Registration of Multiple Sensor Earth Science Data

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What is Image Registration ?

- I1(x,y) and I2(x,y): images or image/map
  - find the mapping (f,g) which transforms I_1 into I_2:

  $I_2(x,y) = g(I_1(f_x(x,y),f_y(x,y))$
    - f : spatial mapping
    - g: radiometric mapping
- Spatial Transformations
  - Translation, Rigid, Affine, Projective, Perspective, Polynomial, ...
- Radiometric Transformations (Resampling)
  - Nearest Neighbor, Bilinear, Cubic Convolution, Spline ...

What is Image Registration (cont.)?

- *Navigation* or Model-Based Systematic Correction
  - Orbital, Attitude, Platform/Sensor Geometric Relationship, Sensor Characteristics, Earth Model, ...
- *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
- 2 Approaches

  (1) Image Registration as a Post-Processing (Taken here)

  (2) Navigation and Image Registration in a Closed Loop

Motivations - Applications of Image Registration and Fusion

- Multi-Modal Registration and Fusion
  - **New Sensor Calibration, Classification and Unmixing,**
  - **Extrapolation among Multiple Scales, Temporal, Spatial and Spectral**
- Temporal Registration and Fusion
  - **Change Detection, Earth/Planet Resources Surveying,**
  - **Continuity of Data to Build Long-Term Datasets**
- Viewpoint Fusion
  - **Formation Flying, Planet Exploration, Super-Resolution**
- Template/Chip Registration
  - **Data Mining, Map Updating**
- Scientific Visualization and Virtual Reality

Sensor Webs, Constellation and Exploration

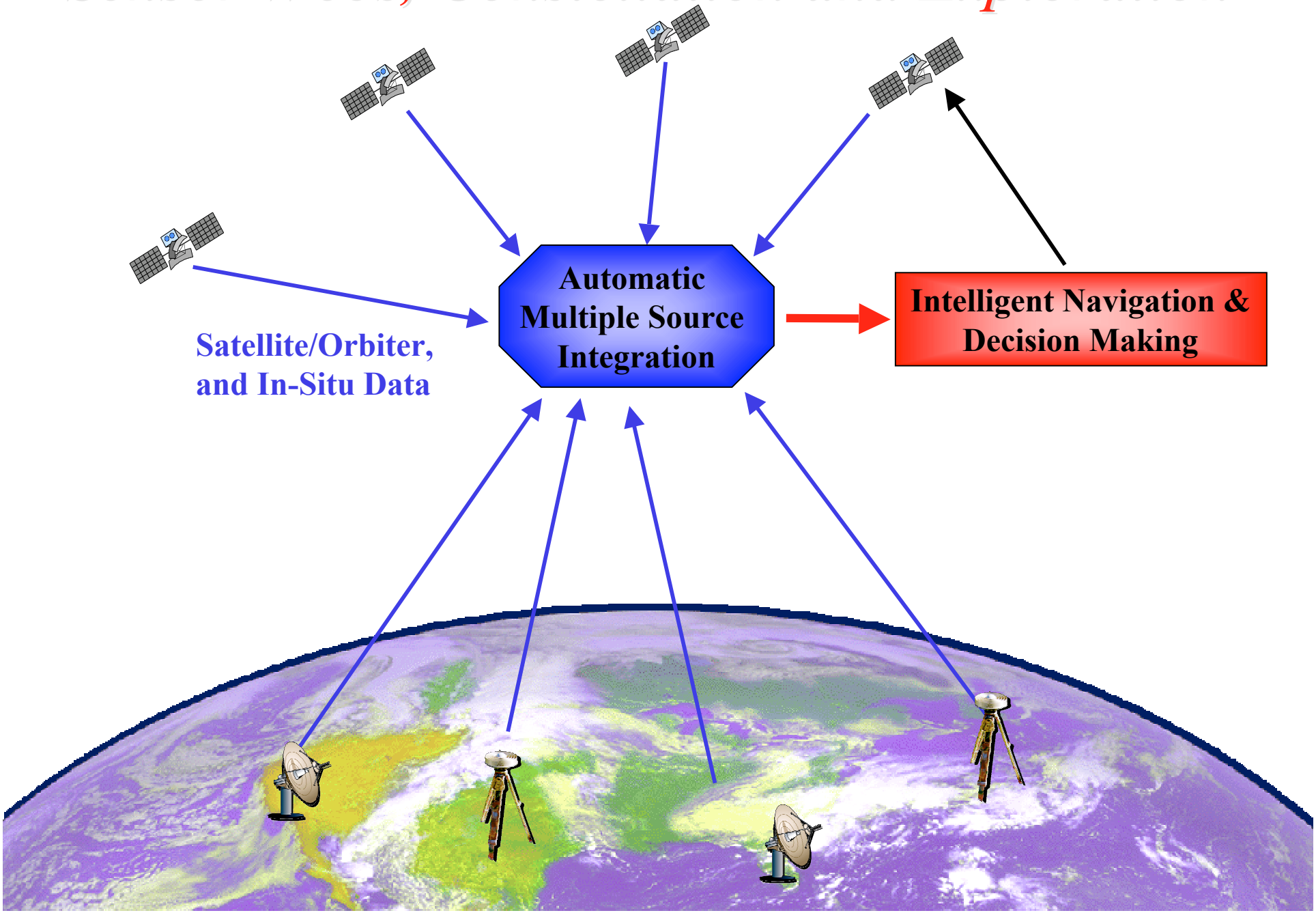


Image Registration Challenges

- Multi-Resolution / Mono- or Multi-Instrument
  - Multi-temporal data
  - Various spatial resolutions
  - Various spectral resolutions
- Sub-Pixel Accuracy
  - 1 pixel misregistration=> 50% error in NDVI computation
- Accuracy Assessment
  - Synthetic data
  - "Ground Truth" (manual registration?)
  - Use down-sampled high-resolution data
  - Consistency ("circular" registrations) studies

Image Registration Components

0 Pre-Processing

- Cloud Detection, Region of Interest Masking, ...

1 Feature Extraction ("Control Points")

- Edges, Regions, Contours, Wavelet Coefficients, ...

2 Feature Matching

- Spatial Transformation (a-priori knowledge)
- Search Strategy (Global vs Local, Multi-Resolution, ...)
- Choice of Similarity Metrics (Correlation, Optimization Method, Hausdorff Distance, ...)

3 Resampling, Indexing or Fusion

Image Registration Components

Features

- Gray Levels
- Edges
- Wavelets or Wavelet-Like

Similarity Measure

- Correlation
- L2 Norm
- Mutual Information
- Hausdorff Distance

Strategy

- Fast Fourier Transform
- Gradient Descent
- Thevenaz, Rutimann, Unser Optimization
- Spall's Optimization
- Robust Feature Matching

Similarity Metrics

- Correlation

$$C(A,B) = \frac{\sum_i (a_i - MeanA) * (b_i - MeanB)}{\sqrt{\sum_i (a_i - MeanA)^2} * \sqrt{\sum_i (b_i - MeanB)^2}}$$

- L2 Norm

$$E(p) = \sum (f - Q_p(g))^2$$

- Mutual Information:

$$I(A,B) = \sum_{a,b} h_{AB}(a,b).\log \frac{N.h_{AB}(a,b)}{h_A(a).h_B(b)}$$

- Partial Hausdorff Distance:

$$H_k(A, B) = K^{th}{}_{a\ in\ A}\ \min_{b\ in\ B}\ dist\ (a,b)$$

($1 \leq k \leq |A|$; K^{th} is the kth smallest element of set; dist(a,b): Euclidean distance)

Matching Strategies

- Exhaustive Search
- Fourier Transform
  - Translations
  - Very Fast Implementations
- Gradient Descent

$$\begin{bmatrix} \sum f_x^2 & \sum f_x f_y & \sum R f_x \\ \sum f_x f_y & \sum f_x^2 & \sum R f_y \\ \sum R f_x & \sum R f_y & \sum R^2 \end{bmatrix} \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta\theta \end{bmatrix} = \begin{bmatrix} \sum (f-g) f_x \\ \sum (f-g) f_y \\ \sum (f-g) R \end{bmatrix}$$

- Robust Feature Matching
  - Hierarchical Subdivisions of Search Space
  - Pruning of Search Space

Feature Extraction Experiments

(1) CORRELATION-BASED

a. Features = ***Gray Levels, Edges or Daubechies Coefficients***

==> • Edges/Wavelets More Robust to Noise and Local Intensity Varying
• Phase Correlation Faster
• Wavelet-Based Faster but Edge-Based More Accurate

b. Features = ***Daubechies and Simoncelli***

==> • Daubechies Low-Pass Sub-Band Almost Insensitive to Translation if Features at Least Twice Filters' Sizes
• Simoncelli's More Accurate and Less Sensitive to Noise than Daubechies' Filters
• Translation-Invariant BP Features More robust, less Accurate than LPs

(2) OPTIMIZATION-BASED (L2-BASED GRADIENT LEAST-SQUARES)

Features = ***Simoncelli (LP and BP) and Splines***

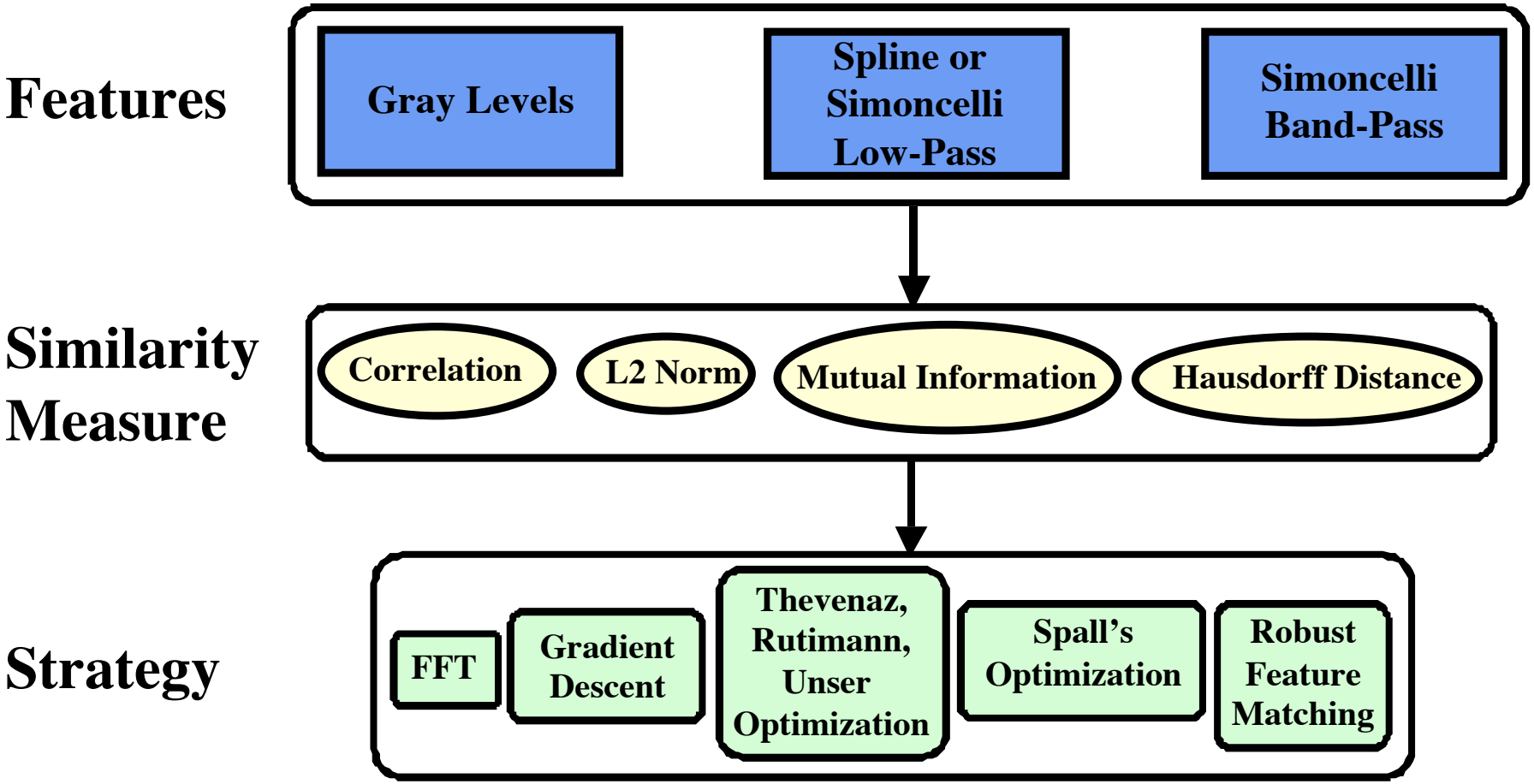
==> • Simoncelli-LP = Best radius of convergence
• Simoncelli-BP = Best for accuracy and consistency
• When CV, Spline features have better accuracy

Mutual Information Experiments

- **Correlation vs Mutual Information:**
  - Sharper Peak for MI => enables better accuracy
  - MI less sensitive to noise

- **MI with Stocchastic Gradient**
  - Spall's Simultaneous Perturbation Stocchastic Approximation (SPSA): based on gradient approximation computed only from measurements of the objective function (200 iterations)
  - On synthetic test data, 0.01 pixel accuracy
  - On Multi-Temporal (cloudy) test data, 0.64 pixel acccuracy compared to manual registration
  - On Multi-Sensor test data, 0.34 pixel accuracy

A Framework for the Analysis of Various Image Registration Components



Purposes of a Modular Image Registration Framework

- **Testing Framework to:**
  - Assess Various Combinations of Components as a Function of the Applications
  - Assess a New Registration Component Compared to Other Known Ones

- **Basis for a Future Registration Tool in Which User Could "Schedule" a Combination of Components as a function of:**
  - Application
  - Available Computational Resources
  - Required Registration Accuracy

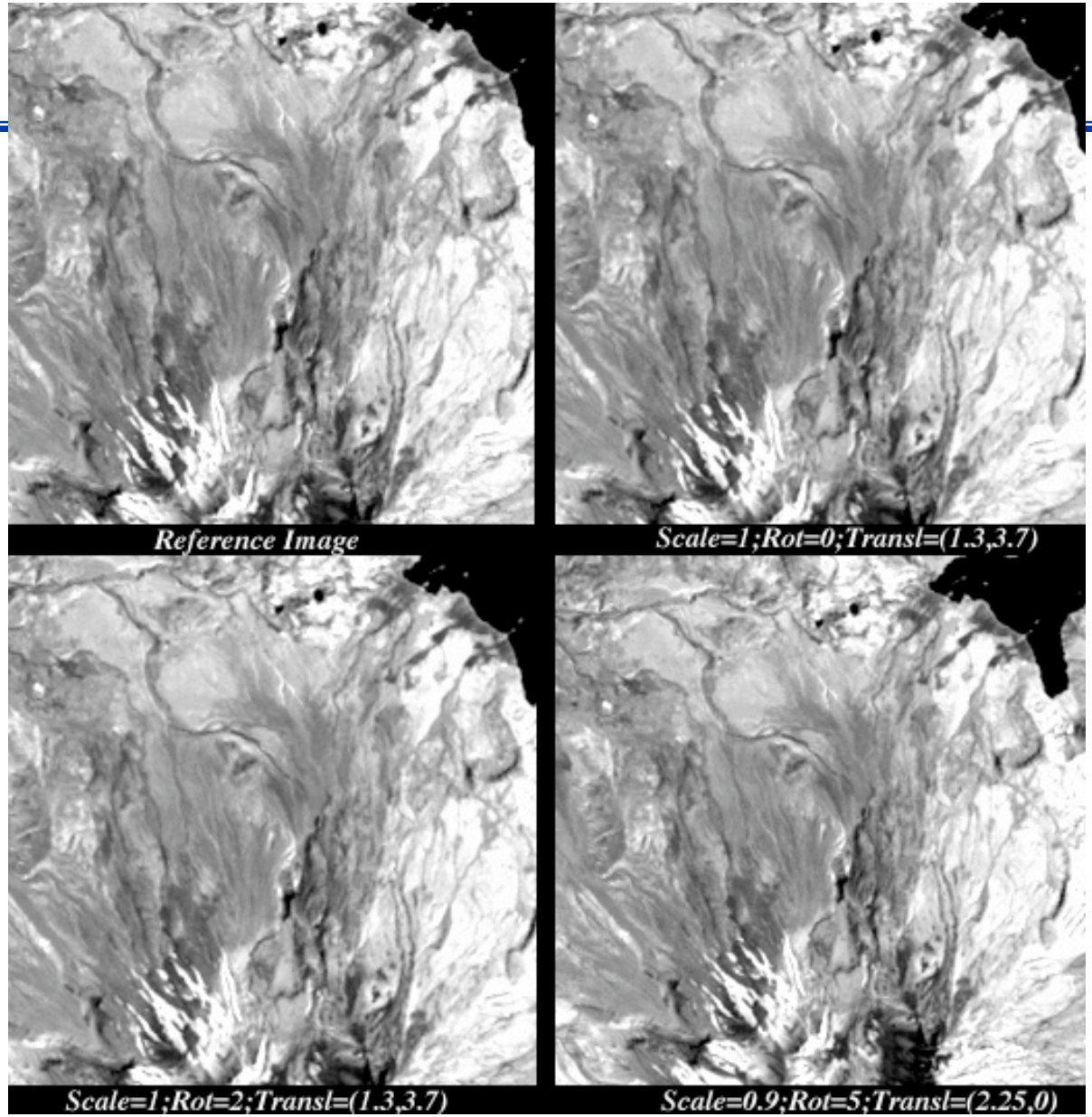
Registration Components Validation

- Controlled Synthetic Test Data
- Meaningful and Representative Data Sets
  - **Multi-Temporal Landsat Data**
  - **Multi-Sensor EOS Validation Core Sites Data**
- Validation Criteria
  - Reliability (Confidence Measurement)
  - Sub-Pixel Accuracy
  - Low Computational Requirements

Test Data Synthetic Images

- Landsat-TM Band 4
  - 512x512 starting scene
  - Extraction of 256x256 Center: Reference Image
- Transformation of Starting Scene by:
    - Scales in [0.9,1.1]
    - Translations in [0,4] pixels
    - Rotations in in [0,3] degrees
  - Extraction of 256x256 centers of transformed scenes: Input Images

Synthetic Images



Results Synthetic Test Data (1)

Synthetic Data wrt r256	Fast Correl	Gauss/L2/GD	Spline/L2/TRU	SimL/L2/TRU	SimB/L2/TRU	SimB/MI/Spal
r256						
Scale	1.0000	-	1.0000	1.0000	1.0000	1.0001
Rotation	0.0000	-	0.0000	0.0000	0.0000	0.0122
Shift-x	0.0000	-	0.0000	0.0000	0.0000	-0.0098
Shift-y	0.0000	-	0.0000	0.0000	0.0000	-0.0108
k_ratio	1.0000	-	1.0000	1.0000	1.0000	1.0001
thetaErr	0.0000	-	0.0000	0.0000	0.0000	0.0122
txErr	0.0000	-	0.0000	0.0000	0.0000	-0.0098
tyErr	0.0000	-	0.0000	0.0000	0.0000	-0.0108
Global Error	**0.0000**	**-**	**0.0000**	**0.0000**	**0.0000**	**0.0145**
i256_r2						
Scale	0.9998	0.9996	0.0000	0.9999	0.9999	1.0001
Rotation	1.9922	2.0132	2.0001	1.9977	1.9977	2.0082
Shift-x	-0.0723	-0.0186	0.0007	-0.0002	-0.0002	-0.0070
Shift-y	0.0662	0.0817	0.0005	-0.0012	-0.0001	0.0278
k_ratio	0.9998	0.9996	0.0000	0.9999	0.9999	1.0001
thetaErr	-0.0078	0.0132	0.0001	-0.0023	-0.0023	0.0082
txErr	-0.0723	-0.0186	0.0007	-0.0002	-0.0002	-0.0070
tyErr	0.0662	0.0817	0.0005	-0.0012	-0.0001	0.0278
Global Error	**0.0980**	**0.0838**	**0.4061**	**0.0012**	**0.0002**	**0.0287**
i256_tx1.3_ty3.7						
scale	0.9997	1.0000	1.0000	1.0000	0.9994	1.0000
Rotation	-0.0294	0.0047	-0.0003	-0.0006	-0.0019	0.0011
Shift-x	1.0131	1.2631	1.3001	1.2996	1.2953	1.2908
Shift-y	3.9321	3.4310	3.6983	3.6996	3.6955	3.7071
k_ratio	0.9997	1.0000	1.0000	1.0000	0.9994	1.0000
thetaErr	-0.0294	0.0047	-0.0003	-0.0006	-0.0019	0.0011
txErr	-0.1772	-0.0542	0.0012	0.0018	0.0033	-0.0132
tyErr	0.1966	-0.2630	-0.0021	-0.0011	-0.0046	0.0085
Global Error	**0.2647**	**0.2685**	**0.0024**	**0.0021**	**0.0056**	**0.0157**
i256_sc1.1						
Scale	1.0996	1.0878	1.1000	1.1000	1.0999	1.0999
Rotation	-0.0001	-0.0047	0.0002	-0.0003	0.0000	0.0049
Shift-x	0.0002	-0.0817	0.0004	0.0001	-0.0011	-0.0117
Shift-y	0.0005	0.0551	-0.0001	-0.0001	0.0043	0.0112
k_ratio	0.9996	0.9889	1.0000	1.0000	0.9999	0.9999
thetaErr	-0.0001	-0.0047	0.0002	-0.0003	0.0000	0.0049
txErr	0.0002	-0.0817	0.0004	0.0001	-0.0011	-0.0117
tyErr	0.0005	0.0551	-0.0001	-0.0001	0.0043	0.0112
Global Error	**0.0005**	**0.0991**	**0.0004**	**0.0002**	**0.0045**	**0.0162**

Results Synthetic Test Data (2)

i256_sc0.9						
Scale	0.9014	0.8893	0.9000	0.9000	0.9001	0.9001
Rotation	-0.0392	-0.0056	0.0000	0.0000	0.0005	0.0080
Shift-x	0.0000	0.1376	-0.0002	0.0003	0.0002	-0.0099
Shift-y	-0.0003	0.1059	-0.0005	-0.0013	-0.0022	-0.0251
k_ratio	1.0016	0.9881	1.0000	1.0000	1.0001	1.0001
thetaErr	-0.0392	-0.0056	0.0000	0.0000	0.0005	0.0080
txErr	0.0000	0.1376	-0.0002	0.0003	0.0002	-0.0099
tyErr	-0.0003	0.1059	-0.0005	-0.0013	-0.0022	-0.0251
Global Error	**0.0003**	**0.1747**	**0.0006**	**0.0013**	**0.0022**	**0.0269**
i256_r2_tx1.3_ty3.7						
Scale	1.0001	0.9999	1.0000	1.0000	1.0000	1.0000
Rotation	2.0131	1.9408	2.0002	2.0000	1.9992	2.0004
Shift-x	1.2172	1.1085	1.3001	1.3009	1.2981	1.3049
Shift-y	3.7748	3.6704	3.6997	3.7027	3.6950	3.7052
k_ratio	1.0001	0.9999	1.0000	1.0000	1.0000	1.0000
thetaErr	0.0131	-0.0592	0.0002	0.0000	-0.0009	0.0004
txErr	-0.1313	0.0297	-0.0008	0.0009	0.0013	0.0035
tyErr	0.0918	-0.0998	0.0000	0.0028	-0.0060	0.0057
Global Error	**0.1602**	**0.1041**	**0.0008**	**0.0029**	**0.0061**	**0.0067**
i256_sc0.9_r5_tx2.25						
Scale	0.9018	0.8897	0.9000	0.8999	0.9616	0.9000
Rotation	4.9566	5.0016	4.9996	4.9991	3.8120	5.0080
Shift-x	2.2876	2.5018	2.2505	2.2513	-4.3352	2.2517
Shift-y	0.3609	0.3697	-0.0014	-0.0026	4.7762	0.0034
k_ratio	1.0020	0.9885	1.0000	0.9999	1.0685	0.9999
thetaErr	-0.0434	0.0016	-0.0004	-0.0009	-1.1880	0.0080
txErr	0.0352	0.2777	0.0005	0.0015	-5.2331	0.0019
tyErr	0.2631	0.3732	-0.0024	-0.0047	2.5461	0.0214
Global Error	**0.2652**	**0.4679**	**0.0024**	**0.0049**	**5.6300**	**0.0215**
i256_sc1.1_r3_tx3.1_ty2.75						
Scale	1.1002	1.0890	1.1000	1.1000	1.0632	1.1000
Rotation	2.9922	2.8758	3.0001	3.0002	-3.0035	2.9981
Shift-x	2.7988	2.5993	3.1000	3.1002	-3.2838	3.0782
Shift-y	2.6428	2.6139	2.7500	2.7503	-8.8802	2.7507
k_ratio	1.0002	0.9900	1.0000	1.0000	0.9665	1.0000
thetaErr	-0.0078	-0.1242	0.0000	0.0002	-6.0035	-0.0019
txErr	-0.2802	-0.1089	-0.0002	-0.0003	-6.8974	-0.0166
tyErr	-0.1318	-0.4679	0.0001	0.0009	-10.6076	-0.0052
Global Error	**0.3096**	**0.4828**	**0.0002**	**0.0010**	**12.8701**	**0.0174**
MEAN ERROR	**0.1569**	**0.2401**	**0.0590**	**0.0019**	**2.6456**	**0.0190**

Some Results on Synthetic Test Data

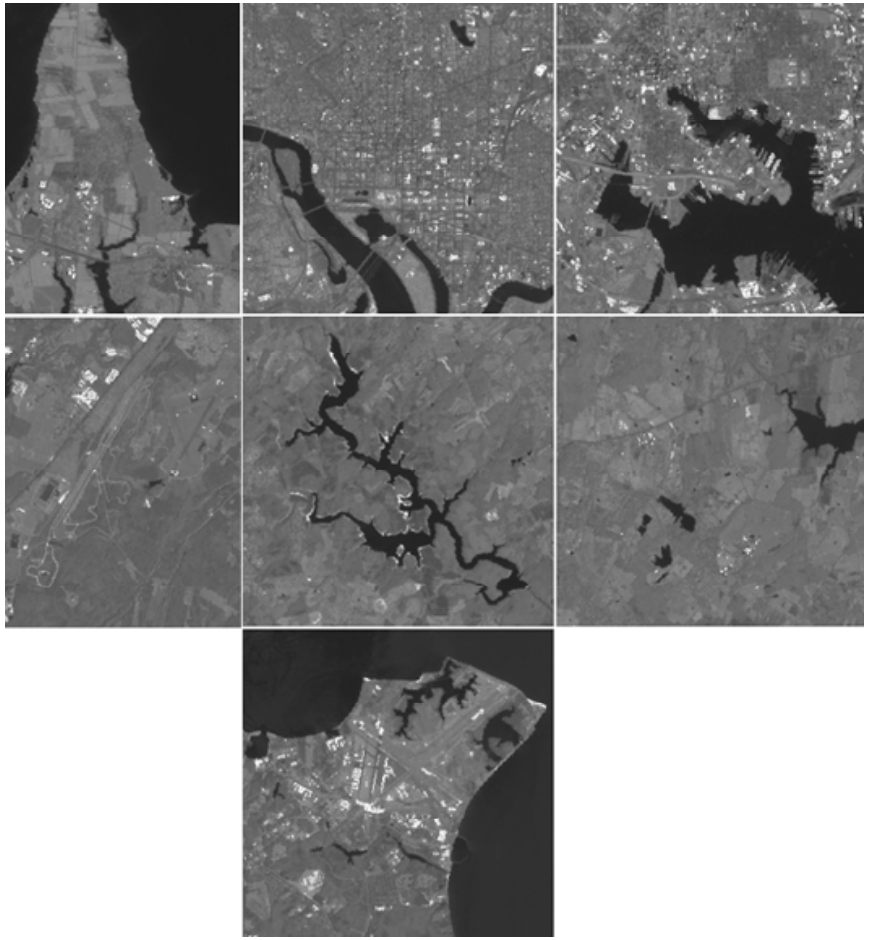
i256_sc0.9						
Scale	0.9014	0.8893	0.9000	0.9000	0.9001	0.9001
Rotation	-0.0392	-0.0056	0.0000	0.0000	0.0005	0.0080
Shift-x	0.0000	0.1376	-0.0002	0.0003	0.0002	-0.0099
Shift-y	-0.0003	0.1059	-0.0005	-0.0013	-0.0022	-0.0251
k_ratio	1.0016	0.9881	1.0000	1.0000	1.0001	1.0001
thetaErr	-0.0392	-0.0056	0.0000	0.0000	0.0005	0.0080
txErr	0.0000	0.1376	-0.0002	0.0003	0.0002	-0.0099
tyErr	-0.0003	0.1059	-0.0005	-0.0013	-0.0022	-0.0251
Global Error	**0.0003**	**0.1747**	**0.0006**	**0.0013**	**0.0022**	**0.0269**
i256_r2_tx1.3_ty3.7						
Scale	1.0001	0.9999	1.0000	1.0000	1.0000	1.0000
Rotation	2.0131	1.9408	2.0002	2.0000	1.9992	2.0004
Shift-x	1.2172	1.1085	1.3001	1.3009	1.2983	1.3049
Shift-y	3.7748	3.6704	3.6997	3.7027	3.6990	3.7052
k_ratio	1.0001	0.9999	1.0000	1.0000	1.0000	1.0000
thetaErr	0.0131	-0.0592	0.0002	0.0000	-0.0009	0.0004
txErr	-0.1313	0.0297	-0.0008	0.0009	0.0013	0.0035
tyErr	0.0918	-0.0998	0.0000	0.0028	-0.0060	0.0057
Global Error	**0.1602**	**0.1041**	**0.0009**	**0.0029**	**0.0061**	**0.0067**
i256_sc0.9_r5_tx2.25						
Scale	0.9018	0.8897	0.9000	0.8999	0.9616	0.9000
Rotation	4.9566	5.0006	4.9996	4.9991	3.8120	5.0080
Shift-x	2.2876	2.2018	2.2505	2.2513	-4.3352	2.2517
Shift-y	0.3609	0.3397	-0.0014	-0.0026	4.7762	0.0034
k_ratio	1.0000	0.9885	1.0000	0.9999	1.0685	0.9999
thetaErr	-0.0034	0.0016	-0.0004	-0.0009	-1.1880	0.0080
txErr	0.0332	0.2777	0.0005	0.0015	-5.2331	0.0019
tyErr	0.2631	0.3732	-0.0024	-0.0047	2.5461	0.0214
Global Error	**0.2652**	**0.4679**	**0.0024**	**0.0049**	**5.6300**	**0.0215**
i256_sc1.1_r3_tx3.1_ty2.75						
Scale	1.1002	1.0890	1.1000	1.1000	1.0632	1.1000
Rotation	2.9922	2.8758	3.0001	3.0002	-3.0035	2.9981
Shift-x	2.7988	2.5993	3.1000	3.1002	-3.2838	3.0782
Shift-y	2.6428	2.6139	2.7500	2.7503	-8.8802	2.7507
k_ratio	1.0002	0.9900	1.0000	1.0000	0.9665	1.0000
thetaErr	-0.0078	-0.1242	0.0000	0.0002	-6.0035	-0.0019
txErr	-0.2802	-0.1089	-0.0002	-0.0003	-6.8974	-0.0166
tyErr	-0.1318	-0.4679	0.0001	0.0009	-10.6076	-0.0052
Global Error	**0.3096**	**0.4828**	**0.0002**	**0.0010**	**12.8701**	**0.0174**
MEAN ERROR	**0.1569**	**0.2401**	**0.0590**	**0.0019**	**2.6456**	**0.0190**

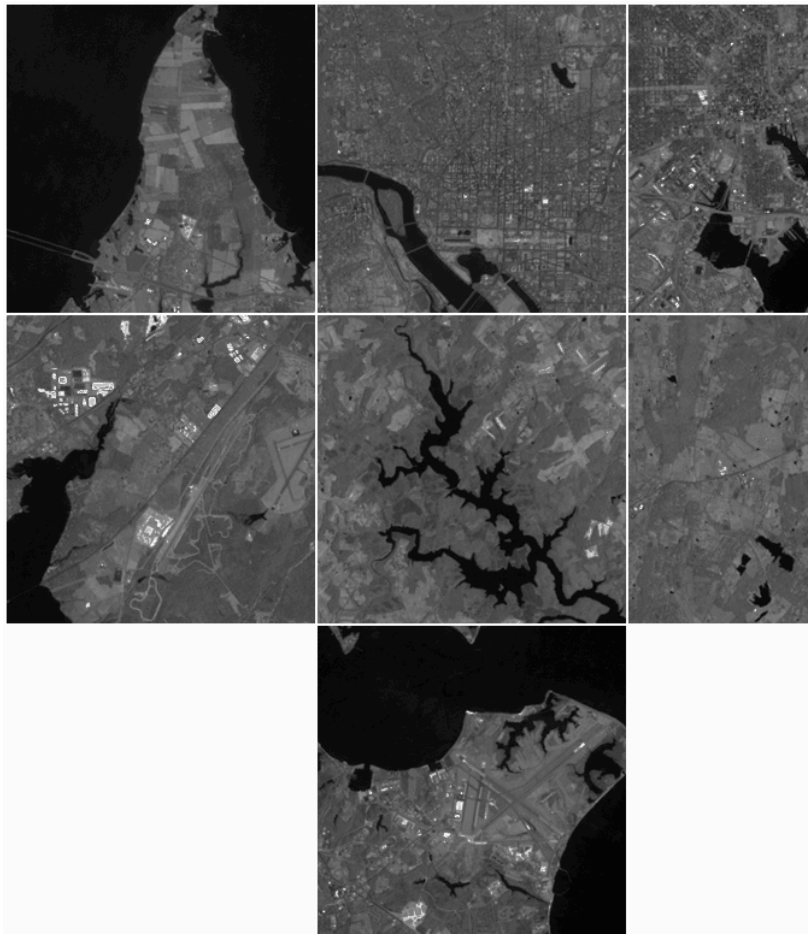
»Best Accuracy of 0.019 Pixels - Average: 0.5 pixel

Multi-Temporal Landsat Image Registration

- Landsat Data Continuity Mission
- Landsat-5 and -7 Multi-Temporal Data
- 2 Areas, Central VA and DC/Baltimore
- For each area:
  - 1 reference scene with 6 to 8 reference chips (256x256)
  - 4 input scenes, for each:
    - Extract windows corresponding to chips
    - Local registrations chip/window pairs, using Simoncelli-Band Pass Features and Robust Feature Matching
    - Global registration using a generalized LMS
- Accuracies Between 0.21 and 0.59 pixel

Chip-Window Pairs





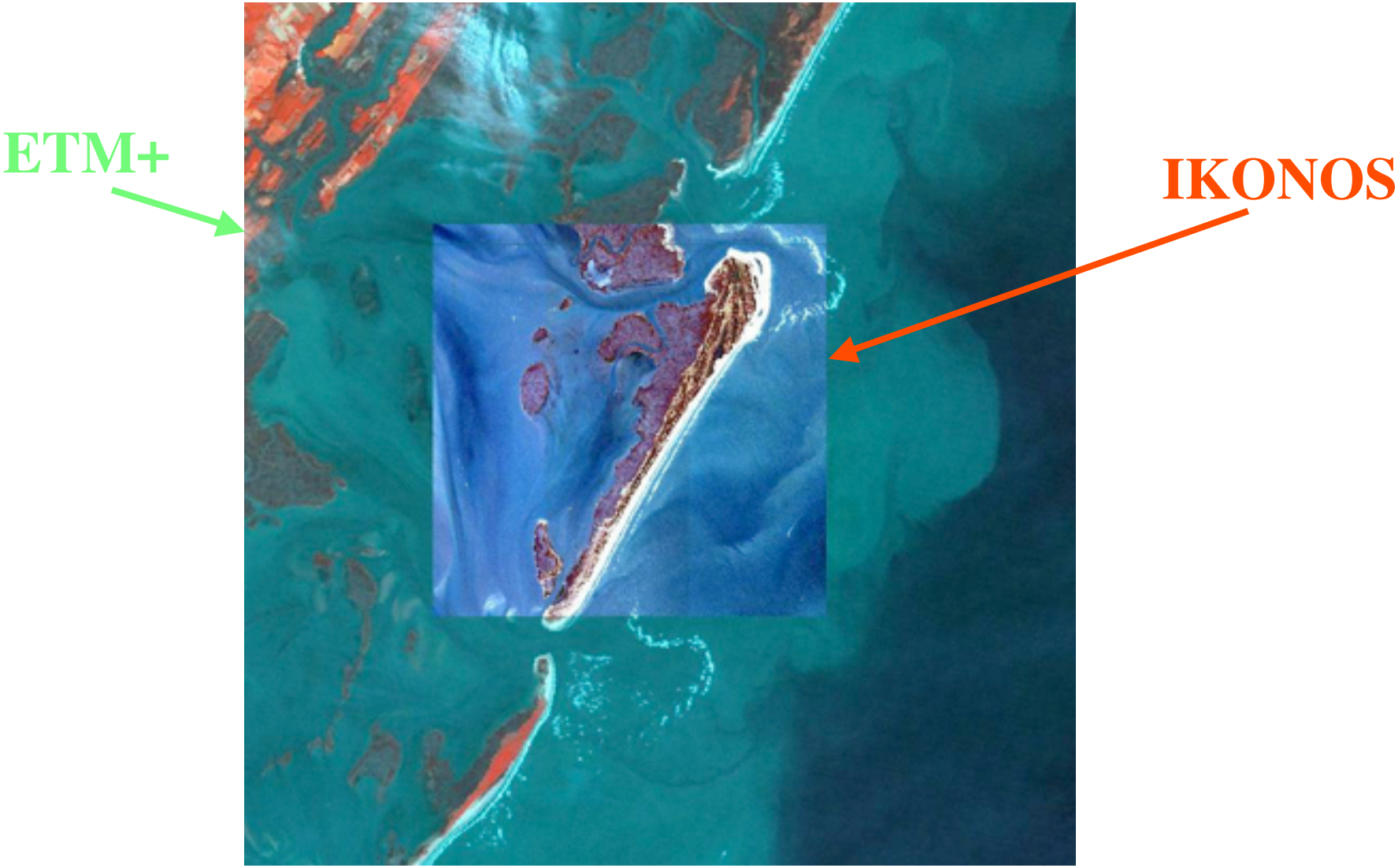
Test Data
EOS Validation Core Sites

- Landsat-7/IKONOS/MODIS/SeaWiFS
  - Red and NIR for each sensor
  - 4 Spatial Resolutions:
    - IKONOS: 4 m; ETM+: 30 m; 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

Test Data

EOS Validation Core Sites

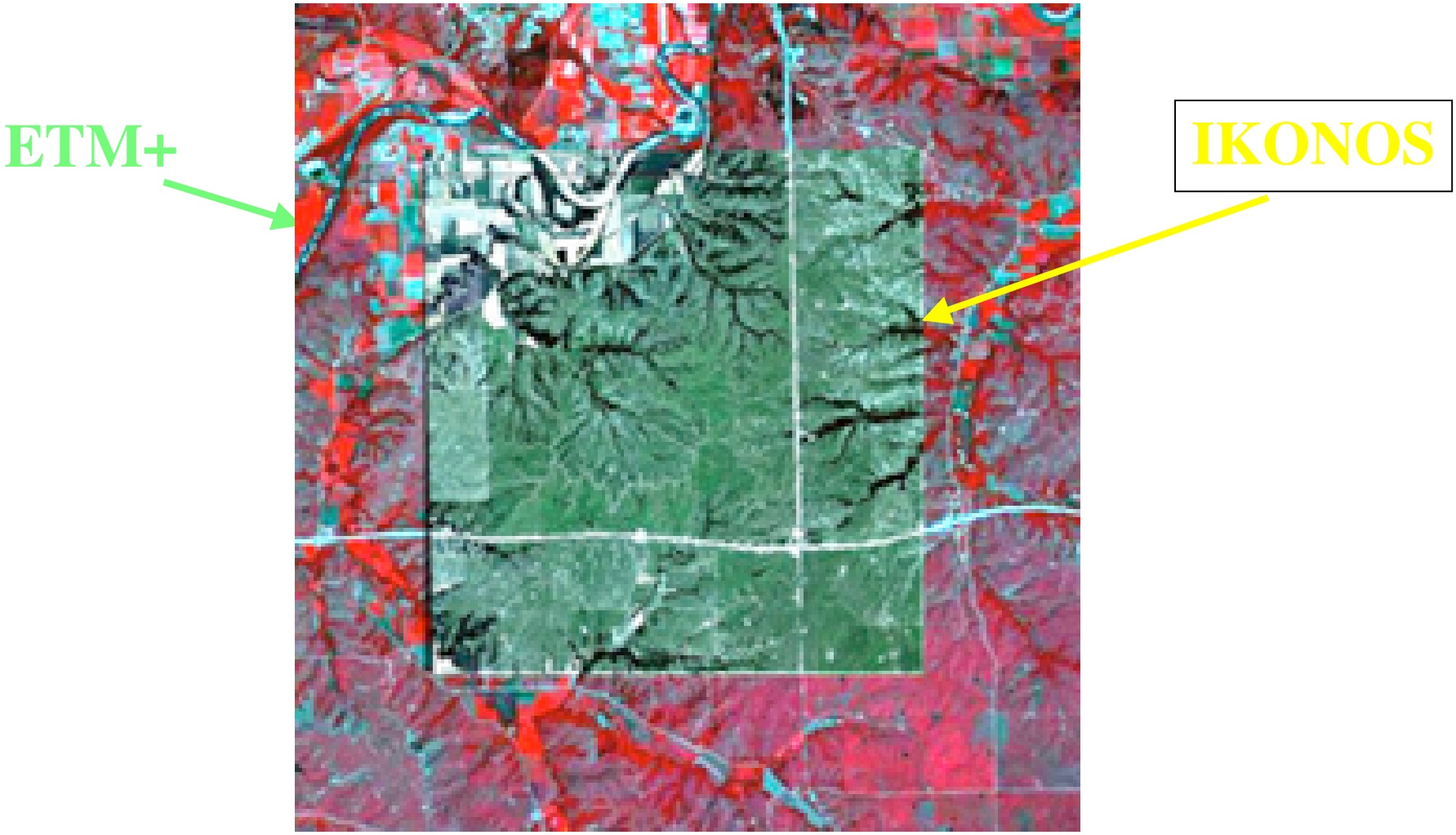
ETM/IKONOS Mosaic of Coastal VA Data



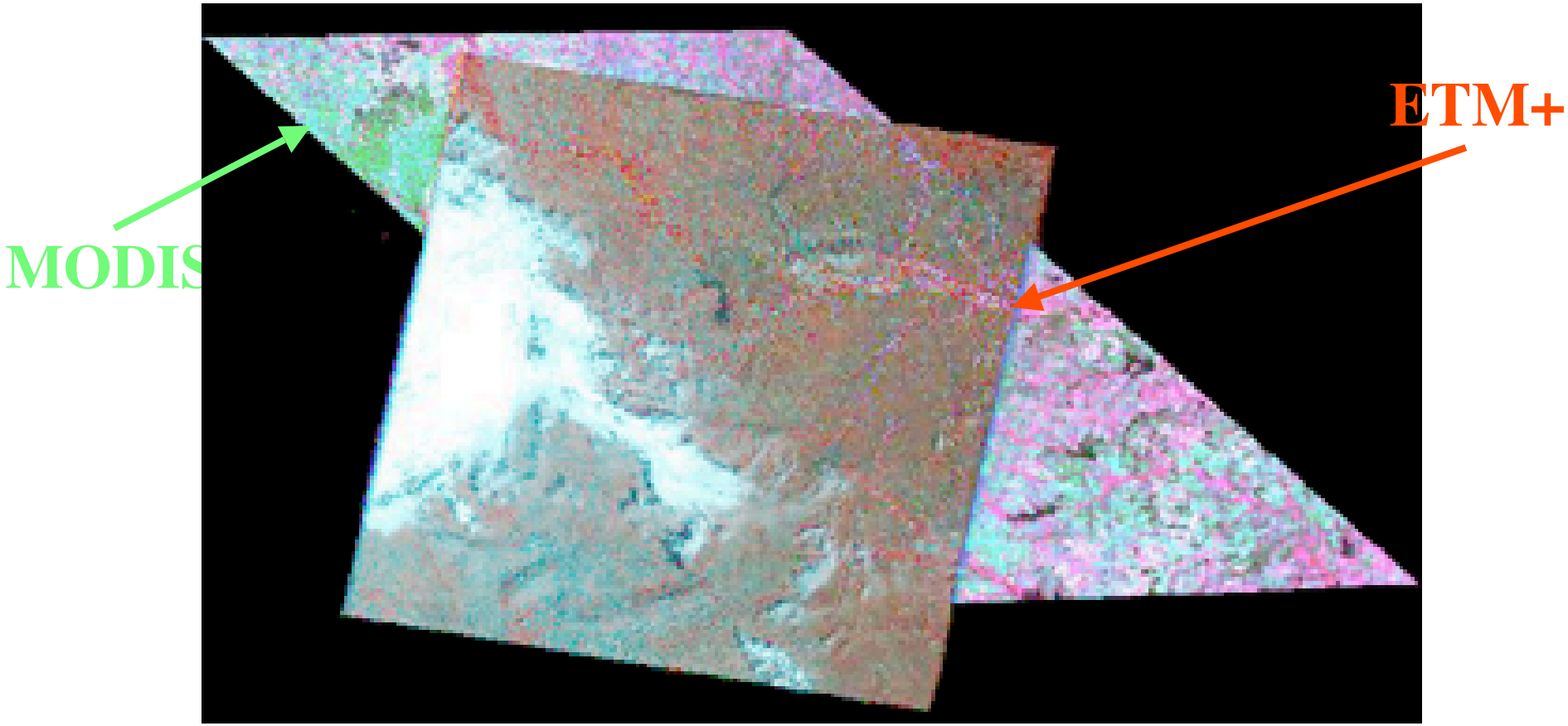
Test Data

EOS Validation Core Sites

ETM/IKONOS Agricultural Konza Data



Test Data
EOS Validation Core Sites
ETM/MODIS of Agricultural Konza Data



Results VA - IKONOS/ETM+

VA_Coast	Fast Correl	Gauss/L2/GD	Spline/L2/TRU	SimL/L2/TRU	SimB/L2/TRU	SimB/MI/Spall
IKONOS/Red-IKONOS/NIR						
Scale	1.0000	1.0001	1.0000	1.0000	0.9999	0.9997
Rotation	-0.0008	0.0117	-0.0005	-0.0002	0.0017	0.0271
Shift-x	0.0072	-0.2482	-0.1644	-0.2421	0.0523	0.7761
Shift-y	-0.0542	-0.3789	-0.4944	-0.5315	-0.5597	0.4016
IKONOS/Red-ETM/Red						
Scale	1.0661	1.0529	1.0662	1.0669	1.6094	1.0661
Rotation	0.0013	-1.5730	0.0204	0.0568	-1.3397	0.1040
Shift-x	12.8575	14.1783	12.9748	12.9902	-105.3350	13.0244
Shift-y	13.1722	15.8991	13.2198	13.3562	83.6175	14.1378
IKONOS/Red-ETM/NIR						
Scale	1.0619	1.0440	1.0515	3.0250	1.5185	1.0664
Rotation	-0.1210	-1.2434	1.5185	6.6137	7.5141	0.0103
Shift-x	12.3951	12.5628	10.6674	-205.4730	-45.6183	12.2158
Shift-y	12.2179	13.6363	9.3905	248.2180	69.9682	13.1563
IKONOS/NIR-ETM/Red						
Scale	1.0610	1.0524	1.0564	1.0516	0.9886	1.0674
Rotation	-0.9030	-2.0357	-1.0406	-1.1490	-0.5544	0.9718
Shift-x	10.3298	14.7560	27.7790	28.2731	-1.5585	16.0900
Shift-y	11.5491	17.9961	6.6591	6.5726	-1.7722	16.0972
IKONOS/NIR-ETM/NIR						
Scale	1.0654	1.0548	1.0651	1.0668	1.4050	1.0663
Rotation	-0.1093	-1.3526	0.0111	0.0375	3.7209	0.0063
Shift-x	12.5909	13.7730	13.0008	12.9493	-38.6769	12.8556
Shift-y	12.8984	14.5991	13.1058	13.2238	2.5245	13.2462
ETM/Red-ETM/NIR						
Scale	1.0000	0.9883	0.9998	0.9997	0.9998	1.0001
Rotation	0.0015	0.1146	-0.0146	-0.0214	-0.0136	-0.0020
Shift-x	-0.0670	-0.9907	-0.2048	-0.2243	-0.2107	0.8507
Shift-y	-0.0136	-1.2419	-0.4854	-0.6841	-0.5024	0.6654

Results - Cascades IKONOS/ETM+

CASCADES_Mountains	Fast Correl	Gauss/L2/GD	Spline/L2/TRU	SimL/L2/TRU	SimB/L2/TRU	SimB/MI/Spall
IKONOS/Red-IKONOS/NIR						
Scale	1.0000	1.0005	1.0000	1.0000	1.0001	1.0003
Rotation	0.0003	0.0537	0.0006	0.0009	0.0009	0.0177
Shift-x	0.0135	-0.0091	-0.0240	-0.0464	-0.0362	0.0204
Shift-y	0.0135	0.0902	-0.1603	-0.2090	-0.1827	0.0535
IKONOS/Red-ETM/Red						
Scale	1.0644	1.0603	1.1006	1.0646	1.0642	1.0645
Rotation	0.0917	-0.1207	-0.0500	0.0703	0.0760	0.1302
Shift-x	8.6744	9.5412	11.4319	8.6323	8.6515	8.7768
Shift-y	10.1616	8.1125	12.3680	10.0836	10.0627	10.0392
IKONOS/Red-ETM/NIR						
Scale	1.0651	1.0604	0.9962	1.0000	1.0649	1.0640
Rotation	0.0883	-0.1026	-0.0316	0.0000	0.0878	0.1138
Shift-x	8.6944	9.5610	0.0321	0.0000	8.6573	8.8979
Shift-y	10.2174	8.1167	0.2538	0.0000	10.1193	10.2239
IKONOS/NIR-ETM/Red						
Scale	1.0641	1.0593	1.0765	1.0981	1.0646	1.0656
Rotation	0.0390	-0.1909	-0.5836	0.0694	0.0807	0.1277
Shift-x	8.5615	9.5090	10.5558	11.9510	8.5537	8.7318
Shift-y	10.1641	7.9072	9.9043	8.3562	10.1538	9.9239
IKONOS/NIR-ETM/NIR						
Scale	1.0647	1.0609	1.0649	1.0648	1.0649	1.0652
Rotation	0.1086	-0.0992	0.0725	0.0683	0.0714	0.1096
Shift-x	8.6681	9.5998	8.7279	8.6437	8.7094	8.6629
Shift-y	10.1669	8.1866	10.1404	10.1489	10.1394	10.1561
ETM/Red-ETM/NIR						
Scale	1.0000	1.0005	1.0000	1.0000	1.0001	1.0000
Rotation	-0.0006	0.0992	-0.0079	-0.0085	-0.0087	0.0929
Shift-x	0.0793	-0.0427	-0.1191	-0.0995	-0.1415	0.9420
Shift-y	-0.0290	0.1675	-0.1663	-0.1334	-0.2173	0.7340

Conclusions - Future Work

- **Reported Results Showed:**
  - Synthetic Data: best accuracy 0.019, average 0.5 pixel
  - Multi-Temporal Landsat: accuracy between 0.21 and 0.59 pixel
  - Multi-Sensor EOS Core Sites: inter-algorithm average consistency of about 1/3 pixel, self-consitency of 1/8 pixel
- **Current Systematic Modular Comparison, Including:**
  - All possible components combinations
  - Study of sensitivity to noise, radiometric transformations, and initial conditions
  - Computational and memory requirements
- **Future Studies:**
  - Additional datasets with accurate ground truth
  - Generalization of framework to other planetary data, e.g. Mars
  - Implementations on HP and reconfigurable computers