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TAKING THE PULSE OF OUR PLANET FROM SPACE

On-orbit spatial performance characterization for thermal infrared imagers of Landsat 7 and 8 and ECOSTRESS

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Motivation

- <u>Evapotranspiration (ET) is a key parameter for Surface Biology</u>
  ET is an effective indicator of plant health and water availability.

Earth Science Decadal Survey 2017;
"Quantifying ET and understanding its linkages is a grand challenge for Earth system science in the coming decade"

- Thermal infrared (TIR) imagers can provide key diagnostics on the water use of crops and natural ecosystems through the latent heat signature embedded in land surface temperature.
- The availability of high-resolution thermal images will improve dramatically in the coming years thanks to continued Landsat and Sentinel programs, as well as new missions like NASA's Surface Biology and Geology (SBG) and ESA's Copernicus Land Surface Temperature Monitoring (LSTM).
- For these thermal imagers, crop water use monitoring is often the single most demanding application in terms of both spatial and temporal resolution.

ALEXI Suite

<u>Multi-scale ET products with Two-source SEB approach (TSEB)</u>

Heritage thermal imagers with 100-m to 5-kilometer resolution are used to assess changes in evaporative stress with the Atmosphere Land-Exchange Inverse model (ALEXI, Anderson et al. 1997). ALEXI mitigates the impact of conflicting biases in temperatures by modelling an internally consistent boundary layer based on the change in temperature over the morning. It requires an observation near sunrise and near noon and is implemented with moderate resolution observations of LST (Geostationary: Anderson et al. 2007, or LEO: Hain et al. 2017). Passive Microwave LST observations are used to estimate ET when clouds obscure the surface for TIR and VSWIR wavelengths (Holmes et al. 2018).

PMW-ALEXI (10 -25 km) enables all-weather TSEB studies 2003-present, 2-daily

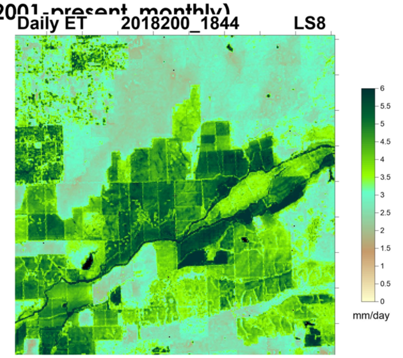
Holmes et al. 2018

ALEXI (1-5 km) Moderate resolution Polar orbiting and geostationary TIR imagers enable core TSEB-based ET estimates (2001-present, weekly)

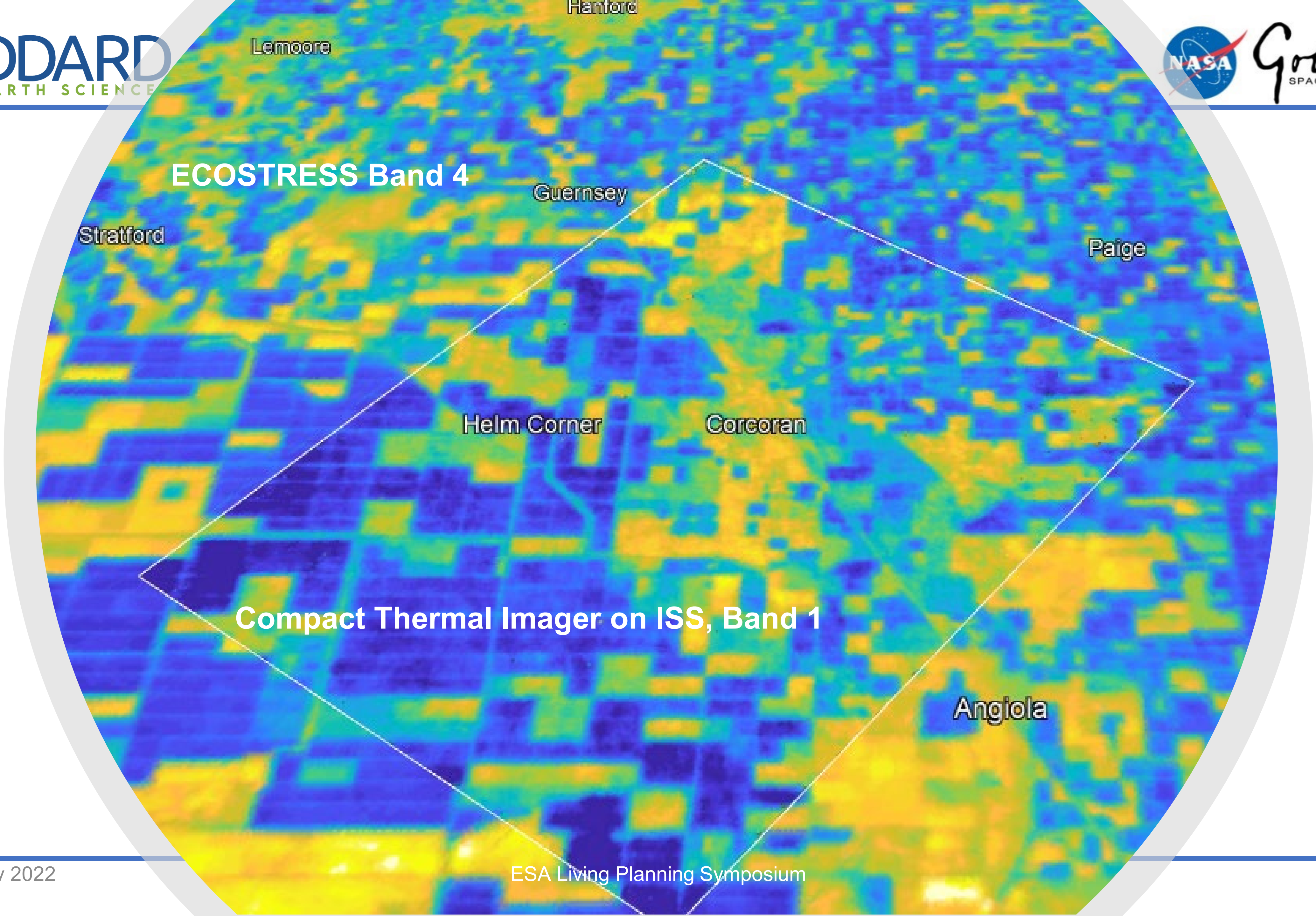
Hain et al. 2017, Anderson et al.2007

DisALEXI (5-120 m) High resolution Polar orbiting or airborne imagers enable disaggregation to field scale (2001-present, monthly)

Anderson et al 2011, 2018



Vineyards in California: Landsat-based 30 m ET over a 9 km x 9 km area. The ability to quantify water use from cloud-free imagery at field scale, by crop and landcover type, informs water management and irrigation practices to conserve resources and improve efficiency.
Credit: M. Anderson/USDA


Hanford
Lemoore
ECOSTRESS Band 4
Guernsey
Stratford
Paige
Helm Corner
Corcoran
Compact Thermal Imager on ISS, Band 1
Angiola

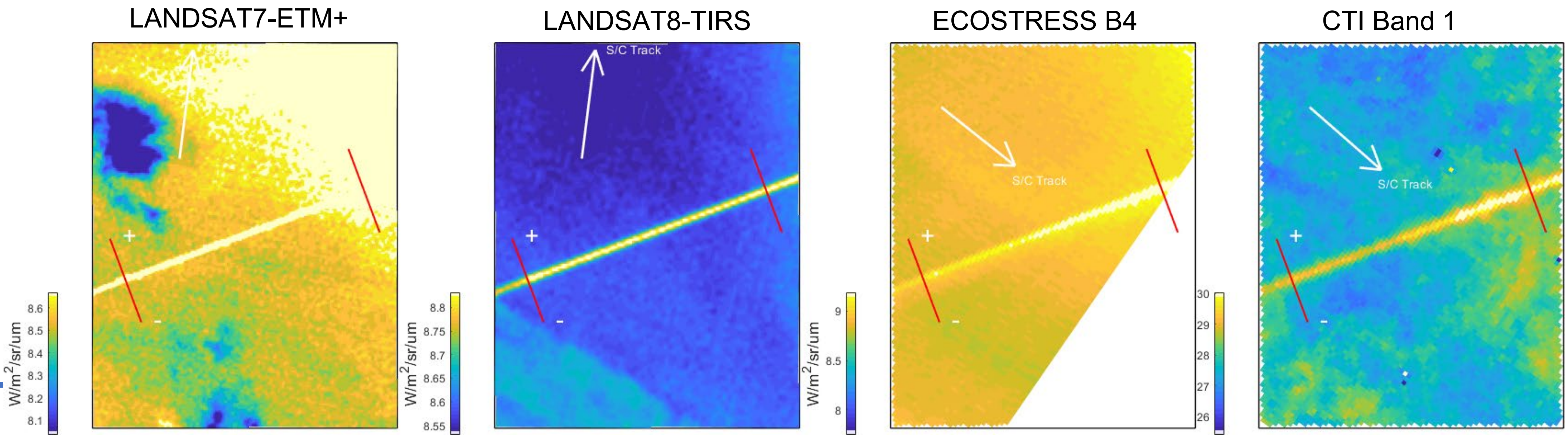
Approach

What is the spatial resolving power of current thermal imagers?

- Evaluate the on-orbit spatial resolution of thermal imagery based on landmarks with defined geometrical shapes and sharp contrast in thermal radiance.

- Bridges have large enough thermal contrast with water to measure the Full-width-half-max of the Linespread functions resulting from the imaging system.

San Mateo – Oakland bridge: 40 m wide, 7 km long

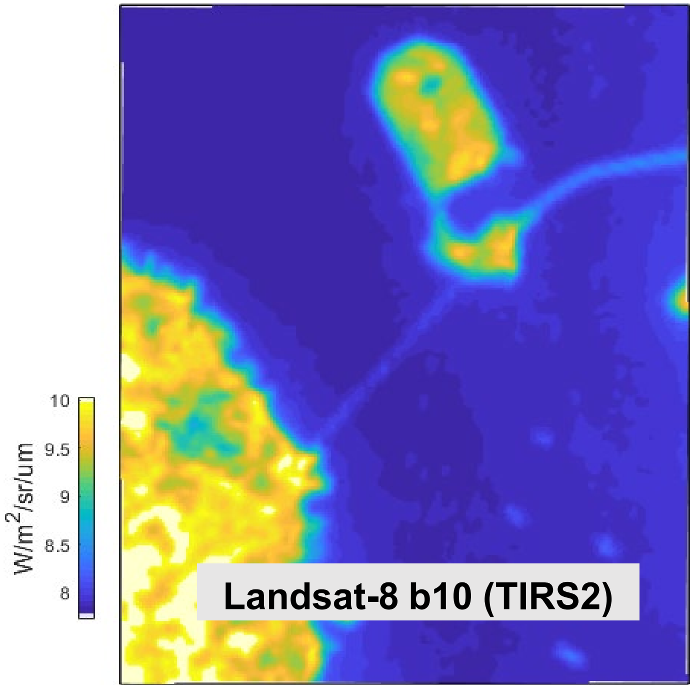


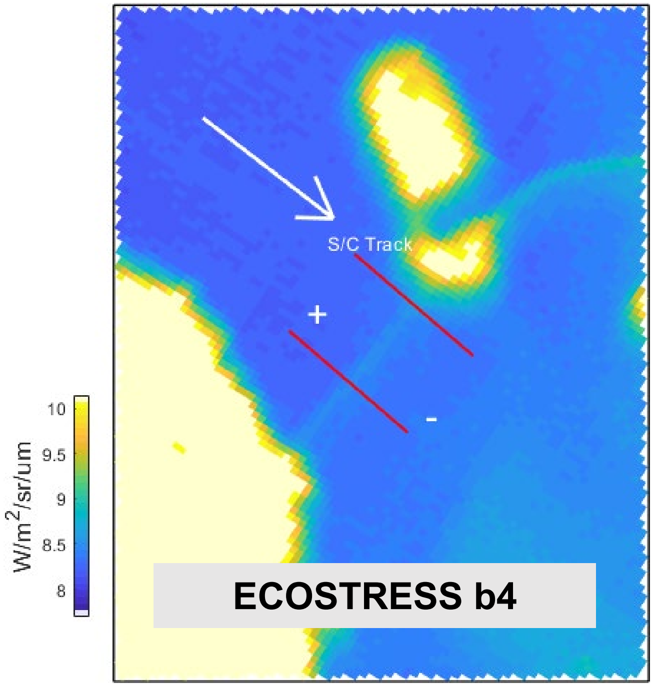
Thermal Imagers

LANDSAT 7 ETM+
LE07 L1TP, Focus on band 6: 10.4-12.5 micron

LANDSAT 8 TIRS
LC08 L1TP, Focus on band 10: 10.9micron

LANDSAT product version:
Level 1 Terrain (Corrected) (L1TP) product — Includes radiometric, geometric, and precision correction, and uses a DEM to correct parallax errors due to local topographic relief; the accuracy of the terrain-corrected product depends on the availability of Ground Control Points (GCPs), as well as the resolution of the best available DEM
Uses Cubic convolution to resample the native 100-m data to the Landsat 30-m grid.





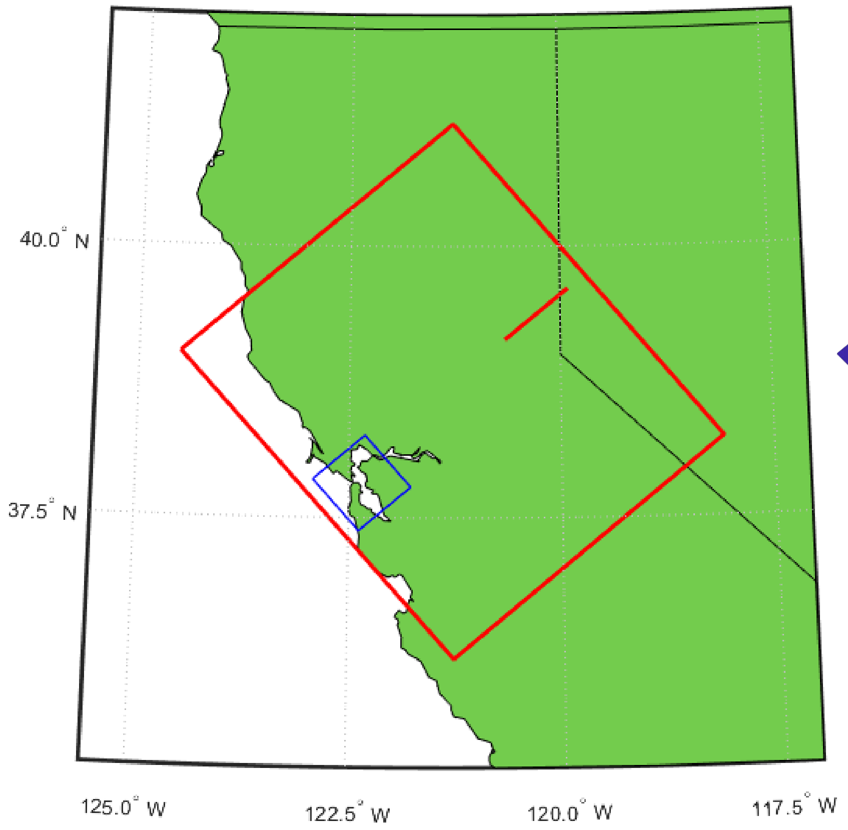
San Francisco – Oakland bridge
((West):
20 m wide
(East):
70 m wide

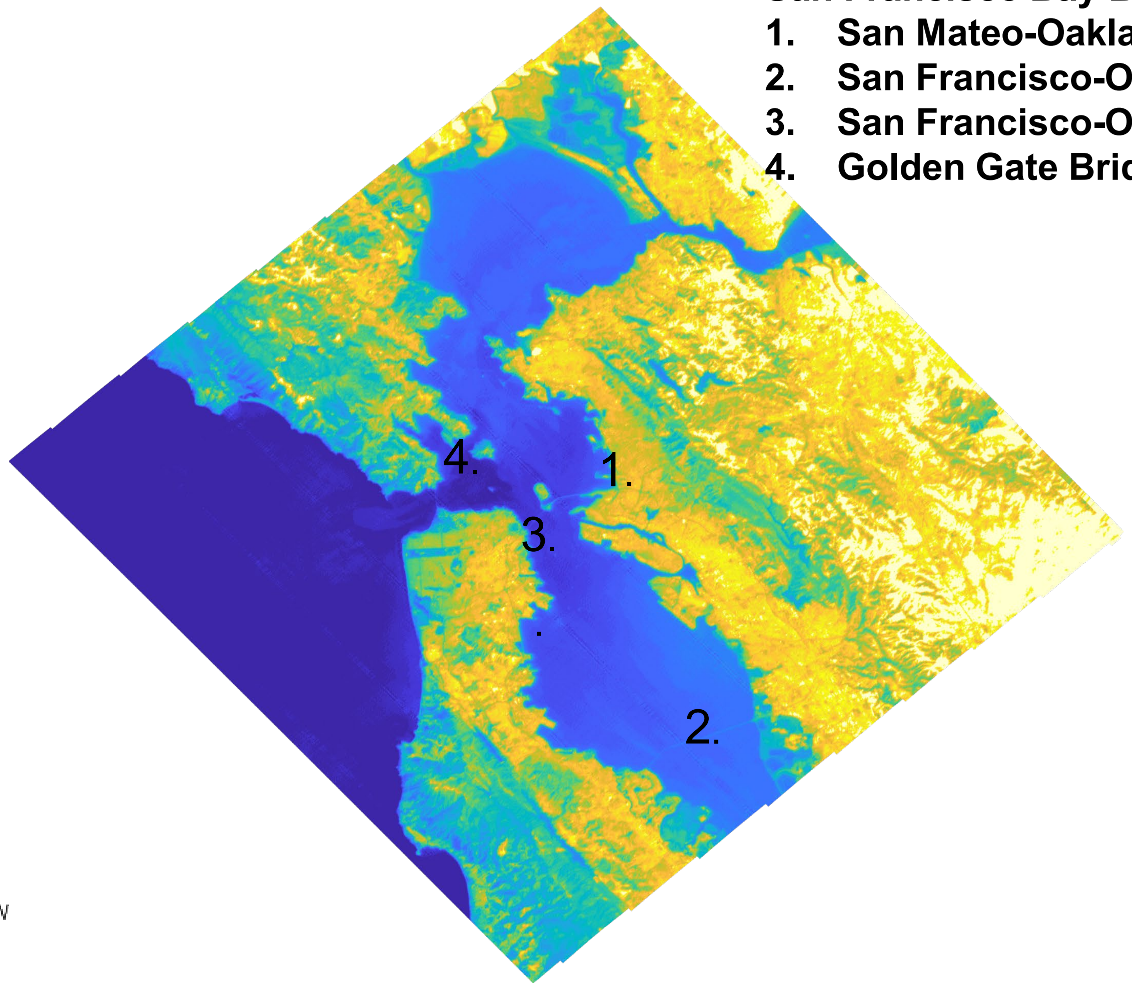
ECOSTRESS
ECO_1B_RAD, Focus on band 4: 10.522 (0.54) micron

Compact Thermal Imager on ISS, Focus on band 1: 3.3-5.4 micron
A technology demonstration. We developed procedures for flattening and calibrating the raw image counts to radiance.

Instrument Characteristics

	L7 ETM+	L8 TIRS	ECOSTRESS PHyTIR	CTI
Number of thermal bands	1	2	6 (4 after May 15, 2019)	2
Selected thermal band	Band 6 10.4-12.5 micron	Band 10: 10.6-11.19micron	Band 4: 10.522 (0.54) micron	Band 1 (of 2): 3.3-5.4 micron
Nominal res (m)	60x60	100	38x69 GSD (Nadir)	80
Ground Sample Distance (GSD)	60x60	100	75x68	Pixel ground IFOV 82 m
	30m IFOV dwell time 9.611 µs	70 Hz framerate	IFOV 96 µrads, scan speed 25.4 rpm, scan angle +/- 25 degrees	
Integration time (ms)	0.02 ms	3.4 ms	0.7 ms (183ms/256)	10 ms | 1.8 ms
Orbital speed (km/s)	7.5	7.5	7.7	7.7 km/s
Along-track smear (m)	0.15	25.5	4	77 m
Scene size			44 swaths of 9.8km x 384km (at 400km), 1.29 s between swaths	



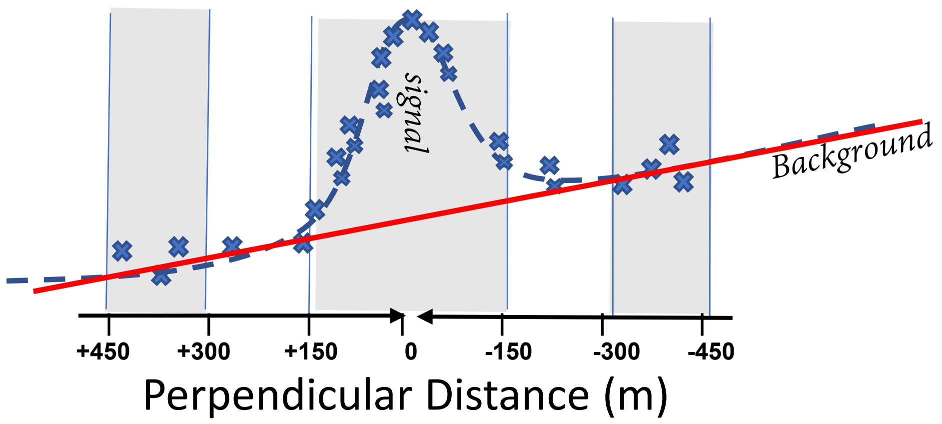


San Francisco Bay Bridges:

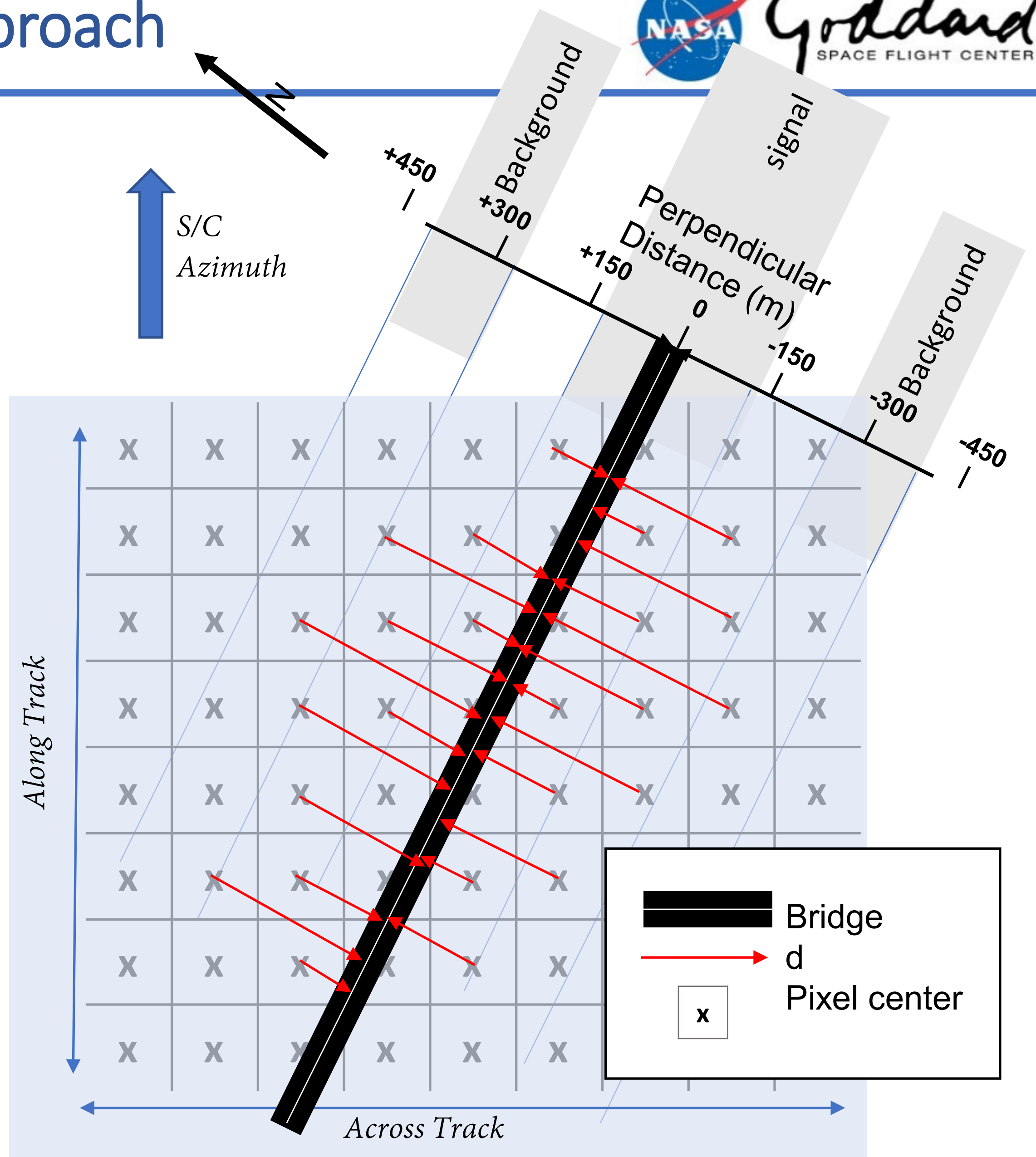
1. **San Mateo-Oakland Bay Bridge**
2. **San Francisco-Oakland Bridge, Eastern Span**
3. **San Francisco-Oakland Bridge, Western Span**
4. **Golden Gate Bridge**

Summary of Approach

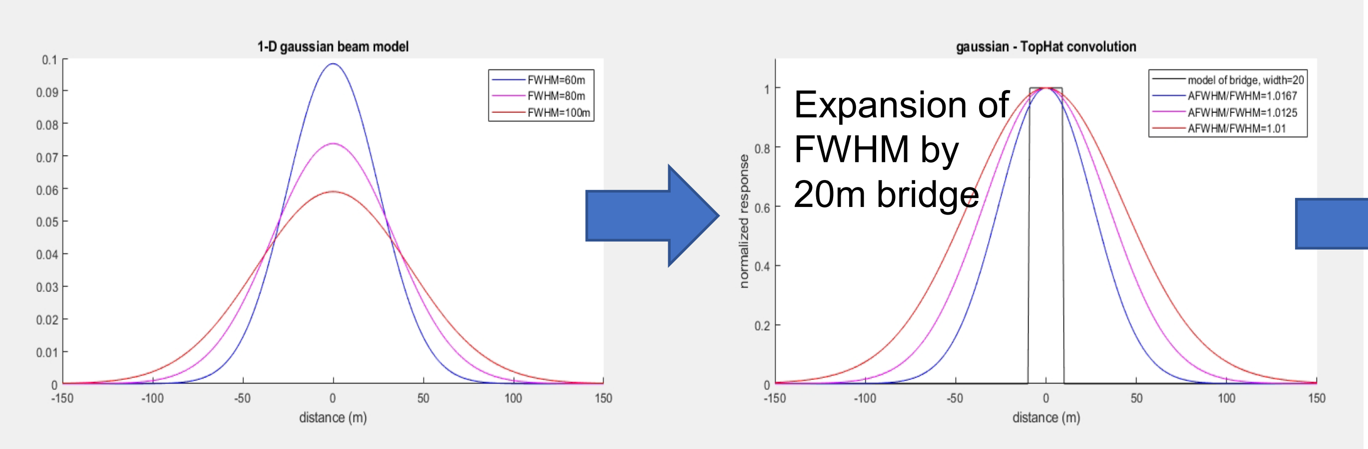
1. Bridges (20-70m wide) serve as fixed line elements with strong (daytime) thermal contrast
2. 'Collapse' 2D image into perpendicular cross-sections for each 500m section of bridge.
3. Remove background thermal signal and center thermal maximum on the line element.

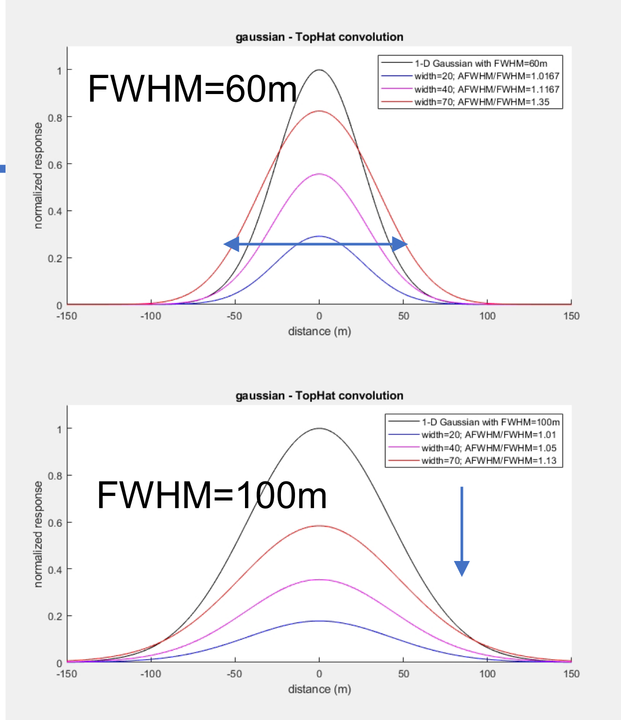


4. This thermal cross-section, Y(d)-B(d), represents the convolution of the imagers linespread function and the true thermal emission.



numerical convolution of Beam model and 'TopHat' function

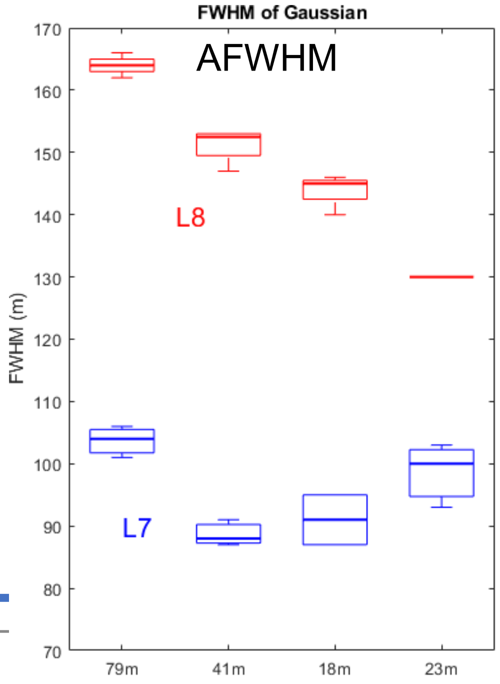


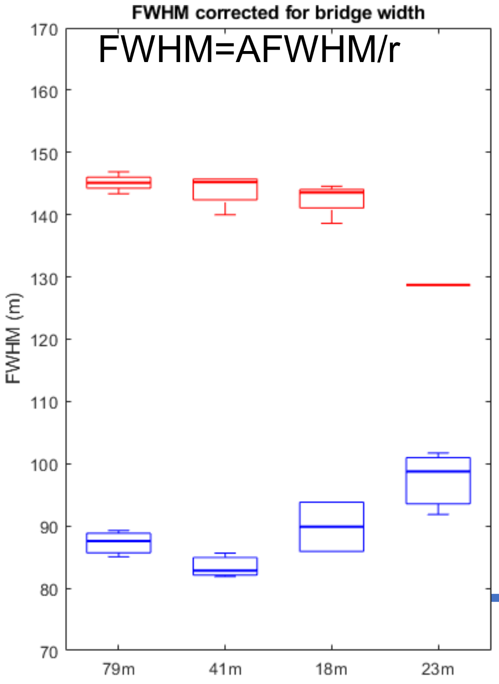


Expansion of FWHM (r) increases with bridge width.

But also, contrast is proportional to width/FWHM

6. 1-D Gaussian beam model is fitted to the thermal signal, Y(d)-B(d)
7. FWHM of fit gaussian is adjusted to compensate for bridge width; correction factors determined based on numerical analysis where a square function represents expected thermal signature of bridge in daytime.





After correction for bridge width, the FWHM measurements for L7 and L8 images are return consistent results.

Other considerations for understanding these FWHM in relation to the sensors LSF:

- Along track blur due to S/C motion (V) during integration time (t):

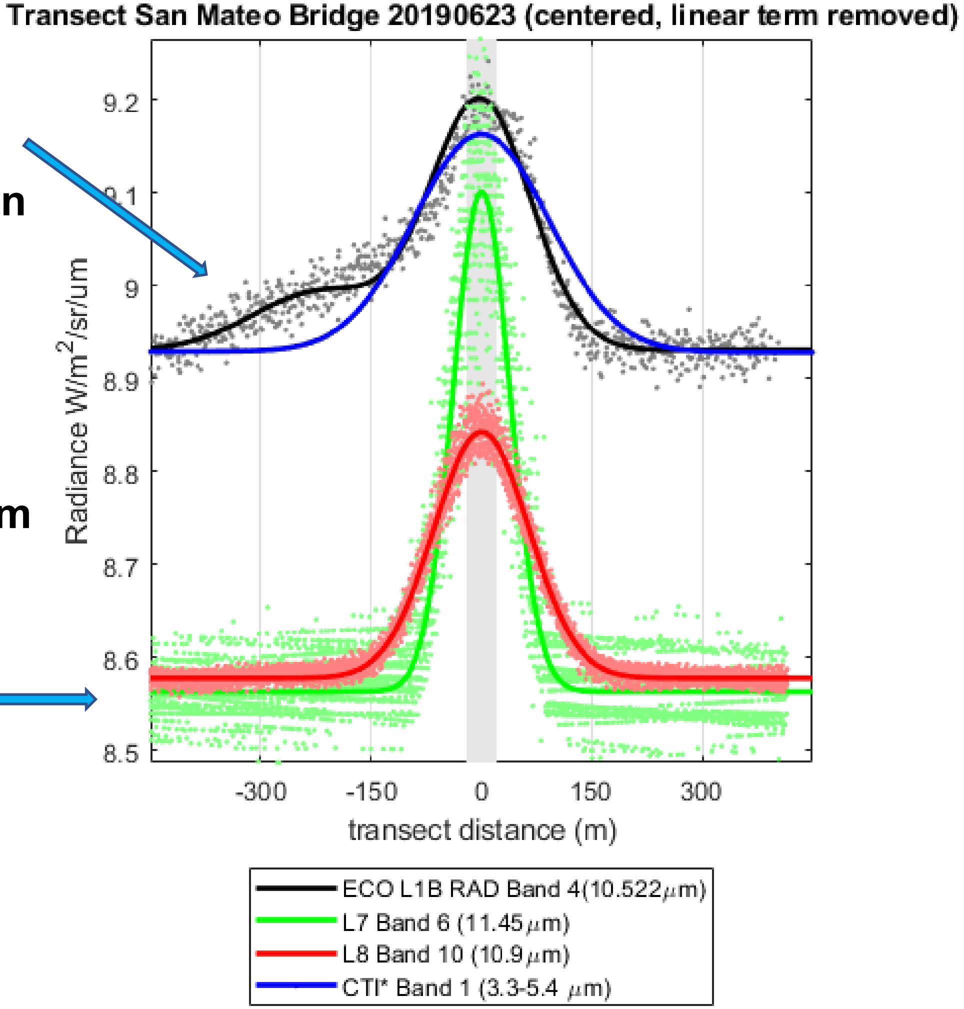
  $$\text{smear} = V^{*}\ t\ ^{*}\ |\cos(\text{Bridge\_angle} - \text{SC\_az} - \pi/4)|$$

  For Landsat 8 with a 3.4 ms integration time and NNE S/C azimuth this works out to 24, 22, 13, and 6 m (in the order of the bridges in the figure).
- Scan-to-scan line jitter due to S/C and motor motion (e.g. ECOSTRESS) could obscure the instrument performance in constructed image-> we therefore analyzed each scan individually as a 10km x400 km image
- Low signal to noise can result in overestimating the width of the fitted gaussian. We focus on clear sky with highest contrast.

Result for single image

ECOSTRESS, and sometimes CTI, show non-Gaussian behavior

Gaussian beamform is good approximation for L7, L8



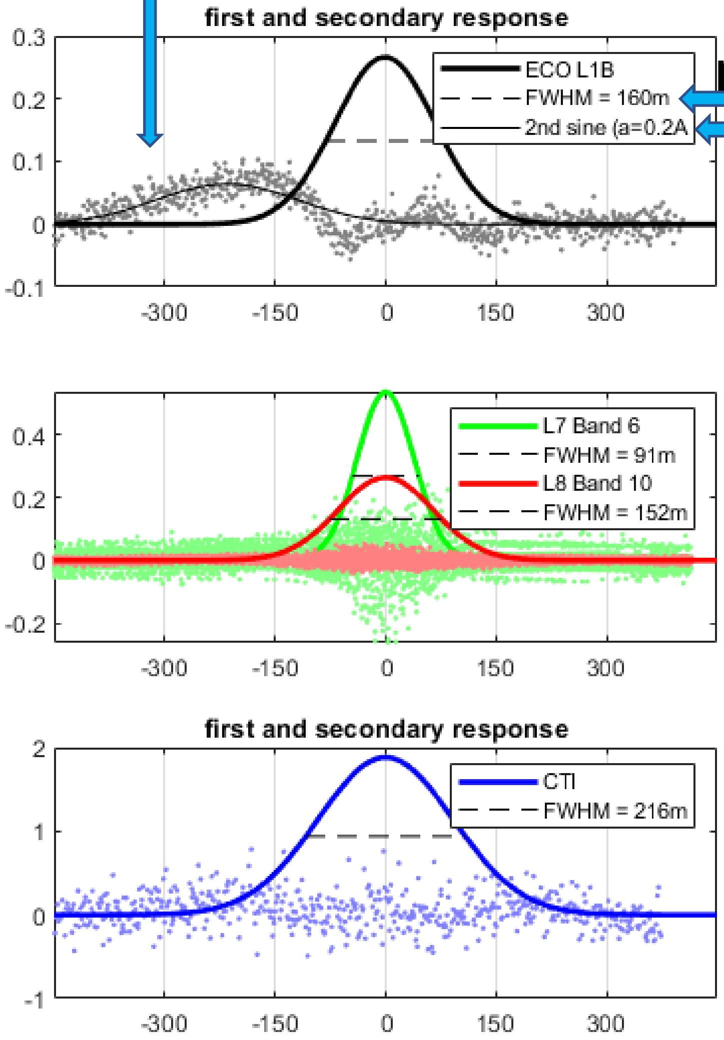
Residual after removing Gaussian is modeled by 2nd Gaussian

Legend lists: primary signal FWHM

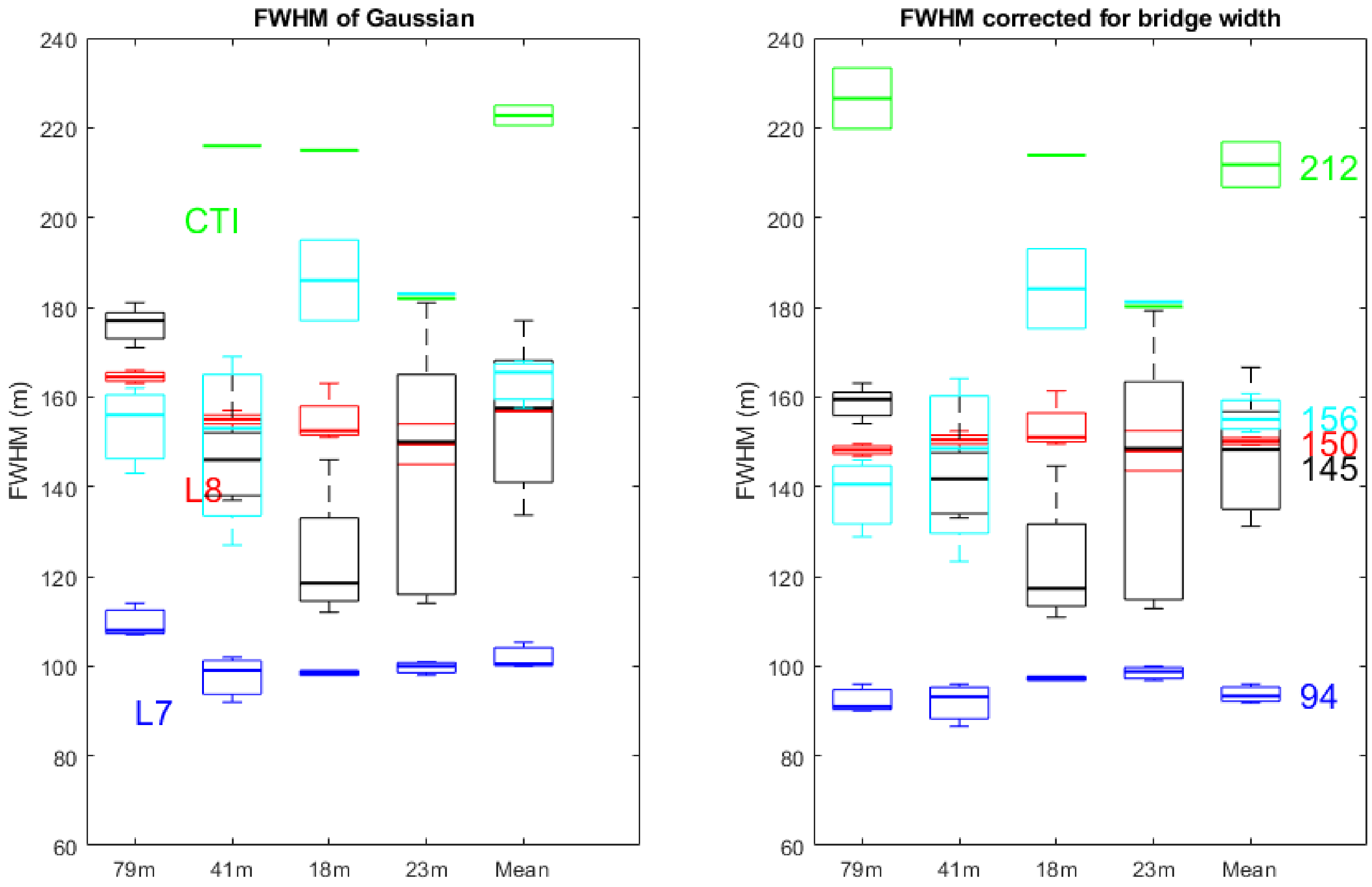
Secondary response strength as fraction of primary signal

Low SNR for L8

High SNR for CTI



FWHM Summary of clear-sky scenes



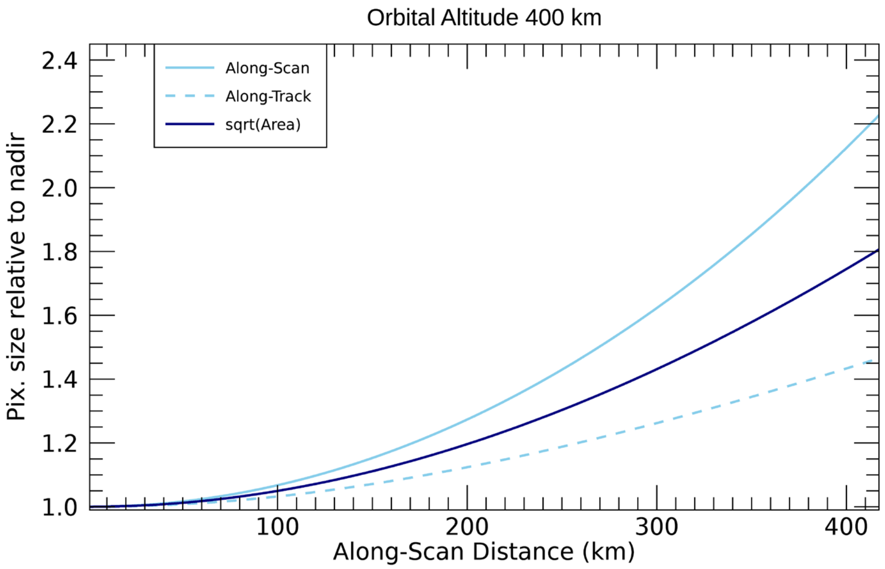
- L7 and L8: apparent FWHM is 45% higher than nominal FWHM. Factor in integration time blur (24 for L8, but none for L7)
- ECOSTRESS FWHM is more than double the nominal FWHM at center of scan. Difference increases towards scan edge, see next slide.

ECOSTRESS
(nom. 70-90m)

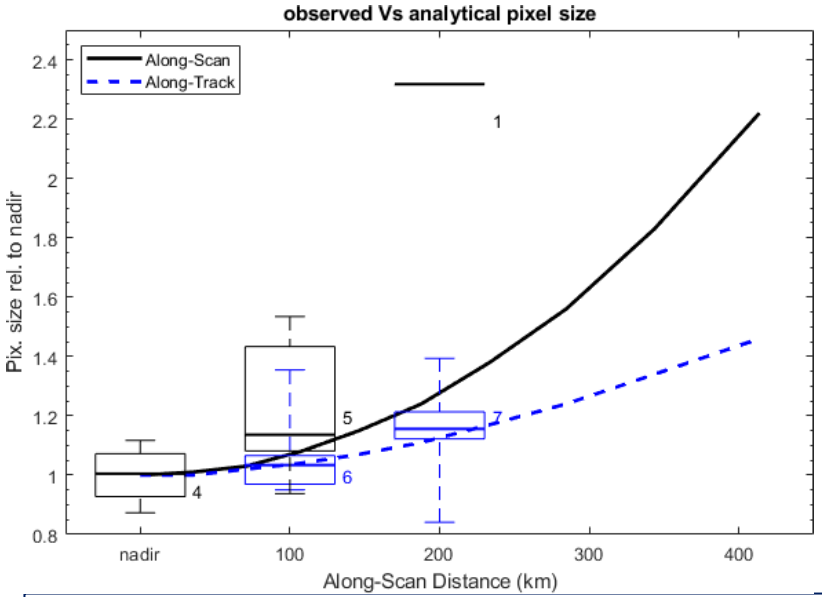
LANDSAT 8
(nom. 100m)
150 – 24 smear

LANDSAT 7
(nom. 60m)

Pixel Size vs Scan Angle: Pixel size increases both along scan and across scan with increasing scan angle. Analytical results by **Boryana Efremova/618.**



Pixel size relative to nadir, as function of distance along the swath from nadir. The degradation is a function of the scan angle, altitude, and curvature of earth. It's not related to MTF or optical performance of the system.



Pixel size relative to nadir (FWHM at nadir is 163 m), as function of distance along the swath. Observed FWHM are separated by the angle between the scan line and the bridge. The observed FWHM over bridges that are perpendicular to the scan line (black) show greater pixel sizes than the ones for bridges oriented along the scan line (blue).

Conclusions

- We used the sharp thermal contrast between day-time bridges and their surrounding waters to characterize the spatial performance of thermal infrared imagers after launch.
- This preliminary analysis finds that the FWHM of the line spread function is 1.5 to twice the length of the nominal spatial resolution.
- Further investigations are needed to attribute the divergence of these metrics to environmental or S/C conditions.

Backup

Compact Thermal imagers on ISS

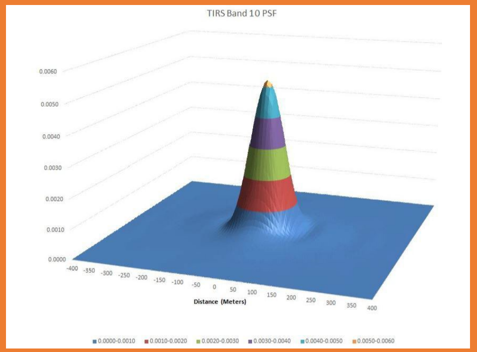
- Focus on band 1: 3.3-5.4 micron
- A technology demonstration. Custom rocedures for flattening and calibrating the raw image counts to radiance.
- Despeckle
- median filter per scene: (pixel – median(3x3 pixels)) > 3sigma (positive speckles only)
- Corrects for fixed (lens imperfections) and intermittend (e.g. cosmic rays)
- Calibration:
- Target: Rr (ECO), Original: R(CTI)
- Normalized: $R^* = (R - \text{median}(R)) / \sigma(R) * \sigma(Rr) + \text{median}(Rr)$

Methods

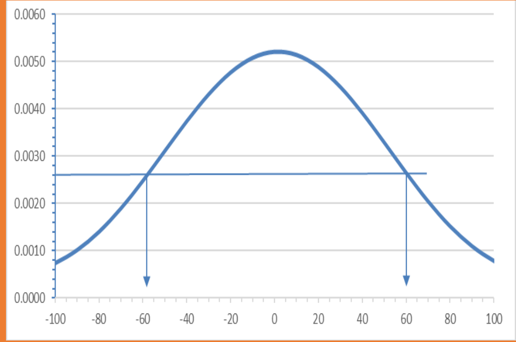
Spatial quality of optical system. Combined effect of optics, detectors, electronics. Modulates the true thermal scene into the recorded thermal image. Spatial quality refers to the interaction between ground sample distance (GSD) and the point spread function (PSF) of an imaging system.
For an imaging system in space, the atmosphere and S/C motion during integration time result in further blurring of the image.

DETERMINE FWHM IN ORBIT
In orbit, it is easier to find strong signals (sharp contrast in thermal radiance) in line features and get the linespread function (LSF) by analyzing perpendicular transects. The full width at half maximum (FWHW) of the LSF summarizes the overall spatial resolution.

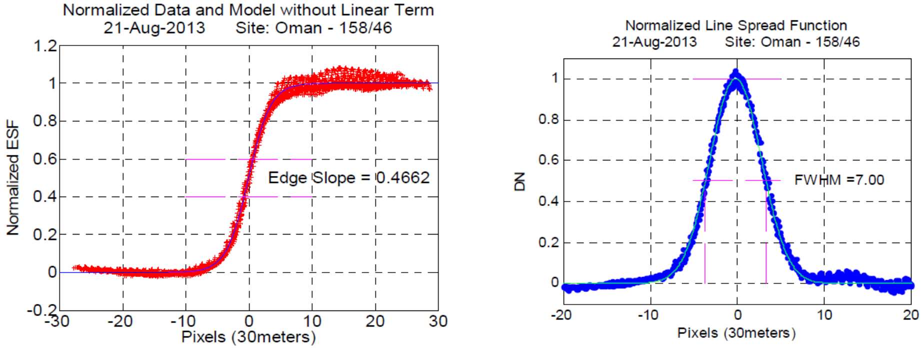
1. Schowengerdt et al. 1985 estimated the LSF of the thematic mapper (TM) instrument on the Landsat-4 spacecraft based on a spatial frequency analysis of images of the San Mateo Bridge over lower San Francisco Bay, USA.
2. Bryan Wenny et al 2015: **Edge spread function**
   - Determine exact edge position (Fits a modified Fermi function to),
   - LSF off transects aligned relative to edge-> FWHM, edge slope.
   - Fourier transform to get Mod Transfer Function (MTF).
   - Post-launch **L8 TIRS 10.9-µm band: FWHM~ 180**, edge slope ~0.55



Plot of the 2D point spread function for the TIRS 10.8 micron band (band 10).



Crosscut of the pre-launch PSD for the TIRS 10.8 micron band (band 10).
-> FWHM=120m
See https://www.usgs.gov/land-resources/nli/landsat/landsat-geometry for more information.



(a) (b)

Materials

ECOSTRESS **ECO_1B_RAD,** Focus on band 4: 10.522 (0.54) micron

- ECO1BRAD is at sensor calibrated radiance, needs geolocation files separate
- ECO1BMAPRAD: map registered product that is in a rotated geographic projection with a spatial resolution of 70 m. Resolution is slightly degraded compared to ECO1BRAD, see below.

Resolution of ECO1B image is slightly degraded after map registration (FWHM ~+20m). It also includes artifacts (striping). See example on right for image taken on 6/18/21.
(or 6/23/2019).