High Spatial Resolution Thermal Satellite Technologies

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Arizona State University
High Spatial Resolution Thermal Band

- **Problem**
  - No follow-on exists for Landsat 7 or ASTER high spatial resolution thermal systems
  - Can new technologies be implemented to allow for a low-cost, useful alternative?

- **Approach**
  - Investigate both traditional cooled cross-track scanners and new architectures (cooled and uncooled) that could enable a low-cost thermal capability
General Approach

- Perform Thermal Surveys
  - Science
  - Application

Set Requirements

Simulate Datasets

NO

Requirements Met?

YES

Industry or Government

Develop Sensor Model

Perform Design Trades

Define Constraints

NO

Requirements Met?

YES

Estimate Cost

Cost Benefit Analysis

POOR

GOOD

1st Order System Design

Sensor Specifications
What Has Been Done?

- Landsat 7 Science Team and others were asked for thermal system requirements:
  - Spectral
  - Temperature range
  - NEDT
  - Ground sample distance
  - Point spread function
  - Revisit time

- First order look at present systems and possible uncooled and cooled detector options
  - Standard pushbroom options
  - Backscanned systems
## Thermal Study

### Research or Area of Interest

<table>
<thead>
<tr>
<th>Field</th>
<th>Cloud Detection for LTAP</th>
<th>Monitoring Surface Energy and Water Fluxes 1</th>
<th>Monitoring Surface Energy and Water Fluxes</th>
<th>Monitoring Surface Energy and Water Fluxes</th>
<th>Material Transport in Aquatic Systems</th>
<th>Material Transport in Aquatic Systems 1</th>
<th>Agriculture Studies</th>
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<tr>
<td>NEDT (K)</td>
<td>0.5</td>
<td>-0.2</td>
<td>0.1</td>
<td>0.2 K</td>
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<td>Tmin (K)</td>
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<td>263</td>
<td>250</td>
<td>373</td>
<td>260</td>
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<td>310</td>
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<td>350</td>
<td>305</td>
<td>320</td>
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<td>1K(4%)</td>
<td>0.5</td>
<td>1 K Absolute</td>
<td>1 K Absolute</td>
<td>0.2 Absolute</td>
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<tr>
<td>GSD (m)</td>
<td>60 (ideal) 120 (acceptable)</td>
<td>~100</td>
<td>20</td>
<td>30m</td>
<td>~100</td>
<td>60</td>
<td>Canopy Heat Exchange1</td>
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<tr>
<td>PSF FWHM (m)</td>
<td>76 m</td>
<td>~100</td>
<td>40</td>
<td>30m</td>
<td>~100</td>
<td>ETM+</td>
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<tr>
<td>Revisit Time (days)</td>
<td>per image</td>
<td>~15</td>
<td>7 (&gt;14 um, 6 bands equally spaced)</td>
<td>weekly</td>
<td>~15</td>
<td>Hourly</td>
<td>Crop Health</td>
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<td>Spectral Band(s)</td>
<td>1-ok, 2 or more better</td>
<td>daynight pairs are very useful</td>
<td>10-11 microns</td>
<td>10-11 AM local time overpass</td>
<td>1-ok, 2 to improve ATM cat would be better</td>
<td>Vis/TIR Split Window for ATM</td>
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<tr>
<td>Other Requirements</td>
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<td>Source</td>
<td>GSFC</td>
<td>RIT</td>
<td>JPL</td>
<td>UW-Madison</td>
<td>RIT</td>
<td>Brown University</td>
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</table>

### Other Details

- **GSD Ground Sample Distance**
- **PSF FWHM Point Spread Function Full Width Half Maximum (system blur)**
- **Tmin, Tmax Temperature Range of Phenomena**
- **NEDT Temperature Sensitivity**

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## Thermal Study (cont.)

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<thead>
<tr>
<th>Research or Area of Interest</th>
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<th>Tmin (K)</th>
<th>Tmax (K)</th>
<th>Radiometric Accuracy (%)</th>
<th>GSD (m)</th>
<th>PSF FWHM (m)</th>
<th>Revisit Time (days)</th>
<th>Spectral Band(s)</th>
<th>Other Requirements</th>
<th>Source</th>
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<td>1</td>
<td>275</td>
<td>1500</td>
<td>5</td>
<td>15</td>
<td></td>
<td>8</td>
<td>8.1-8.4, 8.4-8.8 10.2-11</td>
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<td>Volcanology1</td>
<td>3</td>
<td>273K</td>
<td>373K</td>
<td>5%</td>
<td>1m</td>
<td>1.2m</td>
<td>1-1000</td>
<td>0.4-2.5um: 5 bands; 3-5um: 2 bands; 8-12um: 5 bands</td>
<td>Predawn observations are highly desirable for thermal bands</td>
<td>JPL</td>
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<tr>
<td>Low temperature thermal mapping (&lt;100degC)</td>
<td>0.6</td>
<td>273K</td>
<td>373K</td>
<td>1%</td>
<td>1m</td>
<td>1.2m</td>
<td>1-1000</td>
<td>3-5: 2 bands; 8-12: 5 bands</td>
<td>Predawn observations are highly desirable for thermal bands</td>
<td>JPL</td>
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<tr>
<td>Moderate temperature thermal mapping (100-800degC)</td>
<td>5</td>
<td>373K</td>
<td>1073K</td>
<td>5%</td>
<td>3m</td>
<td>3.6m</td>
<td>1-10</td>
<td>3-5: 2 bands</td>
<td>Night observations highly desirable</td>
<td>JPL</td>
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<td>10</td>
<td>1073</td>
<td>1573</td>
<td>10%</td>
<td>10m</td>
<td>12m</td>
<td>1-3</td>
<td>1-2.5: 3 bands; 3-5: 2 bands</td>
<td>Night observations highly desirable</td>
<td>JPL</td>
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<td>Ash plume detection/discrimination/tracking</td>
<td>0.1</td>
<td>190K</td>
<td>273K</td>
<td>&lt;1%</td>
<td>300m</td>
<td>360m</td>
<td>1-3</td>
<td>3-5: 2 bands; 7-14: 10 bands</td>
<td>Day/night observations</td>
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<td>773K</td>
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<td>120m</td>
<td>1-3</td>
<td>3-5: 2 bands; 7-14: 10 bands</td>
<td>Day/night observations</td>
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<td>773K</td>
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<td>100m</td>
<td>120m</td>
<td>1-3</td>
<td>3-5: 2 bands; 7-14: 10 bands</td>
<td>Day/night observations</td>
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<td>Urban Heat Islands</td>
<td>0.3</td>
<td>275</td>
<td>325</td>
<td>2%</td>
<td>5</td>
<td></td>
<td>8</td>
<td>8.1-8.4,10.2-11</td>
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<td>JPL</td>
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<td>Land Cover / Land Use</td>
<td>0.3-0.5</td>
<td>265</td>
<td>340</td>
<td>±1</td>
<td>60-90</td>
<td>100-150</td>
<td>16 ≤</td>
<td>Current ETM+ Band 6</td>
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<td>JPL</td>
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<td>Land Cover / Land Use 1</td>
<td>0.5</td>
<td>250</td>
<td>340</td>
<td>0.5 K</td>
<td>60m</td>
<td>ETM+</td>
<td>Seasonal</td>
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<td>Geological Mapping</td>
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<td>275</td>
<td>375</td>
<td>2</td>
<td>15</td>
<td></td>
<td>16</td>
<td>5-6 bands</td>
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<td>JPL</td>
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<tr>
<td>Urban Land Use</td>
<td>0.5</td>
<td>273</td>
<td>320</td>
<td>1k</td>
<td>~100</td>
<td>~100</td>
<td>~15</td>
<td>1-0K, 2-better</td>
<td></td>
<td>RIT</td>
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</tbody>
</table>

**Legend:**
- **GSD:** Ground Sample Distance
- **PSF FWHM:** Point Spread Function Full Width Half Maximum (system blur)
- **Tmin, Tmax:** Temperature Range of Phenomena
- **NEDT:** Temperature Sensitivity
• Many Landsat thermal applications will work with >60 meter GSD data
• Wide range of requirements indicates that more work is necessary to define them better
• This workshop should help provide such definition
Traditional TIR Architectures

- Cross-track scanning systems
- Cooled either actively or passively
- Small number of HgCdTe detectors
- Typically large GSD; Landsat is the smallest of the cross-track scanning systems at 60 m
- Telescope diameter typically driven by SNR considerations and not diffraction
- Most systems are multispectral
## Existing TIR Systems

--- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | ---
Landsat 7 | ETM+ | Cross-track scanner | 6 | 10.4 - 12.5 | HgCdTe | 40 | 60 | 0.3 | 185 | 8 of 9 |
Terra | ASTER | Cross-track scanner | 10 | 8.125 - 8.475 | HgCdTe | 24 | 90 | 0.35 | 60 | 12 | 0.2 |
 | 11 | 8.475 - 8.825 | 
 | 12 | 8.925 - 9.275 | 
 | 13 | 10.25 - 10.95 | 
 | 14 | 10.95 - 11.65 | 
NOAA | AVHRR | Cross-track scanner | 4 | 10.3 - 11.3 | HgCdTe | 20 | 1100 | 0.3 | 2800 | 10 | 0.12 |
 | 5 | 11.5 - 12.5 | 
Terra | MODIS | Cross-track scanner | 27 | 6.535 - 6.895 | HgCdTe | 18 | 1000 | 0.35 | 2330 | 12 | 0.25 |
 | 28 | 7.175 - 7.475 | 
 | 29 | 8.400 - 8.700 | 
 | 30 | 9.580 - 9.880 | 
 | 31 | 10.780 - 11.280 | 
 | 32 | 11.770 - 12.270 | 
 | 33 | 13.185 - 13.485 | 
 | 34 | 13.485 - 13.785 | 
 | 35 | 13.785 - 14.085 | 
 | 36 | 14.085 - 14.385 | 
MTI | MTI | Pushbroom | L | 8.00 - 8.40 | HgCdTe | 36 | 20 | 
 | M | 8.40 - 8.85 | 
 | N | 10.20 - 10.70 | 
ERSI-2 | ATSR-2 | Conical scanner | 1 | 11.5 - 12.3 | 
 | 2 | 10.6 - 11.3 |
Uncooled Pushbroom Pathfinding Thermal Instruments

- Thermal Emission Imaging System IR Sensor (THEMIS)
  - Flown on Mars Orbiter launched April 2001 to map Martian surface mineralogy
  - Uncooled Raytheon microbolometer array (320x240 50 µm pitch pixels)
    - Pushbroom imager with precision-aligned stripe filter
    - 9 bands between 6.2 and 15.5 µm
    - f/1.6 optics
    - 4.4 degree FOV
    - 12.9 cm aperture
    - 30 Hz readout
    - 100 m GSD
  - ~ $12M for instrument
New Thermal Architectures

- Pushbroom systems and framing cameras can provide significant sensitivity advantages over cross-track scanners
- \[ \text{SNR} \sim (\text{no. of detectors})^{0.5} \]
- Benefits of increased integration time associated with pushbroom systems and framing cameras:
  - Higher SNR
  - Smaller GSD
  - Potential use of uncooled detectors
Infrared Detector Types

- Cooled detectors
  - Photovoltaic or photoconducting mechanisms; HgCdTe and GaAs quantum well devices
  - High framing rates and low noise
- Uncooled detectors
  - Rely on a thermal response: bolometric, pyroelectric, and thermionic devices
  - Have slow framing rates and are relatively insensitive
  - Lighter and smaller system packaging possible
Uncooled Framing Camera/Pushbroom Pathfinding Thermal Instruments

- Infrared Spectral Imaging Radiometer (ISIR)
  - Flown on space shuttle mission STS-85 in August 1997 as part of a cloud science experiment
  - Uncooled Lockheed Martin microbolometer array (327x240 pixels)
    - Framing imager with filter wheel
    - 3 narrow bands at 8.55, 10.8, and 11.8 μm
    - 1 broad band at 7-13 μm
    - 250 m GSD
    - 85 km swath from shuttle altitude
    - f-number 0.73, lens diameter 50 mm
    - NEDT 0.01-0.06 °K at all wavelengths with TDIx40 for a 300 °K scene temperature
    - Ambient and cold inflight calibration capability
Uncooled Framing Camera/Pushbroom
Pathfinding Thermal Instruments (cont.)

- Extremely good quality imagery was obtained for each band
- Accuracy goal was met to within a factor of 2 or 3
  - Pre-production prototype detector used
Potential New Configurations

- Cooled detectors
  - Advanced Land Imager (ALI) pushbroom architecture (common telescope for all bands)
    - Multispectral Thermal Imager (MTI)

- Uncooled detectors
  - ALI pushbroom architecture (common telescope for all bands)
  - Custom TIR system separate from ALI
    - Framing camera and filter wheel (ISIR)
    - Pushbroom multispectral system (THEMIS)
Uncooled Thermal Detector Characteristics

- Primarily developed for military systems: f/1 optics, 30-60 Hz framing rates
- Microbolometers
  - Silicon micro-machined devices provide excellent thermal isolation from substrate
  - Highest sensitivity demonstrated: f/1 optics, 30-60 Hz framing rate, NEDT ~ 20 mK
- Pyroelectric
  - Older technology: f/1 optics, 30 Hz framing rate, NEDT ~ 100 mK
  - Requires a chopper
- Emerging technologies: Thermionic, SAW Oscillators, Capacitive
Silicon Microbolometers

- Black absorber with a broadband response (atmospheric window 8-14 microns) thermistor
- Typical FPA
  - 320x240 pixels with 50 μm pitch
  - 640x480 pixels with 25 μm pitch
  - Very high fill factor >90%
  - Thermal time constant ~10 ms

Spatial Resolution Drivers

- **Fundamental**
  - Orbit altitude (the lower the better)
  - Telescope diameter
  - NEDT

- **Engineering**
  - Detector size
  - Focal lengths
  - Framing rates
  - Data rates and storage
Thermal GSD Trades

- GSD usually set approximately to FWHM of PSF
- Two sensor characteristics drive PSF:
  - Framing rate
    - Smear is defined as how far a pixel moves in an integration time
    - Typically GSD ~ Orbital Velocity / Frame Rate
  - Telescope diameter
    - Ground spot size for a diffraction limited system is controlled by Airy Diffraction Pattern
    - Ground spot size ~ 2.44 Wavelength*Range/Telescope Diameter
Frame Rate Trades for Landsat Orbit

Framing Rate (Hz) | Smear (m)  
----------------|-----------
30.00          | 250.1     
35.00          | 214.3     
40.00          | 187.5     
45.00          | 166.7     
50.00          | 150.0     
55.00          | 136.4     
60.00          | 125.0     
65.00          | 115.4     
70.00          | 107.2     
75.00          | 100.0     
80.00          | 93.8      
85.00          | 88.3      
90.00          | 83.4      
95.00          | 79.0      
100.00         | 75.0      
105.00         | 71.4      
110.00         | 68.2      
115.00         | 65.2      
120.00         | 62.5      
125.00         | 60.0      
130.00         | 57.7      

60 Hz framing rate limits GSD to 125 meters
Telescope Diameter Trades

Diffraction limited resolution \((\text{Rayleigh criteria})\)

\[
\text{Ground Spot Size} = 2.44 \lambda \text{ Range/Diameter}
\]

\(\lambda = 11.5 \ \mu\text{m}\)

- **ALI**
  - 157 m Ground Spot Size
  - 12.5 cm Telescope Diameter

- **ETM+**
  - 50 m Ground Spot Size
  - 40 cm Telescope Diameter

- 120 m Ground Spot Size
  - 16.4 cm Telescope Diameter
Detector Time Constant Limits

Detector Thermal Time Constant 10 ms

7.5 km/sec produces a 75 m 1/e exponential response
Thermal Time Constant & Spatial Resolution

Detector Thermal Time Constant 10 ms

Spatial width m

Ground Speed km/sec

Stennis Space Center
Custom Thermal Infrared Sensor (Point Design)

- F-number 1.8
  - A little fast but probably achievable (THEMIS f-number 1.6)
  - NEDT for Landsat Band 300 K Background

- NEDT of a single detector ~ 0.3 K with a TDI of 1; TDI of 25 could produce a 0.06 k NEDT system!!!!
Custom Thermal Infrared Sensor (Point Design) (cont.)

- Detector spot size 50.5 μm at λ = 11.5 μm
  - ~1542 detectors at 50 μm pitch for 185 km swath with 120 m GSD
  - ~Five 320x240 FPAs
  - Many detectors available for other bands
  - ASTER-like instrument
  - Oversampling: use 25 μm pitch detectors and oversample PSF
Possible FPA Configuration

Double bank of uncooled microbolometer detector arrays

Spacecraft Direction

5,000 50 μm pitch detectors or 10,000 25 μm pitch detectors

320x240 or 640x480 detector FPA
Backscanning System

- Trade off coverage for GSD by backscanning the system
  - Used by 1 m class GSD commercial systems such as IKONOS and QuickBird
  - Cutting the ground speed down by a factor of 2 or more produces dramatic results
  - Improved NEDT for a fixed GSD
- 30 m GSD or better system possible with backscanning, creating a high system with MTI-like performance without cooled detectors
Simulation

- Landsat 7 thermal imagery was synthesized from ATLAS 10-meter imagery
- Microbolometer-simulated imagery was produced with several parameters varied
LDCM Thermal Trade Simulation

Microbolometer 30 m detector; 60 m PSF; 125 m smear; 0.3 K NEDT; decimation (3x3). Final product: 30 m GSD.
LDCM Thermal Trade Simulation

Landsat 7 60 m detector; 60 m PSF; NEDT 0.22 K; decimation (6x6). Final product: 60 m GSD.
LDCM Thermal Trade Simulation

Microbolometer 60 m detector; 120 m PSF; 125 m smear; NEDT 0.30 K; LPF (2x2); decimation (6x6). Final product: 60 m GSD.
Microbolometer 60 m detector; 120 m PSF; 125 m smear; no noise; LPF (2x2); decimation (6x6). Final product: 60 m GSD.
LDCM Thermal Trade Simulation

Microbolometer 30 m detector; 60 m PSF; 125 m smear; no noise; decimation (3x3). Final product: 30 m GSD.
Summary

- Conventional microbolometer pushbroom mode offers potential for low-cost LDCM thermal or ASTER capability with at least a 60-120 meter GSD
- Backscanning could produce MTI-like performance without cooled detectors
- Cooled detectors could produce hyperspectral thermal class system or extremely high spatial resolution class instrument
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