Tools and Methods for the Registration of Remotely Sensed Data

Jacqueline Le Moigne

(NASA Goddard Space Flight Center)

Extracted from Tutorial by A.A. Goshtasby and J. Le Moigne,
"HD-5: Tools and Methods for the Registration and Fusion of Remotely Sensed Data,"
2010 IEEE International Geoscience and Remote Sensing Symposium, IGARSS'10, Hawaii, July 25, 2010

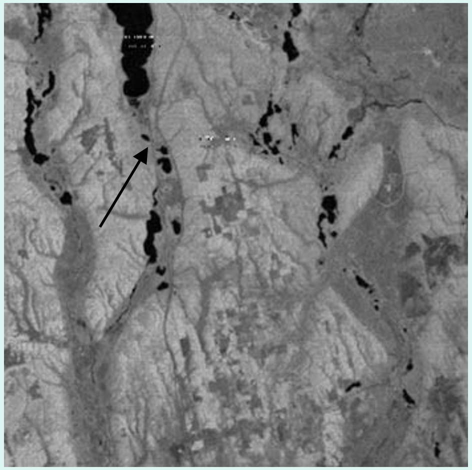
Introduction and background

A digital image: An array of scalars or vectors.

Scalar: *Reflectance, temperature, range*
Vector: *RGB, multispectral, hyperspectral*

126	132	124	120	126	124	116	132	126	106	100	104	122	130	120	108
130	136	124	124	124	126	126	132	128	114	104	104	126	136	122	112
130	136	132	126	104	108	122	122	126	120	108	112	128	130	118	112
132	132	128	84	42	40	54	82	112	118	108	118	136	134	114	114
130	132	132	70	4	0	10	32	64	102	116	116	134	130	114	114
128	134	136	102	44	20	16	10	22	78	116	108	124	120	116	114
132	132	136	128	102	60	20	10	22	60	108	108	120	120	112	110
128	126	124	122	124	110	78	48	34	50	100	98	90	118	122	116
122	126	120	114	122	132	128	108	90	86	106	100	84	114	120	114
126	134	130	124	124	124	124	136	140	134	120	110	110	110	106	102
138	138	136	128	124	124	132	130	132	136	124	106	114	114	108	104

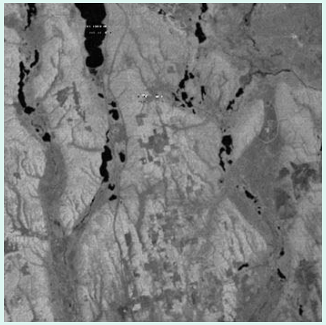
A digital image



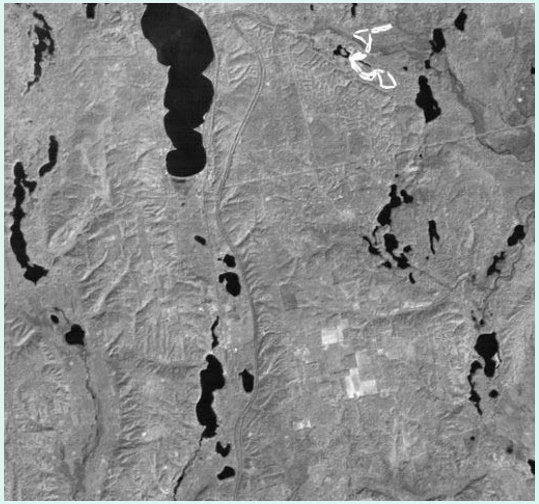
Landsat MSS image, courtesy of NASA

Image registration and image fusion

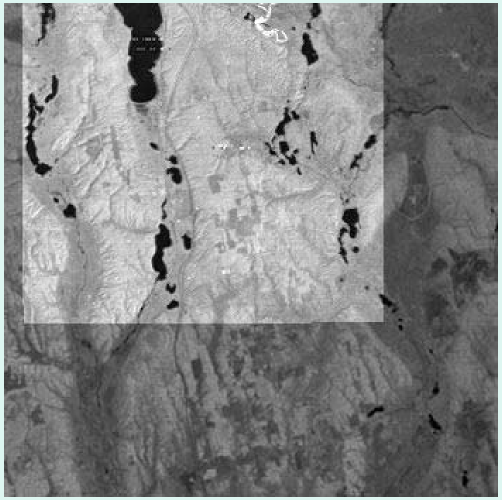
Image registration is the process of spatially aligning two or more images of a scene. This spatial alignment is needed to fuse information in the images.



Landsat MSS



Landsat TM

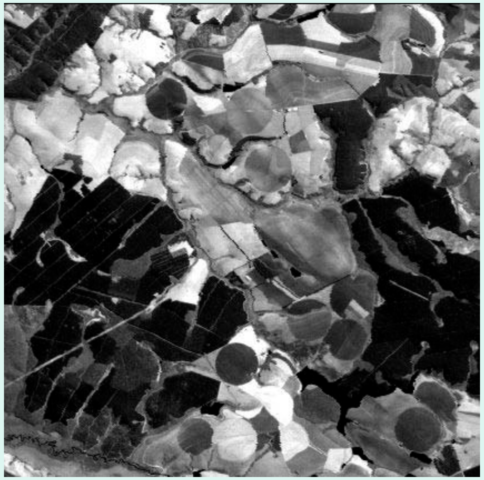


Registered MSS & TM

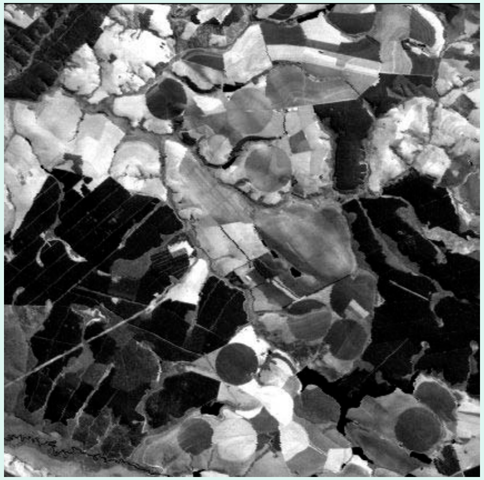
Data courtesy of NASA

Applications of image registration and image fusion

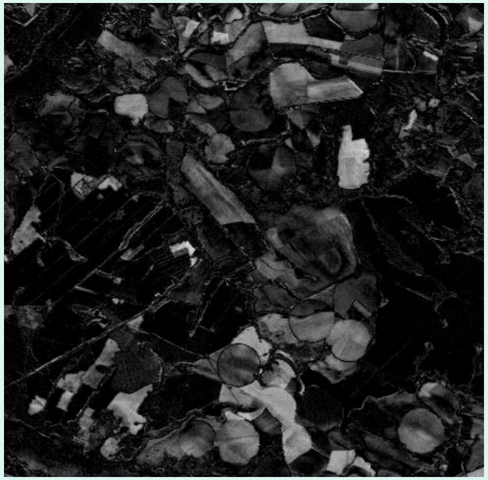
Change detection



Landsat 1



Landsat 2



Change image

Data courtesy of NASA

Fusion of multimodal data

Fused image

Data courtesy of NASA

Landsat TM bands 1 & 7

Image mosaicking

Mosaicked image

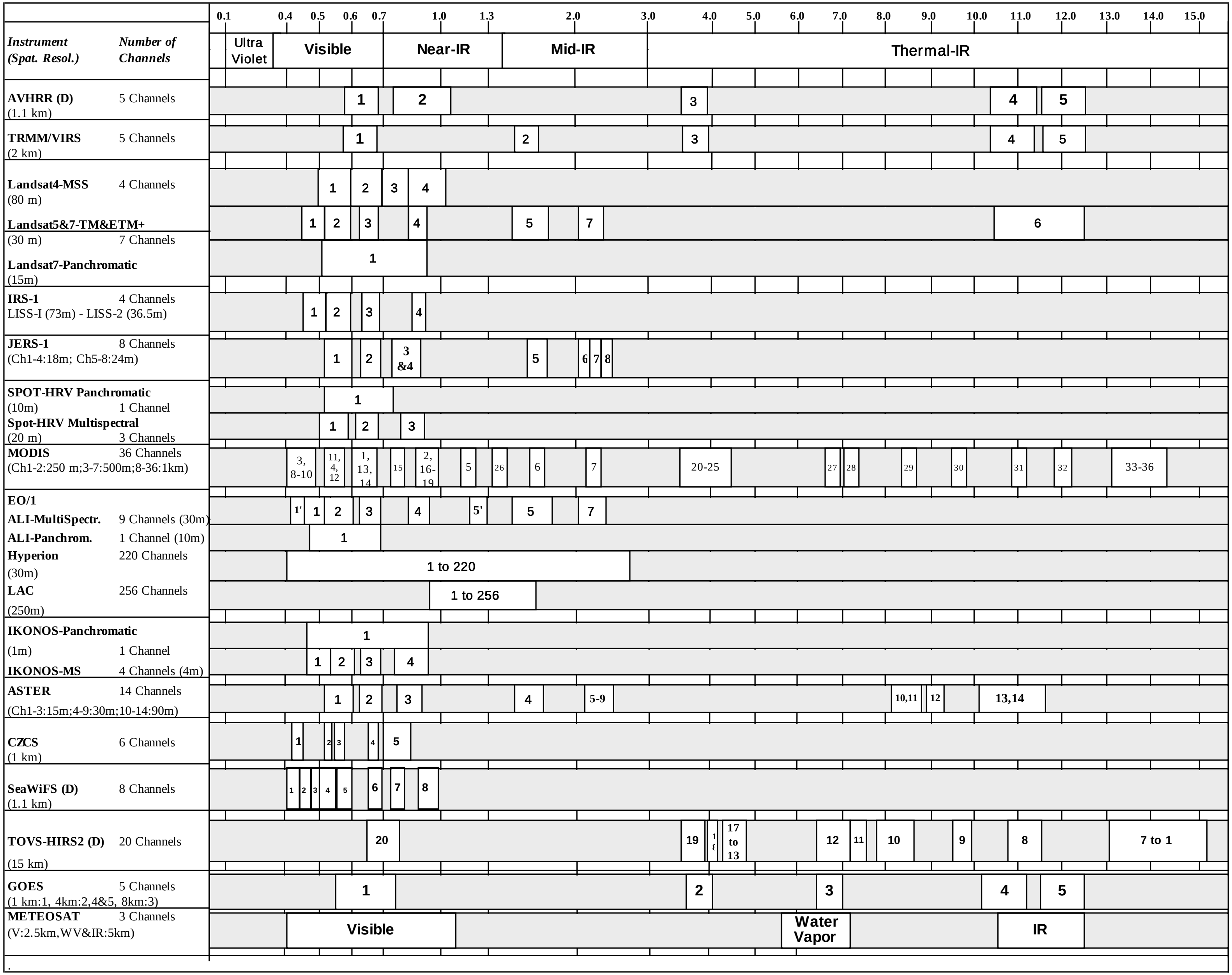
Two aerial images of Honolulu, HI.

Need for Fast and Accurate Image Registration

- Earth Science studies, e.g.:
  - Predicting crop yield
  - Evaluating climate change over multiple scales
  - Locating arable land and water resources
  - Monitoring pollution
  - Understanding the impact of human activity on major Earth ecosystems, etc.

- Global and repetitive measurements from a wide variety of satellite remote sensing systems

Some Examples of Complementary Earth Science Missions



Landsat ETM and IKONOS Registration
US, Virginia Coast

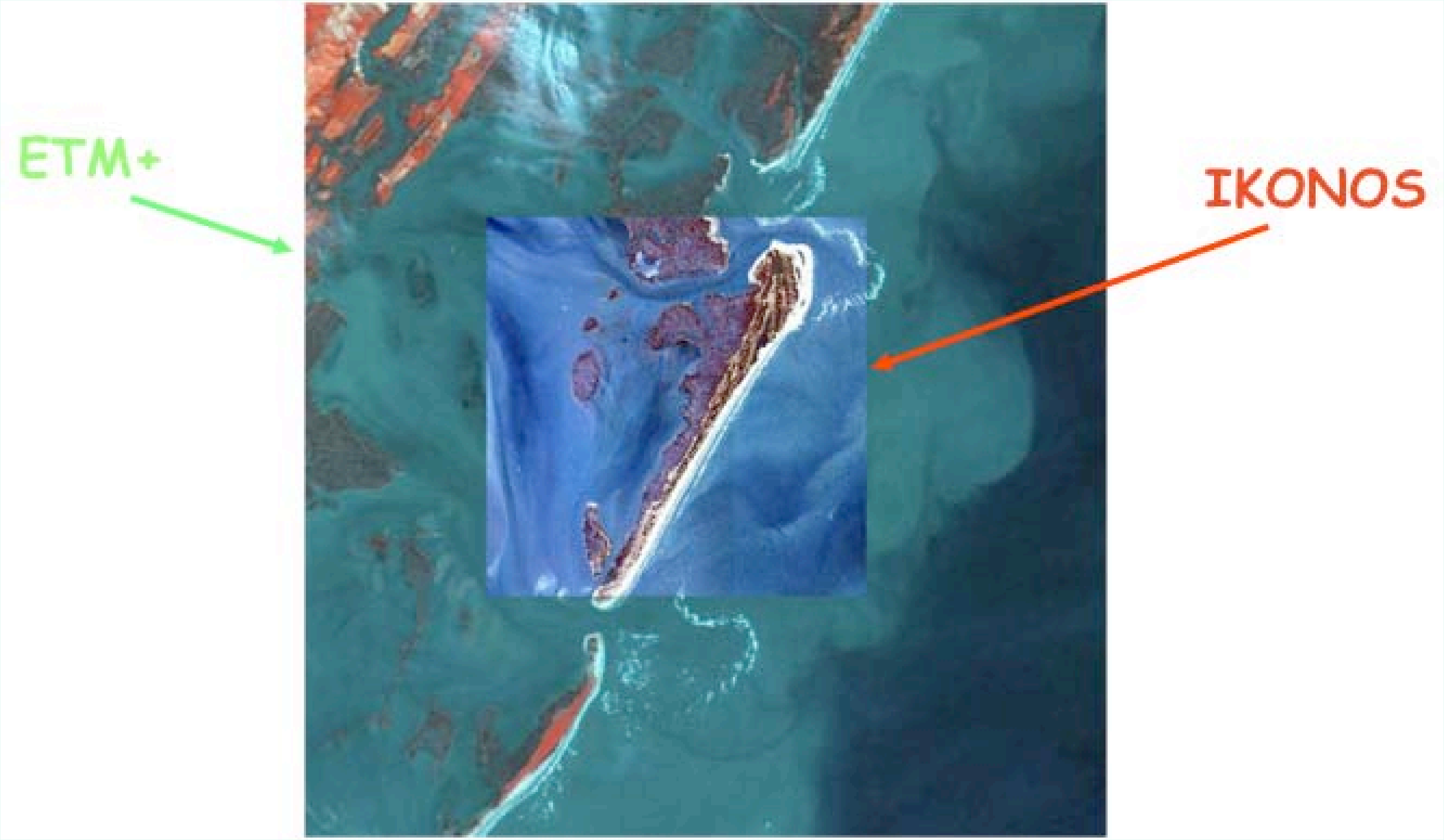
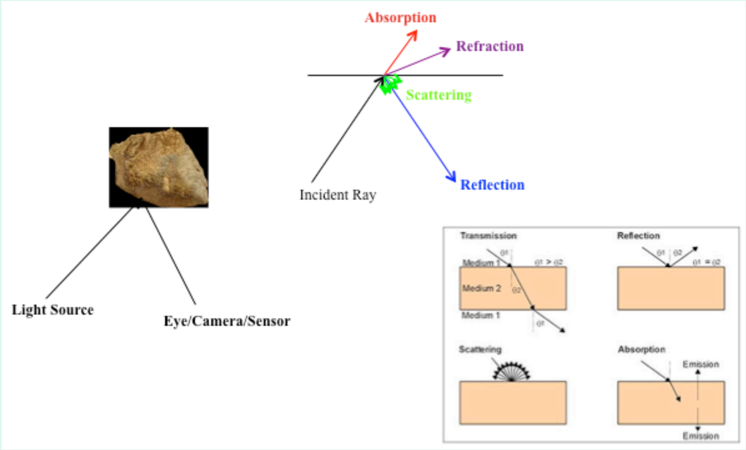
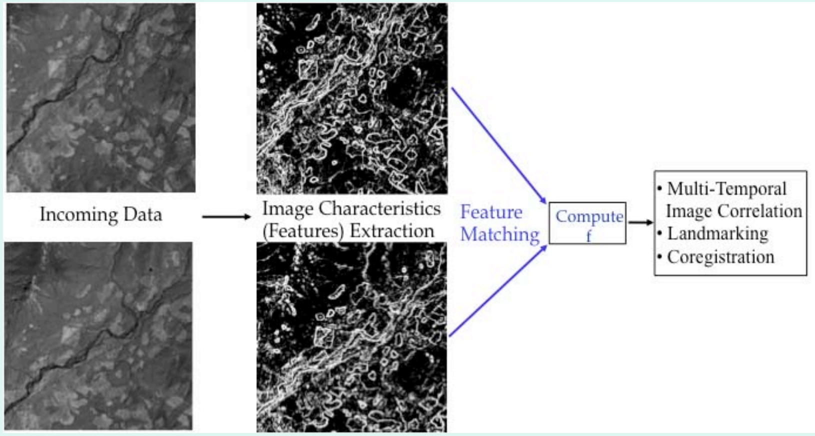
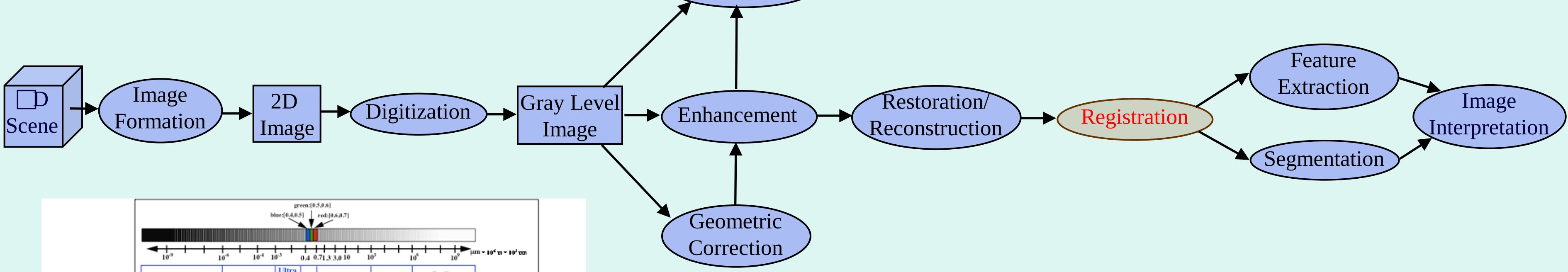
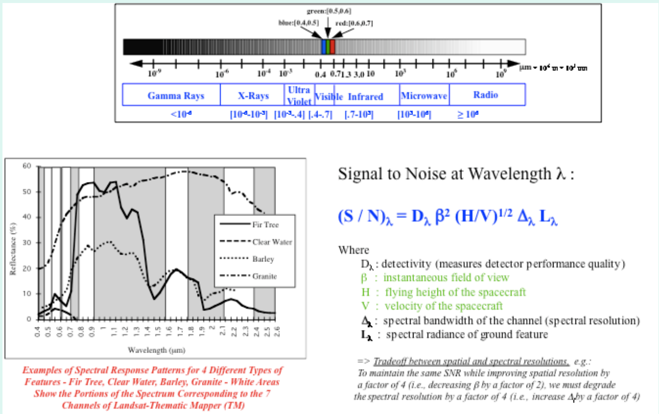


Image Processing Framework for Remotely Sensed Data









The role of Image Registration in the Processing of Remotely Sensed Data

- Essential for spatial and radiometric calibration of multitemporal measurements for creating long-term phenomenon tracking data
- Used for accurate change detection:
  - (Towsnhend et al, 1992) and (Dai & Khorram, 1998): small error in registration may have a large impact on global change measurements accuracy
  - e.g., 1 pixel misregistration error => 50% error in NDVI* computation (using 250m MODIS data)
- Basis for extrapolating data throughout several scales for multi-scale phenomena (distinguish between natural and human-induced)

* Normalized Difference Vegetation Index

Classifying Image Registration Utilization

- *Multimodal registration*, for integrating complementary information from multiple sensors
- *Multitemporal registration*, for change detection and Earth resource surveying
- *Viewpoint registration*, for landmark navigation, formation flying (sensor web) and planet exploration
- *Template registration*, for content-based searching or map updating

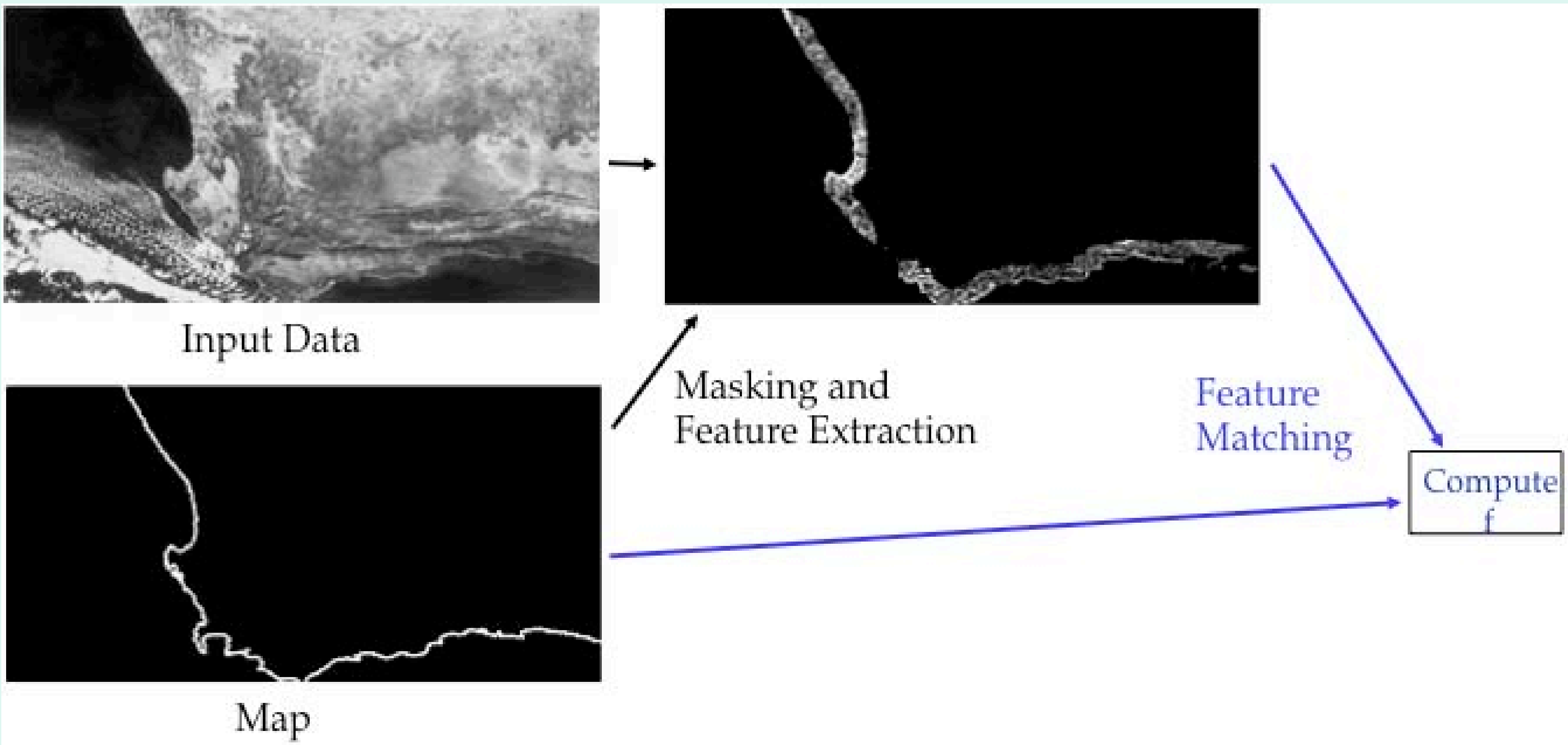
Image Registration Requirements

- *High Accuracy:* Goal of sub-pixel accuracy
- *Consistency:* Robustness to recurring use
- *Speed and High-Level of Autonomy:* Needed for
  - Large amounts of data
  - Near- or Near-real time applications (e.g., disaster management)

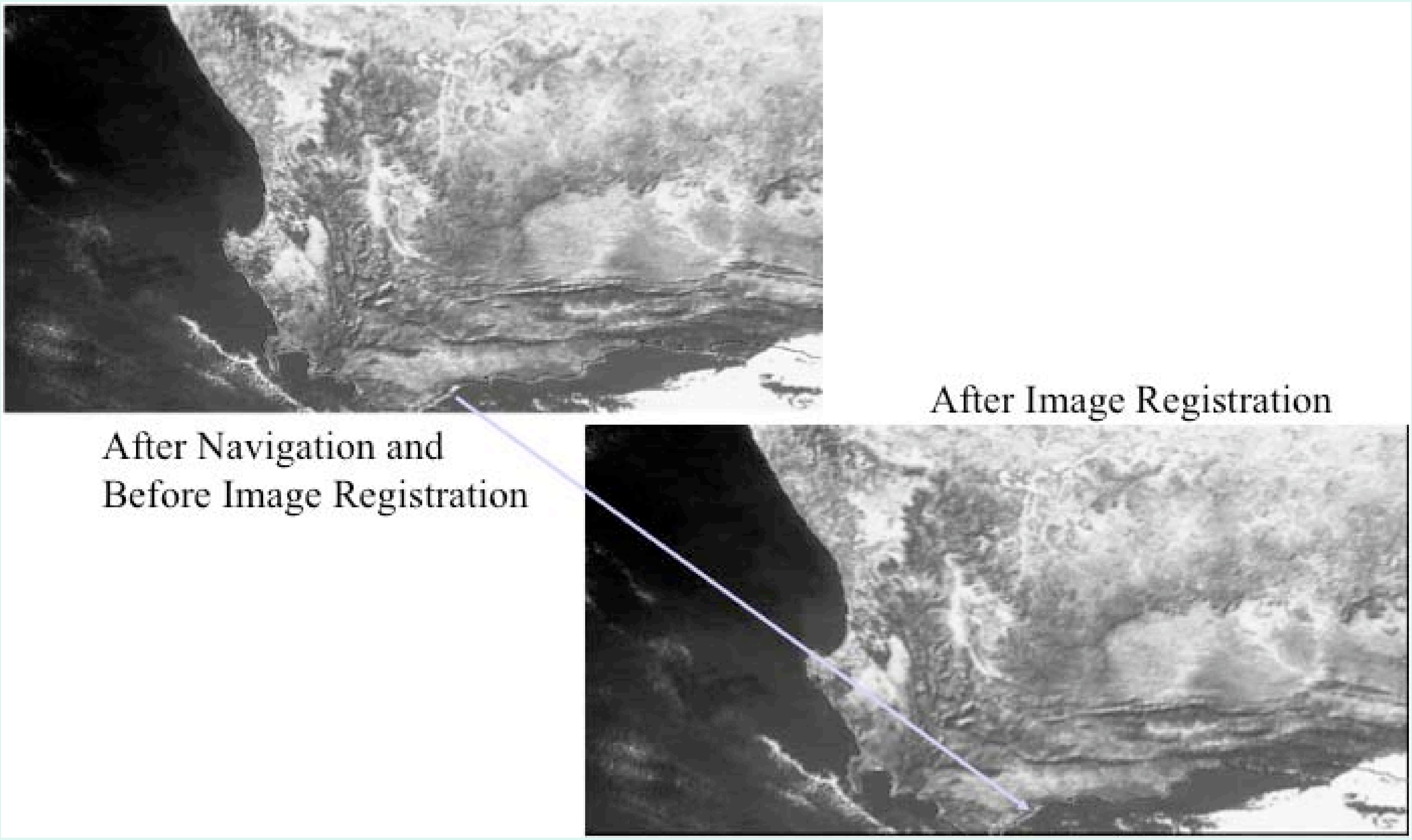
Systematic and Precision Corrections

- Navigation or Model-Based Systematic Correction
  - Orbital, attitude, platform/sensor geometric relationship, sensor characteristics, Earth model, etc.
- Image Registration or Feature-Based Precision Correction
  - Navigation within a few pixels accuracy
  - Image registration using selected features (or Control Points) to refine geo-location accuracy
- Two approaches
  1. Image registration as post-processing
  2. Navigation and image registration in a closed loop

Systematic and Precision Corrections
AVHRR Example



Systematic and Precision Corrections AVHRR Example (cont.)



Challenges in Registration of Remotely Sensed Data

- Image registration developed in other domains (medical, military, etc.) not always applicable
  - Variety in the types of sensor data and the conditions of data acquisition
  - Size of the data
  - Lack of a known image model
  - Lack of well-distributed "fiducial point" resulting in the difficulty to validate image registration methods in the remote sensing domain
    - » use synthetic data, "ground truth", finer resolution data and "circular" registrations

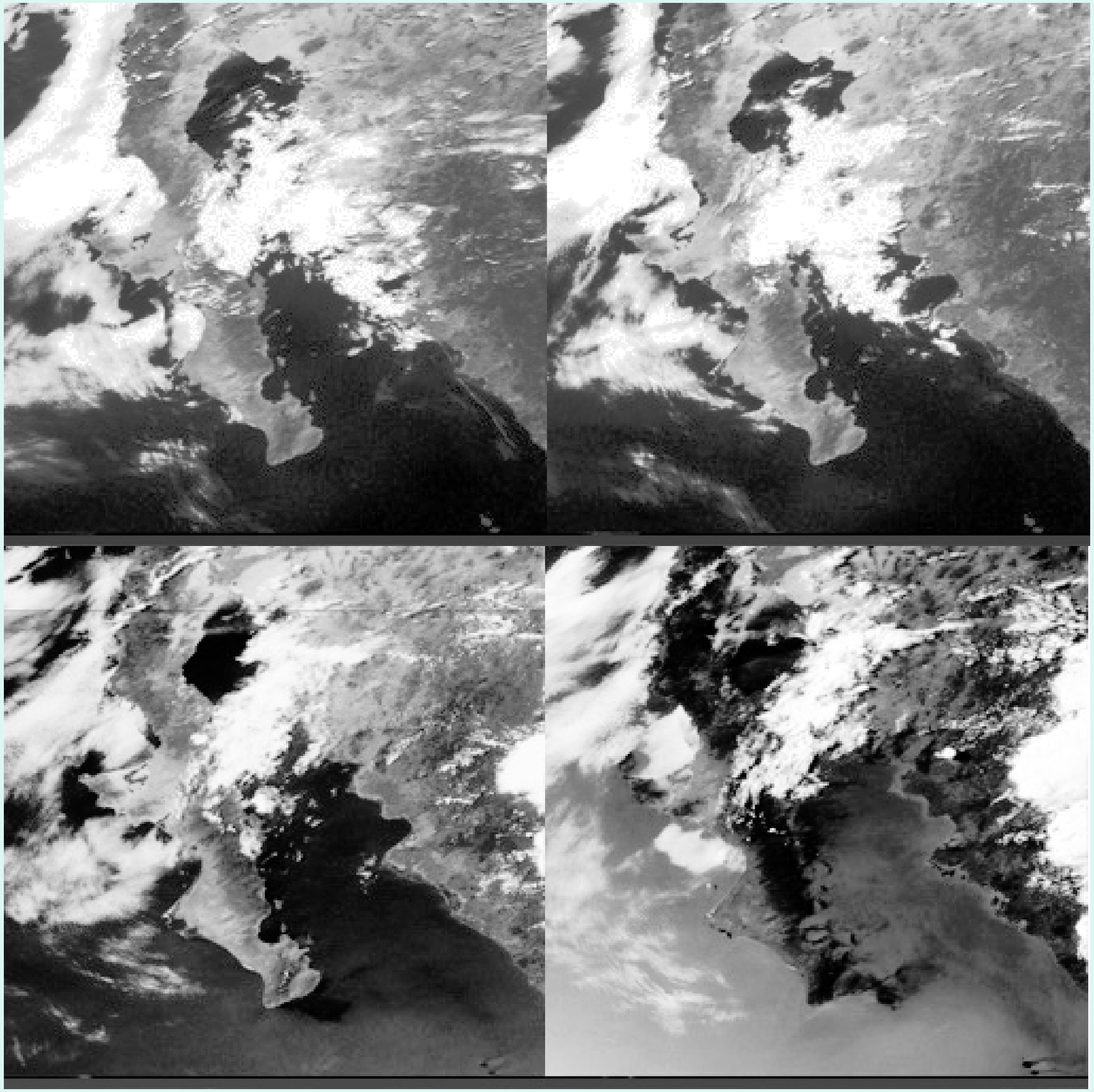
Other Challenges Facing Image Registration In the Remote Sensing Domain

- Navigation error
  - Historical satellites (e.g., Landsat-5 compared to Landsat-7)
  - Following a maneuver (e.g., star tracking)
  - Need for sub-pixel accuracy
- Atmospheric and cloud interactions
- Multitemporal effects
- Terrain/relief effect
- Multisensor data with different spatial and spectral resolutions

Atmospheric and Cloud Interactions

Baja Peninsula, California; 4 different times of the day (GOES-8)

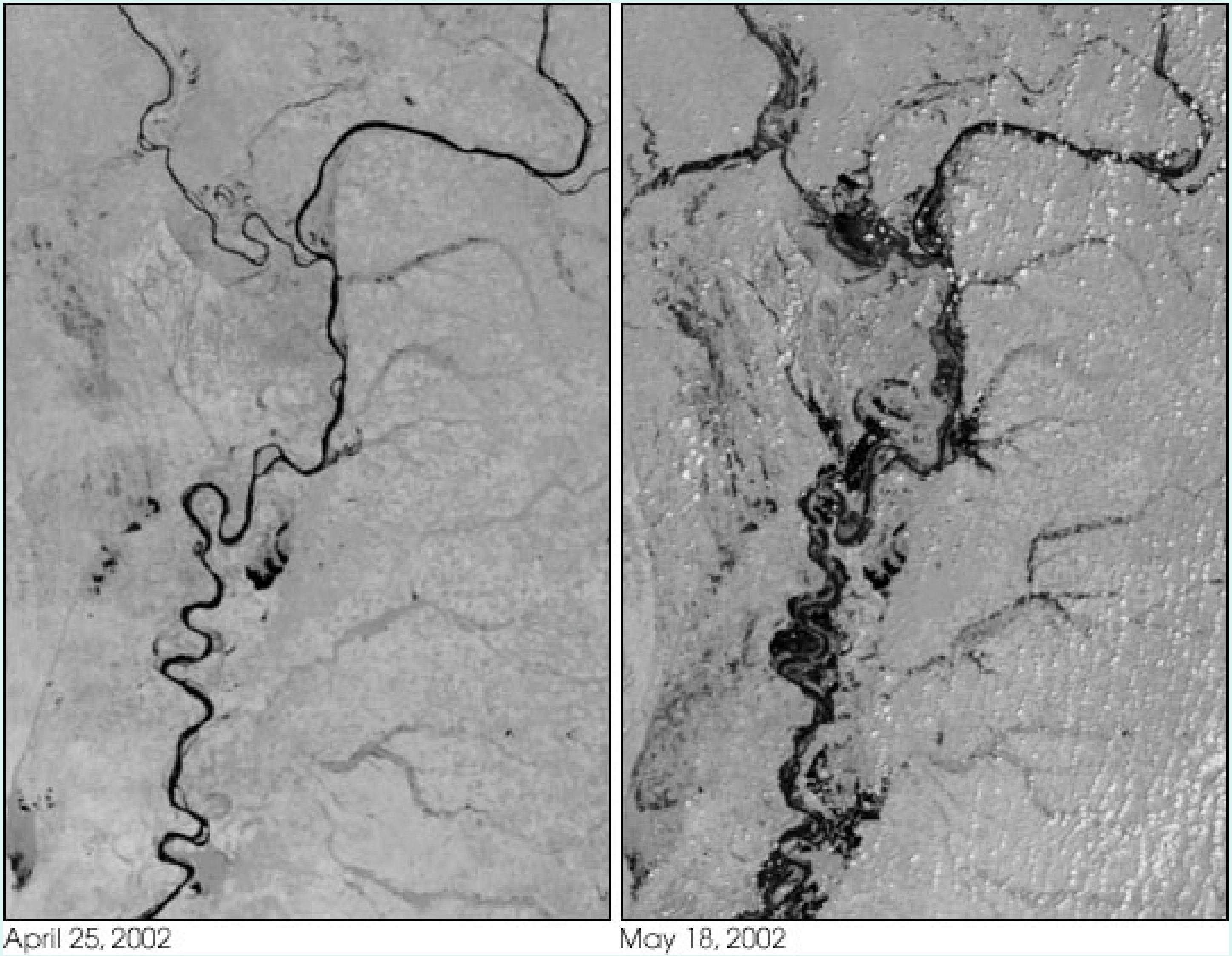
(Reproduced from Le Moigne & Eastman, 2005)



Multitemporal Effects

Mississippi and Ohio Rivers before & after Flood of Spring 2002 (Terra/MODIS)

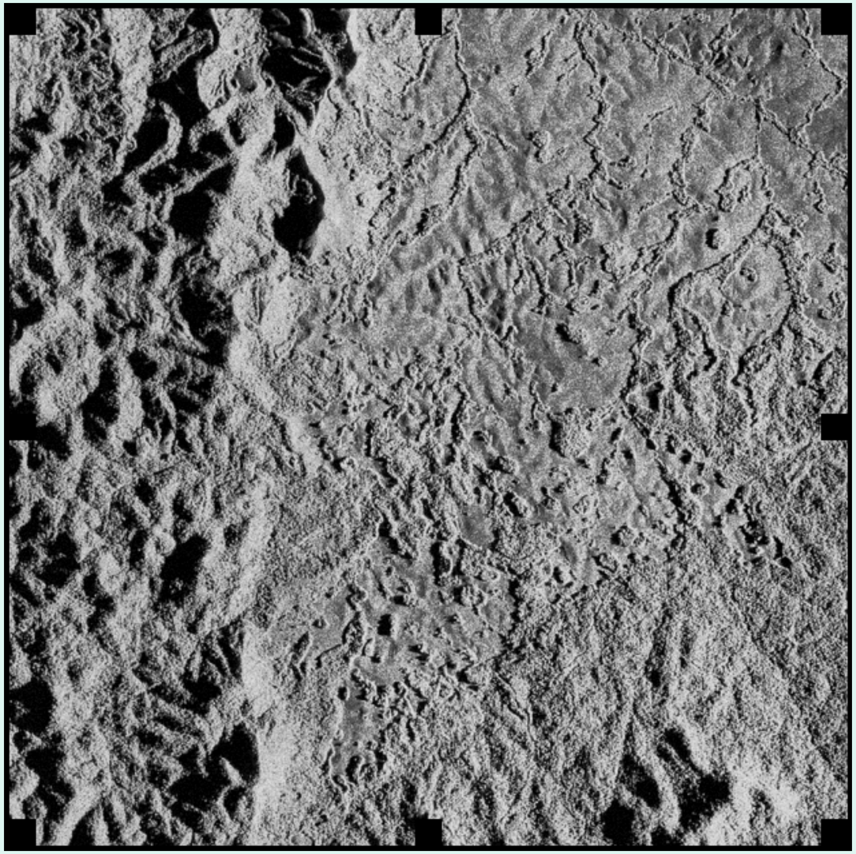
(Reproduced from Le Moigne & Eastman, 2005)

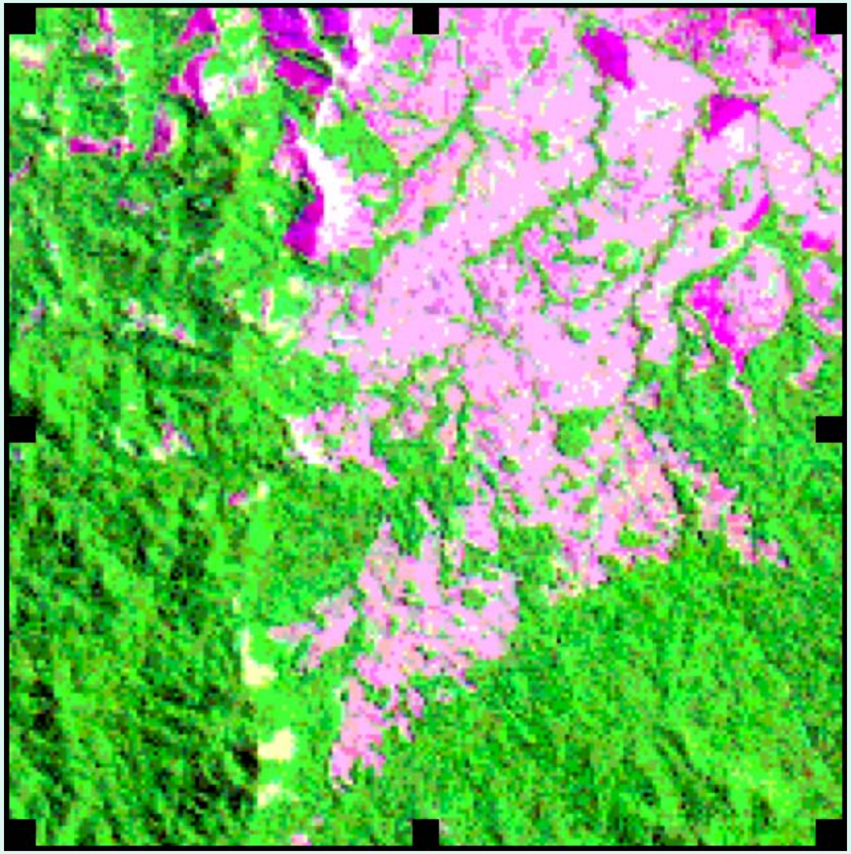


Relief Effect

SAR and Landsat-TM Data of Lopé Area, Gabon, Africa

(Reproduced from Le Moigne et al., 2001)





Precision Correction in Operational Systems

- Operational Environment
  - Platform/sensor models integrated
  - Historical data available for statistics/modeling
  - Robustness and consistency over time is a requirement
- Operational Needs
  - Systematic correction (close to 1 pixel) using navigation model
  - Precision correction (less than 1 pixel) used to:
    - Check navigation model and ephemeris data
    - Perform band to band geometric calibration
    - Perform radiometric calibration of new sensor (relative to old one)
- General Characteristics
  - Use database of Ground Control Points (GCP) or Chips
  - Normalized Cross-Correlation (NCC) is the most common similarity measure
  - Digital Elevation Model (DEM) is rarely integrated in the registration process
  - Cloud masking usually integrated
  - Errors in the [0.15-0.5] range

Precision Correction in Operational Systems

Some Examples - Highlights

- *AVHRR:* AUTONAV algorithm computes attitude corrections using Maximum Cross-Correlation (MCC) method between sequential images
- *GOES/METEOSAT:* CPs and NOAA Shoreline database (GSHHS) used to match edges extracted from meteorological images
- *LANDSAT:* CP image chips (1m orthorectified) using Gaussian pyramid, automatic Moravec window extraction and NCC or Mutual Information
- *MISR:* Database of 120 GCPs (each a collection of nine geolocated image patches of a well-defined and easily identifiable ground features, from Landsat, terrain-corrected, data) &ray casting simulation software
- *MODIS:* Biases and trends in the sensor orientation determined from automated control point (CP) matching and removed by updating models of the spacecraft and instrument orientation; finer CGPs from Landsat TM and ETM aggregated using PSFs and correlated with NCC
- *SEAWIFS:* Reference catalog of islands GCPs and matching using spectral classification and clustering of data, "nearest neighbor" and pattern matching techniques
- *SPOT:* Reference3D™ using DEM ortho-rectified simulated reference image in focal plane geometry, matching of input image to simulated using NCC and resampling into a cartographic reference frame
- *VEGETATION:* Database of CPs from SPOT for VEGETATION1 and VEGETATION1 for VEGETATION2; Matching by NCC

Image Registration at NASA GSFC

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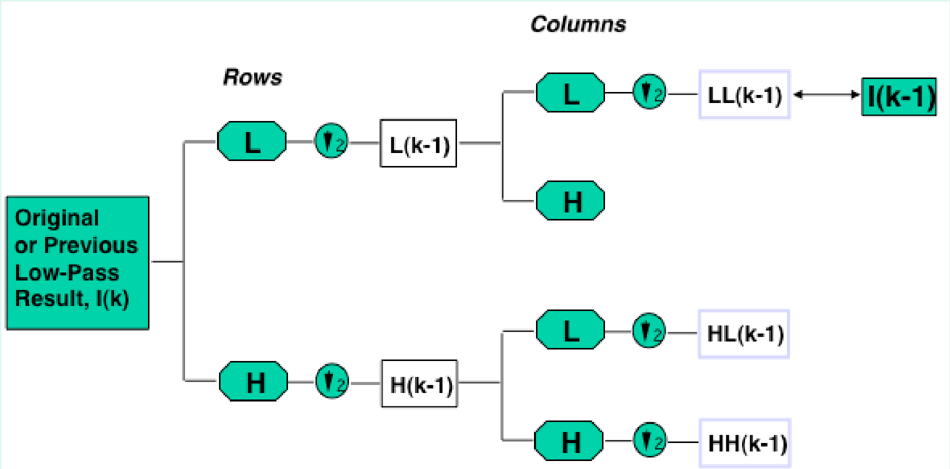
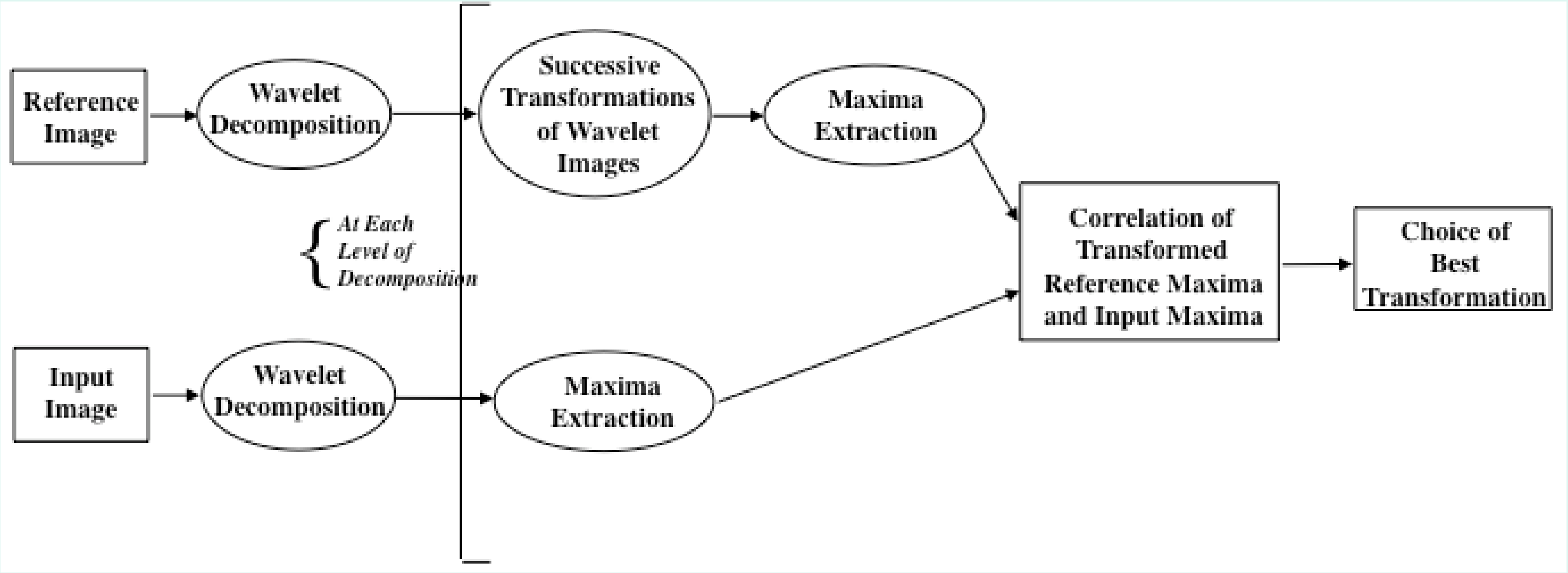
Orthogonal Wavelet Image Registration

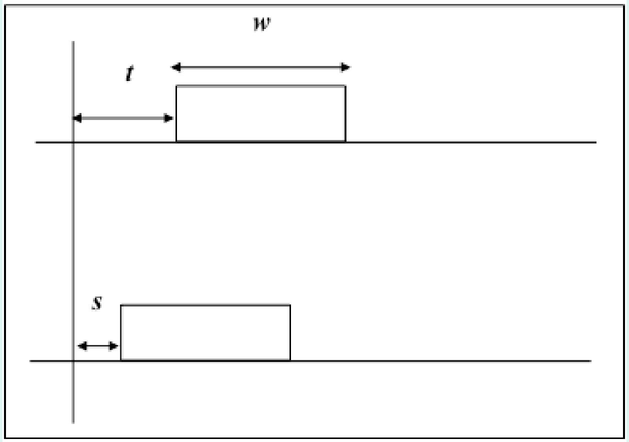




Orthogonal Wavelet Image Registration

Rotation and Translation Invariance Issues

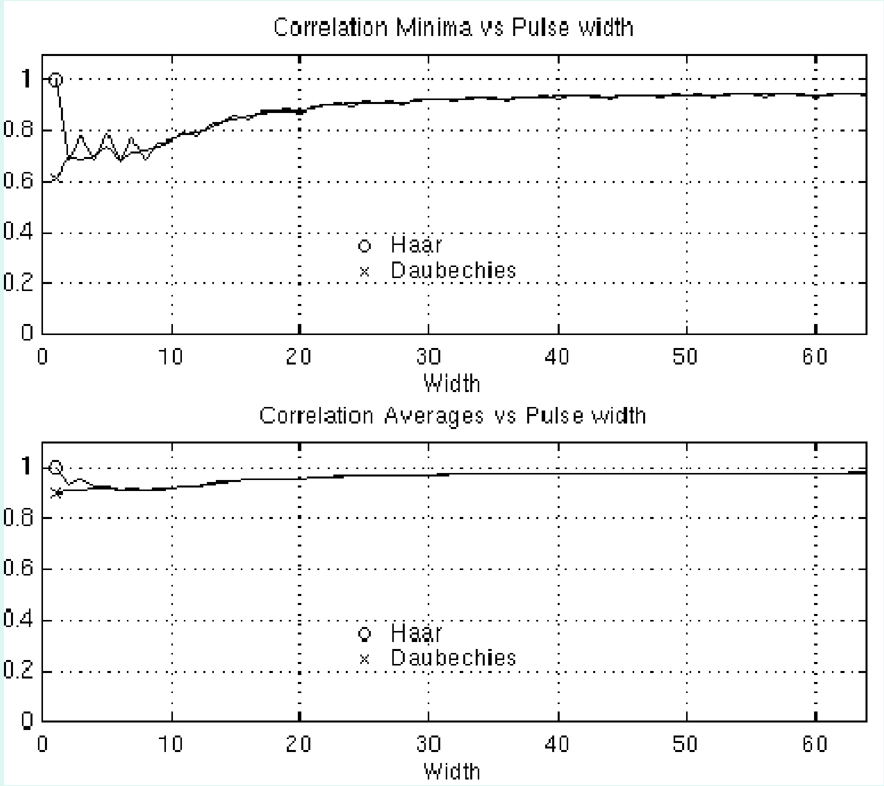
- Nyquist criterion, sample signal at least twice frequency of highest frequency component
  - in og wavelets, signal changes within or across subbands with subsampling
- Study for Shift Sensitivity (Stone et al, 1999):
  - low-pass subband relatively insensitive to translation, if features are twice the size of wavelet filters
  - high-pass subband more sensitive but can still be used.



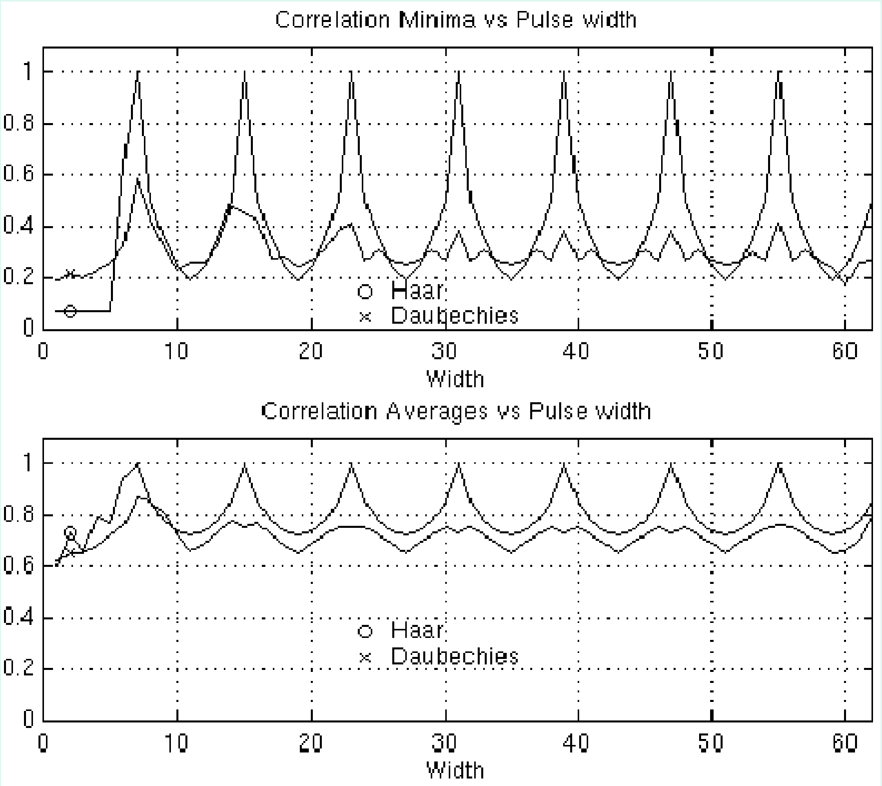
Correlate Wavelets of Two Pulses

Orthogonal Wavelet Image Registration

Rotation and Translation Invariance Issues (cont.)



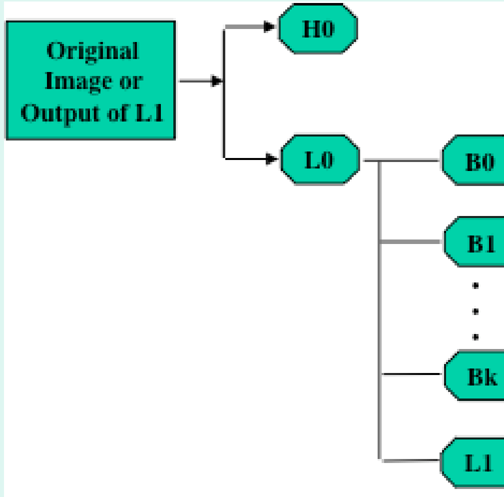
Translation Sensitivity Low-Pass Level 3



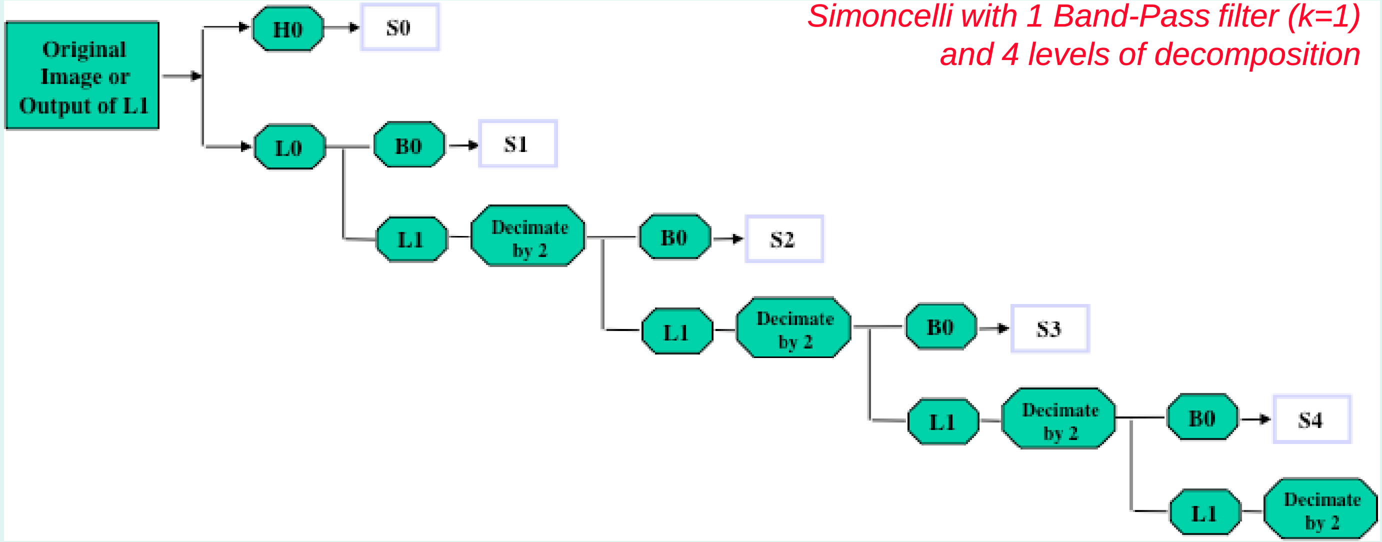
Translation Sensitivity High-Pass Level 3

Rotation- and Translation-Invariant Pyramids

- Simoncelli:
  - Relax critical sampling condition of wavelet transforms
  - Overcomplete representation by 4k/3 (k: number of band-pass filters)
- Splines:
  - Recursive anti-aliasing prefiltering followed by a decimation of 2
  - Only low-pass bands



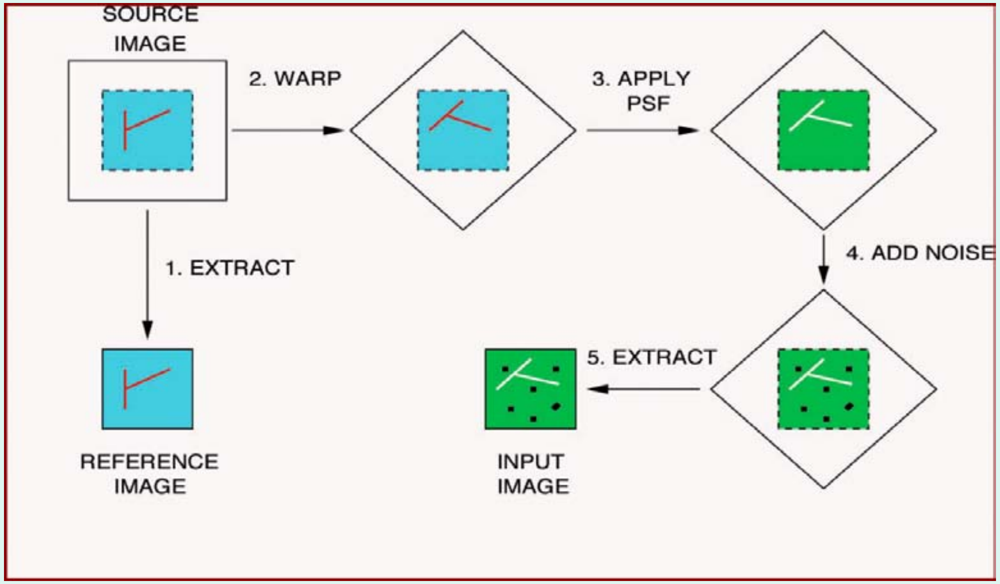
Simoncelli Steerable Pyramid



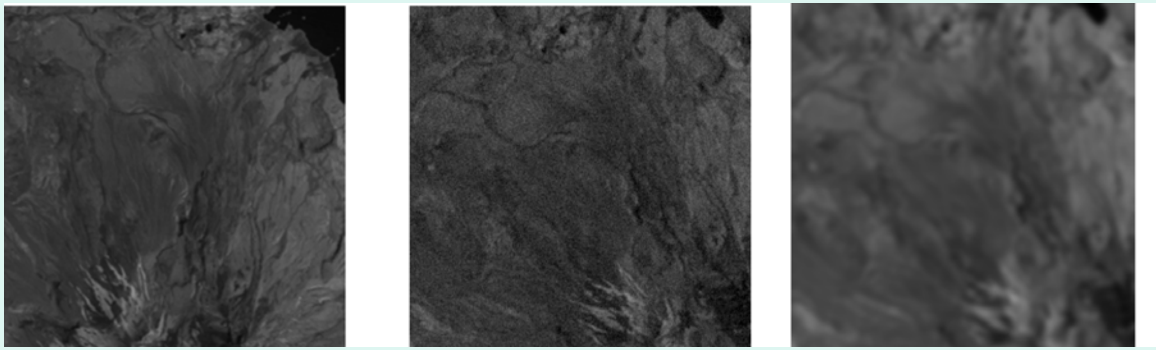
Simoncelli with 1 Band-Pass filter (k=1) and 4 levels of decomposition

Comparative Studies Using Synthetic Data

(Reproduced from Zavorin & Le Moigne, 2005)



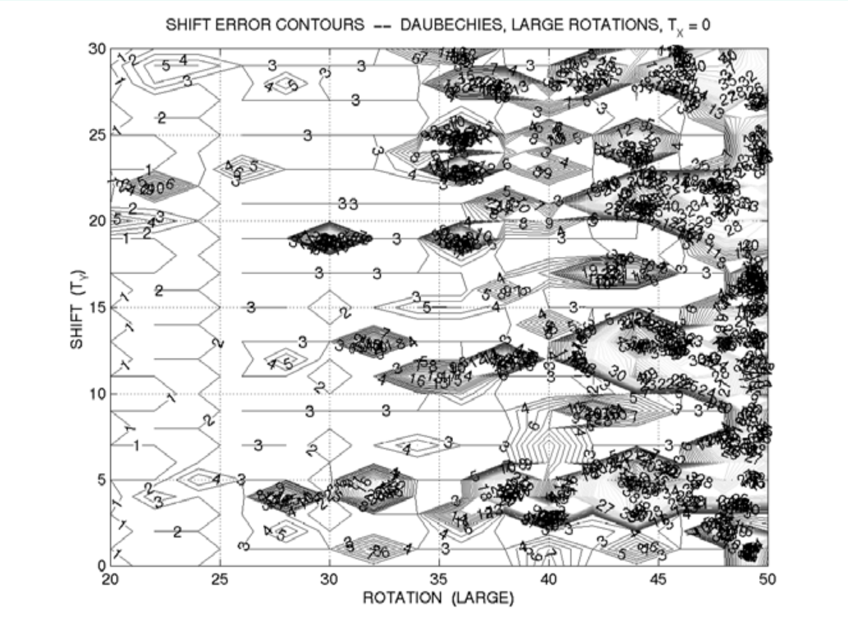
Synthetic Image Generation



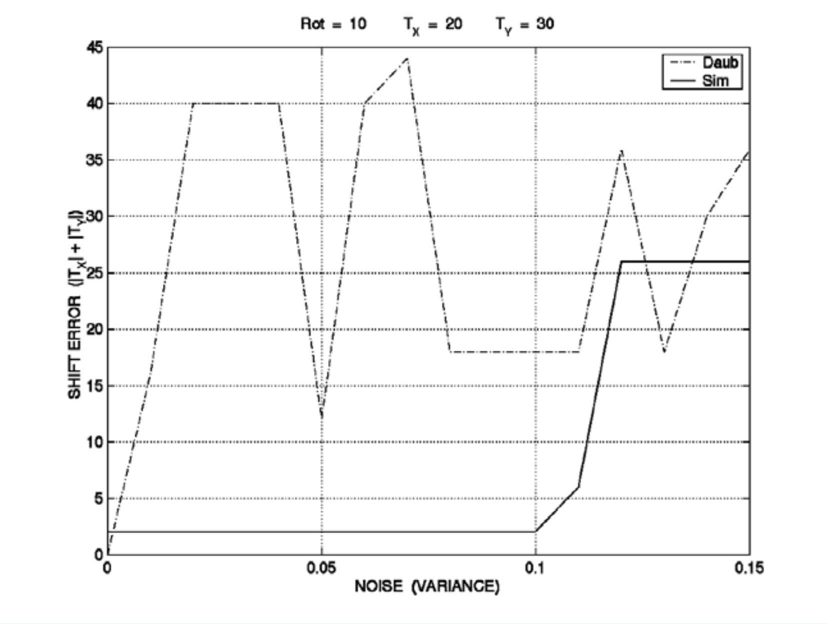
Synthetic Image Examples (Original; Warp & Noise; Warp & PSF)

Orthogonal Wavelet Studies

(Reproduced from Le Moigne & Zavorin, 2000)



Shift Errors – Daubechies – Large Rotations



Shift Errors Function of Noise – Daubechies
Large Rotation and Translation

Spline and Simoncelli Pyramids Studies

(Reproduced from Zavorin & Le Moigne, 2005)

	Number of converged	*Median converged error*	*Mean converged error*	*Standard deviation converged error*
TRU-SplC	1657/7236 ≈ 22.9%	0.0219008	0.086284	0.148911
TRU-SimB	1552/7236 ≈ 21.5%	0.0411122	0.141976	0.212933
TRU-SimL	3693/7236 ≈ 51%	0.0214522	0.056263	0.109165

Average Error for Converged Region of Test Dataset (Warp & Noise)

	Number of converged	*Median converged error*	*Mean converged error*	*Standard deviation converged error*
TRU-SplC	2831/9801 ≈ 28.9%	0.285565	0.300596	0.082751
TRU-SimB	725/9801 ≈ 7.4%	0.052036	0.065967	0.032609
TRU-SimL	2918/9801 ≈ 29.8%	0.320529	0.331067	0.091969

Average Error for Converged Region of Test Dataset (Warp & PSF)

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TRU-SplC	1424/7236 ≈ 19.7%	0.216392	0.278916	0.168494
TRU-SimB	1415/7236 ≈ 19.6%	0.164233	0.252788	0.213441
TRU-SimL	4038/7236 ≈ 55.8%	0.243106	0.289142	0.142683

Average Error for Converged Region of Test Dataset (Warp & PSF & Noise)

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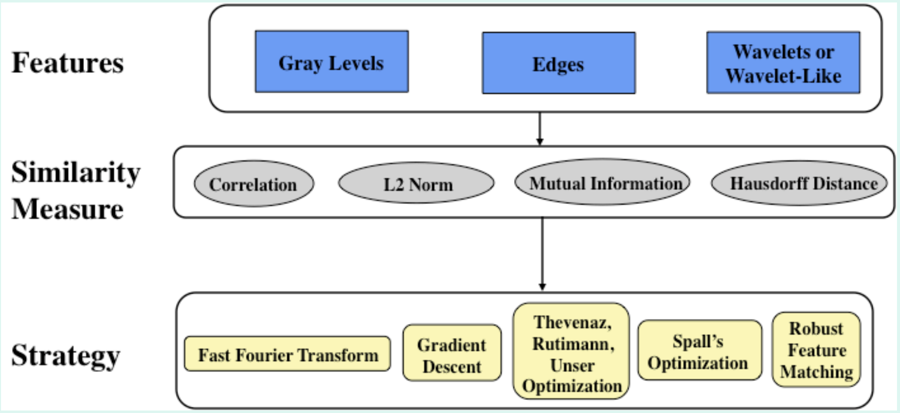
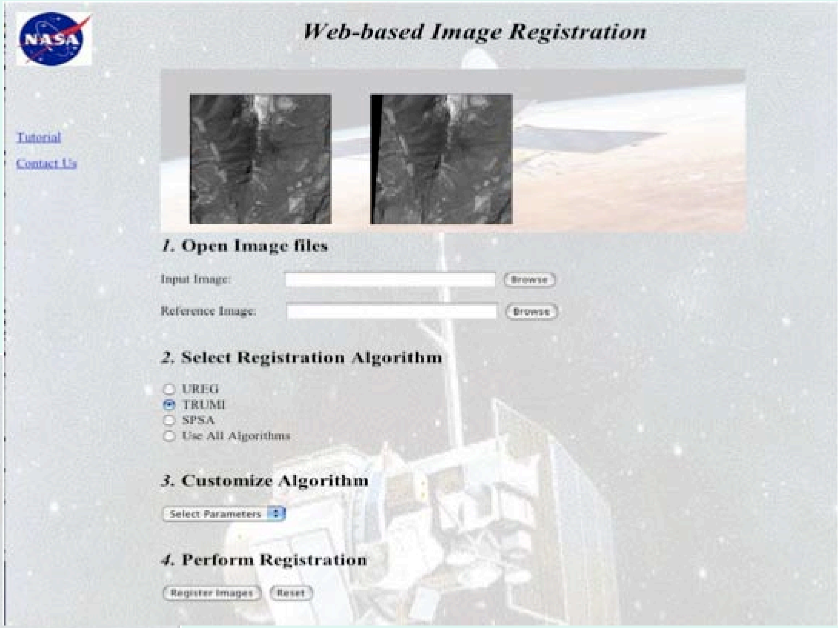
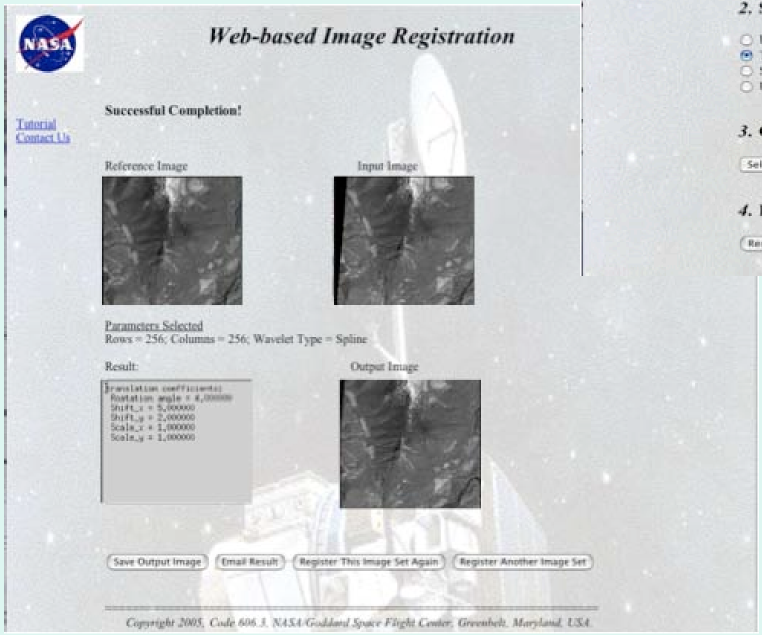
Average Error for Converged Region of Test Dataset (Warp & PSF & Noise)

A Framework for the Analysis of Various Image Registration Components

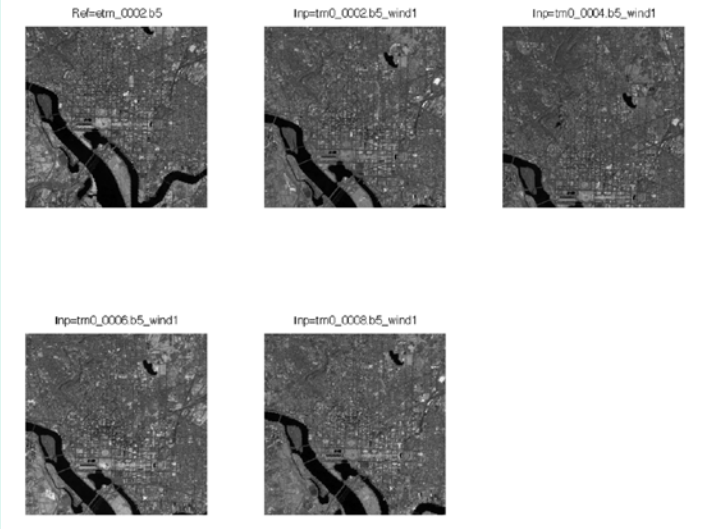


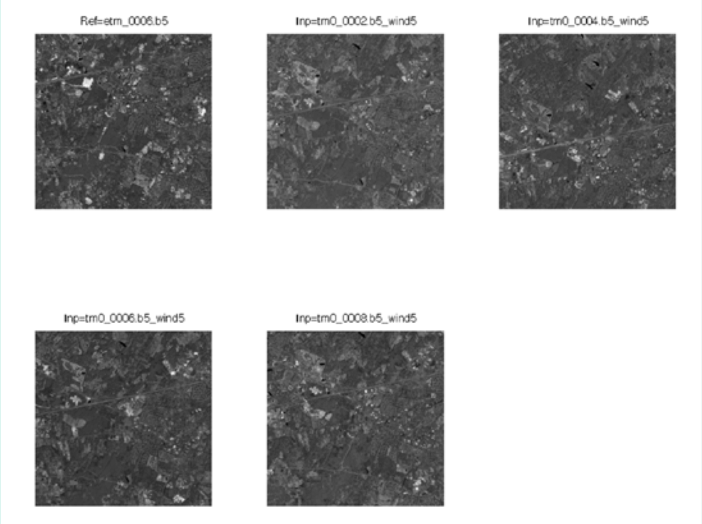


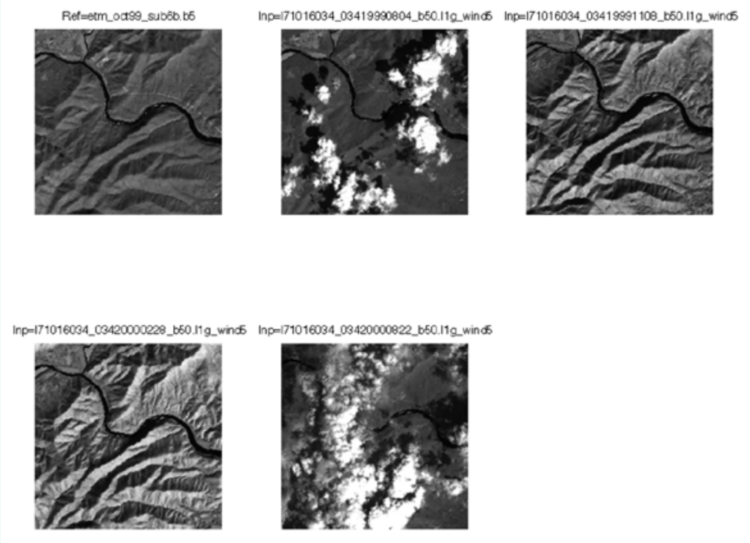


TARA (Toolbox for Automated Registration and Analysis)

Algorithm Testing Using Landsat-TM Multitemporal Data

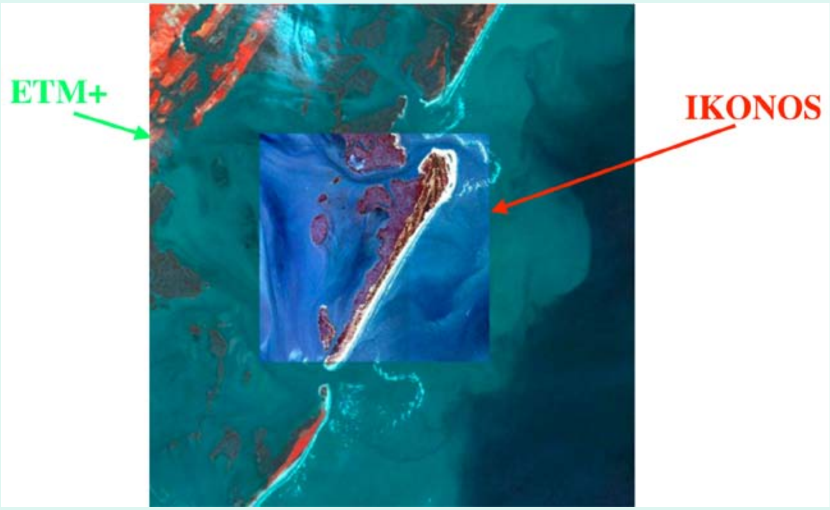


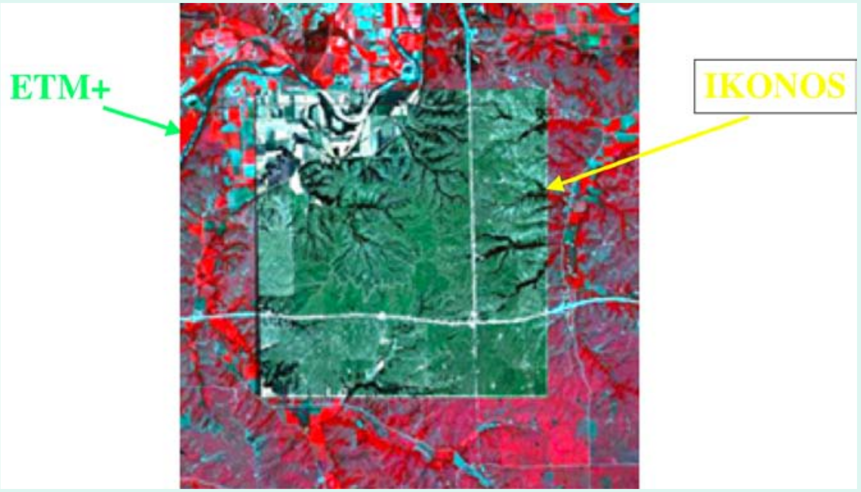


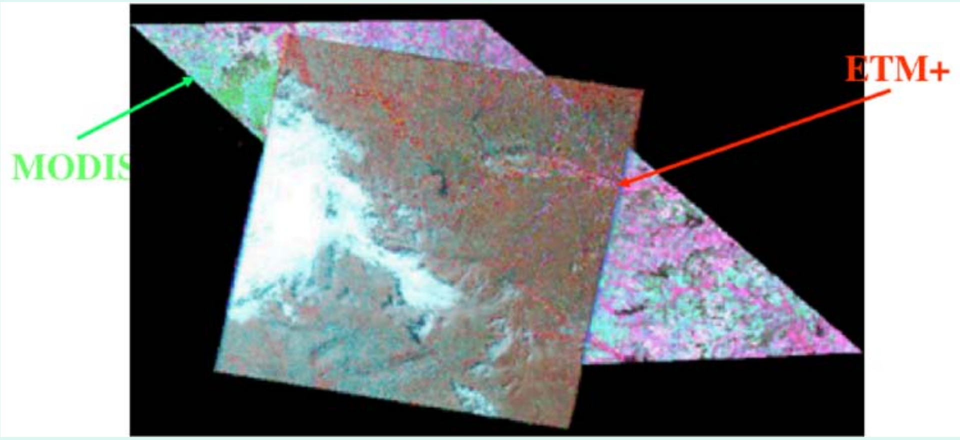


Algorithm Testing Using Multisensor Data (ETM, IKONOS and MODIS)

Red and NIR Bands; 30m – 4m – 250 and 500 m respectively



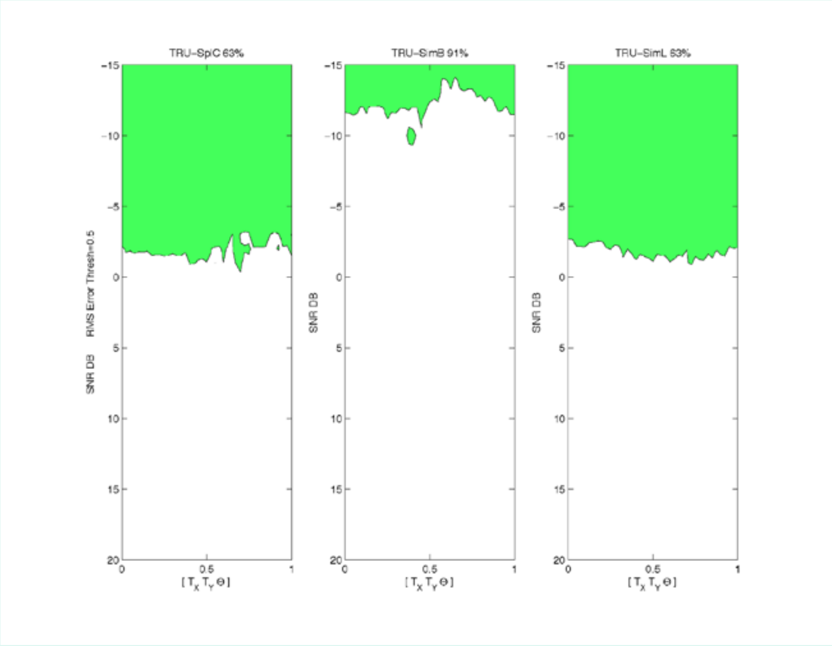




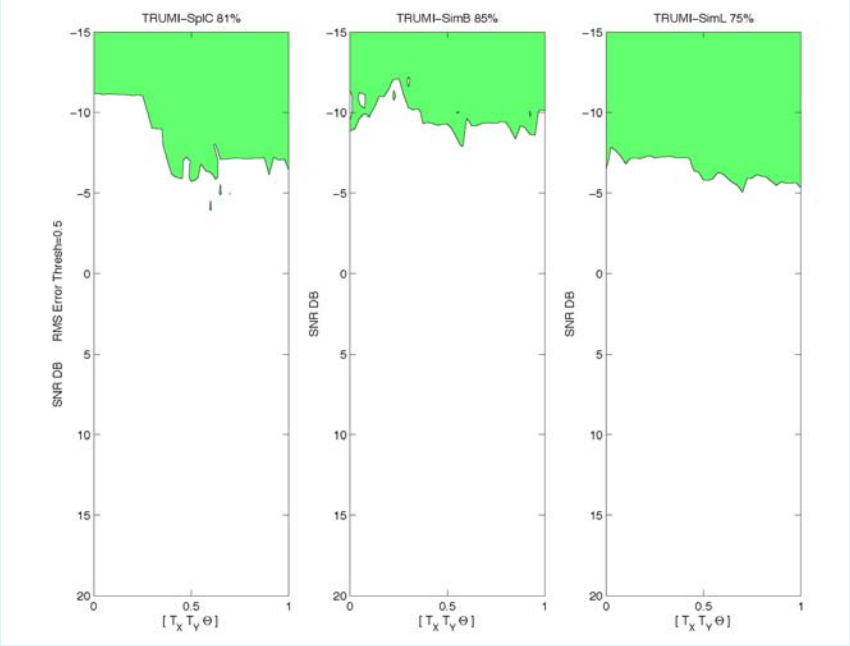
Framework Testing Using Synthetic Datasets

Marquart-Levenberg Optimization Using L2-Norm and Mutual Information

(Reproduced from Zavorin & Le Moigne, 2005)



Contour Plot "SameRadNoisy" Dataset
Optimization Using L2-Norm
Threshold of 0.5

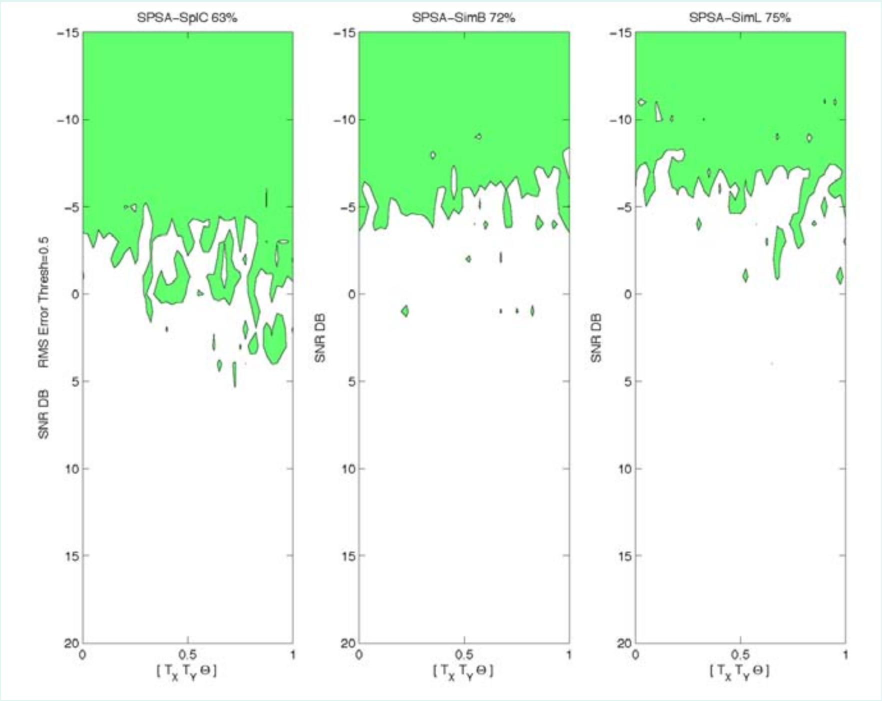


Contour Plot "SameRadNoisy" Dataset
Optimization Using Mutual Information
Threshold of 0.5

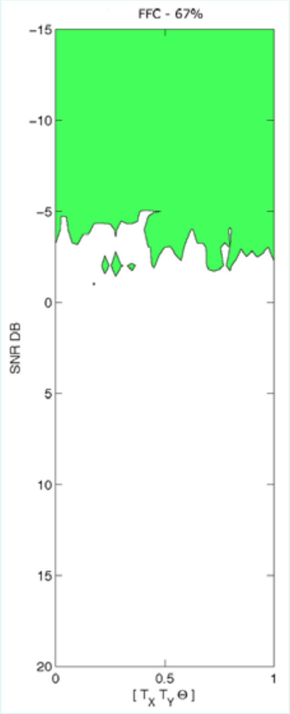
Framework Testing Using Synthetic Datasets

Stocchastic Gradient Optimization Using L2-Norm and Mutual Information

(Reproduced from Zavorin & Le Moigne, 2005)



Contour Plot "SameRadNoisy" Dataset
Stocchastic Gradient and Mutual Information
Threshold of 0.5



Contour Plot "SameRadNoisy" Dataset
Fast Fourier Correlation
Threshold of 0.5

Multitemporal Datasets

Robust Feature Matching Using Simoncelli Band-Pass Features

(Reproduced from Netanyahu et al, 2004)

	RFM REGISTRATION			MANUAL GROUND TRUTH			ABSOLUTE ERROR		
Scene	Q	T_x	T_y	Q	T_x	T_y	$\lvert DQ \rvert$	$\lvert DT_x \rvert$	$\lvert DT_y \rvert$
840827	0.031	4.72	-46.88	0.026	5.15	-46.26	0.005	0.43	0.62
870516	0.051	8.49	-45.62	0.034	8.58	-45.99	0.017	0.09	0.37
900812	0.019	17.97	-33.36	0.029	15.86	-33.51	0.010	0.11	0.15
960711	0.049	8.34	- 101.97	0.031	8.11	- 103.18	0.018	0.23	1.21

Results of Multitemporal Registration
Using Landsat-TM Data over DC/Baltimore Area

	RFM REGISTRATION			MANUAL GROUND TRUTH			ABSOLUTE ERROR		
Scene	Q	T_x	T_y	Q	T_x	T_y	$\lvert DQ \rvert$	$\lvert DT_x \rvert$	$\lvert DT_y \rvert$
990804	0.009	0.36	3.13	0.002	0.04	3.86	0.011	0.40	0.73
991108	0.000	1.00	13.00	0.002	1.20	13.53	0.002	0.20	0.53
000228	0.005	0.88	-2.32	0.008	1.26	2.44	0.003	0.38	0.12
000822	0.002	0.41	9.22	0.011	0.35	9.78	0.013	0.06	0.56

Results of Multitemporal Registration
Using Landsat-TM Data over Virginia Area

Multisensor Datasets

All Algorithm Comparison

(Reproduced from Le Moigne et al, 2001)

PAIR TO REGISTER	FFC		GGD		SIMB-CORREL		SIMB-MI		RFM	
	Rot	Transl	Rot	Transl	Rot	Transl	Rot	Transl	Rot	Transl
ETM_nir/ETM_red	otation =0, Translation = (0,0) computed by all methods, using 7 sub-window pai									
IKO_nir/ETM_nir	-	(2, 1)	0.0001	(1.99,-0.06	0	(2, 0)	0	(2, 0)	0.00	(0.0, 0.0)
IKO_red/ETM_red	-	(2, 1)	-0.0015	(1.72, 0.28	0	(2, 0)	0	(2. 0)	0.00	(0.0, 0.0)
ETM_nir/MODIS_nir	-	(-2,-4)	0.0033	(-1.78,-3.92	0	(-2, -4)	0	(-2, -4)	0.00	(-3.0,3.5)
ETM_red/MODIS_red	-	(-2,-4)	0.0016	(1.97,-3.90	0	(-2, -4)	0	(-2, -4)	0.00	(-2.0,-3.5)
MODIS_nir/SEAWIFS_	-	(-9, 0)	0.0032	(-8.17 ,0.27	0	(-8, 0)	0	(-9, 0)	0.50	(-6.0,2.0)
MODIS_red/SEAWIFS_	-	(-9, 0)	0.0104	(-7.61, 0.57	0	(-8, 0)	0	(-8, 0)	0.25	(-7.0,1.0)

[redacted]

Results of Multisensor Registration
Using ETM, IKONOS and MODIS Data over Konza Agricultural Area

- Similar Tests performed on:
  - Urban Area (USDA site; Greenbelt, MD)
  - Coastal Area (VA Coast)
  - Agricultural Area (Cascades Site, CO)
  - Mountainous Area (Konza Prairie, Kansas)
- Consistency studies show between 0.125 and 0.25 pixel errors using circular registrations of IKONOS NIR and Red data
- Additional studies performed on EO1-Hyperion data

Fusion of Remotely Sensed Data

- Data Fusion
  - Use multi-source data of different natures to increase quality of information contained in data (Pohl and Genderen, 1998)
  - A *process* dealing with *association*, *correlation*, and *combination* of data and information from single and multiple sources to achieve refined position and identity estimates, and complete and timely assessments of situations and threats, and their significance (Hall and Llinas, 2001).
- Image Fusion
  - Data are images
  - General Objectives:
    - » Image sharpening
    - » Improving registration/classification accuracy
    - » Temporal change detection
    - » Feature enhancement
  - Example Application
    - » Invasive Species Forecasting System
    - » Objective
      - » Improvement of classification accuracy
        - » Tamarisk, Leafy Spurge, Cheat grass, Russian olive,etc.
      - » Feature enhancement

Image Fusion Methods

- Principal Component Analysis, PCA
  - Input
    - Multivariate data set of inter-correlated variables
  - Output
    - Data set of new uncorrelated linear combinations of the original variable
- Wavelet-based Fusion
  - Use of Different Subbands in Reconstruction
- Cokriging

Image Fusion Methods

Wavelet-Based Image Fusion

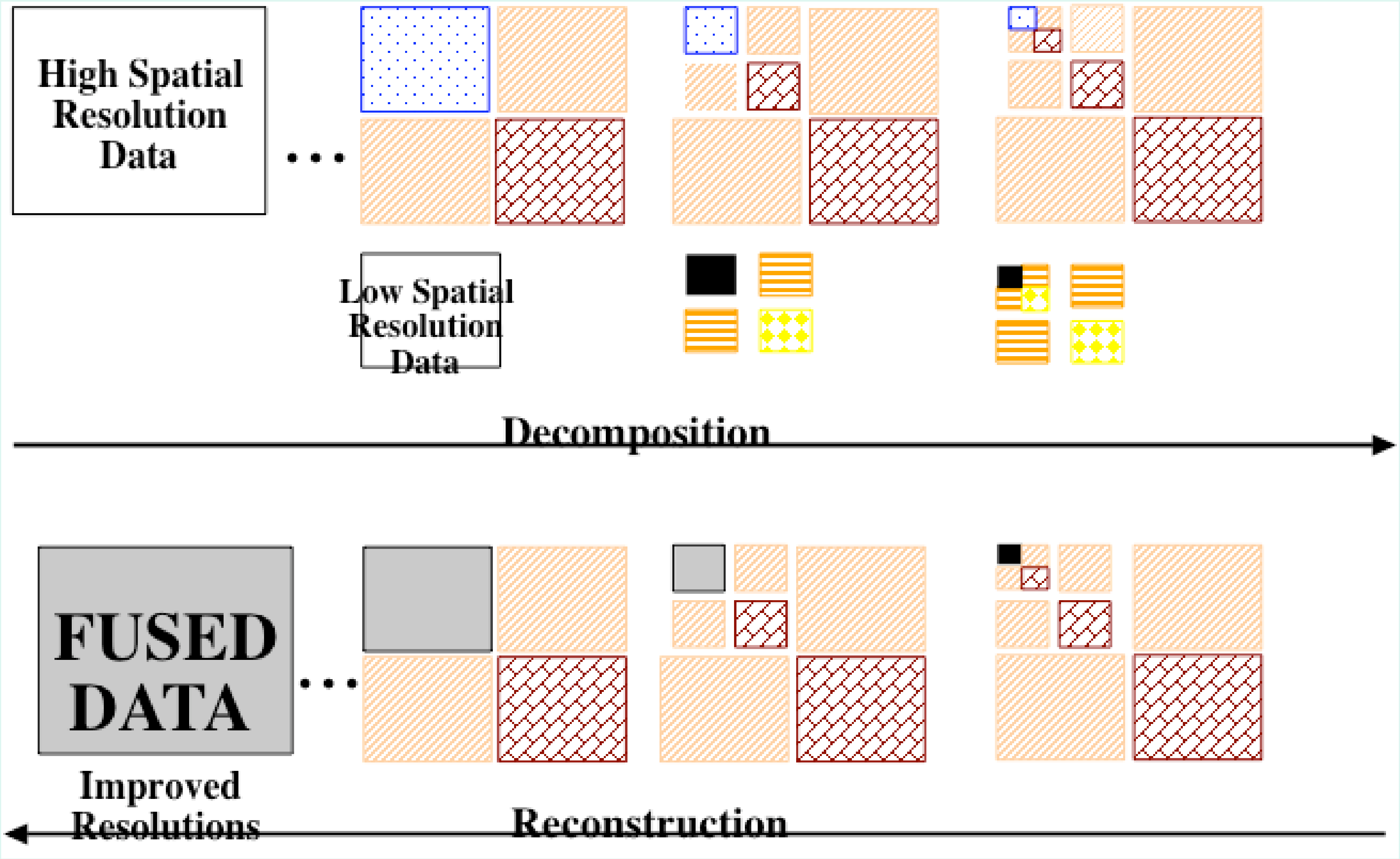


Image Fusion Methods

Cokriging

- Interpolation Method
  - Geo-statistics, mining, and petroleum engineering applications (pioneered by Danie Krige, 1951)
  - Generalized version of *kriging (B.L.U.E):*
    - *Best:* aims to minimize variance of the errors
    - *Linear:* estimates are weighted linear combination of the available data
    - *Unbiased:* tries to have mean residual, or error, equal to zero.
    - *Estimator*

- Interpolation using more that one type of variable to estimate an unknown value at a particular location

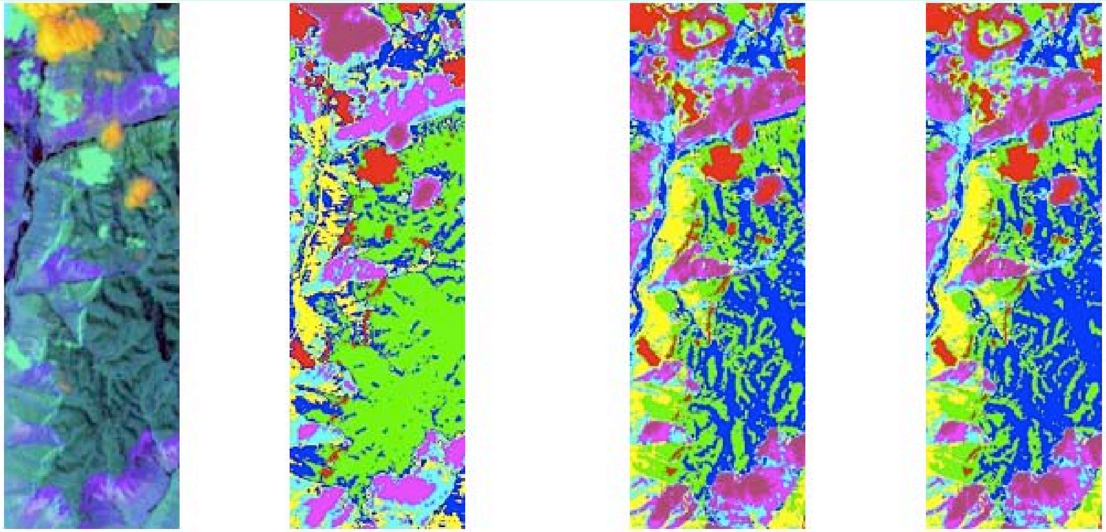
- Goal of cokriging is to *minimize variance of error* subject to some constraints (to ensure unbiasedness of our estimate)

Image Fusion Experiments

Using Principal Component Analysis

(Reproduced from Memarsadeghi et al, 2005)

- Input
  - 9 bands of ALI
  - 140 bands of Hyperion (calibrated and not corrupted bands)
  - Stack of both ALI and Hyperion bands above
- Output
  - Same number of PCs as input bands
  - Select PCs containing 99% of information



ALI PCs 1,2,3

ALI PCs 1,2,3 clustering

Hyperion First 7 PCs clustering

ALI-Hyp First 9 PCs clustering

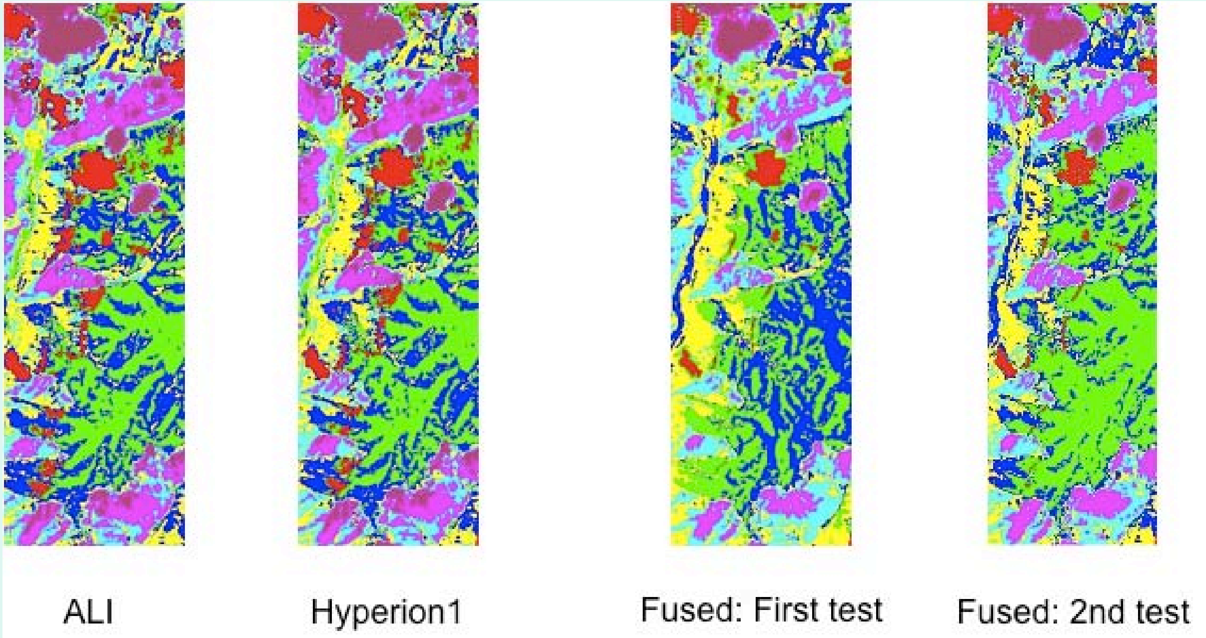
ALI V	Hyp V	Fused V
143.98	137.64	180.10

Image Fusion Experiments

Using Wavelet-Based Fusion

(Reproduced from Memarsadeghi et al, 2005)

- Fuse each multispectral band of ALI with one band of Hyperion
  - For each of 9 ALI bands
  - Select a Hyperion band within the wavelength range of corresponding ALI band which is
    - » closest to the center of ALI's wavelength range (experiment 1)
    - » least correlated to the corresponding ALI band (experiment 2)
  - Clustering of fusion result of 9 bands of ALI with 9 bands of Hyperion
  - Fusion: 4 Levels of Decomposition, Daubechies Filter of size 2



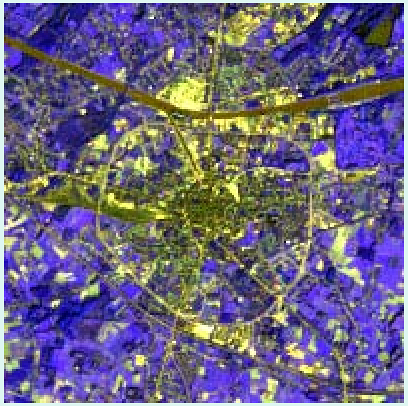
– Experiment 1 Variances: ALI: 179.73; Hyperion: 159.96; Fused: 195.27

– Experiment 2 Variances: ALI: 179.73; Hyperion: 165.34; Fused: 173.77

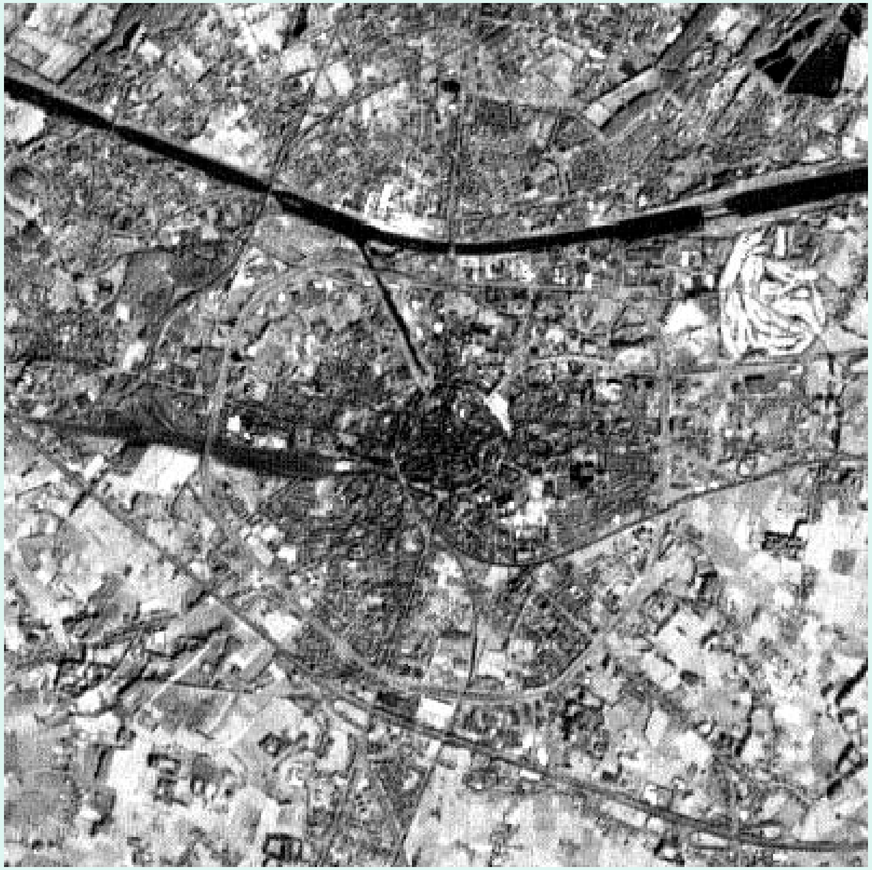
Image Fusion Experiments

Using Cokriging

(Reproduced from Memarsadeghi et al, 2006)



Landsat-TM
Multispectral Bands 2, 3, 4
(30m resolution)



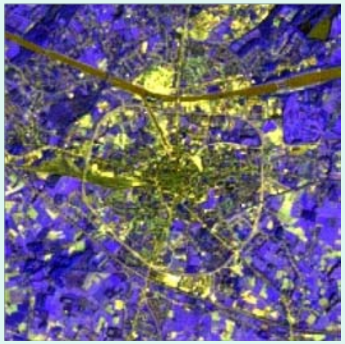
Landsat-TM Panchromatic
(15m resolution)

Image Fusion Experiments

Using Cokriging (cont.)

(Reproduced from Memarsadeghi et al, 2006)

Landsat-7 Multispectral Bands 2,3 and 4

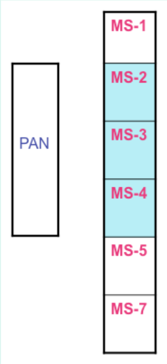


Landsat-7 Panchromatic Band 8

FUSION

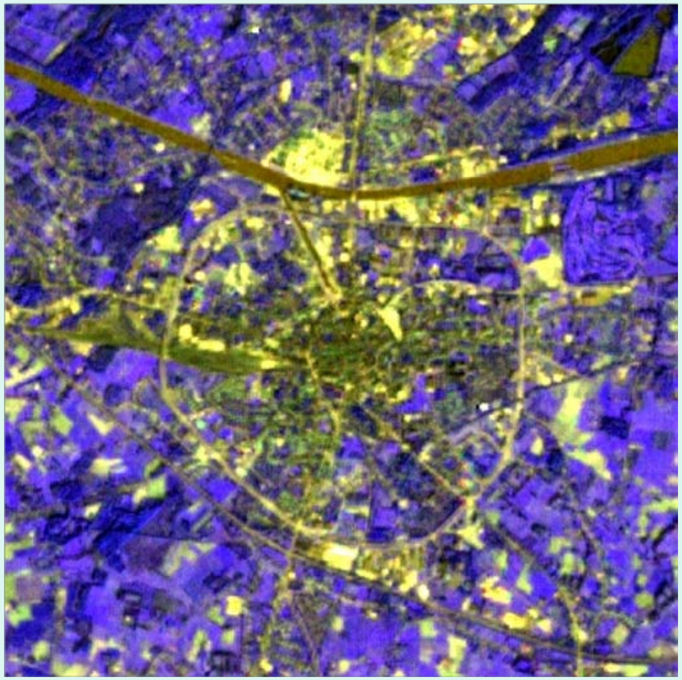
Pan + MS-2	⇨	fused_b2
Pan + MS-3	⇨	fused_b3
Pan + MS-4	⇨	fused_b4

Spectral Resolution
1 pixel of an MS band



x1	y1	p1	?
x2	y2	p2	?
x3	y3	p3	ms1
x4	y4	p4	?

Landsat-7 Pan-Sharpened MS Bands 2,3 and 4 Through Cokriging with Pan Band 8



Results:

- Correlation: Wavelet: 0.86; PCA: 0.91; Cokriging: 0.92
- Entropy: Wavelet: 3.44; PCA: 3.87; Cokriging: 3.92

References

Jacqueline Le Moigne

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ACRONYMS

- AVHRR: Advanced Very High Resolution Radiometer
- CP or GCP: Control Point or Ground Control Point
- GSHHS: Global Self-consistent Hierarchical High-resolution Shoreline
- GOES: Geostationary Operational Environmental Satellite
- GSFC: Goddard Space Flight Center
- MISR: Multiangle Imaging SpectroRadiometer
- MODIS: MODerate resolution Imaging Spectrometer
- NDVI: Normalized Difference Vegetation Index
- SeaWiFS: Sea-viewing Wide Field-of-view Sensor
- SPOT: Satellite Pour l’Observation de la Terre
- WSU: Wright State University