AUTOMATIC CO-REGISTRATION OF MULTI-TEMPORAL LANDSAT-8/OLI AND SENTINEL-2A/MSI IMAGES

S. Skakun\textsuperscript{1,2}, J.-C. Roger\textsuperscript{1,2}, E. Vermote\textsuperscript{2}, C. Justice\textsuperscript{1}, J. Masek\textsuperscript{3}

\textsuperscript{1} Department of Geographical Sciences, University of Maryland, College Park MD 20742, USA
\textsuperscript{2} NASA Goddard Space Flight Center Code 619, Greenbelt, MD 20771, USA
\textsuperscript{3} NASA Goddard Space Flight Center Code 618, Greenbelt, MD 20771, USA
Introduction

- Many applications in climate change and environmental and agricultural monitoring rely heavily on the exploitation of **multi-temporal** satellite imagery.

- Combined use of freely available Landsat-8 and Sentinel-2 images can offer **high temporal frequency** of about 1 image every 3–5 days globally.

- Data should be consistent
  - Including **co-registration**
Introduction: Sentinel-2A/MSI

- MSI = Multi-Spectral Instrument

(Gascon et al. 2017)
Introduction: Landsat-8

- Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) instruments

Comparison of Landsat 7 and 8 bands with Sentinel-2

https://landsat.gsfc.nasa.gov
Introduction

- Both sensor geolocation systems are designed to use **ground control** to improve the geolocation accuracy and repeatability (Storey et al. 2016)

- **Sentinel-2A**
  - The Sentinel-2 geolocation will use a **Global Reference Image (GRI)** derived from orthorectified Sentinel-2 cloud-free images (Déchoz et al. 2015)
  - Planned to be available at the end of 2017

- **Landsat-8**
  - The Landsat-8 geolocation uses a global sample of ground control points (Storey et al., 2014) derived for each WRS-2 path/row of circa 2000 **Global Land Survey (GLS)** Landsat-7 imagery (Gutman et al., 2013).

Landsat-8/Sentinel-2A Harmonization

- Pixel value misalignment
  - LC8 (center) and S2 (UL)

- Different UTM zones:
  - L8 uses north zone even for southern hemisphere, while S2 uses south zones
    • e.g. 20N from LC8 vs 20S from S2

- Misregistration
  - “estimate of the expected Sentinel-2 to Landsat-8 misregistration .... yields a 38 meter (2σ) expected registration accuracy between the sensors” [Storey et al., RSE, 2016]
Landsat-8/Sentinel-2A Misregistration

T20HNH – Sentinel-2A, band 08 (NIR), 10 m – Landsat-8, band5 (NIR), 30 m
**Methodology**

- **Automatic generation of control points (CPs).**
  - Phase-only correlation image matching method introduced by Guizar-Sicairos et al. (2008).
  - It uses:
    - a **cross-correlation** approach in the **frequency domain** by means of the Fourier transform and
    - exploits a computationally efficient procedure based on nonlinear optimization and Discrete Fourier Transforms (DFTs) to detect **sub-pixel shifts** between reference and sensed images.

Methodology

- **CPs filtering.**
  - A peak cross-correlation normalized magnitude is used for initial rejection of CPs.
  - After that, a RANdom SAmple Consensus (RANSAC) algorithm (Fischler and Bolles 1981) is run for the linear transformation model to detect inliers and outliers.

Methodology

- **Transformation function.**
  - A transformation function $F()$ is built to find correspondence between CPs in the reference image $x_r = (x_r, y_r)$ and points in the sensed image $x_s = (x_s, y_s)$: $(x_s, y_s) = F(x_r, y_r)$.

  - The following functions are evaluated:
    - **Polynomial**
    - **Radial Basis Functions (RBFs)**
      - Gaussian
      - Thin-plate splines (TPS)
    - **Random Forest (RF) regression**
Data used

- Co-registration of **45 Landsat-8 to Sentinel-2A pairs** and **37 Sentinel-2A to Sentinel-2A pairs** were analyzed.

<table>
<thead>
<tr>
<th>Country</th>
<th>Tile number</th>
<th>Acquisition date of Sentinel-2A reference image</th>
<th>Acquisition dates of Landsat-8 co-registered images</th>
<th>Acquisition dates of Sentinel-2A co-registered images</th>
</tr>
</thead>
<tbody>
<tr>
<td>Argentina</td>
<td>20HNH</td>
<td>2015358</td>
<td>2015354, 2015185, 2015201, 2015242, 2015249, 2015258, 2015290, 2015306, 2015329, 2015338, 2015345, 2015361, 2016021, 2016037, 2016053</td>
<td>2015341, 2016006, 2016013, 2016016, 2016023, 2016026, 2016036, 2016043, 2016046, 2016063, 2016065, 2016073, 2016083, 2016093, 2016096</td>
</tr>
<tr>
<td>Argentina</td>
<td>20HPH</td>
<td>2015358</td>
<td>2015242, 2015258, 2015290, 2015306, 2015338, 2015354, 2016021, 2016037, 2016053</td>
<td>2016003, 2016013, 2016023, 2016043, 2016063, 2016073, 2016083, 2016093</td>
</tr>
<tr>
<td>US (Texas)</td>
<td>14SKF</td>
<td>2016012</td>
<td>2015245, 2015261, 2015293, 2015309, 2015325, 2015341, 2015357, 2016024, 2016040, 2016056, 2016072, 2016088, 2016104</td>
<td>2016042, 2016072, 2016132</td>
</tr>
<tr>
<td>Ukraine</td>
<td>36UUU</td>
<td>2016169</td>
<td>2016076, 2016092, 2016108, 2016156, 2016172, 2016188</td>
<td>2016096, 2016109, 2016119, 2016156, 2016166, 2016179, 2016196, 2016199, 2016206</td>
</tr>
<tr>
<td>Ukraine</td>
<td>34UFU</td>
<td>2016198</td>
<td>2016063, 2016182</td>
<td>2016048, 2016208</td>
</tr>
</tbody>
</table>

Note: Acquisition dates are given in the format YY YY DOY (where DOY is the day of the year).
Results

Figure 3. Location of CPs shown in the form of vectors outlining the direction and magnitude of shifts ($\Delta_x$ and $\Delta_y$ (Equation (2)) found between Landsat-8 image acquired on 2016021 (21-Jan-2016), and Sentinel-2A image acquired on 2015358 (24-Dec-2015) and used as a reference image, over the study area in Argentina, tile T20HNNH. Vector lengths were multiplied by 100 for visual clarity. Overall, 1634 CPs were found using the phase-correlation approach in this case. The background is a Landsat-8 TOA NIR (band 5) image with TOA reflectance values scaled from 0.05 to 0.65.
Distribution of misregistration values $\Delta_x$ and $\Delta_y$ when co-registering Landsat-8 to Sentinel-2A images for different tiles used in the study. Units are shown in pixel values at 30 m spatial resolution.
Results

Distribution of misregistration values $\Delta_x$ and $\Delta_y$ when co-registering multi-temporal Sentinel-2A images for different tiles used in the study. Units are shown in pixel values at 10 m spatial resolution.
Results

- Performance of different transformation functions when co-registering Landsat-8 to Sentinel-2A at 30 m

Table 4. Average and standard deviation of the RMSE error (Equation (4)) calculated for different transformation functions using CPs from testing set when co-registering Landsat-8 and Sentinel-2A images.

<table>
<thead>
<tr>
<th>Tile</th>
<th>Translation (Equations (7)–(8))</th>
<th>1st order polynomial (Equations (9)–(10))</th>
<th>Gaussian RBFs (Equations (11)–(12), (13))</th>
<th>RF regression</th>
<th>TPS (Equations (11)–(12), (14))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Standard deviation</td>
<td>Mean</td>
<td>Standard deviation</td>
<td>Mean</td>
</tr>
<tr>
<td>20HNH</td>
<td>0.119</td>
<td>0.031</td>
<td>0.091</td>
<td>0.026</td>
<td>0.093</td>
</tr>
<tr>
<td>20HPH</td>
<td>0.123</td>
<td>0.014</td>
<td>0.078</td>
<td>0.016</td>
<td>0.081</td>
</tr>
<tr>
<td>36UUU</td>
<td>0.108</td>
<td>0.011</td>
<td>0.072</td>
<td>0.015</td>
<td>0.074</td>
</tr>
<tr>
<td>14SKF</td>
<td>0.145</td>
<td>0.037</td>
<td>0.094</td>
<td>0.018</td>
<td>0.095</td>
</tr>
<tr>
<td>34UFU</td>
<td>0.095</td>
<td>0.045</td>
<td>0.056</td>
<td>0.034</td>
<td>0.060</td>
</tr>
</tbody>
</table>

Note: RMSE values are shown in pixel units at 30 m spatial resolution.
Results

- Performance of different transformation functions when co-registering Sentinel-2A to Sentinel-2A at 10 m

<table>
<thead>
<tr>
<th>Tile</th>
<th>Translation (Equations (7)–(8))</th>
<th>1st order polynomial (Equations (9)–(10))</th>
<th>Gaussian RBFs (Equations (11)–(12), (13))</th>
<th>RF regression</th>
<th>TPS (Equations (11)–(12), (14))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Standard deviation</td>
<td>Mean</td>
<td>Standard deviation</td>
<td>Mean</td>
</tr>
<tr>
<td>20HNH</td>
<td>0.141</td>
<td>0.104</td>
<td>0.125</td>
<td>0.076</td>
<td>0.125</td>
</tr>
<tr>
<td>20HPH</td>
<td>0.133</td>
<td>0.064</td>
<td>0.128</td>
<td>0.062</td>
<td>0.127</td>
</tr>
<tr>
<td>36UUU</td>
<td>0.181</td>
<td>0.126</td>
<td>0.114</td>
<td>0.046</td>
<td>0.114</td>
</tr>
<tr>
<td>14SKF</td>
<td>0.133</td>
<td>0.066</td>
<td>0.123</td>
<td>0.050</td>
<td>0.118</td>
</tr>
<tr>
<td>34UFU</td>
<td>0.122</td>
<td>0.101</td>
<td>0.092</td>
<td>0.086</td>
<td>0.091</td>
</tr>
</tbody>
</table>

Note: RMSE values are shown in pixel units at 10 m spatial resolution.

Table 6. The same as Table 5, but for adjacent Sentinel-2A orbits.
Results

Without co-registration

With co-registration

T20HNN – Sentinel-2A, band 08 (NIR), 10 m – Landsat-8, band5 (NIR), 30 m
A 30 m “chessboard” composed of alternating Landsat-8 (acquired on 20-Dec-2015) and Sentinel-2A (24-Dec-2015) images before (left) and after co-registration (right).
**Sentinel-2A Multi-spectral Misregistration**

![Diagram showing staggered detector configuration and inter-detector/inter-band parallax angles]

<table>
<thead>
<tr>
<th>Band</th>
<th>2</th>
<th>8</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8a</th>
<th>1</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Odd/even detector parallax angle (B/H)</td>
<td>0.022</td>
<td>0.026</td>
<td>0.030</td>
<td>0.034</td>
<td>0.038</td>
<td>0.042</td>
<td>0.046</td>
<td>0.051</td>
<td>0.055</td>
<td><strong>0.059</strong></td>
<td>0.030</td>
<td>0.040</td>
<td>0.050</td>
</tr>
</tbody>
</table>

**Figure 2:** Staggered detector configuration and inter-detector/inter-band parallax angles

[Sentinel-2 Products Specification Document
https://sentinel.esa.int/documents/247904/685211/Sentinel-2-Product-Specifications-Document]
A subset of Sentinel-2A true color image (combination of bands B4, B3, and B2) acquired on 13 June 2017 (a). Shift maps were estimated from different pairs of visible bands at 10 m spatial resolution using a phase correlation approach with a sliding window size $nw=16$ and step size $ns=2$: bands 3 and 2 (b); bands 4 and 3 (c); and bands 4 and 2 (d).

Example of cloud detection for Sentinel-2A/MSI images acquired over the US (tile 16TCK) on 15 June 2016 (a) and 21 May 2017 (d). True color images (combination of bands 4, 3 and 2) at 10 m spatial resolution along with the built-in cloud mask (in red) are shown in subplots (a) and (d); shifts estimated from band 4 and 2 images using phase correlation are shown in (b) and (e); cloud masks (in magenta) derived from the multi-spectral misregistration using a threshold of 0.2 pixels for shifts are shown in subplots (c) and (f).
Conclusions

- **Phase correlation** proved to be a robust approach that allowed us to identify 100’s and 1000’s of control points on Landsat-8/Sentinel-2A images acquired more than 100 days apart.

- **Misregistration** of up to 1.6 pixels at 30 m resolution between multi-temporal Landsat-8 and Sentinel-2A images, and 1.2 pixels (same orbits) and 2.8 pixels (adjacent orbits) at 10 m resolution between multi-temporal Sentinel-2A images were observed.

- The **Random Forest** regression used for constructing the mapping function showed best results, yielding an average RMSE error of $0.07 \pm 0.02$ pixels at 30 m, and $0.09 \pm 0.05$ at 10 m

- **Sentinel-2A multi-spectral misregistration:**
  - shifts of more than 1.1 pixels can be observed for moving targets such as airplanes
  - sub-pixels shifts of 0.2 to 0.8 pixels are observed for clouds, and can be used for cloud detection as one of the criteria
Thank You!