ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station

Simon J. Hook and the ECOSTRESS Team
Jet Propulsion Laboratory,
California Institute of Technology, Pasadena, CA

With support, encouragement and participation from many!

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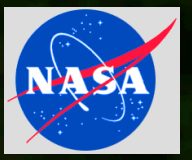
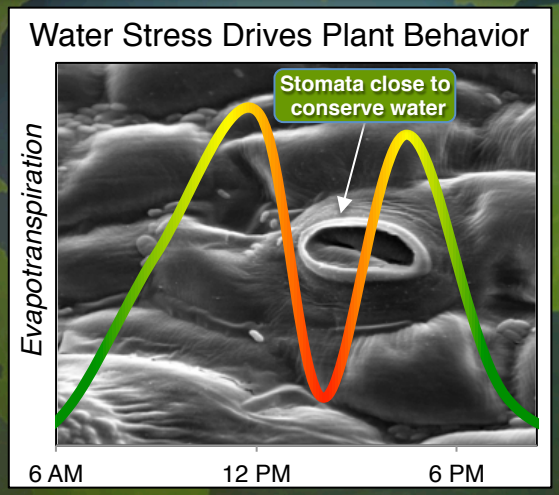


ECOSTRESS

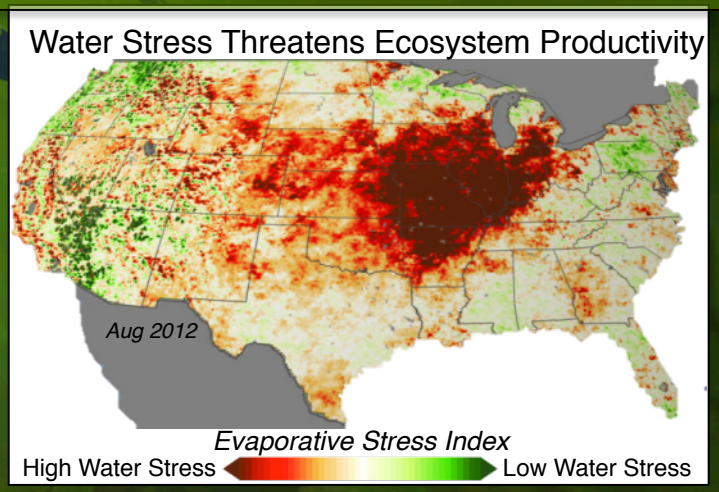
ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station

Dr. Simon J. Hook, JPL, Principal Investigator

*ECOSTRESS will provide critical insight into **plant-water dynamics** and how **ecosystems change with climate** via **high spatiotemporal** resolution thermal infrared radiometer measurements of evapotranspiration from the International Space Station (ISS).*



When stomata close, CO_2 uptake and evapotranspiration are halted and plants risk starvation, overheating and death.

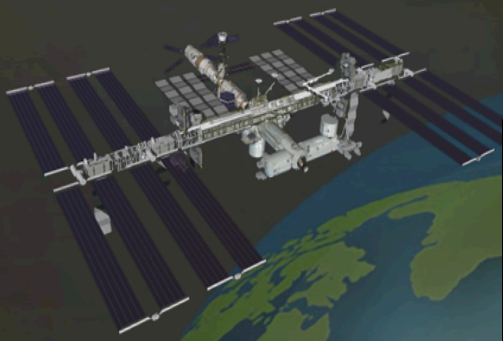


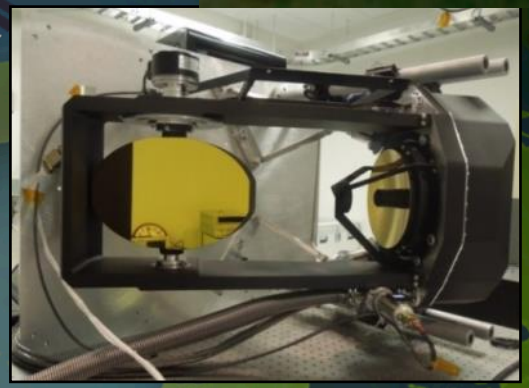
Water stress is quantified by the Evaporative Stress Index, which relies on evapotranspiration measurements.

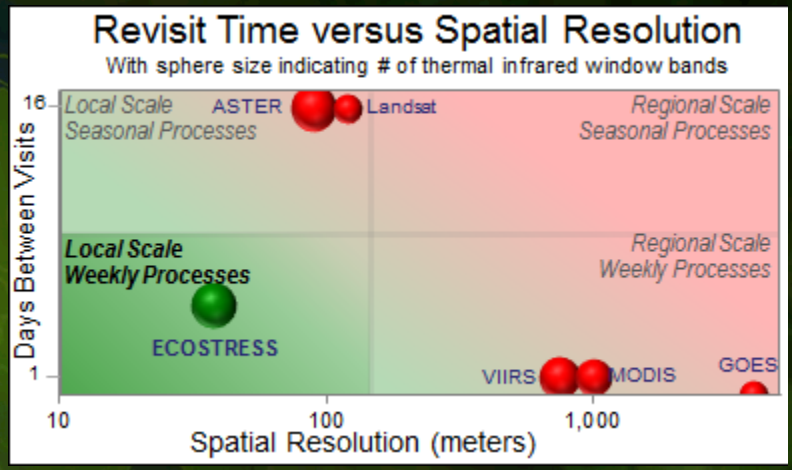
Science Objectives

- Identify **critical thresholds of water use and water stress** in key climate-sensitive biomes
- Detect the timing, location, and predictive factors leading to plant **water uptake decline** and/or cessation over the **diurnal cycle**
- Measure **agricultural water consumptive use** over the contiguous United States (CONUS) at spatiotemporal scales applicable to improve drought estimation accuracy

ECOSTRESS







Mission

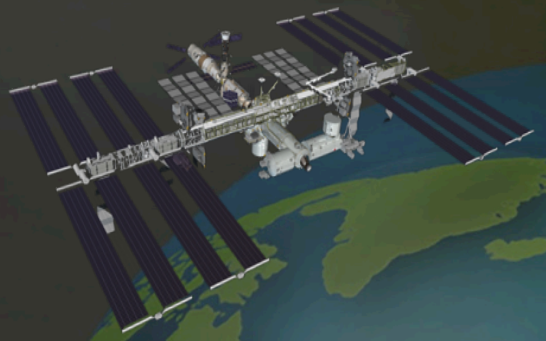
- Class D $30M cost cap
- 31-months from project start to delivery
- JPL implementation and management
- 69-month project duration (Phase A-F)
- On ISS-JEMS Module
- 12-month Science Operations (Phase E)

The inclined, precessing ISS orbit enables ECOSTRESS to sample the diurnal cycle in critical regions across the globe at spatiotemporal scales missed by current instruments in Sun-synchronous polar and high-altitude geostationary orbits.

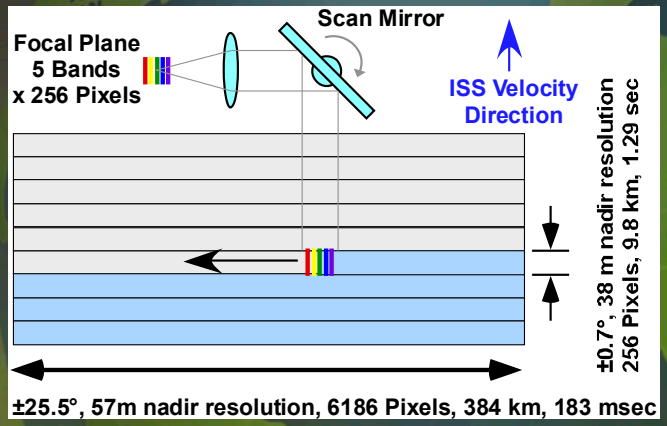
Instrument

- Leverages functionally-tested PHyTIR space-ready hardware developed under the NASA Instrument Incubator Program:
  - Spectral resolution: 5 bands in the thermal infrared window (8-12.5 µm) part of the electromagnetic spectrum
  - Noise equivalent delta temperature: ≤ 0.1 K
  - Spatial resolution: 38 m x 57 m
  - Swath width: 384 km (51°)
- *Well understood measurement and algorithms based on prior missions, such as ASTER, MODIS, and Landsat*

ECOSTRESS



Push-whisk System



Science Data Products	
L0	Raw data
L1	Radiometrically corrected Brightness Temperature
L2	Surface Temperature and Emissivity
L3	Evapotranspiration
L4	Water Use Efficiency, Evaporative Stress Index

Science Team

Principal Investigator

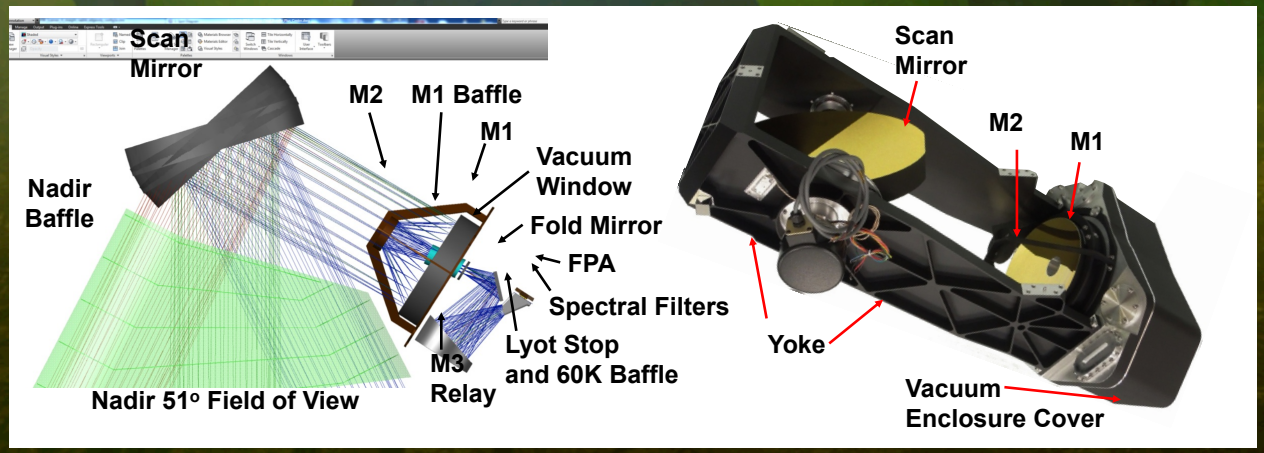
Simon Hook, JPL

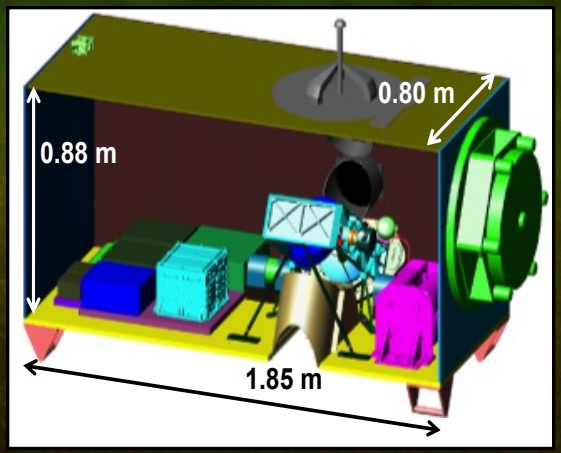
Co-Investigators

Rick Allen, Univ. of Idaho
Martha Anderson, USDA
Joshua Fisher, JPL
Andrew French, USDA
Glynn Hulley, JPL
Eric Wood, Princeton Univ.

Collaborators

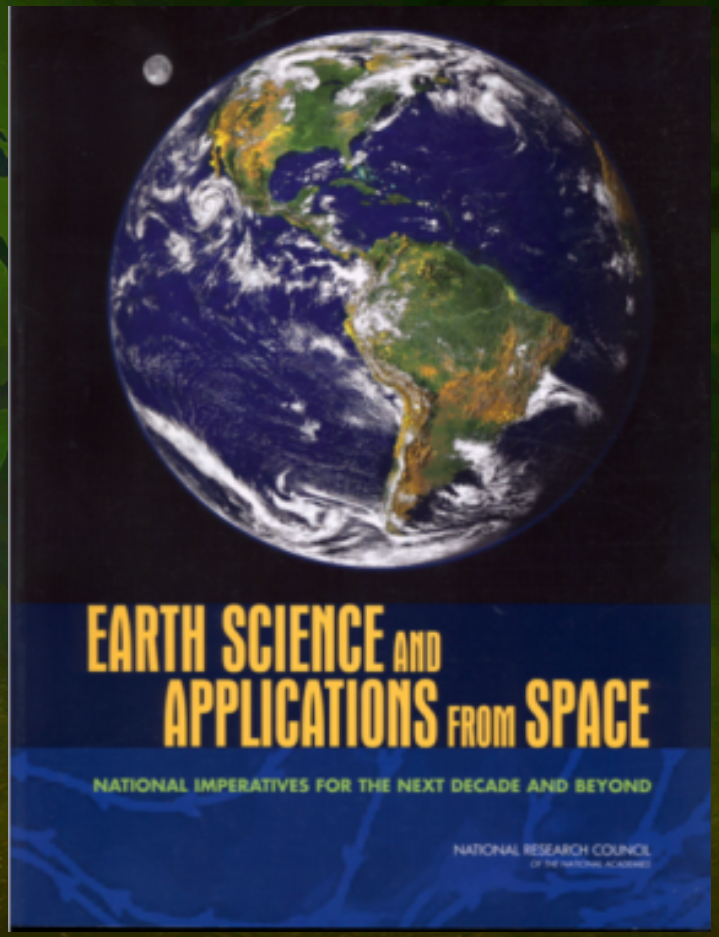
Christopher Hain, Univ. Maryland





Background

In 2007 The National Reseach Council recommended the Hyperspectral Infrared Imager (HyspIRI) as one of the Tier II missions in the Decadal Survey



HyspIRI Decadal Survey Mission

Key Science and Science Applications

Climate: Ecosystem biochemistry, condition & feedback; evapotranspiration

Ecosystems: Global biodiversity, plant functional types, physiological condition, and biochemistry

Fires: Fuel status; fire frequency, severity, emissions, and patterns of recovery globally

Coral reef and coastal habitats: Global composition and status

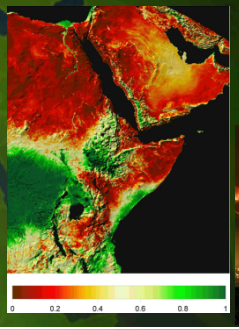
Volcanoes: Eruptions, emissions, regional and global impact

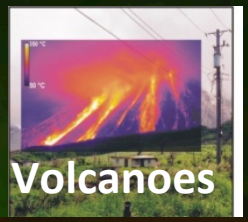
Geology and resources: Global distributions of surface mineral resources

Mission Urgency

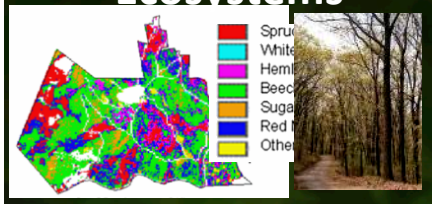
The HyspIRI science and applications objectives are critical today and uniquely addressed by the combined imaging spectroscopy, thermal infrared measurements, and IPM direct broadcast.

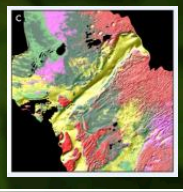
Evapo-transpiration





Ecosystems





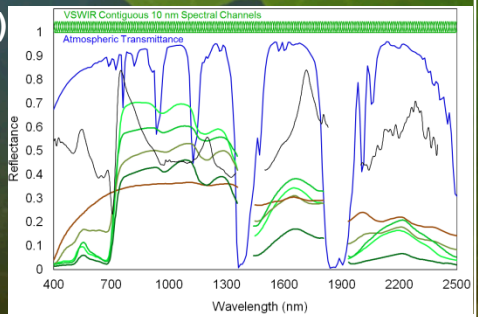
Measurement

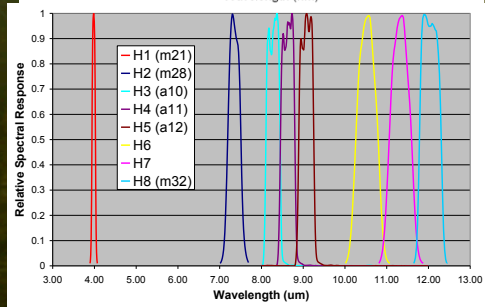
Imaging Spectrometer (VSWIR)

- 380 to 2500nm in 10nm bands
- 60 m spatial sampling
- 19 days revisit
- Global land and shallow water

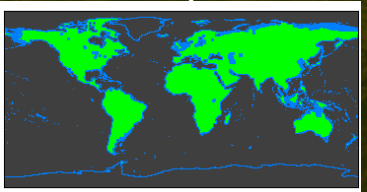
Thermal Infrared (TIR):

- 8 bands between 4-12 µm
- 60 m spatial sampling
- 5 days revisit; day/night
- Global land and shallow water





IPM-Low Latency data subsets



Mission Concept Status

Preliminary Draft Program Level 1 Requirements: Stable

Payload: Imaging Spectrometer, Thermal Infrared Imager, and IPM-Low Latency subsets

Spacecraft: RFI responses in

Payload: TBD - JPL/GSFC concept

Launch Vehicle: Small class

Launch date: ≥2024

Mission: Class C, 3-year baseline

Trajectory or Orbit: LEO, Sun sync.

S/C & Instrument Mass: 686kg (30% margin)

S/C & Instrument Power: 708W (45% margin against peak)

Mission Cost (FY12 est.): $506M incl. 30% reserve except for LV

The HyspIRI mission concept is mature and stable with excellent heritage, low risk and modest cost.

(Examples above demonstrate existing capabilities.)

HyspIRI-TIR Quad Chart

Science Questions:

TQ1. Volcanoes/Earthquakes

– How can we help predict and mitigate earthquake and volcanic hazards through detection of transient thermal phenomena?

- *TQ2. Wildfires*

– What is the impact of global biomass burning on the terrestrial biosphere and atmosphere, and how is this impact changing over time?

- *TQ3. Water Use and Availability*

– How is consumptive use of global freshwater supplies responding to changes in climate and demand, and what are the implications for sustainable management of water resources?

- *TQ4. Urbanization/Human*

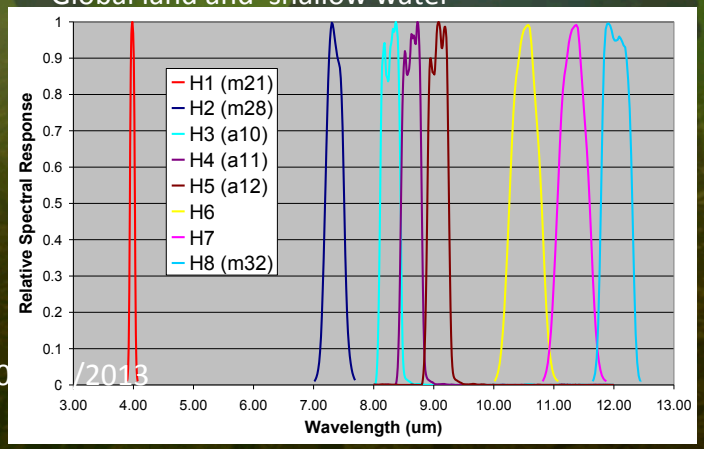
– How does urbanization affect the local, regional and global environment? Can we characterize this effect to help mitigate its impact on human health and welfare?

- *TQ5. Earth surface composition and change*

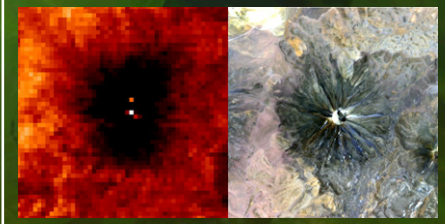
– What is the composition and temperature of the exposed surface of the Earth? How do these factors change over time and affect land use and habitability?

Measurement:

- 7 bands between 7.5-12 µm and 1 band at 4 µm
- 60 m resolution, 5 days revisit
- Global land and shallow water

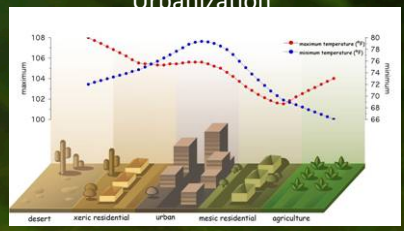


Andean volcano heats up

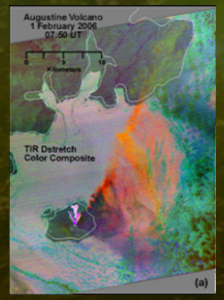


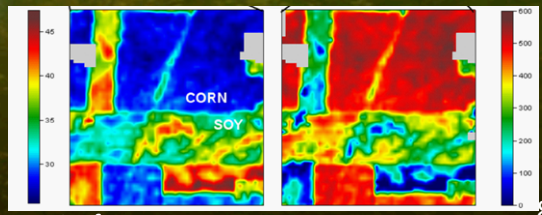
Volcanoes

Urbanization



Water Use and Availability





Surface Temperature

Evapotranspiration

HyspIRI Risk Reduction
PHyTIR and HyTES

VSWIR

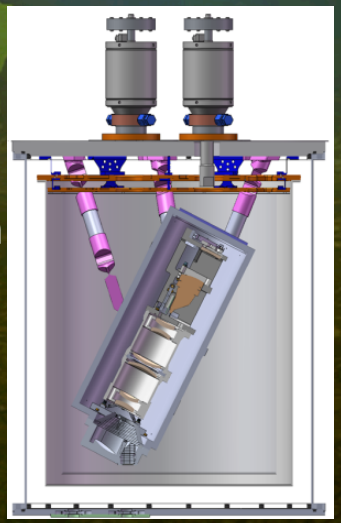
TIR

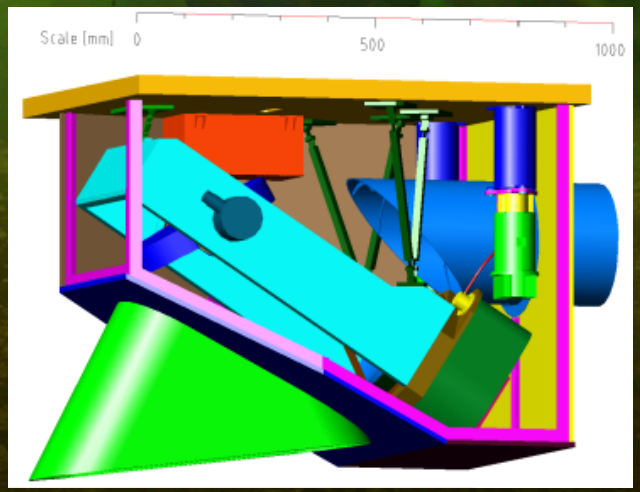
Hyperspectral Infrared Imager (HyspIRI)

Science Risk Reduction

Engineering Risk Reduction

Hyperspectral Thermal Emission Spectrometer (HyTES)

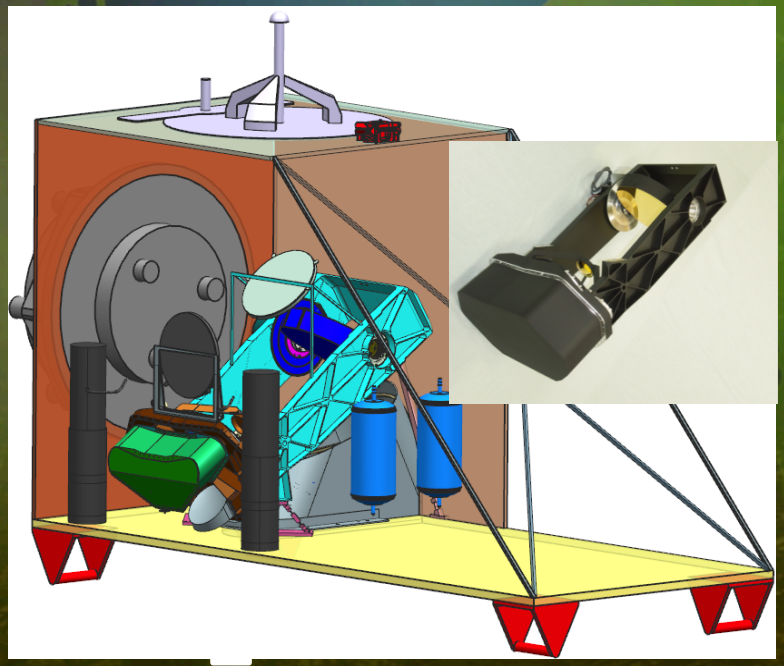




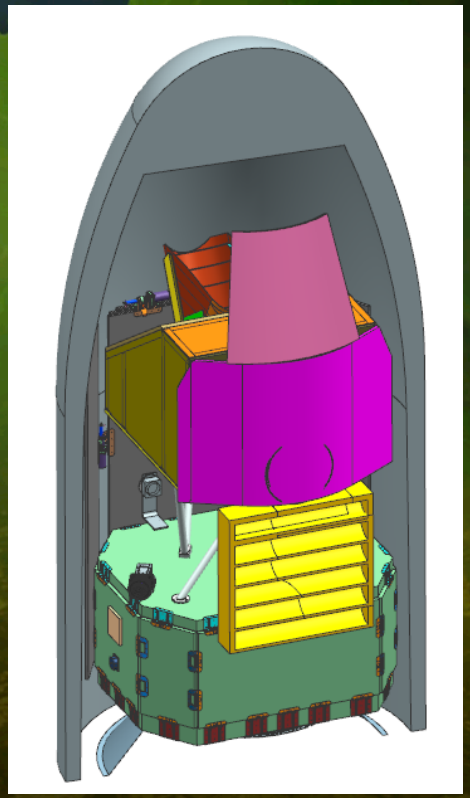
Prototype HyspIRI Thermal Infrared Radiometer (PHyTIR)

HyspIRI Instruments on Separate Platforms Options

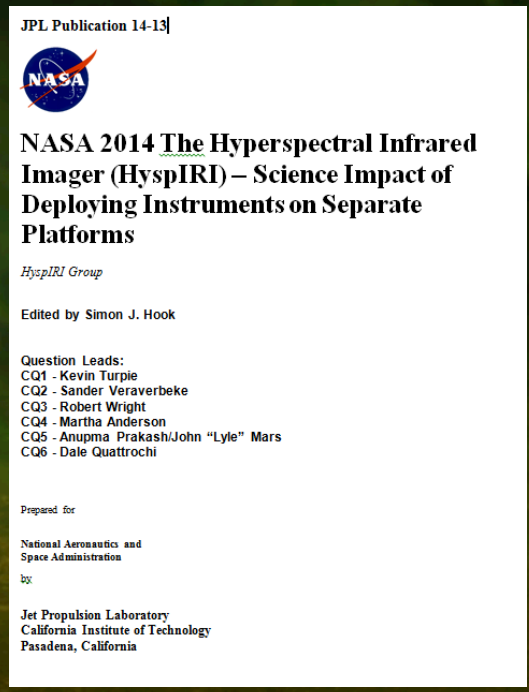
PHyTIR on ISS Tech Dem



PHyTIR-Compact on Pegasus



Separate Platforms Science Impact



JPL Publication 14-13

NASA 2014 The Hyperspectral Infrared Imager (HyspIRI) – Science Impact of Deploying Instruments on Separate Platforms

HyspIRI Group

Edited by Simon J. Hook

Question Leads:
CQ1 - Kevin Turpie
CQ2 - Sander Veraverbeke
CQ3 - Robert Wright
CQ4 - Martha Anderson
CQ5 - Anupma Prakash/John "Lyle" Mars
CQ6 - Dale Quattrochi

Prepared for

National Aeronautics and Space Administration

by

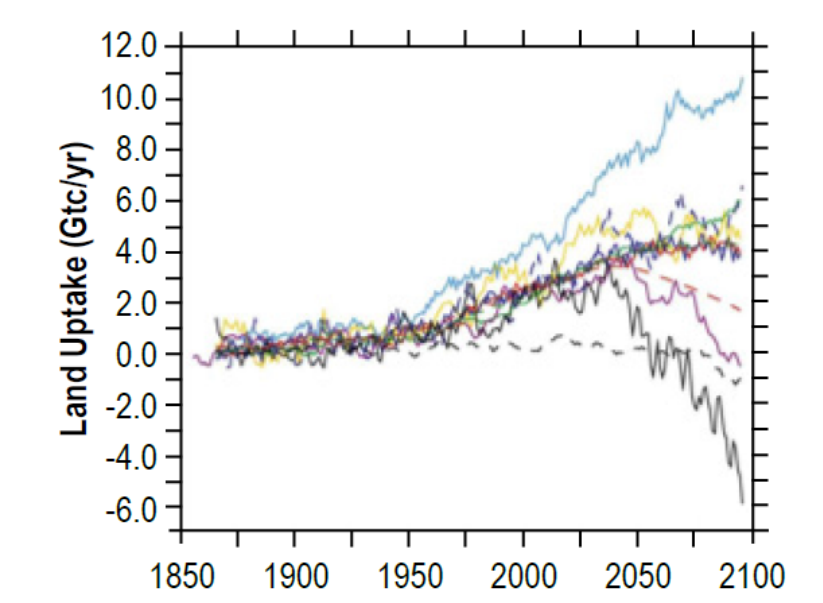
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

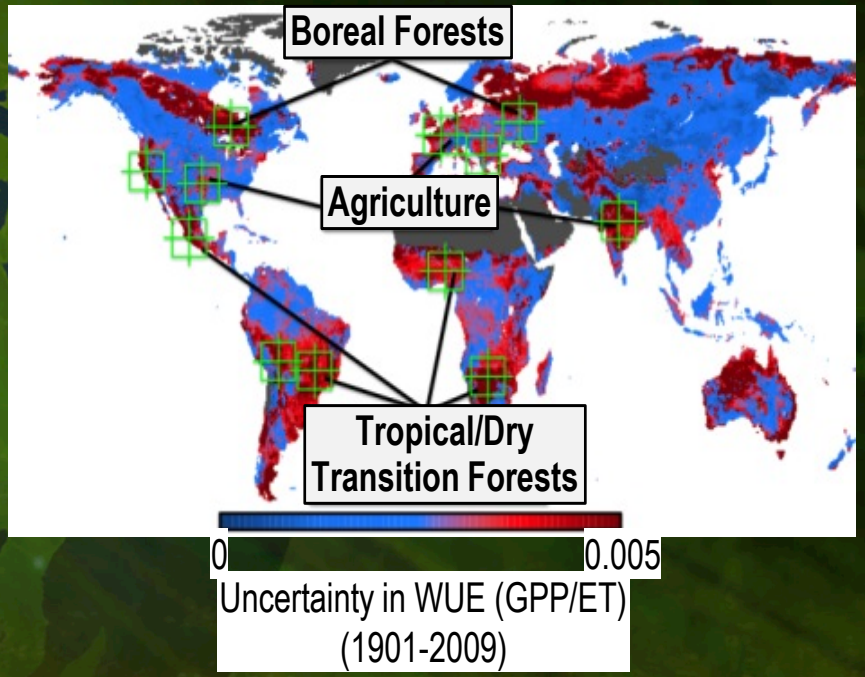
Looked at various options with HyspIRI instrument suite flying together and separately during Preformulation

ECOSTRESS

- Some facts and figures
  - Focused on water use and availability
  - Selected in EVI-2
  - Class D mission on ISS
  - Uses PHyTIR developed under ESTO IIP
  - Deliver in early 2017
  - Nominal mission lifetime 1 year

Q1. How is the terrestrial biosphere responding to changes in water availability?

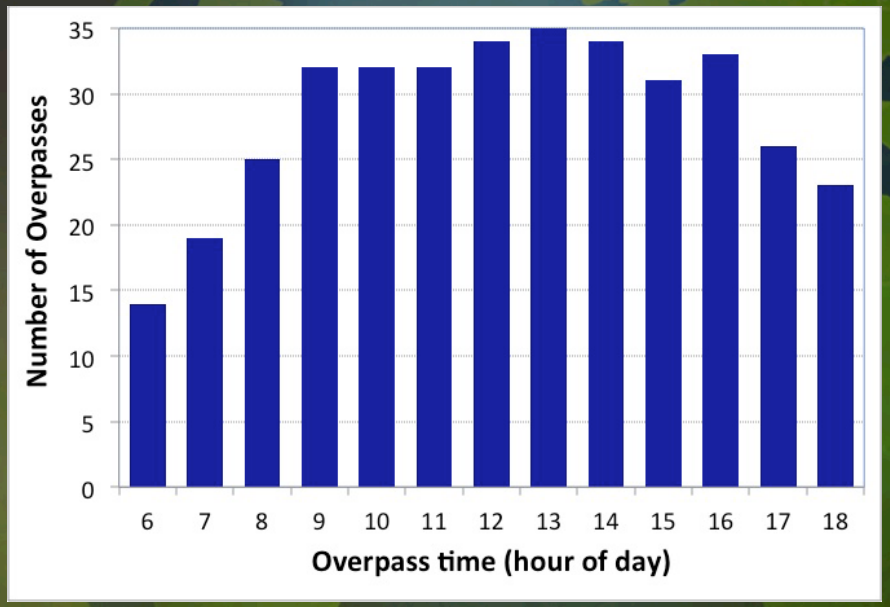




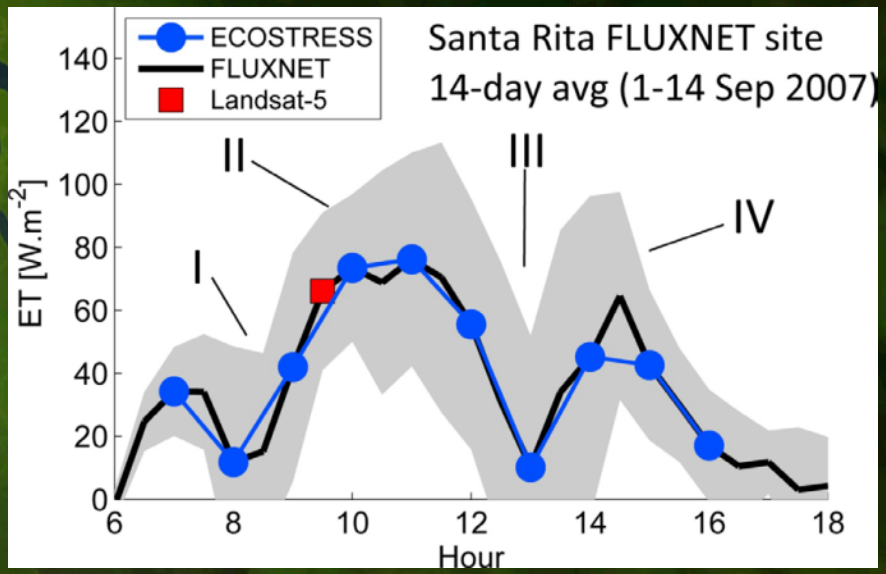
Uncertainty in our knowledge of carbon response is directly dependent on water response uncertainty and how plants use water under drying conditions.

Red areas ("hotspots") are where global models disagree on water use efficiency (WUE) based biome changes with climate change. ECOSTRESS will reduce this uncertainty with measurements for WUE (GPP/ET).

Q2. How do changes in diurnal vegetation water stress impact the global carbon cycle?



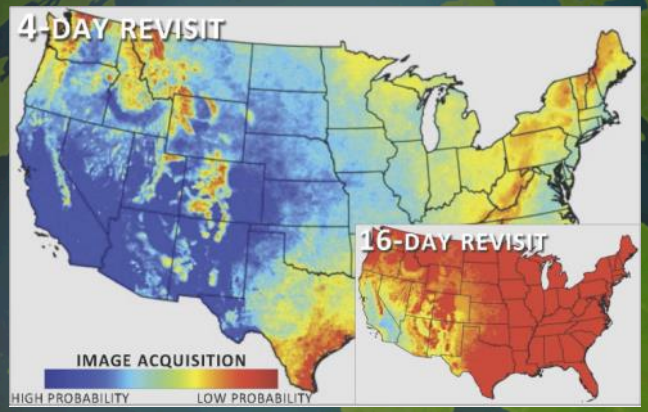
ECOSTRESS acquires numerous samples throughout the day over 1 year (at 50o latitude shown, for example).



ECOSTRESS's diurnal sampling measures the shape of the daily ET cycle. The afternoon decline in ET is related to water stress (clear day).

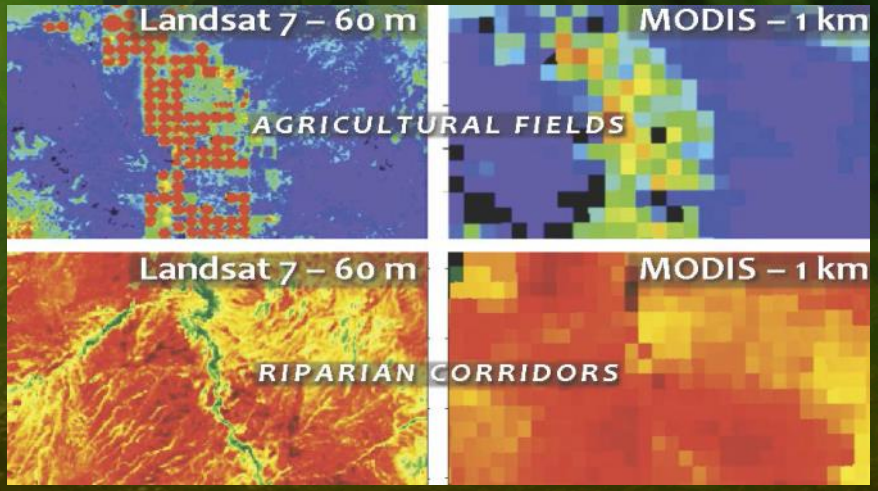
I: Xylem refilling after initial water release.
II: ET at maximum/potential rate in the morning.
III: Stomata shut down water flux in the afternoon.
IV: ET resumes at maximum/potential in early evening when demand is reduced

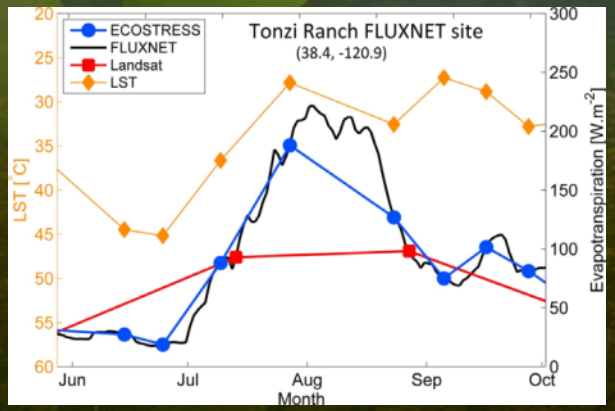
Q3. Can agricultural vulnerability be reduced through advanced monitoring of agricultural water consumptive use and improved drought estimation?



Probability of producing valid ET estimates when satellite revisit time is 16 days (lower-right inset) vs. 4 days

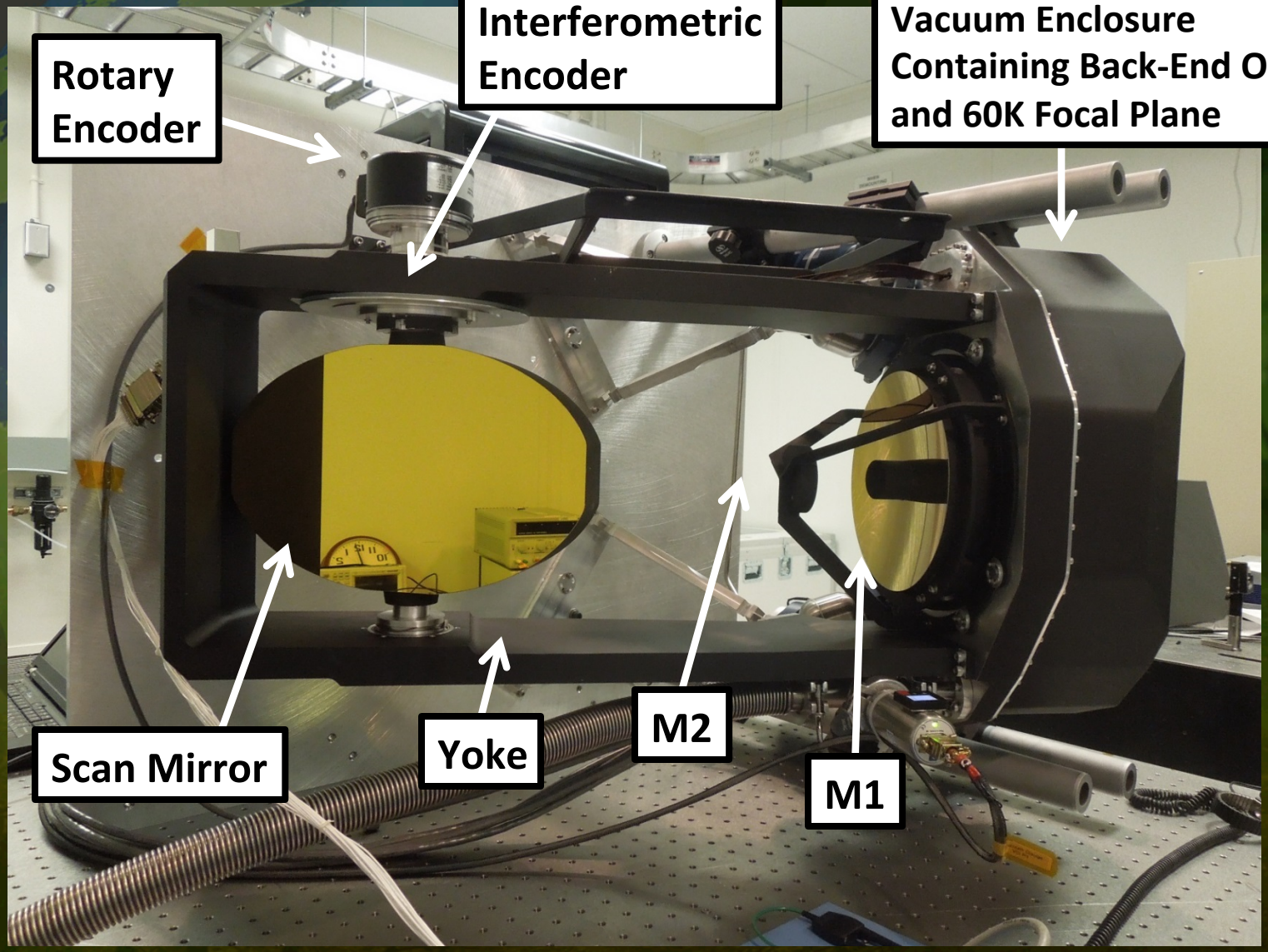
ECOSTRESS's spatial resolution will distinguish fine-scale landscape heterogeneity such as agricultural systems (top) and riparian corridors (bottom) similar to Landsat (left), whereas MODIS (right) does not.



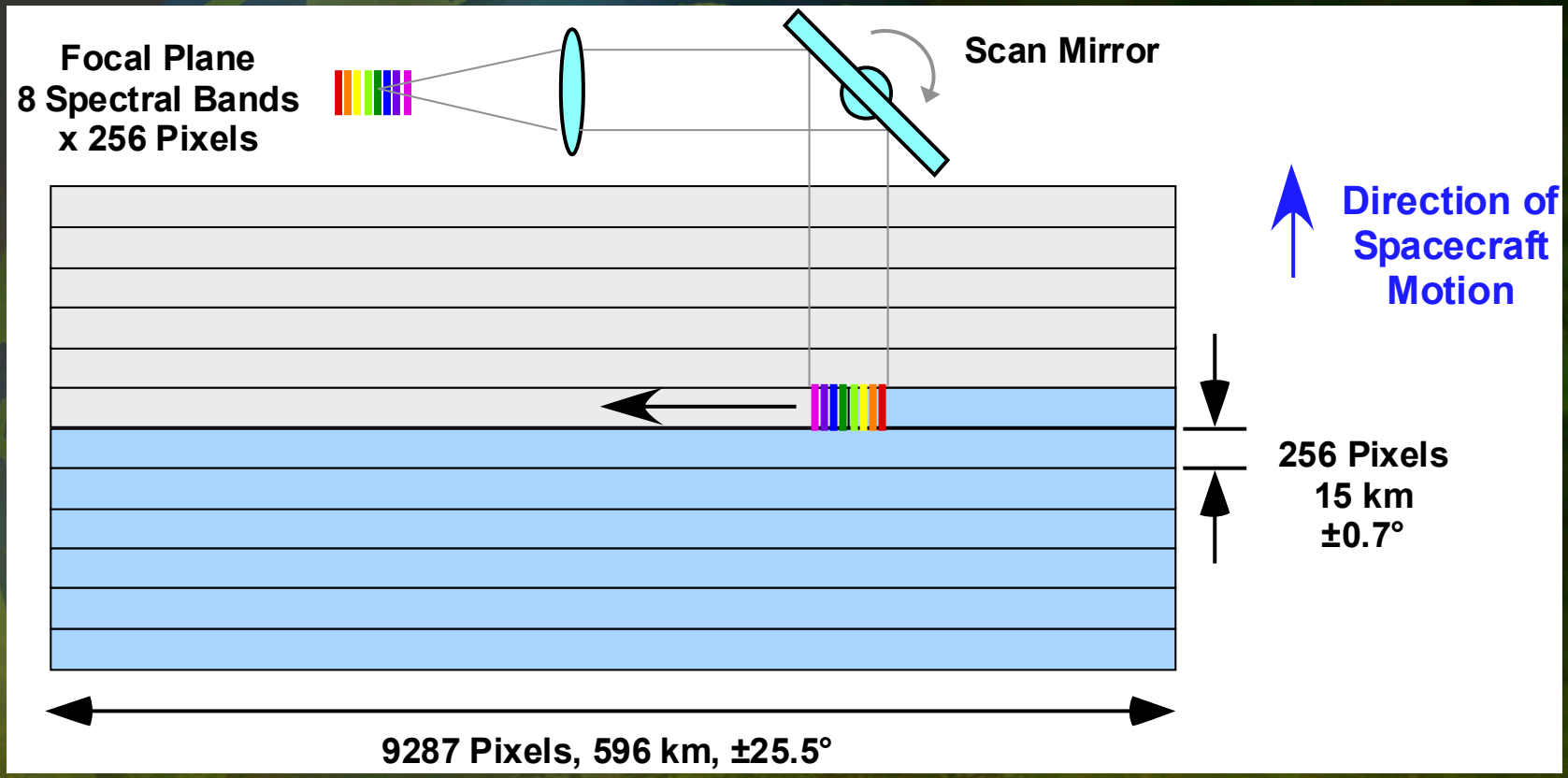


ECOSTRESS's temporal resolution provides a *9-fold* decrease in ET error relative to Landsat.

Prototype HyspIRI Thermal Infrared Radiometer (PHyTIR)



HyspIRI/PHyTIR Scan Concept



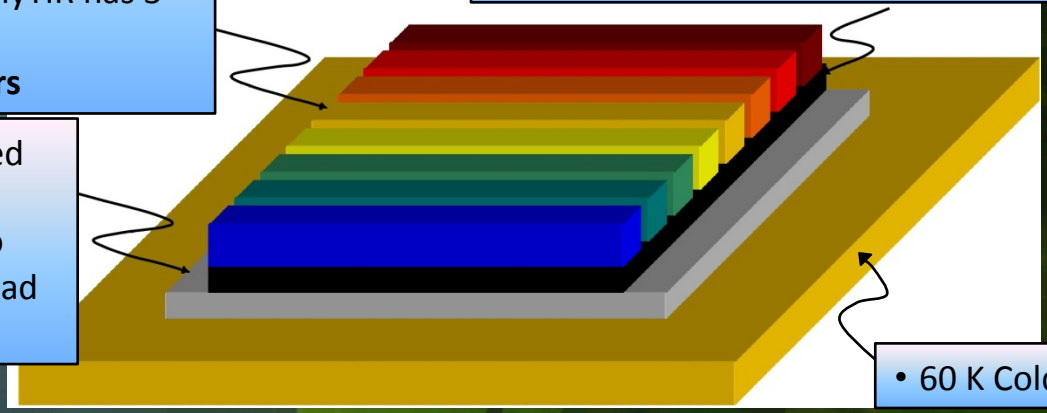
- 60 m Pixel Footprint at Nadir
- Time-Averaged Science Data Rate 0.020 Gbps
- Assuming 14 bits, 2:1 Compression, 31% Land
- Scan Mirror Rotation Rate 14.2 RPM
- Pixel Dwell Time 32 microseconds

PHyTIR/ECOSTRESS Focal Plane

- Butcher-Block Filter Assembly
- Baffles to Prevent Crosstalk Between Spectral Channels
- HyspIRI will have 8 filters, PhyTIR has 3 filters.
- **ECOSTRESS will have 5 filters**

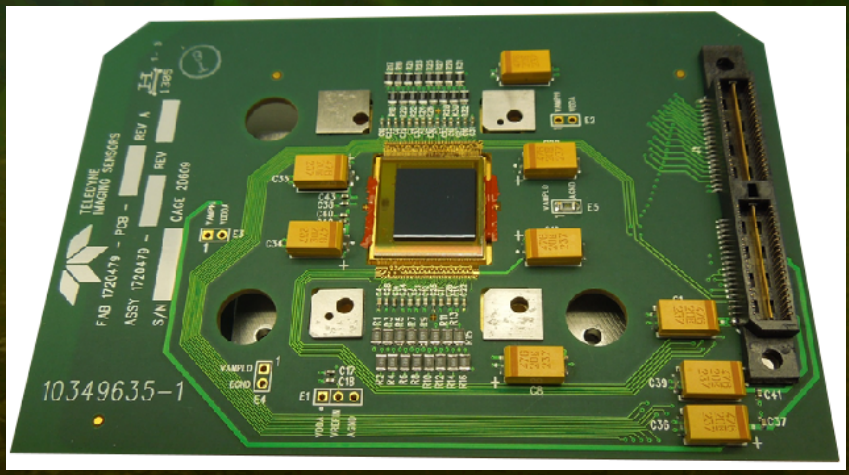
- MCT Detector Array – 256 elements cross-sweep
- 1 Bandgap to Cover Full Spectral Range
- ≥ 4 Detector Columns per Spectral Channel to Allow Time Delay and Integration (TDI)

- CMOS Read-Out Integrated Circuit (ROIC)
- 32 Analog Output Lines to Enable Necessary Pixel Read Rate

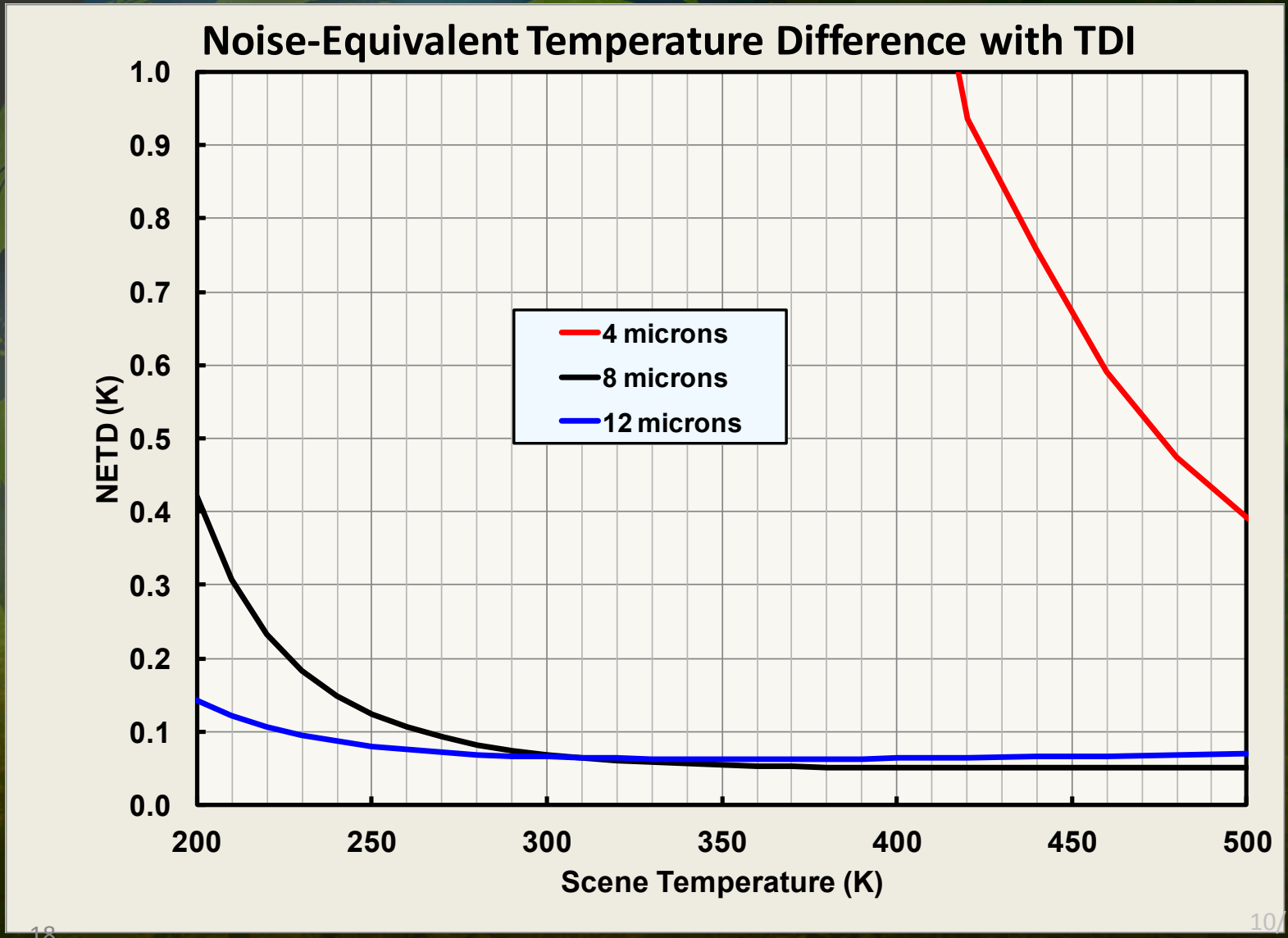


- 60 K Cold Tip of Cryocooler

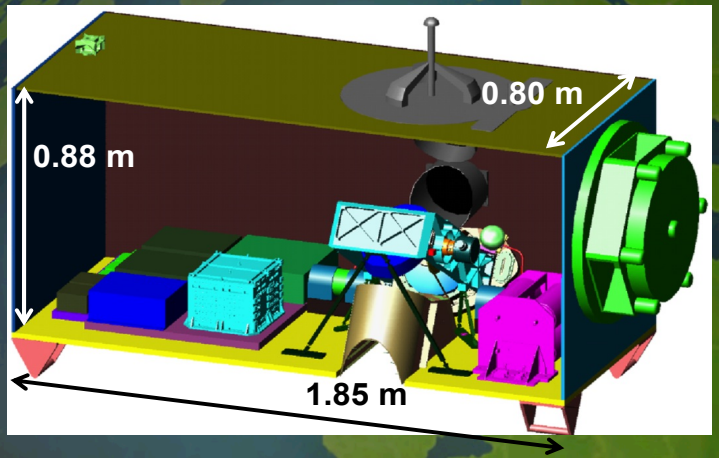
- JPL/Teledyne focal planes are in hand at JPL
- Digitization in off-chip ADCs
- TDI performed after digitization
- Cold testing shows expected performance at full readout speeds

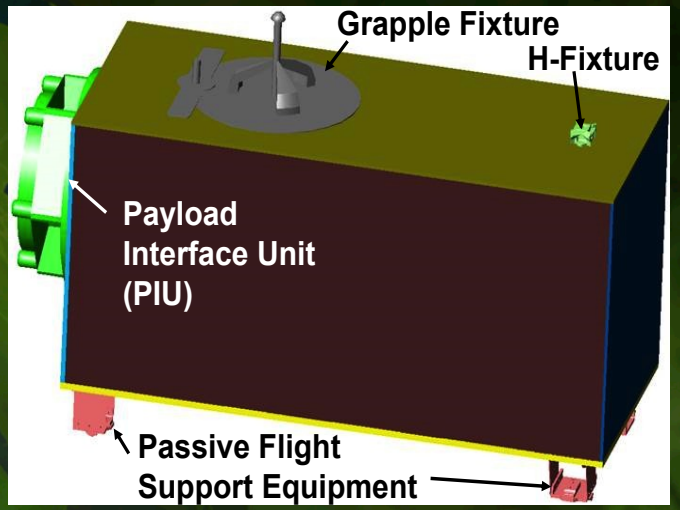


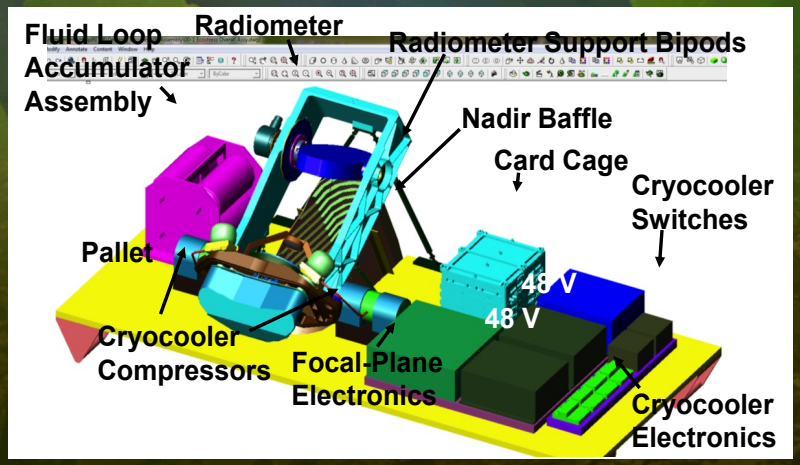
NETD of PhyTIR Bands

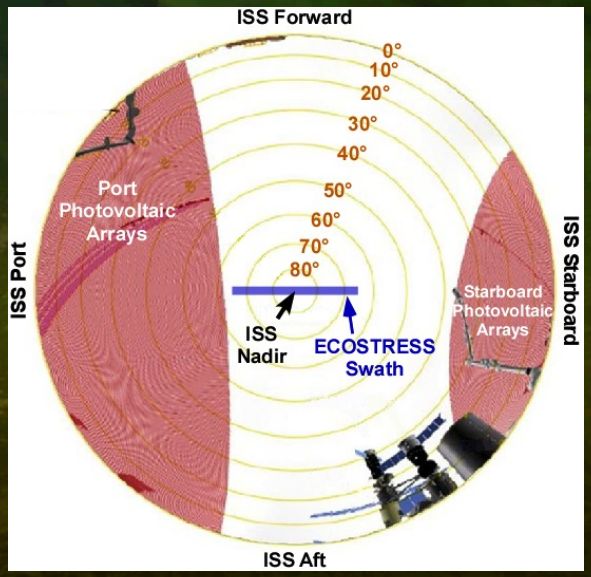


PHyTIR on ISS







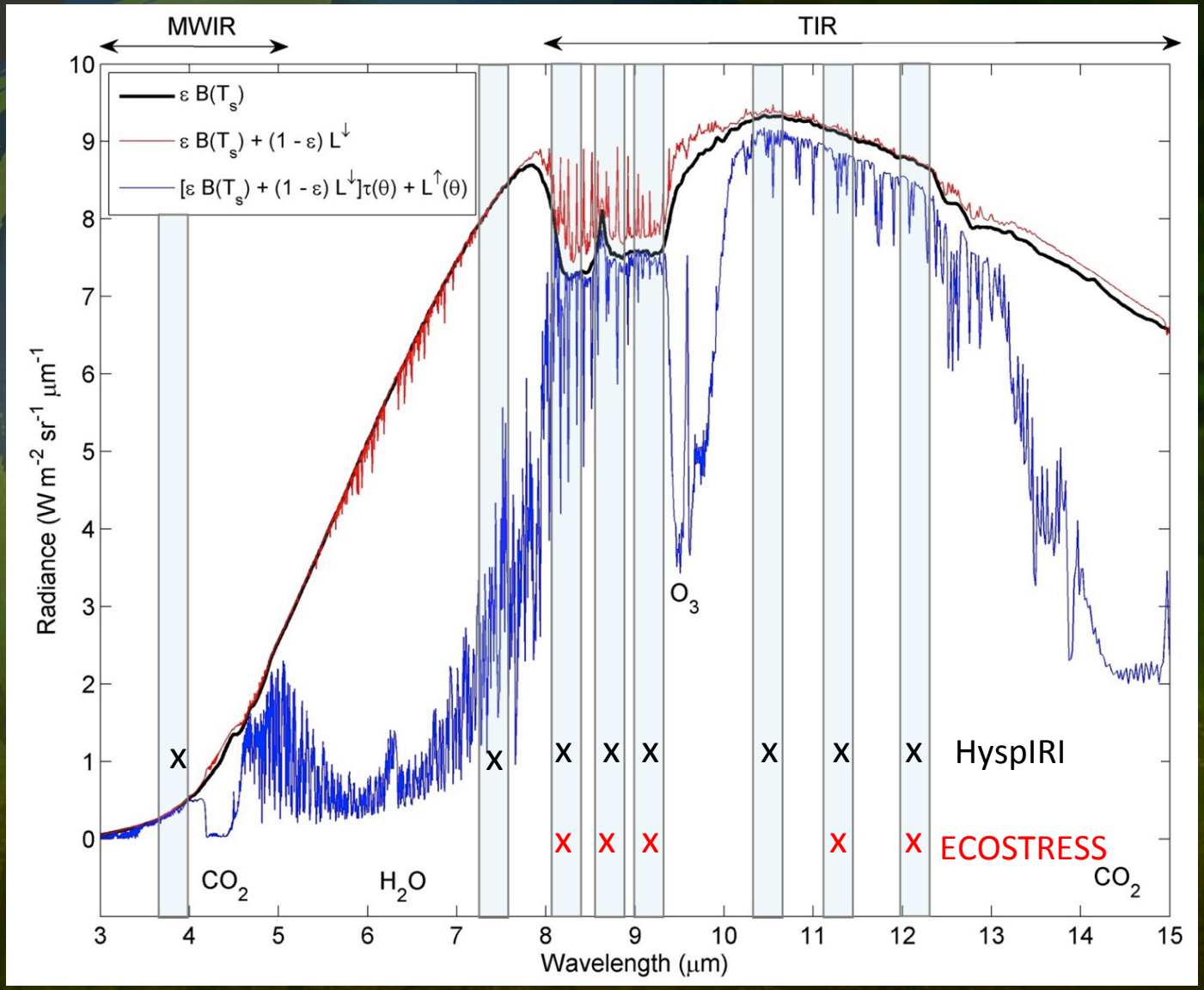


ECOSTRESS Data Products (L0->L4)

Data Products	Description	Information Required	Plans for Validation/Reprocessing
Level-0	Reconstructed, unprocessed instrument data at full resolution; any communication artifacts removed.	Raw science data packets	Automated process, no reprocessing needed.
Level-1A	Reconstructed unprocessed instrument data at full resolution, time-referenced, and annotated with ancillary information, including radiometric and geometric calibration coefficients.	Level-0 raw data	Automated process, minimal reprocessing.
Level-1B	Level 1a data that have been processed to sensor units by applying the coefficients for radiometric calibration and geometric resampling	Level-1A & radiometric and geometric coefficients	Automated process, with full reprocessing as needed. Validation of at-sensor radiance using data from autonomous Lake Tahoe and Salton Sea cal/val sites.
Level-2	LST and spectral emissivity	Level-1B data, cloud mask, NWP atmospheric profiles, ASTER digital elevation data.	Automatic process, with full reprocessing as necessary (e.g. algorithm changes). Validation (T-based and R-based) using a global set of sites including water, vegetation, sand dunes, grasslands, and soil land cover types.
Level-3	Evapotranspiration (ET),	Level-2 products, VNIR data from Landsat, met. data from NCEP.	Reprocessing as needed based on Level 2 reprocessing. Validation with eddy covariance data from FLUXNET sites (global).
Level-4	Water Use Efficiency (WUE), Evaporative Stress Index (ESI)	Level-3 products, GPP	Reprocessing as needed based on Level 2 and 3 reprocessing. Validation with eddy covariance data from FLUXNET sites (global).

Thermal Infrared Radiative Transfer

$$L_{sat,\lambda} = \left[\varepsilon_\lambda B_\lambda(LST) + (1 - \varepsilon_\lambda) L^{\downarrow}_{sky,\lambda}\right] \tau_\lambda + L^{\uparrow}_{sky,\lambda}$$



LST retrieval algorithms

To solve the under-determined temperature-emissivity problem:

N spectral measurements (N radiances) with N + 1 unknowns (N emissivity, 1 Temperature)

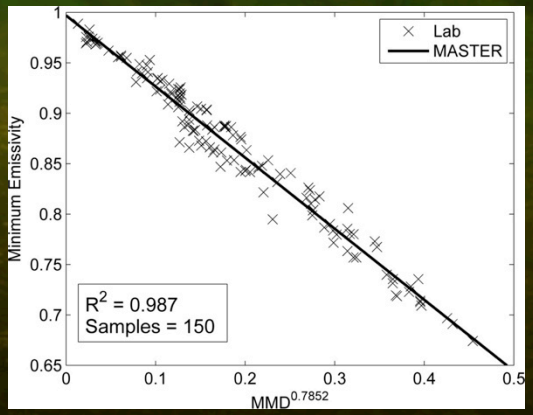
1. Split window approach

$$LST = a_0 + a_1 T_{11\mu m} + a_2 \left(T_{11\mu m} - T_{12\mu m}\right)$$

   - Prescribed spectral emissivity
   - Regression coefficients should represent all configurations (atmospheric water content, view angle, surface T_{air}, …)

2. Temperature-Emissivity Separation (TES) ← ECOSTRESS
   - Requires atmospheric profiles
   - Based on spectral emissivity contrast

TES Calibration Curve



TES vs Split-window Uncertainty Analysis

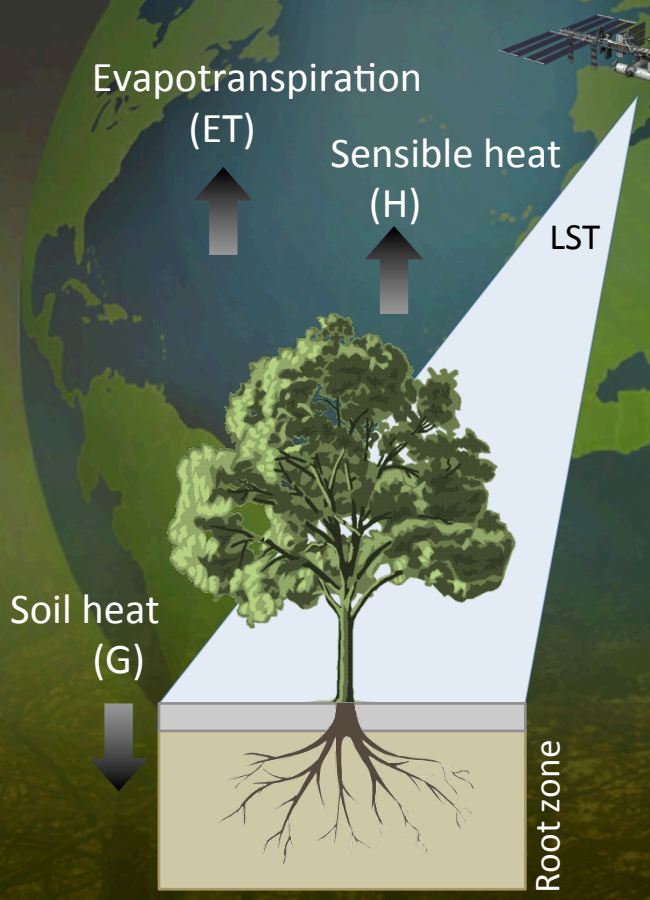
ECOSTRESS algorithm (5-bands)

			LST Uncertainty (K)		
Surface type	**Samples**	**Simulations**	**MOD21 (3-band TES) RMSE (Bias)**	**MOD11 (2-band Split-Window) RMSE (Bias)**	**VIIRS (2-band Split-Window) RMSE (Bias)**
Vegetation, Water, Ice, Snow	8	660,096	2.19 (0.66)	1.59 (-0.53)	1.77 (-0.97)
Rocks	48	3,960,576	1.44 (-0.73)	4.31 (-3.32)	4.29 (-3.69)
Soils	45	3,713,040	0.89 (0.09)	1.27 (-0.25)	1.81 (-1.43)
Sands	10	825,120	1.12 (-0.12)	2.38 (-1.79)	3.11 (-2.69)
Total	**111**	**9,158,832**	**1.49 (-0.24)**	**2.66 (-1.85)**	**2.93 (-2.49)**

TES has larger scatter over graybodies, but for all surface types TES has lowest RMSE compared to split-window approaches

ECOSTRESS approaches to mapping ET

Relationship between LST and ET



$$ET = R_n - H - G$$

with
- R_n the net radiation
- H the sensible heat flux
- G the soil heat flux

} LST dependent

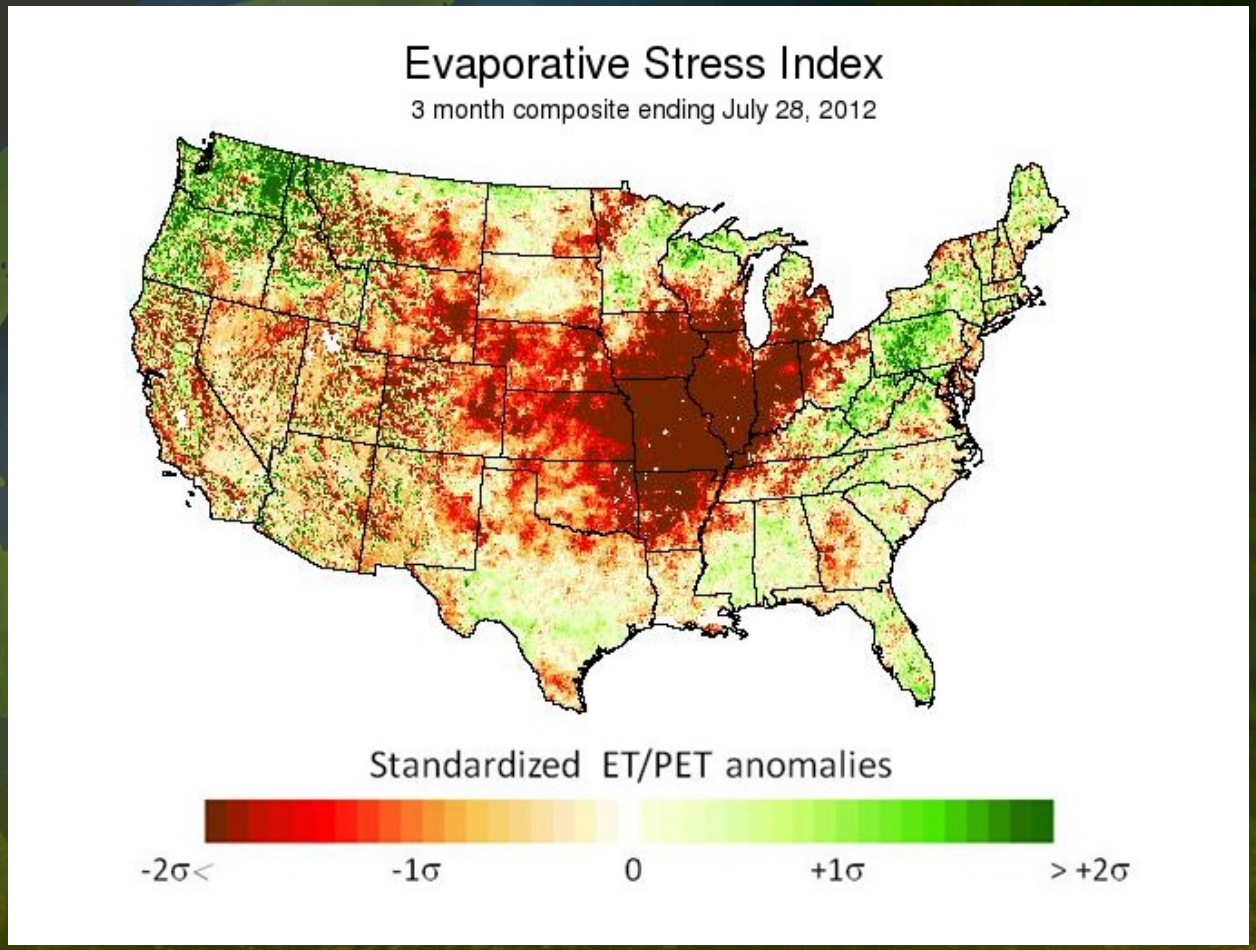
Energy balance approach:

Given known radiative energy inputs (R_n), how much water loss is required to keep the soil and vegetation at the observed temperatures?

Ensemble of ET models for ECOSTRESS:

- ALEXI from USDA (Two-source Energy balance)
- METRIC from U. of Idaho (In-scene approach)
- PT-JPL from JPL (Radiation based model)

ALEXI – Advantage and applications



The Evaporative Stress Index from ALEXI is part of the National Integrated Drought Information System (NIDIS)

Applications of ALEXI

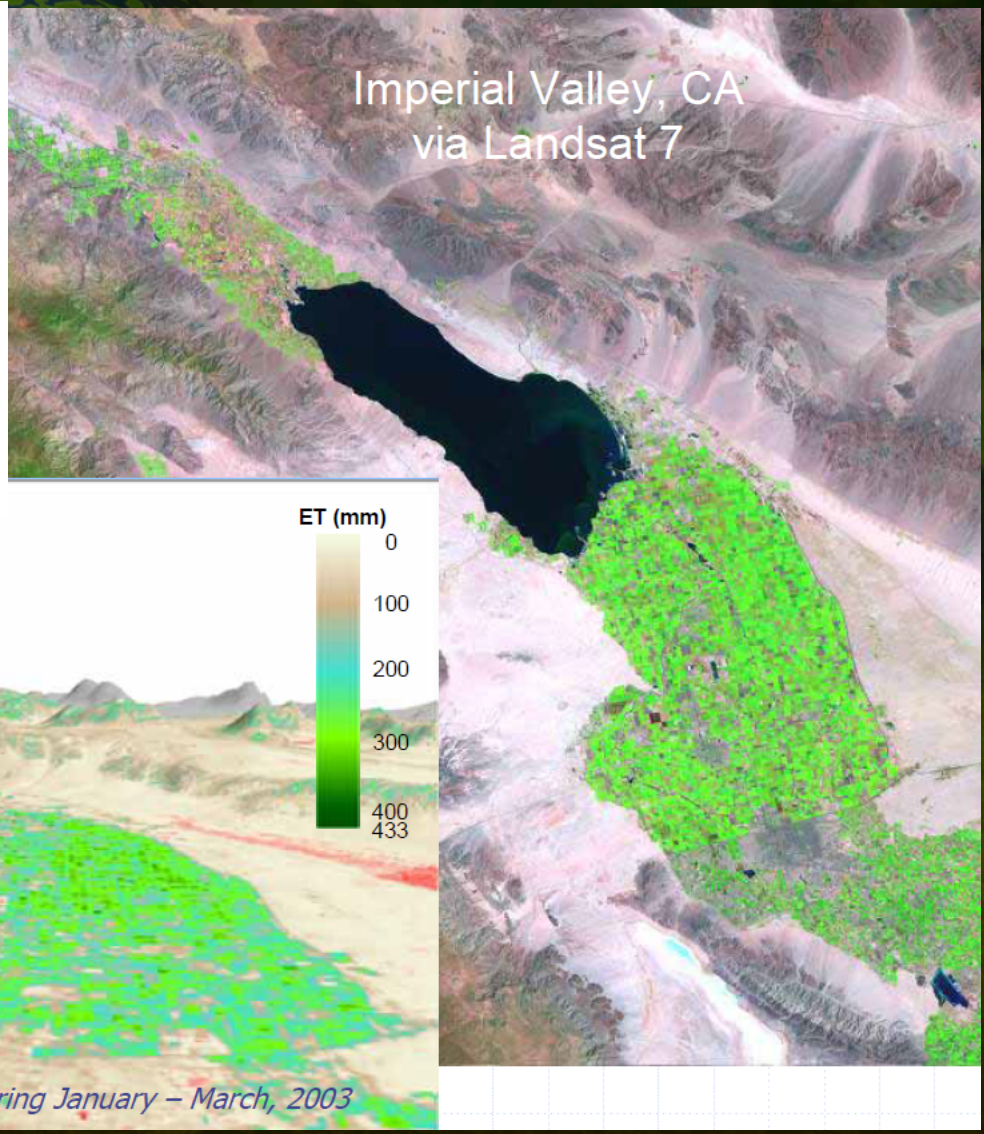
- Crop water use
- Crop phenology monitoring
- Drought early warning (water stress detection)

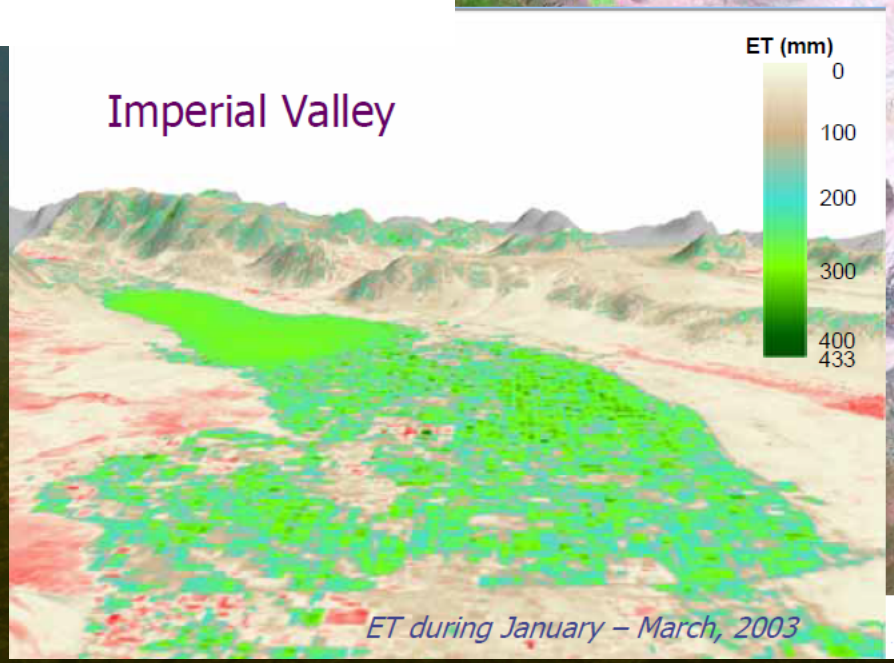
METRIC – Advantage and applications

Operational applications of METRIC in Idaho:

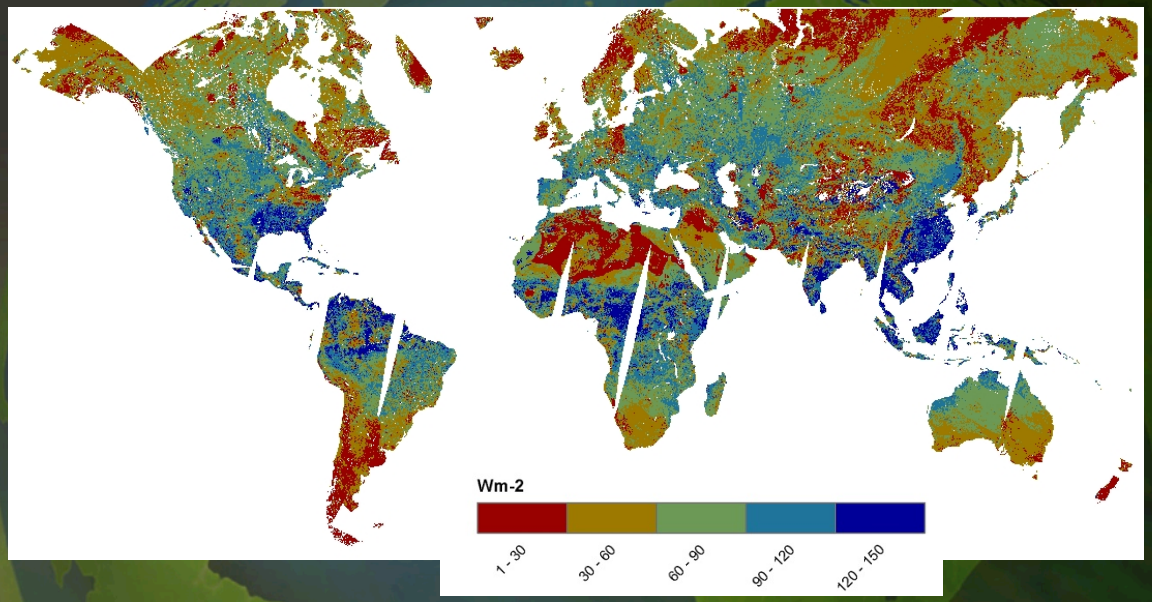
- Quantify net depletion from ground water pumping
- Compare actual ET with water right
- Calculate natural and irrigation-induced recharge to aquifers
- Monitor crop phenology

Dedicated for high resolution imagery, METRIC is used by more western states





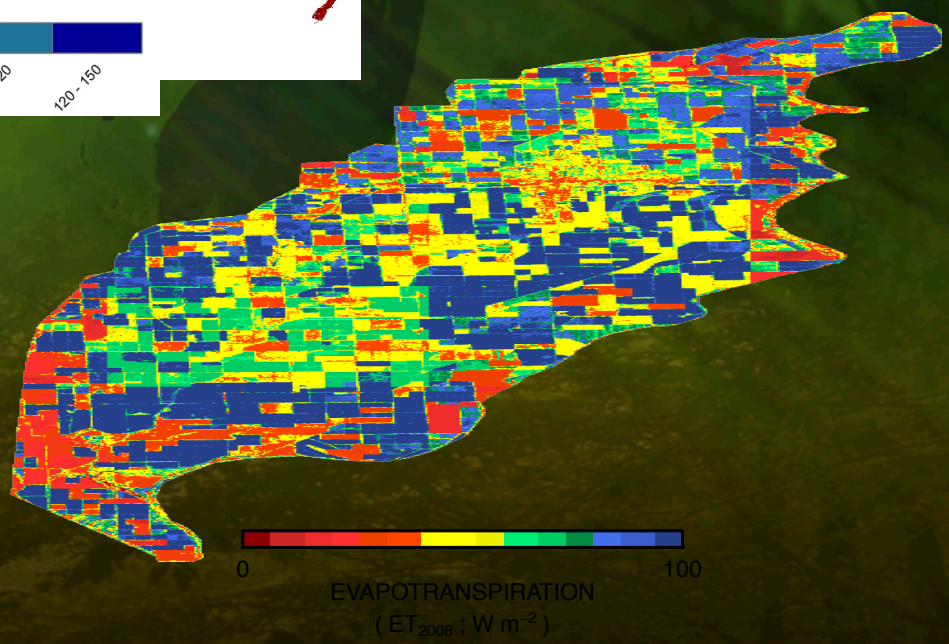
PT-JPL – Advantage and applications



PT-JPL is used to derive ET at various spatial resolutions:

- Global scale (MODIS)
- Field scale (Landsat)

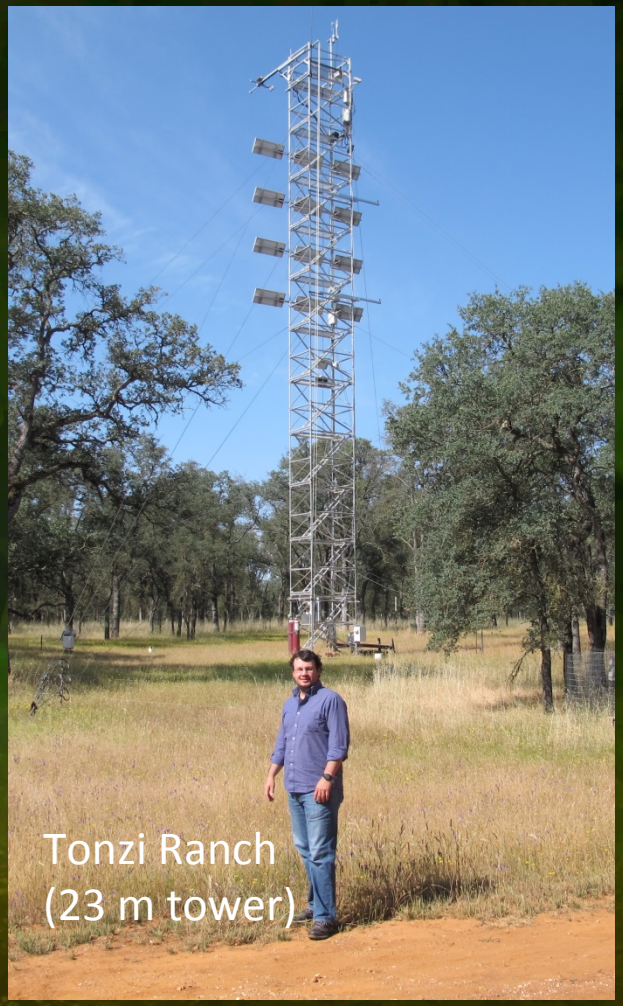
PT-JPL has shown the **best performance** in simulating daily to monthly ET average in recent model comparison studies



Calibration and Validation

- On-board blackbodies
- Vicarious calibration sites
- Validation sites (FLUXNET)

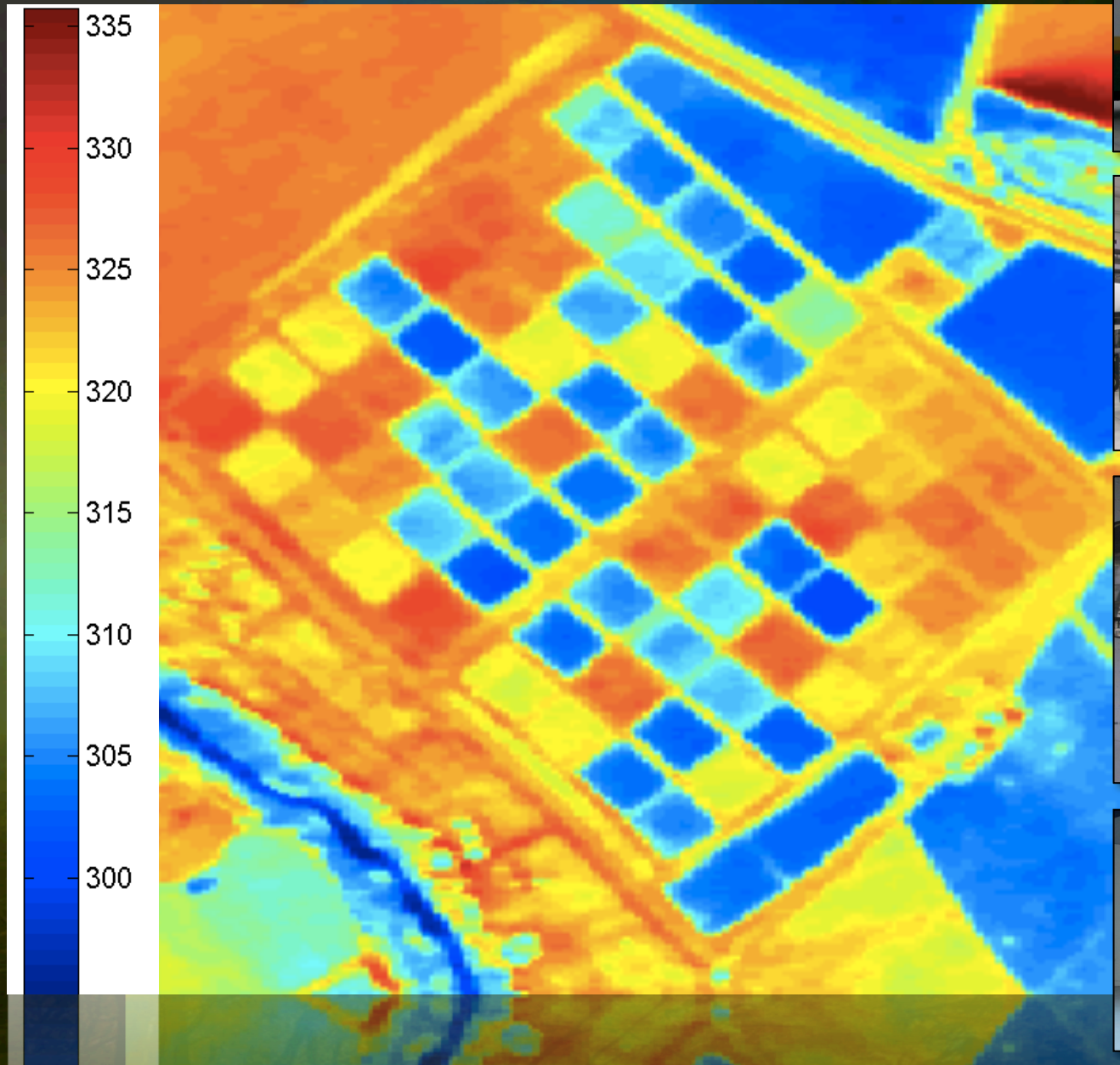
Lake Tahoe



HyTES: Hyperspectral Thermal Emission Spectrometer

JPL Airborne Capability

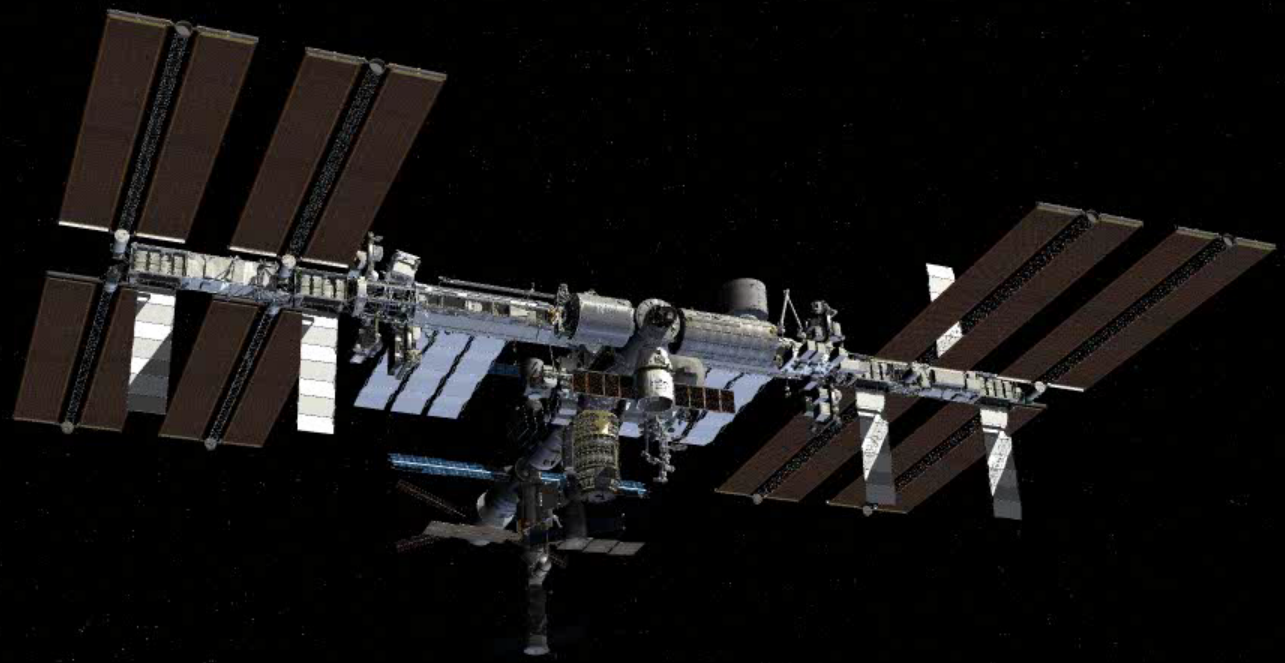
Image Acquisition: 9 JUL 2014



Take Home Messages

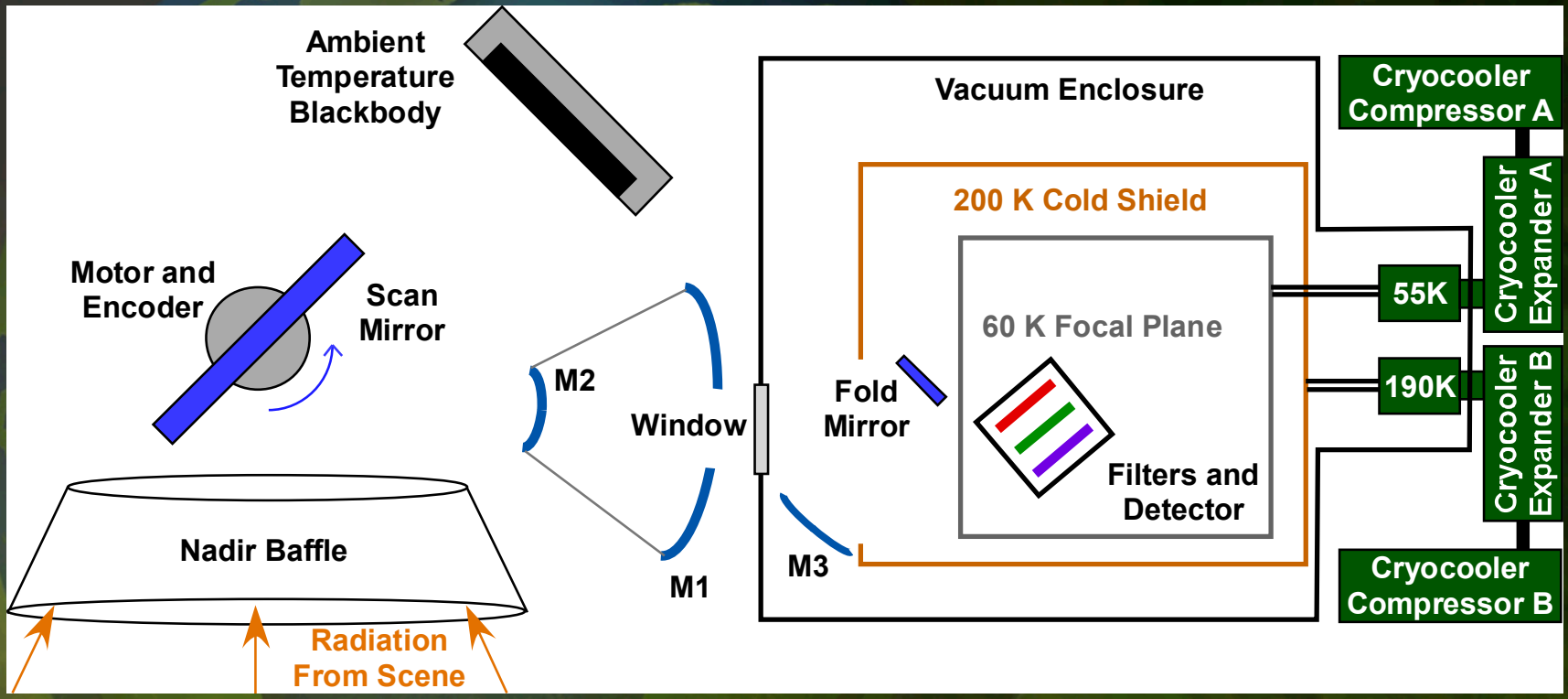
- ECOSTRESS measures whether plants have enough water to determine:
  - Will key ecosytems thrive, survive or transition?
  - How does plant water stress vary over the day?
  - Can drought estimation accuracy be improved by measuring agricultural water consumptive use
- ECOSTRESS capitalizes on the Preformulation work undertaken for the HyspIRI Mission including development of HyTES and PHyTIR instruments through the ESTO-IIP Program and ongoing development of HyTES through the Earth Science Research and Analysis Program

Movie Time




Backup

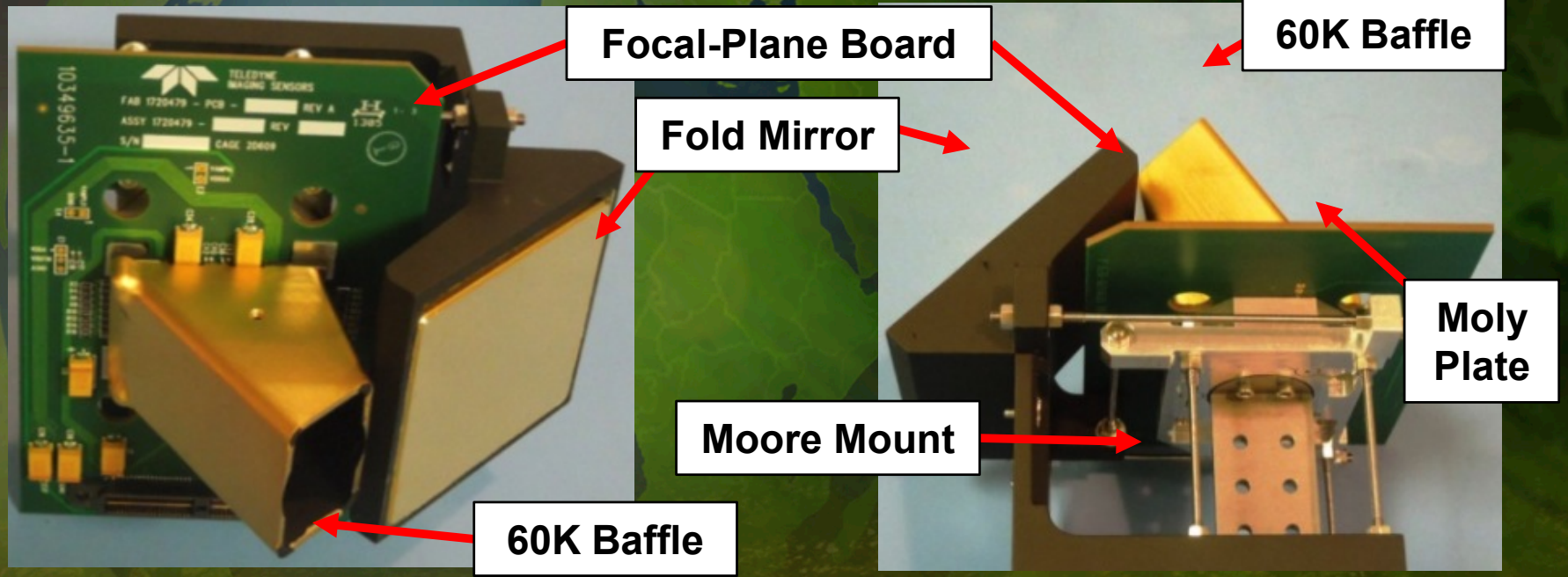
PHyTIR Block Diagram



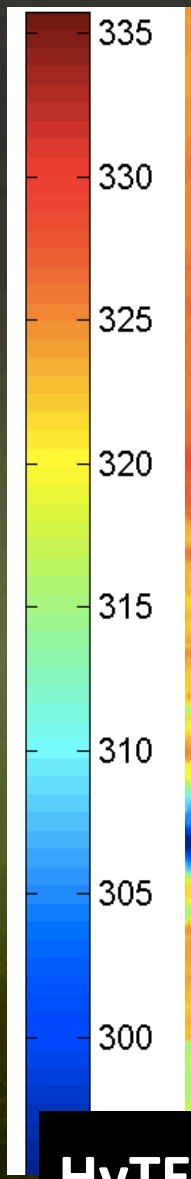
Key Differences from HyspIRI TIR Instrument

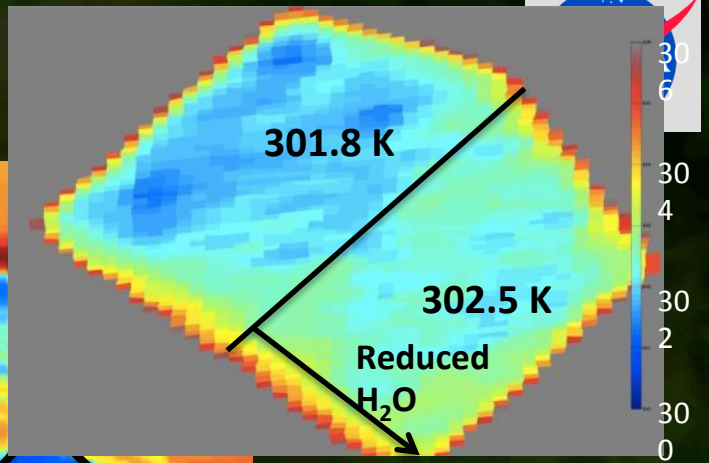
- Commercial cryocoolers used
- 3 representative spectral filters instead of 8
- Laboratory electronics used for control

PhyTIR Focal-Plane Assembly



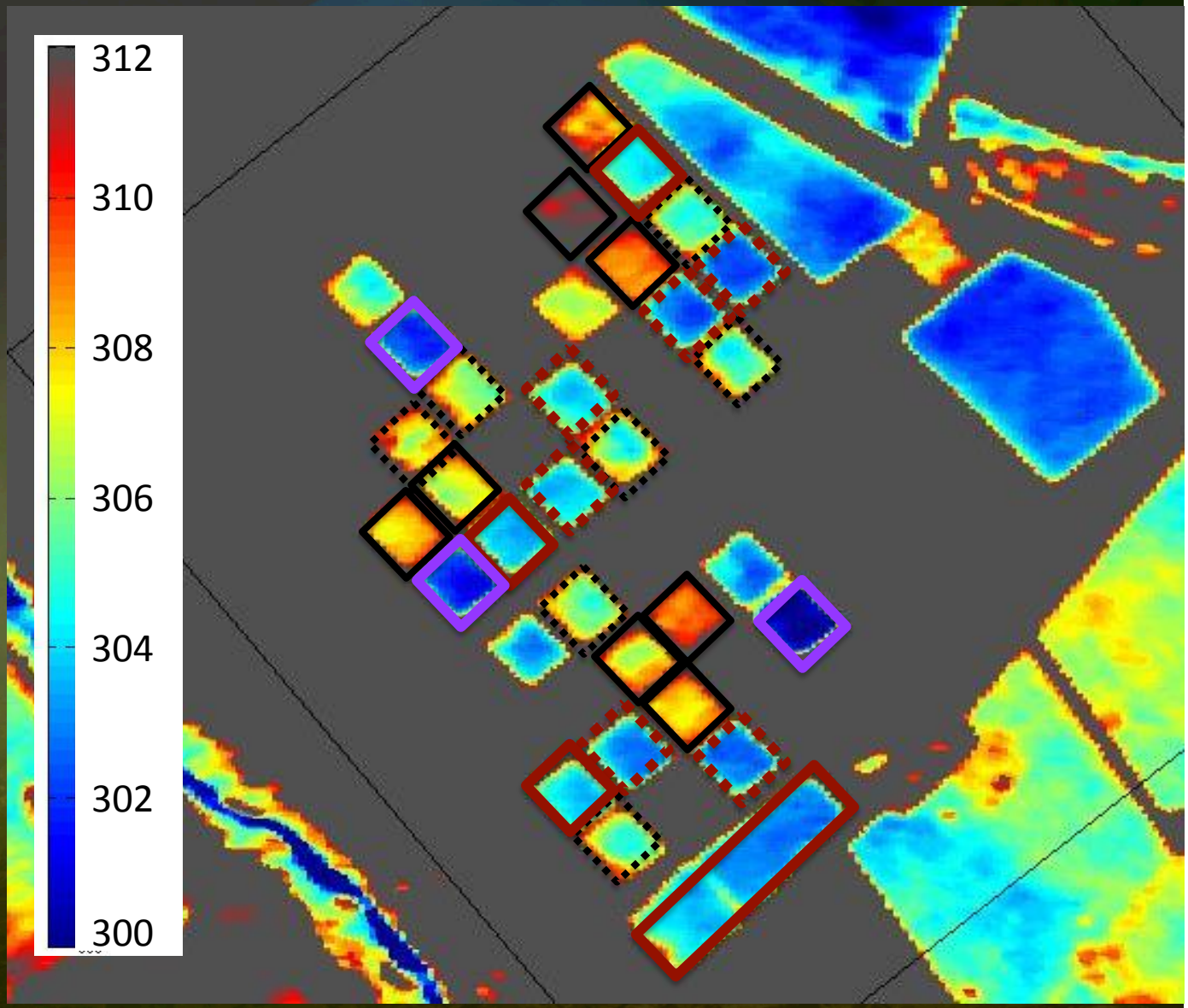
Using JPL Airborne Instruments for Precursor Studies:





HyTES Acquisition: July 9, 2014

HyTES Acquisition: July 9, 2014



Irrigated July 7-8:

Organic Tomato

→ **Mean LST = 309 K**

Conventional Tomato

→ **Mean LST = 306 K**

Irrigated July 2-3:

Organic Corn

→ **Mean LST = 304 K**

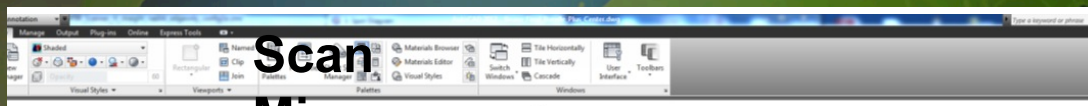
Conventional Corn

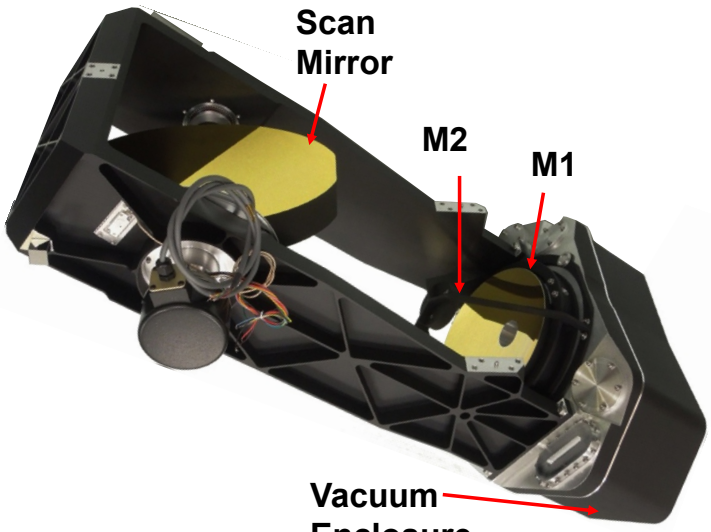
→ **Mean LST = 303 K**

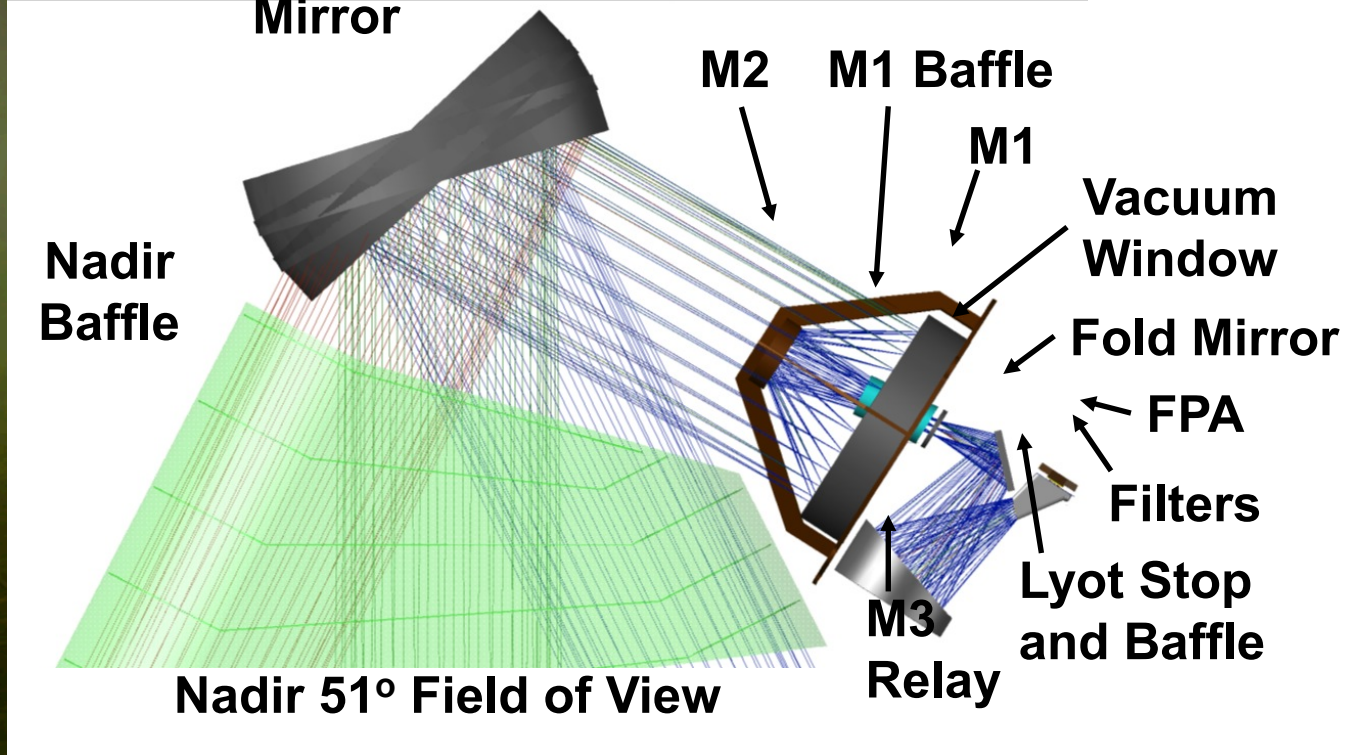
Alfalfa

→ **Mean LST = 301.5 K**

PHyTIR Optics







Focal Plane Readout Architecture