# Image Registration for Remote Sensing

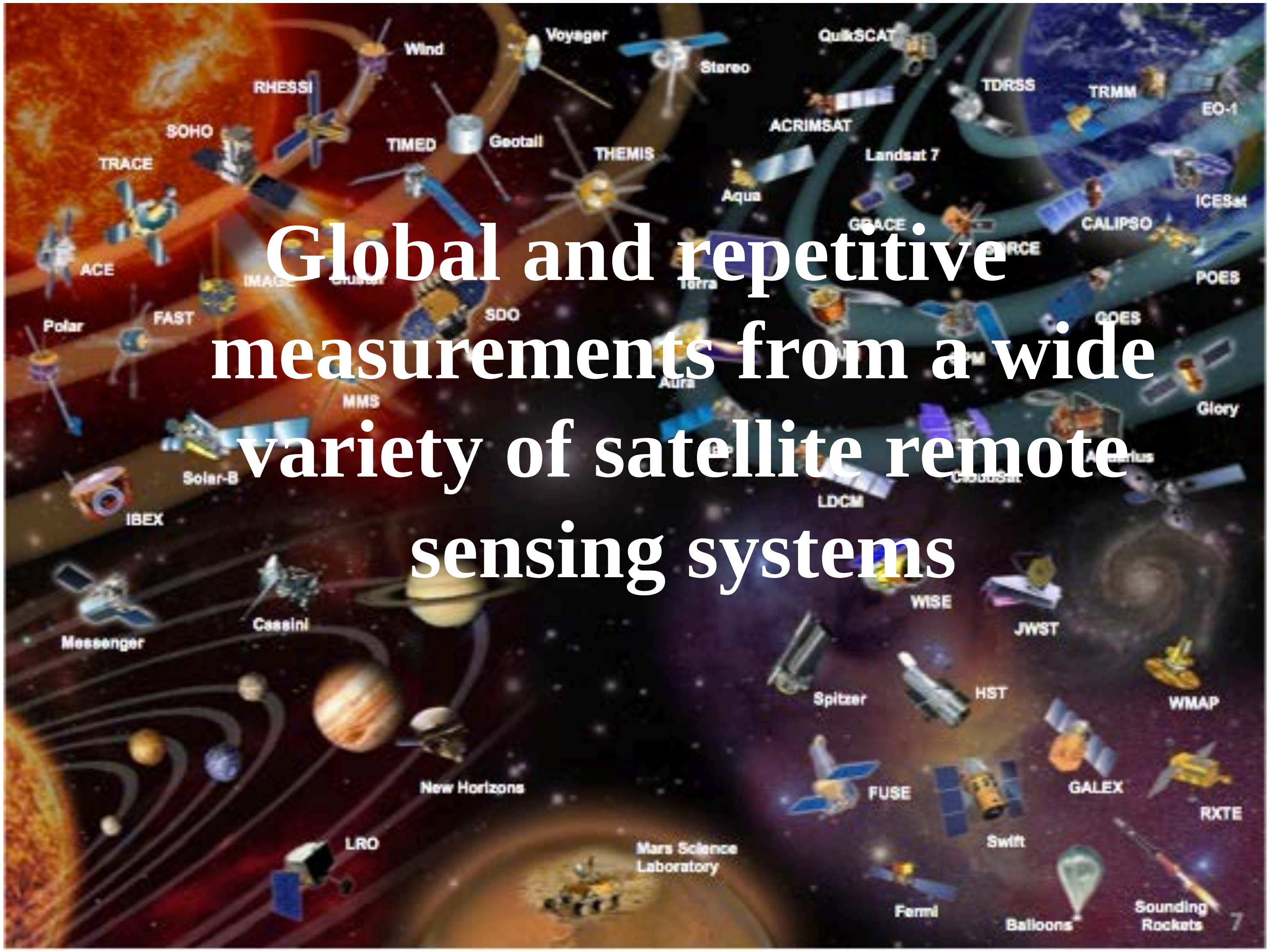
*Jacqueline Le Moigne*

# Image Registration

# in the Context of Space M

# Image Registration

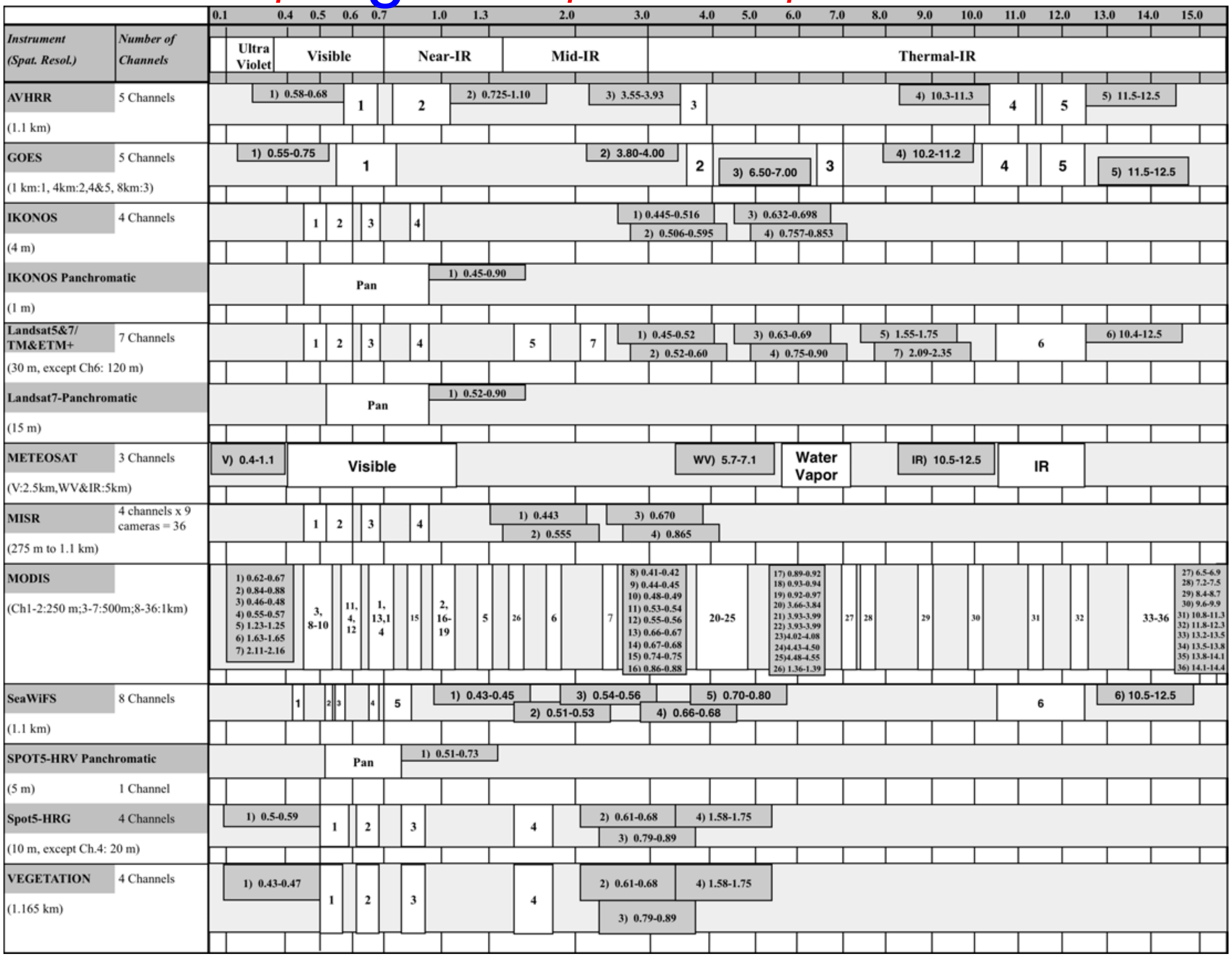
# in the Context of Space M




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

# Image Registration in the Context of Earth Remote Sensing

*Example of Various Spatial and Spectral Characteristics*



# What is Image Registration …

- Definition

  *"Exact pixel-to-pixel matching of two different images or matching of one image to a map"*

- Navigation or Model-Based Systematic Correction
  - Orbital, Attitude, Platform/Sensor Geometric Relationship, Sensor Characteristics, Earth Model, etc.
- Image Registration/Feature-Based Precision Correction
  - Navigation within a Few Pixels Accuracy
  - Image Registration Using Selected Features (or Control Points) to Refine Geo-Location Accuracy
- Image Registration as a Post-Processing or as a Feedback to Navigation Model

# The Role of Image Registration in the Processing of Remotely Sensed Da

- 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)
  - Impact of misregistration on legal, economic and sociopolitical (e.g., resource management), etc
- Basis for extrapolating data throughout several scales for multi-scale phenomena (distinguish between natural and human-induced)

* Normalized Difference Vegetation Index

# Image Registration Applications


***Human-induced land cover changes observed by Landsat-5 in Bolivia in 1984 and 1998(Courtesy: Compton J. Tucker and the Landsat Project, NASA Goddard Space Flight Center)***

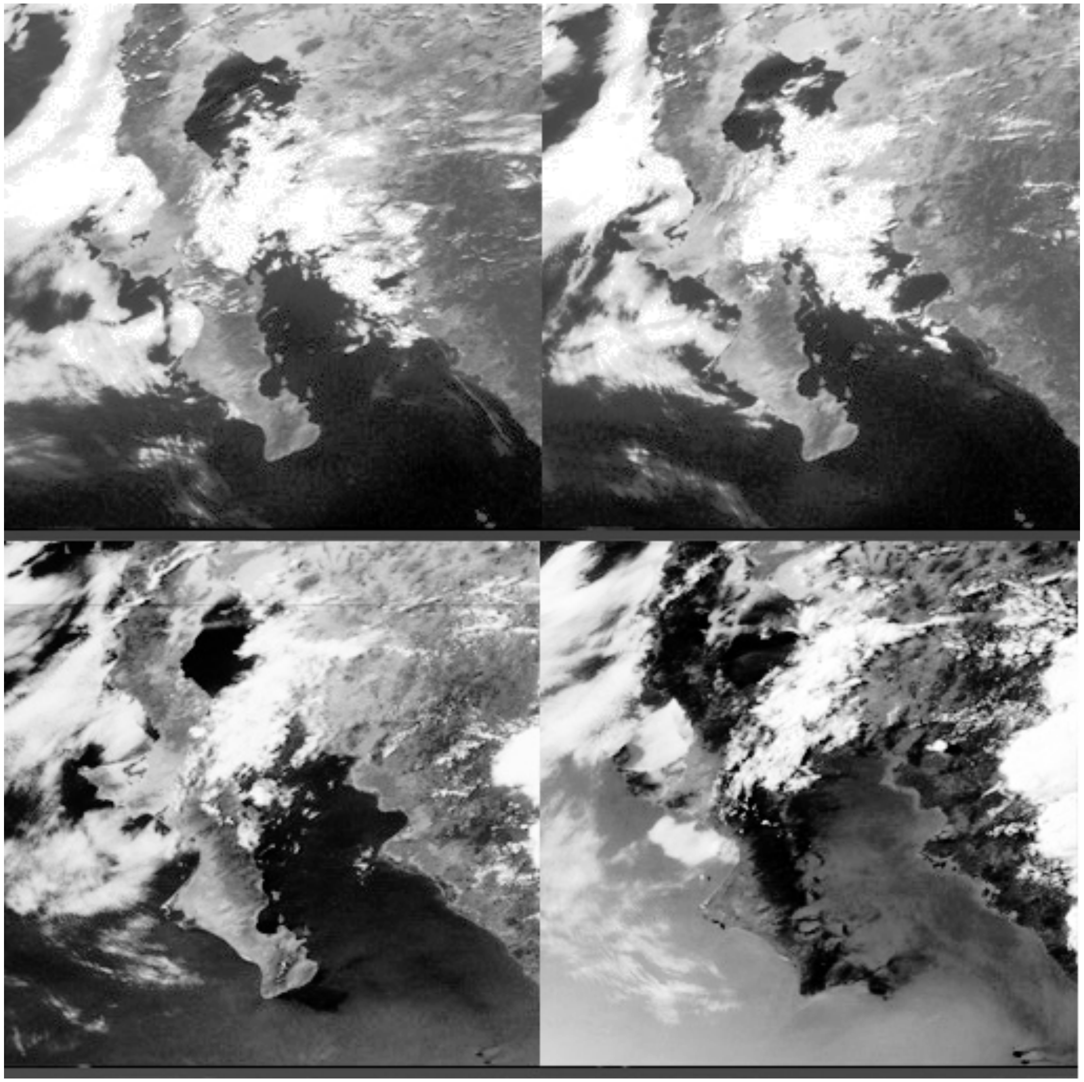
- *Multimodal registration,* for integrating complementary information from multiple sensors
- *Multitemporal registration,* for change detection and Earth resource surveying
- *Viewpoint registration,* for landmark navigation, formation flying (sensor web) and planet exploration
- *Template registration,*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

# Challenges in Image Registration for Remote Sensing

- Remote Sensing vs. Medical or Other Imagery
  - 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 points”
- Navigation Error (or varying “Initial Conditions”)
  - Historical satellites (e.g., Landsat-5 compared to Landsat-7)
  - Following a maneuver (e.g., star tracking)
- Needs:
  - Sub-pixel accuracy
  - Robustness to recurring use
  - Speed and High-Level of Autonomy (Near- or Near-real time applications, e.g., disaster management)
  - On-the-ground or On-Board Processing

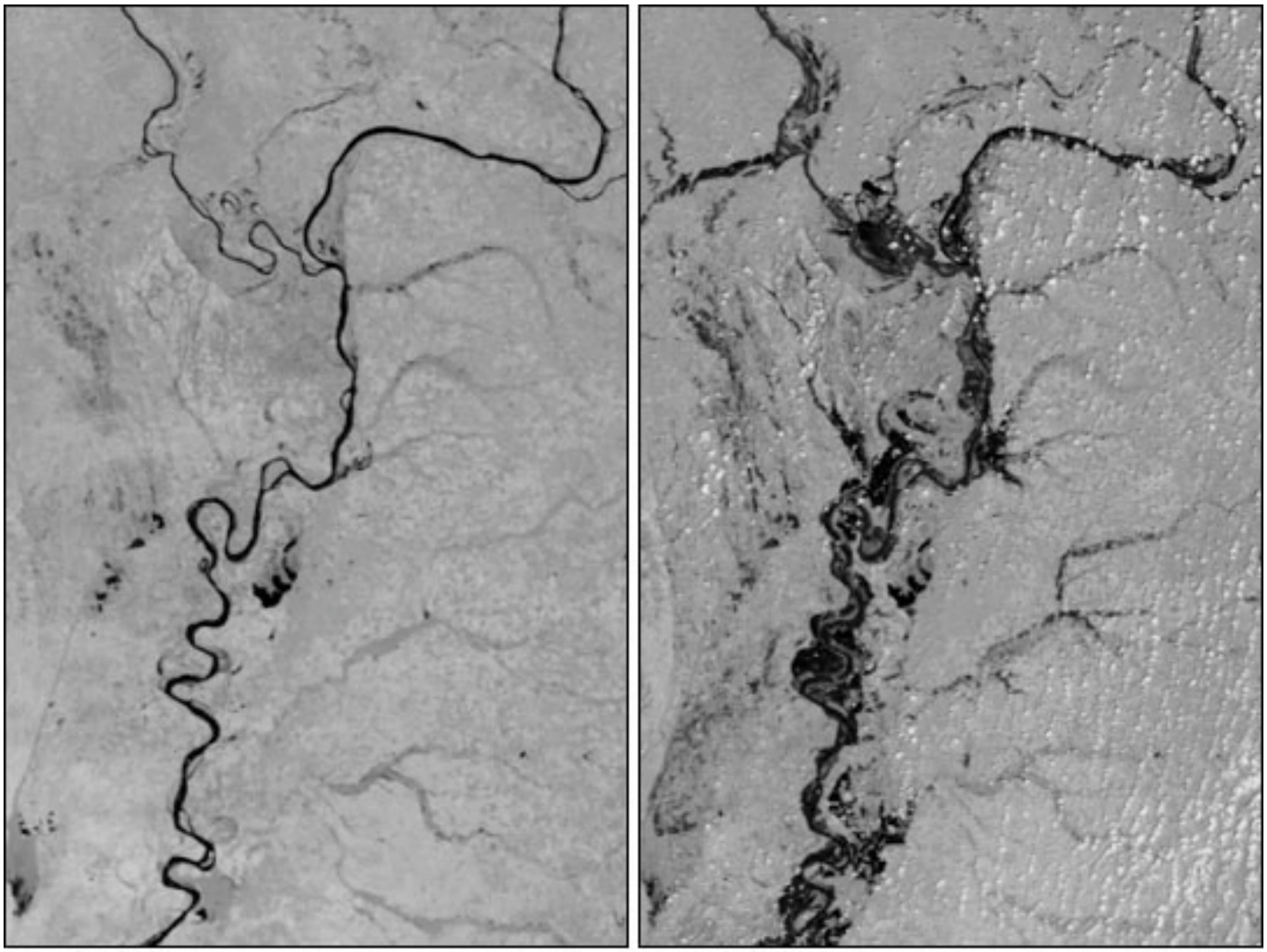
# Challenges with Atmospheric and Cloud Interactions

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



# Challenges with
# Multitemporal Effects

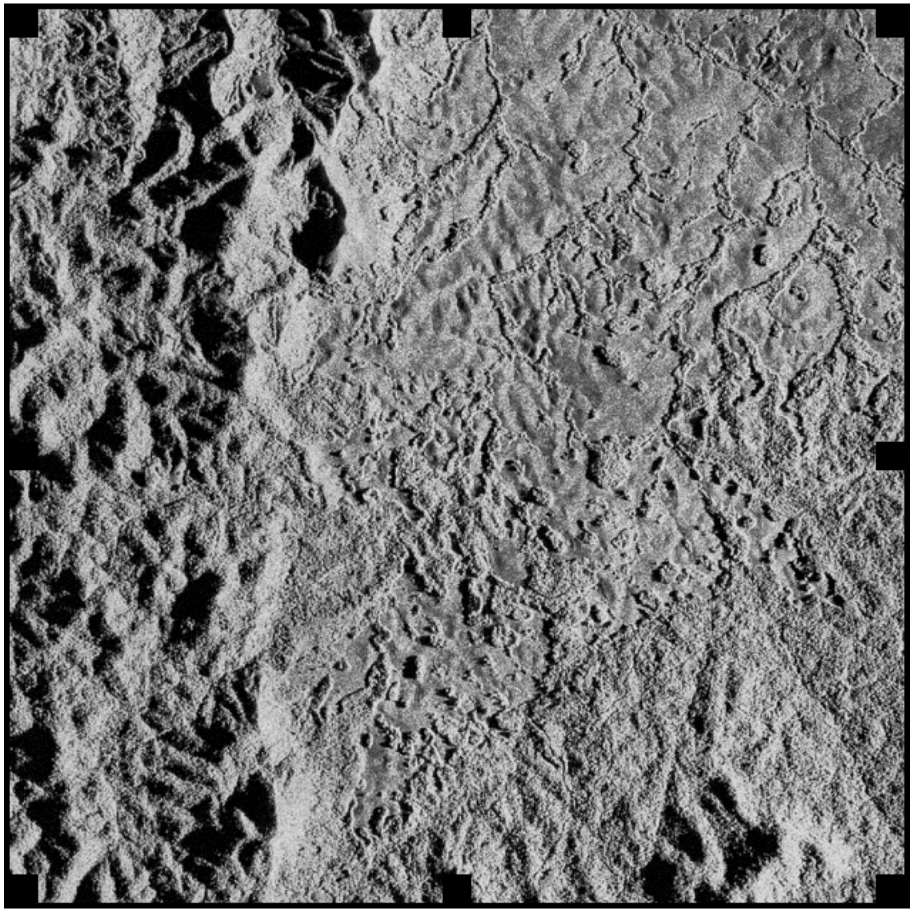
***Mississippi and Ohio Rivers before & after Flood of Spring 2002 (Terra/MODIS)***

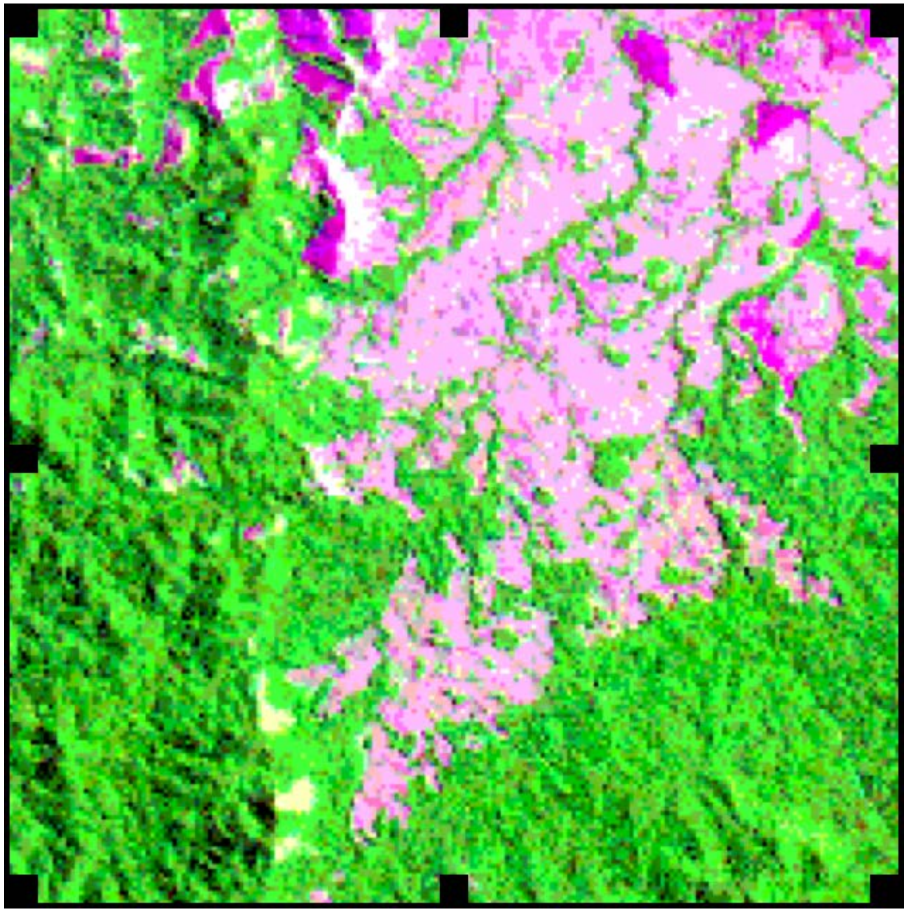


April 25, 2002 May 18, 2002

# Challenges with Relief Effect

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





# Image Registration Frameworks

- Mathematical Framework
  - I1(x,y) and I2(x,y): images or image/map
    - find the mapping **(f,g)** which transforms I1 into I2:

      **I2(x,y) = g(I1(fx(x,y),fy(x,y))**

      » **f** : spatial mapping

      » **g**: radiometric mapping
  - Spatial Transformations "**f**"
    - Translation, Rigid, Affine, Projective, Perspective, Polynomial, …
  - Radiometric Transformations "**g**" (Resampling)
    - Nearest Neighbor, Bilinear, Cubic Convolution, ...

- **Algorithmic Framework (Brown, 1992)**
  1. **Feature Extraction**
  2. **Feature Matching (Similarity Metrics & Matching Strategy)**
  3. **Image Resampling**

# Image Registration Components

0 Pre-Processing

- Cloud Detection, Region of Interest Masking, …

1 Feature Extraction ("Control Points")

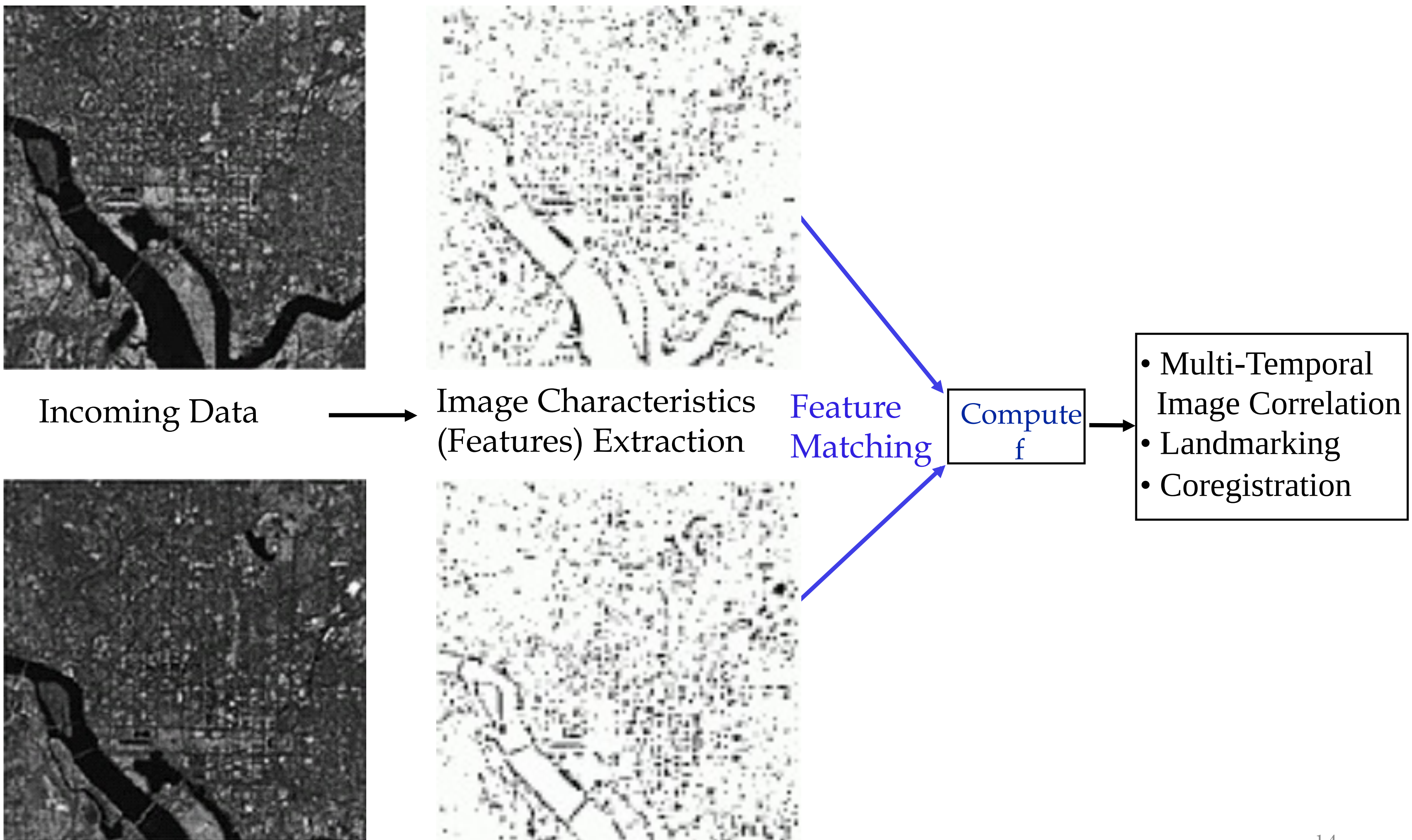
- Gray Levels, Salient Points (e.g., Edges, Edge-like such as Wavelet Coefficients, Corners), Lines, Contours, Regions, Scale Invariant Feature Transform (SIFT), etc.

2 Feature Matching

- Choice of Spatial Transformation (**function f**: a-priori knowledge)
- Choice of Search Strategy :
  - Global vs Local, Multi-Resolution, Optimization, ...
- Choice of Similarity Metrics
  - L2-Norm, Normalized Cross-Correlation, Mutual Information, Hausdorff Distance, …

3 Remapping/Resampling (**function g**: if necessary)

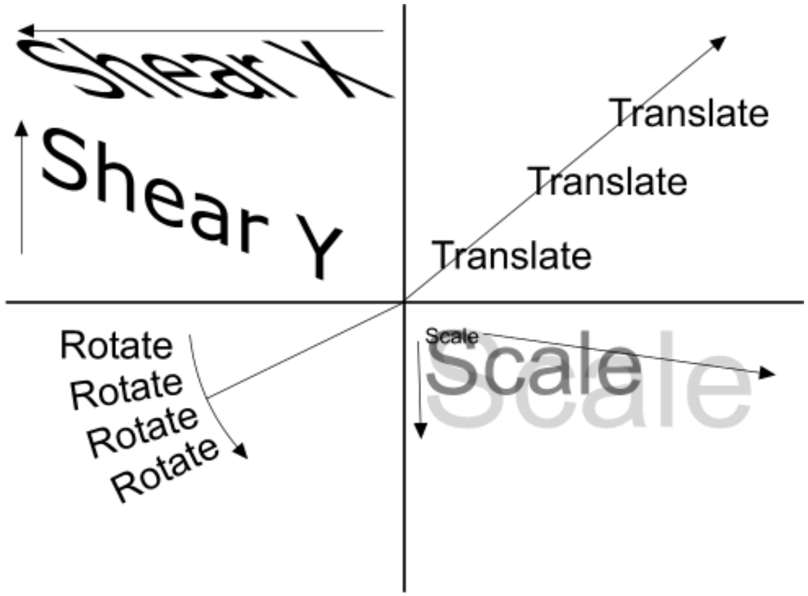
# Wavelet Decomposition as Feature Extraction



# Transformation Functions …

- Translation-only, rigid
- Rotation, scale, and translation (RST)
- Affine (6 degrees of freedom)
- Projective/homography (e.g., for perspective effects in image mosaicing); 8 parameters

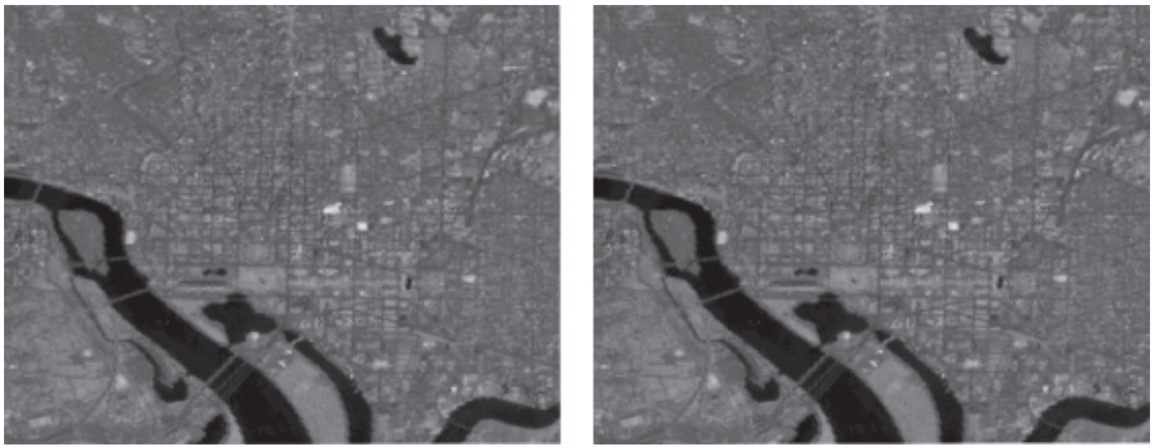
$$x' = s\cos\theta \cdot x - s\sin\theta \cdot y + t_x$$
$$y' = s\sin\theta \cdot x + s\cos\theta \cdot y + t_y$$



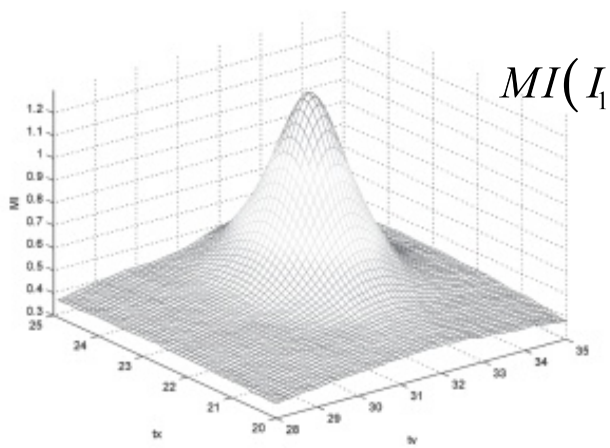
# Similarity Metrics (cont.)…

- **Mutual information (MI):**

  Maximizes the degree of statistical dependence between images



Pair of Landsat images over DC




$$MI(I_1, I_2) = \sum_{g_1} \sum_{g_2} p_{I_1,I_2}(g_1, g_2) \cdot \log\left(\frac{p_{I_1,I_2}(g_1, g_2)}{p_{I_1}(g_1) \cdot p_{I_2}(g_2)}\right),$$

MI surface of above images

# 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

# Precision Correction in Operational Systems

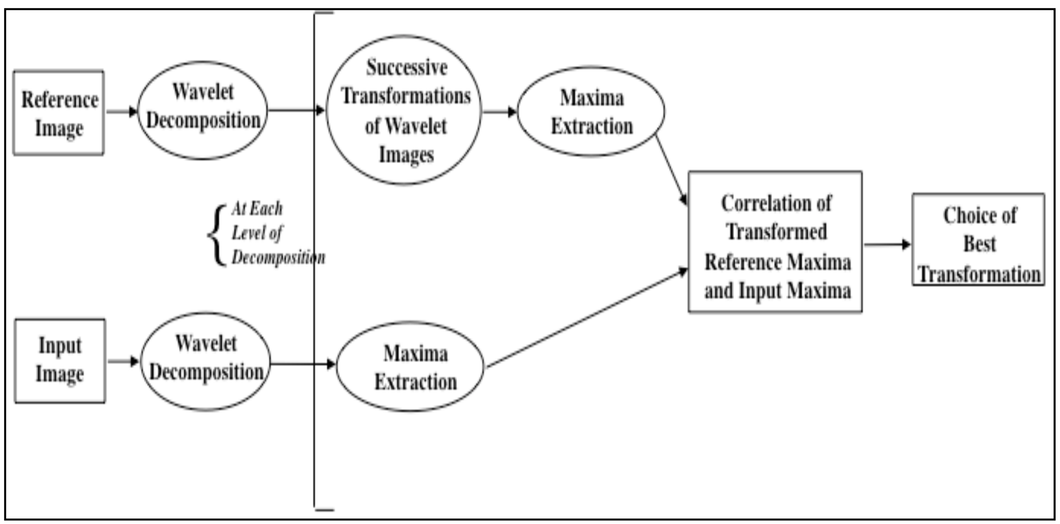
- Operational Environment
  - Platform/sensor models integrated
  - Historical data available for statistics/modeling
  - Robustness and consistency over time is a requirement

- 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

- Various approaches. No gold standard approach => Our work:
  - Create framework to validate new image registration components and algorithms
  - For each algorithm, define "region of convergence" and "region of divergence"
  - Provide guidance/recommendations for utilization of algorithms and their components
  - Provide fast algorithms for real-time/near-real-time and on-board applications

# NASA Goddard Image Registration Group

- 1994: First results on the utilization of orthogonal Daubechies wavelets for image registration



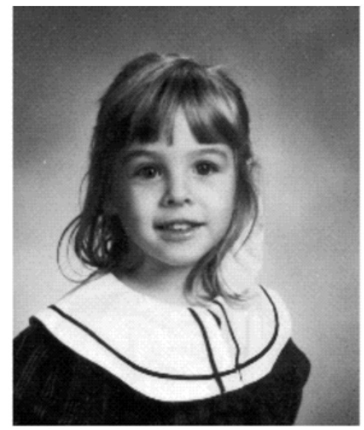



**Figure 1**
**Original Image**

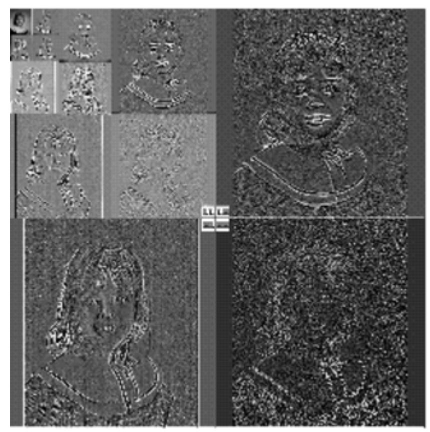


**Figure 2**
**Wavelet Coefficients Corresponding to Figure 1**

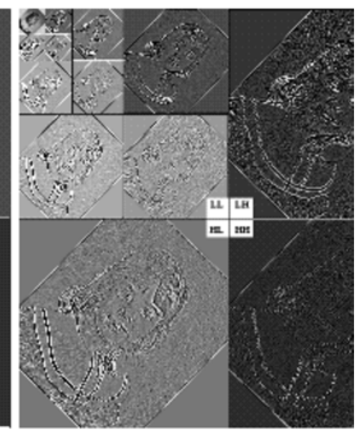
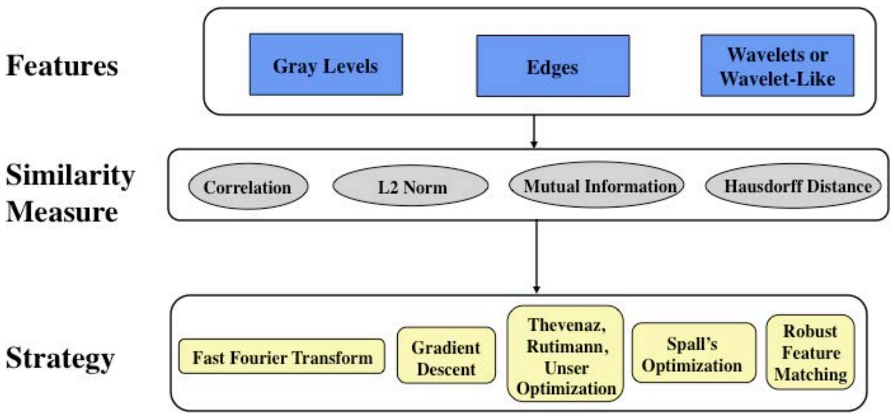


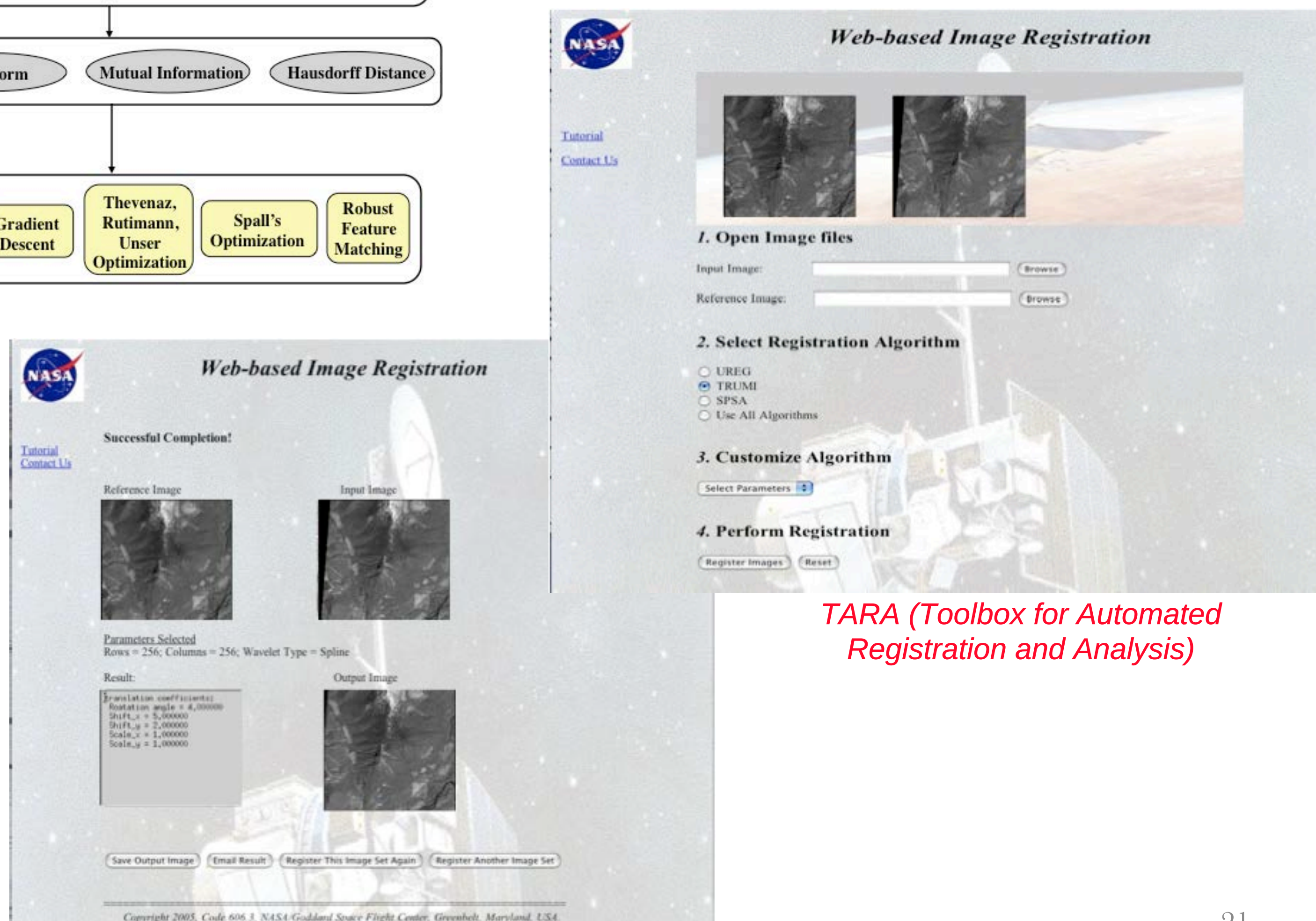
**Figure 3**
**Wavelet Coefficients Correspond to Figure 1 rotated 44 degrees**

# NASA Goddard Image Registration Group

- Study of different feature extraction methods, e.g., rotation- and translation-invariant wavelet filters (Spline, Simoncelli)
- Study of different matching strategies and metrics
- Parallel implementations (SIMD/MasPar, Beowulf Cluster, MIMD/Cray-T3E, FPGA-Hybrid)
- Development of an image registration framework based on Brown's framework
- Development of TARA, Toolbox for Automated Registration and Analysis
- Cambridge University Press Book "Image Registration for Remote Sensing" (2011)

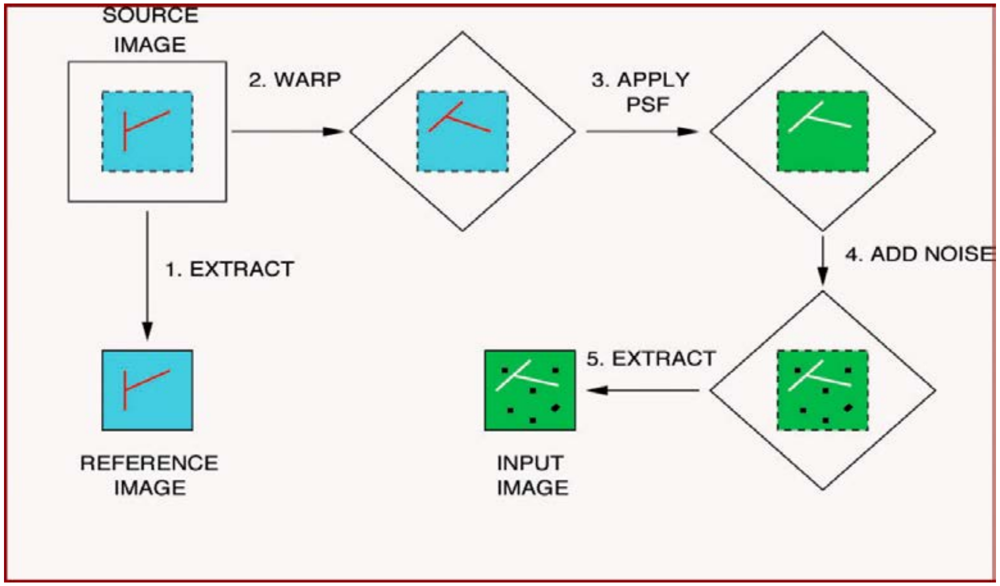
# Framework for Evaluation of Image Registration Components



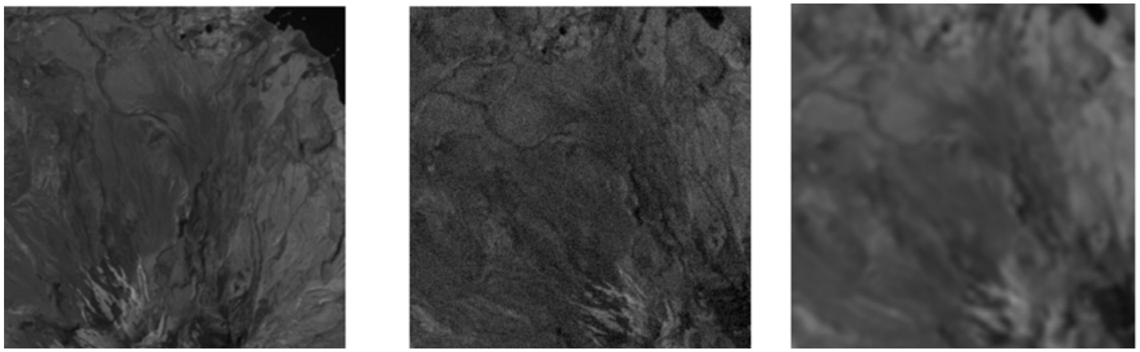




*TARA (Toolbox for Automated Registration and Analysis)*

# Algorithm Testing Using …
# Synthetic Data

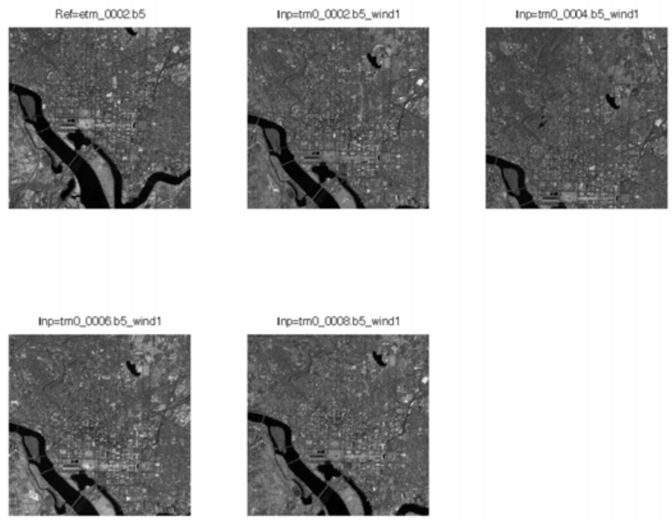


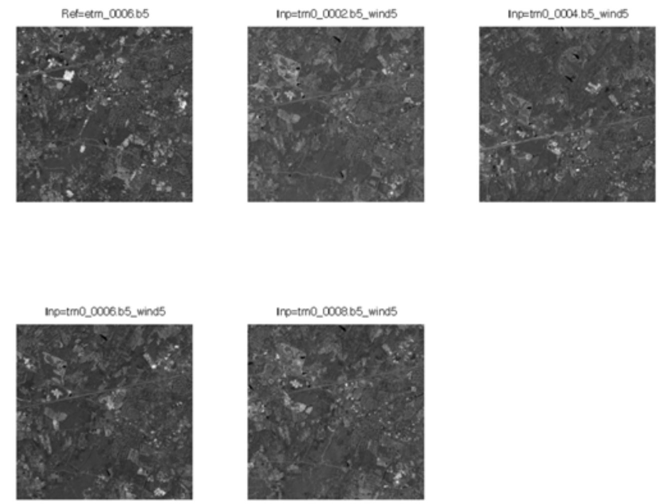

*Synthetic Image Generation*

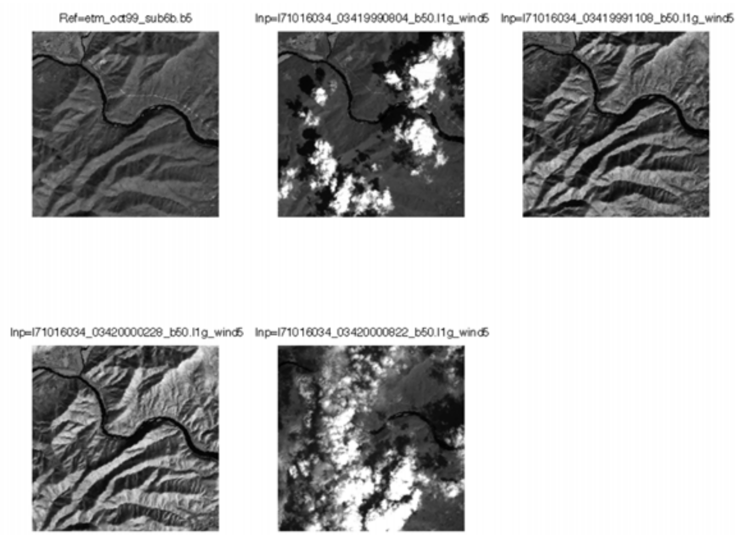


*Synthetic Image Examples (Original; Warp & Noise; Warp & PSF)*

# Algorithm Testing Using …
# Landsat-TM Multitemporal Data



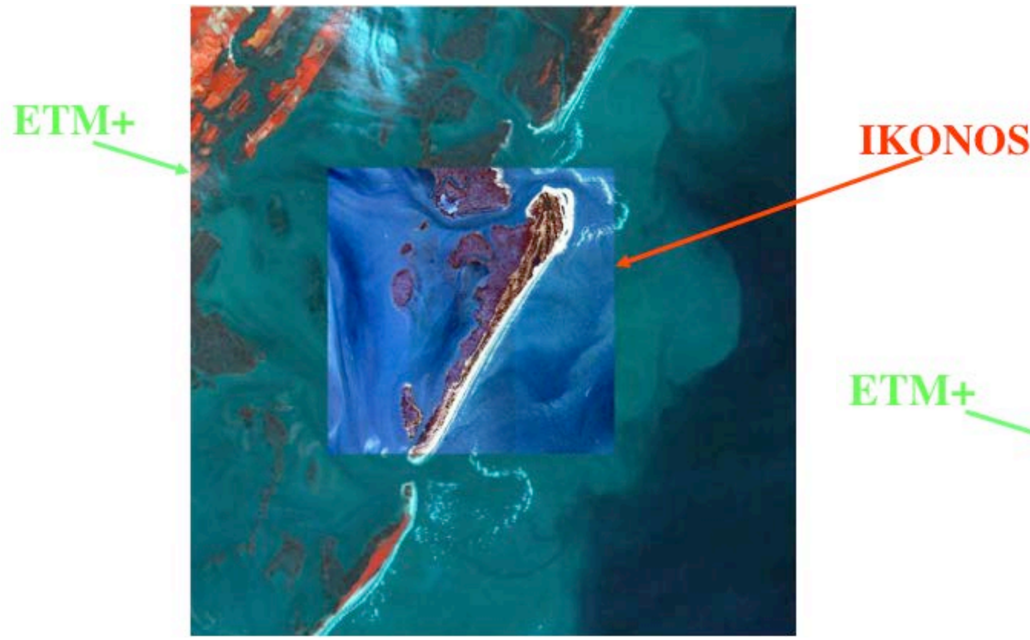



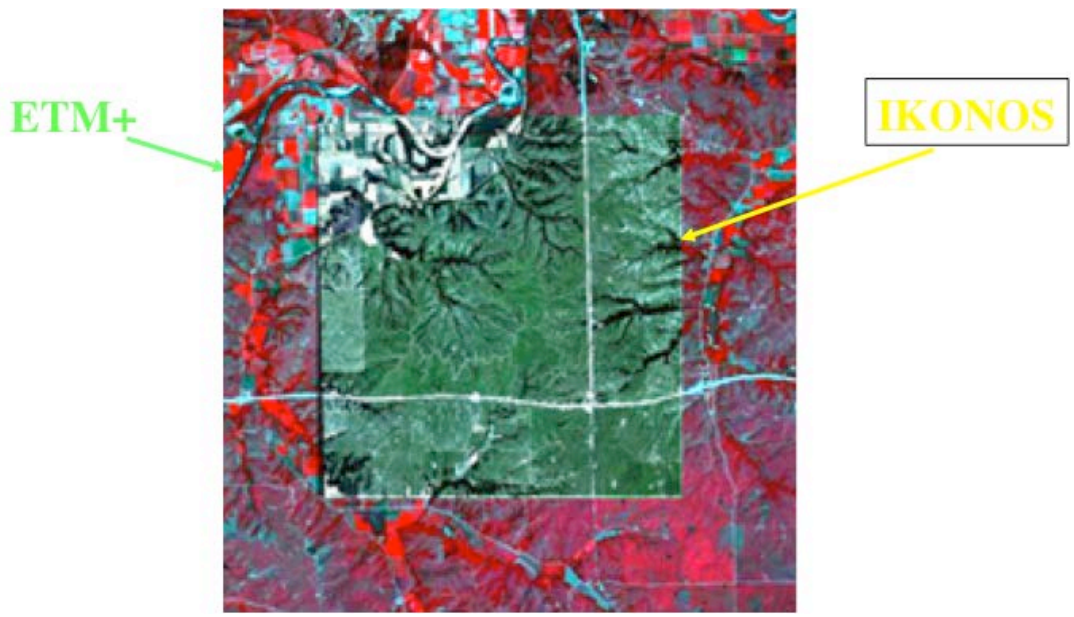
# Algorithm Testing Using …
# Multisensor Data

- Multi-Sensor Data
  - EOS Validation Core Sites
  - IKONOS/Landsat-7/MODIS/SeaWiFS
    - **Red and NIR** bands for each sensor
    - **Spatial resolutions**: IKONOS: 4m; ETM+: 30m; MODIS: 500m; SeaWiFS: 1000m
  - 4 different sites:
    - **Coastal Area:** VA, Coast Reserve Area, October 2001
    - **Agriculture Area**: Konza Prairie in State of Kansas, July to August 2001
    - **Mountainous Area**: Cascades Site, September 2000
    - **Urban Area**: USDA Site, Greenbelt, MD, May 2001

# Algorithm Testing Using … Multisensor Data



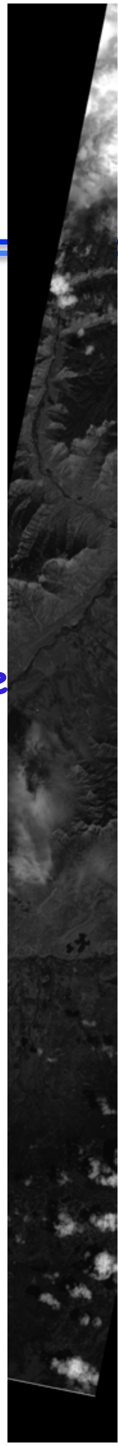

***ETM/IKONOS - Coastal VA Data***



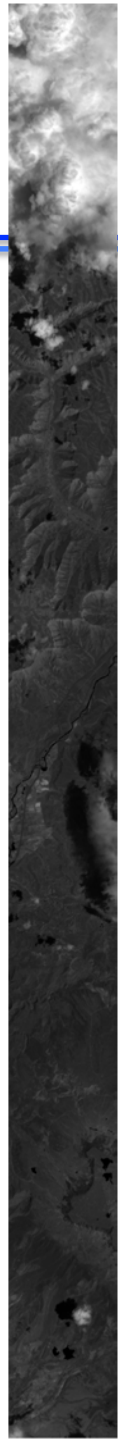

***ETM/IKONOS - Agricultural Konza Data***

# Other Tests …
# EO-1 Data

*ALI and Hyperion Registration*

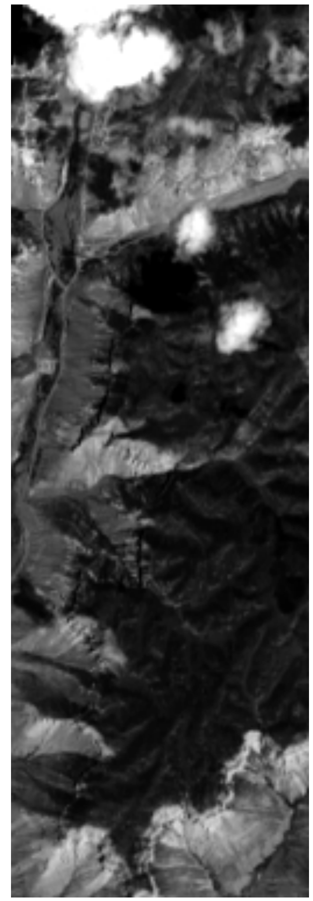


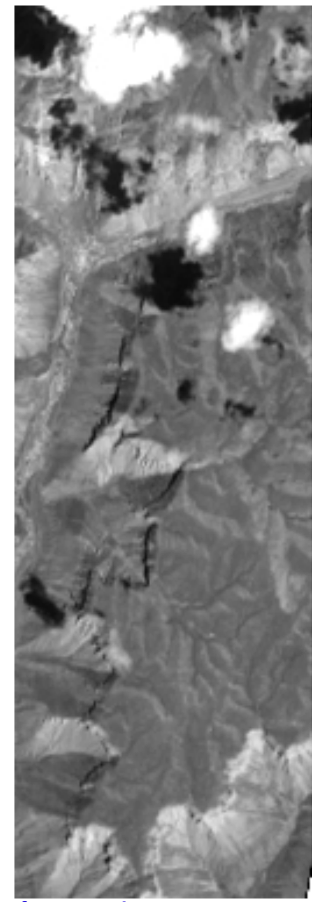
ALI
Band 4:
Reference



Hyperion
Band 47:
Input

Hyperion
Band 47
Registered
to ALI
Band 4



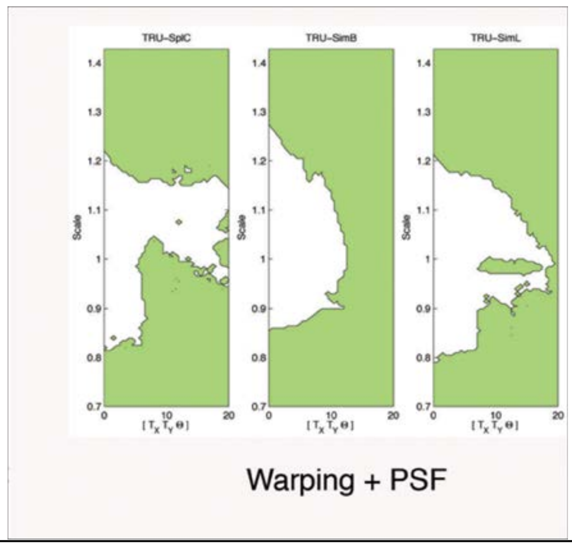


Registered Subset
ALI Hyperion

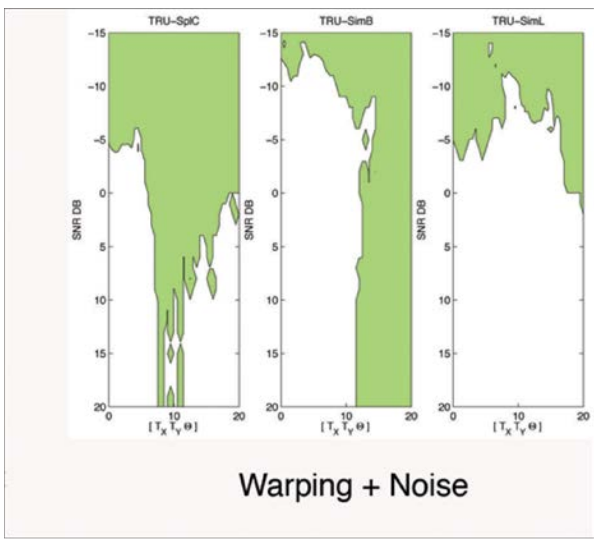
# Algorithm Testing Using … Synthetic Data

- Various Features; Convergence as a function of noise and radiometric variations

*(white areas – regions of convergence with errors less than threshold, e.g. 0.5)*

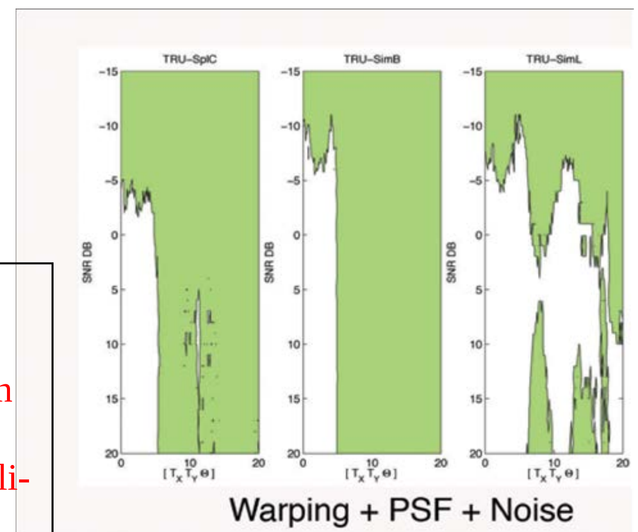



Warping + PSF




Warping + Noise

- Simoncelli-based methods outperform Spline pyramid-based methods
- Optimization based on Mutual Information does not perfom better than L2-Norm
- Simoncelli-LowPass better than Simoncelli-BandPass for Low Noise and Same Radiometry and for Initial Guess Sensitivity




Warping + PSF + Noise

# Algorithm Testing Using … Landsat-TM Multitemporal Data

***With Robust Feature Matching Using Simoncelli Band-Pass Features***

| | RFM REGISTRATION | | | MANUAL GROUND TRUTH | | | ABSOLUTE ERROR | | |
|---|---|---|---|---|---|---|---|---|---|
| Scene | Q | $T_x$ | $T_y$ | Q | $T_x$ | $T_y$ | $\|DQ\|$ | $\|DT_x\|$ | $\|DT_y\|$ |
| 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 | $T_x$ | $T_y$ | $\|DQ\|$ | $\|DT_x\|$ | $\|DT_y\|$ |
| 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*

# Algorithm Testing Using … Multisensor Data

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

| PAIR TO REGISTER | FFC | | GGD | | SIMB-CORREL | | SIMB-MI | | RFM | | [redacted] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 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) | |

- Additional consistency studies show between 0.125 and 0.25 pixel errors using circular registrations of IKONOS NIR and Red data

# The Future of Image Registration

- **Future research and challenges**
  - Improve registration by combining multiple band-to-band registrations (e.g., hyperspectral data)
  - Automatically extract windows of interest (decreasing processing time and increasing accuracy)
  - Deal with other data sources (e.g., planetary imagery, or verification of optical systems)
  - Integrate Digital Elevation Models (DEMs)
  - Integrate and fuse multiple source imagery (various satellites, vector map, airborne, ground data, etc.)
  - Perform onboard implementations on specialized hardware
  - Develop multistage registration algorithms combining multiple principles and approaches, thus increasing algorithms robustness and applicability
  - Generalize methods to very high resolution and commercial satellites data

# *Thank You!*

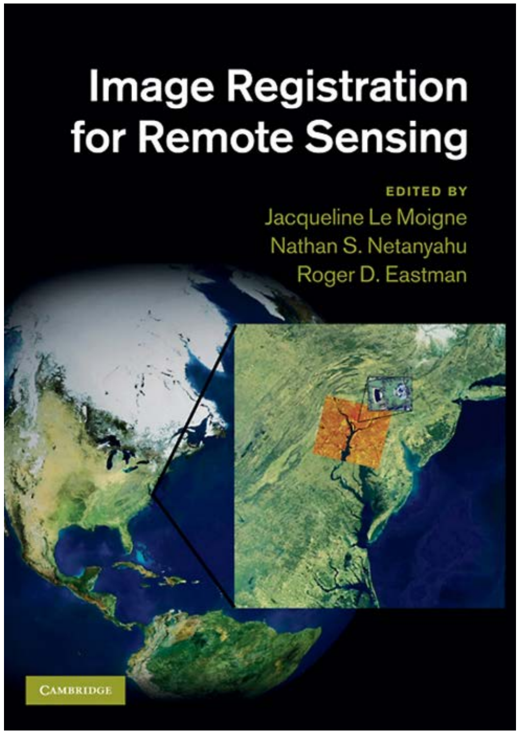
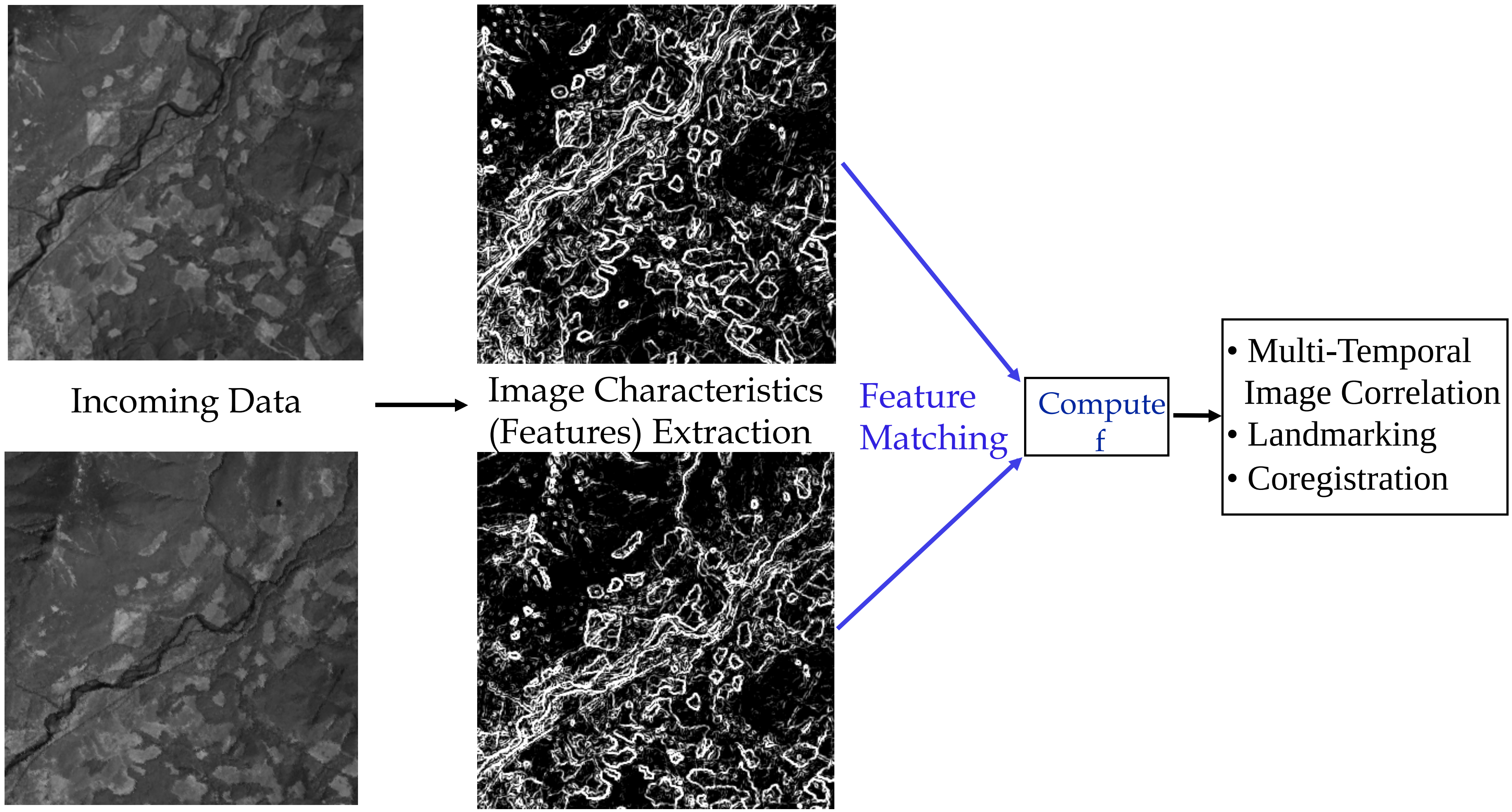


Image Registration for Remote Sensing
EDITED BY
Jacqueline Le Moigne
Nathan S. Netanyahu
Roger D. Eastman
CAMBRIDGE

# Appendix

# Edge Detection as Feature Extraction



# Similarity Metrics …

- ***$L_2$*-norm:**
  - Minimize the sum of squared errors (SSD) over overlapping subimage

$$SSD(x,y)=\sum_{m=0}^{M-1}\sum_{n=0}^{N-1}\left[I_1(m,n)-I_2(m-x,n-y)\right]^2$$

- **Normalized cross-correlation (NCC)**
  - Maximize normalized cross-correlation

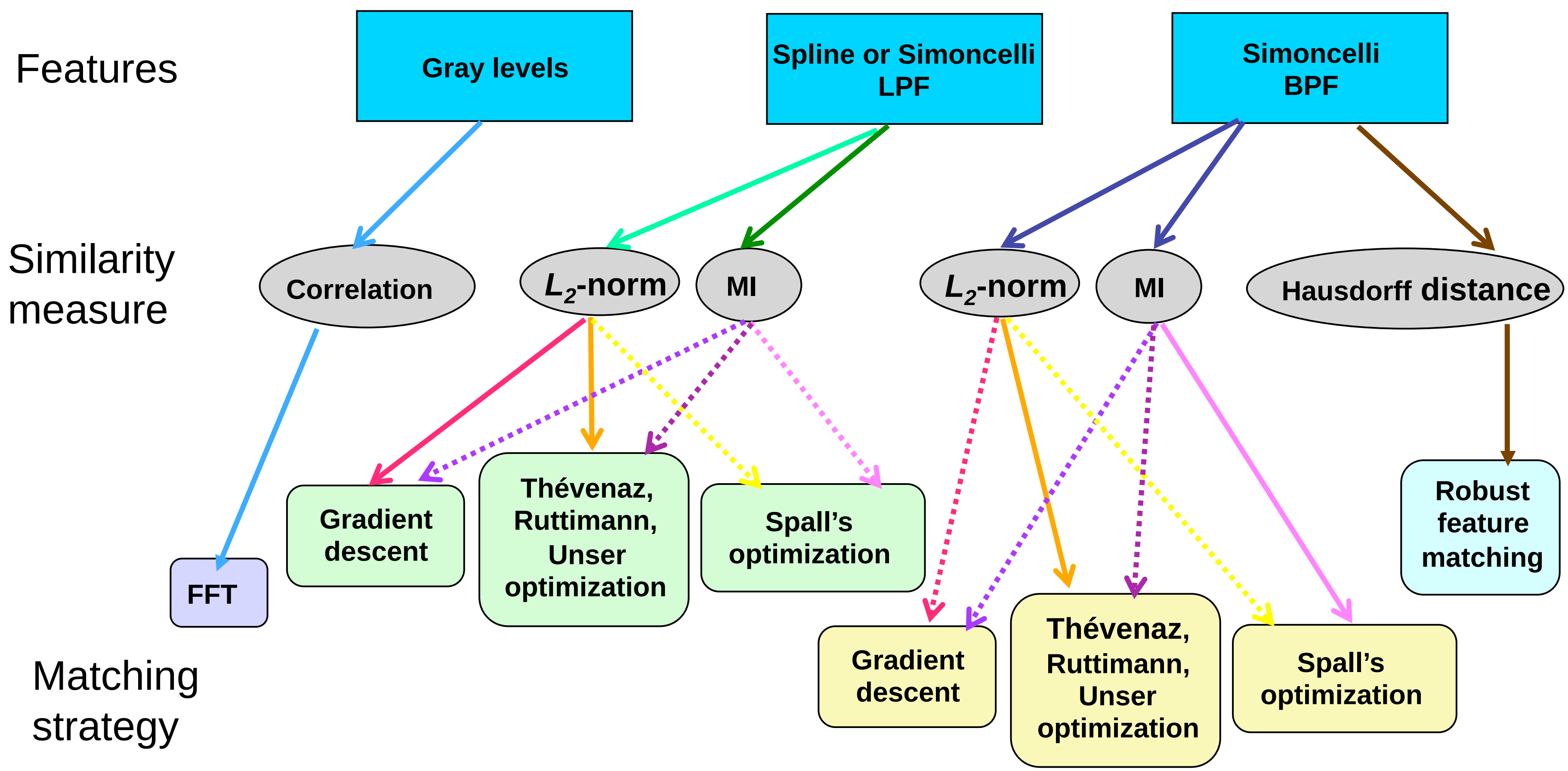
$$NCC_{I_1,I_2}(x,y)=\frac{\sum_{m=0}^{M-1}\sum_{n=0}^{N-1}\left[I_1(m,n)-\bar{I}_1\right]\left[I_2(x+m,y+n)-\bar{I}_2\right]}{\sqrt{\sum_{m=0}^{M-1}\sum_{n=0}^{N-1}\left[I_1(m,n)-\bar{I}_1\right]^2\cdot\sum_{m=0}^{M-1}\sum_{n=0}^{N-1}\left[I_2(x+m,y+n)-\bar{I}_2\right]^2}}$$

- **Hausdorff and Partial Hausdorff distance (PHD):**

$$H_K\left(I_1,I_2\right)=K^{th}_{p_1\in I_1}\min_{p_2\in I_2}\operatorname{dist}\left(p_1,p_2\right),$$

where $1\leq K\leq\left|I_1\right|$

# Framework for Evaluation of Image Registration Components



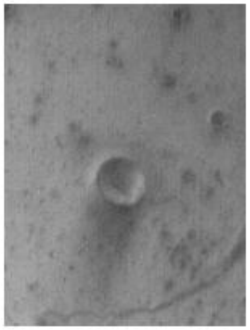
# Other Tests …
# Mars THEMIS Data

Region Segmentation after edge detection because low contrast and fewer strong features compared to Earth Science data:

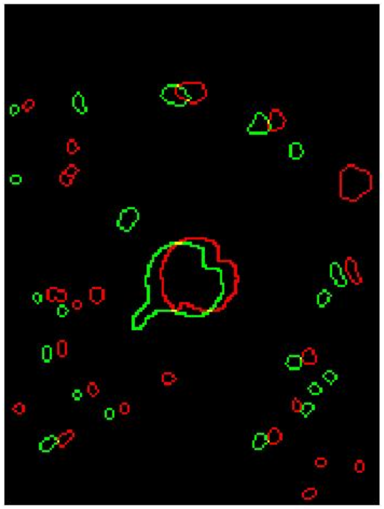
- Canny Edge Detection
- Generalized Hough Transform
- Watershed Segmentation

Input

Reference



Superimposed unregistered image boundaries



Registered Images