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Computational Reconfigurable Imaging Spectrometer (CRISP) final report

A. Milstein

3 December 2021

Lincoln Laboratory
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LEXINGTON, MASSACHUSETTS



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Massachusetts Institute of Technology
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Adam B. Milstein
Group 97

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FINAL REPORT

Computational Reconfigurable Imaging Spectrometer (CRISP)

03 December 2021



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1. INTRODUCTION

Spaceborne spectral imagers such as those on Landsat have provided decades of continuous and highly valuable data that are used for surface imaging applications including land/water usage, evapotranspiration, and monitoring of volcanoes and fires. Despite the high value of such imaging spectrometers, high cost and complexity have limited the number of fielded instruments and dramatically increased the impact of losing any one instrument. Longwave thermal infrared instruments, in particular, historically require significant size, weight, and power (SWaP) due to the need for cryocooling, with the cost of existing instruments typically in the hundreds of millions of dollars. Hence, a significant opportunity exists for new technologies that reduce SWaP while providing more operational flexibility. The future of spaceborne remote sensing will include measurements that are distributed throughout large constellations of smaller spacecraft equipped with more affordable and integrated payloads capable of autonomous mission planning, intelligent data processing, and reconfigurable sensing.

In this context, we introduce the Computational Reconfigurable Imaging Spectrometer (CRISP), a new imaging spectrometer. CRISP is a compact, low power thermal infrared hyperspectral imaging system fully compatible with the future Landsat mission (as well as that of heritage Landsat systems). It has the potential to provide significant additional scientific benefit to the Landsat mission via its higher native spectral resolution while concurrently providing the heritage wavebands of previous Landsat sensors. CRISP's advantageous use of computational imagery provides increased performance in a smaller and simpler platform compared to traditional solutions. CRISP's unique design has enabled its rapid evolution from concept [1] to successful flight demonstration and performance assessment [2].

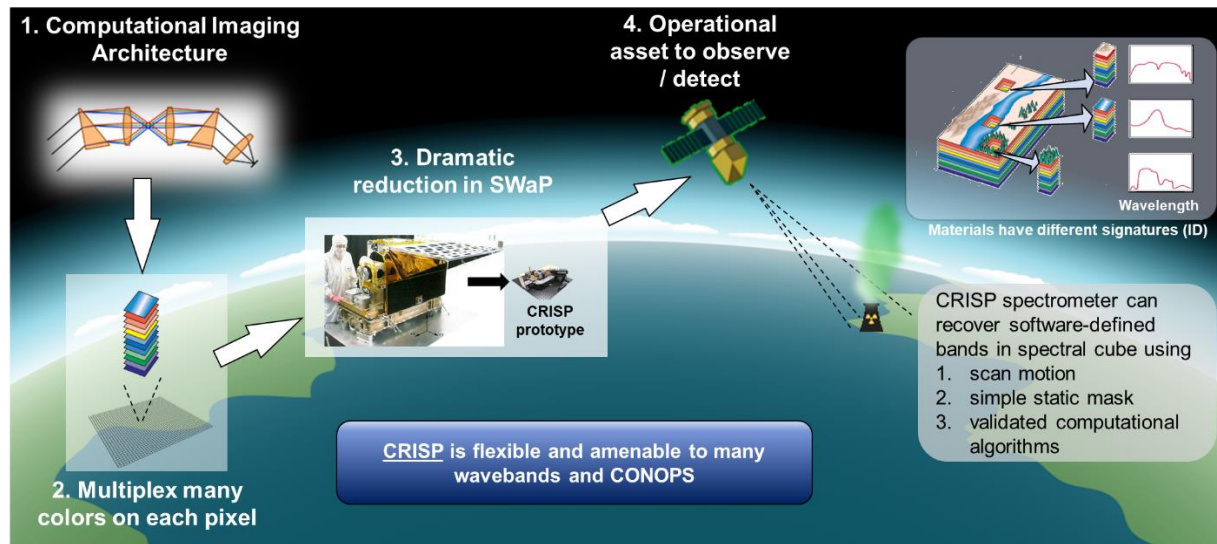


Figure 1 Overview of CRISP

As described in Figure 1, CRISP's novel design provides three overarching advantages relative to other spectral imaging solutions: (1) a lower SWaP solution with high performance via the use of uncooled or high operating temperature components; (2) high spatial resolution, limited only by the optical system

and not by the frame rate of the imager; and (3) reconfigurable operation. These advantages are achieved via the use of an encoding mask and optical design that enable multiplexing of spectral information and encoding of fast temporal information. CRISP relies upon a spectral encoding mask and platform motion to collect successive looks at a ground sample area. Spectra are recovered from these successive looks via inversion of the data by utilizing the (known) spectral encoding pattern provided by the encoding mask. As shown below, this sensing approach offers significant sensitivity as well as other advantages over existing conventional longwave spectral imaging approaches, enabling lower SWaP. In particular, CRISP enables high performance from smaller and less-expensive components such as uncooled microbolometers, and, compared to previous hyperspectral imager designs, is thus more suitable for small satellites than previous spectral imaging approaches. CRISP, uniquely, can achieve the high spatial resolution demanded by key scientific applications such as Sustainable Land Imaging (SLI) without motion blur even with uncooled detectors that have frame rate limitations, as the spectral image is encoded with a known pattern at a temporal rate greater than the camera readout. In addition, CRISP's measurement approach allows for significant operational flexibility, including different scan modes in which scan rates and area coverage can be varied in response to observations. For example, higher revisit rates and area coverage can be prioritized to respond to rapidly evolving events and environmental disturbances such as fires or volcanic activity. Alternatively, longer dwell times and higher sensitivity can be prioritized over a region of interest with a slower scan mode.

This report effort describes the technology advancement accomplished via an existing Advanced Component Technology program and previous internal investment at MIT Lincoln Laboratory (MIT-LL). This advancement has progressed over a timeline described in Figure 2 and reviewed in this report, including a proof of concept laboratory demonstration, an initial airborne performance demonstration, an airborne trace gas and target detection demonstration, and, most recently, airborne validation of Landsat requirements. As part of this effort, we demonstrate via radiometric, spectral, and spatial ground testing that CRISP can scale to meet the specifications required for SLI, as well as other Earth science applications of great interest.

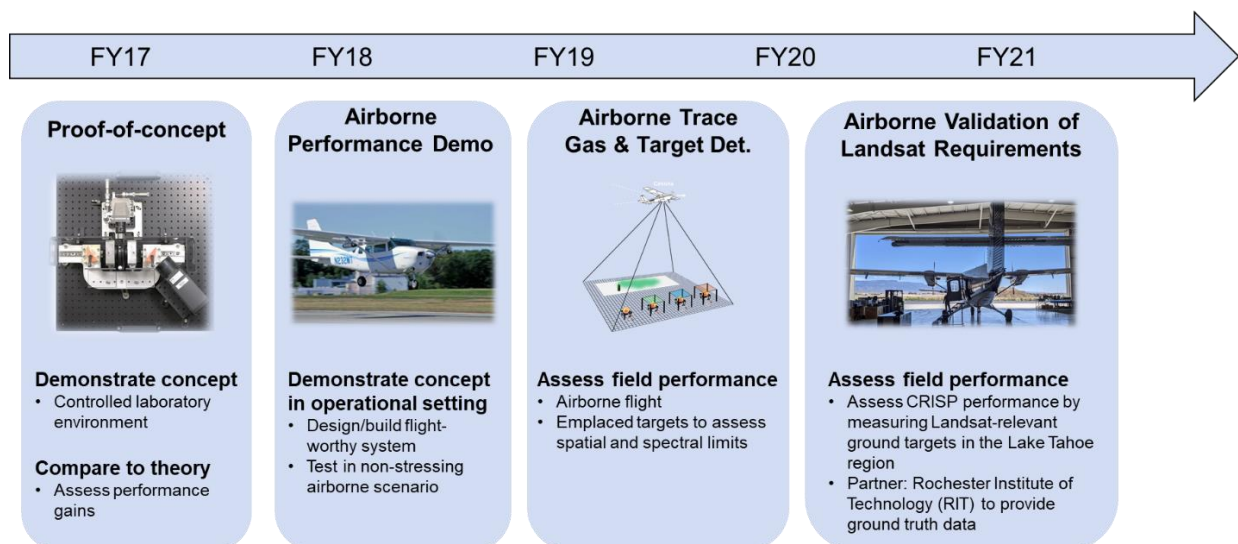


Figure 2 Timeline of CRISP advancement

1.1. KEY FINDINGS

Our key findings, as detailed in this report, can be briefly summarized as follows:

CRISP works

We have validated the performance, key scaling laws and key performance limits of the CRISP concept versus theoretical prediction. In addition, CRISP has a simple and robust design, with our first laboratory breadboard working on a plane and flying with external ruggedization alone.

A known upgrade path exists

While the current, low-cost “CRISP 1.0” breadboard design was intended to validate the CRISP operating principles, we have identified low-risk “CRISP 1.5” and “CRISP 2.0” upgrades (including uncooled and cooled detector upgrade paths, respectively) that are suitable for missions such as SLI.

Field testing and data analysis show upgrades (CRISP 2.0) will exceed SLI requirements

The scaling laws and performance predictions we have validated with CRISP 1.0 can be projected to improved designs, such as our “CRISP 2.0” concept, to establish that SLI requirements will be readily met or exceeded.

1.2. PATHS FORWARD

Figure 3 describes the example “CRISP 1.5” upgrade path, along with a simple radiometric math model for both the current “CRISP 1.0” system and the proposed future system, highlighting where the projected future improvements will come from – namely, the improved microbolometer (with large 1920-row format and lower NETD) and the improved optics which enable use of the whole field of view with better image quality. The detector parameters are chosen to match a commercially available microbolometer camera, the Sierra Olympic Vayu HD, and the specifications communicated to us by the vendor. The Vayu is presented to illustrate the capability of a commercial available product for its price category, and it does not represent a final design decision for this category. We note that other implementations of large-format uncooled imagers with NETD in this range have been presented as research instruments. For example, Raytheon Vision Systems has previously shown progress toward fabricating a 2048 x 1536 imager based on stitching 640 x 480 microbolometer arrays together [3]. Microbolometers with smaller formats and ~20 mK NETDs have been presented (for example, [4]), suggesting that further optimizations of CRISP 1.5 are likely possible in principle. Conservative (worst-case) assumptions are made for transmission loss, based on a preliminary optical design which is not optimized. The radiometry improvements assume scaling rules validated by this ACT effort, and establish that an uncooled CRISP system can meet the SLI requirement for NETD, even with conservative assumptions about losses. One key variable not shown in Figure 3 is frame rate. While COTS microbolometers typically have ~60 Hz or comparable frame rates, 120 Hz is required to avoid motion blur or skipping of 1 or more GSD rows per frame for a drift scanned CRISP instrument such as that described in the Section 1.3.1. Hence, an additional $\sqrt{120\text{Hz}/60\text{Hz}}=1.41$ penalty factor is required for the CRISP 1.5 model in drift scan mode, for a rolled up NETD value of 0.30 K, still under the 0.4K SLI requirement.

To obtain lower noise performance, cooled detectors can be used, and still benefit from the SNR enhancements offered by the CRISP system. Figure 4 describes a suitable “CRISP 2.0” cooled upgrade path, including improved, cooled detectors, and improved optic, resulting in significant reductions in NETD. The detectors are assumed to be High Operating Temperature (HOT) fully depleted HgCdTe (“MCT”) [5, 6] with a cutoff wavelength of 13 μm , a new category which can be obtained from vendors such as Teledyne. These detectors can operate at 130K with near-background-limited performance, significantly warmer than the 80K required for most existing cooled LWIR detectors. (Our modeling efforts suggest that a dark-noise limited CRISP system with these HOT detectors can meet SLI requirements even at $\sim 200\text{K}$ operation.) The readout integrated circuit uses a digital focal plane array (DFPA), previously introduced by MIT-LL [7] and transitioned to industry [8], offering TDI and elementary on-chip processing operations prior to readout as well as improved dynamic range and reduced readout noise. The detection system would be sealed in an MIT-LL-built integrated dewar-cryocooler assembly (IDCA) with an electric Stirling cooler. Based on the size of the existing CRISP breadboard, the SWaP of existing MIT-LL IDCA systems, and current optical reference designs, a small satellite is expected to be the appropriate platform size.

Other variants of these concepts will benefit from further research and development to advance low-noise, sensitive detectors with larger formats and faster readouts. For example, MIT-LL, in combination with Kent State University, have developed uncooled thermal imagers that use LCDs rather than conventional microbolometers [9, 10]. In these images, the thermal radiation imaged onto an LCD array changes its birefringence, and therefore its transmission with suitable polarization optics. The imagery is captured by transmitting visible light through the LCDs, and reimaging the light onto a CCD array. These imagers can have higher sensitivity than microbolometers due to the lack of $1/f$ noise, and therefore can achieve closer to background-limited performance. In addition, very large formats – even tens of megapixels – are possible due to the different readout approach versus microbolometers, a property which is very synergistic with CRISP’s measurement approach.

CRISP 1.5 Uncooled Upgrade Path Example: Improved Microbolometer and Optics

Terms	CRISP 1.0 (Current system)	“CRISP 1.5” (Upgrade path)	Notes
$NEDT_{channel} =$	2.4 K =	0.21 K =	11x improvement
$(NEDT_{nominal} \text{ over LWIR at } 300\text{K})$	0.095 K	0.030 K	Nominal NETD for Sierra Olympic Vayu HD
$\times (f - \text{number})^2$	$(1.1)^2$	$(1.1)^2$	
$\times (\# \text{ spectral bins})$	77	77	
$\times (\text{along track array size})^{-1/2}$	$(425)^{-1/2}$	$(1920)^{-1/2}$	
$\times (\text{transmission loss})^{-1}$	$(0.21)^{-1}$	$(0.3)^{-1}$	TBR: Design not finalized
$\times (\text{impact of mask contrast})^{-1}$	$(0.42)^{-1}$	$(0.5)^{-1}$	
$\times (\text{bins averaged for synthesized band})^{-1/2}$	$(4)^{-1/2}$	$(4)^{-1/2}$	

Improved optics and uncooled microbolometer enables CRISP to exceed 0.4K NETD spec for SLI

Figure 3 “CRISP 1.5” upgrade path: Simple radiometric math model showing feasible improvement due to upgraded optics and microbolometer detectors assuming scaling rules validated by this ACT effort

**CRISP 2.0 Cooled Upgrade Path Example:
HOT MCT Detector with MIT-LL DFPA and Improved Optics**

Terms	CRISP 1.0 (Current system)	"CRISP 2.0" (Upgrade path)	Notes
$NEDT_{channel} =$	$2.4 K =$	$0.077 K =$	~31x improvement
$(NEDT_{nominal} \text{ over LWIR at } 300K)$	$0.095 K$	$0.0037 K$	NEDT for Teledyne HOT MCT at 130K (high TRL, low risk); LL DFPA ROIC
$\times (f - \text{number})^2$	$(1.1)^2$	$(1.7)^2$	1.7 driven by cold stop in IDCA
$\times (\# \text{ spectral bins})$	77	77	
$\times (\text{along track array size})^{-1/2}$	$(425)^{-1/2}$	$(1280)^{-1/2}$	
$\times (\text{transmission loss})^{-1}$	$(0.21)^{-1}$	$(0.3)^{-1}$	TBR: Design not finalized
$\times (\text{impact of mask contrast})^{-1}$	$(0.42)^{-1}$	$(0.5)^{-1}$	
$\times (\text{bins averaged for synthesized band})^{-1/2}$	$(4)^{-1/2}$	$(4)^{-1/2}$	

Improved optics and HOT MCT detector with MIT-LL DFPA enables CRISP to exceed 0.4K NEDT spec for SLI

Figure 4 “CRISP 2.0” upgrade path: Simple radiometric math model showing feasible improvement due to upgraded optics and HOT MCT detector with MIT-LL DFPA detectors assuming scaling rules validated by this ACT effort

As part of the ACT effort, we created a reference design for the optical improvements similar to those required for CRISP 1.5. (CRISP 2.0 would follow a similar approach, with a larger f-number to accommodate the cold stop of the IDCA.) Figure 5 shows the system layout of an existing reference design similar to the proposed brassboard. The materials used were chosen to maximize transmission and minimize aberration in the 8-12.5 μm range. The design is passively athermalized over a range that includes 20C+/-20C, enabling consistent optical performance under a range of field test conditions. The optical system incorporates three lens groups, along with two prisms, the coding mask, and a camera window. The optics were designed for diffraction limited performance over the entire field of view, which includes the camera’s field of view and the prism-induced spectral spread. The prism angle was designed to achieve the spectral resolution requirement. The optical system is telecentric, removing aberrations and vignetting currently impacting the COTS breadboard. The first two groups of prisms and lenses are designed to be symmetric, which ensures that keystone and smile distortion are removed in the final collected samples, and also that the dispersed spectrum is successfully recombined. Figure 6 shows the spot diagram and ensquared energy for the previous reference design, demonstrating near diffraction limited performance. We have shown via analysis that the previous reference optical design remains diffraction limited over the whole 20°C+/-20°C temperature range. We have also performed Monte Carlo tolerancing analysis on the single lens group predicting that performance remains diffraction limited with commercial-grade fabrication tolerances.

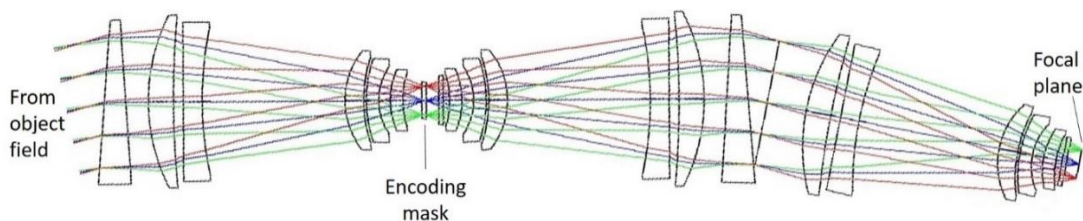


Figure 5 Brassboard reference optical design system layout

Figure 7 shows the proposed design for the lens barrel. The design includes an aluminum barrel in which each element sits on its own seat integral to the barrel. The lens elements will be centered and held in place by 566 RTV around the perimeters, a technique that MIT-LL has used successfully in a number of space-flight systems.

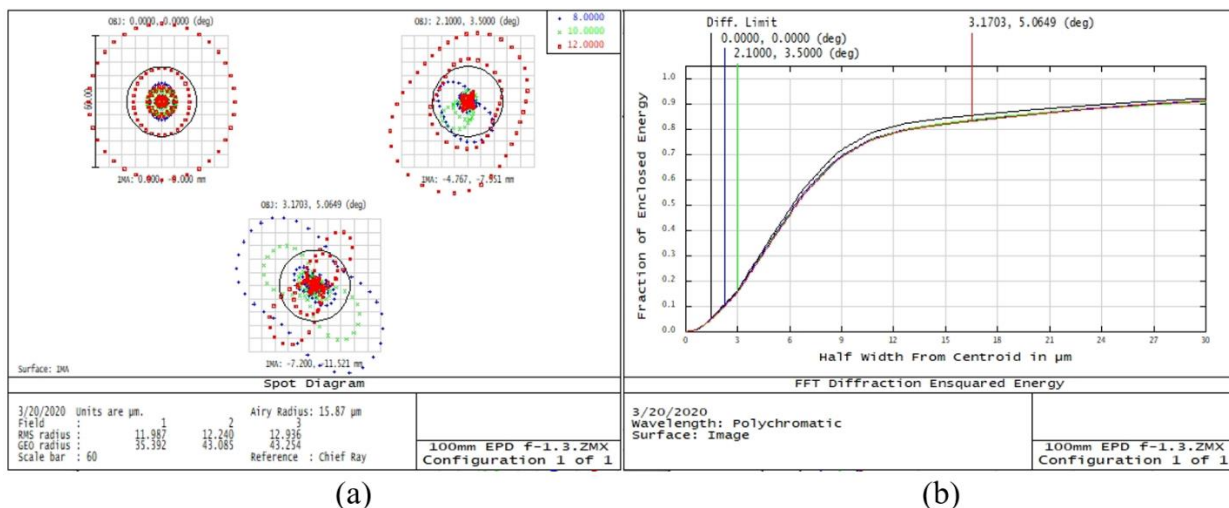


Figure 6 (a) Spot diagram for the reference design lens over the field of view and (b) Ensquared Energy for the reference design lens over the field of view

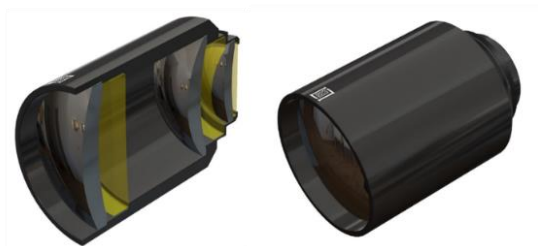


Figure 7: Brassboard optomechanics: Lens barrel design

1.3. SCIENCE RELEVANCY

1.3.1. Application to science: spaceborne system concept

The CRISP instrument can, in principle, support multiple missions, including multiple Targeted Observables and science objectives highlighted in the National Academy of Sciences in the 2017 Decadal Survey for Earth Science and Applications from Space (“ESAS 2017”). [11]. The scan mode is dynamically on orbit depending in response to observations, including autonomous on-board processing of the measurement or cueing from other members of a constellation observing system. We project that a space-optimized CRISP system can be designed and built which utilizes a computational imaging chip hybridized with state of the art LWIR detectors. An example instrument is described in Figure 8 (a) with realistic optical and detector parameters comparable to CRISP 2.0 from the previous section, but with more specific spectral and optical parameters chosen for scientific utility.

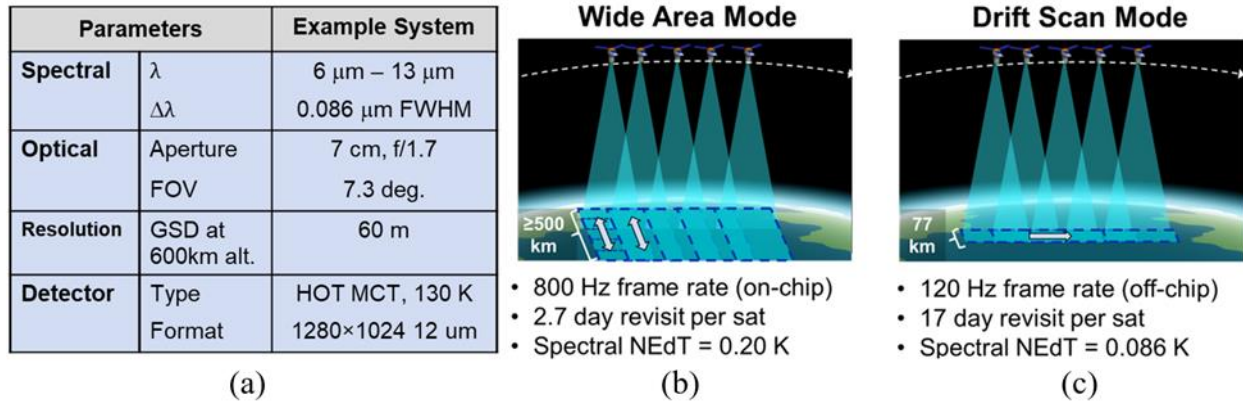


Figure 8 (a) Example CRISP thermal IR reference system b) Wide Area Mode, c) Drift Scan Mode

As introduced in 2.3, the CRISP imaging approach provides for reconfigurable scanning. In Wide Area Mode (shown in Figure 8 (b)), the instrument is rapidly scanned in the cross-track direction, which also provides a valid spectral encoding, producing a wide swath of data. In Drift Scan Mode (shown in Figure 8 (c)), the instrument is pointed at a fixed view angle during a drift scan (akin to pushbroom systems). Wide Area Mode prioritizes global coverage, with each spacecraft able to obtain high resolution global coverage (at 60 m GSD) over the whole Earth in a single day. The tradeoffs for operating in this mode are shorter dwell times (hence lesser SNR), and the need for high frame rates. For the example of Figure 8 (a), an effective frame rate of 800 Hz is required to provide wide swath coverage, and reading out a 16 bit, 1280×1024 frame at this rate would require ~32 Gb/s, among the highest readout rates under development to date with digital focal plane imagers. In Drift Scan Mode, longer dwell times (hence greater SNR) and slower frame rates (120 Hz in this example) are prioritized. The spectral NETD projections are based on modeled optical losses, detector performance, and SNR scaling laws for CRISP confirmed experimentally [1, 2].

1.3.1.1. Relevancy scenario: Evapotranspiration and surface temperature

The reference instrument described in Figure 8 is well-suited to thermal IR (TIR) imaging of the Earth surface, significantly exceeding the performance of current and planned Landsat missions. CRISP, as a hyperspectral imaging system offers significantly greater native spectral resolution than the 5 TIR bands described in a 2019 Reference Mission Architecture (RMA) provided by ESTO as part of the most recent SLI call for proposals. However, CRISP, in Wide Area mode, can produce the 5 TIR bands as linear combinations of native spectral bands. This mode also provides dramatically greater revisit rates, particularly if a constellation is employed, enabling new science capabilities. For example, diurnal, high-resolution characterization of evapotranspiration, a key bioclimatic variable linking the water, energy, and carbon cycles, is proposed as a “very important” science objective (“H2a”) in the Decadal Survey [11]. A 10-satellite-constellation of CRISP instruments observing soil and vegetation temperature with ~6 hour revisit time in Wide Area mode readily addresses this capability, which is not addressed by any other current or planned system with sufficient temporal and spatial resolution. As a hyperspectral system, CRISP offers significant additional flexibility to support improved temperature-emissivity separation (TES) beyond what fixed-band systems like Landsat provide.

CRISP 2.0 can observe high-temperature events such as wildfires and volcanic activity and their immediate aftermath in the surrounding ecosystem using the DFPA’s true high dynamic range detection to quantify radiated energy without saturation. CRISP can also support mineral mapping using TIR spectral

features such as those of quartz and silica, with spectral and temporal resolution well beyond the parameters identified by ESAS 2017 [12] (as requested by this call).

1.3.1.2. Relevancy scenario: Planetary boundary layer

Improved understanding of thermodynamics within the Planetary Boundary Layer (PBL), including its structure and PBL height over land and water as a function of time of day, is of high priority to NASA, as recommended by ESAS 2017. Recently, the PBL Incubation Study Team delivered a white paper [13] outlining key science needs and technology development recommendations for improved PBL characterization. While passive IR observation of the PBL is difficult due to sensitivity and cloud cover limitations, the white paper describes passive infrared sounding and imagers as key PBL instruments, along with other measurement approaches. Technology development needs are described, including “Improvements in ROIC readout speeds to enable very large array formats” and more compact spectrometer designs, both advanced by the proposed CRISP 2.0 technologies. The white paper also points to a need for LWIR instrument options, noting that existing initiatives to miniaturize IR sounders have focused on the MWIR[14, 15], limiting PBL sensitivity as a result. In addition, current sounders of record such as Cross-Track Infrared Sounder (CrIS) have >15 km ground resolution, far coarser than needed for PBL.

Parameters	Optimized for Moisture Profile	Optimized for Temperature Profile
λ	6-8 μm	13-15 μm
GSD	540 m (after 9x9 on-chip binning)	
Spectral bands	$\Delta\lambda = 10 \text{ nm}$	
Global revisit	<6h with 10-sat constellation	
Spectral NE Δ T	0.1 K	

Figure 9 Example reference designs targeted at moisture and temperature sounding applications

Passive IR instruments can contribute to PBL in three key ways: PBL cloud and aerosol height, vertical sounding of moisture, and vertical sounding of temperature, all at subkilometer spatial resolution with 6 hour revisits. PBL cloud and aerosol height can be accurately observed using stereoscopic imaging with a LEO-LEO formation of IR imaging instruments[13, 16], including the CRISP 2.0 reference system described in Figure 8(a). Temperature and water vapor sounding demand greater spectral resolution and thus require designs which are more targeted at those applications, such as those described in Figure 9. For example, a CRISP concept addressing these spectral resolutions and ranges is likely to require designs with gratings rather than prisms, and suitable optical coatings and detector cutoff wavelengths. In this concept, 9x9 spatial binning is employed with spectral components optimized for retrieving PBL moisture and temperature while operating in Wide Area Mode, providing the vast majority of the required spectral information content.

2. PRINCIPLE OF OPERATION

2.1. TECHNICAL APPROACH

The CRISP system is a recently developed [1, 2] hyperspectral imaging (HSI) system, which, like FTIR systems, utilizes multiplexing to enable higher optical throughput. In contrast to FTIR systems, CRISP does not require moving parts. Instead, CRISP utilizes a dual-disperser reimaging design (Figure 10), with a static encoding mask in the image plane, and relies on platform motion or scanning to achieve coding diversity and successive looks. Spectra are recovered from these successive looks via inversion of the data by utilizing the (known) encoding mask pattern. The CRISP approach for HSI enables two sensitivity gains: (1) the traditional Fellgett or multiplex advantage and (2) an additional coding gain. As the along-track format size of the focal plane array grows beyond the minimum number of platform shifts needed to reconstruct the data cube (x , y , and wavelength), the measurement becomes more overdetermined, and the signal-to-noise (SNR) of the reconstructed data cube continues to improve. The result, which we refer to as coding gain, is that the SNR grows ever-larger in proportion to the square root of the along-track focal plane array format size [1]. The coding and Fellgett gains can be obtained simultaneously in practical designs and applications. These gains are especially pronounced for detector-noise limited focal planes such as uncooled microbolometer arrays.

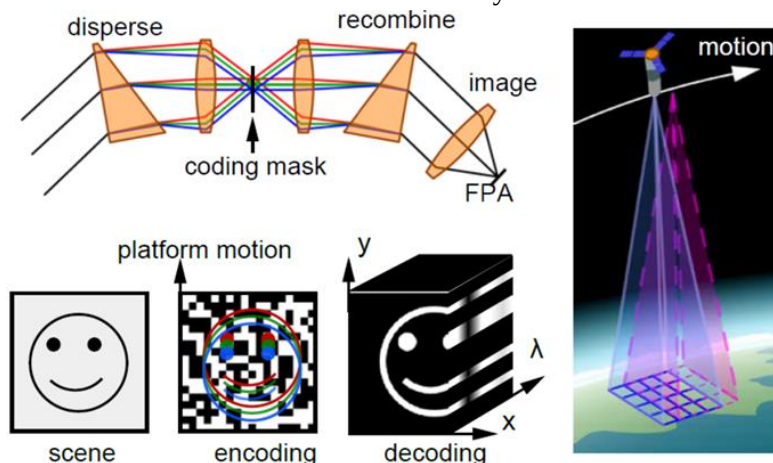


Figure 10 Measurement approach. The scene's colors are dispersed by a prism and focused onto an encoding mask. The colors are then recombined using a second prism and imaged by a microbolometer camera. After sufficient unique measurements (which are obtained as the dispersed scene travels across the mask due to platform motion), the collected data can be inverted to yield the hyperspectral cube.

In addition to the lack of moving parts, the CRISP design provides an additional advantage in that it reduces spectral distortion. Most HSI systems containing dispersive elements suffer from unavoidable spectral distortions known as “smile” and “keystone” [17]. The dual dispersers in the CRISP design minimize these image-position-dependent effects since the second prism undoes the effect of the first, recombining the spectral energy back into a given pixel.

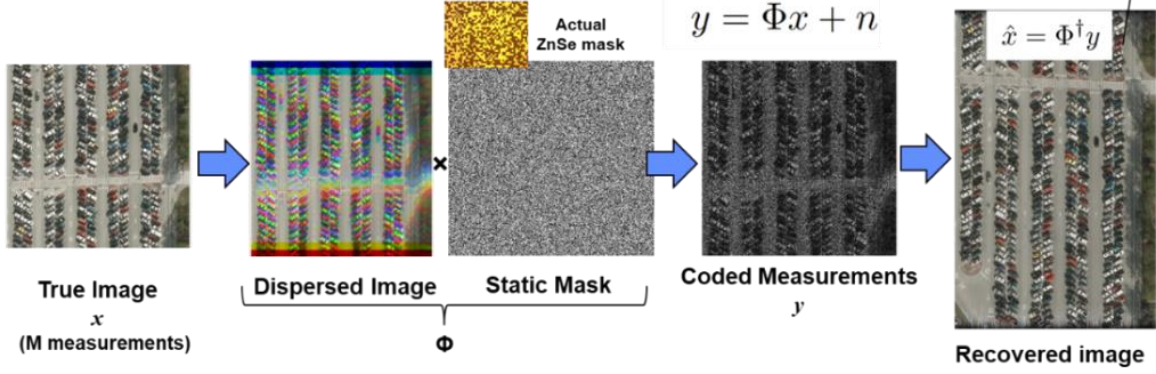


Figure 11 CRISP spectral encoding and decoding

2.2. ENCODING AND DECODING PROCESS

Figure 11 illustrates the spectral encoding and decoding process. The 3-D spatial spectral data cube x is encoded in this measurement sequence y with a known measurement matrix ϕ . With a well-designed mask, ϕ is well-determined or overdetermined. We have previously shown that the binary mask can use a Hadamard S-matrix code [18] or a pseudorandom binary pattern, with expected performance converging to a similar result for both choices for sufficiently high ratio of measurement count to number of spectral channels. The pseudoinverse, ϕ^+ is then used to compute the reconstructed data cube $\hat{x}$. The dispersion can be performed in the along-track dimension or cross-track dimension, with suitable choice of coding mask. The spectral encoding process is further illustrated in Figure 12 for the case of along-track dispersion. For a given spectrum x , each color is shifted a different amount by prism dispersion before being imaged onto the binary mask, and is therefore blocked by a different portion of the mask. As the line of sight is scanned, each color is temporally modulated with a uniquely delayed sequence defined by features on the mask. The colors are recombined by the second prism and imaged onto the detector plane, which then records a sequence of observations, which we call y . The encoding is described by the overdetermined system of equations $y = \phi x$, where ϕ is a known measurement matrix that is determined by the coding mask. This system is illustrated in Figure 12. The spectrum $\hat{x}$ can be determined independently from its corresponding observations y by computing and using the pseudoinverse of the observation matrix $\hat{x} = \phi^+ y$, where $\phi^+ = (\phi^T \phi)^{-1} \phi^T$.

In Figure 12, the binary observation matrix is illustrated with “1” and “0” represented as white and black, respectively, and is cyclic due to the delayed modulation applied to each color. In practice, ϕ is generally not purely binary due to the resolution limits of the imaging system, but the formulation above is still applicable, provided ϕ is well-characterized in the laboratory, which we have found to be a key requirement for this measurement approach. For cross-track dispersion, ϕ is not cyclic in the scan direction but the encoding and decoding process are otherwise similar. We have previously shown that the binary mask can use a Hadamard S-matrix code [18] or a pseudorandom binary pattern, with expected performance converging to a similar result for both choices for sufficiently high measurement count ($\sim 3x$ overdetermined or greater).

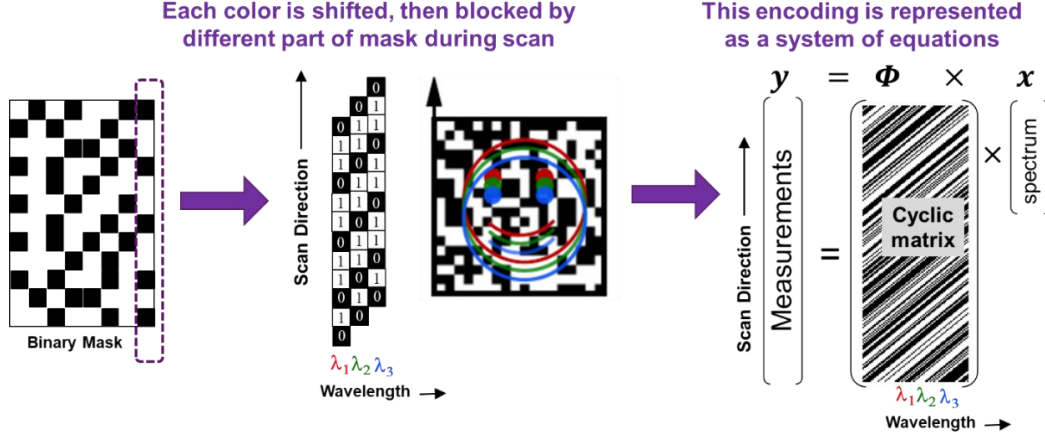
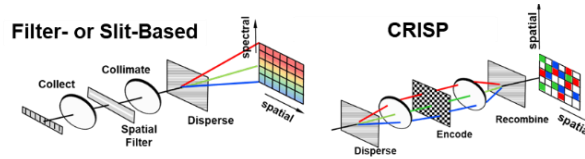


Figure 12 Mask features encode each (shifted) color during a scan, resulting in overdetermined system of equations.

The CRISP design enables significantly greater SNR than a conventional slit-based spectrometer or filter-based system such as heritage Landsat instruments, as summarized in Figure 13. We define the number of wavelength bins as N_λ , and the number of along-track measurements as M . (We require $M \geq N_\lambda$.) By incorporating all wavelengths in the measurement, CRISP gains a sensitivity advantage (known as the multiplex or Fellgett advantage[19]) versus the slit-based or filter-based system. For dark noise-limited measurements, SNR enhancement for CRISP versus the slit-based or filter-based system is $\frac{\sqrt{M}}{2}$, enabling sensitive measurements using lower performance detectors such as uncooled microbolometers. (SNR is defined as average signal intensity over the noise standard deviation.) Under background-limited (hence shot-noise-limited) conditions, SNR enhancement relative to existing dispersive spectrometers is possible as well. Specifically, if $M > N_\lambda$ then the reconstruction problem is overdetermined, and SNR enhances by a factor we call “coding gain” $\sqrt{\frac{M}{2N_\lambda}}$. For example, for a system with $M = 1920$ along-track measurements and $N_\lambda = 52$ spectral channels, CRISP enhances SNR by a factor of 22× for a dark-noise limited system and a factor of 4.5× for a background-limited system.

2.3. RECONFIGURABLE SCANNING

In contrast to other spectral imaging methods, the CRISP measurement approach allows for reconfigurable scanning, allowing scan rate (and, therefore, revisit rate and area coverage rate) to be traded off versus SNR, depending on current mission goals. Specifically, SNR for a given spectrum scales with $\sqrt{\text{dwell time}}$, which is inversely proportional to revisit rate. For example, higher revisit rates and area coverage can be prioritized to respond to rapidly evolving events and environmental disturbances such as fires or volcanic activity. Alternatively, longer dwell times and higher sensitivity can be prioritized over a region of interest with a slower scan mode. This capability allows a single CRISP instrument to be optimized in real time, in response to autonomous on-board processing of the measurement or cueing from other members of the constellation observing system. A key and unique strength of CRISP versus other spectrometer types is that CRISP can provide valid spectral encodings in both the along-track and cross-track directions for the same system, allowing scan directions to be varied as well as scan rate.



Example*:
 $M = 1920$ imager rows
 $N_\lambda = 52$ wavelengths

	Filter- or Slit-based SNR scaling	CRISP SNR scaling	Rationale
Background-noise limited (e.g, cooled MCT)	1	$\sim \sqrt{M/2N_\lambda}$ Example*: $\sim 4.5\times$	CRISP is overdetermined: $M \gg N_\lambda$
Detector-noise limited (e.g., uncooled microbolometer)	1	$\sim \sqrt{M}/2$ Example*: $\sim 22\times$	Additional “multiplex” advantage when all λ measured at once

Figure 13 CRISP SNR advantage versus a conventional pushbroom spectrometer. CRISP enables significant SNR improvement over conventional designs due to measurement count and wavelength multiplexing

Figure 14 illustrates three proposed configurations of CRISP which vary the tradeoff between area coverage rate (ACR) versus SNR in three different ways. Figure 14 (a) illustrates “drift scan”, in which the instrument is pointed at nadir as with a traditional pushbroom system. Figure 14 (b) illustrates “wide area” mode, which places greater priority on area coverage and lesser priority on SNR. The instrument is scanned in the cross-track direction, which also provides a valid spectral encoding. The tradeoffs for operating in this mode are shorter dwell times (hence reduced SNR), and additional processing utilizing a forward model that accounts for the motion blur and solving for a greater number of unknowns at once. Figure 14 (c) illustrates “long-dwell” mode, in which the scan rate is greatly reduced to increase dwell time over a region of interest. With the reduced scan rate, encoding the spectrum at temporal resolutions approaching the frame rate requires either microtranslation of the mask or small step-stare changes in scan angle using a fast steering mirror in front of the optical system. In addition, geometric and nadir corrections are required due to the larger change in aspect angle throughout the acquisition process. We note that this long-dwell measurement is significantly overdetermined, and can be split into multiple acquisitions and reconstructions of the spectral data cube, each encompassing much smaller variations of the aspect angle.

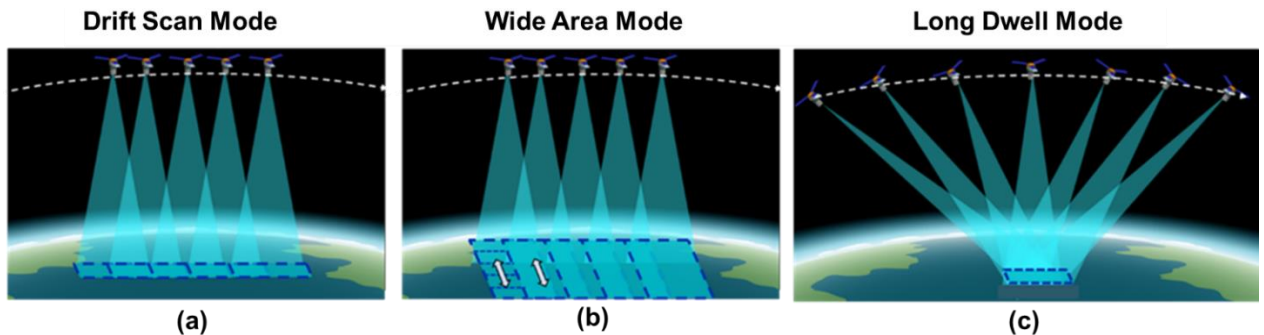


Figure 14 Three configurations trading off ACR vs. SNR: a) Drift scan mode, b) Wide-area mode, c) Long-dwell

2.4. VARIABLE VS FIXED MASK FOR SPECTRAL RECONFIGURABILITY

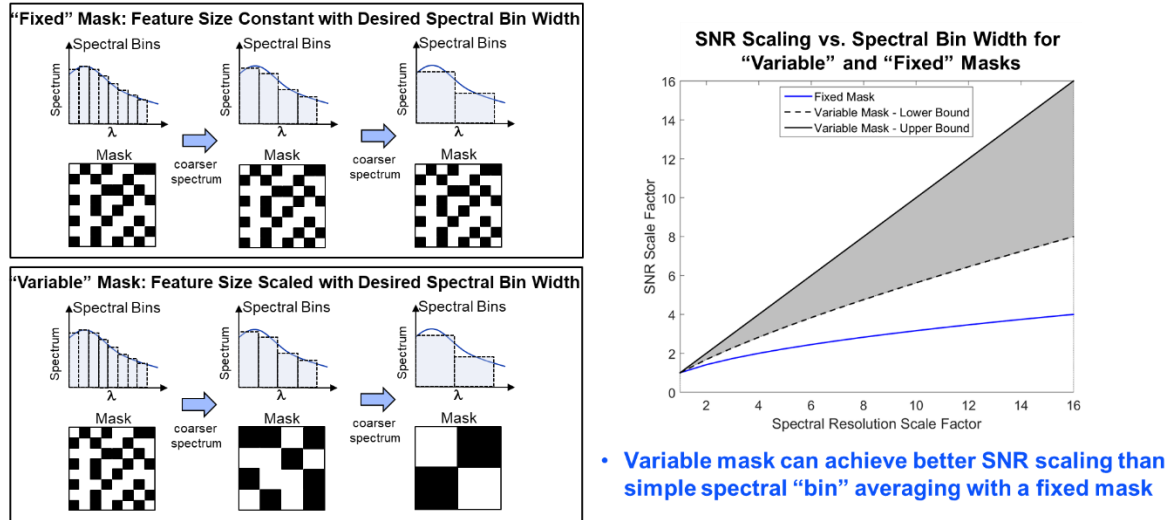


Figure 15 Comparison of SNR scaling as a function of spectral resolution for a system with a fixed mask versus a variable mask

An additional proposed way to reconfigure the CRISP system is a variable mask rather than a fixed mask. For example, consider a multipurpose sensor where different spectral resolution is required at different time. For a given spectral resolution, the mask features and mask design can be optimized to maximize SNR. In particular, if a coarser spectral resolution is desired from the CRISP system than its native spectral response, then the mask could be swapped (e.g., via a mechanism such as a filter wheel) with a different mask that has coarser features optimized for that resolution. This is illustrated in Figure 15 (left). Our analytical and numerical models have established that a system with a variable mask, with feature size optimized for the desired spectral resolution can achieve significantly higher SNR than a system with a fixed mask where simple spectral averaging of the native-resolution spectrum is employed to change the resolution. Figure 15 (right) illustrates the predicted SNR scaling as a function of spectral resolution for a binary CRISP system for different cases:

- "Fixed mask": The spectrum is initially formed at a high spectral resolution from a single mask with fixed feature size. The desired coarser resolution spectrum is then achieved by numerically averaging the finer spectrum to synthesize it
- "Variable mask" The mask features are tuned to the desired scaled resolution. For example, if the desired resolution is 4x native spectral resolution, then some or all of the binary mask features are 4x the native spatial resolution.

The variable mask case is bounded by two cases:

- Step-stare case: The mask features are all scaled, and a step-stare system is used to guarantee transmission through the desired coarse mask features on each frame. (The step-stare is required to avoid contamination of the coarse spectrum with higher spectral resolution features.)
- Smooth-scan case: The mask is optimized iteratively to maximize predicted SNR at the desired spectral resolution. The result typically includes a mix of scaled (coarse) and unscaled (fine) features. No step-stare mechanism is required, and all CRISP scan configurations are supported.

Our SNR scaling predictions, evaluated through Monte Carlo simulation, are as follows:

- “Fixed mask” case: SNR scales as $\sqrt{(\text{resolution})}$
- “Variable mask”, step-stare case: SNR scales as (resolution)
- “Variable mask”, smooth-scan case: SNR scales between $\sqrt{(\text{resolution})}$ and (resolution) , empirically about $(\text{resolution})^{\frac{3}{4}}$

The results establish that, in principle a variable mask system optimized for a desired resolution can achieve significant SNR enhancement versus the traditional process of synthesizing the spectrum after the fact from the finest scale. While we believe a system with the variable mask capability can be useful, our lab efforts focused on reconfigurable scanning described in 2.3 for the most part, due to the relatively more significant effort required to perform repeated mask installations, system function measurements, and step-stare scanning. We therefore believe this warrants additional consideration with a dedicated investigation.

2.5. COMPARATIVE TECHNOLOGY ASSESSMENT

CRISP’s computational measurement approach enables several key advantages over other spectral imagers, including SNR, reconfigurability, and lack of moving parts (apart from steering mirror). The CRISP design offers increased SNR versus other spectrometer types due to the Fellgett advantage (from making multiplexed measurements of all wavelengths at the same time) and coding gain (from making multiple views of the whole scene), allowing for lower-size/weight/power instruments such as uncooled microbolometers to achieve projected sensitivity similar to existing systems. For a notional SLI system which synthesizes Landsat bands from the spectrometer bands, these same SWaP advantages with uncooled sensing would apply versus heritage cryo-cooled Landsat TIR instruments [20]. Other groups have presented uncooled instruments using filters and mechanical motion compensation (for example, [21]), but these instruments cannot achieve the same maximum area coverage as CRISP, and lack the additional TES capacity provided by the additional spectral channels.

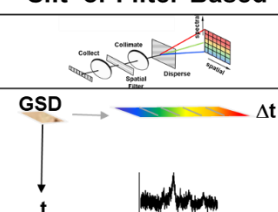
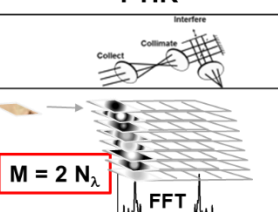
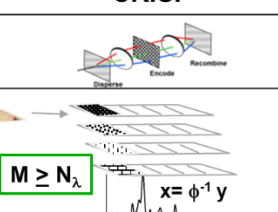
	Slit- or Filter-Based	FTIR	CRISP
	 GSD Δt t	 $M = 2 N_\lambda$ FFT	 $M \geq N_\lambda$ $x = \phi^{-1} y$
Dwell time	Δt	$M \Delta t$	$M \Delta t$
Throughput	1	$\frac{1}{2}$ (beamsplitter)	$\frac{1}{2}$ (mask)
Photon-limited SNR	$\frac{SNR_{Filter}}{SNR_{Filter}} = 1$	$\frac{SNR_{FTIR}}{SNR_{Filter}} = \frac{1}{2}$	$\frac{SNR_{CRISP}}{SNR_{Filter}} = \sqrt{\frac{M}{2N_\lambda}}$
Detector-limited SNR	$\frac{SNR_{Filter}}{SNR_{Filter}} = 1$	$\frac{SNR_{FTIR}}{SNR_{Filter}} = \frac{1}{4} \sqrt{\frac{M}{2}}$	$\frac{SNR_{CRISP}}{SNR_{Filter}} = \frac{\sqrt{M}}{2}$

Figure 16 Comparison of CRISP to other technologies, with red as “lowest performing” ranking and green as “best”

In comparison to other spectrometers, Figure 16 compares CRISP performance to a filter-based or slit-based dispersive system and an FTIR systems [22]. Note that CRISP’s SNR has similar performance

gains vs filter-based systems (such as heritage Landsat’s imagers) as it does vs slit-based pushbrooms. For the dark-noise-limited case, FTIR systems possess a multiplex advantage similar to that of CRISP which improves performance relative to a slit- or filter-based pushbroom system. However, FTIR systems require precision moving parts such as a traveling mirror to measure a spectrum. In addition, FTIR systems are typically limited to $M = 2N_\lambda$ and cannot easily make overdetermined measurements with $M > N_\lambda$ as CRISP can. Hence, the multiplex advantage for FTIR is limited to $\sim\sqrt{N_\lambda}$ rather than $\sim\sqrt{M}$ as with CRISP. A similar distinction comes into play for the shot-noise limited case, in which the overdetermined measurement of CRISP offers a coding gain of $\sqrt{\frac{M}{2N_\lambda}}$, while FTIR typically offers no such advantage. A recent spatial FTIR system using a variable-gap etalon [23] lacks moving parts but otherwise has similar limitations to FTIR shown in Figure 16, with additional signal losses due to etalon transmission. A more recent version of this system uses innovative cooled detectors but is not sensitive beyond $10.7\ \mu\text{m}$ [24]. In addition to SNR advantages, only CRISP can accommodate reconfigurable scan modes and high revisit rates described in Section, as these schemes are enabled by use of the coding mask. In addition, other spectrometer types (such as slit spectrometers, FTIR, and variable-gap etalon [24]), cannot support the reconfigurable scans mode we propose, as they do not provide valid spectral encodings in both the along-track and cross-track directions for the same system.

3. INITIAL LABORATORY EXPERIMENTS AND RESULTS

3.1. CALIBRATED BLACKBODY MEASUREMENTS

We have built a CRISP breadboard using commercial off-the-shelf (COTS) components and used it to validate spectral recovery feasibility, distortion impact, spectral resolution, and SNR scaling versus theory. The CRISP breadboard is shown in Figure 17. The breadboard was built for concept demonstration and thus has not been optimized for optical throughput or controlling aberrations. It uses a 50 fps 640 x 480 resolution microbolometer camera with 17 μm pixels and 52 mm, f/1 lenses (aspheric triplets) by FLIR (model A655sc), ZnSe dispersive prisms, and a 50 mm ZnSe coding mask with a random checkerboard pattern (composed of printed aluminum) applied using contact lithography. The mask features are 17 μm in size, matched 1:1 with the microbolometer pixel pitch. The optical design of the CRISP breadboard yields $N_\lambda = 67$ spectral bins across 7.7 – 14 μm , a resolution of $\Delta\lambda = \sim 94$ nm. The instantaneous field of view (IFOV) of each pixel is 410 μrad .

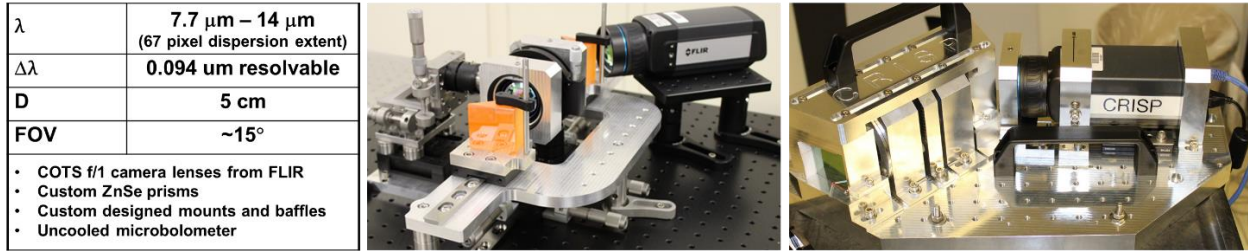


Figure 17 Existing CRISP breadboard along with its parameters. The ruggedized spectrometer components assembly, with the spectrometer in an environmental box, is shown on the right

Breadboard experiments have shown good spectral reconstructions of blackbody, narrowband, and trace gas targets, as shown in. All examples show good agreement between prediction measurement and theory.

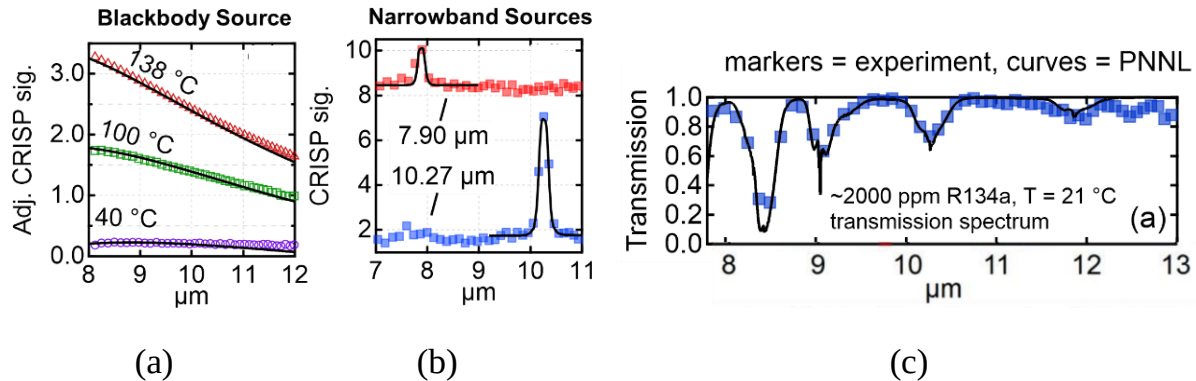


Figure 18 (a): Predicted and measured blackbody spectra; (b) Predicted and measured narrowband source spectra (c) Trace gas transmission spectrum of blackbody signal through R134a

3.2. COMPARISON TO DISPERSIVE PUSHBROOM SPECTROMETER

We also performed breadboard measurements to validate SNR scaling of CRISP relative to the same spectrometer modified to operate in a traditional pushbroom measurement scheme by removing the first dispersive prism and replacing the coding mask with a slit. Figure 19 shows the results. The measurements confirm the predicted $\sim\sqrt{M}$ SNR scaling of CRISP relative to the slit system. The measured performance enhancements are within the theoretical bounds for shot noise and detector noise limited cases for two temperature extremes, though a factor of less than ~ 2 discrepancy between the green 40 °C (near dark-noise-limited) curve and the prediction for a dark noise limited system exists. Modeling efforts suggest that aberrations and diffraction effects in the system, which will be improved in the proposed brassboard, can account for this factor, as described in subsequent sections.

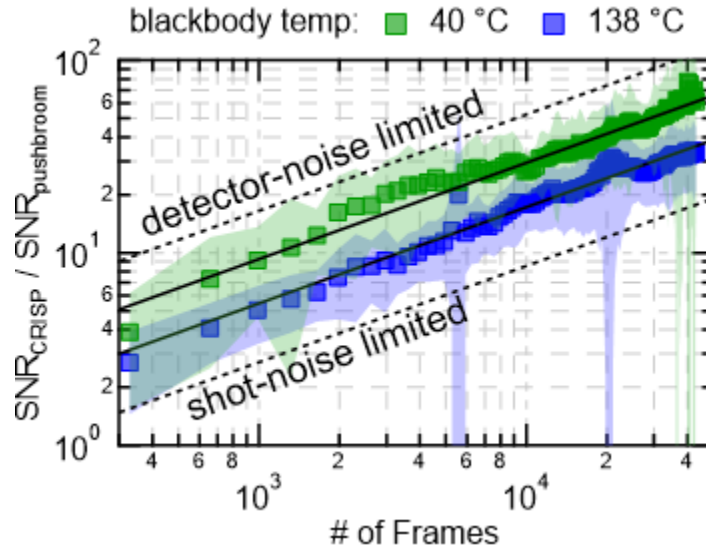


Figure 19 SNR of the CRISP spectrometer compared to same spectrometer reconfigured to operate in a traditional pushbroom measurement scheme . The CRISP SNR gains grow as $\sqrt{M}$ (shown as lines).

3.3. SPECTRAL RESPONSE FUNCTION AND SYSTEM TRANSFER FUNCTION

As described in 2.2, determination of a spectrum requires solving a system of equations $y = \phi x$ where the coefficient matrix ϕ describes the encoding of each color by the mask. To form this matrix, accurate knowledge of the “mask function”, the transmission of the CRISP system for a given wavelength, is needed. This “mask function” can be measured by imaging the mask through the CRISP system using near-monochromatic illumination. While the mask itself is binary, the actual mask transmission (“mask function”) is actually grayscale rather than binary. The mask function is measured by peering into an integrating sphere illuminated with a quantum cascade laser (QCL) with $\lambda = 8.85 \mu\text{m}$, and is shown in Figure 20. The grey scale nature of the mask image is apparent, especially away from the center, as shown in Figure 21. Near the center, grey scale masking is a result of diffraction, with the diffraction-limited point spread function (PSF) in the LWIR ($\sim 20 - 34 \mu\text{m}$) being larger than the nominal $17 \mu\text{m}$ mask feature size. Away from the center, aberrations due to the quality of the selected COTS optics are apparent. In particular, defocusing takes place due to Petzval curvature, in which the image is apparently focused on a curved surface rather than a focal plane as desired. While these image quality limitations can be readily overcome with an improved optical design, they impacted our efforts to date with the current breadboard by limiting

the usable field of view to a region of ~ 300 -pixel extent close to the center of the field. Vignetting is also apparent in the mask function due in part to the lack of telecentricity in the optics (also addressable in future iterations with design improvements).

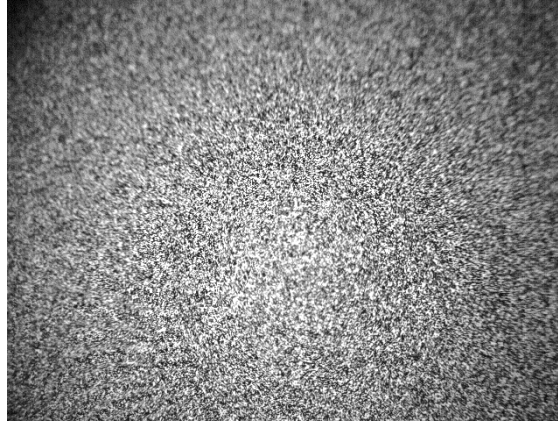
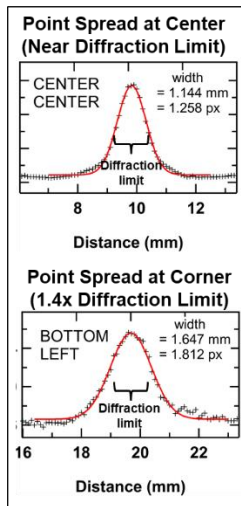


Figure 20 CRISP system "mask function". Flat field illumination at the output of an integrating sphere is used with a QCL at $8.85 \mu\text{m}$



- **Petzval field curvature: Curved image plane inherent to COTS lenses defocuses part of image and limits usage over whole field**

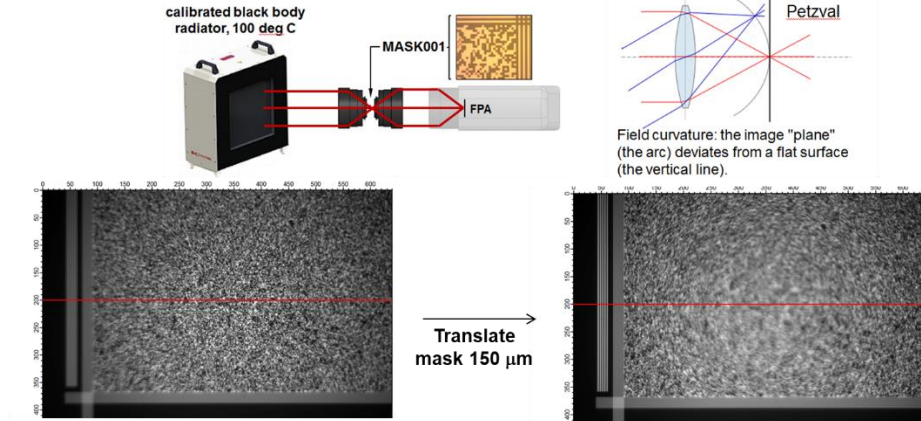


Figure 21 Grey scale mask function features and point spread functions near the center versus away from the center. The image quality is diffraction limited near the center of the field, but additional blur due to defocusing from optical aberrations such as Petzval curvature is apparent

The spectral response function (SRF) describes the response of each spectral channel as a function of wavelength. The CRISP SRF was measured using the tunable QCL and integrating sphere of Figure 22 (a). The spectral response function (SRF) was predicted to be directly related to the Airy disk created by the optics due to the formation of a dispersed image with a finite point spread on the mask plane, as shown in Figure 22 (b). The Airy disk at $\lambda = 8.9 \mu\text{m}$ is of extent $\text{FWHM}_{\text{Airy}} = 18.2 \mu\text{m}$, and, with the expected prism dispersion of $0.117 \mu\text{m}$ per $17 \mu\text{m}$, the SRF is therefore expected to be $\text{FWHM}_{\text{Airy}} / (17 \mu\text{m}) \times (0.117 \mu\text{m}) = 0.125 \mu\text{m}$. The actual SRF was measured as $0.147 \mu\text{m}$, 15.5% more than expected, which we believe are due to (aforementioned) lens imperfections and slight misalignments in the optical system.

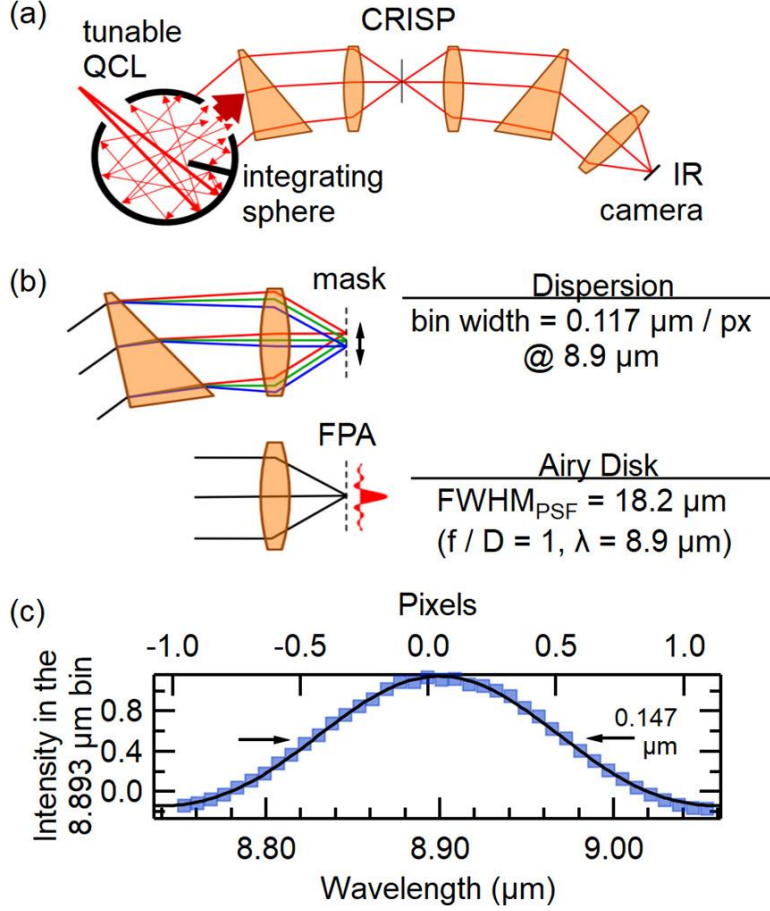


Figure 22 Spectral response function (SRF) measurement. (a) Measurement approach, in which a tunable QCL illuminates into an integrating sphere, providing a near-monochromatic flat field. (b) Predicted dispersion by the CRISP prism is 0.117 μm / px at laser wavelength, giving a predicted Airy disk of 18.2 μm (FWHM). (c) SRF, with FWHM of the SRF curve is 0.147 μm,

3.4. DISTORTION IMPACT MODEL AND MEASUREMENT

Dispersive spectrometers commonly experience distortions which need to be corrected, including “keystone” and “smile” distortion. The CRISP design, by having two prism groups, is not expected to have these distortion effects in the measured imagery. (Additional barrel or pincushion distortion of recombined image may take place due to third lens.) Specifically, the image that is dispersed by the first prism group is expected to contain these distortion effects when imaged onto the coding mask. However, the distortion imposed by the first prism group is reversed by the second, identical prism group. Any distortions in the masked/dispersed imagery must be characterized by multiwavelength measurement of the system transfer function, which we have performed (following section). Figure 23 shows an analytical representation and illustration of the impact of prism-induced distortion on the CRISP measurement. Define the true spectral image cube $F(x, y, \lambda)$, the mask transmission function as $M(x, y)$, the dispersed spectral image cube impinging on the mask as $G(x, y, \lambda)$, and the recombined spectral image cube (including spectral encoding) impinging on the detector array as $\tilde{F}(x, y, \lambda)$. In the absence of prism-induced distortion, the dispersed image is given by $G(x, y, \lambda) = F(x, y - a\lambda + y_0, \lambda)$, where a is dispersion per unit wavelength. The recombined image cube is given by $\tilde{F}(x, y, \lambda) = \sum_{i=1}^{N_\lambda} M(x, y + a\lambda_i - y_0) F(x, y, \lambda_i)$. Note that this is the

original image cube, modulated by a mask function (our spatial/spectral encoding on each frame) which is shifted as a function of wavelength by the reverse of the first prism's dispersion. The mask features, in effect, are dispersed by the action of the second prism group, while the scene spectral image features, which had been dispersed by the first prism, are restored to their original mapping. Now, assume that the prism induces distortion. Specifically, $G(x, y, \lambda) = F(x + d_x(x, y, \lambda), y - a\lambda + y_0 + d_y(x, y, \lambda), \lambda)$, where $d_x(x, y, \lambda)$ is the spatially- and spectrally-dependent shift of the original image's x coordinate, and $d_y(x, y, \lambda)$ is the shift of the y coordinate. The second prism reverses both the dispersion and the distortion, resulting in $\tilde{F}(x, y, \lambda) = M(x - d_x(x, y, \lambda), y + a\lambda - y_0 - d_y(x, y, \lambda), \lambda)F(x, y, \lambda)$. Note that the original image, once again, lacks distortion, while the mask encoding is shifted by the dispersion and distortion functions. This result indicates that the original image features, when collected by the focal plane, are not distorted. The mask encoding $M(x - d_x(x, y, \lambda), y + a\lambda - y_0 - d_y(x, y, \lambda), \lambda)$, including all distortion effects, can be characterized by illuminating the CRISP system with monochromatic light at multiple wavelengths and creating coefficients for the system of equations used to solve for the spectra.

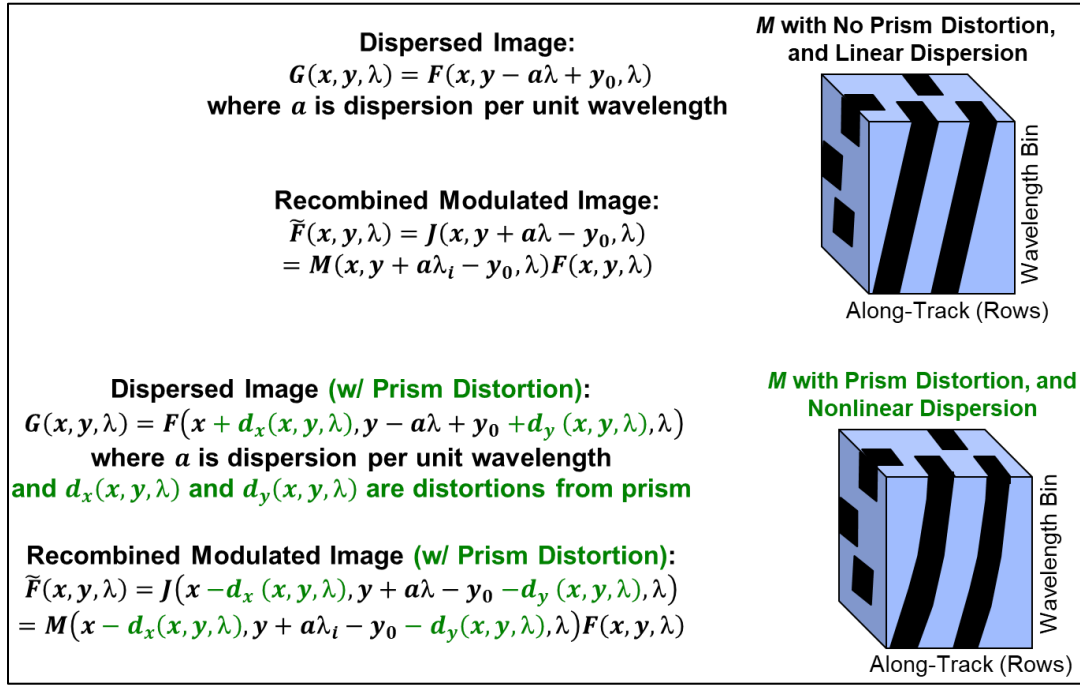


Figure 23 Analytical representation and illustration of the impact of prism-induced distortion

To test this model experimentally with the CRISP breadboard, we constructed a test screen constructed for distortion measurements containing 24" steel bars at even spacing, in front of a hot plate (18" wide, 24" long). While "smile" distortion from first prism is apparent on the mask plane (as shown from an example image through the system, when the second prism is removed), the final image of the target is corrected by second prism, and not present in measured imagery. No spectral shifting is apparent throughout the scene either in spectra recovered using measured system function.

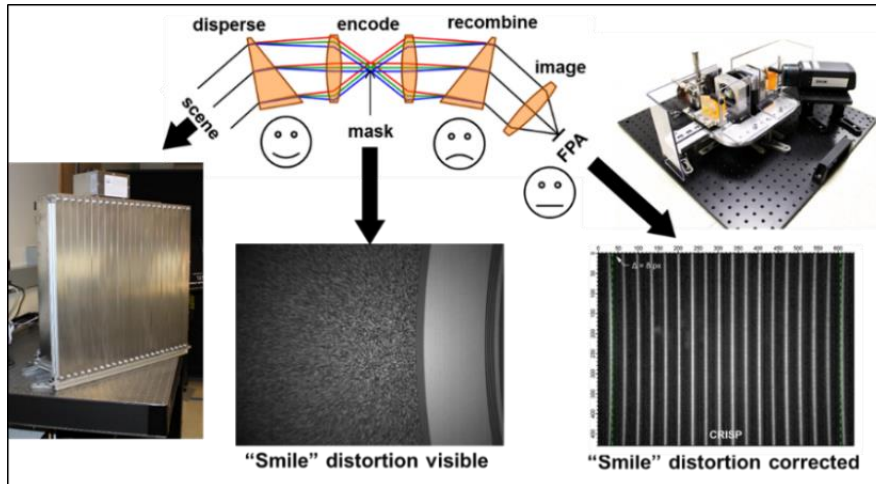


Figure 24 Experiment to characterize distortion impact.

3.5. RECONFIGURABLE SCAN MODE DEMONSTRATION

We have performed laboratory and field measurements to demonstrate the reconfigurable scan modes described in Figure 14, “wide area mode” and “long-dwell mode”, as described below.

3.5.1. Wide area scan mode

Wide area scan mode, as depicted in Figure 25, involves scanning faster than a traditional pushbroom-style drift scan to achieve high mapping rates and area coverage. One rationale for doing this is “tip and cue” operation, in which the satellite searches for a phenomenon of interest over the widest possible area, identifying it, and then reconfiguring to a longer-dwell scan mode to get a closer look. To support this mode, we have developed and demonstrated new techniques for using the CRISP measurement approach to overcome motion blur. The remainder of Section 3.5.1 is reproduced from our recent conference paper [25], which is cited in applicable paragraphs.

Traditional imaging systems suffer from motion blur and loss of spatial information if they are scanned at an angular rate faster than one ground sample distance per frame readout. The work on coded exposure photography by Raskar et. al. [26] demonstrated a solution based on an active modulation of a measurement that enables algorithmic recovery of the information normally lost due to motion blur. The CRISP architecture can achieve the same capability using a passive mask through platform or scene motion. The scene motion blur is temporally modulated by the mask during exposure. This modulated blur, with a well-designed mask and sufficient frames, is invertible, allowing recovery of spectral information at full spatial resolution. In contrast to other spectral imaging systems that lack such a coding element, CRISP can provide spectral images which do not contain motion blur, even when frame rates are limited, as is often the case with uncooled microbolometers. [25]

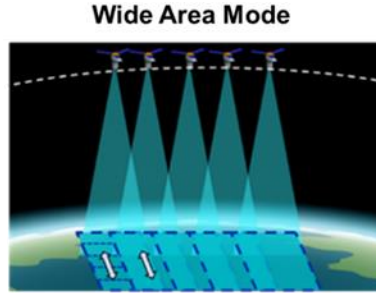


Figure 25 Wide area scan mode

We extend the model of the CRISP system introduced earlier in order to capture the effect of motion blur. In this new model, $y = SB\Phi x + n$. As before Φ represents the mapping between the unknown spectral cube and a set of unblurred CRISP measurements. However, in this extended model these measurements are followed by a blurring operation B , in matrix notation, which maps an unblurred set of frames to a blurry set of frames. We note that the blur operator combines pixels across multiple frames and that the blur does not occur within a single frame. Figure 26(a) below shows a depiction of the effect of these various operations on a scene. Further, the blur kernel may not be uniform. In the case of the microbolometer, the blur kernel is a decaying exponential as can be seen in Figure 26(b) below. The blur operator is followed by a downsampling operator S , written in matrix notation, that removes a fraction of the blurry stack of measurement frames. Using this combined model, we formulate recovery as a least squares problem which we solve using a standard conjugate gradient-based method called LSQR [27]. Figure 26(a) shows theoretical feasibility, depicting with simulated data a sample result where spectral and spatial information is recovered despite motion blur. While these results demonstrate feasibility, the computation is significantly more expensive due to the fact that the product of the B and Φ matrices lacks the computationally advantageous structure of either matrix alone. We are currently developing more advanced methods that take advantage of the structure of the individual matrices while solving the overall problem. [25]

The results shown in Figure 26 (b), using lab data, demonstrate that recovery of spectral information at full spatial resolution is feasible in practice despite motion blur. In this experiment, a hot point source was scanned across the field of view of the CRISP system at various rates, leading to commensurate increase in blur width. An example of spatial deblurring and the spectral recovery performance are shown on the right side. We note that due to the limited focal plane size, the number of measurements available for each reconstruction decreased as the blur width increased. Nonetheless, useful processed results were demonstrated even for the stressing case of a ten-pixel wide blur. This suggests that the system could be scanned at rates ten times faster than the unblurred case for certain applications where the increased error in the spectral estimation was tolerable. For larger blur widths, while spatial information could be satisfactorily recovered the spectral reconstruction was increasingly large. This was expected due to the reduced number of measurements that ultimately lead to an under-determined system of equations. Based on these results the deblurring approach presented in this section may be particularly advantageous for large format focal planes with modest frame rates. [25]

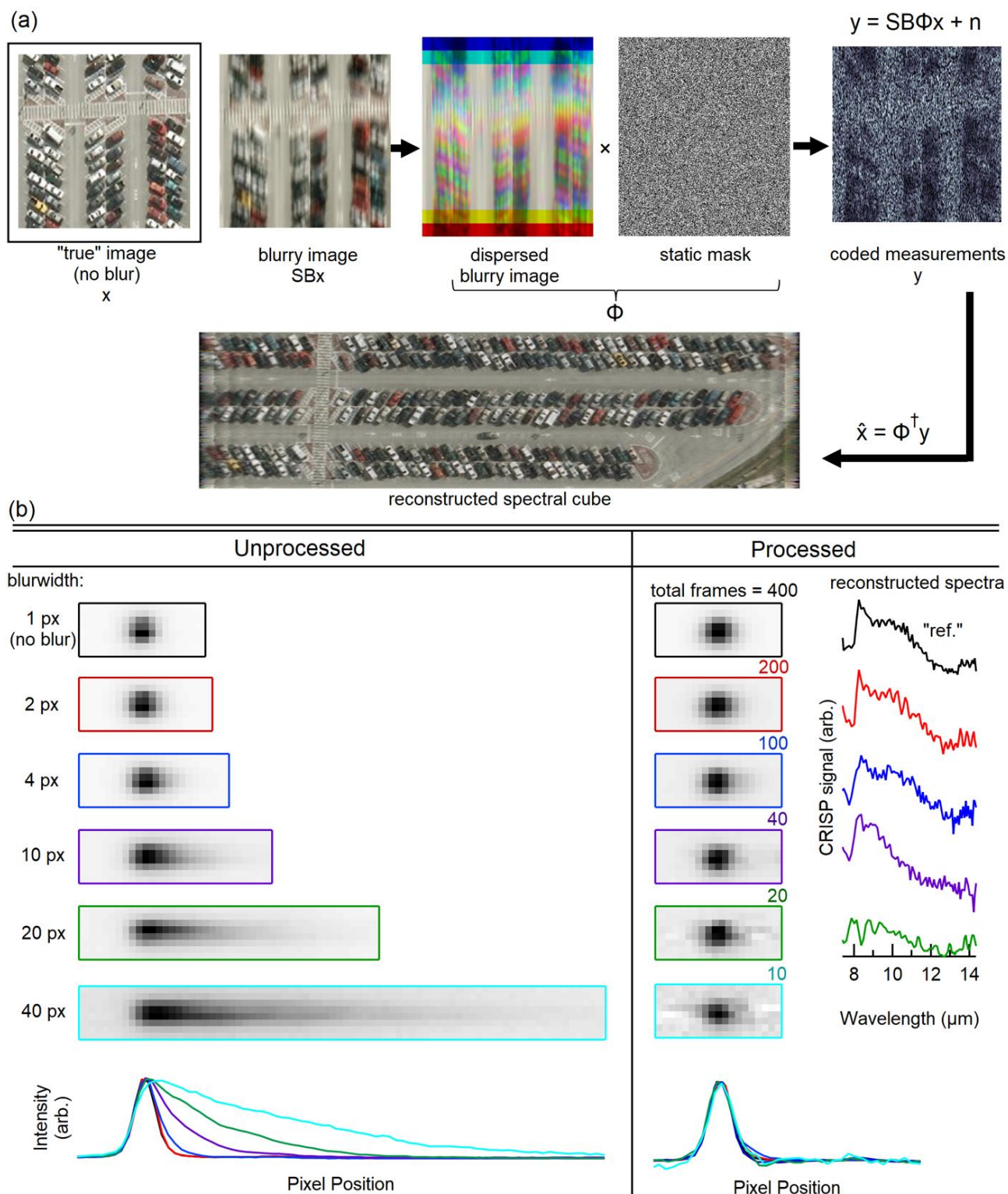


Figure 26 (a) An illustration of the extended measurement model used to capture the relationship between the spectral cube and blurred measurements. The recovered cube demonstrates theoretical feasibility. 6(b). Recovery of spectral information at full spatial resolution is demonstrated using proposed technique with lab data. The microbolometer frames are blurred with a characteristic exponentially decaying blur kernel. After processing, the blur is removed and spectral information is recovered. Due to the finite focal plane size, as the blur size increases there are fewer measurements available and so the spectral recovery becomes underdetermined. [25]

3.5.2. Long-dwell scan mode

Long-Dwell Mode

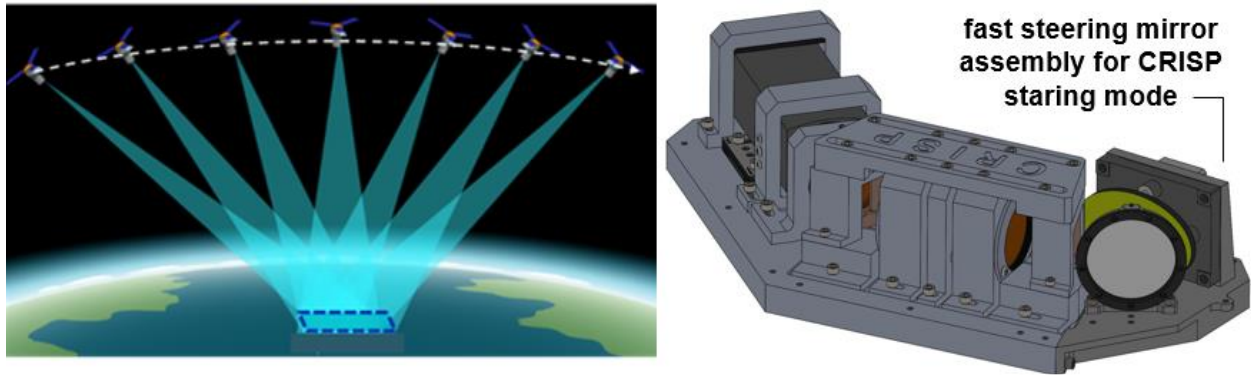


Figure 27 CRISP Long-Dwell, Staring Mode. Left: concept of operations for a long-dwell configured CRISP satellite. Right: prototype CRISP spectrometer modified with a "staring mode" fast steering mirror assembly attached to the output to enable laboratory and outdoor field measurements.

A series of laboratory and outdoor field measurements were performed to demonstrate the long-dwell staring mode configuration for CRISP. In this configuration (see Figure 27) CRISP's field of view (FOV) is fixated on one particular area of interest, enabling a higher sensitivity mode of operation, with the trade-off of lower area coverage rate (ACR). Instead of relying on 1-dimensional platform motion for hyperspectral encoding, the long-dwell staring mode relies on a 2-dimensional scanning motion created by a fast steering mirror (FSM) for the encoding process, allowing for significantly longer integration times. The ruggedized CRISP spectrometer hardware normally used for airborne tests was modified to accept a FSM assembly (see Figure 27 [Right]) that was engineered to enable the long-dwell staring mode operation via its ability to scan up to ± 5 degrees (corresponding to approximately ± 100 pixels) in 2-dimensions.

The long-dwell staring mode operation was first demonstrated in the laboratory, by staring at a large area calibrated blackbody radiator. A series of 40,000 frames was collected of the flat field source from the blackbody. Using this set of 40,000 frames, we then processed the data to mimic different staring times. We varied two parameters during processing: the number of processed frames (varying between 100 – 40,000 frames) and the raster scan size (the raster scan patterns we used were square, with shape N_{scan} by N_{scan} pixels). The SNR of the spectra was calculated for a range of combinations. The results of these laboratory tests analyzing the effects of different staring times are shown in Figure 28. We observe that the SNR increases by the $\sqrt{M}$ (where M is the number of processed frames), as expected. It is also noted that the SNR saturates when $M \geq N_{scan}^2$ (see Figure 28 [Right]). N_{scan}^2 can be thought about as the total number of unique encoding positions a single ground sample distance (GSD) can experience as it is scanned across the encoding mask. To avoid SNR saturation operationally, a raster scan pattern should be chosen such that $M \leq N_{scan}^2$; thus, larger scanning angles are required for higher SNR gains. The reason for the SNR saturation is an area of ongoing investigation, but we suspect that it might be due to clutter in the measurements introduced by (1) an imperfect non-uniformity correction (NUC) of the microbolometer that results in fixed pattern noise in the CRISP images, (2) an imperfect measurement of the encoding mask system function, or a combination of both.

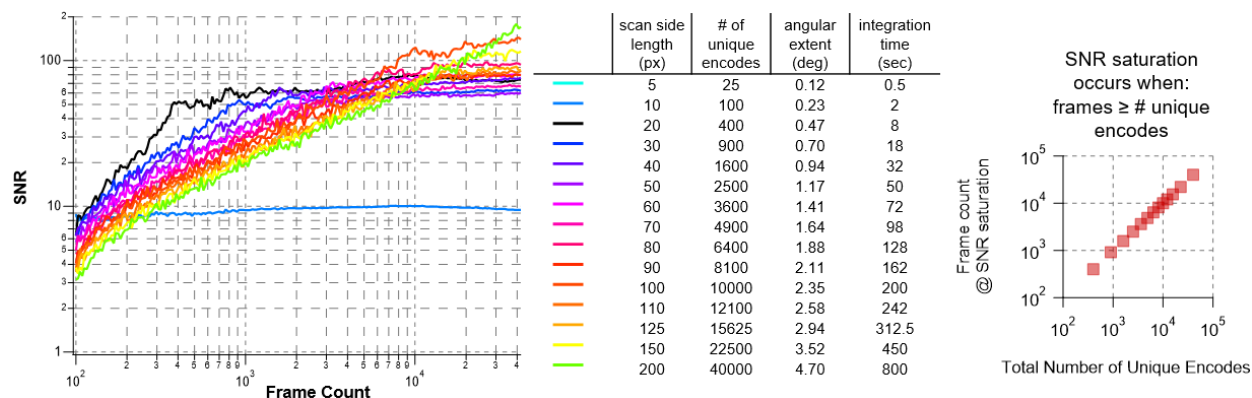


Figure 28 CRISP Staring Mode laboratory measurements of a large area blackbody radiator. Left and Middle: SNR versus Frame Count. This SNR measurement is generated from an average of 100 spectra, sampled from a 10 by 10 pixel grid, evenly spread out across the focal plane, in an effort to average out the spectrometer’s spatial non-uniform sensitivity. SNR is observed to grow at a rate of $M^{1/2}$, where M is the Frame Count. Right: the location of the SNR saturation corresponds directly to the total number of unique encodes available. For our case of an N_{scan} by N_{scan} pixel raster scan pattern, SNR saturation occurs when $M \geq N_{scan}^2$.

To test the long-dwell staring mode outside, a wood fire was started to create hot emissions for CRISP to observe. With the modified staring mode CRISP spectrometer fixed to a tripod, we captured 15,400 total frames in a raster scan pattern (~124 by 124px) of the cold blue sky, while staring through the emission plume of the fire (see Figure 29 [left]). The resultant long dwell spectrum is shown in Figure 29 (Right). Distinct, sharp emission peaks are found in the CRISP spectrum between 9 – 11 μm , which are in good agreement with a published spectrum of “burning tree” from the PNNL database. The peaks correspond to a mixture of monoterpenes, including α -pinene, β -pinene, and d-limonene.

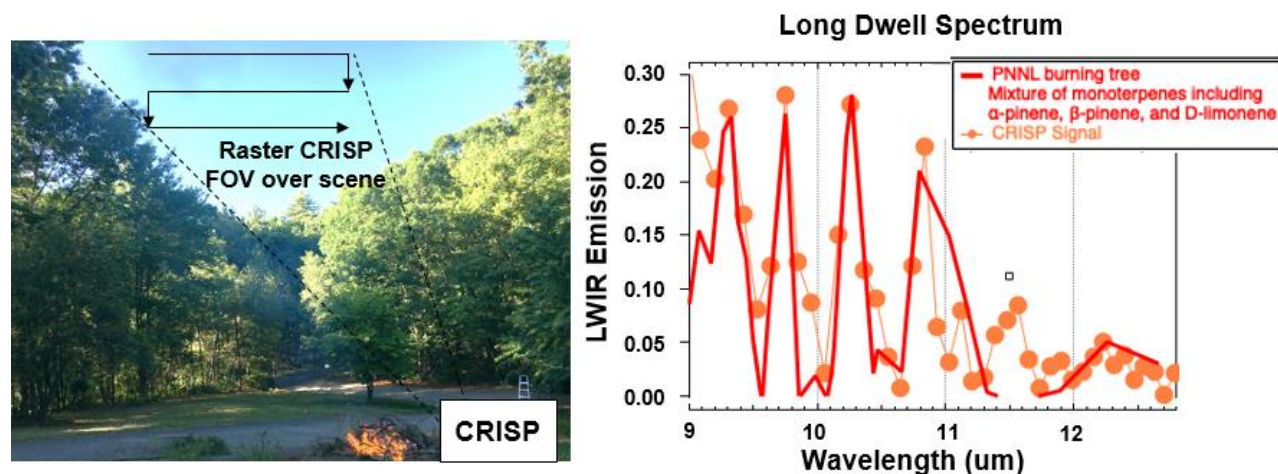


Figure 29 CRISP Long-Dwell Mode outdoor field data. Right: outdoor fielding setup. As a wood fire burns outdoors, CRISP stares through the hot emissions, collecting data in a raster scan pattern against the cold blue sky. Right: resultant spectrum, with features (four prominent peaks) that match the PNNL’s spectra database for a burning tree (mixture of monoterpenes including α -pinene, β -pinene, and d-limonene).

3.6. SUMMARY OF INITIAL BREADBOARD EXPERIMENTS

In summary, we have successfully demonstrated a computational imaging spectrometer with significant performance gains compared to existing architectures that unlocks the ability to build compact, sensitive systems with less-expensive components (e.g., uncooled microbolometers). Blackbody radiation spectra were obtained from a benchtop, proof-of-concept CRISP spectrometer and are found to be in good agreement with theory. In addition, transmission / emission spectra from a trace gas (R-134a) were obtained and are found to match well with published data from PNNL. CRISP performance gains are measured with respect to the performance of a pushbroom spectrometer of identical hardware components, and are found to be close to our theoretical predictions. The methods described here provide a new architecture for developing compact, sensitive hyperspectral imaging systems, with particular appeal for use on moving platforms such as small satellites.

4. AIRBORNE PERFORMANCE DEMONSTRATION AND TRACE GAS AND TARGET DETECTION

The CRISP breadboard hardware has been functionally demonstrated in flight on a Cessna aircraft owned by Lincoln Laboratory [2]. Despite the very challenging motion of the aircraft and known optical image quality limitations of the breadboard, the results in show successful recovery of a spectral data cube, including land-surface discrimination and detection of a trace gas release. We detail these demonstrations in the sections that follow.

The remainder of Section 4 is reproduced from our recent paper [2], which is cited for all applicable paragraphs.

4.1. SYSTEM DESIGN/DESCRIPTION

The flight system (Figure 30) uses the same design as the laboratory breadboard, with several improvements. The optical throughput was significantly improved via two modifications: (1) the 30° ZnSe prisms were anti-reflection (AR) coated improving their optical transmission from 70% to 94%, and (2) the position of the final prism was moved closer to the final lens to reduce vignetting and increase field-of-view (FOV) and throughput. The flight system was mechanically ruggedized to withstand handling during transport and the vibrational environment inside of an aircraft. All adjustable optomechanical mounts were eliminated and replaced with custom designed fixed, rugged mounts. The prisms and encoding mask were held in their rigid mounts using custom-made RTV 566 gaskets, specifically designed to eliminate stresses due to thermal expansion / contraction. The CRISP optical components were mounted onto a rigid 25 mm thick aluminum plate for increased ruggedization. A GoPro visible camera (Hero6; 60 Hz; 2704 x 1520 pixels; 85.5° x 55.2° FOV) was added to provide reference imagery in the visible spectrum. The entire spectrometer assembly was enclosed in an aluminum environmental box with a thermostat-regulated heater unit designed to maintain a stable temperature (21°). The CRISP system sees outside of the environmental box through a 100 mm diameter AR coated germanium window, equipped with an RTV 566 gasket. [2]

Georeferencing and timing information was recorded using an Applanix POS AV V510 V5 OEM with LN-200 IMU which provided INS / GPS information at a rate of 200 Hz. The system has a 140 μ rad absolute precision in pitch / roll and a 1,222 μ rad absolute precision in heading. Relative drift is 8727 μ rad / hr. Each image captured by the CRISP system includes a GPS timestamp. [2]

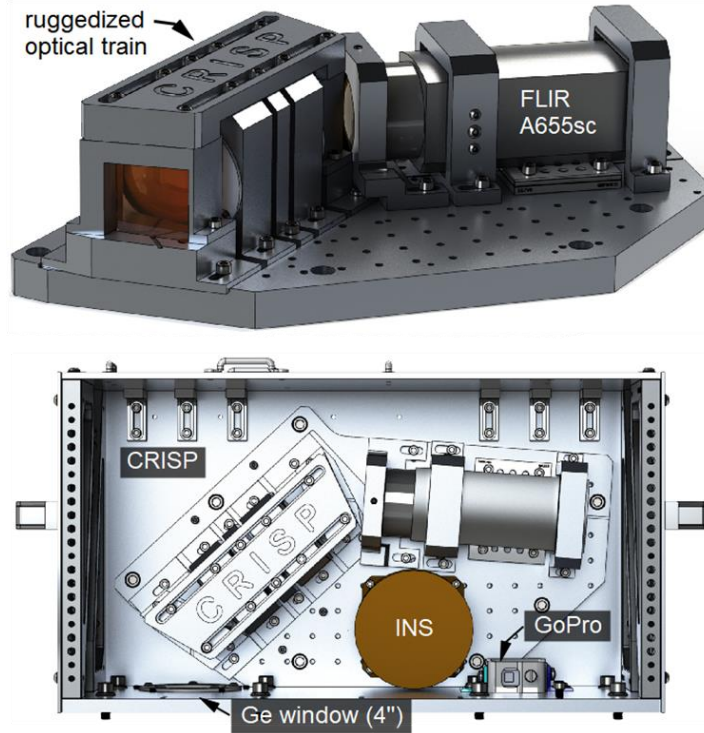


Figure 30 CRISP flight instrument, ruggedized spectrometer components assembly (top), and spectrometer components integrated into environmental box (bottom). [2]

4.2. GROUND CHARACTERIZATION

The flight system was tested before installation on the airplane and showed generally similar performance as the laboratory breadboard. The optical throughput improved from 11% (breadboard) to 21% (flight system). These values are for an extended object, which is impacted by an occluded field of view due to the final prism location and size. Note that the encoding mask contributes a 50% throughput loss. Background radiation due to Narcissus (an image of the detector itself created by a reflection from the mask) as well as the room temperature optical mounts and elements were measured by peering into a pool of liquid nitrogen. This background image (an average of 1000 frames) was subtracted from the raw data prior to CRISP processing. [2]

The flight system was designed to be robust enough that our ground calibration would be sufficient for flight data collection, i.e. no need for in-flight calibration. The “mask function” in addition to reference target spectra were measured both before and after the flight. The target spectra showed no change (within our spectral resolution), and the “mask function” showed very little change as well, indicating that our mechanical and thermal design was sufficient to achieve our stability goals. [2]

A radiometric calibration was performed using a CI Systems NIST-traceable extended area blackbody radiator, which was varied from 20°C to 125°C while CRISP spectra were recorded [Figure 31 (top)]. Assuming our source was Lambertian, these yielded sensitivities of $0.00039 \text{ CRISP}_{\text{signal}} / \mu\text{flick}$ (8 – 9 μm) to $0.00018 \text{ CRISP}_{\text{signal}} / \mu\text{flick}$ (11 – 12 μm), where $1 \mu\text{flick} = 10^{-6} \text{ W/sr/cm}^2/\mu\text{m}$. Given a noise floor of $0.0205 \text{ CRISP}_{\text{signal}}$, the noise equivalent spectral radiance (NESR) was calculated for several wavelength bands [Figure 31 (bottom)]. [2]

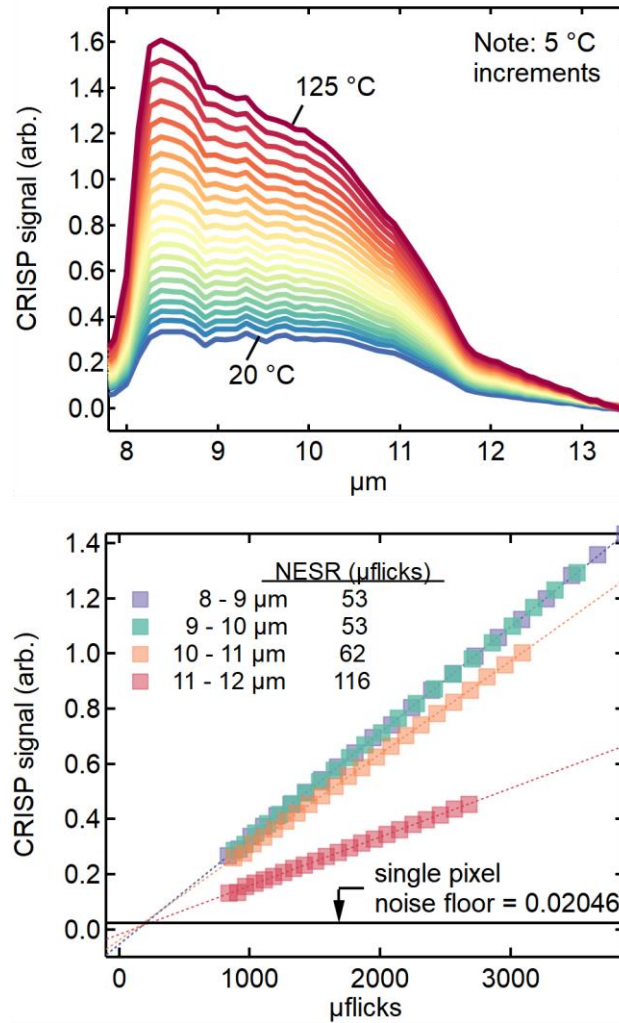


Figure 31 Radiometric Calibration of the CRISP system. Response of the system to a blackbody at various temperatures (top): Signal as a function of spectra radiance, assuming a Lambertian blackbody emitter (bottom). [2]

4.3. FLIGHT TEST OBJECTIVES / DESCRIPTION

The flight system was mounted in a Cessna aircraft owned by Lincoln Laboratory equipped with a hole cut out of the bottom that allows for mounted scientific equipment to view the Earth below. The CRISP system was mounted such that its field of view was directly below the airplane (nadir). The Cessna flew at a speed of ~50 m/s, and at an altitude of 1675 m for all of our collected data. [2]

4.3.1. Coastal: extended target spectra

Two flights were conducted in August 2018 along the coast of Massachusetts. The objective of these tests was to demonstrate the ability of the CRISP system to extract useful spectra from extended ground targets. A coastal environment was chosen for the ability to capture sand and ocean water in the same datasets. Ocean water appears largely as a blackbody radiator in the LWIR, whereas quartz-containing sand has several distinct LWIR features between 8 – 9 μm, making a coastal scene an ideal choice for evaluating

a CRISP system. Flights were conducted at two locations: the shoreline of Plum Island, MA on Aug. 20, 2018 from 12 – 4 pm (near 42°43'02.3"N 70°46'37.2"W); and Cape Cod, MA on Aug. 23, 2018 from 2 – 4 pm (near 41°51'31.9"N 69°57'04.5"W). The weather during both flights was sunny and warm with good visibility. Passes parallel to the shoreline were flown at an altitude of 1675 m, with a field-of-view (FOV) on the ground of 448 m x 336 m (15° x 11.25°), and a GSD of 0.7 m. With a flight speed of ~ 50 m/s and frame rate of 50 Hz, the image shifted ~ 1.39 GSD per frame. [2]

Local reference measurements of the temperatures of the air, sand and ocean water were collected along the shorelines using a Type-K thermocouple (Cooper Atkins 50336-K coupled with a Fluke 80TK thermocouple module for digital multimeters). The air temperature was 21°C at Plum Island (24°C at Cape Cod), the water temperature was 22°C at Plum Island (17 – 20°C at Cape Cod), and the sand temperature was 29 – 44°C at Plum Island (22 – 43°C at Cape Cod), dependent on the location relative to the water. Local sand samples were also collected and used to provide spectral reflectance measured using an FTIR instrument in the laboratory. The atmospheric transmission from ground to 1675 m was modeled via MODTRAN ® [28] assuming a standard mid-latitude summer atmosphere with 74% relative humidity in the lower 1 km layer and 64% relative humidity in the 1 – 2 km layer. The relative humidity on the beach test flights was 70% (Plum Island) and 50-60% (Cape Cod). The MODTRAN ® model yielded an average transmission of 78% averaged over the 8 – 12 µm band. The transmission curve is relatively flat but dips on either end of the LWIR spectrum. It has a minimum of 53% near 8 µm, and a maximum of 87% near 9 µm. The weather during the coastal flights was mostly sunny (little cloud cover, with clouds never coming between the CRISP sensor and the ground during data collections). [2]

4.3.1. Inland : Point targets and gas release

A flight was conducted in May 16, 2019 over Fort Devens, MA. The objectives of the tests were to (1) observe point targets to determine the PSF of the spectrometer during flight, as well as (2) demonstrate the ability to extract spectra from single pixel objects. Additionally, (3) a controlled gas release was performed in order to assess the ability of CRISP to identify gas releases. Similar to the previous flights, the plane flew at an altitude of 1675 m with a velocity of ~50 m/s. The weather was mostly cloudy. The ground temperature was 20 – 25°C. Bright point targets were created using propane burners which heated charcoal filled cast iron skillets. These skillets were ~30 cm in diameter, encompassing ~1/5 of a GSD in area (for our 1675 m altitude flight). Three of the bright point targets were underneath thin films of different materials (the films were positioned ~2.5 m above the propane burners). Reference spectra of the three films had been measured with the CRISP spectrometer in the laboratory prior to the flight. The films were Kapton, Mylar, and Teflon, all 25.4 µm thick. An additional point target was left uncovered and served as a reference to aid in ascertaining the transmission spectrum of the three films. [2]

The release of a known gas was timed to occur during the overflight. The gas was SF₆, which was released at a rate of $1.5 \times 10^3 \text{ cm}^3/\text{s}$ over ~30 s. It was released in the center of a 30 x 15 m sheet of aluminum foil, which was emplaced to reflect the cold sky background and thus ensure a temperature contrast between the airborne gas and the surface below it, without which no gas detection is possible [29]. Gas plume dynamics are driven by a combination of diffusion, drift and mixing with ambient air. In order to estimate concentration path-lengths, we assumed a simplified model in which wind in one direction plays a dominant role. Wind speeds were variable with estimated strengths of 2 m/s to 10 m/s, based on nearby weather station data. Assuming wind-driven drift dominates the gas dynamics, the gas extends in the wind direction to somewhere between 60 m (2 m/s wind) and 300 m (10 m/s wind). If we assume the gas diffuses 10 m in the other horizontal direction (consistent with our imagery) and a 1 m vertical expansion, the resultant

gas volumes are $10 \times 60 \times 1 \text{ m}^3$ and $10 \times 300 \times 1 \text{ m}^3$. The corresponding concentration path-length of the gas plume ranges from 15 ppm-m to 75 ppm-m. [2]

A schematic of the point target and aluminum foil setup is shown in Figure 32(a). The ground targets were setup near $42^\circ 30' 20.5'' \text{N}$ $71^\circ 39' 53.6'' \text{W}$. The hot point targets and the aluminum foil sheet were placed in close proximity such that they could be imaged simultaneously from the CRISP system during a flyover. A CRISP image of the ground targets is shown in Figure 32(b) (the image is cropped for better visibility of the targets). Photographs of the point targets and aluminum foil can be seen in Figure 32(c) and Figure 32(d) respectively. [2]

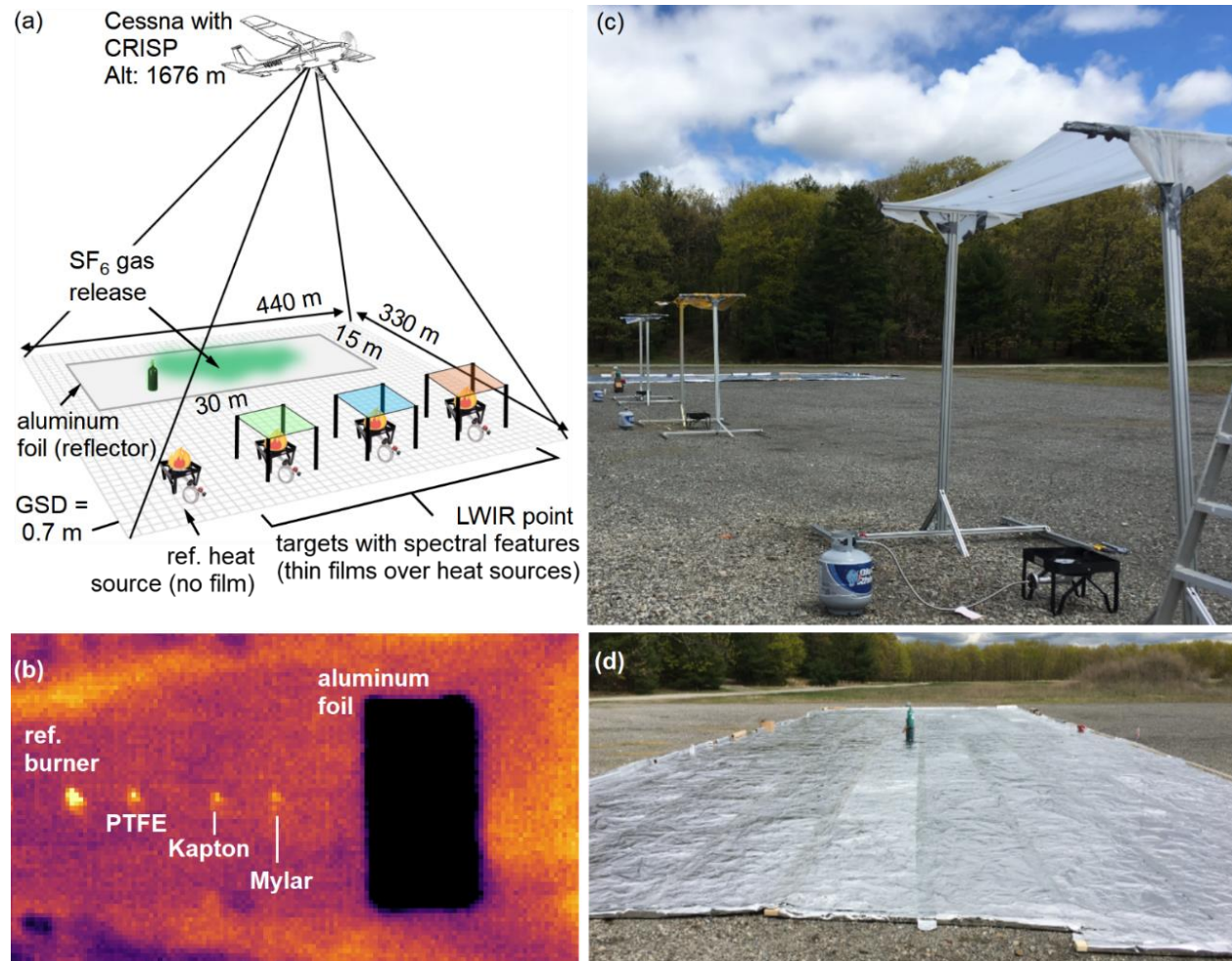


Figure 32 Inland point target setup. (a) Schematic of flight targets; (b) CRISP LWIR image of the scene; (c) bright point sources (propane heated charcoal) covered by thin films; (d) Al foil with SF_6 cylinder used for gas release [2]

4.4. FLIGHT TEST RESULTS / ANALYSIS

Example imagery from the CRISP flight tests is shown in Figure 33. Coastal imagery, urban imagery as well as sample imagery taken over our point target / gas release ground setup can be seen. In the coastal imagery (top set of images), we see a nice contrast in temperature between the relatively hot sand and the colder ocean water. Houses, streets and several industrial buildings are visible in the urban imagery (middle set of images). A large contrast in the apparent temperatures of the two separate industrial buildings is

noted. The “colder” rooftop is likely made of a metal material which reflects the cold blue sky, making it appear as a lower temperature. In the third set of images (bottom), the 30 x 15 m sheet of reflective aluminum foil is clearly visible (as a dark, cold spot in the CRISP imagery), as well as the four bright point targets to the left of the aluminum foil. Six bright spots are visible in the third CRISP image in total, the two bright spots furthest to the left side are two cars parked in line with the bright point targets. The test targets were setup on a large patch of gravel surrounded by trees and / or dirt on all sides. The apparent fixed pattern noise in the raw, unprocessed CRISP imagery is caused by the encoding mask (residuals left behind from the recombination of the dispersed scene, encoded with a randomly-chosen binary grid). We note that these artifacts are not present in processed CRISP data. [2]

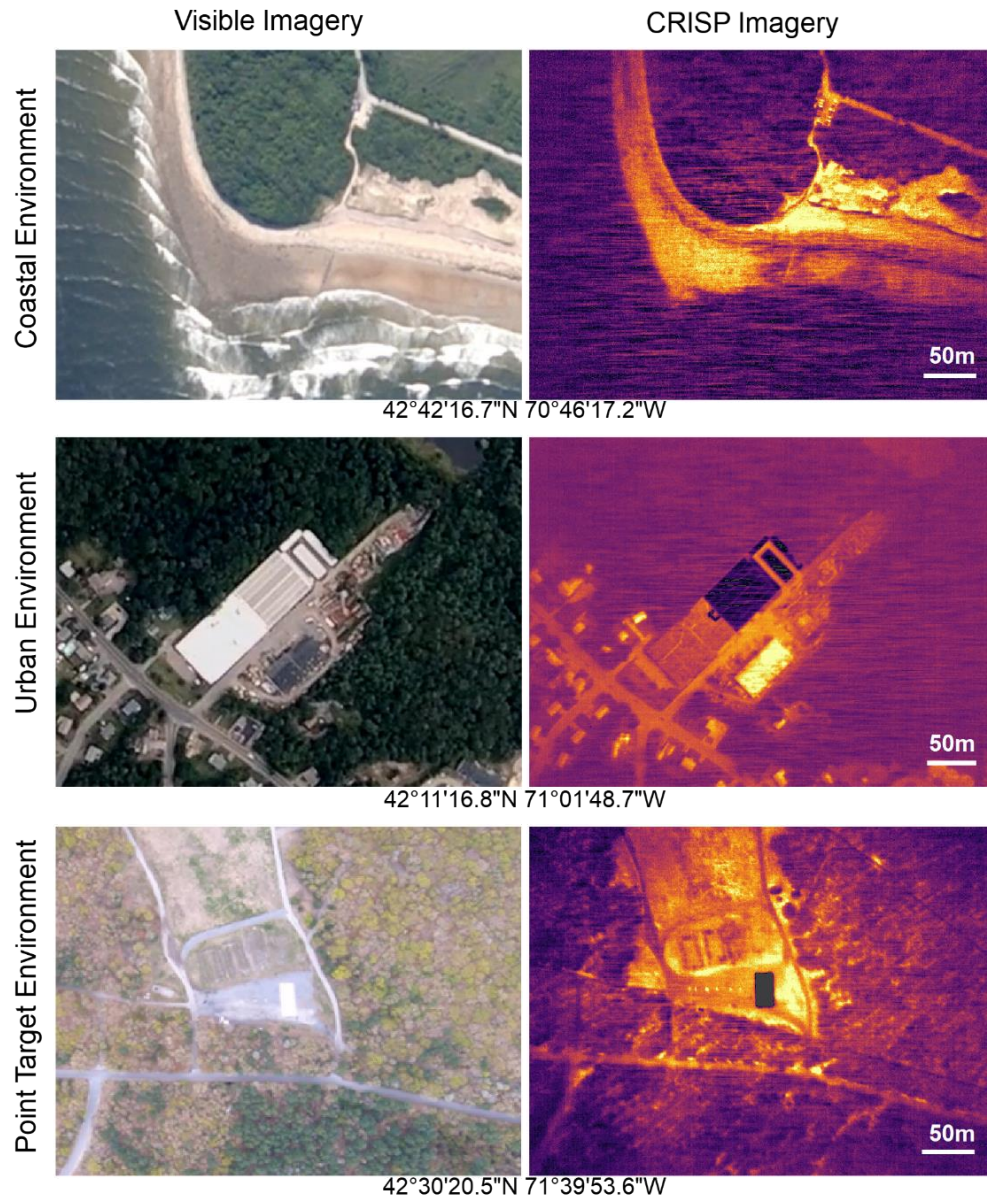


Figure 33 Aerial images collected during the flight missions. Visible imagery (left), versus CRISP raw, i.e., unprocessed, imagery (right). [2]

A major benefit of our imaging spectrometer is the ability to conduct frame-to-frame image registration for motion tracking. A simple frame-to-frame image registration algorithm was implemented to track targets in the CRISP datasets in order to process the data and create spectra. This algorithm is outlined in Figure 34. A 2D cross correlation between every n-frames (for our data we used $n = 20$) in each dataset is computed and x- and y-translations are determined. We then interpolate these values to obtain translation data for each image in the dataset. In our tests, we determined that such an algorithm for motion tracking is adequate and comparable to tracking provided by our INS data. All spectra discussed in this work used CRISP-derived registration to remove motion artifacts and isolate targets. [2]

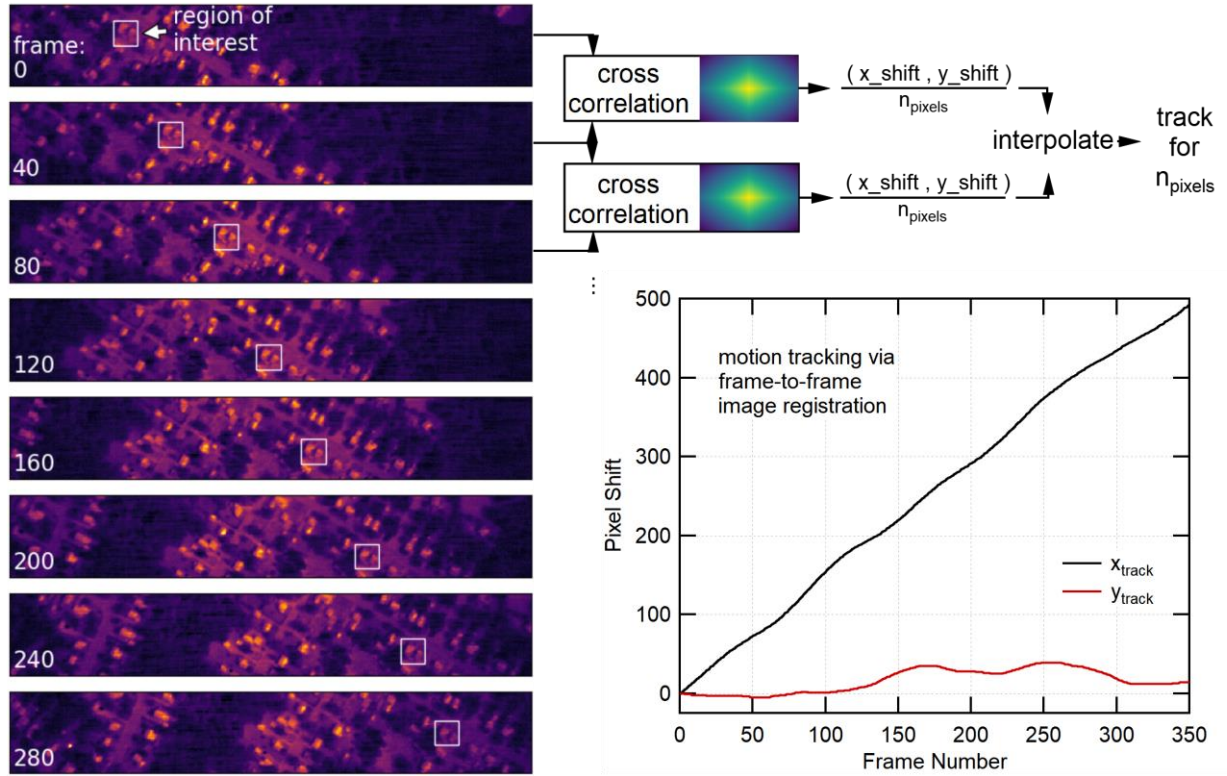


Figure 34 Motion tracking using CRISP image data. Input imagery (left) and cross correlation output (right). [2]

4.4.1. Coastal

Emissivity spectra of sand and ocean water from coastal environments located in Plum Island, MA, and Cape Cod, MA are shown in Figure 35. The spectra were produced by taking an average of a 15 px by 15 px area ($\sim 10.5 \text{ m} \times 10.5 \text{ m}$). Emissivities were calculated using the measured temperatures of the objects, and referencing the CRISP spectra to our calibrated blackbody data library collected in the lab prior to the flights. Note that atmospheric corrections were not included. Given that we estimated $\sim 80\%$ atmospheric transmission, we are neglecting the effects of 20% of the energy that manifests as upwelling and downwelling radiance. Since atmospheric transmission losses are greatest at the edges of the LWIR spectrum, exactly where our sensor sensitivity is most noisy, we found that corrections generally resulted in an even noisier spectrum. Nonetheless, the CRISP spectra of sand and water closely resemble sand and water spectra from the NASA Joint Emissivity Database Initiative (JEDI) [30] and NASA ASTER databases [31, 32] respectively. Note that the CRISP data tends to overestimate the emissivity especially

near emissivity minima. This difference between the apparent emissivity we report with CRISP and the literature results is exactly what one would expect given that we have not accounted for the effects of downwelling radiance. Near the emissivity minima, more of the downwelling radiance is reflected from the sand, adding radiance at the detector and thus apparent emissivity. Additionally, we include a laboratory-collected D&P Instr. Model 102 FTIR spectrometer emissivity spectrum of a sand sample we collected from Plum Island. The FTIR spectrum of sand (the measurement was made by collecting the diffuse scatter off the sand and comparing that to the scattered light from an Infragold reference target) closely resembles our CRISP spectra, but includes a periodic oscillation between 9.5 – 11.5 μm . This oscillation is most likely caused by instrumental interferences (within the FTIR itself). [2]

During the coastal flight campaign we collected CRISP data outside of our planned coastal area so that we could examine CRISP imagery of various types of terrain. This allowed for the possibility of capturing targets of opportunity. One such target of opportunity was a metal rooftop reflecting the cold blue sky above it [see in Figure 33 (middle)]. The LWIR temperature of the rooftop was estimated at 15°C based on comparison to laboratory blackbody data. Emission of the metal rooftop relative to a 15°C blackbody is pictured in Figure 35 (bottom). Emission lines near 9.5 μm , which are greater than the background 15°C blackbody radiation, reveal evidence of atmospheric ozone (O_3). [2]

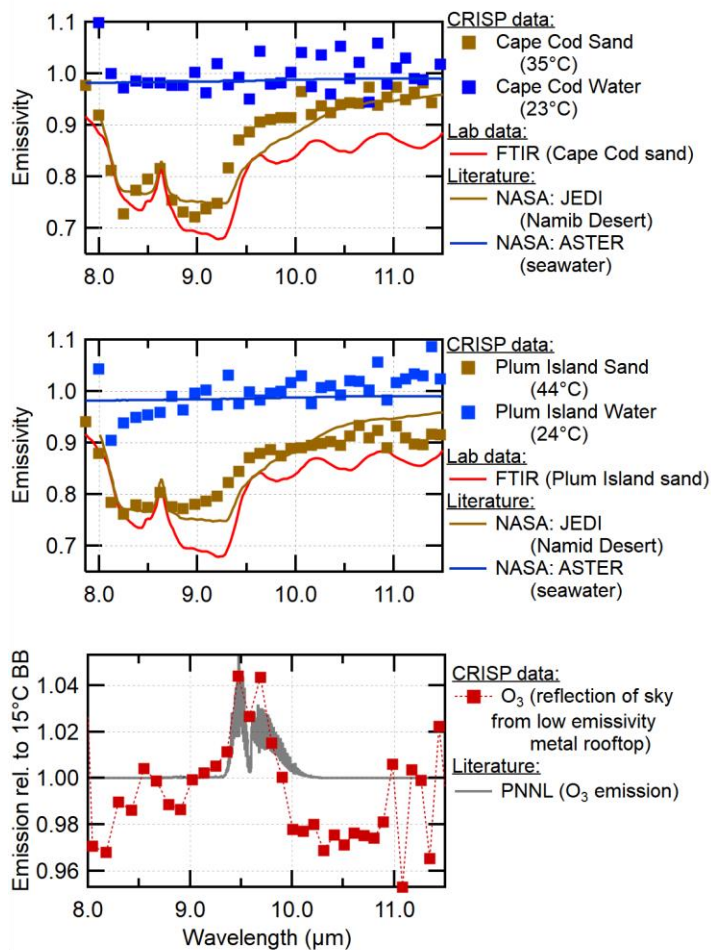


Figure 35 Coastal CRISP spectra. Sand and ocean water spectra from (left, top) Cape Cod, MA, and (left, middle) Plum Island, MA. Atmospheric ozone emission was also captured with the CRISP system (left, bottom). Photographs of the locations of each dataset is shown in the right column. [2]

The expected ozone signal was estimated assuming a 25°C uniform 80 ppb concentration [33] of ozone throughout the entire column below the CRISP sensor. Given that the effective reflected roof temperature was 15°C, we would not expect to observe significant emission from higher atmospheric O₃ as the temperature difference would vanish. Within the bounds of our air temperature measurements (21 - 25°C), 25°C yielded the best match to the expected maximum emission for an 80 ppb concentration of O₃. Thin plume and linear Planck function assumptions [29] yield the following relationship: $L = C_B \Delta T \tau_{\text{atm}} A$ where L is the radiance change due to the plume, C_B is the change in blackbody radiance with temperature, ΔT is the temperature difference between plume and background, τ_{atm} is the atmospheric transmission, and A is the absorption due to the plume. Using this relationship, our estimated temperature difference ($\Delta T = 10^\circ\text{C}$), estimated atmospheric transmission ($\tau_{\text{atm}} = 0.8$), and an ozone spectrum from HITRAN [34], the estimated emission from ozone matches the measured CRISP signal quite well (Figure 35). [2]

4.4.1. Point targets and gas release

An example overhead CRISP image of the point targets used to estimate PSF is shown in Figure 33 (bottom). To calculate the PSF from the flight data, we fit Gaussians to the reference propane burner (the propane burner without a film elevated above it) for various locations across the focal plane (unprocessed, raw data) and took an average of the Gaussian fits. The average Gaussian fit is shown in Figure 36 (left, top), and has a FWHM of $\text{PSF}_{\text{unprocessed}} = 2.8$ px. We also measured the PSF of CRISP processed data by fitting a Gaussian to a point target in a CRISP processed hyperspectral cube. The PSF after CRISP processing is negligibly different from the unprocessed data, with a FWHM of $\text{PSF}_{\text{processed}} = 2.9$ px, (Figure 36 left, bottom). [2]

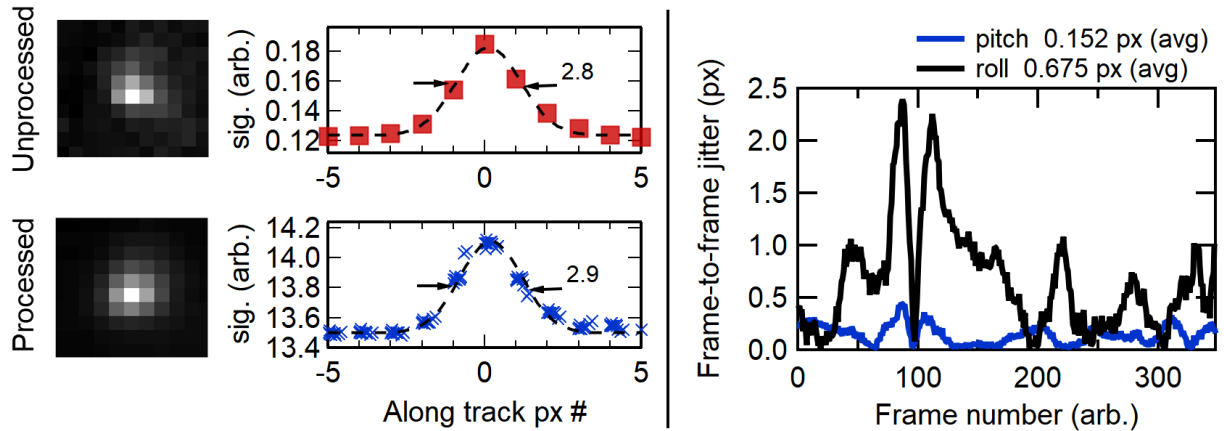


Figure 36 CRISP point spread function: image (left) and along-track cross section (middle). Raw unprocessed data and post CRISP processed data are both shown. (Right) typical frame-to-frame aircraft pointing jitter (pitch, roll, in units of pixels) during the flight. [2]

The theoretical (Airy disc) diffraction-limited PSF for the CRISP spectrometer is $\text{FWHM}_{\text{PSF}} / \text{px} = 1.07$, for a 17 μm pixel. This value is a weighted mean for the $\lambda = 7.7 - 14 \mu\text{m}$ wavelength span of the spectrometer. The measured flight PSF of the CRISP system is larger than the theoretical motionless value for two reasons: (1) the velocity of the aircraft during data collections was slightly faster than the ideal velocity of 1 GSD / frame, resulting in some blurring of the PSF; and (2), the frame-to-frame pitch / roll jitter caused by vibrations in the aircraft. Aircraft velocity during CRISP data collects was ~ 50 m/s, which

equates to 1.39 GSD / frame. INS data yield typical frame-to-frame jitter values of 0.152 px (pitch) and 0.675 px (roll) [see Fig. 10 (right) for typical data]. We account for these two phenomenon via the simple relationship: $PSF_{flight} = (PSF_{CRISP, Motionless} - jitter) \cdot velocity$

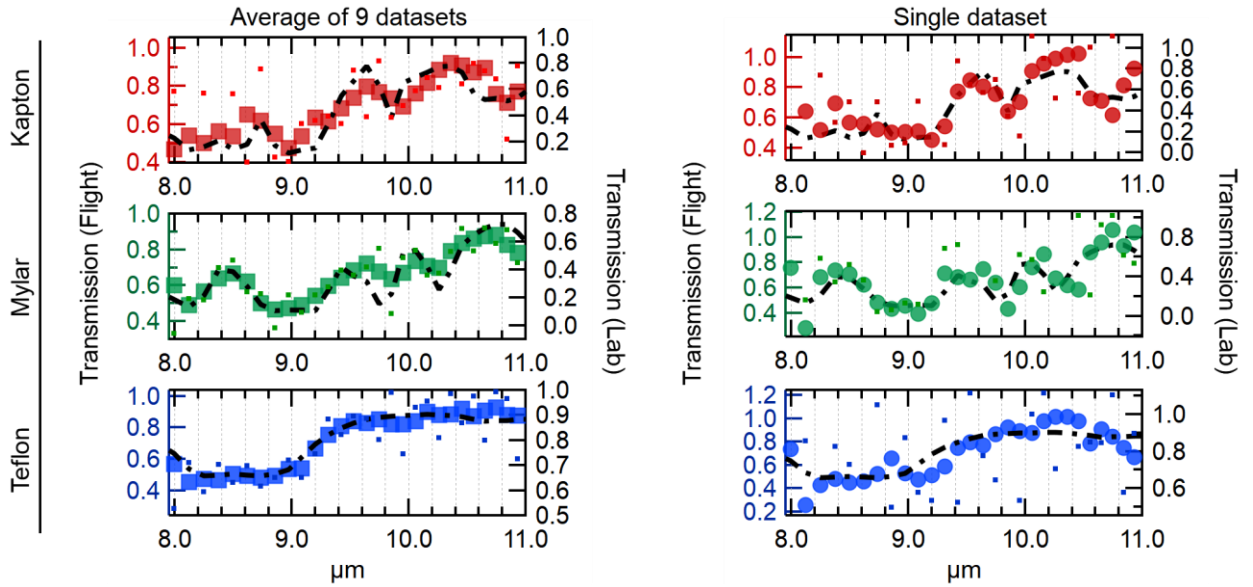


Figure 37 Transmission spectra of thin films positioned over bright point sources. Transmission is calculated relative to an unobstructed (no films) bright point source. In each spectrum, black dashed lines are CRISP data measured in the laboratory. Raw data is represented as small dots, and the larger markers represent the spectra after processing with a locally-weighted regressing smoothing algorithm (LOESS). The left-hand side is an average over 9 overflights, while the right-hand side is from a single flight. [2]

This yields $PSF_{CRISP, Motionless} = 1.10$ px, which is within 2.76% of the theoretical diffraction-limited spot size noted above. [2]

Transmission spectra of our three thin-film point targets (Kapton, Mylar and Teflon) captured with the CRISP system during flight are shown in Figure 37. Spectra of the thin films processed from a single dataset (one flight over the point targets, ~316 frames captured) are shown in the right column. Average spectra from all flyovers (9 total flights) are shown in the left column. Reference spectra (collected with the CRISP system of the same films in the laboratory) are shown in the plots as a black dotted line. In each spectrum, the raw data are represented as small dots. The larger markers represent the spectra after processing with a locally-weighted regressing smoothing algorithm (LOESS). The transmission spectra collected during flight closely resemble the reference data collected in the laboratory, demonstrating that CRISP is able to extract useful spectra from point targets. [2]

Results from a release of SF_6 gas during a flyover are shown in Figure 38. At $\lambda_1 = 10.55$ μm , a strong feature exists in the SF_6 LWIR spectrum [35], which can be seen in Figure 38b. Figure 38a shows a heatmap of the location of the SF_6 gas during the release over the aluminum foil. A heatmap of a nonrelease is also shown for reference. To produce these heatmaps, we plot the ratio of two wavelengths, λ_1 / λ_2 , where λ_1 is on resonance and λ_2 is off resonance (10.36 μm). 4 x 4 pixel spectral binning was used to achieve a higher signal-to-noise (SNR) ratio for better clarity. The SF_6 is clearly evident in the center of the aluminum foil, especially when compared to a dataset with no gas release. [2]

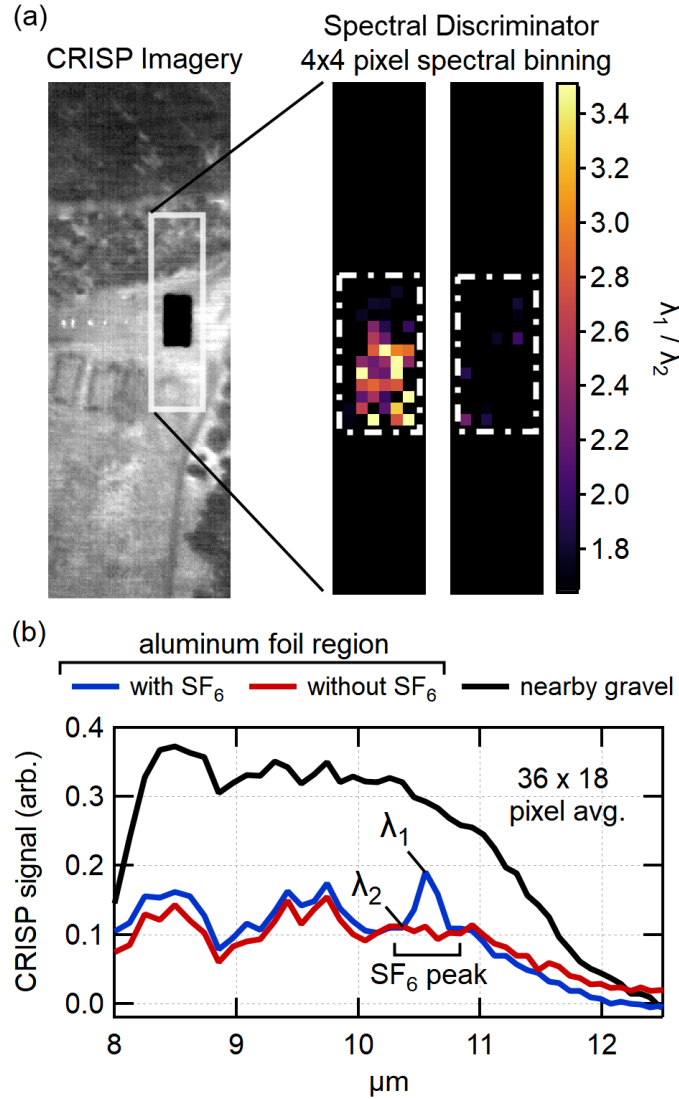


Figure 38 SF₆ gas release detection. (a) Broadband LWIR imagery (top left) next to imagery of a spectral discriminator (top right) designed to detect SF₆ (see text). The middle panel is the discriminator in the presence of the gas release, while the right panel is the discriminator in the absence of a release; (b) CRISP spectra of the aluminum foil both with and without the gas release, and nearby gravel. [2]

We compare CRISP's observed absorption change of $\sim 100\%$ (signal with SF₆ relative to signal without SF₆) to gas concentration levels as follows. We once again assume a thin plume and linear Planck function [29], and make use of $L = C_B \Delta T \tau_{\text{atm}} A$. An estimate of the temperature difference, ΔT , between the gas plume and ground below is necessary in order to calculate the plume's concentration path-length. We measured the gas temperature at the nozzle (13°C) and directly in front of the nozzle at a range of ~ 0.6 m (18°C). The air temperature was 25°C. We estimate the background aluminum foil temperature (reflecting the cold sky) at -12°C based on a comparison of its spectrum to an extrapolation of our radiative calibration data, though we note that this is an extrapolation beyond our calibration range with associated error of $\pm 12^\circ\text{C}$. We thus bound ΔT at an upper limit of 37°C and a lower limit of 13°C. Using our MODTRAN estimate of $\tau = 0.8$ and the PNNL absorption for SF₆ of $0.047 \text{ ppm}^{-1}\text{m}^{-1}$ at $10.55 \mu\text{m}$ [35], we

estimate the concentration-pathlength between 9 and 25 ppm-m. Our estimates based on actual gas flow rates (*vide supra*) put the gas concentration-pathlength between 15 and 75 ppm-m, in reasonable agreement with these estimates based on the CRISP spectra. [2]

4.5. SUMMARY OF AIRBORNE PERFORMANCE DEMO

In summary, we have successfully demonstrated the ability to collect airborne LWIR spectra from an imaging spectrometer that uses an uncooled microbolometer detector array. We captured hard target (sand and ocean water) emissivity spectra from coastal regions at an altitude of 1675 m. Additionally, we captured transmission spectra of three different point targets from a similar altitude. Finally, we detected gas species including a release of SF₆ gas and were able to produce a heatmap showing the location of the gas. [2]

5. AIRBORNE VALIDATION OF LANDSAT REQUIREMENTS

In May 17-21 of 2021, we performed a new flight campaign focused on Sustainable Land Imaging (SLI). Specifically, the goal of the campaign was to assess CRISP performance as it relates to Landsat requirements by collecting data on relevant ground targets in the Lake Tahoe, NV region. The key metrics assessed during this work included:

- Absolute Radiometric Uncertainty
- Noise Equivalent delta Temperature (NETD)
- Radiometric Stability
- Edge slope (i.e., spatial resolution)

The CRISP team partnered with the Rochester Institute of Technology (RIT) to provide ground truth data and to help analyze the flight data. We also evaluated the ability to use Temperature / Emissivity Separation (TES) algorithms on CRISP data, a key focus of SLI.

The goal of this effort was to validate the CRISP concept for this application by showing that performance against these requirements agrees with theoretical expectation. In particular, the current system, CRISP 1.0, is the first incarnation of CRISP ever built and was not expected to meet the SLI requirements on a pixel by pixel basis, as the radiometric predictions of Figure 4 (left) show. However, successful demonstration of CRISP 1.0 meeting theoretically expected performance, including applicable scaling laws, clears the path for proposed future upgrades, such as the “CRISP 2.0” concept described on the right of Figure 4.

5.1. FLIGHT AND DATA COLLECTION PLAN

Due to COVID-driven travel and schedule challenges the MIT Flight Test Facility (FTF) and LL-owned aircraft were not able to support this specific campaign as with the previous ones. Instead, we partnered with Twin Otter International, Limited (“TOIL”) to support this flight campaign the time window and budget we had available. MIT-LL has had an ongoing relationship with Twin Otter, and they are a DOE and NASA approved vendor to provide airborne research services. Figure 39 shows integration of the CRISP payload onto a Twin Otter aircraft in Grand Junction, CO and the CRISP flight team inside the Twin Otter aircraft.



Figure 39 (left) Integration of the CRISP payload onto a Twin Otter aircraft in Grand Junction, CO. (right) The CRISP flight team inside the Twin Otter aircraft

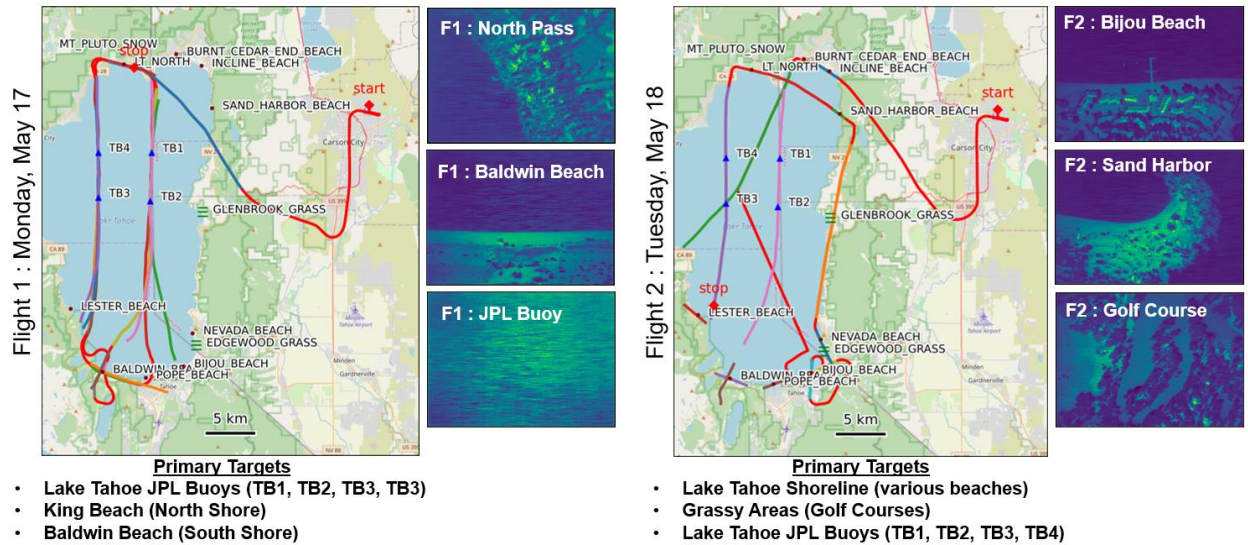


Figure 40 Flight plans for (left) Day 1 and (right) Day 2

Initially, a five day campaign was planned, with the highest priority measurements scheduled earliest (on the first two days). Days 1, 2, and 3 were completed successfully, but due to snow, days 4-5 of flight operations were canceled. Day 3's flights are described further in 5.5.2. Figure 40 illustrates the flight plans for Days 1 and 2. The flights began at Carson City airport, about 10 miles away from the Lake Tahoe region. For Day 1, we focused on flying over JPL Buoys located in Lake Tahoe, including many passes over the JPL buoys for several hours), with the buoys providing surface temperature ground truth. The flight path include a loop that captured the 4 buoys as well as the north and south Lake Tahoe coastline (King Beach and Baldwin beach, respectively). Day 2 involved additional flights over the JPL buoys, as well as additional passes over the shoreline (including Bijou Beach, Sand Harbor), and a grassy golf course area. Figure 41 shows the RIT truth measurement locations. Figure 41 (left) shows the location of water temperature truth measurements. The red "X" marks indicate JPL buoy locations, while the zoomed insets show locations where temperature measurements were made by RIT using Tidbit dataloggers. Figure 41 (right) shows the location where RIT measured land surface temperature and emissivities (using FTIR spectrometer measurements), including Bijou Beach, Sand Harbor, and Baldwin Beach.



Figure 41 (left) Water temperature ground truth measurement locations (including RIT Tidbit data loggers in zoomed areas and JPL buoys as red “X” marks) and (right) RIT land temperature ground truth locations

5.2. FLIGHT SYSTEM

5.2.1. Ground Calibration

Prior to flight, the CRISP system was calibrated while installed in the aircraft, to ensure the validity of the flight measurements performed immediately afterward. To enable this, we developed new procedures and capabilities, including a new compact in-field system for measuring the system mask function (as defined in Section 3.3). Figure 42 describes the ground calibration approach and results. In Figure 42 (upper left) the radiometric sensitivity curves and relative SNR as a function of detector row are shown, closely matching previous ground calibrations (Figure 31). In Figure 42 (upper right), the installed CRISP flight hardware is shown, along with the new in-field mask function calibration system. Figure 42 (Lower Left) shows the theoretical NETD calculated (at the native spectral resolution) using the radiometric model for “CRISP 1.0” in Figure 4 (left). Figure 42 (Lower Right) shows the measured NETD. The results match theory as well as previous measurements (Figure 31).

The calibration, in summary, remained strongly consistent with theory and prior laboratory measurement, giving us confidence that the system was performing well just prior to flight.

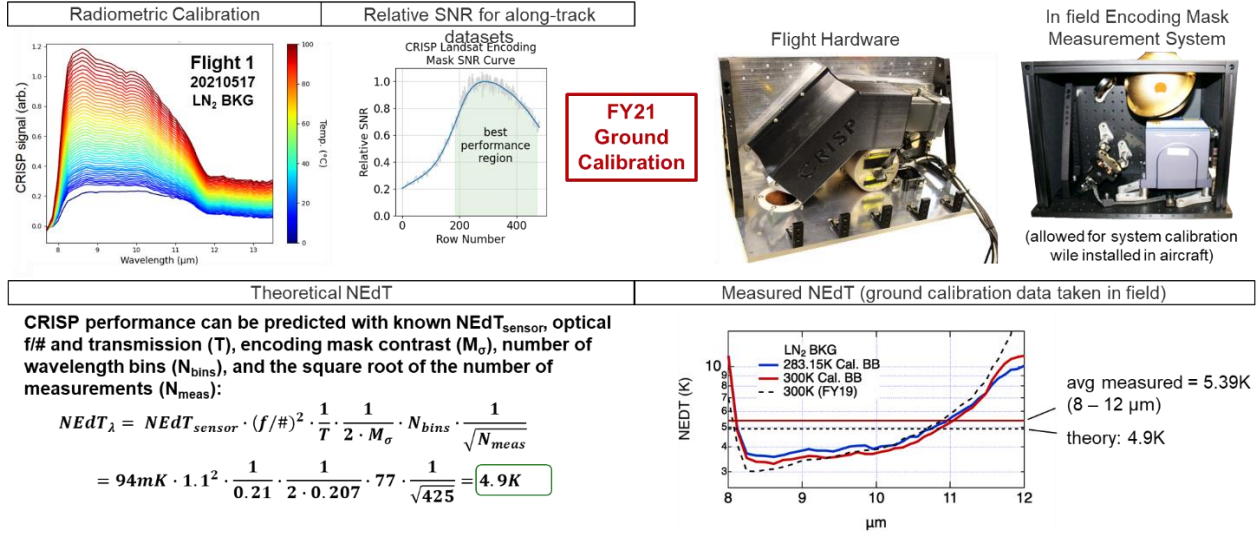


Figure 42 Flight spectrometer calibration, as performed for the FY21 Lake Tahoe Campaign

5.2.2. Flight Data Processing: In-scene Background compensation and Artifact Resolution

Over the course of processing data collected on flight, a spatial-spectral banding artifact was identified in our flight datacubes which had not been present in previous lab-collected datasets and required correction. This artifact was most significant for nonlinear, 2D trajectories which are representative of aircraft travel, but not uniform 1D linear motion typical of spaceborne measurements. Our subsequent analysis and modeling efforts suggest that the apparent and most likely cause is an unmodeled systematic offset in the collected measurement framestack, which remained in the flight data even after we performed our usual background subtraction (using a pre-flight LN₂ or black body flat field background measurement). We hypothesize that this is due to variations in environmental temperature between flight and the ground which remained despite the instrument being in an enclosure which is temperature-controlled to some degree. Figure 43 shows an example of this artifact from a slice through the spectral and along-track spatial axes of a 3D spectral data cube from a relatively homogeneous scene collected on flight, with a diagonal spatial-spectral banding effect apparent. The error was 3x or greater above the actual noise floor, potentially posing an initial problem for Landsat validation efforts.

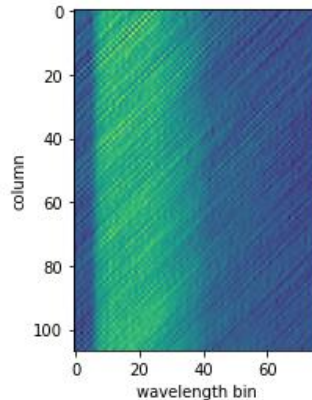


Figure 43 Example spatial-spectral artifact found in some flight data before correction. The vertical axis is along-track ground position, while the horizontal axis is wavelength bin

A simple model establishes how an unremoved offset or “background” (which we will call it here for shorthand) affecting the measured frames can cause the artifact. Our system of equations can be described, as in Section 2.2, as:

$$\mathbf{y} = \boldsymbol{\varphi} \mathbf{x}$$

Suppose our observations $\mathbf{y}$ contain an unremoved “background” component $\mathbf{c}$:

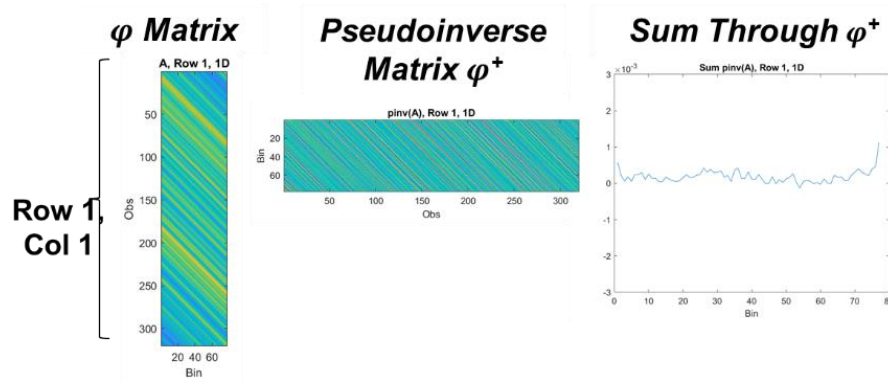
$$\mathbf{y} = \mathbf{y}_0 + \mathbf{c}$$

(We neglect noise terms for this example.) Then, for a given spot, our spectrum, when recovered by the pseudoinverse ($\boldsymbol{\varphi}^+$) of observation matrix $\boldsymbol{\varphi}$, would contain a systematic error:

$$\hat{\mathbf{x}} = \boldsymbol{\varphi}^+ (\mathbf{y}_0 + \mathbf{c}) = \mathbf{x}_0 + \boldsymbol{\varphi}^+ \mathbf{c}$$

The error term highlighted above in red is a weighted sum through one dimension of the pseudoinverse matrix. We hypothesize that this term is the systematic error in the estimated spectrum causing the artifact, and have reproduced similar artifacts in simulation. We also have shown via example that sums through $\boldsymbol{\varphi}^+$ have greater magnitude for nonlinear 2D aircraft-like trajectories than 1D linear trajectories, due to key differences in the structure of $\boldsymbol{\varphi}$. Figure 44 shows, for an example ground position, a matrix $\boldsymbol{\varphi}$, its pseudoinverse $\boldsymbol{\varphi}^+$, and a sum through $\boldsymbol{\varphi}^+$, for (Top) a 1-D trajectory, and (Bottom) a 2-D irregular aircraft trajectory. For the 1D case, $\boldsymbol{\varphi}$ has regular cyclic structure described in Section 2.2, as does $\boldsymbol{\varphi}^+$. The sum through $\boldsymbol{\varphi}^+$ is relatively small and flat, suggesting that for this case, the process of solving for the spectrum assigns relatively equal credence for all of the measurements. However, for the 2D case, $\boldsymbol{\varphi}$ has irregular, non-cyclic structure. The pseudoinverse $\boldsymbol{\varphi}^+$ is also irregular, with greater variability, and the sum through it also contains far greater variability and noise-like fluctuations than the 1D case, suggesting that the process of solving for the spectrum in this case assigns more variable credence to all the measurements. As a result, the systematic error term highlighted above is greater in magnitude and more likely to rise above the detector-noise floor for the 2D trajectory case than for the 1D case.

1D Trajectory Example



2D Irregular Aircraft Trajectory Example

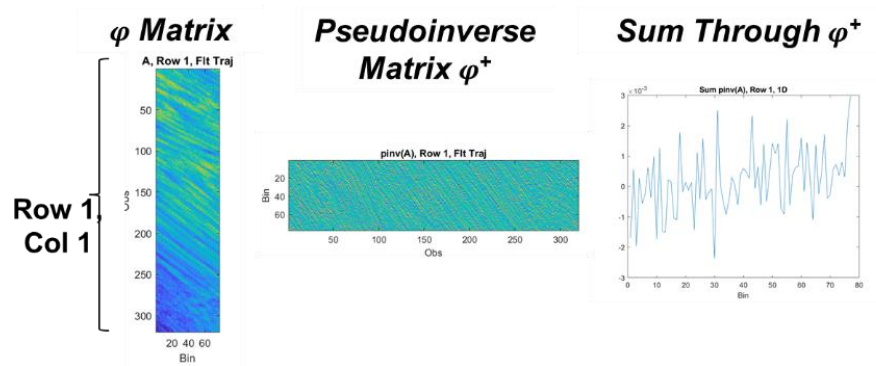


Figure 44 The matrix ϕ , its pseudoinverse ϕ^+ , and a sum through ϕ^+ , for (Top) a 1-D trajectory, and (Bottom) a 2-D irregular aircraft trajectory

To resolve these artifacts, for the purpose of processing this flight campaign's data, we developed algorithmic techniques to compensate, including improved calibration and automatic/in-scene techniques to remove “backgrounds”. One effective technique we employed is in-scene background compensation. Broad regions of Lake Tahoe can be considered a near-uniform scene with apparent surface temperature of 10°C. The “in-scene compensation” can therefore be employed as follows:

In-Scene Compensation Approach

- On the ground, measure a flat field background for a 10°C black body, and a cold liquid nitrogen (“LN2”) background, for the purpose of background subtraction
- Create a background image: (Lake Tahoe 10°C “background”) – (Ground 10°C background) + (Ground LN2 background)
- Use this background image for background subtraction

This approach requires flight over a uniform region to determine the background, but is functionally a stand-in for an in-flight calibration target look that one might typically employ in a space system on orbit. The in-scene compensation, along with rigorous row-by-row calibration, allowed acceptable, noise-limited spectral processing to take place for scenes in which a 1D linear trajectory could be reasonably assumed.

For 2D trajectories, a different, “blind compensation” approach for error removal was proposed and tested:

Blind Compensation Approach

- Using the best available background for subtraction, make a first-pass estimate of the spectrum from the pseudoinverse:

$$\hat{\mathbf{x}}_a = \boldsymbol{\varphi}^+ \mathbf{y}$$

- Using the system matrix as a forward model, compute the estimated measurement frames from $\hat{\mathbf{y}}_a$ from the estimated spectrum $\hat{\mathbf{x}}_a$:

$$\hat{\mathbf{y}}_a = \boldsymbol{\varphi} \hat{\mathbf{x}}_a$$

- Estimate the background error as follows:

$$\widehat{bkg} = \frac{1}{(\# \text{ frames})} \sum_{\text{frames } m} \mathbf{y}_{[\text{frame } m]} - \hat{\mathbf{y}}_{a,[\text{frame } m]}$$

The rationale behind this step is that the residual error between the actual measurements $\mathbf{y}$ and the $\hat{\mathbf{y}}_a$ term is expected to be 0 in the absence of systematic errors, and any nonzero residual must therefore be a removable background.

- Remove this estimated background from all measured frames in $\mathbf{y}$, forming $\mathbf{y}_{[\text{corrected}]}$
- Compute the final estimate

$$\hat{\mathbf{x}}_{\text{final}} = \boldsymbol{\varphi}^+ \mathbf{y}_{[\text{corrected}]}$$

This blind compensation approach was found to also be effective, and not require a flat background scene as a prerequisite. Initial testing with 2D aircraft trajectories found that this approach reduced the systematic error to a fraction (about 30%) of the expected noise floor rather than $\sim 3\times$ or greater. This approach was not developed or implemented until weeks after the flight campaign data was collected and largely processed and reviewed by RIT and MIT-LL, and further algorithmic correction remains an area of ongoing study, but the significant progress in removing the artifact even for the challenging 2D cases provides additional confidence that systematic errors such as these can be even further removed with more effort.

On orbit, we expect this artifact and associated systematic error to disappear, if the spacecraft and instrument optics are controlled thermally, a calibration target is employed, and 1D scans or trajectories typical of spaceborne swath measurements are employed, obviating the need for algorithmic corrections like those above.

5.3. LANDSAT REQUIREMENT DEFINITIONS AND ASSESSMENT APPROACHES

Below, for the remainder of 5.3, we have reproduced, from RIT's flight campaign report, the definitions and assessment approaches for the key Landsat TIRS requirements that were the focus of this campaign.

5.3.1. Absolute Radiometric Uncertainty

TIRS-427 The thermal band absolute radiometric uncertainty shall be as given in Table 1 with all uncertainties established relative to National Institute for Standards and Technology (NIST) standards. This requirement applies to extended, spatially uniform, unpolarized targets. Uncertainty estimates include the NIST standard uncertainties.

Table 1. Thermal Bands Absolute Radiometric Uncertainty Requirements

Equivalent Blackbody Temperature Range	Absolute Radiance Uncertainty (1-sigma)
260 K - 330 K	<2%
240K - 260K; 330K - 360K	<4%

To assess CRISP against this parameter:

- Acquire CRISP data over several water targets and convert to at-sensor radiance.
 - CRISP airborne image data were acquired over several water targets (shown in Figure 41) and used to assess its performance against this requirement.
- Forward model reference measurements to at-sensor radiance.
 - JPL buoys and Tidbit temperature sensors were used to measure water temperature, see Figure 41.
 - Nearest GEOS-5 reanalysis data were used to characterize the atmosphere.
 - MODTRAN model used for radiative transfer.
 - Spectrally sampled modeled data to the bands of interest (Spectral/TIRS/ASTER bands).
- Generate per-band plots of modeled vs. CRISP-measured band-effective radiance.
 - Standard deviation of residuals (expressed as a percent) represents metric to be compared against the requirement shown in Table 1.

5.3.2. Pixel Noise Equivalent Delta Temperatures

TIRS-441 For uniform scene temperatures between 240 K and 360 K extending over the full FOV of TIRS, and for a data collection period corresponding to a WRS-2 scene (~ 25 seconds at the nominal frame rate), the median detector standard deviation when converted into radiance units shall be $\leq 0.059 \text{ W/m}^2 \text{ sr } \mu\text{m}$ for the $10.8 \mu\text{m}$ channel and $\leq 0.049 \text{ W/m}^2 \text{ sr } \mu\text{m}$ for the $12.0 \mu\text{m}$ channel. This includes quantization noise.

Any detector with a standard deviation more than 1.25 times these values shall be considered out-of-specification. The Noise Equivalent Delta Temperature (NE Δ T) for each channel for several temperatures is given in Table 2.

Table 2. Noise Equivalent Delta Temperatures (NE Δ T)

Channel	NEAT				
	240 K	260 K	300 K	320 K	360 K
10.8 μm	0.80 K	0.61 K	0.40 K	0.35 K	0.27 K
12.0 μm	0.71 K	0.57 K	0.40 K	0.35 K	0.29 K

To assess CRISP against this parameter:

- Acquired CRISP data over extended uniform targets.
 - CRISP data were collected for extended periods over Lake Tahoe and the JPL buoys between ground targets.
- Convert to at-sensor radiance.
 - Tested both spectrally and sampled to TIRS/ASTER bands.
- Calculate standard deviation of CRISP image data and compare to Table 2

5.3.3. Radiometric Stability

TIRS-547 Thermal band data for all pixels, after radiometric calibration, for radiometrically constant targets with radiances greater than or equal to the radiance corresponding to Typical, shall not vary by more than plus or minus 0.7% (1-sigma) of their radiance over a 40-minute period. Pixels failing this specification are considered out-of-specification and are subject to limitations.

To assess CRISP against this parameter:

- Acquire CRISP data over uniform targets
 - Loops over Tahoe were performed and CRISP image data acquired to support verification of this requirement.
- Convert to at-sensor radiance.
 - Test both spectrally and sampled to TIRS/ASTER bands.
- Calculate the standard deviation of the CRISP data over a 40-minute period.
 - Should not vary by more than 0.7%
 - Note that data for this 40-minute period were not collected continuously due to acquisition constraints. As such, multiple Lake Tahoe water passes were used to assess CRISP against this requirement.

5.4. ASSESSMENT RESULTS (RIT)

Below, for the remainder of 5.4, we have reproduced, from RIT's flight campaign report, the RIT assessment results for key Landsat TIRS requirements. Additional MIT-LL comments are inserted in [blue](#).

5.4.1. Absolute Radiometric Uncertainty

The absolute radiometric uncertainty of the CRISP system was assessed using CRISP image data collected over several water bodies (JPL buoys in Lake Tahoe, Tidbit data loggers along the shoreline of the lake). The CRISP imagery over the JPL buoys was processed to at-sensor radiance by MIT using a 1D trajectory, liquid N2 background subtraction with a 10° C corrected background adjustment (based on

apparent temperatures of the buoys). Calibration coefficients were also generated by MIT based on blackbody sweeps for each-across track direction to enable the conversion from DN to radiance (or apparent temperature). The water measurements from the JPL buoys were forward modeled to at-sensor radiance and then spectrally sampled to the CRISP bands as well as the 5-band system (Aster bands 10, 11 & 12, Landsat bands 10 & 11). The methodology is further detailed in Section 5.3.1. When comparing the CRISP imagery with the forward-modeled at-sensor radiance, a 10 by 10 average ROI of the CRISP data is taken from the center of the across-track direction and 2/3rd down of the along-track direction, since the SNR was observed to be significantly higher for the bottom-half of the along-track pixels. Figure 45 shows the absolute radiometric uncertainty against the JPL buoy reference measurements.

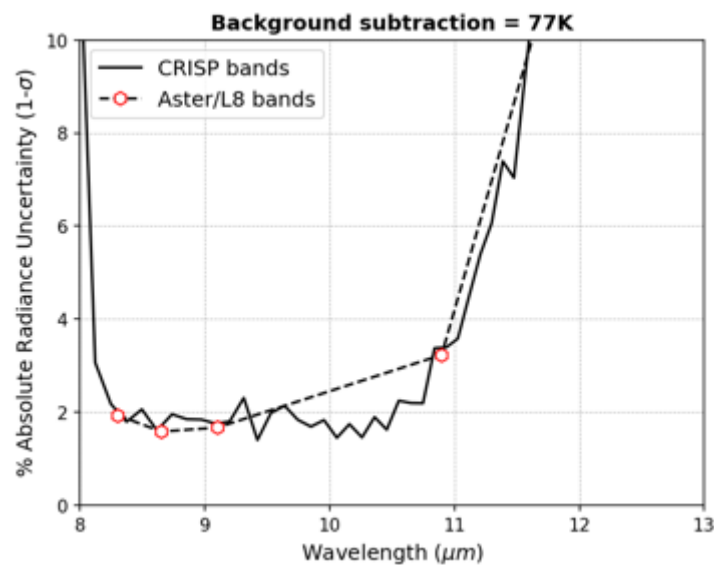


Figure 45 The absolute radiometric uncertainty for the CRISP imagery collected over the Lake Tahoe buoys.

The CRISP imagery over the near-shore tidbit data loggers were processed to at-sensor radiance using a 2D trajectory (the data could not be processed using 1D trajectory over land targets), liquid N2 background subtraction with a 10° C corrected background adjustment (based on apparent temperatures of the buoys), and calibration coefficients applied. (This 2D trajectory processing attempt preceded the development of the blind compensation approach described in 5.2.2 and thus the assessed uncertainty was impacted by unremoved artifacts, as well as use of the noisier portion of the detector array.) When comparing the CRISP imagery with the forward-modeled at-sensor radiance, a 10 by 10 average ROI of the CRISP data is taken wherever the tidbit data loggers were located in the water. Figure 46 shows the absolute radiometric uncertainty for the near-shore water targets.

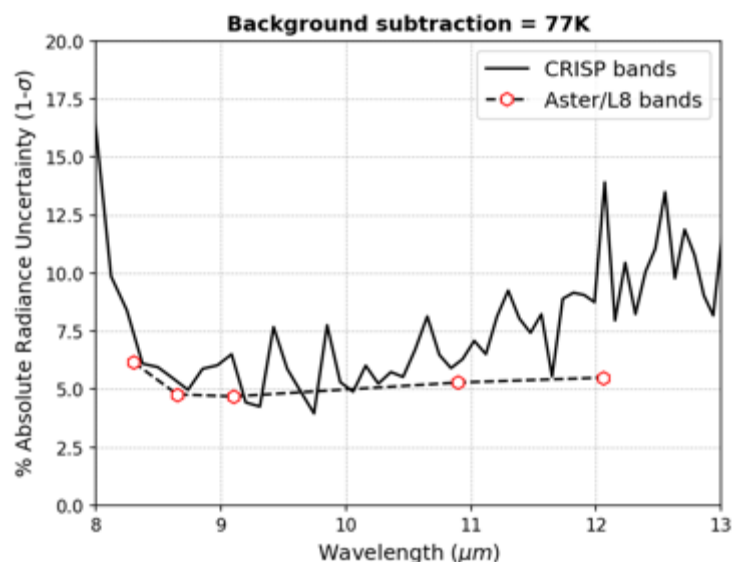


Figure 46 The absolute radiometric uncertainty for the CRISP imagery collected near the shorelines of Baldwin, Bijou and King’s beach as well as a Marriott Pool.

The Landsat requirement for absolute radiometric uncertainty (1-sigma) is <2% for uniform targets between 260-330 K. The CRISP data collected over the JPL buoys meets this requirement within the wavelength range of 8.2-10.5 μm (when spatially averaging a 10 x 10 pixel ROI). The CRISP imagery over near-shore water targets do not meet this requirement at any wavelength. The absolute radiometric uncertainty error is also twice as high for the near-shore water targets compared to the JPL buoys. The processing of the JPL buoy data using a 1D trajectory helped to drive down the noise significantly. Taking ROIs at the bottom-half of the along-track pixels, which has a higher SNR, helped to drive down the noise as well. Note that the CRISP system underperformed in the near-shore region as most of the water-targets were located along the top-half (the noisy half) of the CRISP hypercubes.

The results indicate that CRISP performance is consistent with expectations predicted from theory. In particular, the buoy results are consistent with the “CRISP 1.0” radiometry model described in Section 1.2, establishing that the scaled “CRISP 2.0” system would meet requirement on a per-pixel basis. The current system meets the requirement of < 2% Abs. Radiometric Uncertainty Landsat for the buoy targets within the wavelength range of 8.2 – 10.5 μm over a 10x10 pixel ROI.

5.4.2. Pixel Noise Equivalent Delta Temperatures

The Noise Equivalent Delta Temperature (NEAT) of the CRISP system was assessed using CRISP image data collected over Lake Tahoe JPL buoys from Day 1 of the field-campaign. The imagery were processed to at-sensor radiance as described in Section 5.3.2. There were four passes over the buoys during the flight. The NEAT was calculated ignoring any data from pass 1 since the CRISP instrument had not yet reached thermal stability. The NEAT was measured by taking the standard over only the bottom-half of the along-track pixels. Figure 47 shows the NEAT for the CRISP bands as well as the NEAT for the spectrally sampled CRISP data (i.e., the 5-band system).

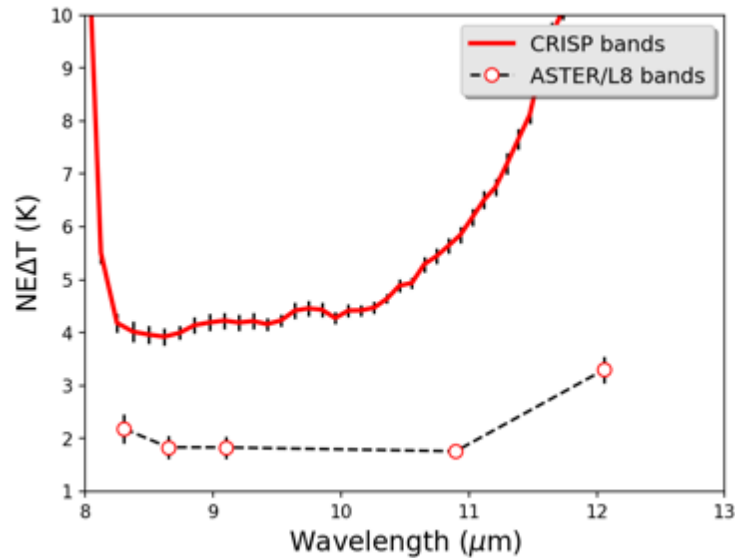


Figure 47 The NEAT for the CRISP imagery collected over the Lake Tahoe buoys. The NEAT is shown for both the CRISP spectral bands and the 5-band system.

The Landsat requirement for NEAT is 0.4K at 300K. This requirement is not met for either the CRISP bands or when spectrally sampling them to the 5-band system. However, spectrally sampling the CRISP bands to the 5-band system did improve the NEAT, which hovered around 2K.

The result is consistent with expectations predicted from theory. In particular, the NEAT closely matches ground calibration data from Figure 31 and Figure 42 and agrees with the radiometric predictions for “CRISP 1.0” described in Section 1.2, establishing that the scaled “CRISP 2.0” system would meet requirement on a per-pixel basis.

5.4.3. Radiometric Stability

The radiometric stability of the CRISP system was assessed using CRISP image data collected over Lake Tahoe JPL buoys from Day 1 of the field-campaign. The imagery was processed to at-sensor radiance as described in Section 5.3.3. There were four passes over the buoys during the flight. Again, the radiometric stability was calculated by ignoring any data from pass 1 since the CRISP instrument had yet to reach thermal stability. The radiometric stability was measured for only the bottom-half of the along-track pixels. Figure 48 shows the radiometric stability for the 5-band system and a histogram distribution of the radiometric stability for all pixels.

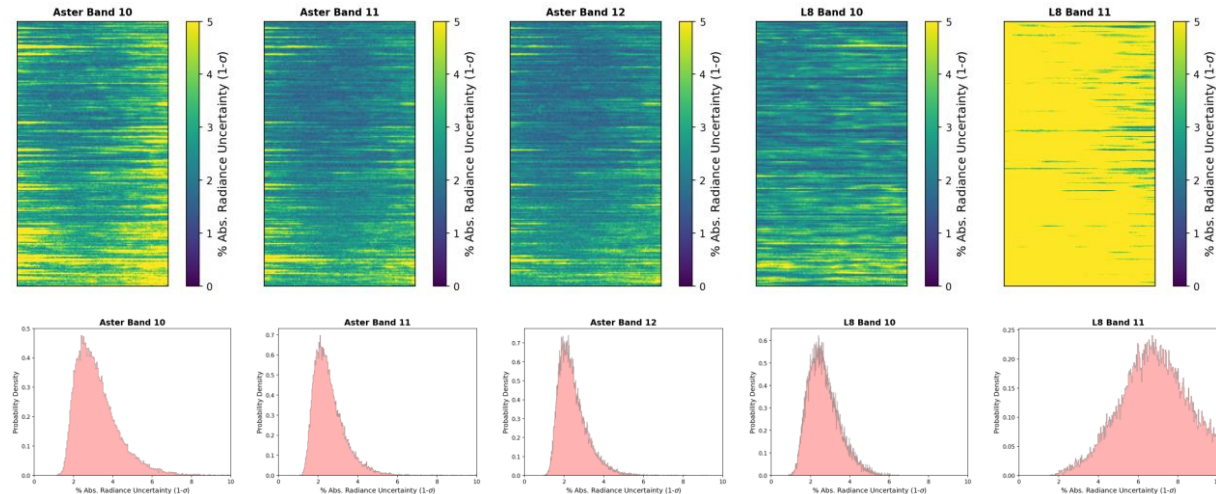


Figure 48 The radiometric stability for the CRISP imagery collected over the Lake Tahoe buoys.

The Landsat requirement for radiometric stability is 0.7%. This requirement is not met for the spectrally sampled 5-band system. The radiometric stability for most of the pixels ranged from 2-4% for the first 4 bands and was significantly higher (4-10%) for the 5th band.

The histograms in Figure 48 are driven by the noise of the system, and the RIT and MIT-LL teams concurred that these are not driven by the thermal drift. This noise-limited performance is consistent with expectations predicted from theory. Future CRISP sensors such as the scaled “CRISP 2.0” system of Section 1.2 would be expected to have lower noise, with and the radiometric stability could be improved by implementing a robust thermal design commensurate with MIT-LL space-flight programs.

5.5. ASSESSMENT RESULTS – EDGE SLOPE AND TES (MIT-LL)

5.5.1. Edge Slope

To evaluate edge slope, we returned to the FY19 flight data, which included point targets optimal for this measurement. These point target measurements and spectra are discussed in Section 4.4.1 and presented in Figure 36. The edge slope derived from this dataset is shown in Figure 49. Extrapolated to an altitude of 705 km, this edge slope corresponds to 0.002 m^{-1} . While this is lesser than the Landsat requirement of 0.01 m^{-1} , it meets expectation and agreed with model prediction for the current CRISP 1.0 due to its aperture, f-number, and the extent of motion blur and jitter experienced on this flight, as mathematically described in detail in Section 4.4.1. The validated model agreement establishes that performance could be improved by reducing motion blur and by incorporating a custom (non-COTS) optical solution commensurate with MIT-LL space-flight programs.

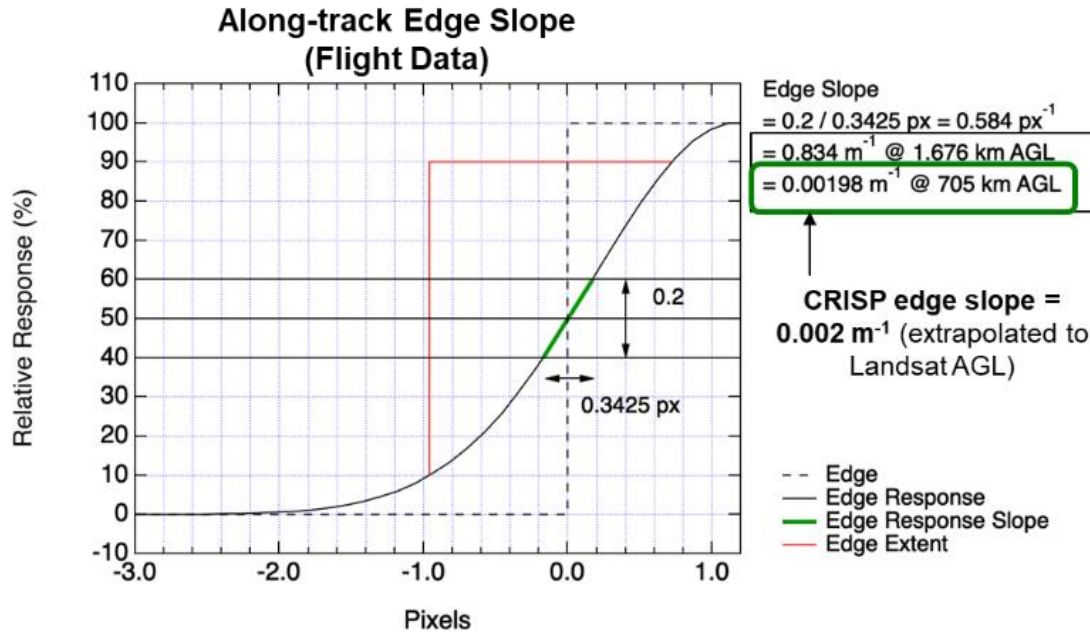


Figure 49 Edge slope computed from flight data

5.5.2. Temperature Emissivity Separation

CRISP's potential for Temperature Emissivity Separation (TES) was also assessed. RIT initially planned to assess TES using datasets from Day 1 and Day 2 of the campaign, with truth assessed using FTIR measurements. However, the aforementioned issues with processing irregular 2D trajectories without significant artifacts (Section 5.2.2) precluded valid TES assessment using these datasets, as did the fact that the targets were only scene with the high-noise detector array region. (The blind compensation approach detailed in Section 5.2.2 was not yet available at the time RIT was under contract to process this data and could not be utilized.) However, MIT-LL was able to use data collected on Day 3, which focused on larger nearly uniform areas, to demonstrate a TES example over a region of interest. Figure 51 shows the flight plan and primary targets measured on Day 3. The primary targets included uniform scenes of a playa (a dry lakebed) and Pyramid Lake. The near-blackbody lake scene was found to be a good source of in-scene compensation data for the methodology described in Section 5.2.2. Atmospheric compensation was performed using the nearest GEOS-5 reanalysis data, as well as the MODTRAN® [28] radiative transfer code. The ASTER TES algorithm [36] was applied to the radiance dataset, over the dry lake bed. Figure 51 shows the retrieved emissivity spectrum results over (lower left) all 11x11 pixel block-averaged regions of interest in the playa dataset, and (lower right) over the average of the whole playa dataset. (The 11x11 pixel average is expected, via the CRISP 1.0 model of Section 1.2, to provide radiometry commensurate with the SLI requirement.) The 1-sigma error bar for the 11x11 ROI results is also shown on the lower left. While FTIR ground truth emissivity and temperature was unavailable for this target, the resulting emissivity spectrum closely resembles the playa signature from the MODIS UCSB Emissivity Library [37]. The surface temperature histogram over the 11x11 ROIs is also shown. While there is no SLI surface temperature retrieval precision requirement, the uncertainty indicated by this histogram is consistent with the surface temperature precision desired by the SLI community.

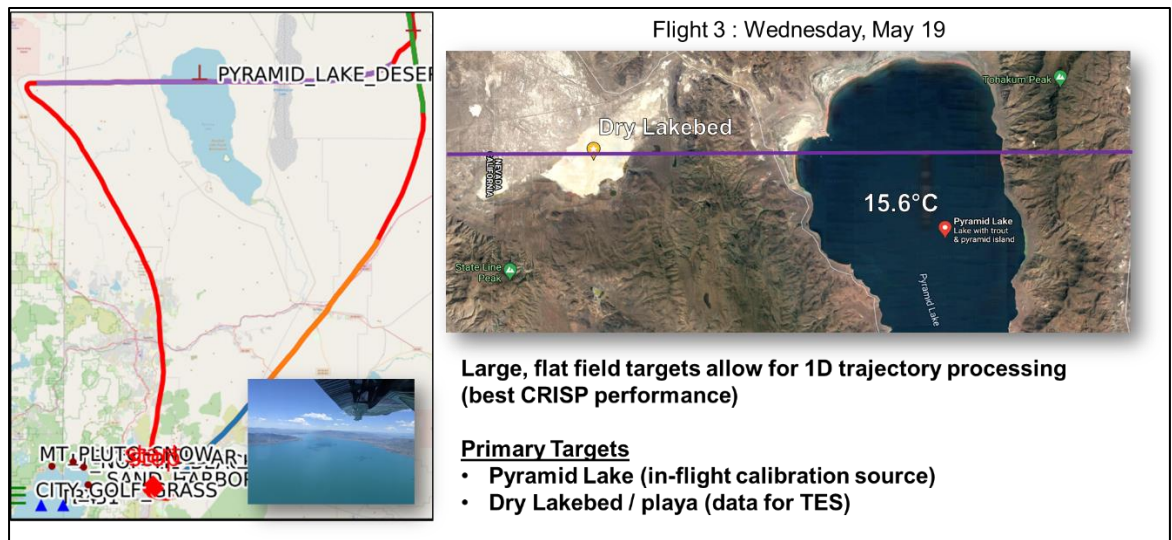


Figure 50 Flight plan and primary targets for Day 3

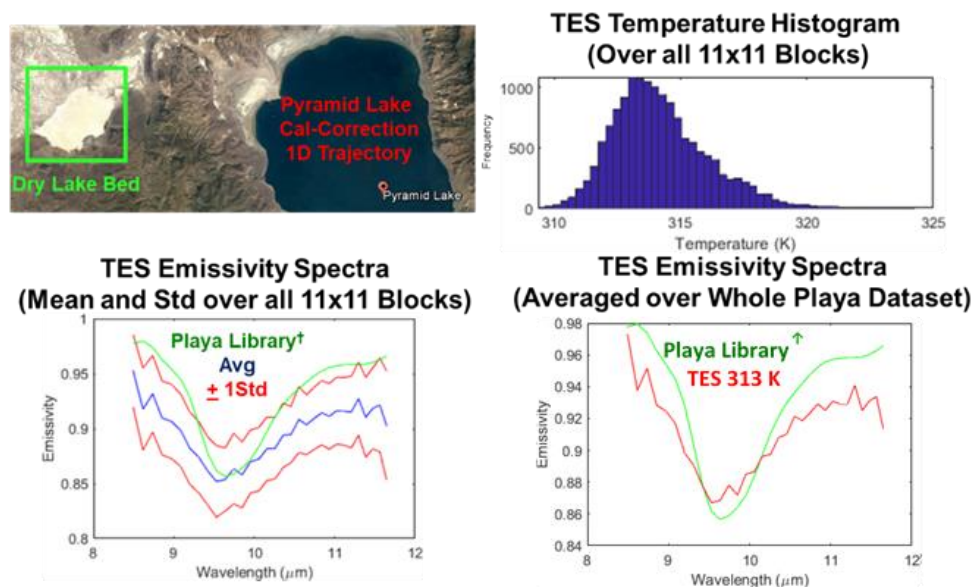


Figure 51 TES results for playa dataset collected on Day 3, for an 11x11 pixel region of interest

5.5.3. Summary of Landsat Validation Findings

In Figure 52 we summarize the assessment results for the Landsat requirement, including for the current “CRISP 1.0” hardware and for the projected “CRISP 2.0” system described in 1.2. We conclude that CRISP 1.0 performance meets expectations, as it concurs with theoretical prediction and previous laboratory experiments. With the concept and performance models validated against real data for CRISP 1.0, we further apply the models to an upgraded design, CRISP 2.0, and we conclude that Landsat requirements can be met and exceeded with the proposed CRISP 2.0 upgrades.

Requirement	Value	Ref.	CRISP 1.0 (this campaign)	CRISP 2.0
Absolute Radiometric Uncertainty	< 2%	TIRS-427	~2% (single pixel, 5-band system, Aster/L8 bands)	≤ 0.08% (enabled by spectrometer design and commercially sourced detector upgrade)
Noise Equivalent delta Temperature (NEdT)	0.4 K	TIRS-441	~2.5 K (single pixel, 5-band system, Aster/L8 bands)	≤ 0.08 K (enabled by spectrometer design and commercially sourced detector upgrade)
Radiometric Stability	< 0.7%	TIRS-547	~3 – 7% (variation across 5-band system)	≤ 0.7% (enabled by spectrometer design and thermal upgrade)
Minimum Edge Slope	0.010 m⁻¹	RMA19 Table 2	~0.002 m⁻¹ (extrapolated to Landsat altitude)	≥ 0.010 m⁻¹ (enabled by spectrometer design and optics upgrade)

Figure 52 Airborne validation of Landsat requirements results summary

6. SUMMARY

The ACT effort described herein has advanced the CRISP technology via theory, modeling, simulation, laboratory measurement, field measurement, and airborne measurement, bringing the concept from TRL3 to TRL4. The CRISP LWIR spectral imager addresses the needs of Sustainable Land Imaging as well as other Earth science applications, offering higher performance, lower SWaP, and the potential for greater area coverage than program-of-record systems. We have shown that these advantages are enabled by CRISP's coded multiplexing architecture, large format imaging, and reconfigurable scan operations, positioning this technology for transition to an improved smallsat-ready instrument design suitable for scientific applications.

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