Next Generation Thermal Imaging Satellite Systems and their Cal/Val Requirements

Civil Commercial Imagery Evaluation Workshop

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April 1, 2009

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Background

- International and commercial access to space is experiencing unprecedented growth
  - By the year 2011 more than 50 imaging satellites with Landsat or better spatial resolution will be operational worldwide
- Small satellite constellations enable cost-effective high spatial resolution high revisit solutions
- Next generation uncooled thermal imaging system solutions are now possible
  - Thermal Infrared (TIR) 8-12 μm wavelength region
  - Enables new applications

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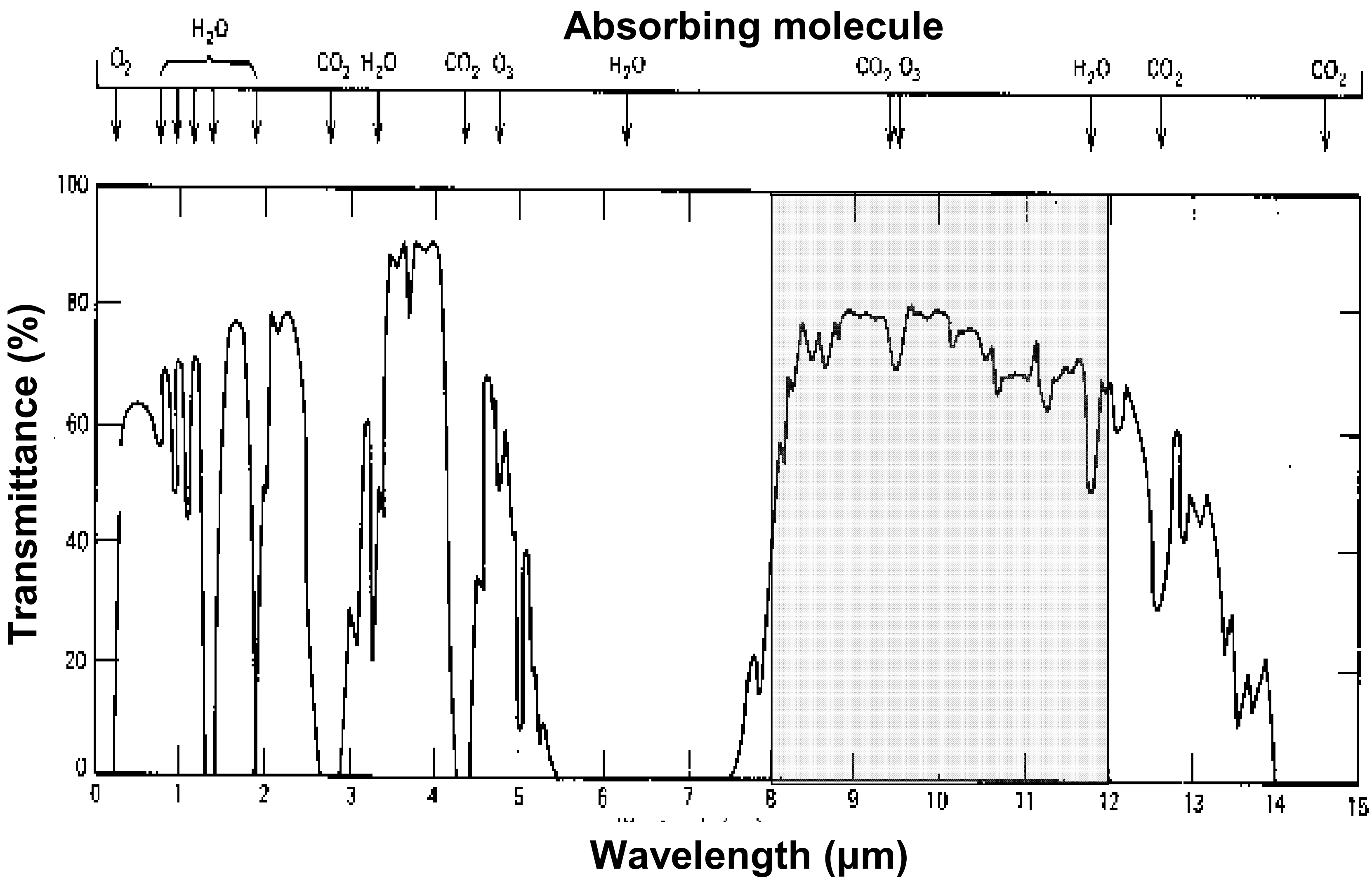
Atmospheric Windows



Traditional Terrestrial TIR Architectures

- Typically cross-track scanning systems
- Small number of HgCdTe detectors
  - Actively or passively cooled (~80 K)
  - Achieve 0.2-0.3 K sensitivity or better
- Typically large GSD
  - Landsat & ASTER are the highest resolution with 60m and 90m GSD
- Typically multispectral with exception of ETM+
- Complex and expensive

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Traditional Terrestrial TIR Systems

- **L7/ETM+** *(Cross-track scanner)*
  - Single band (10.4-12.5 μm) HgCdTe
  - 60m GSD / 0.3 MTF Nyquist / 0.3K NEDT / 8 of 9 bits quantization
- **Terra/ASTER** *(Cross-track scanner)*
  - Five TIR bands (8.125-11.65 μm) HgCdTe
  - 90m GSD / 0.35 MTF Nyquist / 0.2K NEDT / 12 bits quantization
- **AVHRR** *(Cross-track scanner)*
  - Two TIR bands (10.3-12.5 μm) HgCdTe
  - 1100m GSD / 0.3 MTF Nyquist / 0.12K NEDT / 10 bits quantization
- **Terra/MODIS** *(Cross-track scanner)*
  - 10 TIR bands (6.535-14.385 μm) HgCdTe
  - 1000m GSD / 0.35 MTF Nyquist / 0.25K NEDT / 12 bits quantization
- **Multispectral Thermal Imager (MTI)** *(Pushbroom)*
  - Three TIR bands (8.0-10.7 μm) HgCdTe
  - 20m GSD / 0.025-0.045K NEDT / 12 bits quantization
- **ERS-2/ATSR-2** *(Conical scanner)*
  - Two TIR bands (10.6-12.3 μm) HgCdTe
  - 1100m GSD / 0.02K NEDT / 11-12 bits quantization

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Selected TIR Application General Requirements Survey

Application	NEDT (K)	Tmin (K)	Tmax (K)	Accuracy (K)	Revisit Time (Days)	GSD (m)
Land Cover / Land Use	0.3-0.5	265	340	1	16	60-90
Geological Mapping	0.3	275	375	2	16	15
Urban Land Use	0.5	273	320	1	16	~100
Monitoring Surface Energy and Water Fluxes	~0.2	273	310	0.5	1-16	2-120
Cloud Science / Climate Modeling	0.5	198	310	2	1-16	60-500
Urban Heat Islands	0.3	275	325	2	7	5-30
Agriculture Studies/Irrigation Mngt	0.1	273	313	0.5	1-7	20-120
Sea Surface Temp	0.1	273	320	0.1	1	300-1000
Volcano Monitoring	1	275	1500	2	1	15
Material Transport in Aquatic Systems	~0.3	273	305	0.2- 1	0.1-1	60-100
Coastal Monitoring	0.1	273	320	0.1	.5	~100
Fire Monitoring	1	400	1000	2	.1	100-1000

Many TIR applications require spatial resolutions < 100 m and near daily revisits and are not met with today's thermal systems.

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Common Land Imagers

Satellite/ Imager	Country	GSD (meters)	Swath (km)	Repeat Frequency	# Bands	Thermal
Landsat Landsat 7	USA	30, 60 (120)	180	16 days	8	60 m
Aqua/Terra MODIS	USA	250, 500, 1km	2330	1 – 2 days	36	100 m
UK-DMC DMC	UK	32	600	~1 day (constellation)	3	N/A
RapidEye	Germany	6.5	78	1 day (constellation)	5	N/A
IRS-P6 AWifs	India	56	740	5 days	4	N/A
CBERS 1-2 CCD/IRMSS/WFI	China Brazil	20, 80, 160,260	113,120,890	26 days	10	160 m (IRMSS)
SPOT 5 HRG/HRS/VEG-2	France	5, 10, 20	60 x 120 (Twin mode)	2 -3 days	8	N/a
IKONOS	USA	0.82, 4	11.3	~3 days w/ pointing	5	N/A
QuickBird2	USA	0.61, 2.44	16.5	Yes	5	N/A

No systems today provide thermal data at desired spatial resolution and repeat time

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Next Generation Concepts/Architectures to meet TIR Applications

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Potential Next Generation Thermal System Baseline

- Constellation approach
- Single TIR band or split window
- Pushbroom Focal Plane Array (FPA)
- Uncooled microbolometer technology
  - Based on 40 mK Noise Equivalent Delta Temperature (NEDT) at 30-60 Hz frame rate, f/1 optics, 8-14 μm bandpass, 8 ms thermal time constant
- Time Delay Integration (TDI)
  - Application dependent

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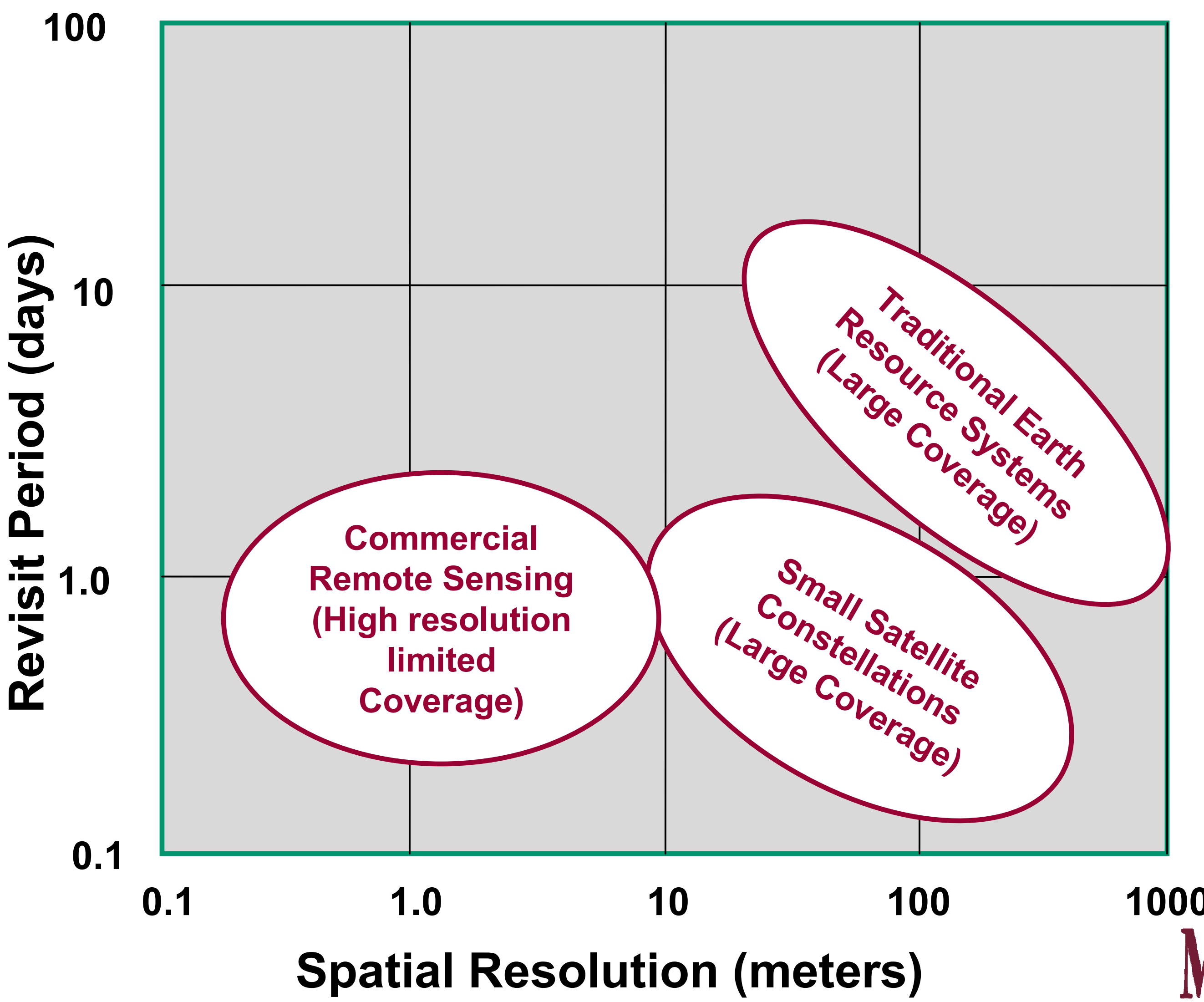
Unique Role for Small Satellite Constellations



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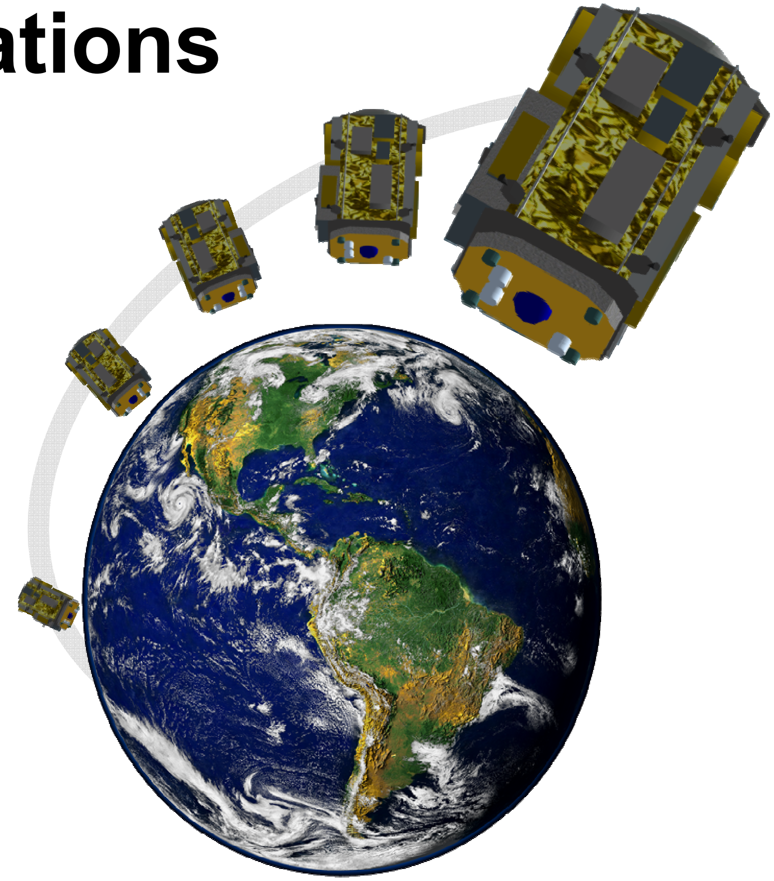
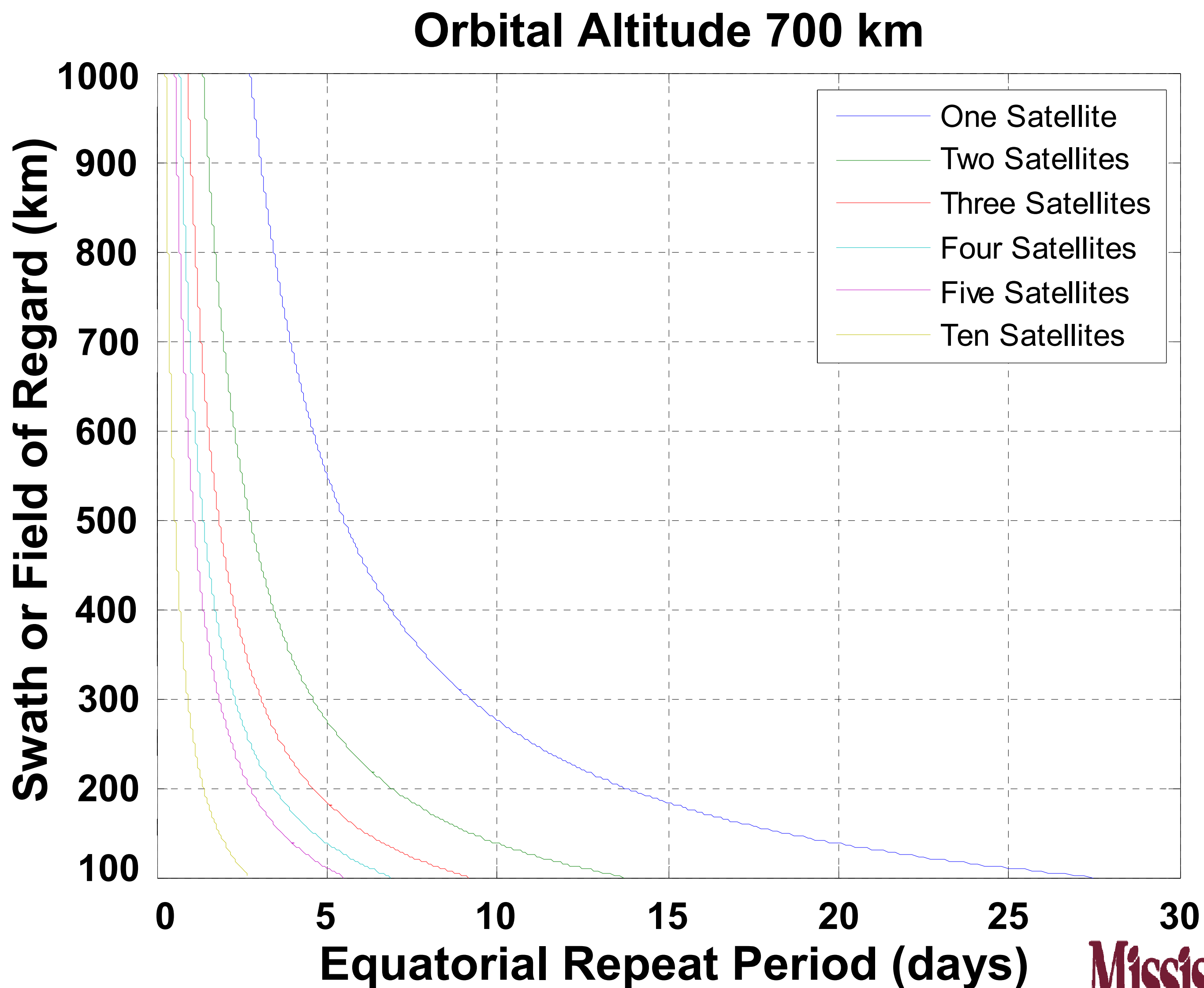
Benefits of LEO Small Satellite Constellations



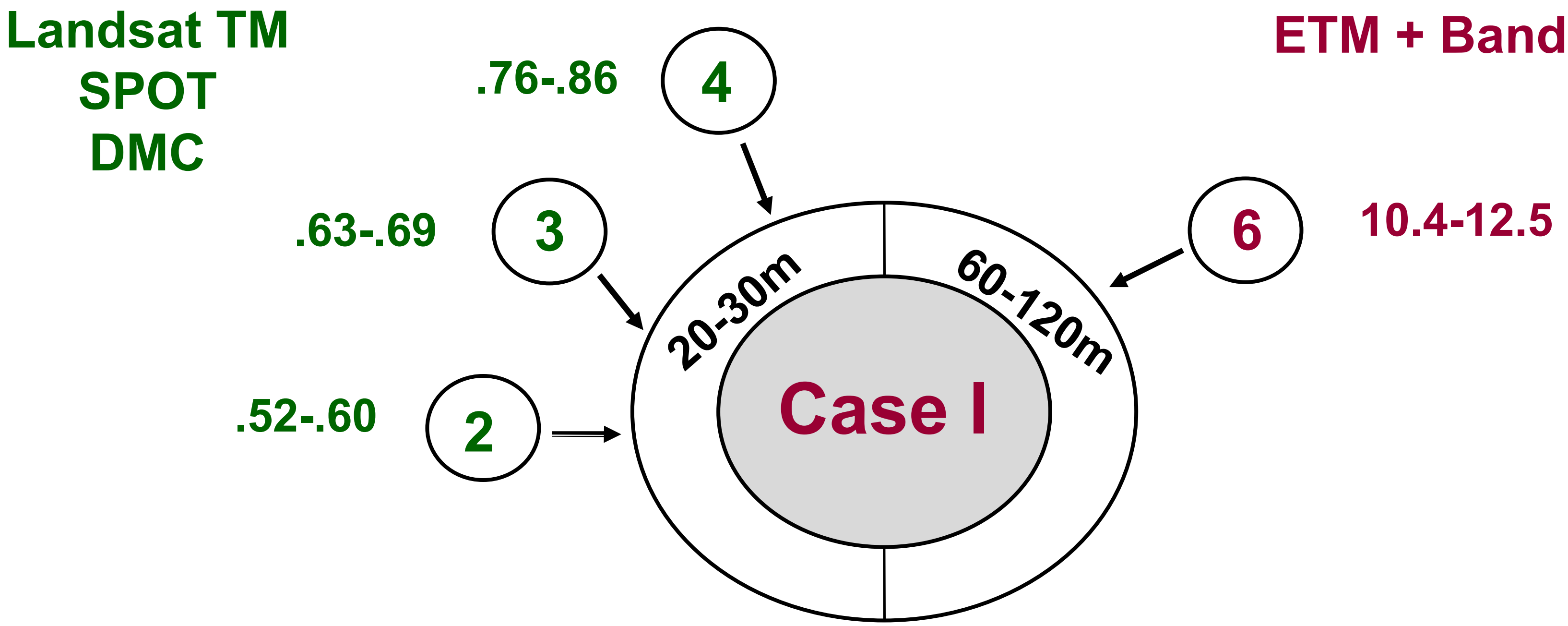
- Enhance performance
  - Global monitoring
  - Increased coverage
  - Increased revisit time
- Increased failure tolerance
- Amortization of non-recurring cost
- Recurring cost reduction
- Launch cost reduction

Great potential to fill critical science data gaps that result from the high cost and long development cycles associated with traditional class science missions

Constellations Improve Coverage & Repeat Period



Potential Next Generation Thermal System - Case I



- Logical extension of many reflective imaging systems
- Possible next generation constellation

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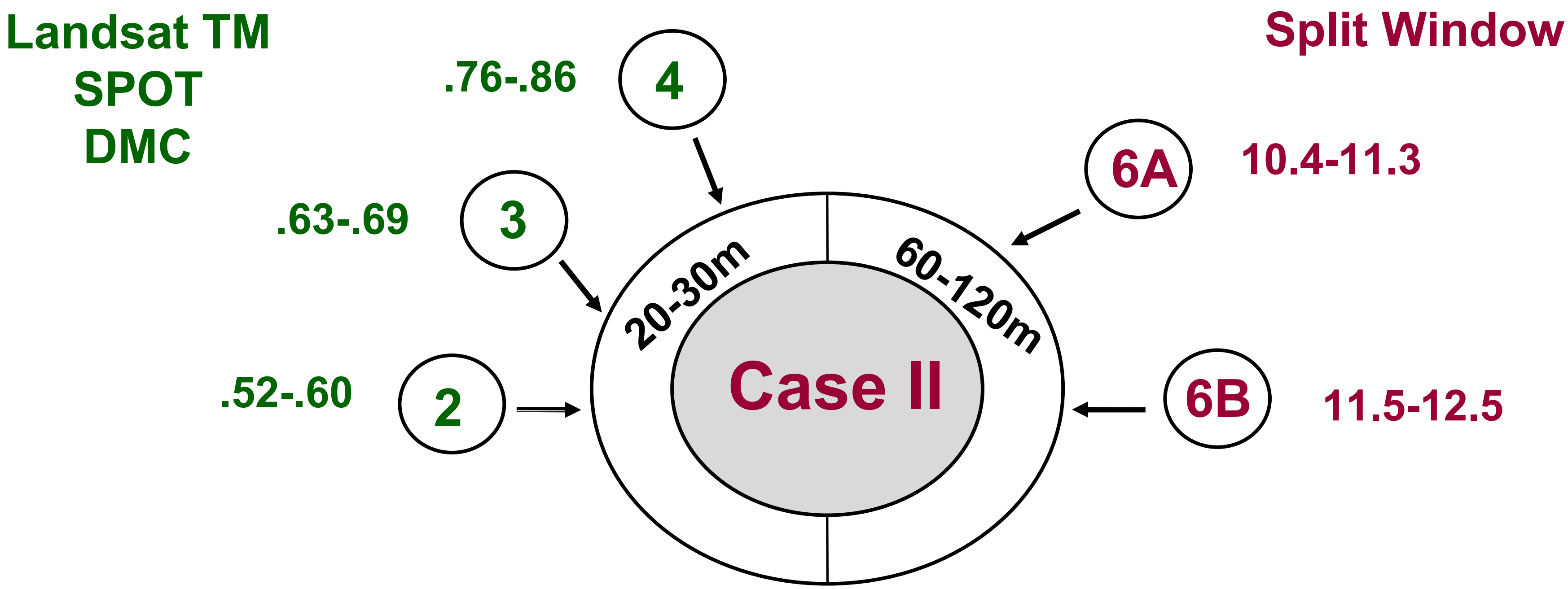
Potential Next Generation Thermal System - Case II



- Logical extension of many reflective imaging systems
- Possible next generation constellation
- Split window gives additional spectral content to improve atmospheric correction

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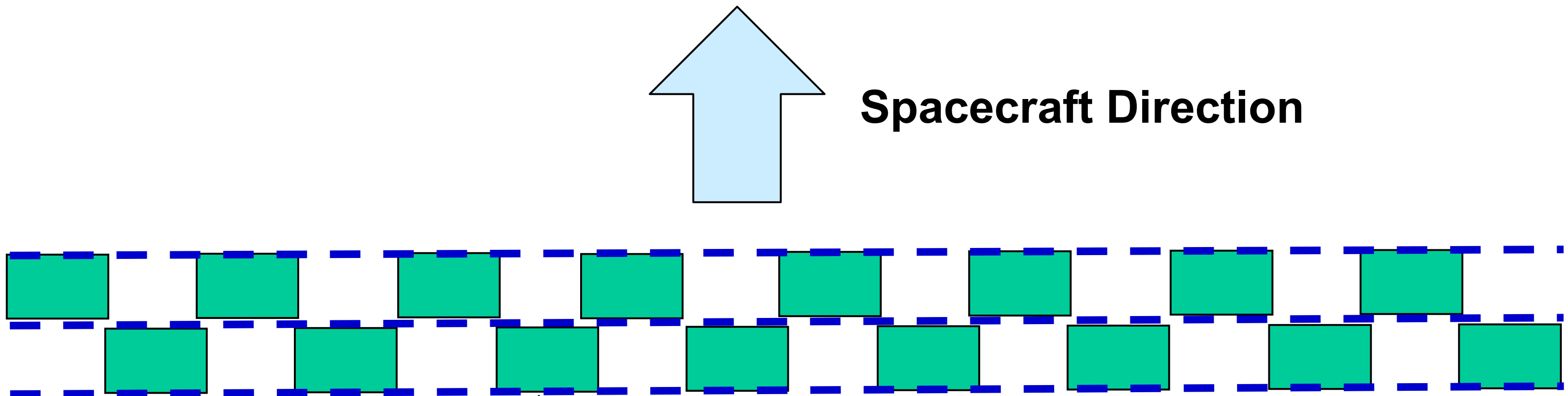
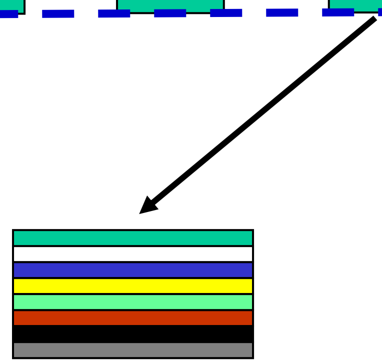
Typical Pushbroom FPA Configuration

Double Bank of Uncooled Microbolometer Detector Arrays





320x240 / 640x480 / 1024x1024 detector FPA with striped interference filters for bandpass selection or filtered line arrays TDI of 64 or more in principle possible

Pushbroom Thermal Architecture Advantages

- Increased integration time increases Signal to Noise Ratio (SNR)
  - SNR ~ *(number of cross track detectors)*$^{0.5}$
  - SNR ~ *(Time Delay Integration)*$^{0.5}$
  - Enables
    - Smaller GSD systems for fixed detector sensitivity
    - Uncooled detectors
      - Large cryogenic arrays add significant complexity but have phenomenal sensitivity (DoE MTI)

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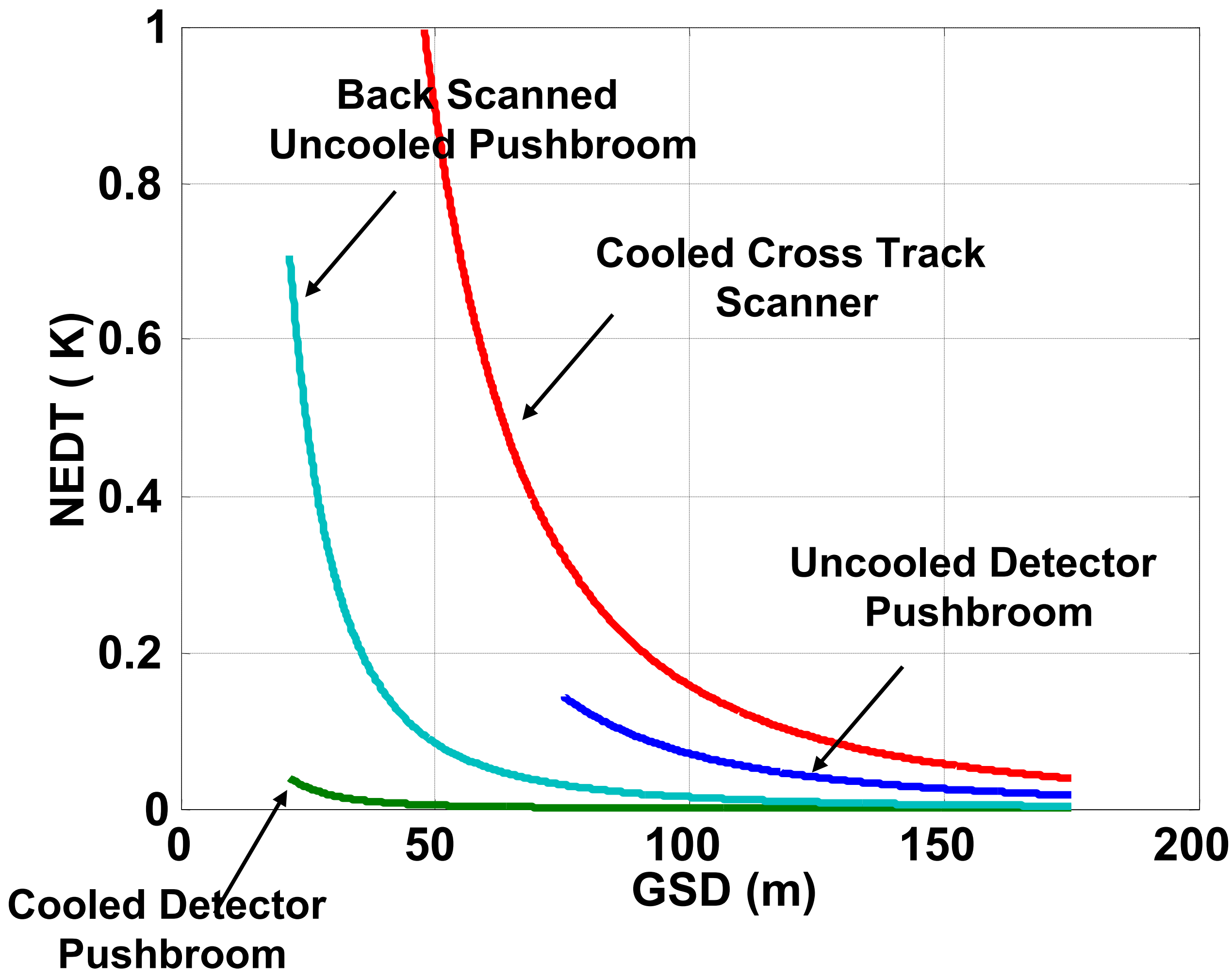
Notional Comparison of Different MS Thermal Architectures



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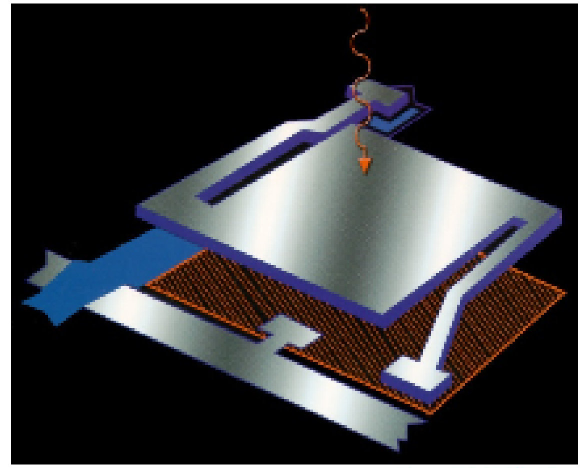
Infrared Detector Types

- **Cooled Detectors**
  - Well established
  - Photovoltaic or photo-conducting mechanisms
    - InSb, HgCdTe and GaAs quantum well devices
  - High framing rates and low noise
- **Uncooled Detectors**
  - Rely on a thermal response
    - Bolometric or pyroelectric
  - Silicon microbolometers are the most mature space based technology
  - Have slow framing rates and are relatively insensitive
  - Lighter and smaller system packaging possible

Uncooled Silicon Microbolometer FPA Characteristics



Typical Focal Plane Sizes

320x240 pixels(~25-50 µm pitch)
640x480 pixels (~25 µm pitch)
1024x1024 pixels (~19 µm pitch)
1x512 pixels (~40 µm pitch)

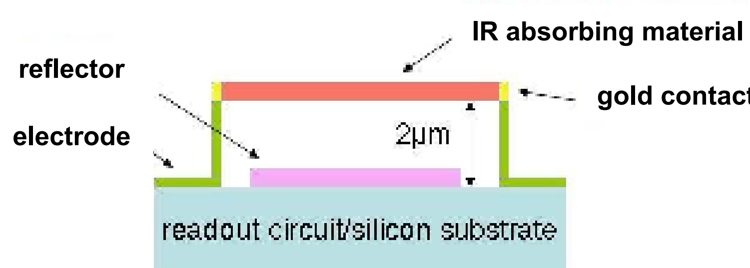
Frame Rates

30 Hz or 60 Hz standard but 100 Hz systems have been demonstrated

Thermal Time Constants ~4-18 ms

NEDT (conservative value)

40 mK or better for 60 Hz, f/1 optics and 8 ms time constant (300K Background)



Absorption coated silicon nitride isolated bridge with broadband response *(8-14 µm)*

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Sample Microbolometers Flown in Space

Satellite	Launch	Mission	Altitude	FPA GSD	Swath	NEDT Bands
ISIR (sensor)	August1997 (STS-85)	Tech demo	250 km	327 x 240 240 m	85 km	.01-.06K @ 300K 4 bands: 8.6, 10.8, 11.8, 7-13 μm
CALIPSO	April 2006	Airborne particles, cirrus emissivity and particle size	705 km	N/A 1000 m	64 km	.3k @ 210K 3 bands: 8.7, 10.5, 12 μm
THEMIS	April 2001 (Mars 2001 Orbiter)	Surface mineralogy Mars physical properties	400 km	320 x 240 100 m	32 km	.5K @ 245K 1K @ 180K 1 band: 6.8-14.9 μm
Flying Laptop	Late 2010	Tech demo	<1000 km	320 x 240 50 m	32 km	.085K @ 300K 8-12 μm
EmberSat		Forest fire detection and monitoring	250 km	320 x 240 250 m	85 km	.01-.06K @ 300K 2 bands: 3.7, 11 μm
Aquarius	May 2010	Global sea surface salinity	657 km	512 x 2 (pushbroom) 351 m	182 km	.08K @ 300K 2 bands: 3.4-4.2, 10.4-11.3 μm

TIR Spatial Resolution Drivers

- **Frame Rate and Ground Velocity**
  - GSD ~ Ground Velocity / Frame Rate
- **Altitude and Telescope Diameter ($D_{telescope}$)**
  - Ground Spot Size (GSS) for a diffraction limited system is controlled by the Airy diffraction pattern

    $GSS = 2.44\ \lambda^*(altitude / D_{telescope})$
- **Thermal Time Constant (tau)**
  - Uncooled detectors only

    Thermal time constant smear (similar to electronic MTF component in cross track scanners)

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TIR System Trades

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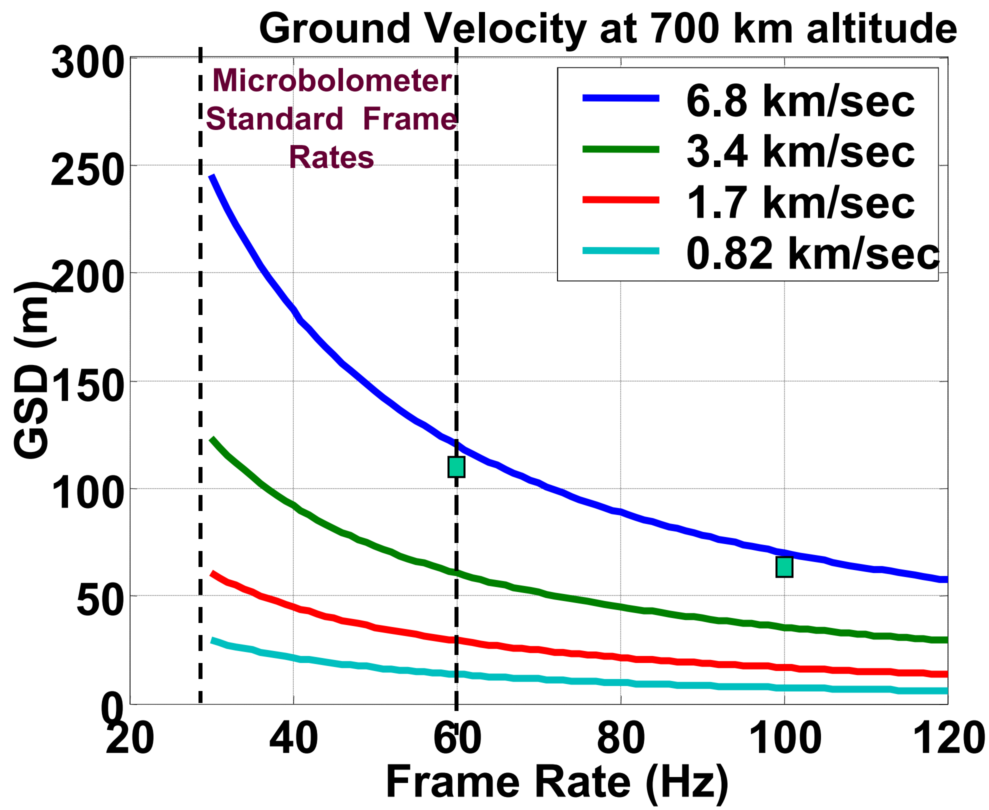
Frame Rate Trades for Low Earth Orbit



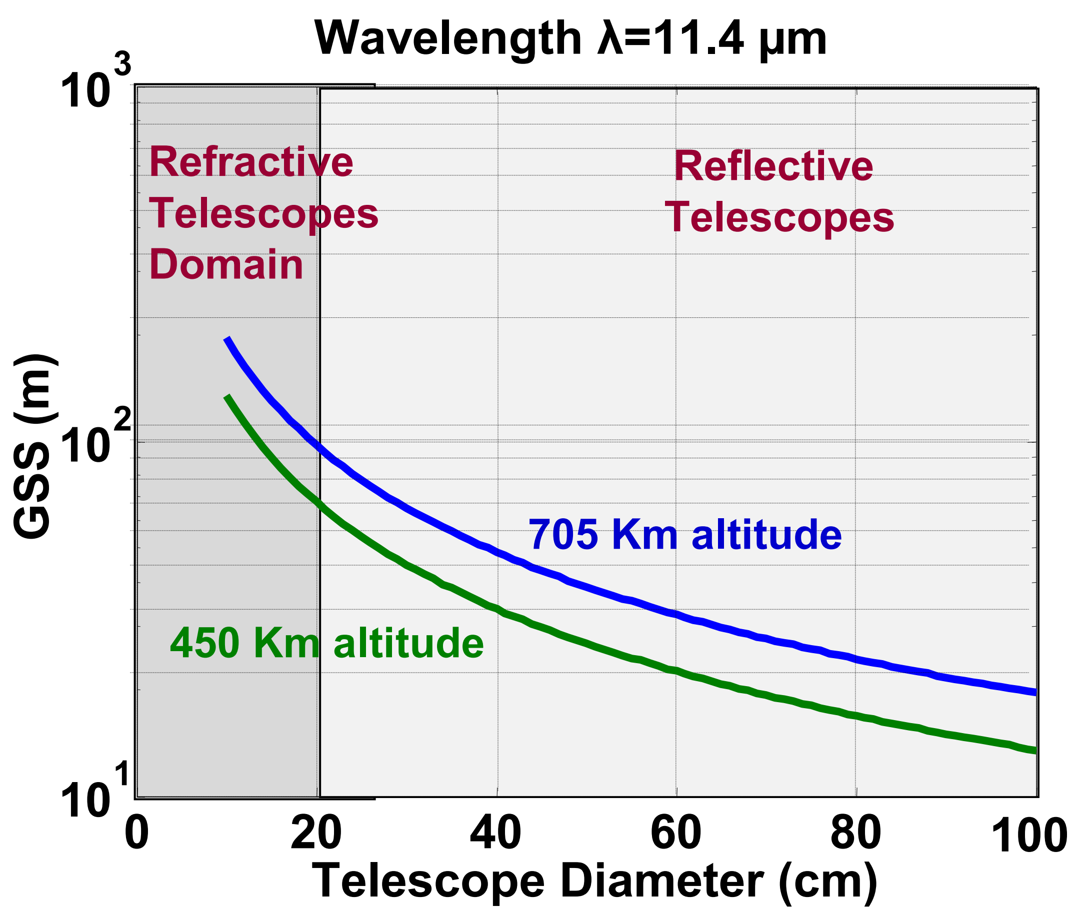
- ALI-like architecture limited to 113 m for 60 Hz and 68 m for 100 Hz readout rates
- Back scanning similar to Ikonos and Quickbird effectively reduces the ground velocity and enables smaller GSDs with standard frame rates

Framing Rate	GSD (Meters)			
(Hz)	Standard	Backscan/2	Backscan/4	Backscan/8
30	227	113	57	28
60	113	57	28	14
100	68	34	17	9
120	57	28	14	7

Telescope Diameter Trades

Diffraction limited resolution *(Rayleigh criteria)*

Ground Spot Size (GSS)= 2.44 λ*(altitude / $D_{telescope}$)



- GSS/GSD ~ 1-2 (most systems)
- Wide FOV f/1 refractive telescopes practical for telescopes ~<20 cm or 50-100m GSD systems at 700 km altitude
- Smaller GSD systems will likely need slower reflective system to achieve reasonable FOV
- Orbit altitude of 450 km allows approximately 36% smaller telescope than a 700 km altitude

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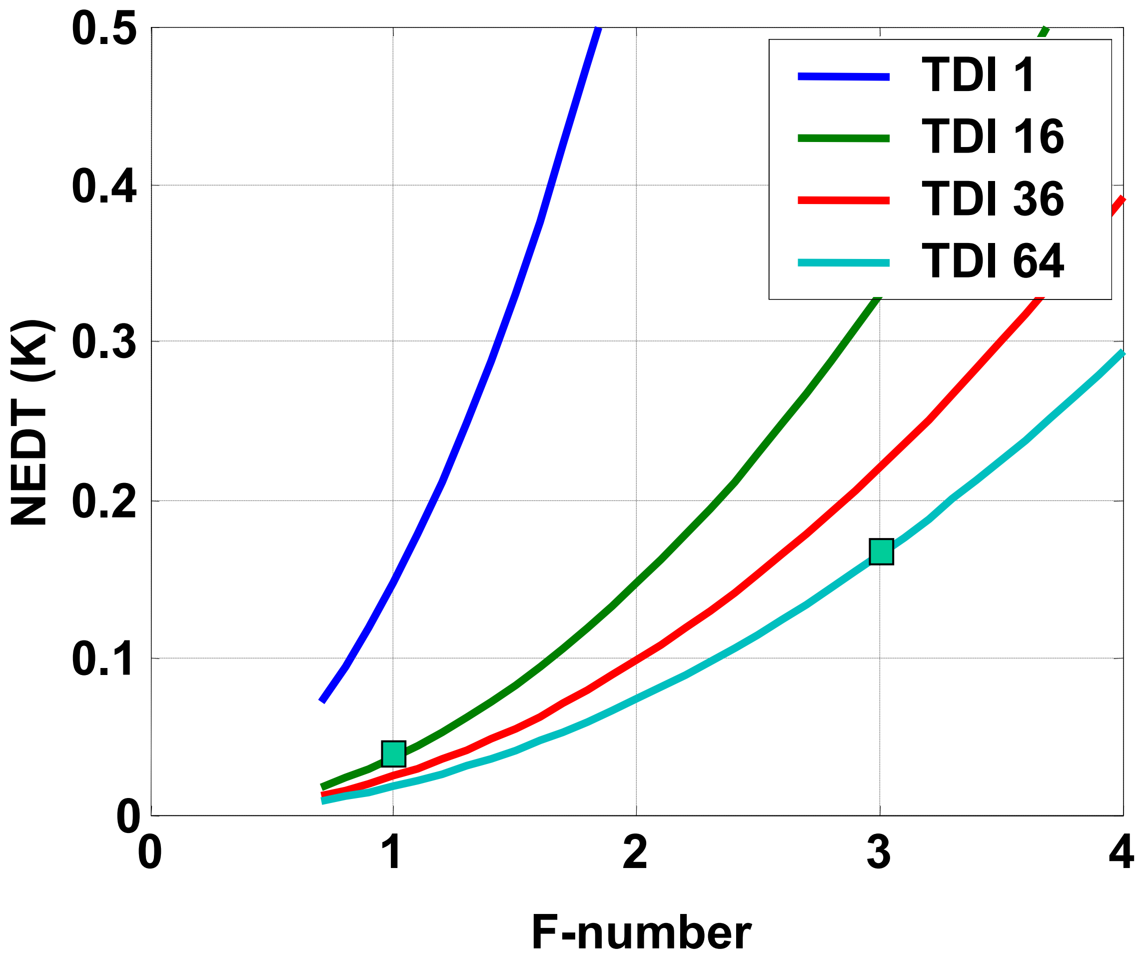
NEDT Scaling

- Increasing the time constant improves NEDT sensitivity but generally impacts other system parameters (e.g. PSF)
- NEDT scales with:
  - Power on detector
    - Power scales as (f-number)$^{-2}$
  - Spectral bandwidth (approx.)
  - Atmospheric transmission loss
  - (TDI)$^{-0.5}$

Example NEDT Scaling (L7 10.4-12.5 μm)



Baseline NEDT of 40 mK at f/1 optics
f/3 optics will produce NEDT < 0.2 K with large TDI

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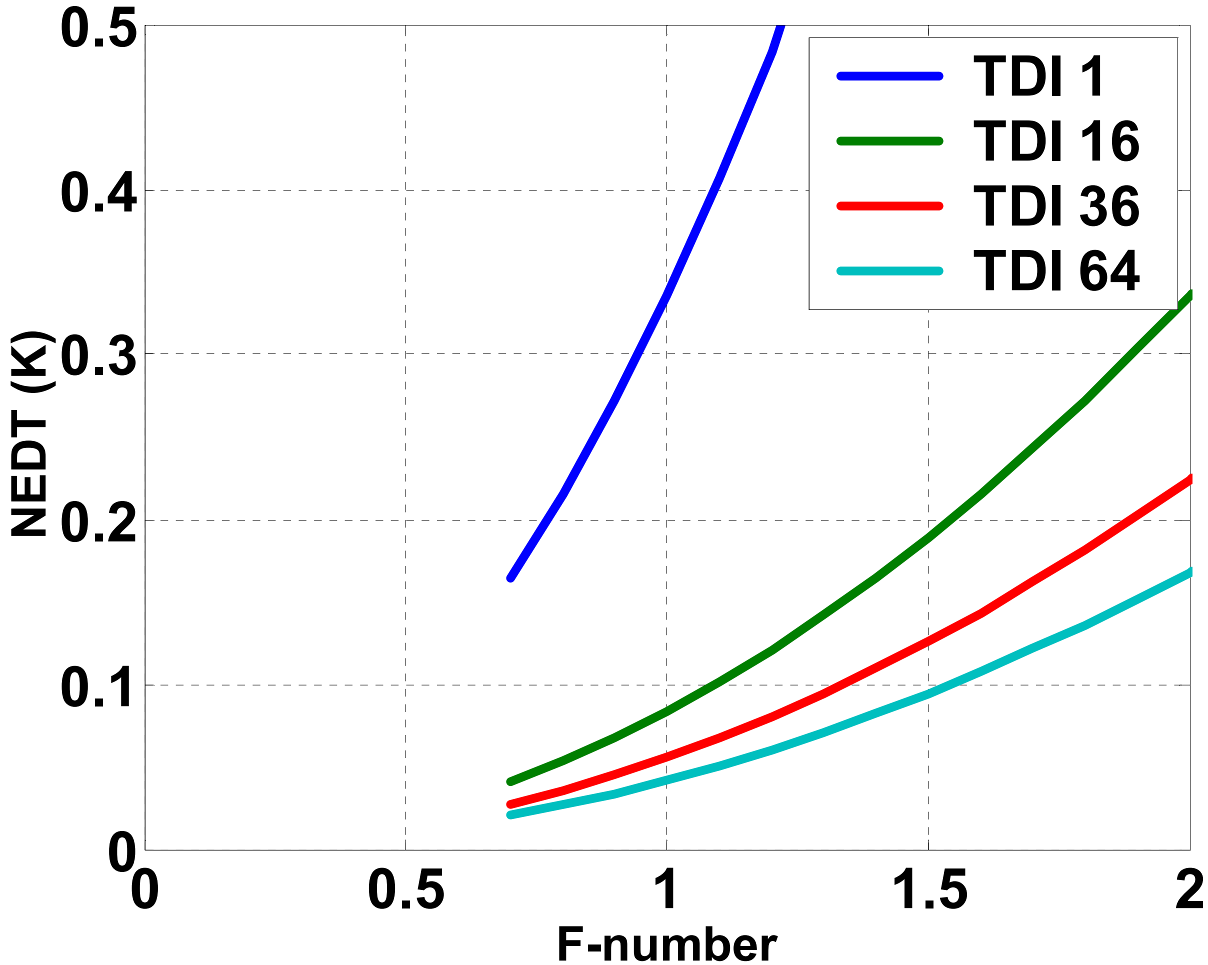
NEDT Scaling Split Window bandpass



Baseline NEDT of 0.04 K at F/1
F/2 optics will produce NEDT < 0.2 K with large TDI

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Application Standards

- Stressing remote sensing problem for a specific application
  - Well defined characteristics
  - Allows for rapid, objective evaluations
- Enables application requirements to be developed through parametric studies
  - Helps define sensing system characteristics

Irrigation Management

- Irrigation currently represents two-thirds of fresh water use worldwide.
- Wide-area evapotranspiration estimates for water management decisions depend on accurate temperature retrieval from remotely sensed data.
- Center-pivot irrigation is common in parts of the world where surface water resources and rainfall are scarce.
- Reasonable confidence in results is attained if the temperature errors of several pixel averages are <0.5 K.
- The accuracy of the temperature retrieved from remote sensing data is fundamentally limited by
  - Finite spatial resolution and noise of the imaging system
  - Physical size of the area of interest (AOI)
  - Temp change between the AOI and adjacent regions

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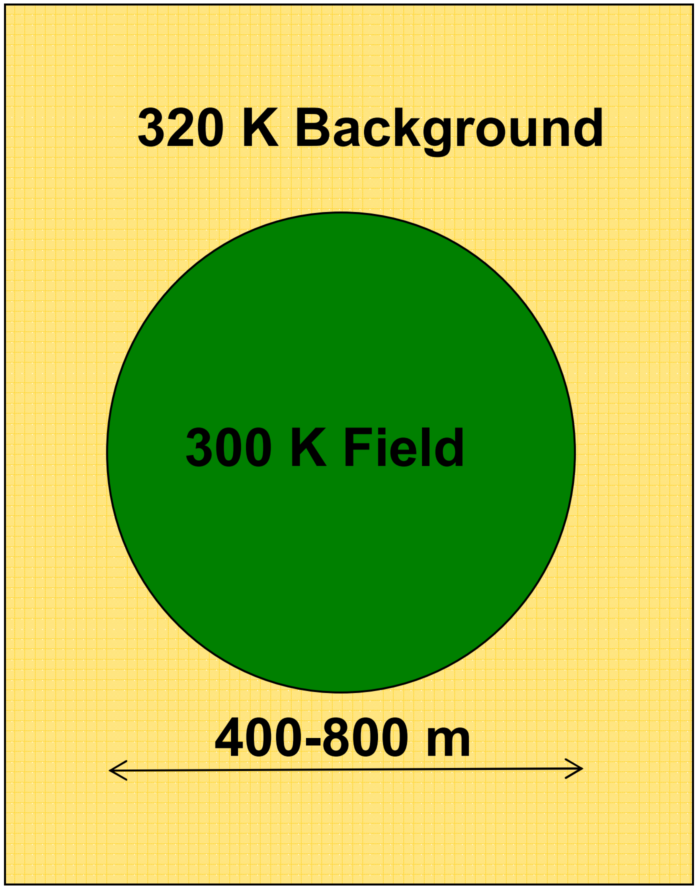
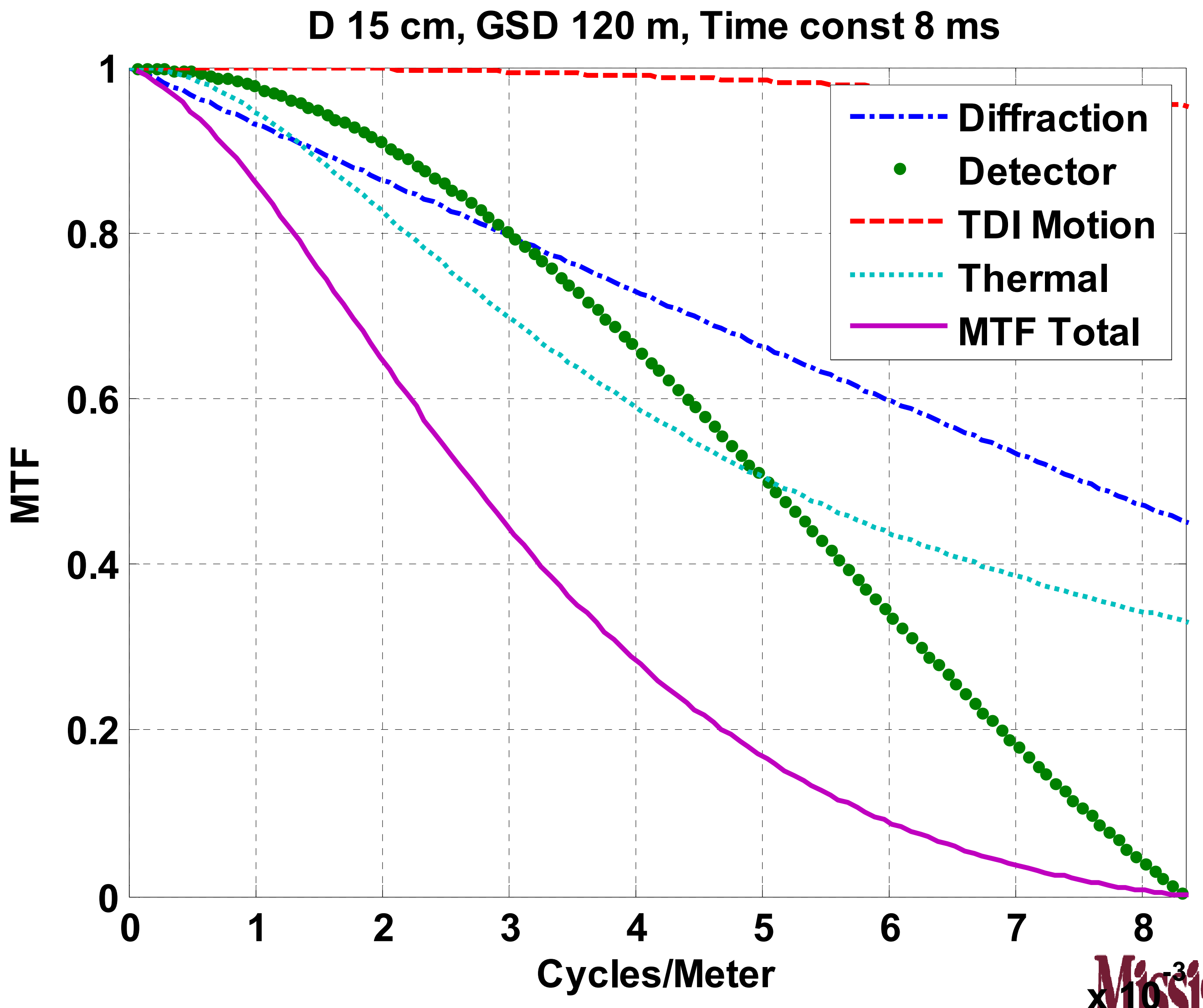
Simulated Center Pivot Irrigation Simulation

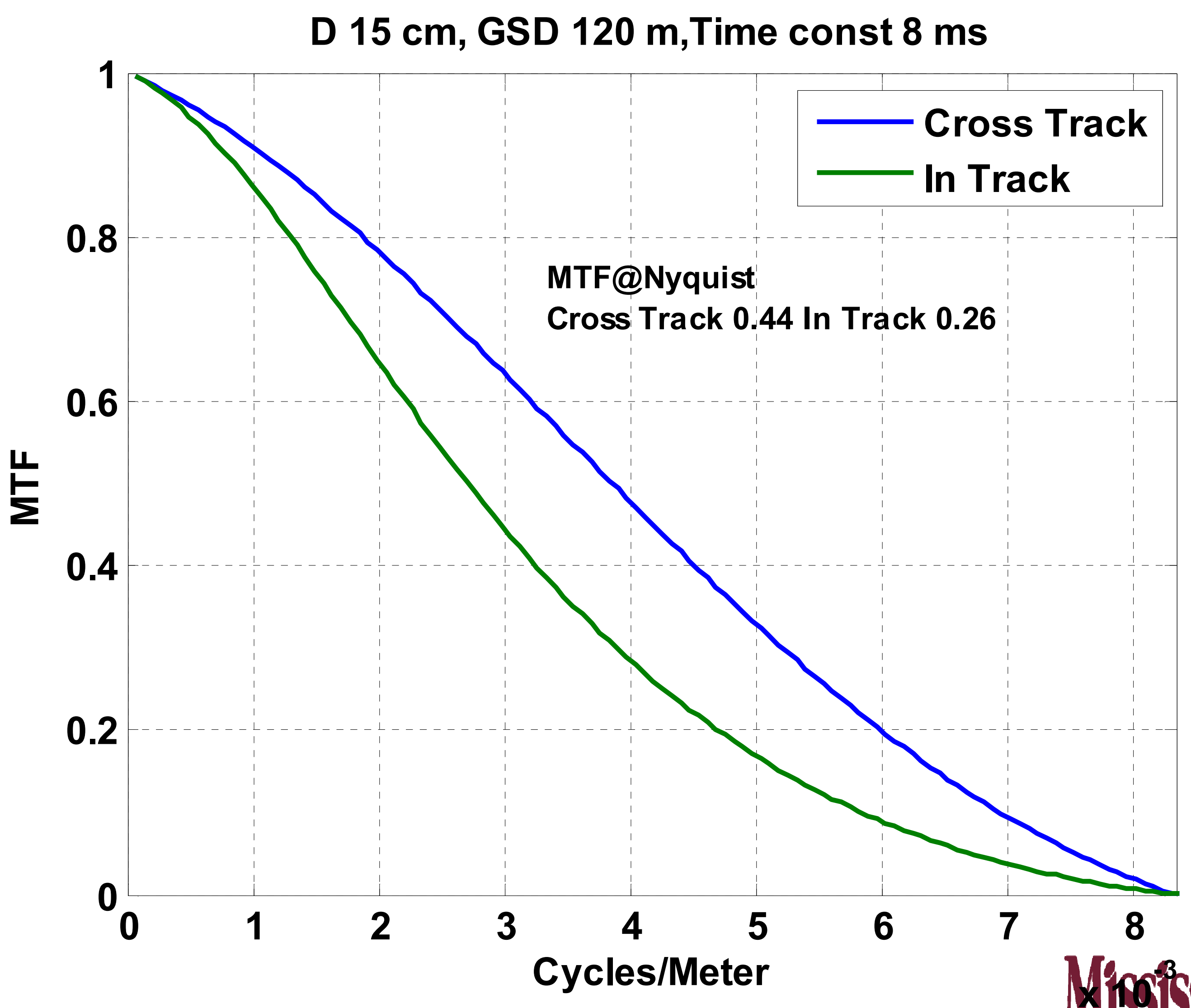
- Typical center pivot irrigation diameters 400-800 m
- Stressing problem
  - Crop temperature 300 K
  - Soil temperature 320 K
  - Goal temperature accuracy ~ 0.5 K taking into account NEDT and finite PSF



System Level MTF Components



Total System Level MTF



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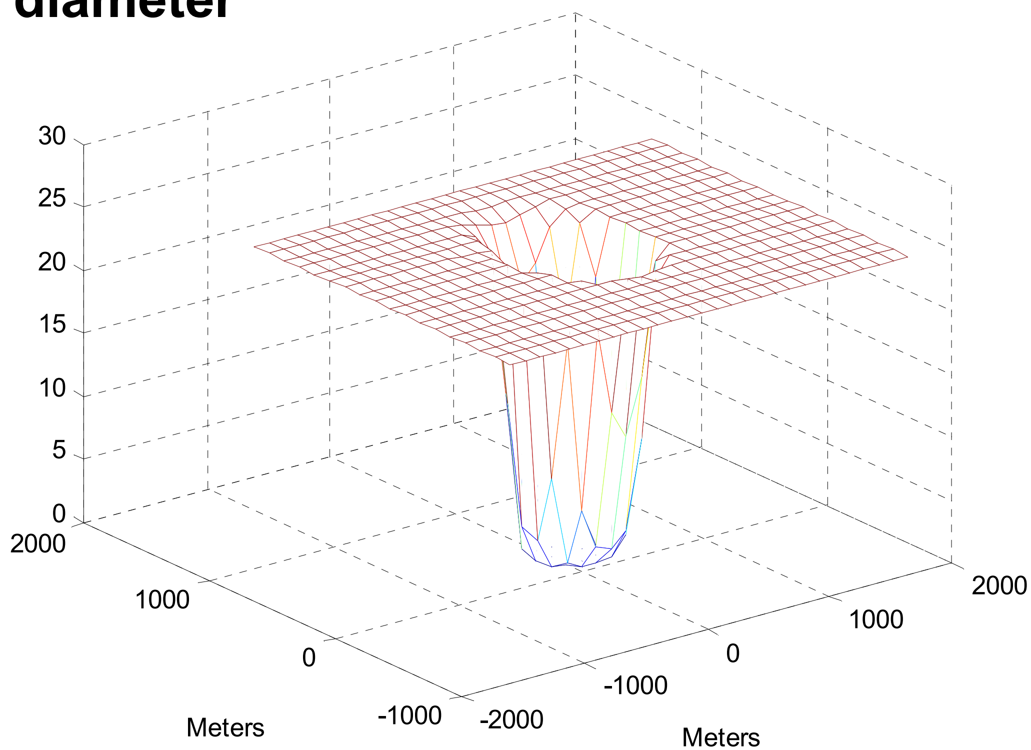
Simulated Center Pivot Irrigation Simulation Results

800 m Center Pivot
15 cm telescope diameter
700 km altitude



Temperature Error Small

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Summary

- Small satellite constellations with 15-20 cm or smaller telescope diameters, refractive f/1 wide field of view optics could enable <100 m GSD class systems with near daily revisit times
- New thermal applications requiring daily revisits and moderate spatial resolution could be performed
  - Irrigation management
  - Fire detection and management
  - Volcano monitoring
- Application standards need to be identified to size specific systems

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Summary, continued

- TDI significantly improves NEDT (TDIs of 40 have been demonstrated)
- Mosaic FPAs required for large swaths
- Further FPA developments at 100 Hz or greater frame rates would have significant impact
- Decreased time constants with small improvements in NEDT would help provide design margin

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Other Considerations

- Radiometric calibration such as a full aperture calibrator may be necessary due to microbolometer drift
  - Smaller aperture systems will be easier
- Microbolometers typically have relatively large nonuniformity in response (TDI helps)

Calibration/Validation Considerations

- Constellations of sensors require cross-calibration studies
  - Separate multiple sensor induced effects from phenomenology
- Vicarious calibration approach required
  - Small satellites may not carry on-board calibrators
  - Small satellites may not be able to perform lunar/stellar calibrations
- Water bodies typically used
  - Lake Tahoe (JPL - Simon Hook)
  - Stennis Space Center

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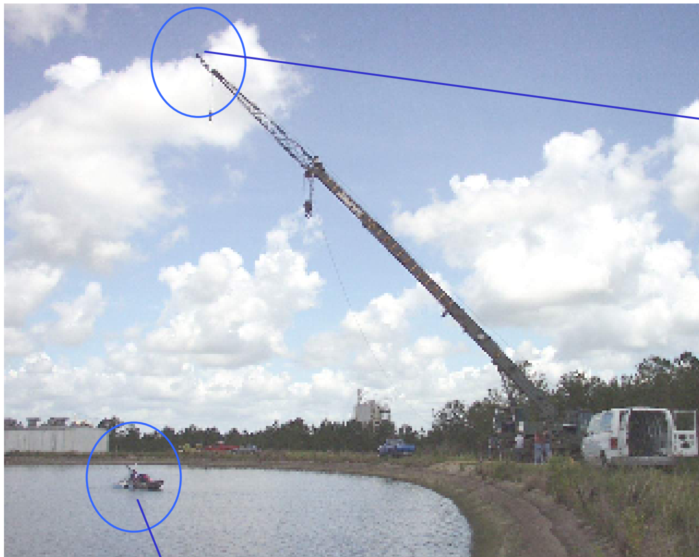
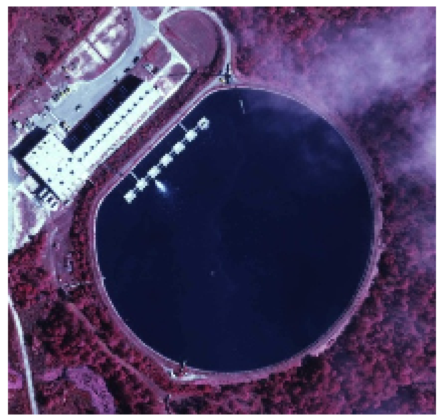
Calibration / Validation Techniques





- *Float employs 2 Heimann radiometers to measure skin surface temperature*
- *Additional Heimann measures cold sky temperature*
- *Two honeycomb black bodies calibrate radiometers during field exercises*
- *Thermocouple probe measures bulk water temperature*