Utility of Thermal-Infrared Spectral Imaging for Assessment of Environmental Hazards in Post-Disaster Scenarios

David M. Tratt, Kerry N. Buckland, and George J. Scherer
Imaging Spectroscopy Department
Space Science Applications Laboratory
The Aerospace Corporation

International Workshop on Small Satellite and Sensor Technology for Disaster Management (SSTDM)
Bangalore, India; March 31 – April 2, 2014

Background

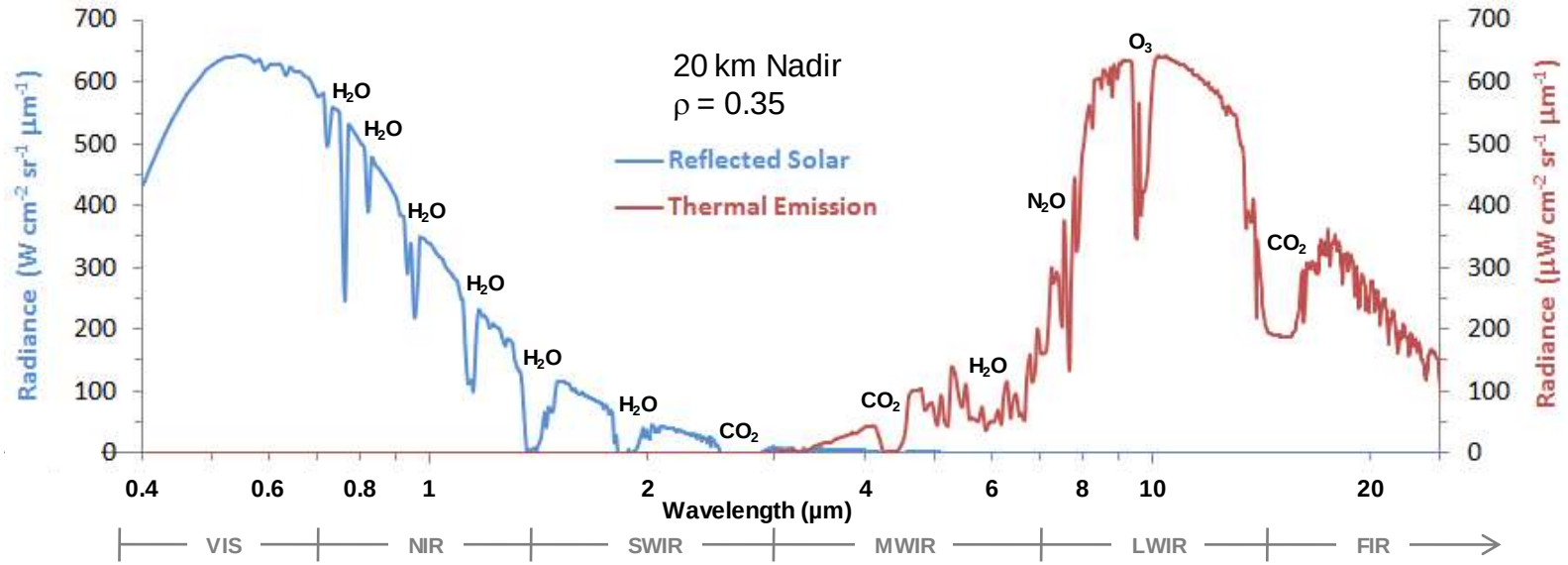
- Airborne hyperspectral thermal-infrared (TIR) imaging is a powerful technique for detecting, identifying, and tracking/sourcing gaseous emissions from compact sources
- Hyperspectral resolution enables full characterization of the thermal radiance distribution and enables detection / identification of gases and solids within the scene
  - *Atmospheric Compensation*
  - *Spectral Matched Filter (SMF) or Adaptive Coherence Estimation (ACE)*
  - *Stepwise (forward) Generalized Least Squares (whitened space)*
- The Aerospace Corporation ("Aerospace") has been an advocate of airborne hyperspectral TIR imaging for more than two decades
- Aerospace maintains an end-to-end capability beginning with sensor system concepts and design and progressing to algorithm development and testing for data processing operations
- Aerospace's airborne TIR HSI sensors have completed >200 field deployments and data collections in the last 15 years, including for significant U.S. disasters

***World Trade Center attack (2001)*:** Debris footprint mapping and hazardous emissions assessment

***Gulf of Mexico oil spill (2010)*:** Coastal wetlands environmental baseline prior to arrival of oil slick

AEROSPACE

Reflective / Emissive Properties

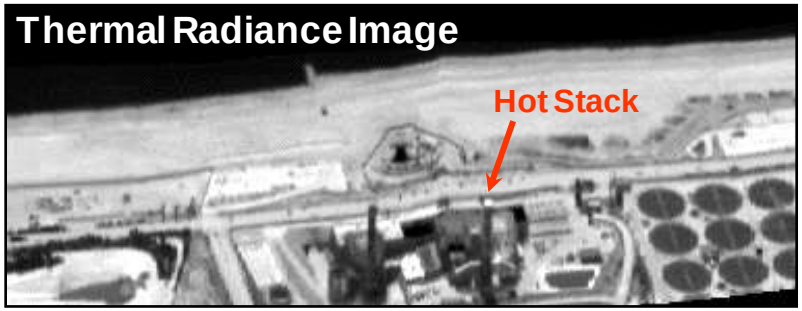


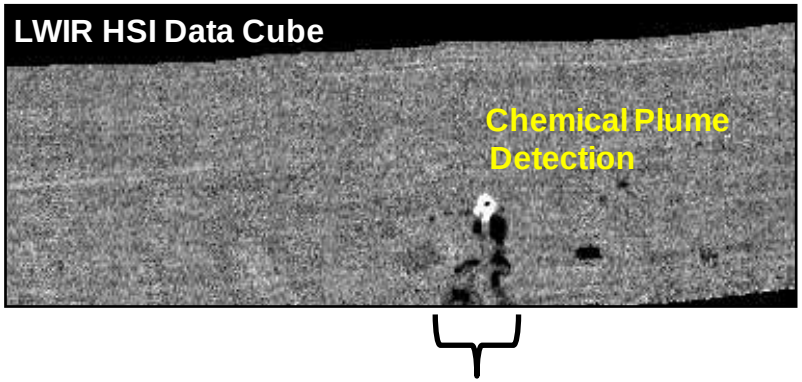
	VIS – NIR – SWIR	MWIR	LWIR
Physics	Reflected Sunlight Daytime operations only Sensor signal depends on surface reflectivity and angle between surface, sun and sensor	Reflected Sunlight / Direct Thermal Emission Day / Night operations Sensor signal depends on surface reflectivity and angle between surface, sun and sensor as well as surface temperature and emissivity	Direct Thermal Emission Day / Night operations Sensor signal depends on surface temperature and emissivity
Observables	Minerals (non-silicate) Surface Materials Vegetation (“red edge”)	Gas (Identification / Quantification) Minerals (silicates / non-silicates) Surface Materials Precision Thermometry	Gas (Identification / Quantification) Minerals (silicates / non-silicates) Surface Materials Precision Thermometry

AEROSPACE

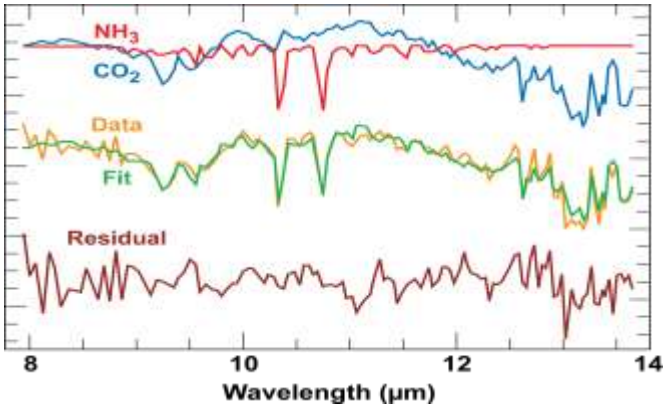
Increasing Information Content

Visible Image → Thermal Image → LWIR HSI Data





Chemical Plume Identification

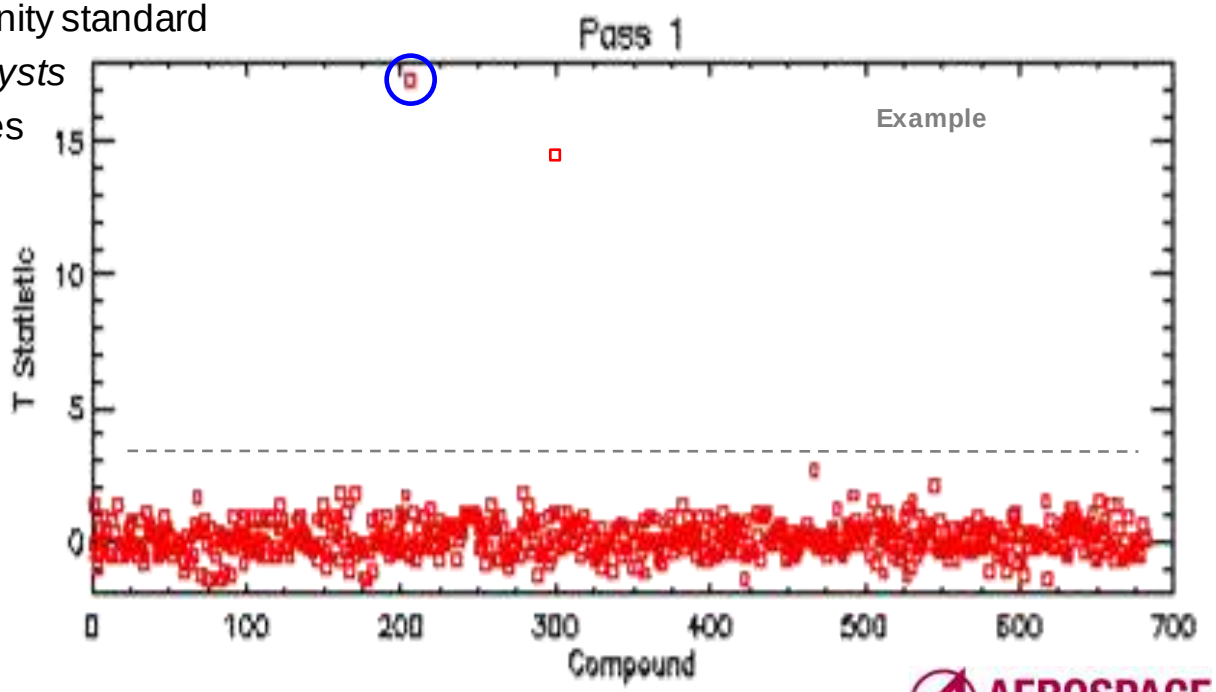


The 7 – 14μm spectral region is commonly referred to as the "molecular fingerprint" region and enables high levels of information extraction.

AEROSPACE

Chemical Identification

- Stepwise GLS (Generalized Least-Squares) regression
  - *Spectral fits done in "whitened space" using scene Covariance Matrix*
  - *Sequentially search all spectral library signatures to determine optimum fit*
    - ~700 gases
    - ~4000 solid/liquid materials
    - Perform t-stat test to assess retrieval quality against user-defined threshold
    - Repeat until noise floor reached
  - *Proven algorithm in multiple field tests*
    - Rigorously tested against ground-truth
    - Now an accepted community standard
  - *Effectively used by most analysts*
    - Implementation differences

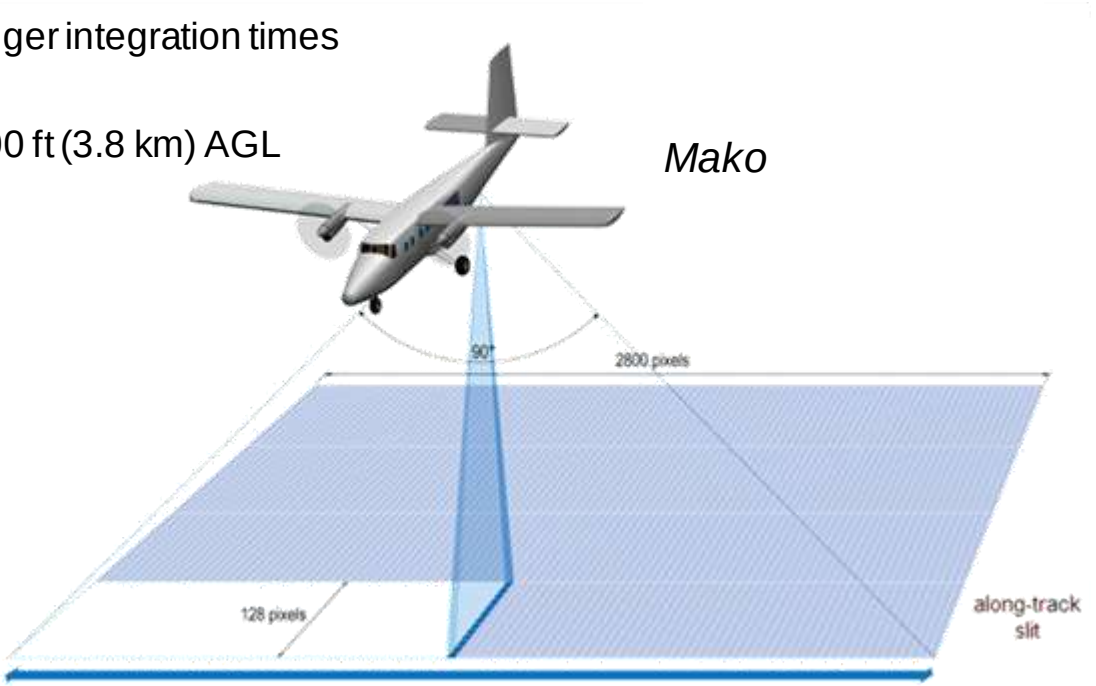


AEROSPACE

Airborne TIR HSI Sensors

- Much foundational work conducted with SEBASS pushbroom imager in the two decades of its existence
- *Mako* whiskbroom scanning imager designed to extend capability forward from previous instruments designed and built by The Aerospace Corporation
  - *Inaugural flights in 2010*
  - *Innovative spectrometer design (f/1.25 Dyson) results in 20x light-gathering power of earlier sensors*
  - *High Sensitivity Mode*
    - Noise reduction achieved using longer integration times
  - *Large Area Coverage Mode*
    - 20 km^2 min^{-1} (2-m GSD) from 12500 ft (3.8 km) AGL
    - ***Enables broad-area surveying***

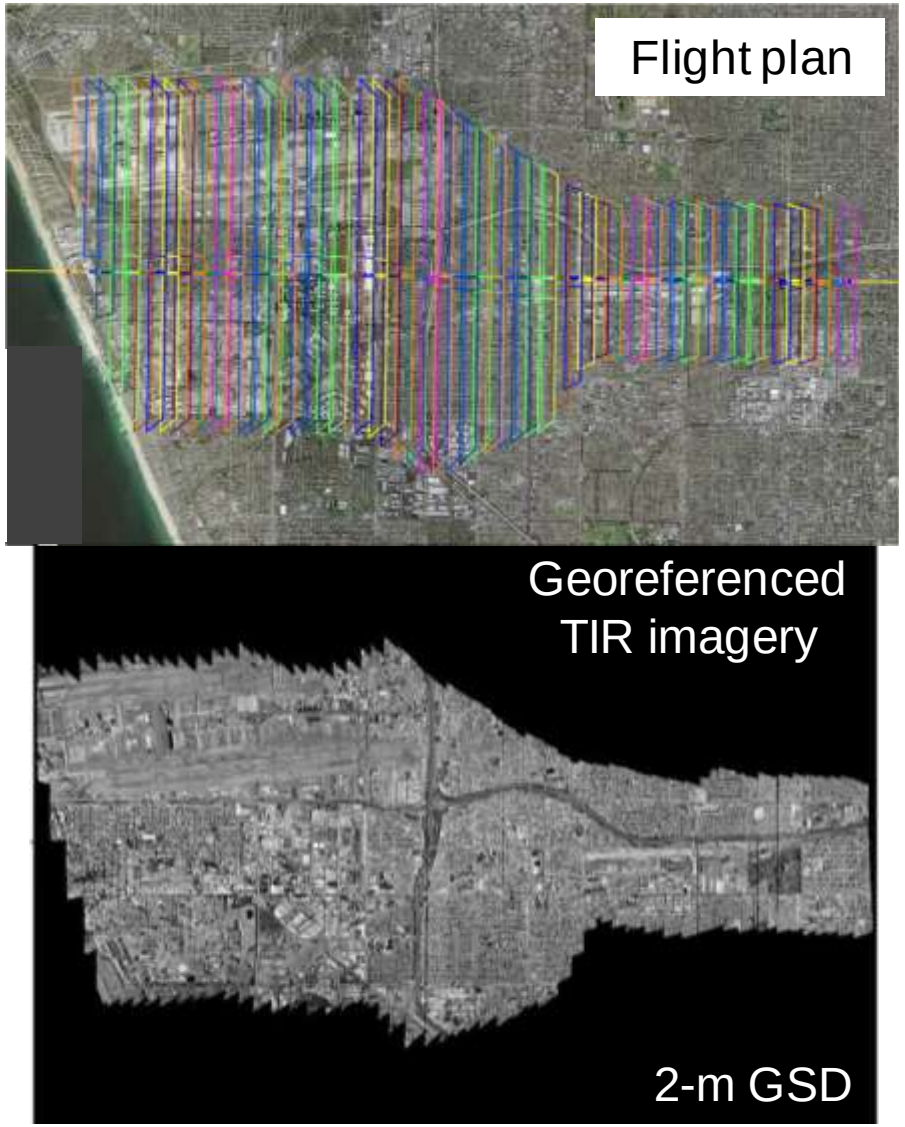
Parameter	*Mako*	SEBASS
Spectral Range (μm)	7.6 – 13.2	7.5 – 13.5; 2.6 – 5.4
Spectral Channels	128	128; 128
Spectral Res'n (nm)	44	47; 22
NESR (μflick)	0.7	0.6; 0.6
Swath Width (pixels)	400 – 2750	128
IFOV (mrad)	0.55	1.1



Versatile Flight Planning System

- An integrated scanning and flight planning tool provides *Mako* with the flexibility to acquire arbitrary polygons such as the 13-km long example at right, which was flown over Los Angeles.

- The flight planning tool also enables multiple sequential looks at an area on the ground during overflight, an example of which is provided by the next chart.

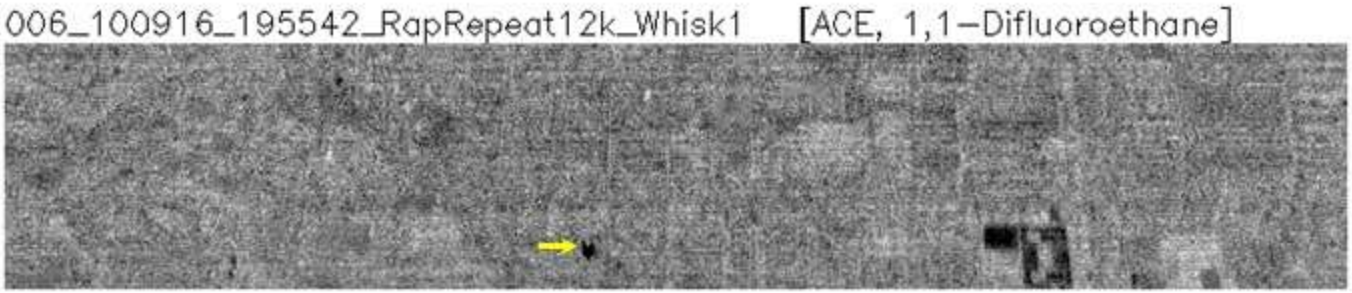


Real-Time Plume Dispersal Tracking

Thermal image

Altitude: 12 kft (3.8 km) AGL (GSD 2 m); 1-sec frame-rate

200 m

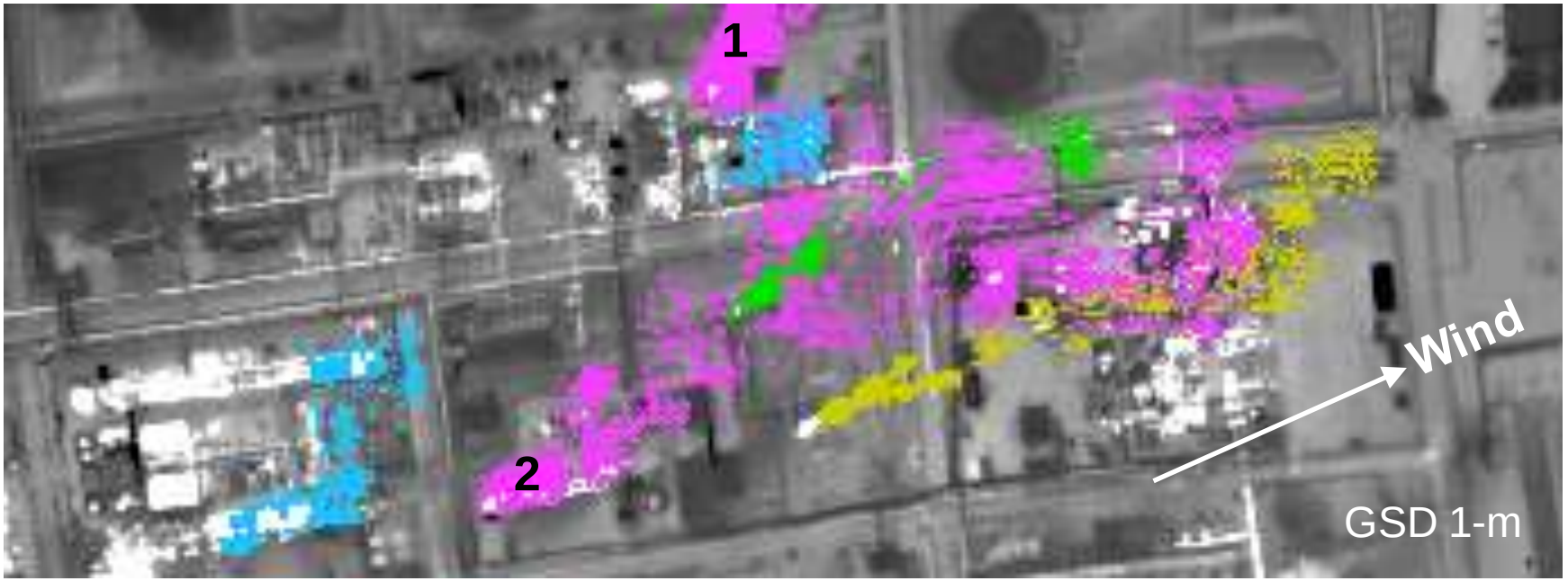


ACE filter

Continuous tracking of controlled tracer release

AEROSPACE

Fugitive Emissions from Oil Refineries



Ammonia Sulfur Dioxide Ethene Methane

- Montage of multiple gas detections at an oil refinery.
- Two ammonia sources (1, 2) appear in the imagery.
- The methane detection near the source of ammonia plume 1 is a far downwind patch from the stack at the lower left.

AEROSPACE

MAKO LWIR HSI - Ammonia Filter Detections
Long Beach, CA - Aug. 24, 2011

Broad-Area Urban Survey

Thresholded ACE Filter Detections

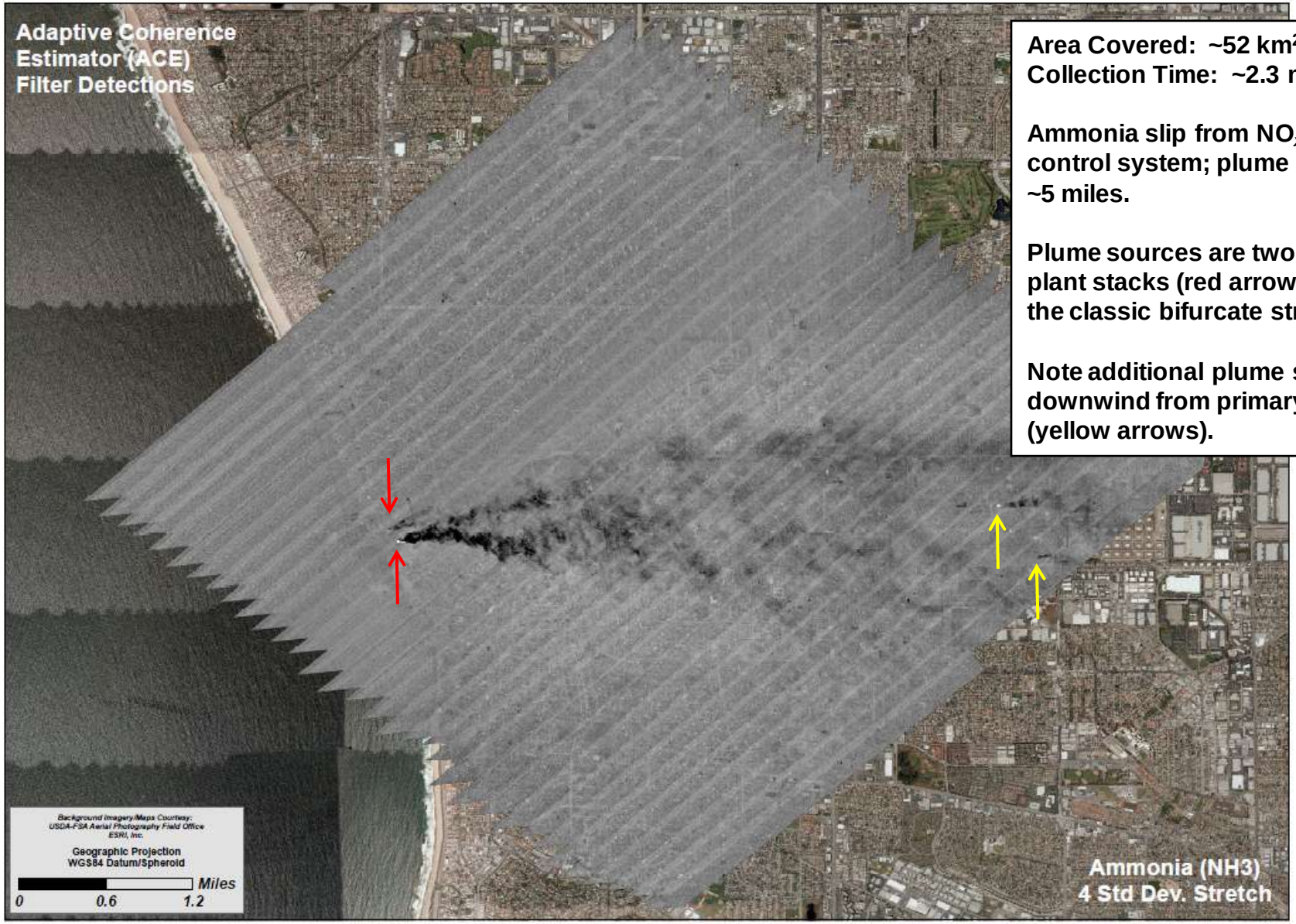
MAKO Overview

- 2 year corporate R&D
- Highly capable LWIR HSI airborne sensor
- 5r As array for best operability
  - ...
  - ...
- Maximize optical throughput
  - ...
  - ...
  - ...
- Agile pointing system
  - ...

MAKO Twin Otter Flight Configuration

MAKO Pointing System/Scan Geometry

Power Plant Emissions (1/2)



Area Covered: ~52 km^2
Collection Time: ~2.3 min

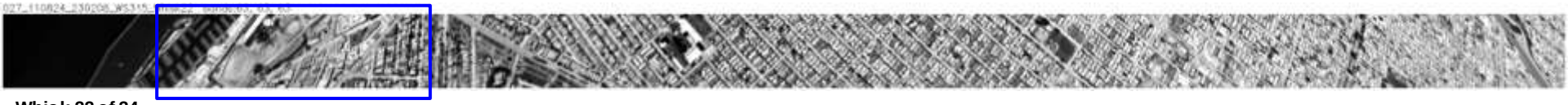
Ammonia slip from NO_x emission control system; plume length is ~5 miles.

Plume sources are two power plant stacks (red arrows). Note the classic bifurcate structure.

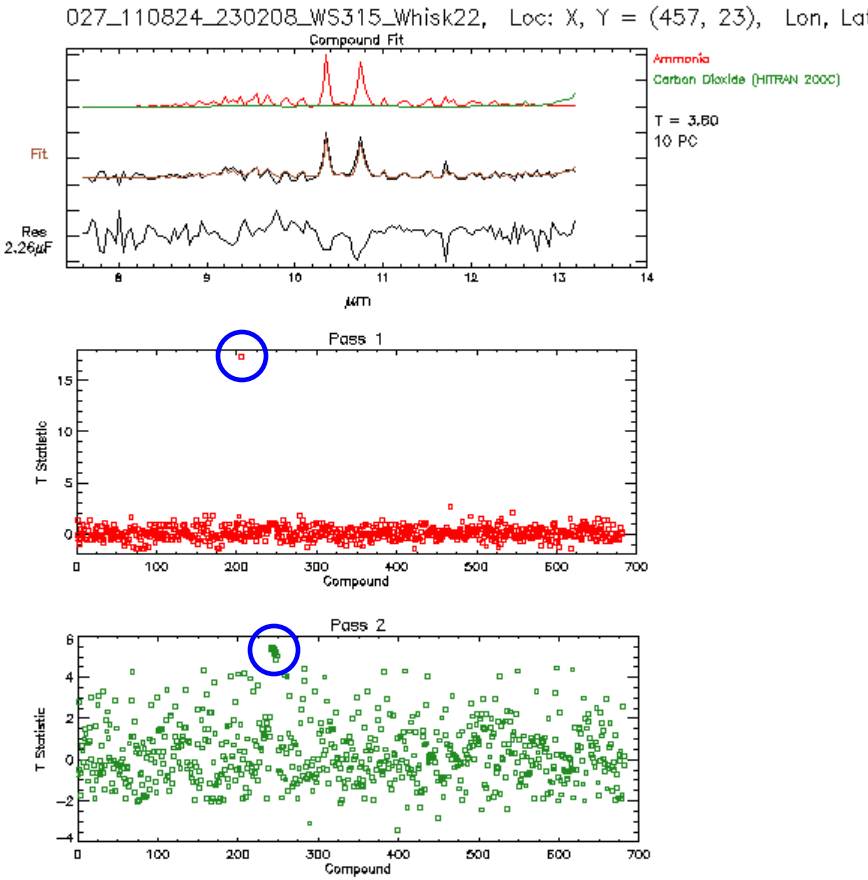
Note additional plume sources downwind from primary sources (yellow arrows).

AEROSPACE

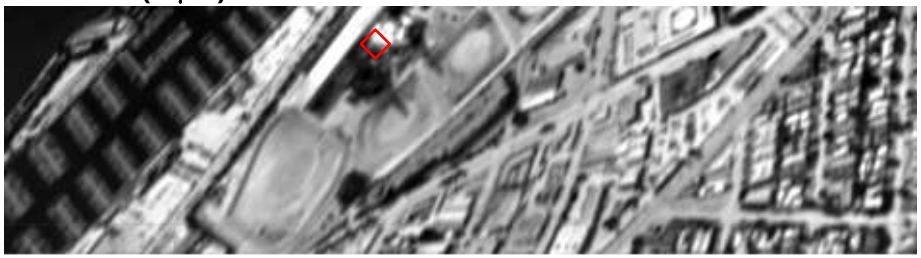
Power Plant Emissions (2/2)



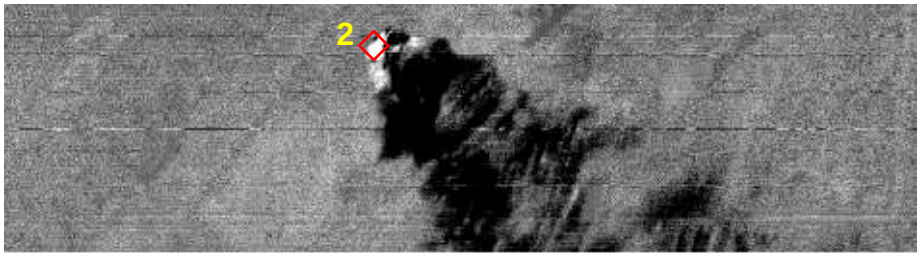
Whisk 22 of 34



Thermal (11μm)



ACE (Ammonia)

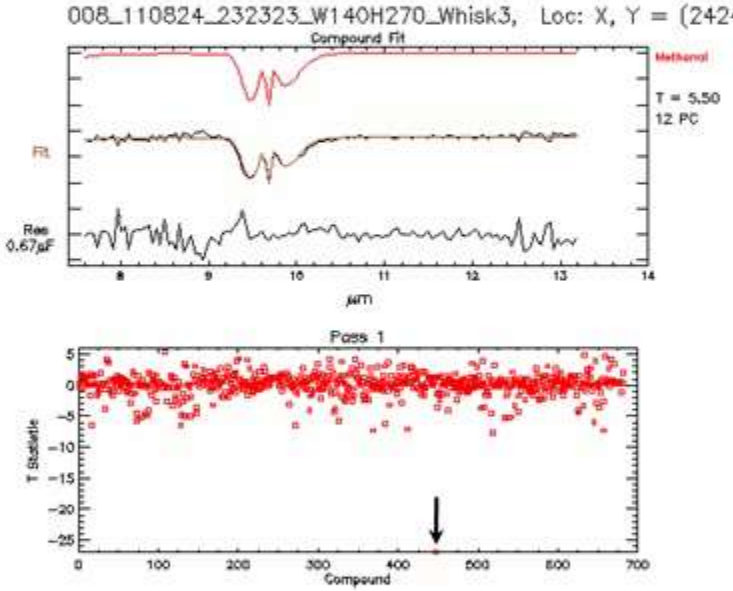


Sensor:	***Mako***	**Detect / ID**
Date:	**Aug 24, 2011**	Ammonia
Time:	**23:04:56 UTC**	Carbon Dioxide

AEROSPACE

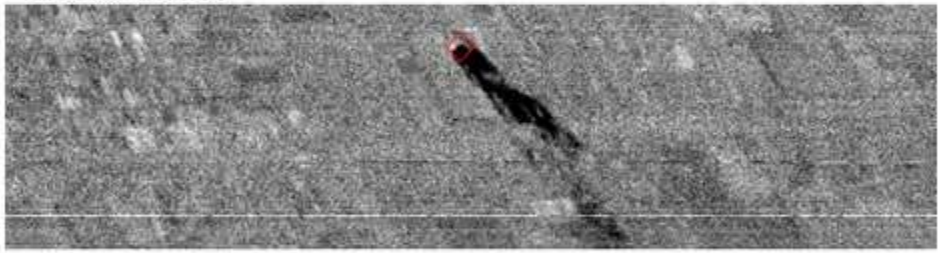
Solvent Emissions from Industrial Plant

Whisk 3 of 140



Thermal (11μm)

ACE (Methanol)



Sensor:	***Mako***
Date:	**Aug 24, 2011**
Time:	**23:24:49 UTC**

Detect / ID	**Flow (kg/hr)**
Methanol	18 ± 6

AEROSPACE

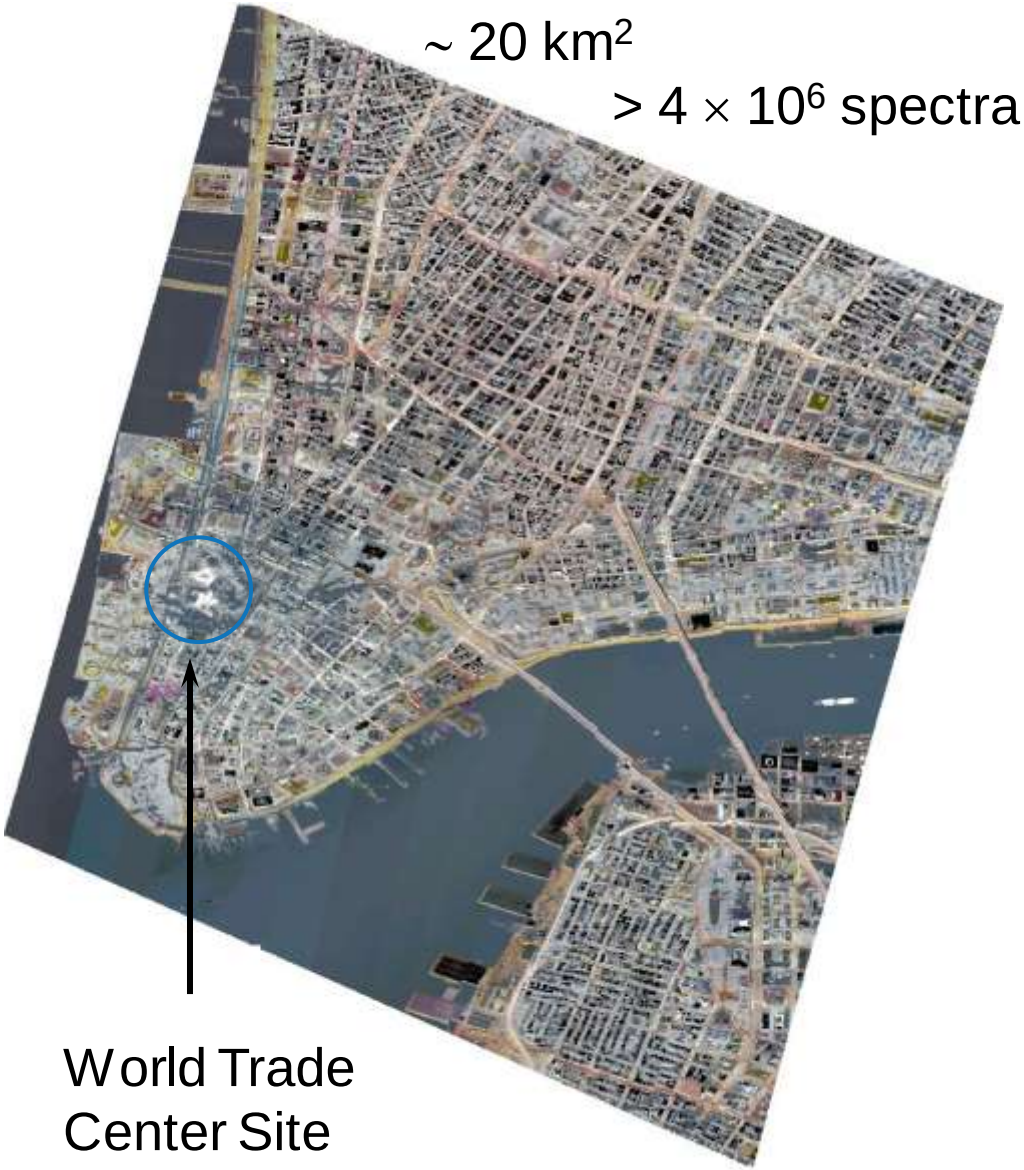
AEROSPACE
Assuring Space Mission Success

Case Study:
World Trade Center, NYC

Statement of Purpose

- There was widespread concern about the production of toxic gases from the rubble pile, either as a result of combustion or pyrolysis, which could have had adverse health impacts on rescue workers
  - *Sulfur dioxide is a common combustion product*
  - *Ammonia and benzene are common products from the pyrolysis of plastics and insulation*
  - *Phosgene can be released during the pyrolysis of some Freons (~70 tonnes of air-conditioning Freon were stored under the Towers)*
- The SEBASS sensor was deployed to the WTC collapse site
  - *First commissioned in 1995 and still in operation*
  - *Pushbroom LWIR/MWIR HSI sensor*
  - *22 flight passes over lower Manhattan and western Brooklyn.*
  - *In addition to the gaseous emissions, 15 passes were analyzed to investigate the distribution of debris around the WTC site (using the spectra of sulfate-laced drywall material as a tracer)*
- Only ammonia and Freon were found during the survey.

Infrared Image of Mapping Area



~ 20 km^2

> 4×10^6 spectra (pixels)

World Trade Center Site

<u>3-Color Composite Image</u>

Red	13.09 μm
Green	9.65 μm
Blue	8.99 μm

<u>Mapping Collection</u>

24 October 2001
9 - 11 pm local time

15 collection strips
2500 lines per strip
6000-ft sensor altitude
2-m ground sample distance

24 October / Noon 6 Strips / 1000 lines 3000 ft / 1-m GSD

AEROSPACE

24 October / Noon 6 Strips / 1000 lines 3000 ft / 1-m GSD

AEROSPACE

24 October / Noon 6 Strips / 1000 lines 3000 ft / 1-m GSD

AEROSPACE

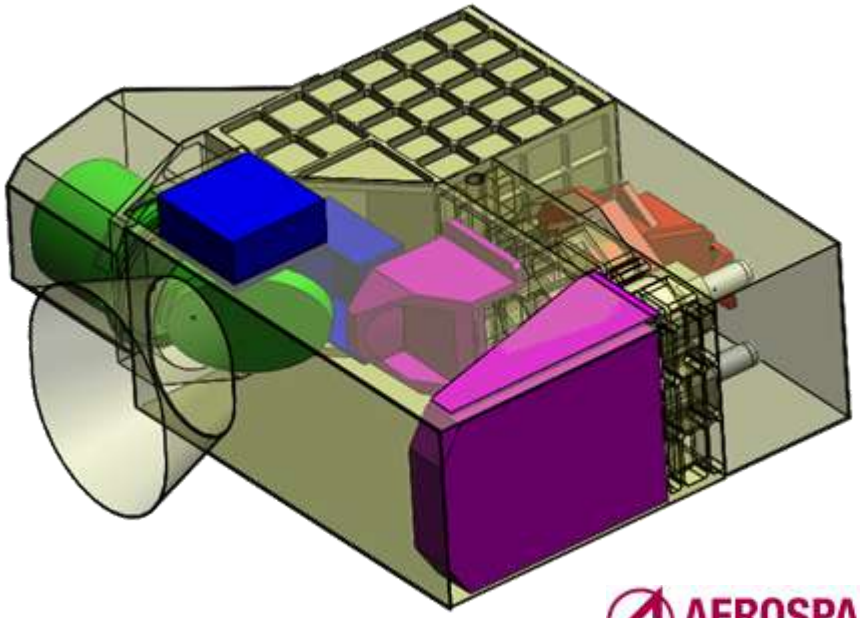
Toward a Space-Based Sensor

Current Orbital Capabilities

- TIR HSI is a powerful tool for environmental hazard assessment in the wake of natural or man-made disasters
- Systematic integration of TIR spectral imaging techniques into post-disaster management activities would directly enhance disaster relief efforts in the wake of such events
- There is a demonstrated and definable role for airborne TIR HSI surveying in post-disaster scenarios
- ***No current or planned space-based TIR imagers have the requisite combination of spatial resolution and spectro-radiometric performance to fulfill an analogous role in Earth orbit***

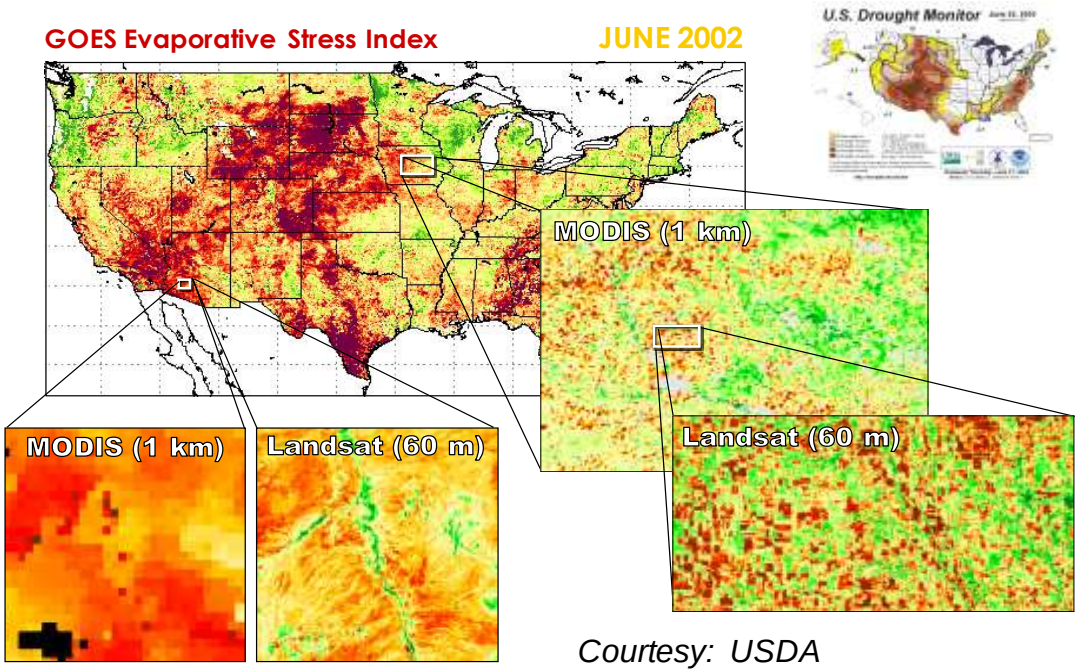
Space-Based TIR Imager for Disaster Mitigation

- A sensor concept has been developed that can be manifested as a primary or secondary payload and adapted for deployment in equatorial or polar orbit
- Sensor operates in 7-14 μm spectral region with ~90-m GSD
- Provisions are included for using datastreams from higher temporal, lower spatial resolution systems (e.g., GOES, VIIRS, SEVIRI) to autotask the sensor for targeted observations of developing events
- Accommodation requirements:
  - *Envelope: 110 x 100 x 50 (cm)*
  - *Mass: 150 kg*
  - *Power: 1000 W*
  - *Orbit: 450 – 850 km*



Imager Utilization Concept

- Design-driving application:
  - *Resolution of evapotranspiration and water stress at the scale of human intervention*
  - *Assessment of water use efficiency and forecasting of drought vulnerability with unprecedented accuracy*
- Secondary applications:
  - *Local effects of urbanization on surface energy flux*
  - *Volcanic eruption and wildfire early warning and targeted tracking*



Courtesy: USDA

Mission/Sensor	Revisit Interval	Swath	GSD	# TIR Channels	NEDT
Proposed imager	***3 days***	***92 km***	***90 m***	***28***	***0.1 K***
Terra/ASTER	3 days	60 km	90 m	5	0.3 K
Terra/Aqua/MODIS	2 days	2300 km	1000 m	5	0.05 K
Landsat 7/ETM+	16 days	185 km	60 m	1	0.5 K
Landsat 8/TIRS	16 days	185 km	100 m	2	0.4 K
HyspIRI/TIR (launch after 2020)	5 days	600 km	60 m	7	0.2 K

AEROSPACE

Summary

- High spatio-spectral resolution airborne thermal-infrared (TIR) imaging spectrometry is shown to be effective in detecting and tracking gaseous emissions from industrial, agricultural, and oil/gas extraction operations in a variety of environmental settings.
- High spatial resolution (1-2 m) of the sensor permits trace-back of emission plumes to their source.
  - *Quantification of emission rate is possible with knowledge of prevailing meteorology*
- High spectral resolution (44 nm across the 7.5-13.5 μm TIR band) enables detection of gas plumes through the application of SMF and/or ACE algorithms and precise identification and discrimination of primary and subsidiary plume components through the application of Stepwise (forward) Generalized Least Squares (whitened space) methodologies.
- Operation in the emissive TIR spectral region allows operations to be conducted throughout the diurnal cycle.
- *Mako* and SEBASS are available to support field study campaigns. The Aerospace Corporation is committed to transitioning high-resolution TIR HSI technology to space.

Acknowledgments

- The Aerospace Corporation's TIR HSI Enterprise is a cross-organizational venture involving personnel from the Space Science Applications Laboratory, Sensor Systems Subdivision, and Advanced Technology Division, many of whom contributed to the work presented here.

- This work was supported by The Aerospace Corporation's Independent Research & Development and Civil & Commercial Operations program offices, and also elements of the U.S. Government.