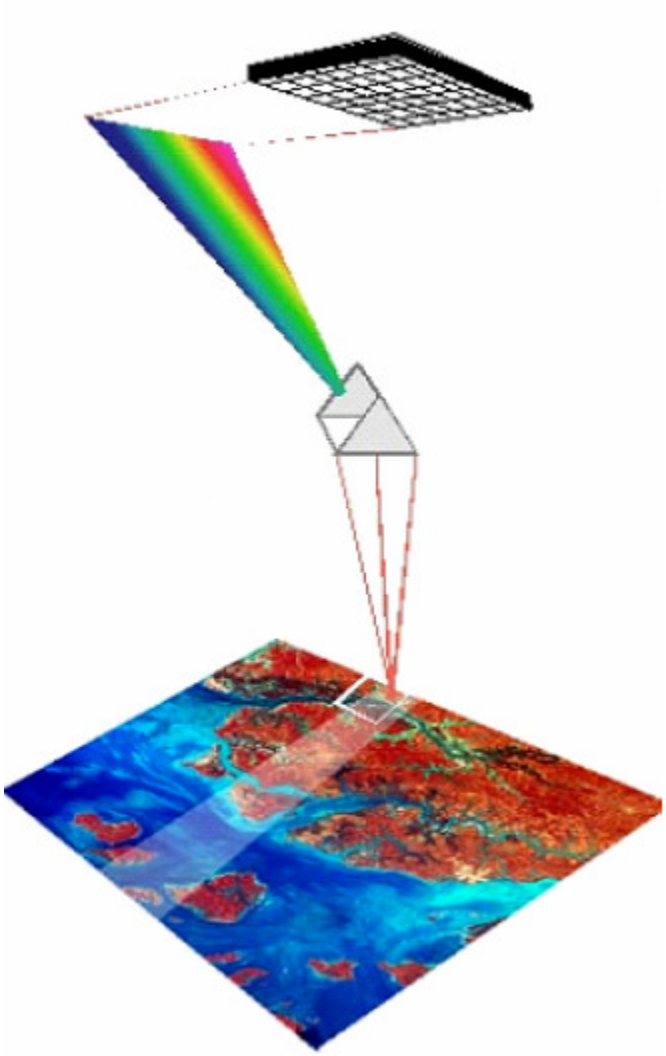

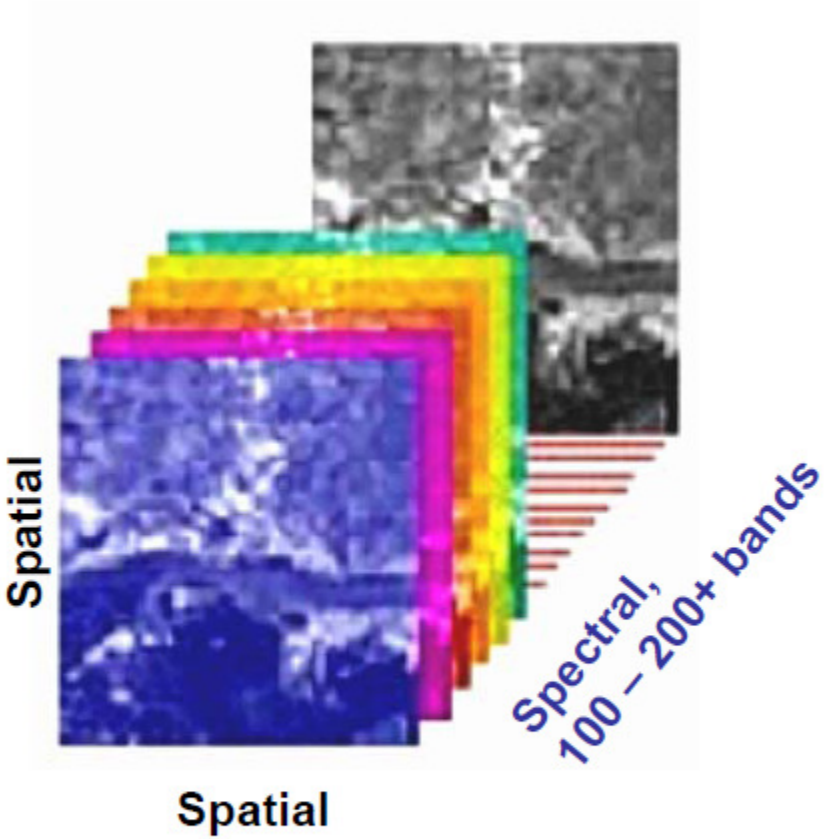

Every Pixel Contains a Complete Spectrum in a Hypercube

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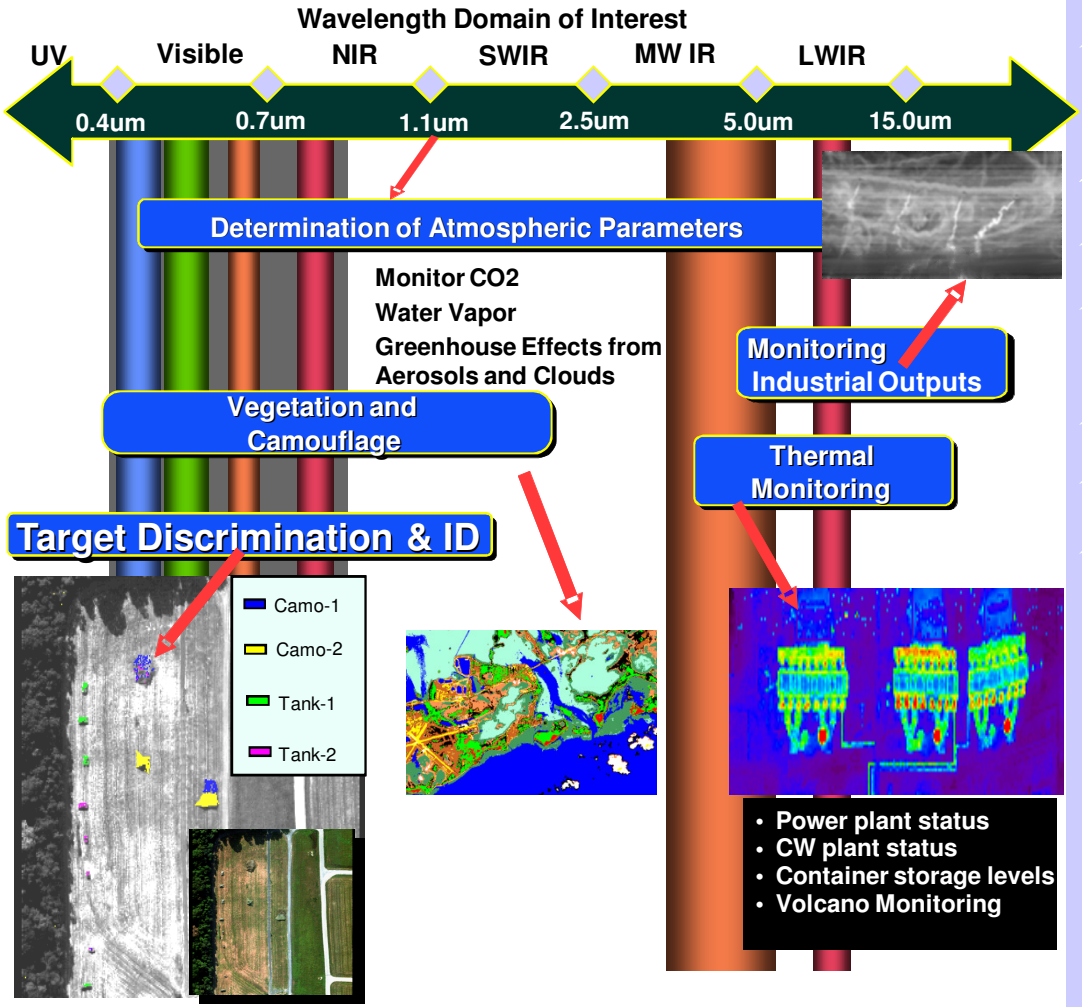
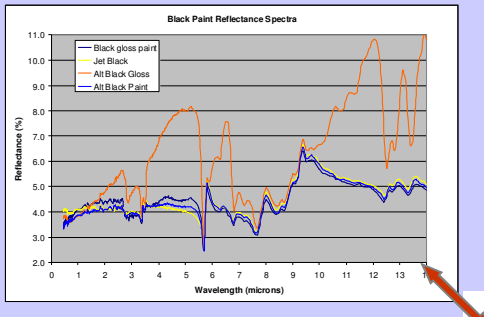
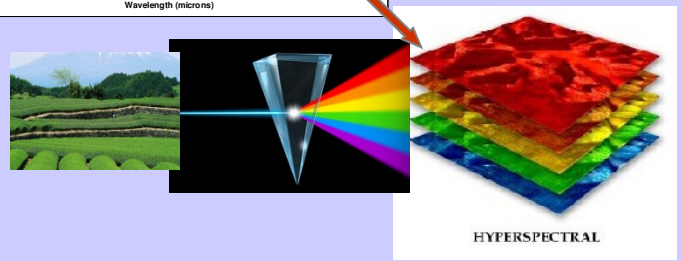
Why Hyperspectral Imaging (HSI)?



- *Collect Imagery In 100s of spectral bands*
- Detects / Quantifies Gases
- Counter CC&D; material ID
- Wide area Automatic Target Cueing reduces Intel analyst load
- Tagging & Tracking
- Single Pixel Detection
- Earth and Atmospheric Science



Materials have unique spectra



Identifying Targets, Materials, & Gases by Chemistry (Not Shape)

Applications of HSI

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- Military/Intel
- Geology
- Forestry
- Agriculture
- Mapping/land use, land cover analysis
- Atmospheric analysis
- Environmental monitoring
- Coastal/Ocean
- Many, many others

CubeSat-Scale Hyperspectral Imager for Middle Atmosphere Investigations, Rick Doe et al, 2009 CUBESAT DEVELOPER'S CONFERENCE, SAN LUIS OBISPO, CA

Spatial Heterodyne Spectrometer (SHS)
Very Fine Spectral Resolution
No Moving Parts
Very large pixels

Raytheon Builds "Small" HSI Sensors

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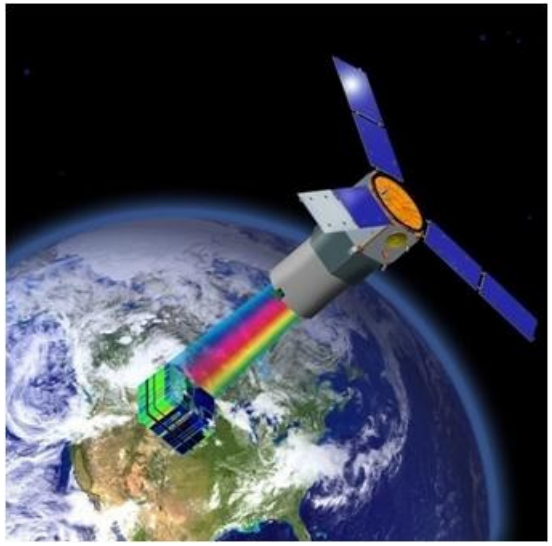
ARTEMIS/TACSAT-3

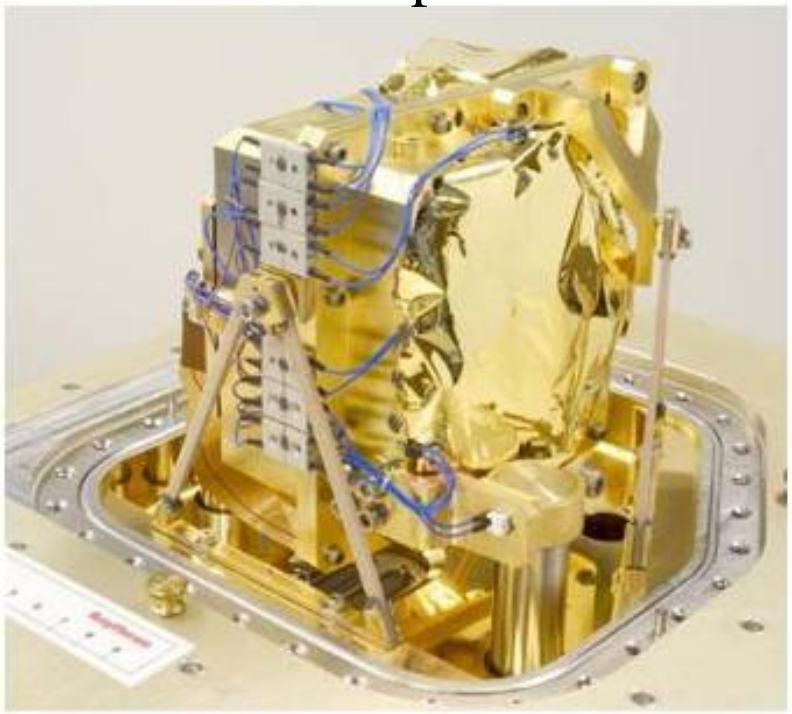


Gary Payton (2010-01-06). "Future of Air Force Space" American Institute of Aeronautics and Astronautics, Inc

Payload ~170Kg

Bus ~140Kg

Dual –Band Spectrometer



TACSAT-3 Is A "Small Sat" But We Go Much Smaller

Top Level Trades and Drivers

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SNR (per band)
Spectral Coverage (microns)
Spectral Resolution (nm)
Ground Sample Distance (GSD, m)
Max Spectral Distortion
Radiometric Accuracy (%)
Swath (Km)
Repeat (days)

Aperture (cm)
Focal Ratio (F/#)
Frame Rate
Max Data Rate (Mbps)
Avg Power (W)
Mass (Kg)
FOV (degrees)
FPA Temperature
Calibration
Orbit
FPA Detector Size

- Can we identify useful missions within CUBESAT and other technological constraints?
- Yes: Many HSI sensors have flown providing Big Science with Small Apertures

HSI Sensor Parameters

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	Hyperion	Landsat OLI	HYSPIRI*	M3**
SNR (per band)	40-200	~100	300-600	100-400
Spectral Coverage (microns)	.38-2.5	6 bands	.4-2.5	.43-3.0
Spectral Resolution (nm)	10	~100	10	10
Ground Sample Distance (GSD, m)	30	30	60	70
Max Spectral Distortion	20%	N/A	5%	10%
Radiometric Accuracy (%)	6	5	~5	5
Swath (Km)	7.7	185	145	40
Repeat (days)	large	16	~21	N/A
Aperture (cm)	12	13.5	~5	1.1
Focal Ratio (F/#)	11	6.4	short	3.55
Frame Rate	224	240	120	60
Max Data Rate (Mbps)	280	265	<200	44
Avg Power (W)	49	200	41	15
Mass (Kg)	51	375	55	8
FOV (degrees)	0.63	15	12	24
FPA Temperature	110	<100	<150	150
Calibration	OB	OB	OB	Cover

* LWIR not included, includes two separate spectrometers
** from 100Km

- LANDSAT is multi-spectral, wide swath, continuous recording of changes
- HYPERION proved additional utility of HSI
- M3 found water on the Moon
- HYSPIRI is two double sized M3s; heading towards a HyperLANDSAT

HYPER Sats

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	Hyperion	Landsat OLI	HYSPIRI*	M3**	HYPERCUBE		HyperLANDSAT
SNR (per band)	40-200	~100	300-600	100-400	>100		>100
Spectral Coverage (microns)	.38-2.5	6 bands	.4-2.5	.43-3.0	0.4-2.35		.4-2.5
Spectral Resolution (nm)	10	~100	10	10	10		10
Ground Sample Distance (GSD, m)	30	30	60	70	30		30
Max Spectral Distortion	20%	N/A	5%	10%	20%		20%
Radiometric Accuracy (%)	6	5	~5	5	10		5
Swath (Km)	7.7	185	145	40	19		185
Repeat (days)	large	16	~21	N/A	16		16
Aperture (cm)	12	13.5	~5	1.1	8.75		12
Focal Ratio (F/#)	11	6.4	short	3.55	4		4
Frame Rate	224	240	120	60	240		240
Max Data Rate (Mbps)	280	265	<200	44	384		>1000
Avg Power (W)	49	200	41	15	~10		TBD
Mass (Kg)	51	375	55	8	~5		TBD
FOV (degrees)	0.63	15	12	24	1.5		15
FPA Temperature	110	<100	<150	150	160		<150
Calibration	OB	OB	OB	Cover	Vicarious		TBD

* LWIR not included, inlcudes two separate spectrometers
** from 100Km

- HyperLANDSAT is a possible concept requiring only one spectrometer; twice the resolution of HYSPIRI but less SWAP
- HYPERCube can blaze the path

HYPERLandsat Can Be Built Today

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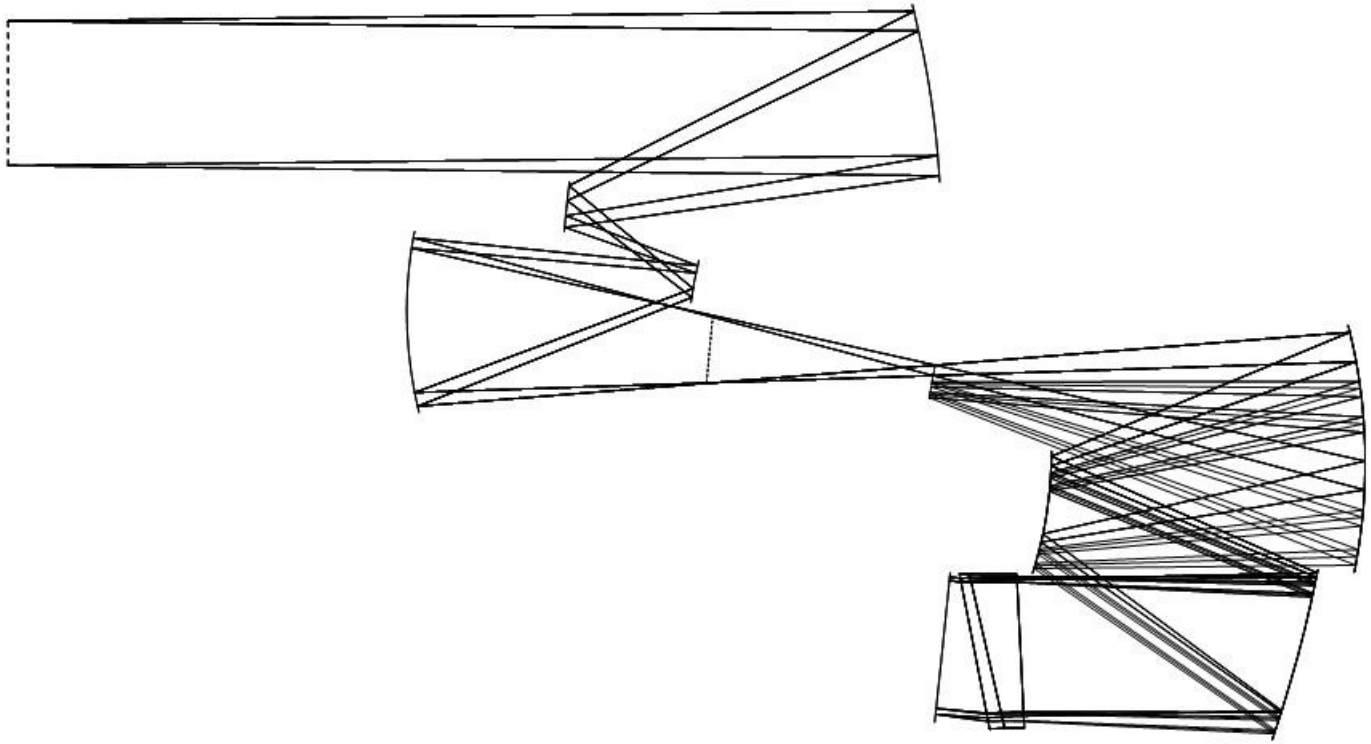
Imaging Spectrometer Trade Studies: A Detailed Comparison of the Offner-Chrisp and Reflective Triplet Optical Design Forms, Cook et al, August 2010, San Diego, Vol. 7813

Design Concept for a Landsat-Class Imaging Spectrometer with Well Corrected Spectral Fidelity by Chrien and Cook (Proceedings of SPIE Vol. 5157, 2003)



Double Pass Reflective Triplet Spectrometer Is The Enabler

HYPERCUBE Needs

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- Small spectrometer
- Low power focal plane assembly and electronics
- Low power/low mass cooling system
- Ability to manage 300+ Mbits/sec

Compact HSI Cameras By Novosol

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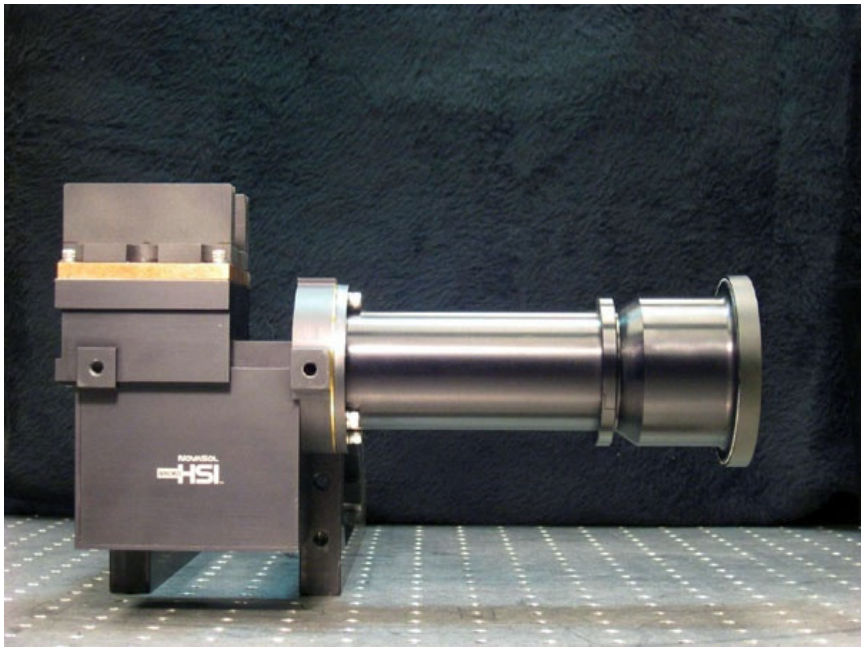
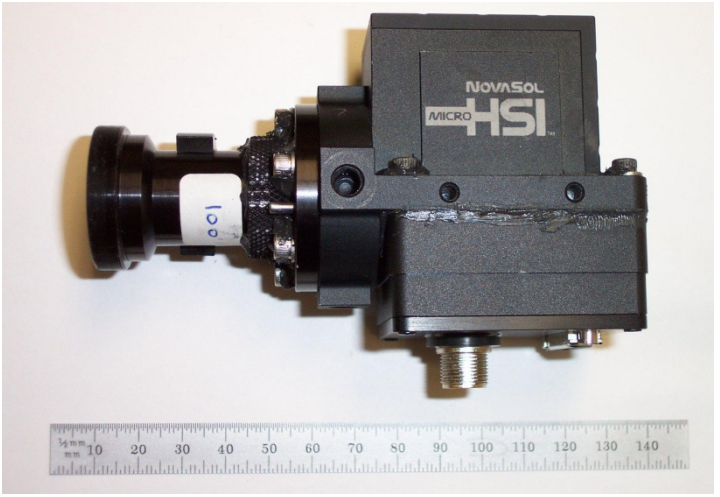


Relative Aperture	f/2.8
Spectral Range	900 – 1700 nm
Spatial Channels	1280
Channel IFOV	0.205 mrad
Full Field of View (FOV)	15 degrees
Dispersion/Spectral Channel	10 nm
Integration Time	12 ms max.
A/D Digitization	13 bits
Read Noise	110 electrons
FPA Detector	InGaAs
Size	11" x 5.9" x 3.2"
Weight	6 lbs.
Power	15W

Sensor Dimensions 4.8” x 3.6” x 2.5” w/Lens Weight 1.2 lb. (0.54 kg) w/Lens Power < 3.3 W @ 12 VDC



Miniaturization of a VNIR hyperspectral imager
Christopher P. Warren, et al, Proc. SPIE 6302, 63020N (2006)

Key Parameters for HYPERCUBE

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- Get closer to target to reduce aperture
  - 8.75 cm ap, F/4
  - 35 cm focal length,
- Match LANDSAT
  - 241 revs in 16 days; 15.0625 revs/day, 95.6 min orbit (525), i=97.5
  - 525 Km altitude
- 30 m Ground Sample Distance (GSD)
  - Pitch =20 um, nadir GSD
  - 250 Hz
- Extend HSI capability beyond HYPERION
  - 200 colors, 640 pixels
  - Data rate at 12 bits is 384 Mbits/sec
  - 20 minute collect is 461 Gbits (58 GB)
- Limit on-board hardware, but can use Vicarious Calibration

On-Orbit Calibration and Focus of Responsive Space Remote Sensing Payloads Chrien, Schiller, et al. 4th Responsive Space Conference, April 24–27, 2006, Los Angeles, CA

Enabling Technologies

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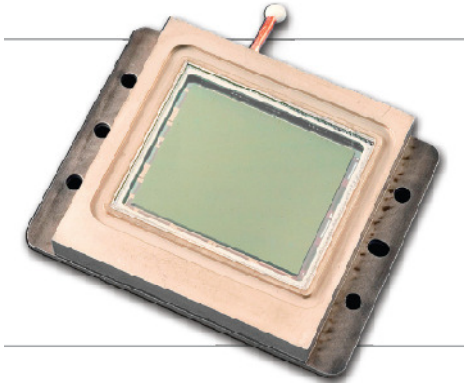
USB 3.0 3-5 Gbits/sec transfer on Amazon

Transcend 500 GB 2.5-Inch USB 3.0 Military-Grade Shock Resistance Portable External Hard Drive for Mac and PC $90.66

Super Talent RAID Drive 128 GB USB 3.0 Flash Drive STU28GSRK (Black)
Buy new: $503.74

Lowest Useable Temp	< 150 K	
Input Power Limit	15 W	
Typical Operating Points	0.4W @ 180K	
	0.2W @ 160K	
Thermal Mechanical Unit		
	Compressor:	Expander:
Mass:	36 g	35 g
Package Size:		
Length:	0.92 in	2.1 in
Width:	0.82 in	0.2 in
Height:	0.82 in	0.2 in
Total Package Volume:	0.49 in^3	0.2 in^3

Raytheon SB339 SWIR HSI: High-performance Solutions for Hyperspectral Imaging Applications



Small-Scale Cryocooler

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Space and Airborne Systems Cryocooler Product Line

Space and Long Life Tactical Cryogenic Cooling Solutions

Summary

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- HSI can provide unique science capabilities
- HSI provides BIG SCIENCE with small apertures
- CUBESATS may be able to host HSI payloads with few or no modifications; HYPERCUBE can blaze path to Hyperspectral LANDSAT mission
- Enabling (non-space qualified) technologies available to support HYPERCUBE mission