High Spatial Resolution Thermal Satellite Technologies

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April 22-23, 2002 23
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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

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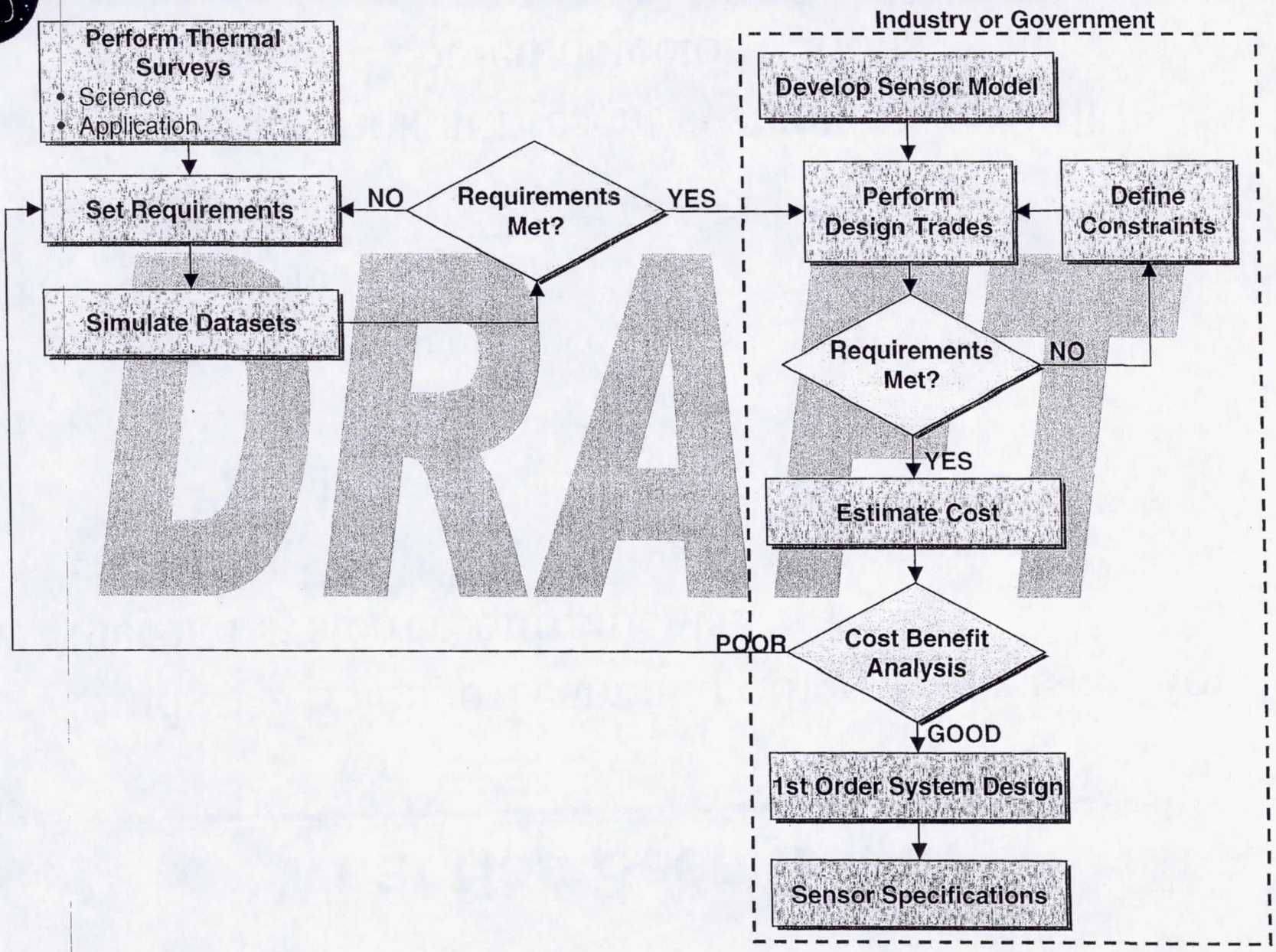
General Approach



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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

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Research or Area of Interest	NEDT (K)	Tmin (K)	Tmax (K)	Radiometric Accuracy (%)	GSD (m)	PSF FWHM (m)	Revisit Time (days)	Spectral Band(s)	Other Requirements	Source
Cloud Detection for LTAP	.5K	198K	310K	5%	60 (ideal) 120 (acceptable)	76 m	per image			GSFC
Monitoring Surface Energy and Water Fluxes 1	~0.2	273	310	1k	~100	~100	~15	1-ok, 2 or more better	day/night pairs are very useful	RIT
Monitoring Surface Energy and Water Fluxes	0.1	263	343	0.5	20	40	7(geostationary is better)	8-14 um, 6 bands equally spaced		JPL
Monitoring Surface Energy and Water Fluxes	0.2 K	250	350	3K (4%)	30m	30m	weekly	10-11microns	10-11AM local time overpass	UW-Madison
Material Transport in Aquatic Systems	~0.3	273	305	1 K Absolute	~100	~100	~15	1-ok, 2 to improve ATM cal would be better		RIT
Material Transport in Aquatic Systems 1	0.25	260	320	0.2 Absolute	60	ETM+	Hourly	Vis/TIR Split Window for ATM		Brown University
Agriculture Studies										JPL
Soil Moisture	0.1	273	313	0.5	20	40	7	same as above		JPL
Soil Moisture1	0.2 K	250	350	3K (4%)	30m	30m	weekly	10-11microns		UW-Madison
Canopy Heat Exchange	0.1	263	343	0.5	20	40	7	same as above		JPL
Canopy Heat Exchange1	0.2 K	250	350	3K (4%)	30m	30m	weekly	10-11microns		UW-Madison
Crop Health	0.1	263	313	0.5	20	40	7	same as above		JPL
Crop Health 1	0.2 K	250	350	3K (4%)	30m	30m	weekly	10-11microns		UW-Madison
Irrigated Crops	0.1	273	313	0.5	20	40	7	same as above		JPL
Irrigated Crops 1	0.5	273	313	Relative is important	120	120		ETM+_		CU-Boulder
Irrigated Crops 2	0.2 K	250	350	3K (4%)	30m	30m	weekly	10-11microns		UW-Madison

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.)

Research or Area of Interest	NEDT (K)	Tmin (K)	Tmax (K)	Radiometric Accuracy (%)	GSD (m)	PSF FWHM (m)	Revisit Time (days)	Spectral Band(s)	Other Requirements	Source
Volcanology	1	275	1500	5	15		8	8.1-8.4, 8.4-8.8 10.2-11		JPL
Volcanology1										
Geologic mapping of surface deposits (e.g., ashfall, lava flows, pre-existing terrain, fumarolic alteration)	3	273K	373K	5%	1m	1.2m	1-1000	0.4-2.5um: 5 bands; 3-5um: 2 bands; 8-12um: 5 bands	Predawn observations are highly desirable for thermal bands	JPL
Low temperature thermal mapping (<100degC)	0.5	273K	373K	1%	1m	1.2m	1-1000	3-5: 2 bands; 8-12: 5 bands	Predawn observations are highly desirable for thermal bands	JPL
Moderate temperature thermal mapping (100-800degC)	5	373K	1073K	5%	3m	3.6m	1-10	3-5: 2 bands	Night observations highly desirable	JPL
High temperature thermal mapping (>800degC)	10	1073	1573	10%	10m	12m	1-3	1-2.5: 3 bands; 3-5: 2 bands	Night observations highly desirable	JPL
Ash plume detection/discrimination/tracking	0.1	190K	273K	<1%	300m	360m	1-3	3-5: 2 bands; 7-14: 10 bands	Day/night observations	JPL
Ash plume temperature/plume height	0.1	190K	773K	<1%	100m	120m	1-3	3-5: 2 bands; 7-14: 10 bands	Day/night observations	JPL
SO_2 plume detection	0.1	190K	773K	<1%	100m	120m	1-3	3-5: 2 bands; 7-14: 10 bands	Day/night observations	JPL
Urban Heat Islands	0.3	275	325	2	5		8	8.1-8.4,10.2-11		JPL
Land Cover / Land Use	0.3-0.5	265	340	±1	60-90	100-150	16 ≤	Current ETM+ Band 6		JPL
Land Cover / Land Use 1	0.5	250	340	0.5 K	60m	ETM+	Seasonal	Vis/TIR 3 TIR Bands for Silicate Feature		Brown University
Geological Mapping	0.3	275	375	2	15		16	5-6 bands		JPL
Urban Land Use	0.5	273	320	1k	~100	~100	~15	1-ok, 2-better		RIT

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 Survey Summary

- 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

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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

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Existing TIR Systems

Satellite	Sensor	Architecture	Band	Spectral Range [μm]	Detector Material	Telescope Diameter [cm]	Spatial Resolution GSD [m]	Spatial Resolution MTF @ Nyquist	Swath [km]	Quant. [bit]	NEΔT [K]
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			"		"	"	0.25
			29	8.400 - 8.700			"		"	"	0.05
			30	9.580 - 9.880			"		"	"	0.25
			31	10.780 - 11.280			"		"	"	0.05
			32	11.770 - 12.270			"		"	"	0.05
			33	13.185 - 13.485			"		"	"	0.25
			34	13.485 - 13.785			"		"	"	0.25
			35	13.785 - 14.085			"		"	"	0.25
			36	14.085 - 14.385			"		"	"	0.35
MTI	MTI	Pushbroom	L	8.00 - 8.40	HgCdTe	36	20		12	12	0.025
			M	8.40 - 8.85			"		"	"	0.027
			N	10.20 - 10.70			"		"	"	0.045
ERS-2	ATSR-2	Conical scanner	1	11.5 - 12.3		11	1100		500	12	0.02
			2	10.6 - 11.3			"		"	11	"

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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

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New Thermal Architectures

- Pushbroom systems and framing cameras can provide significant sensitivity advantages over cross-track scanners
- SNR ~ (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

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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

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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

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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

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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)

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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

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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

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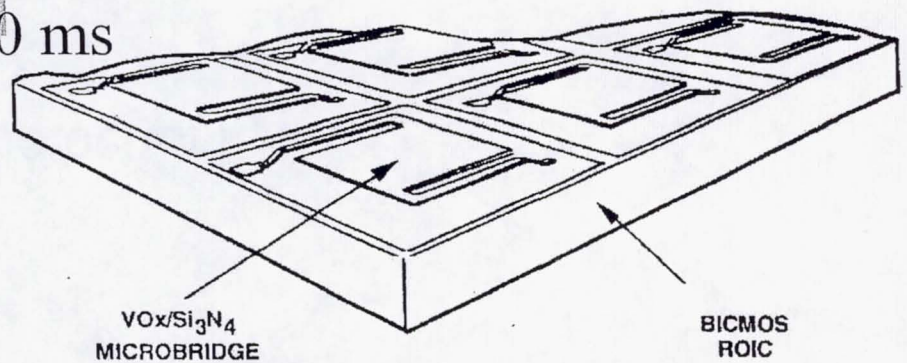

MICROBOLOMETER PIXEL STRUCTURE

W. Radford, D. Murphy, M. Ray, S. Propst, A. Kennedy, J. Kojiro, J. Woolaway, and K. Soch, YEAR. "320 x 240 silicon microbolometer uncooled IRFPAs with on-chip offset correction." SPIE Vol. 2746, pp. 82-92.

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

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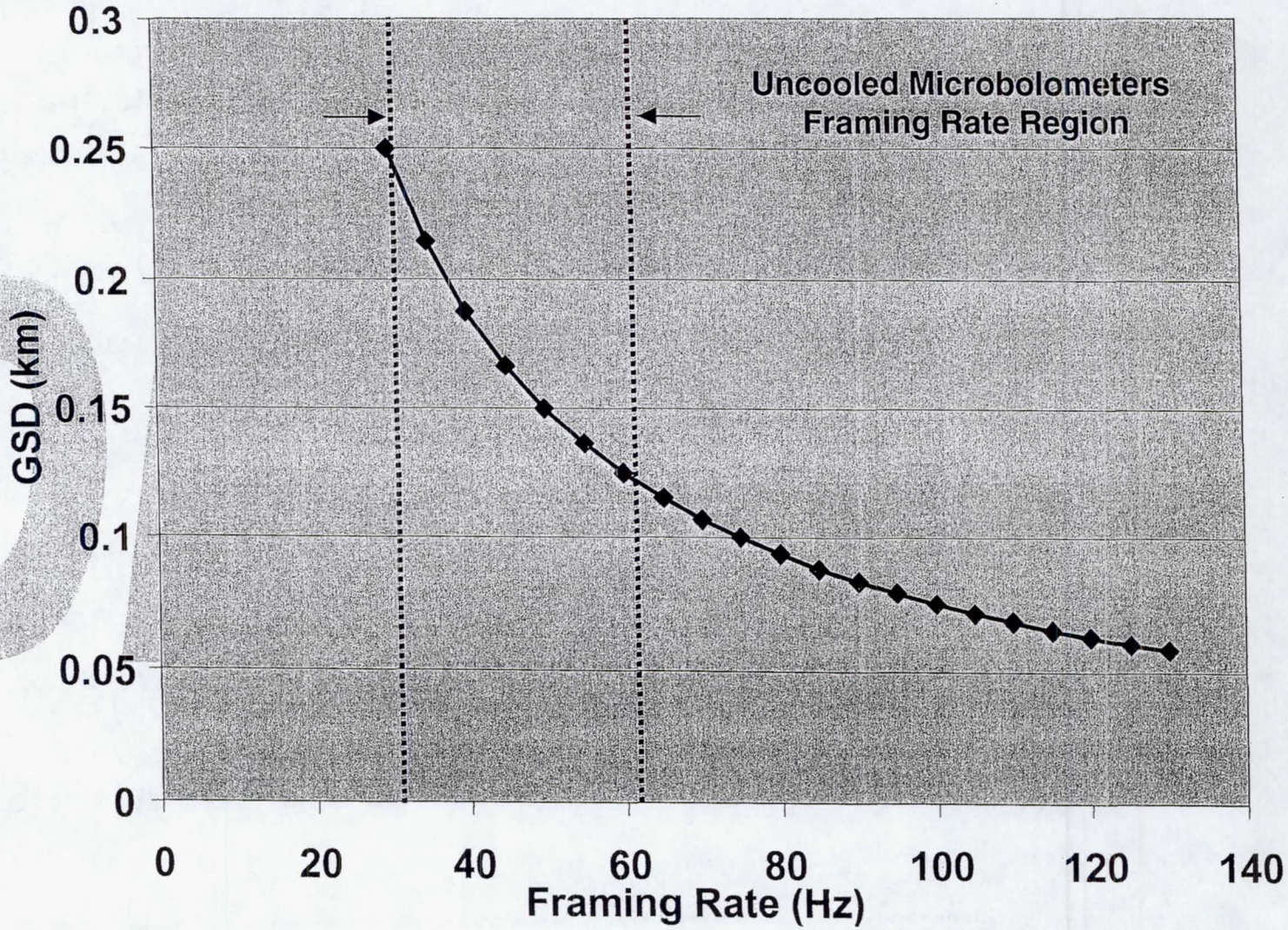
Frame Rate Trades for Landsat Orbit

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

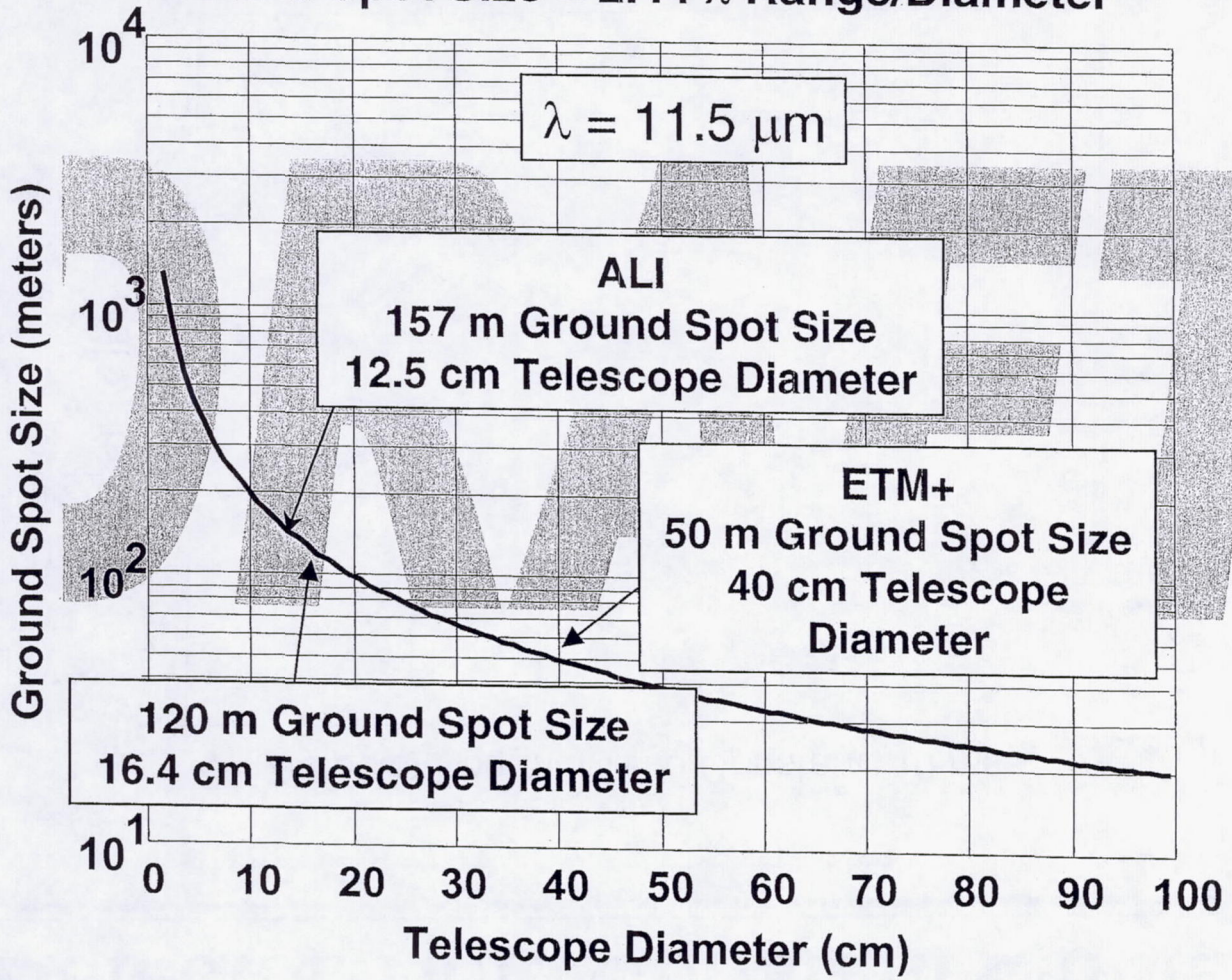


60 Hz framing rate limits GSD to 125 meters

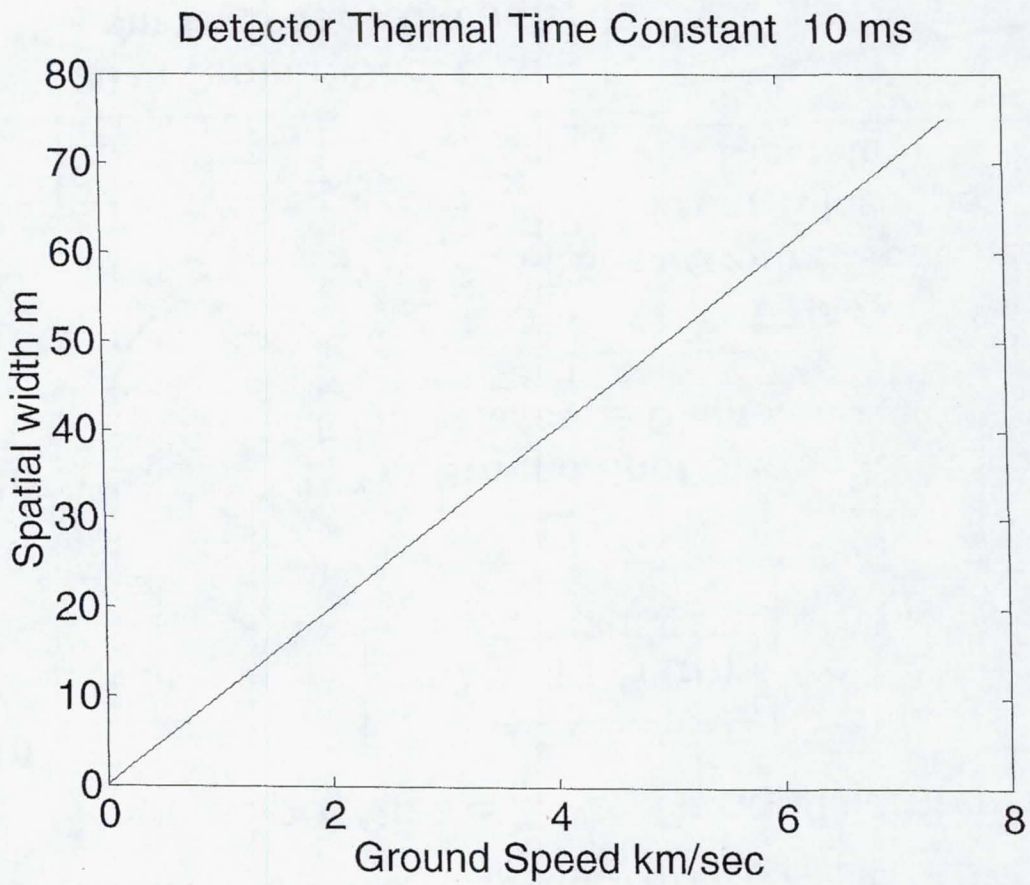
Telescope Diameter Trades

Diffraction limited resolution *(Rayleigh criteria)*

Ground Spot Size = 2.44 λ Range/Diameter

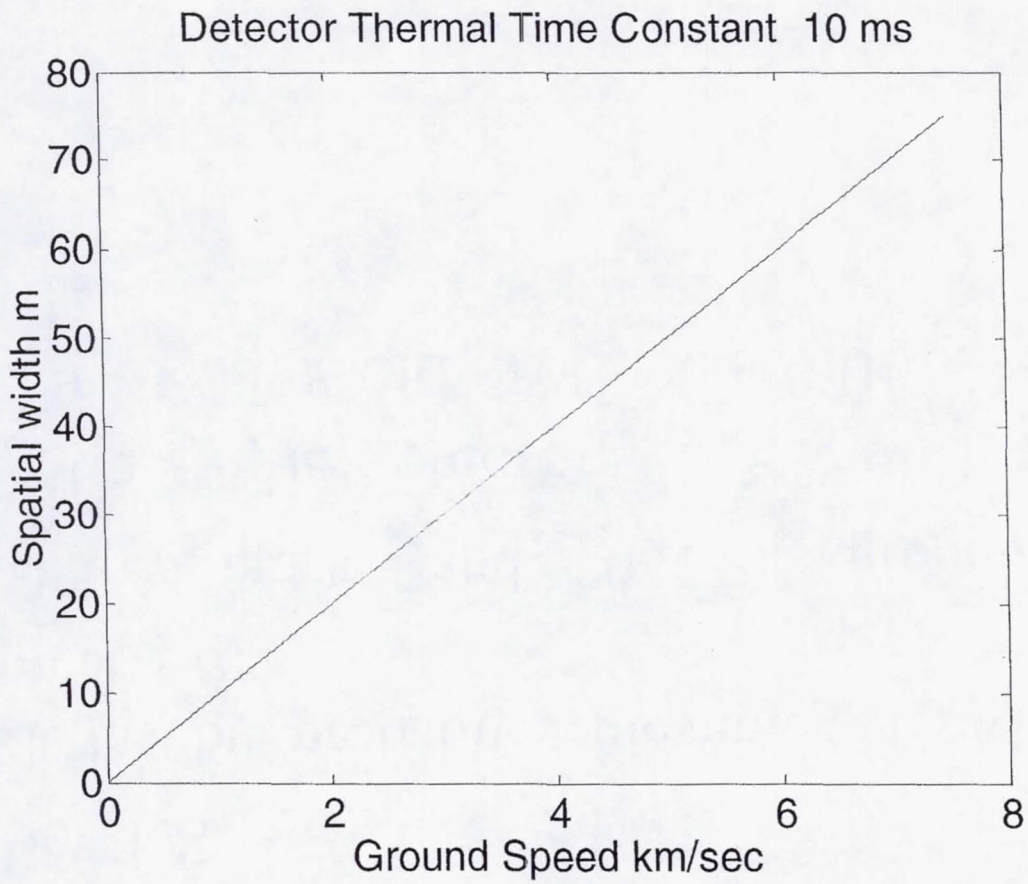


Detector Time Constant Limits



7.5 km/sec produces a 75 m 1/e exponential response

Thermal Time Constant & Spatial Resolution



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!!!!

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Custom Thermal Infrared Sensor (Point Design) (cont.)

- Detector spot size 50.5 μm at l = 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

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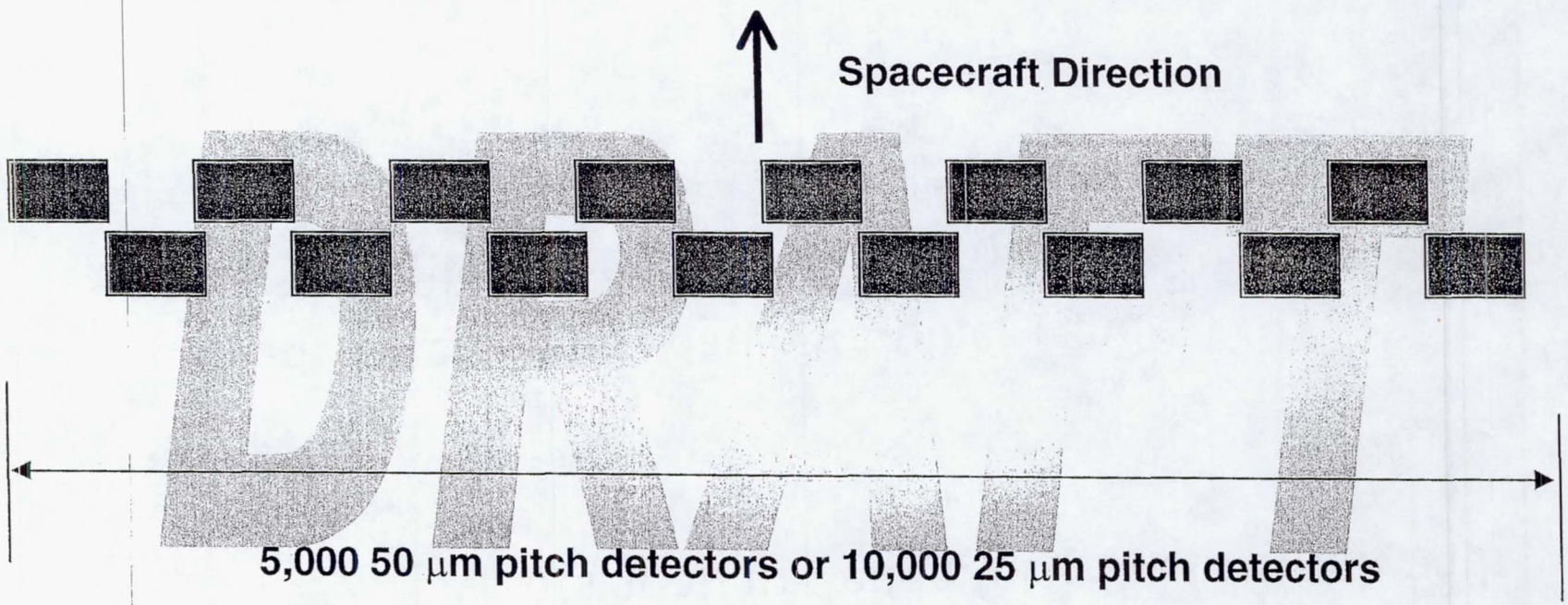
Possible FPA Configuration

Double bank of uncooled microbolometer detector arrays



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

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Simulation

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

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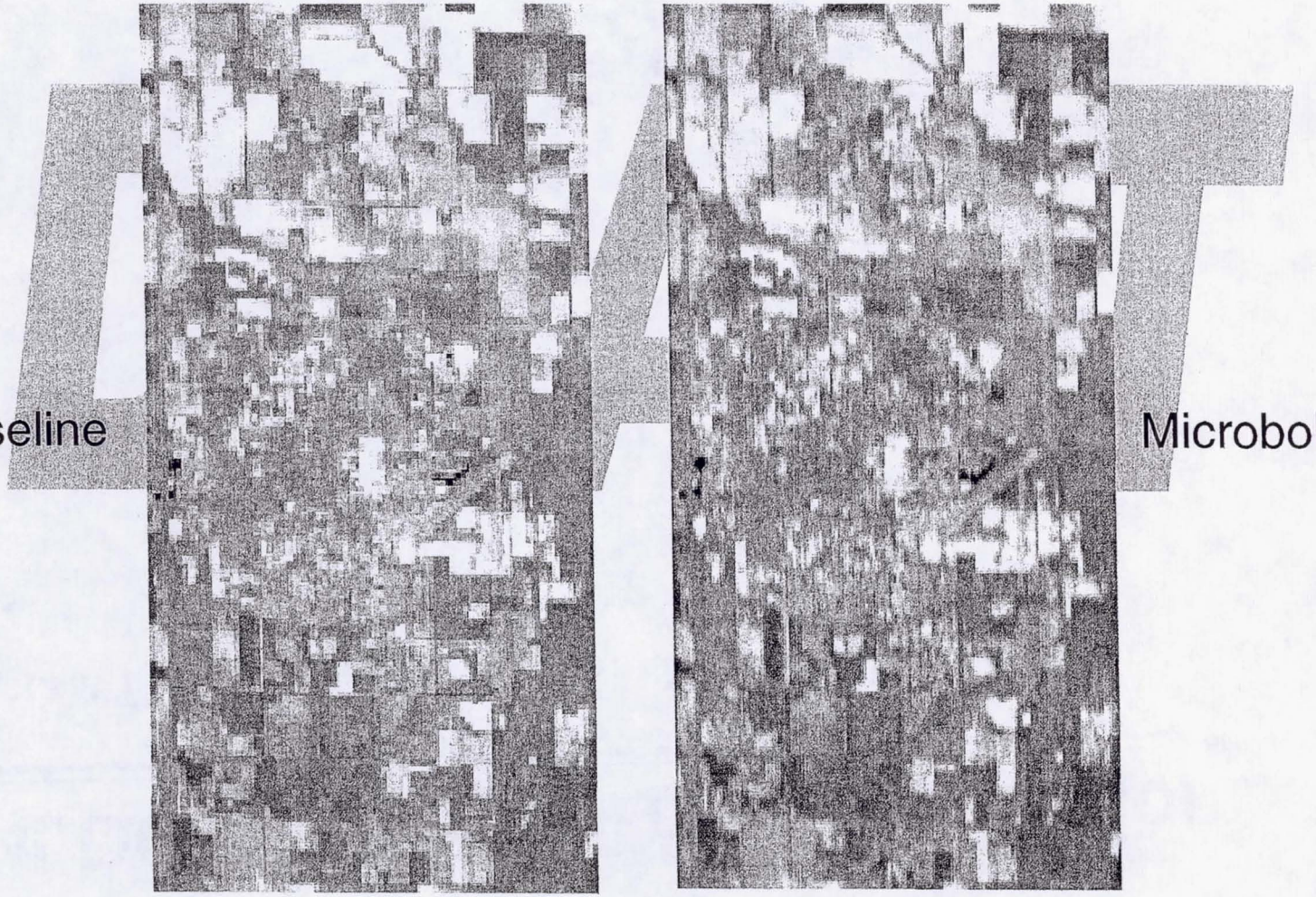
LDCM Thermal Trade Simulation

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

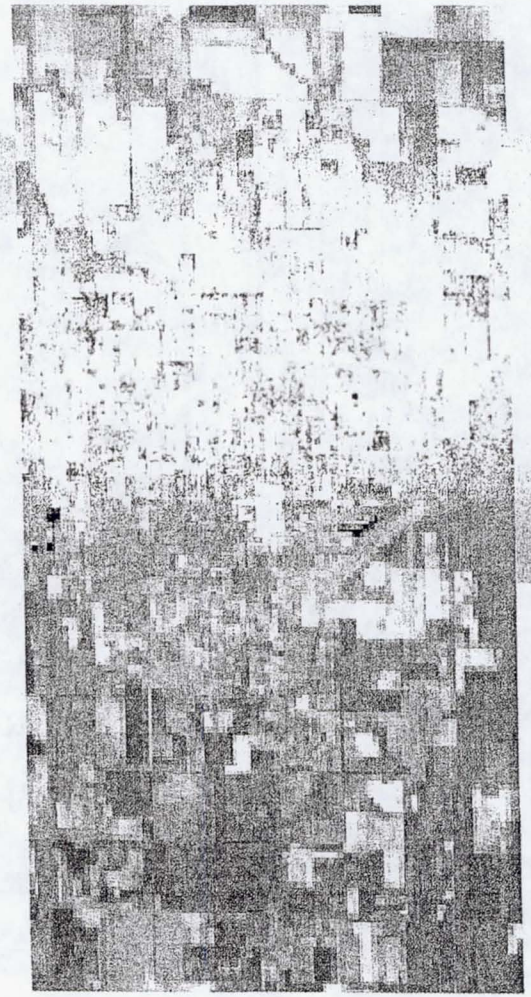
L7 Baseline



Microbolometer

LDCM Thermal Trade Simulation

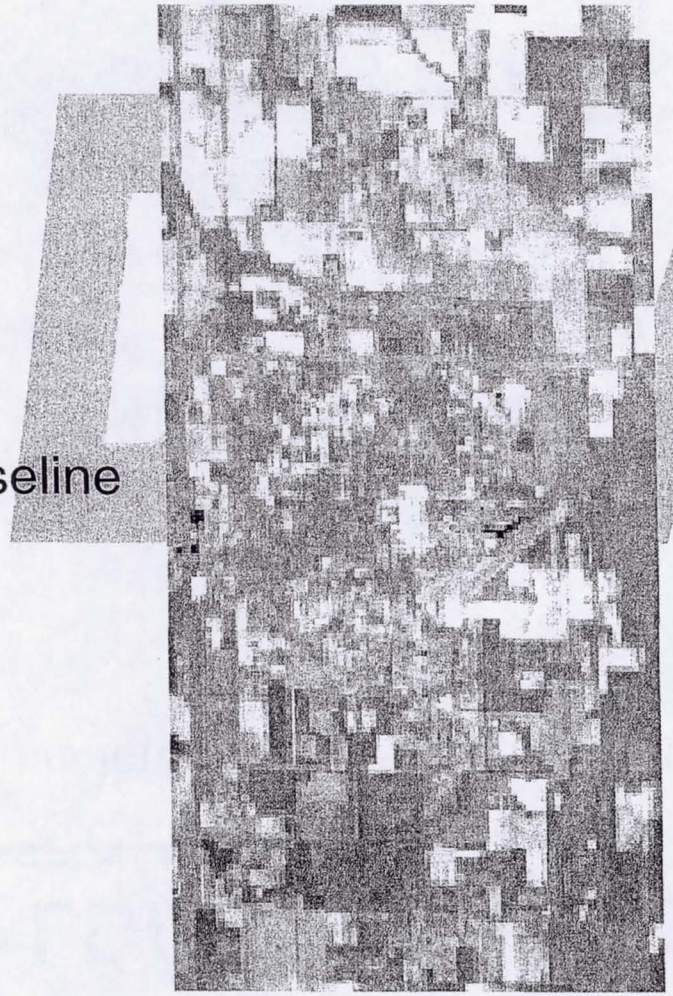
Landsat 7 60 m detector; 60 m PSF; NEDT 0.22 K; decimation (6x6).
Final product: 60 m GSD.

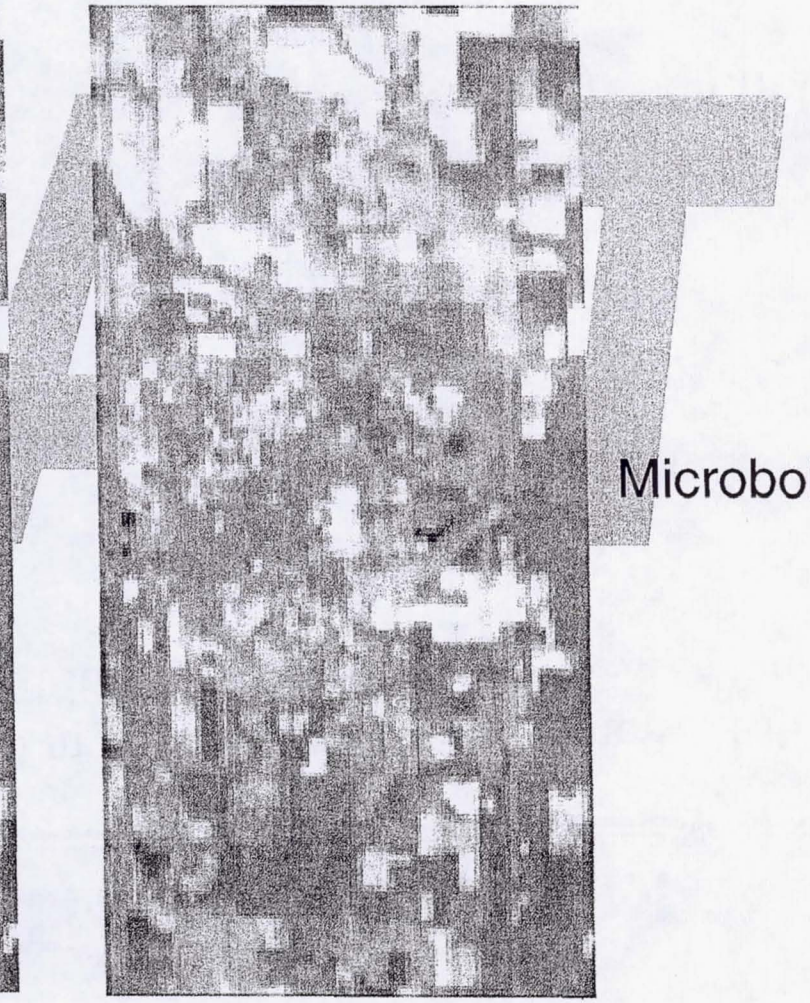


LDCM Thermal Trade Simulation

Microbolometer 60 m detector; 120 m PSF; 125 m smear; NEDT 0.30 K; LPF (2x2); decimation (6x6). Final product: 60 m GSD.

L7 Baseline



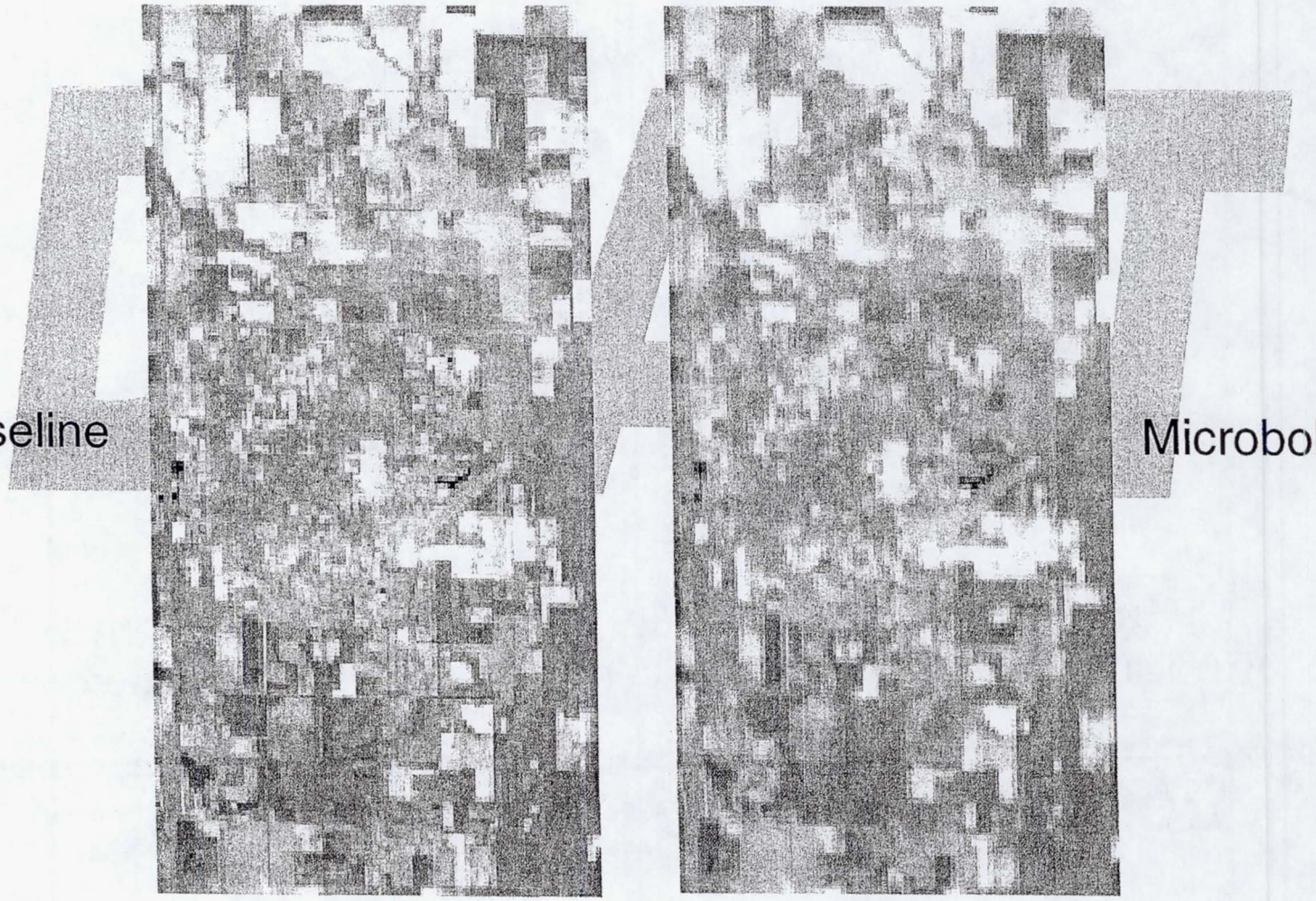


Microbolometer

LDCM Thermal Trade Simulation

Microbolometer 60 m detector; 120 m PSF; 125 m smear; no noise; LPF (2x2); decimation (6x6). Final product: 60 m GSD.

L7 Baseline

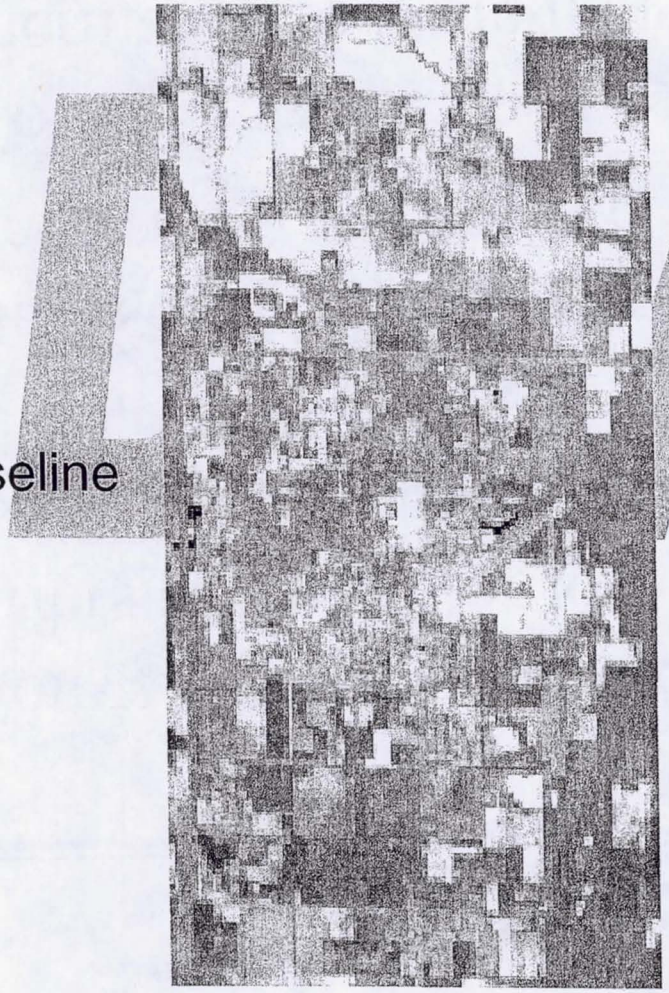


Microbolometer

LDCM Thermal Trade Simulation

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

L7 Baseline



Microbolometer

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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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

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1. REPORT DATE *(DD-MM-YYYY)*
03-04-2003

2. REPORT TYPE

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
High Spatial Resolution Thermal Satellite Technologies

5a. CONTRACT NUMBER
NAS13-650

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Robert Ryan

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Lockheed Martin Space Operations

8. PERFORMING ORGANIZATION REPORT NUMBER
SE-2003-04-00018-SSC

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Earth Science Applications Directorate

10. SPONSORING/MONITOR'S ACRONYM(S)

11. SPONSORING/MONITORING REPORT NUMBER

12. DISTRIBUTION/AVAILABILITY STATEMENT
Publicly Available STI per form 1676

13. SUPPLEMENTARY NOTES
Conference Follow on Next Generation High Resolution Multispectral Thermal Infrared Remote Sensing Workshop

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19b. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Robert Ryan
U		U	UU	35	19b. TELEPHONE NUMBER *(Include area code)* (288) 688-1868