Computational Reconfigurable Imaging Spectrometer (CRISP)

Adam Milstein, Yaron Rachlin, Corrie Smeaton,

Ryan Sullenberger, Charles Wynn, Phil Chapnik, Steven Leman

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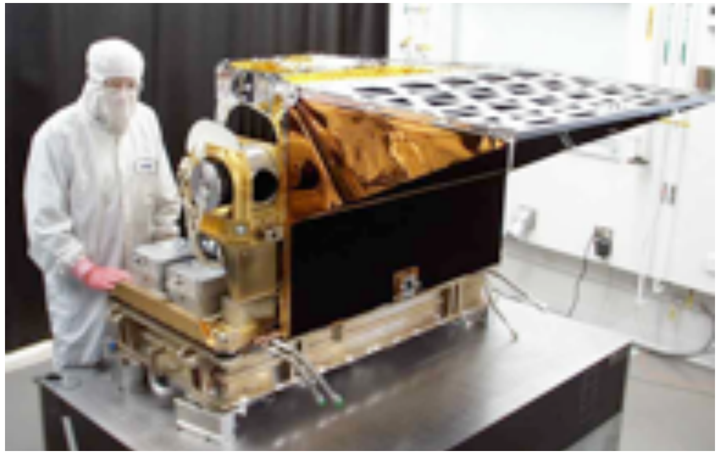
Overview of CRISP: Motivation
Current IR Instruments for Earth Science

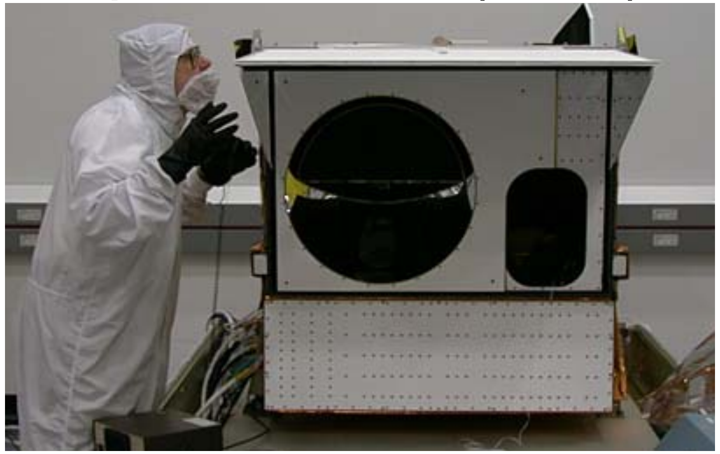
Atmospheric Infrared Sounder (NASA)



Weight
166 kg

Power
256 W

Moderate Resolution Imaging Spectroradiometer (MODIS)



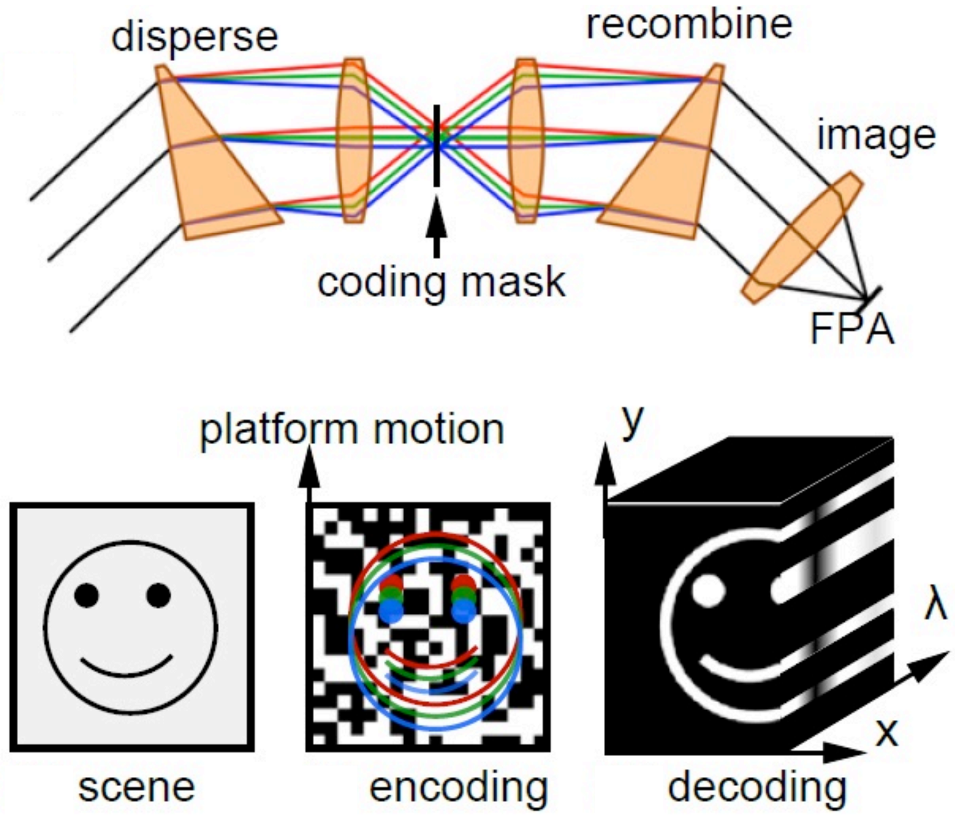
Weight
228 kg

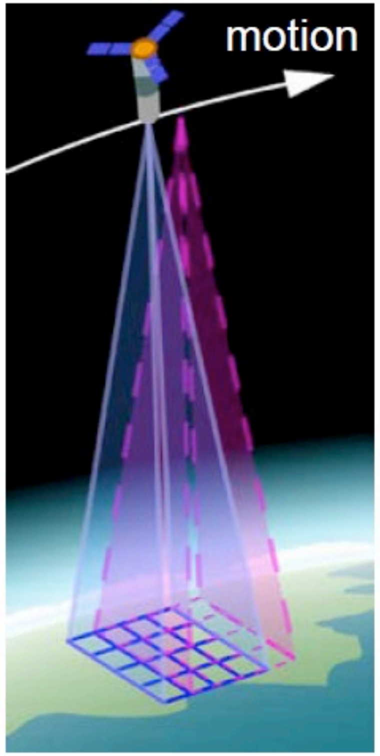
Power
162.5 W

- **Spaceborne imagers and sounders have revolutionized understanding of weather and climate**
- **However, there are limitations in current design approaches**
  - **Expensive ($>100’s of millions)**
  - **Large (>100 kg)**
  - **Consume >100 watts**
  - **Long development cycle**
    - **Failures catastrophic, cause long gap**
    - **Fewer instruments on-orbit limits revisit rate**

Significant opportunity for new technology that can reduce size weight and power (SWaP)

Overview of CRISP: Our Approach





- **Uses static mask and scan/platform motion to encode spectral data cube**
- **SWaP and SNR advantages over traditional designs**

SNR of CRISP vs.
SNR of Conventional Slit-Based Spectrometers

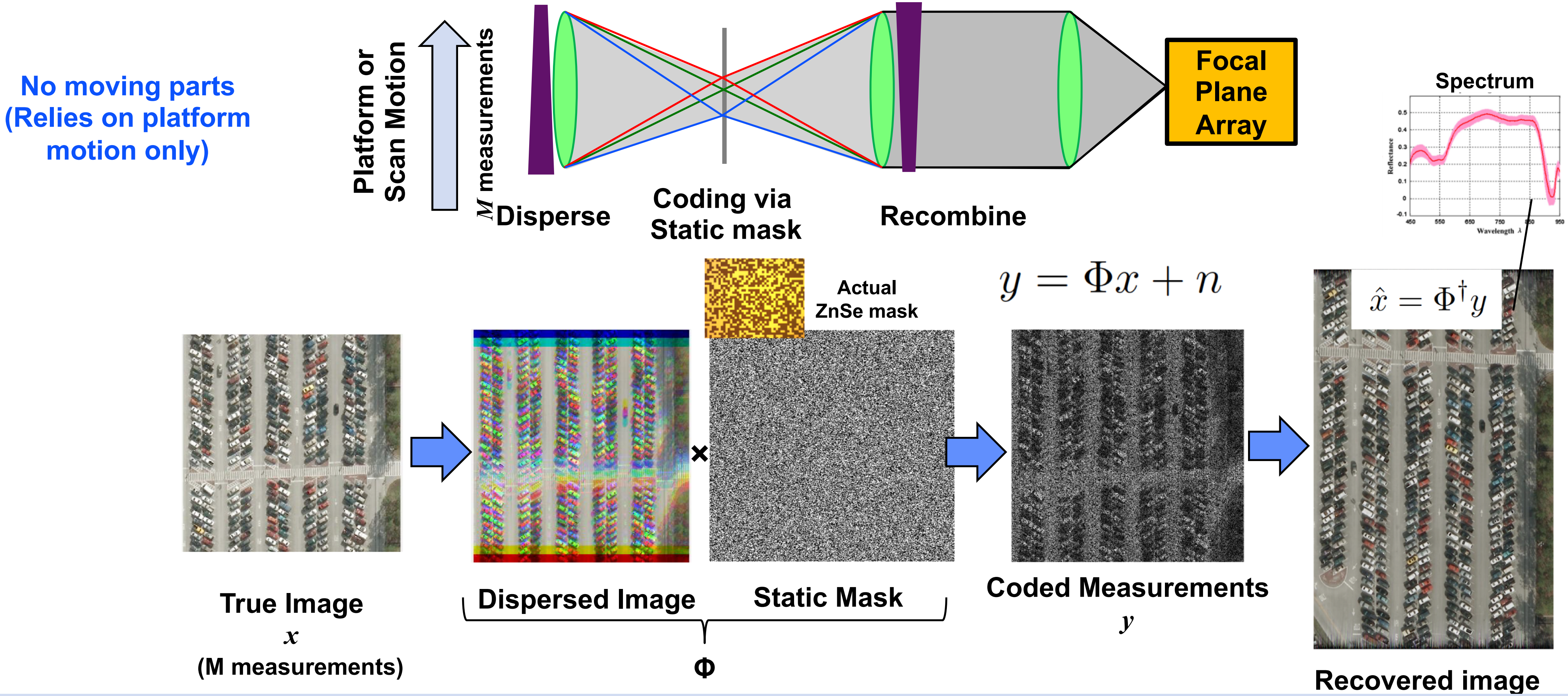
SNR comparison of CRISP to conventional pushbroom spectrometer

	Slit-based system SNR scaling	CRISP SNR scaling	Rationale	Note
Shot-noise limited (e.g., visible CCD, cooled MCT)	1	$\sim\sqrt{M/2N_\lambda}$ Example*: $\sim 6\times$	Overdetermined measurement: $M > N_\lambda$ Traditional design: $N_\lambda = M$	Number of measurements: M Number of measured wavelengths: N_λ
Detector-noise limited (e.g., uncooled microbolometer)	1	$\sim\sqrt{M}/2$ Example*: $\sim 22\times$	All λ measured at once; "multiplexing" advantage	

*Example: $M = 1920, N_\lambda = 30$

- **CRISP enables significant SNR improvement over conventional designs**

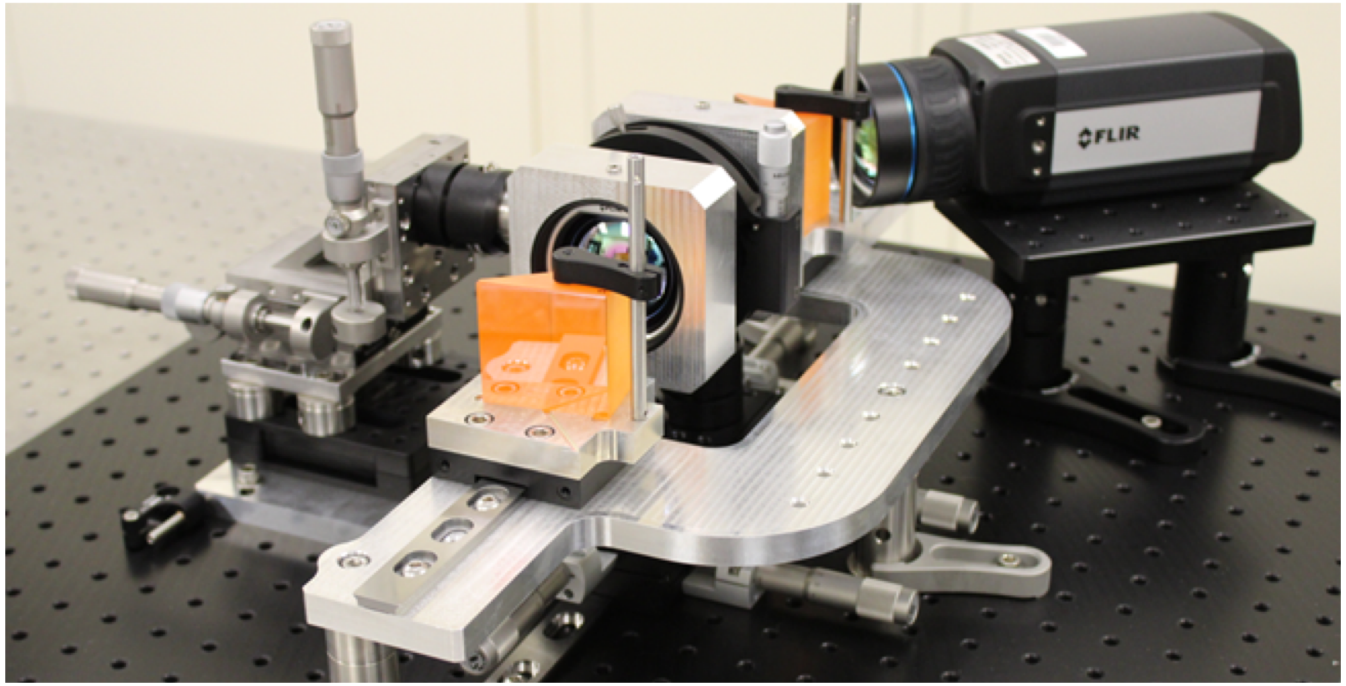
CRISP Spectral Decoding



- CRISP more sensitive than dispersive + FTIR, for both shot-noise and detector-noise limited measurements
- CRISP advantage maximized with noisy detectors

Breadboard Measurements

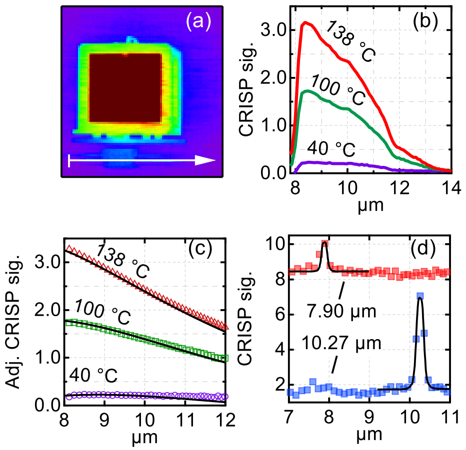
λ	7.7 μm – 14 μm (67 pixel dispersion extent)
$\Delta\lambda$	0.14 um resolvable
D	5 cm
FOV	~15°
COTS f/1 camera lenses from FLIR Custom ZnSe prisms Custom designed mounts and baffles	



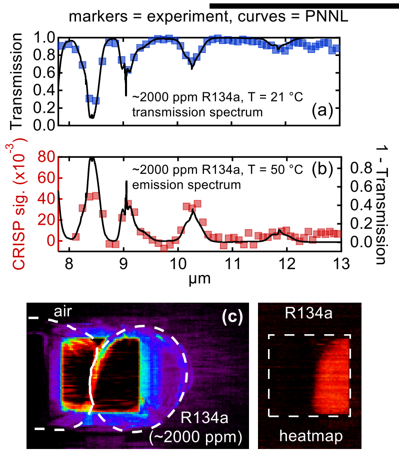
- Use COTS based system to validate model predictions

Breadboard: Example Measured Spectra

Extended and Narrowband Source Example

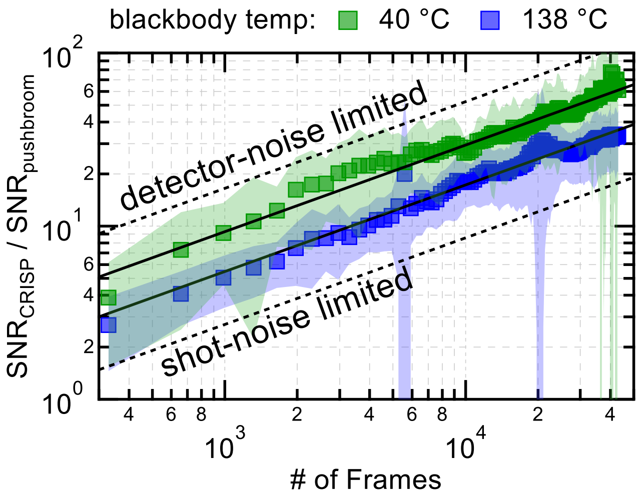


Trace Gas Example



- **Breadboard measurements to date have shown good qualitative spectral reconstructions of narrowband, blackbody, and gas targets**

Breadboard Measurements: SNR Scaling

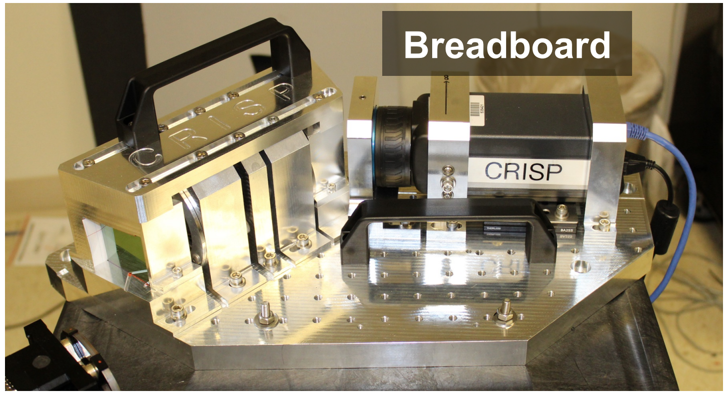


- **SNR scaling with $\sqrt{M}$ is confirmed, with improvement relative to comparable slit based system**

- **Factor of ~2 lower than theoretical limit for binary mask when detector noise limited**
  - **Departure from binary system function appears to account for this**
  - **Additional SNR scaling measurements planned for all configurations**

M

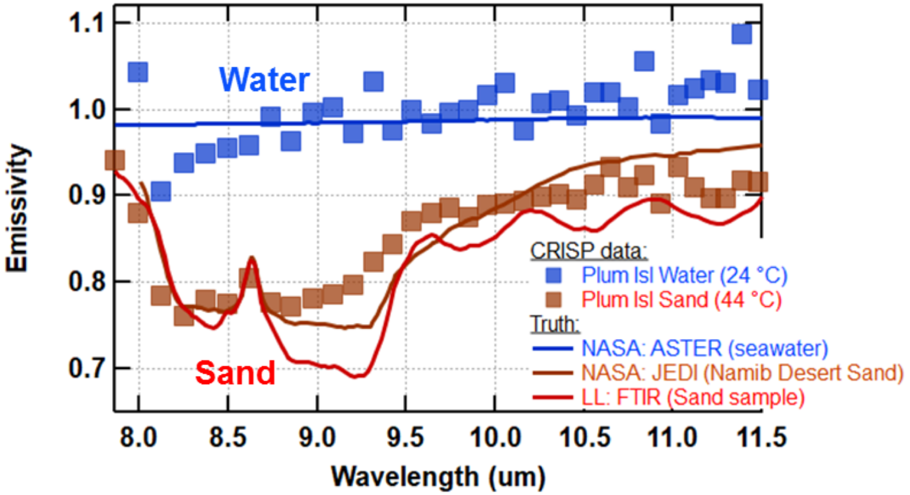
Breadboard Measurements: (Internally Funded) Flight Data and Functional Demo

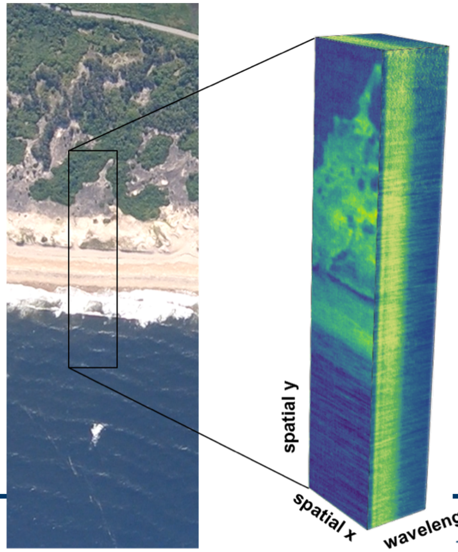


CRISP works on real moving platform, and distinguishes spectra of different materials in high-contrast scene

Spectral Results

Emissivity Examples





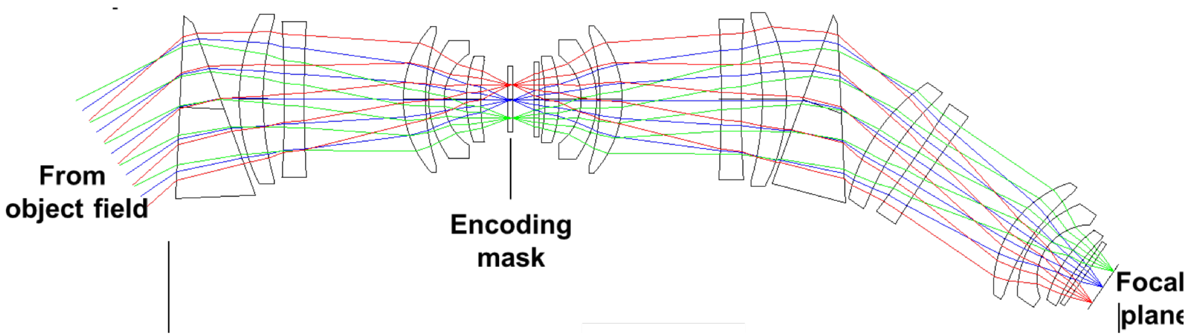
Spectral Data Cube

Brassboard Design

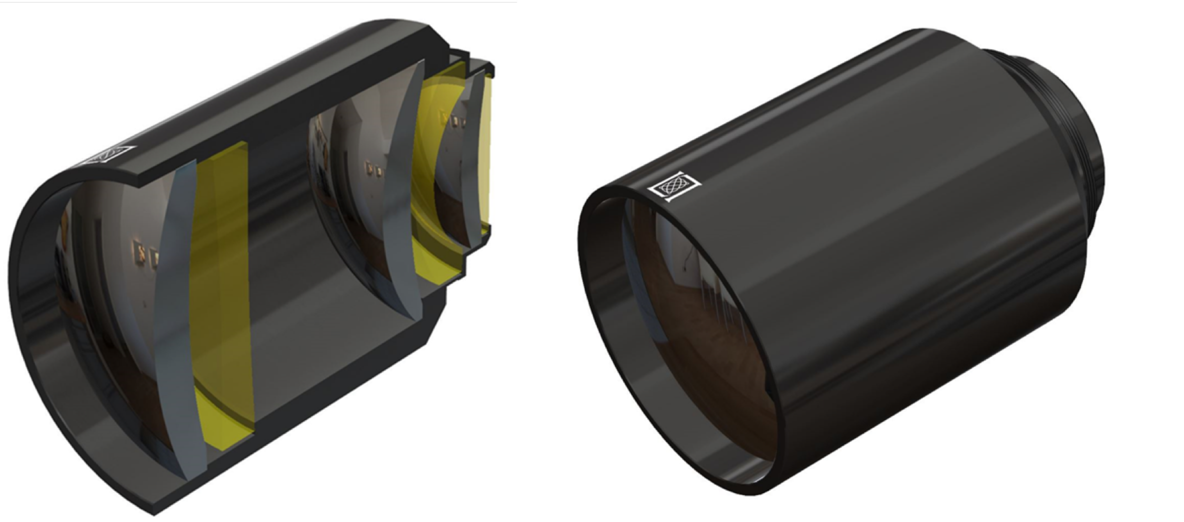
- **Brassboard designed for in-depth field testing**
  - Custom optics, with high image quality over entire FOV
  - As-built lenses are predicted to be diffraction limited with commercial-grade fabrication tolerances
  - Telecentric design provides uniform image illumination
  - Design informed by breadboard and model insights
- **Design close to complete**
  - Optical design 90% completed
  - Optomechanics design 80% completed
  - Future modifications will accommodate reconfigurability

Brassboard is close to a complete design, and is well-positioned for future development

Full System Layout

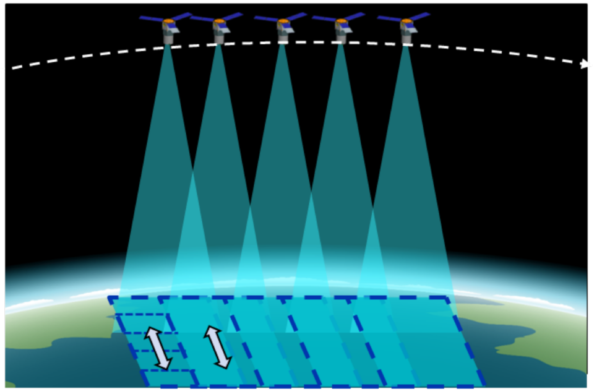


Lens Barrel

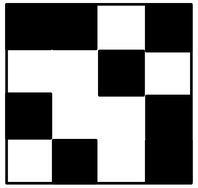


Spatial and Spectral Reconfigurability

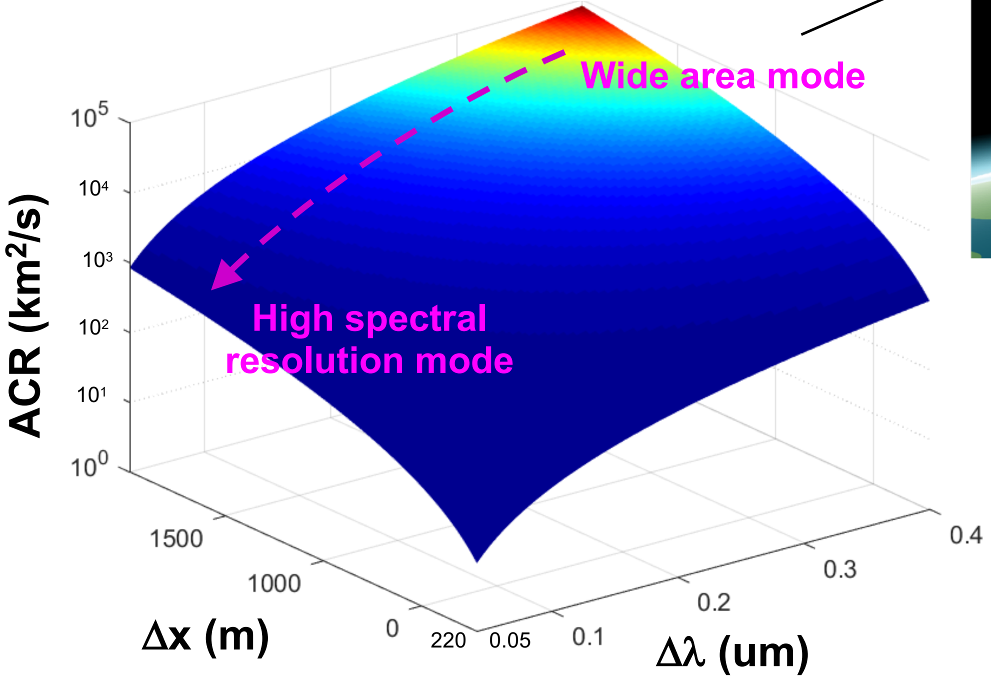
Higher ACR, Lower SNR



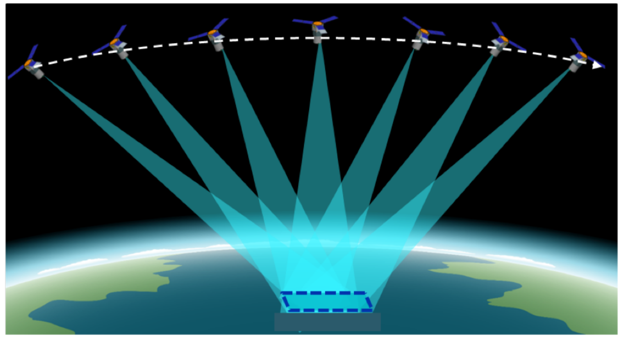
Spectral Coding



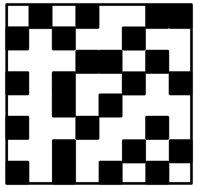
Surface of Constant SNR: ACR, Δλ, and Δx



Lower ACR, Higher SNR



Spectral Coding



- With change of mask and CONOPS, CRISP can be reconfigured to respond to new observations by applying different spatial/spectral encoding design
- Trade off area coverage rate, spatial resolution and spectral resolution

Summary of Technical Efforts and Findings to Date

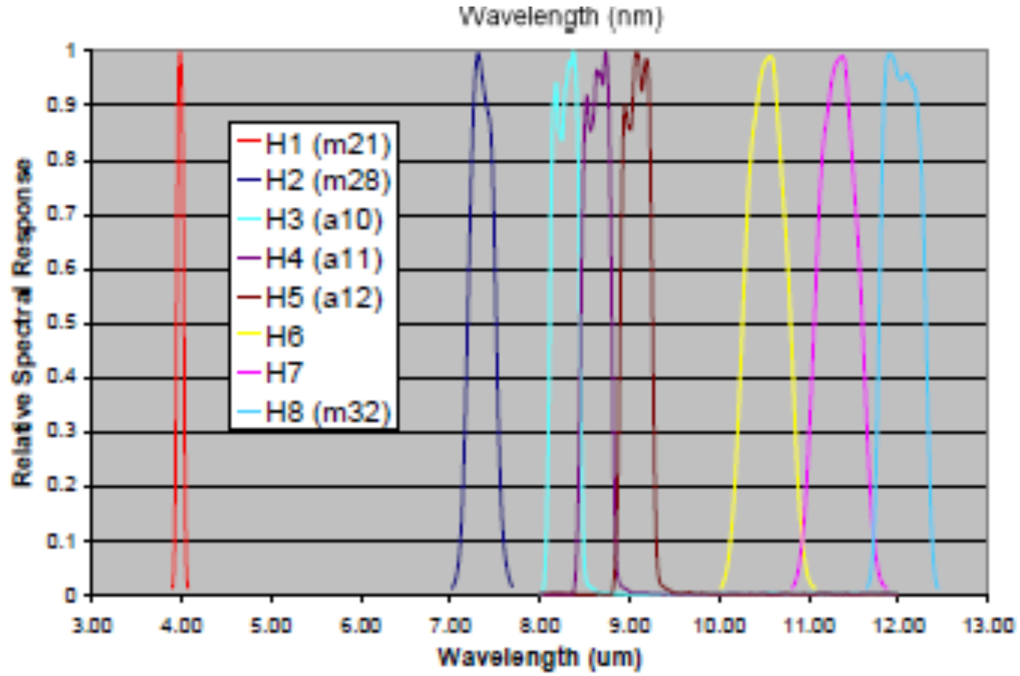
- Developed model of proposed CRISP system, and used model to predict performance
  - SNR scaling, impact of aberrations, spectral/spatial resolution, encoding/decoding process
- Validated these models with laboratory demonstration on breadboard
  - Validated model will guide formulation of future system designs
- Completed 80-90% of design work for proposed brassboard
- Current emphasis on reconfigurability and model validation
  - Allow variation of spatial and spectral capabilities on-orbit
  - Validate models with laboratory demonstrations (indoor and out)
  - Identify performance limits

Toward Science Applications

Thermal Imager Bands and Science Applications [1]

λ Range (μm)	Products
7.22-7.44	Lower-level water vapor, winds, SO2
8.3-8.7	Total water for stability, cloud phase, dust, SO2, rainfall
9.42-9.8	Total ozone, turbulence, and winds
10.1-10.6	Surface and cloud
10.8-11.6	Imagery, SST, clouds, rainfall
11.8-12.8	Total water, ash, and SST
13.0-13.6	Air temperature, cloud heights and amounts

Surface Biology and Geology HySPIRI TIR Bands [2]



Surface temperature and emissivity for volcanoes, wildfires, water use and availability, urbanization, land surface composition and change

- **CRISP potentially addresses several science needs in thermal IR band**

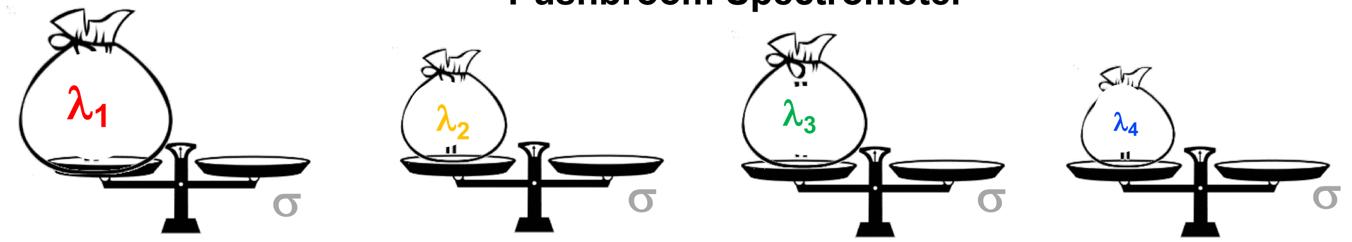
[1] https://www.ssec.wisc.edu/mcidas/doc/users_guide/current/app_d-2.html

[2] S. Hook, "Overview of the HyspIRI Thermal Infrared (TIR) Science Measurement Characteristics"

Backup

Multiplexing Advantage Illustration

Pushbroom Spectrometer

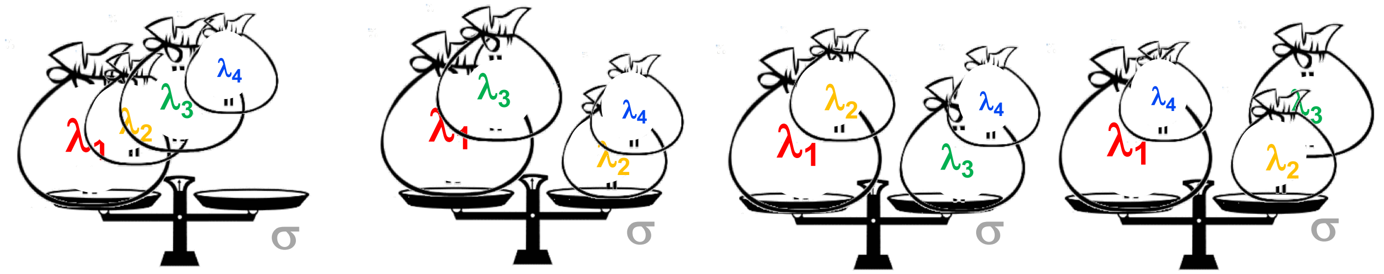


$\lambda_1 \pm \sigma$ $\lambda_2 \pm \sigma$ $\lambda_3 \pm \sigma$ $\lambda_4 \pm \sigma$

Measure each λ independently

Error at each λ = detector noise (σ)

Multiplex Spectrometer



$(\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4) \pm \sigma$ $(\lambda_1 - \lambda_2 + \lambda_3 - \lambda_4) \pm \sigma$ $(\lambda_1 + \lambda_2 - \lambda_3 - \lambda_4) \pm \sigma$ $(\lambda_1 - \lambda_2 - \lambda_3 + \lambda_4) \pm \sigma$

Measure linear combinations of λs

"Encoding"

"Inversion"

$\lambda_1 = ¼ (M_1 + M_2 + M_3 + M_4)$
$\lambda_2 = ¼ (M_1 - M_2 + M_3 - M_4)$
$\lambda_3 = ¼ (M_1 + M_2 - M_3 - M_4)$
$\lambda_4 = ¼ (M_1 - M_2 - M_3 + M_4)$

Measurement estimates

$$\sigma_{\lambda 1}^2 = \frac{1}{4}(\sigma^2 + \sigma^2 + \sigma^2 + \sigma^2) \qquad \sigma_{\lambda 1} = \frac{1}{2}\sigma$$

$$\sigma_{\lambda 2}^2 = \frac{1}{4}(\sigma^2 + \sigma^2 + \sigma^2 + \sigma^2) \qquad \sigma_{\lambda 2} = \frac{1}{2}\sigma$$

… …

Measurement errors*

Error at each λ = $\frac{1}{\sqrt{4}}$ *detector noise (σ)

↑ **# of detectors**

* Errors add in quadrature: If x = x1 + x2 + … then $\sigma_x^2 = \sigma_{x1}^2 + \sigma_{x2}^2 + …$
Multiplicative constant multiplies error: If x = Ax1, then $\sigma_x = A\sigma_{x1}$