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Title: Automatic Change Detection in Synthetic Aperture Radar (SAR)

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Synthetic Aperture Radar (SAR)

- Satellite antenna acts as the aperture in satellite imagery
- Resolution of radar imaging increases with length of antenna
  - Longer antenna allows for smaller pixels and more detailed imagery
- The satellite simulates a larger “synthetic aperture” as it moves forward allowing for better resolution

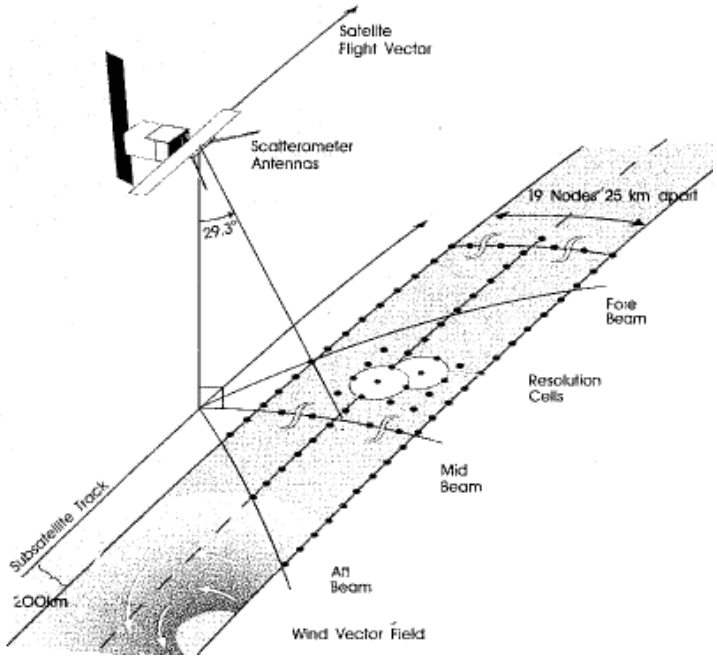
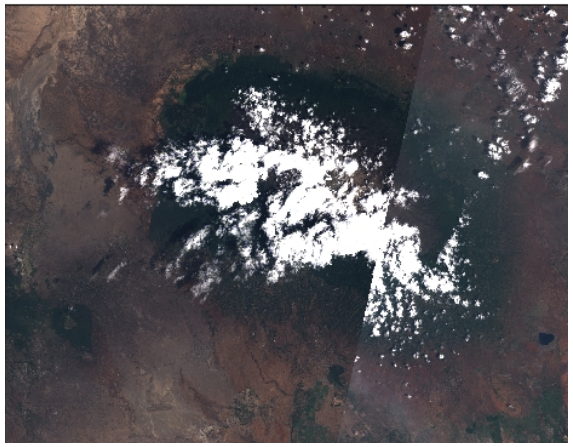


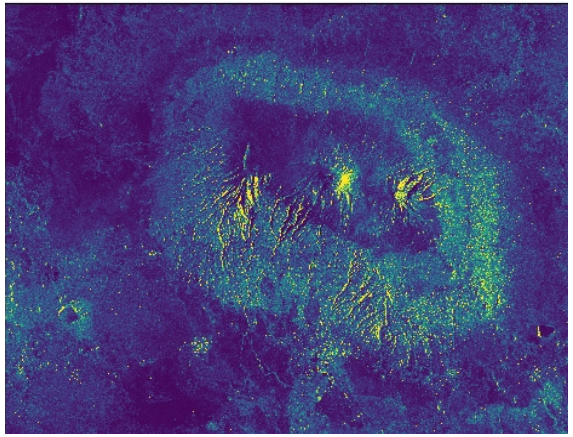
Illustration of satellite flight path and SAR data collection as used by a scatterometer instrument.
(Public Domain, National Oceanic and Atmospheric Administration)

Synthetic Aperture Radar (SAR)

- Penetrates cloud cover for all-weather imaging
- Independent of outside illumination sources (unaffected by time of day)
- Available in both VV and VH polarized bands
  - Radar emissions are vertically polarized
  - Radar can be recorded by vertically or horizontally polarized intensity
  - VV data used (so far) in change detection work
- Available in both SLC and GRD
  - SLC: High storage and processing cost, but retains phase information
  - GRD: Preprocessed, but loses phase information
  - GRD data used in change detection work



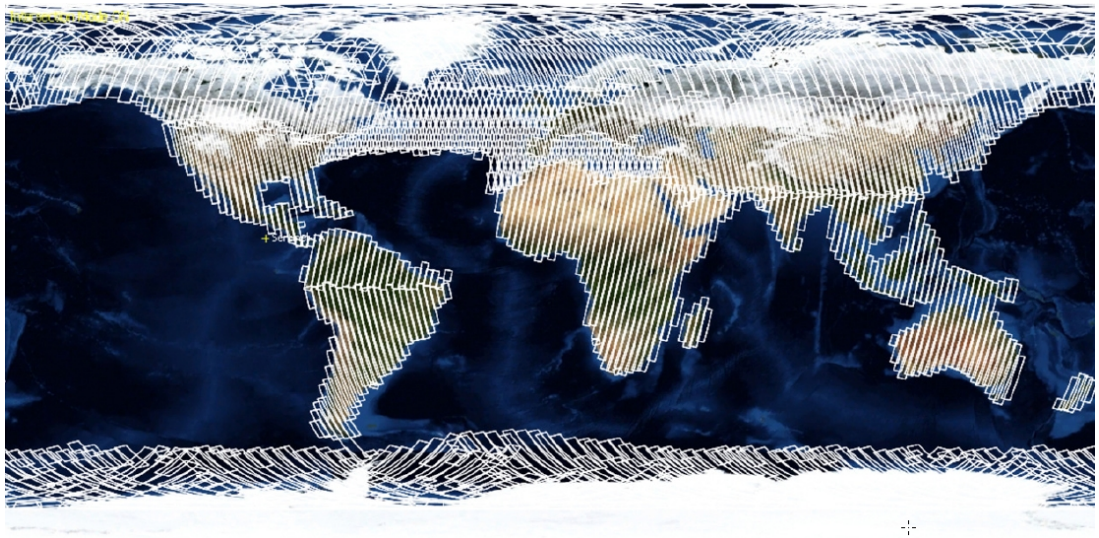
RGB visual spectrum imagery of Kilimanjaro from Landsat 8. Composite image from 26 Jan 17 and 4 Feb 17



SAR VV-band imagery of Kilimanjaro from Sentinel-1A. 9 Feb 17

Sentinel-1 (S1A and S1B)

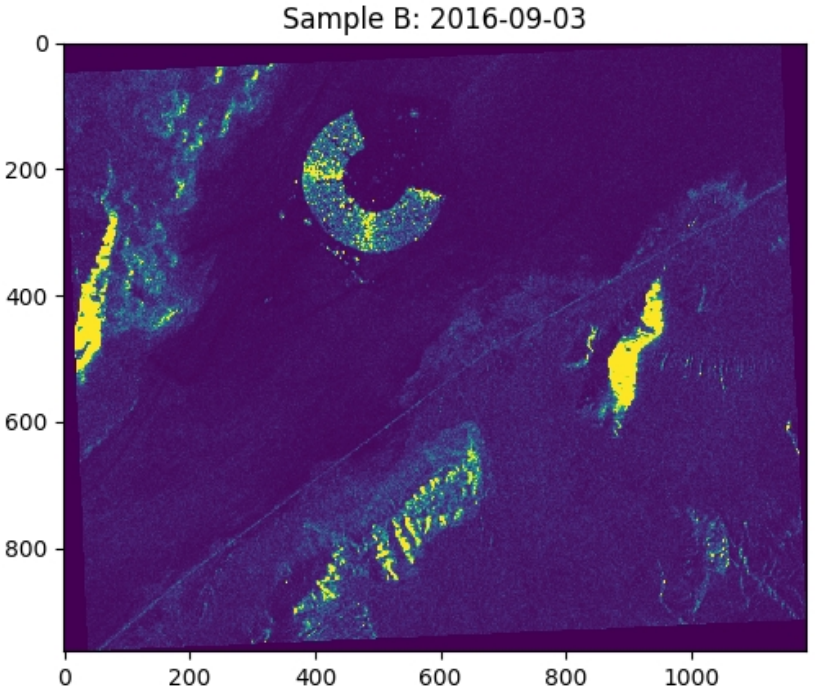
- Constellation of two satellites (S1A and S1B) in sun-synchronized nearly polar orbit
- Coverage of almost all land every 6 to 12 days
  - 12 day (175 orbit) cycle for each satellite to return to the same position
- 15 m by 15 m pixels
- 5cm Wavelength: Penetrates cloud cover and snow but not thick ice
- Data publicly available and updated in real time



Sentinel-1 data collection paths in ascending and descending orbits. (European Space Agency)

Sentinel-1 SAR Imagery

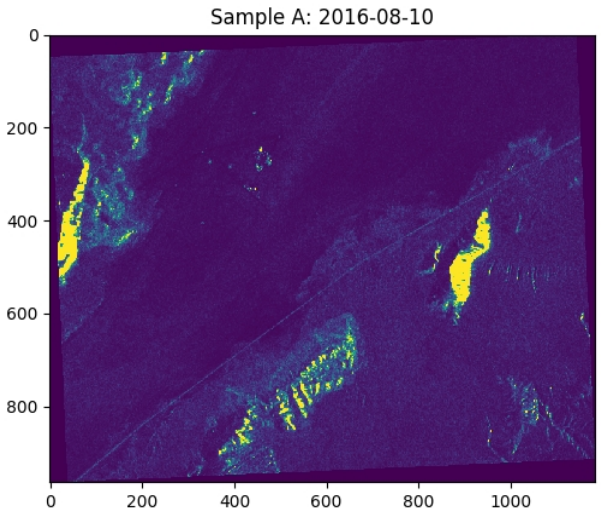
- Black Rock Desert, Nevada
- Descending Pass
  - Mountains bright on east-facing side towards satellite
  - Mountains dark on west-facing side away from satellite
- Steep faces produce bright back scatter (mountains and Burning Man)
- Flat faces produce dim back scatter (desert)

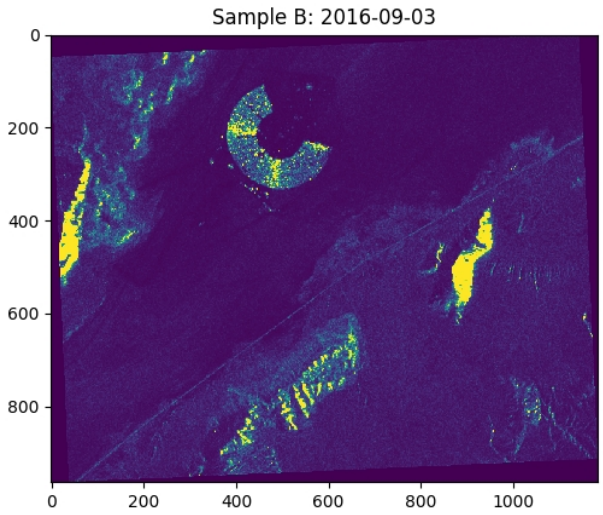


High values yellow. Low values blue.

Change Detection

- **Challenge:** Detect changes in SAR imagery automatically
- **Why SAR?**
  - Insensitive to weather
  - Independent of natural illumination
- **Possible Methods:**
  - Subtraction-Based Detection
  - Anomalous Change Detection
- **Example:** Burning Man Music Festival, Black Rock Desert, Nevada



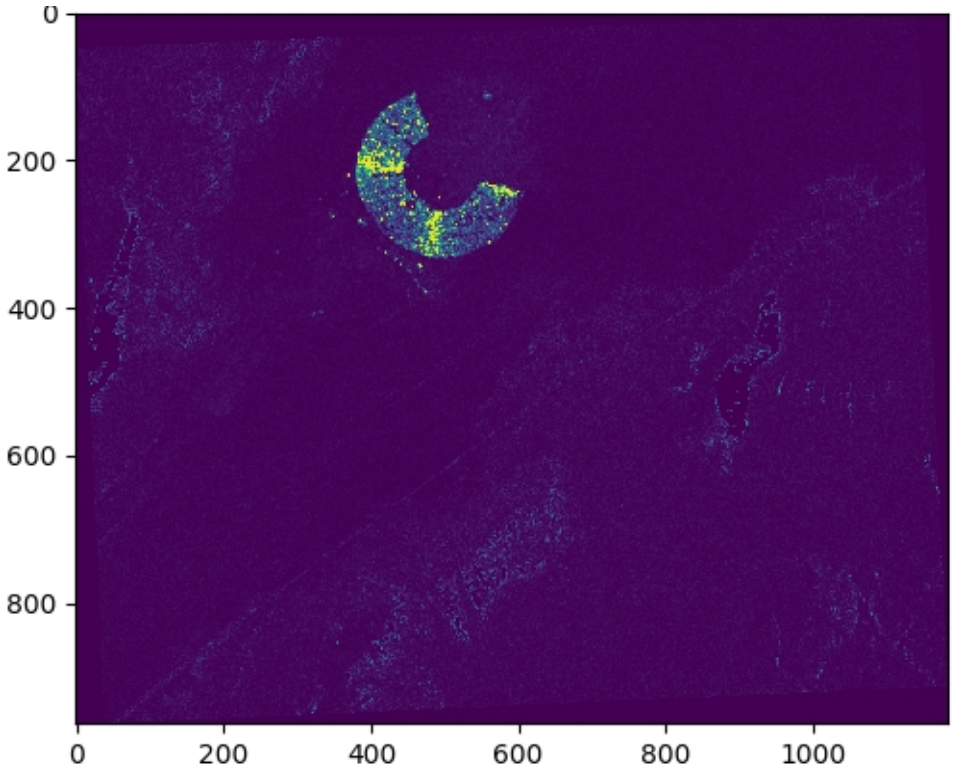


For all images: High values are yellow. Low values are blue.

Subtraction-Based Detection

$$I_{difference} = |I_A - I_B|$$

- Simplest form of change detection
- Favors large changes regardless of context in image
- Successfully emphasizes Burning Man structure, but with varying values

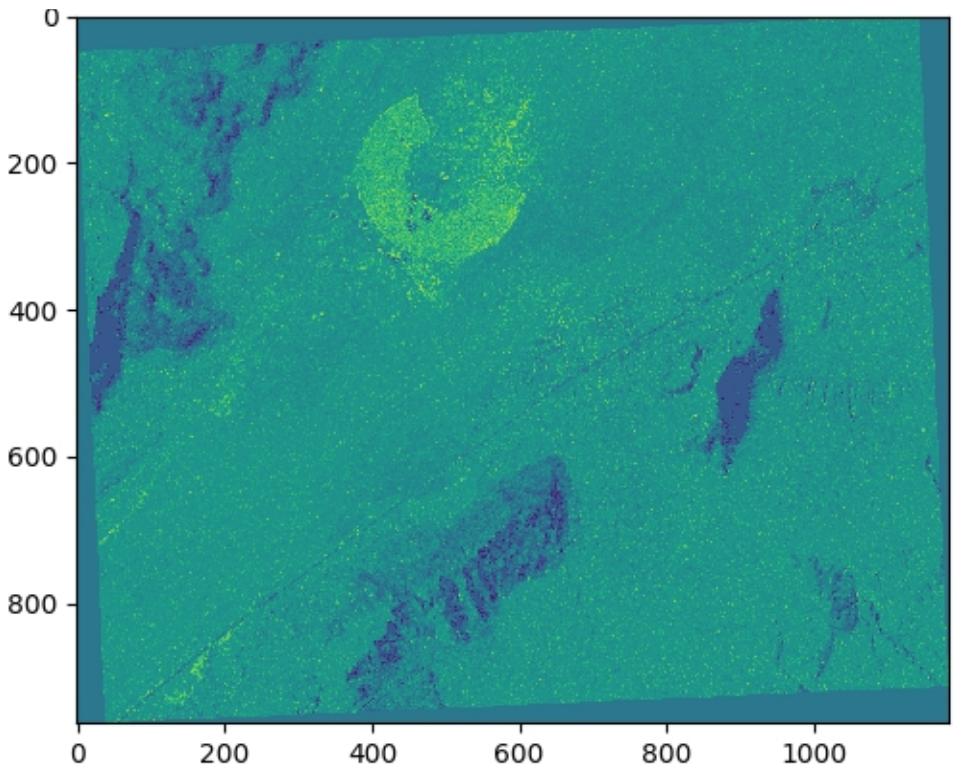


High values yellow. Low values blue.

Anomalous Change Detection (ACD)

$$Anomaly = -\log_{10}\left(\frac{p(I_A, I_B)}{p(I_A)\,p(I_B)}\right)$$

- p(I_A) and p(I_B) refer to probability of given intensity in each image
- Calculates pixel anomaly using mutual information
- Favors uncommon changes at common intensities (regardless of change magnitude)
- Evaluates each pixel in the context of the whole image
- Successfully emphasizes Burning Man Structure with similar values

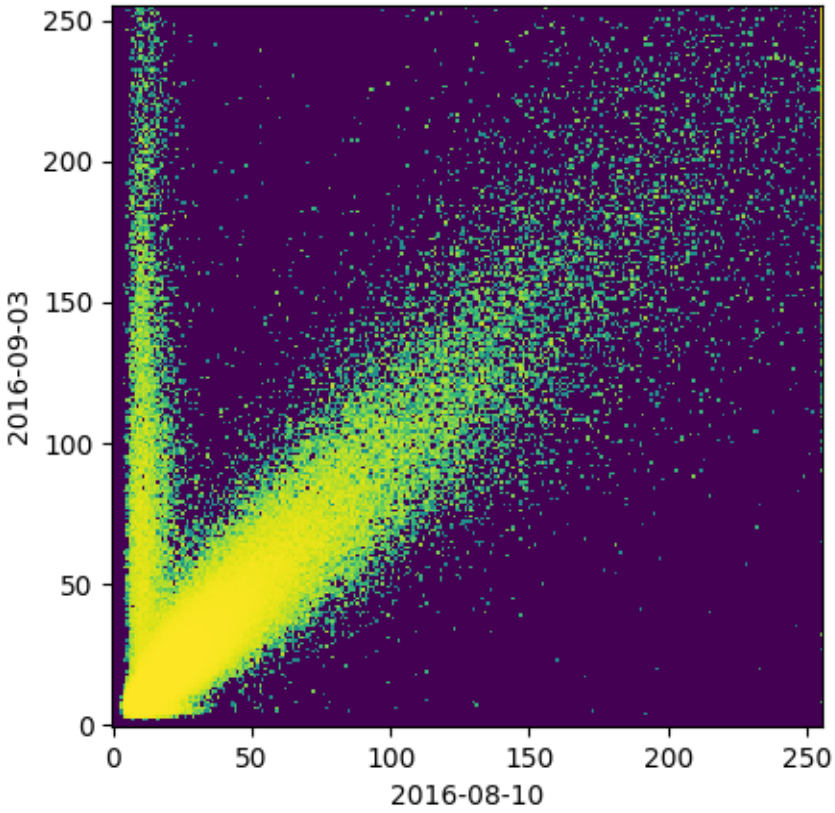


High values yellow. Low values blue.

Anomalous change detection method developed by James Theiler, ISR-3

Distribution of Pixel Intensity Changes

- X-coordinate = Intensity in image A (I_A)
- Y-coordinate = Intensity in image B (I_B)
- Value = Number of points making change from X to Y
- Trend of $y = x$ indicates no change
- Largest changes are away from $y = x$
- Most significant changes are asymmetric about $y = x$



Data points shown after the application of a sigmoid function.

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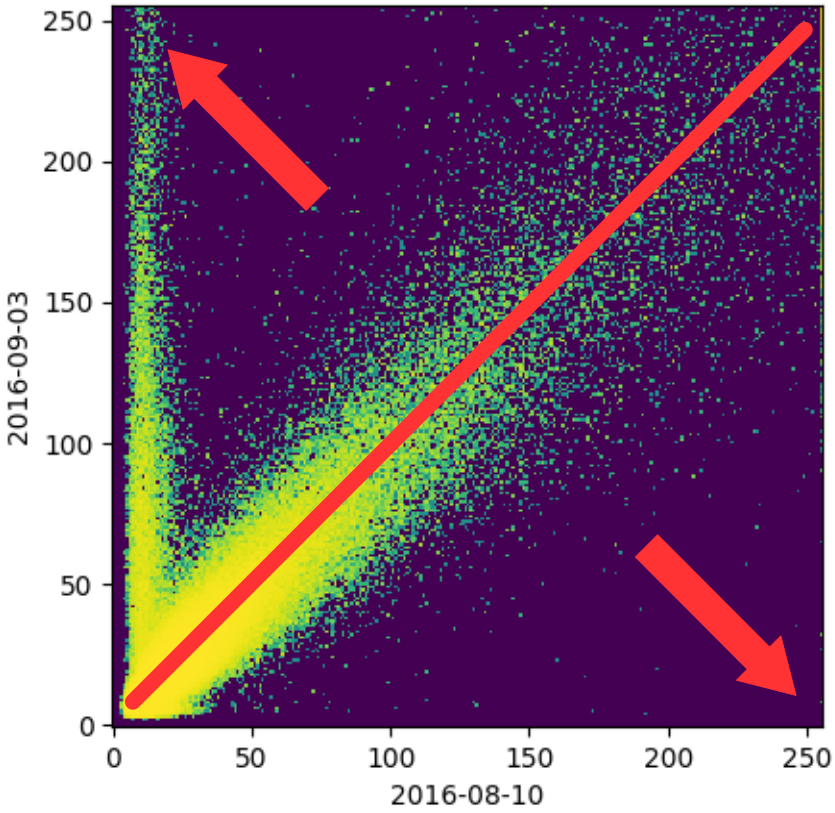

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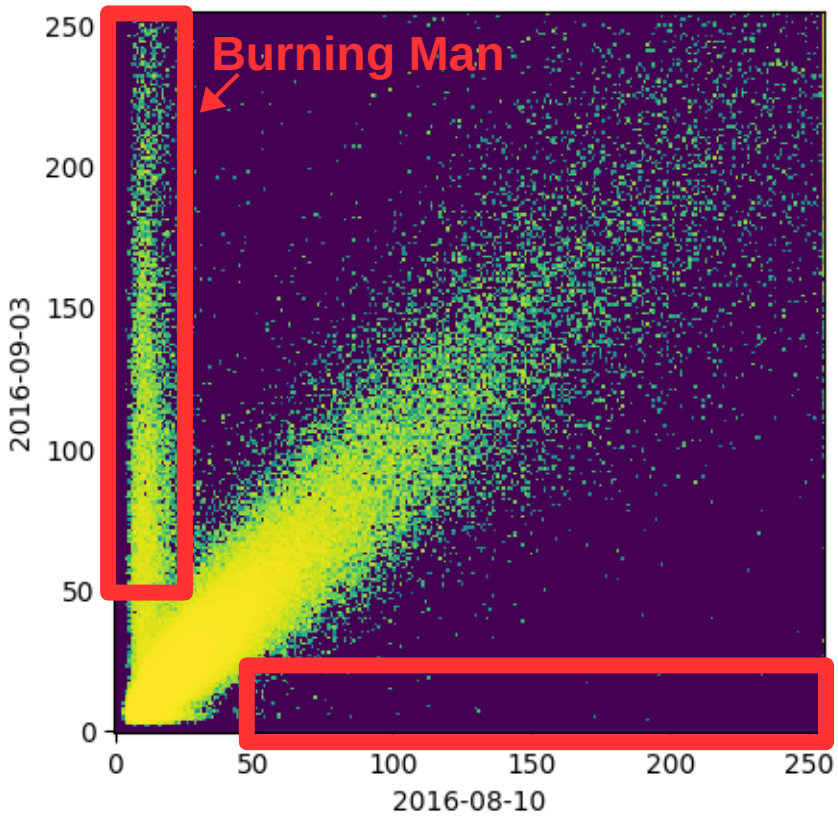

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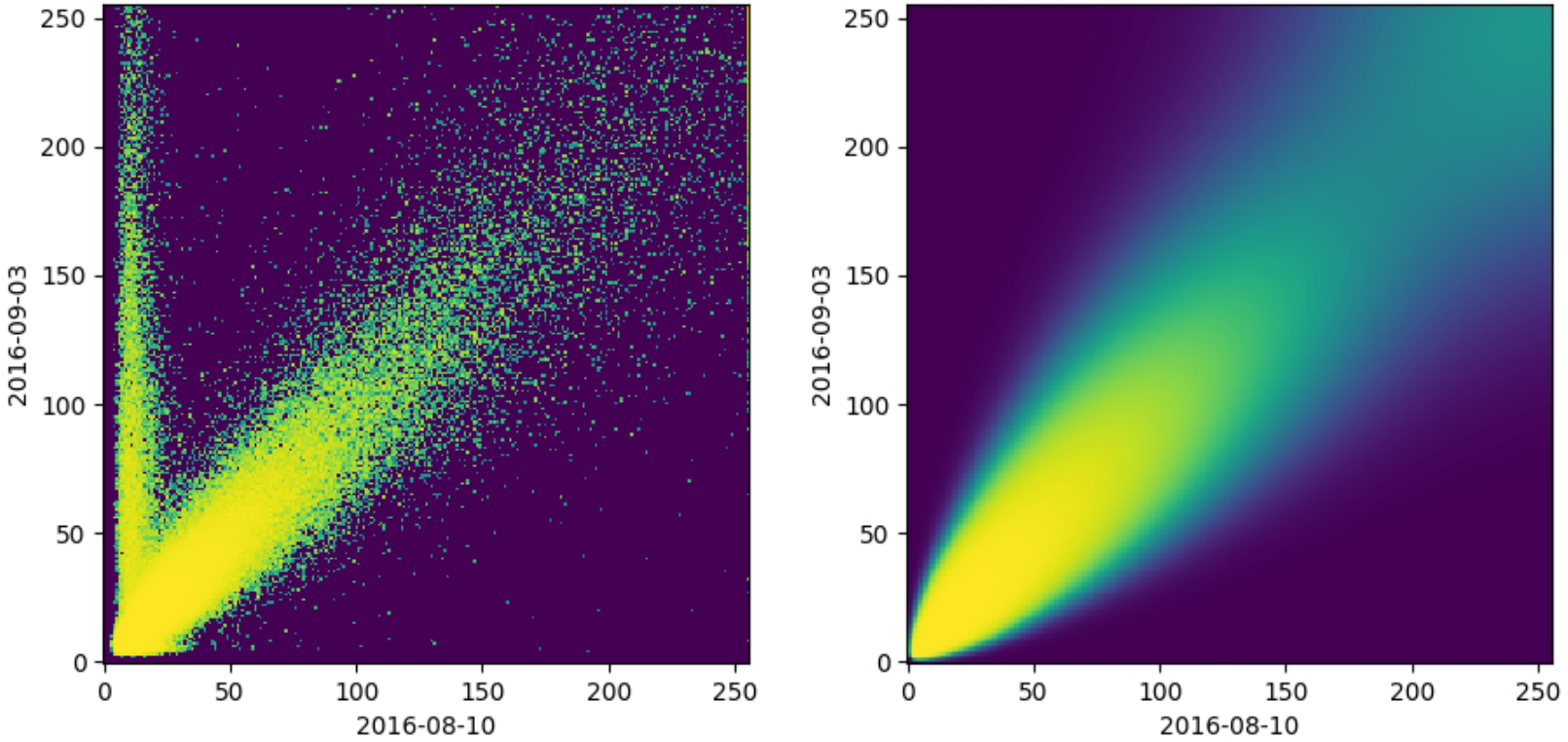
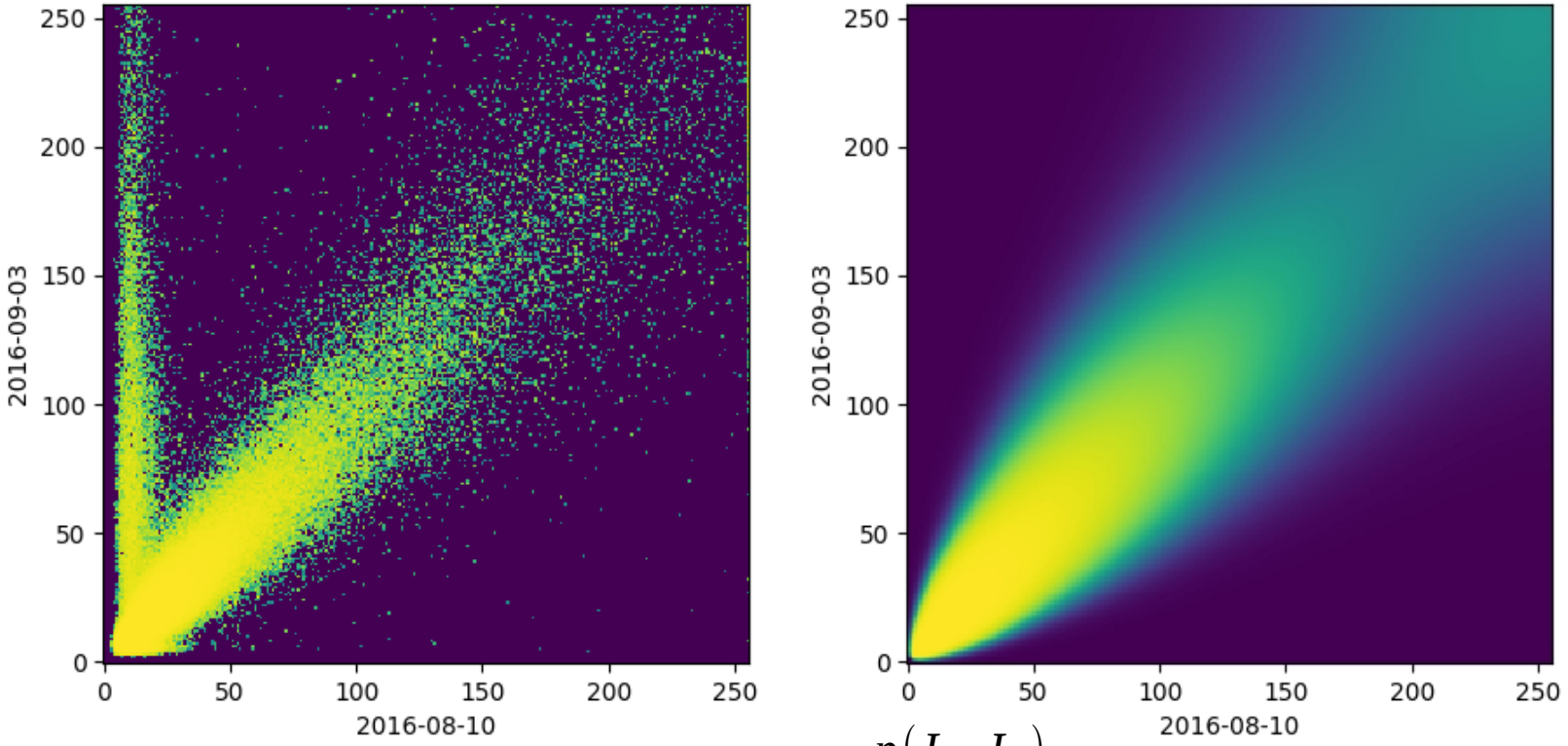
Reconstructed Gaussian Pixel Intensity Change Distributions



- Reconstructed assuming sum of symmetrical Gaussian distributions
- Reduces noise in intensity distributions
- Emphasizes anomaly values in regions of interest
  - Asymmetrical changes
  - Differences of large magnitude

Reconstructed Gaussian Pixel Intensity Change Distributions

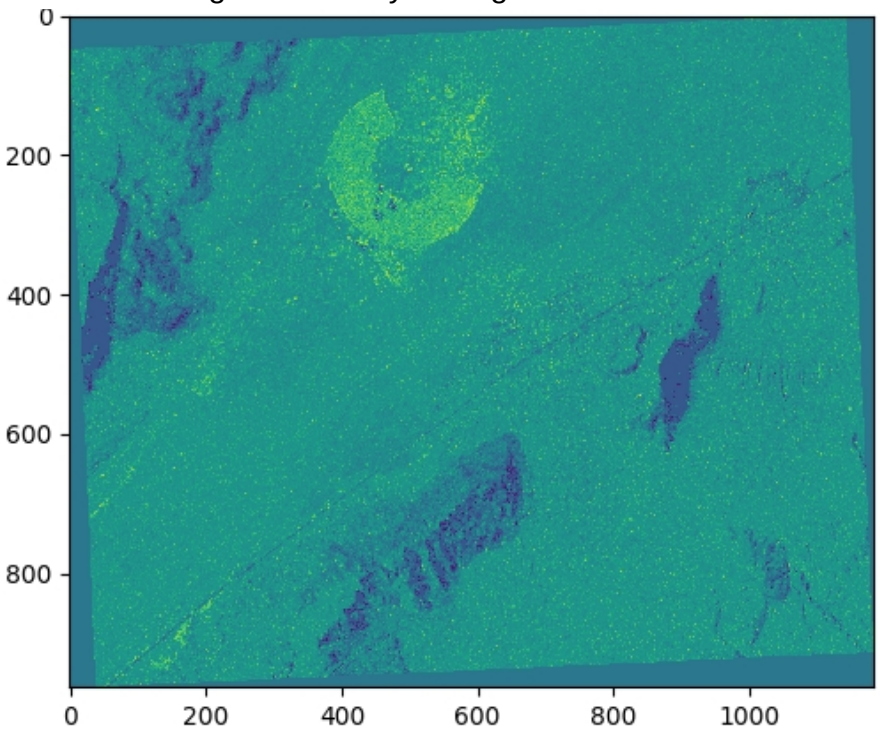


$$Anomaly = -\log_{10}\left(\frac{p(I_A, I_B)}{p(I_A)\,p(I_B)}\right)$$

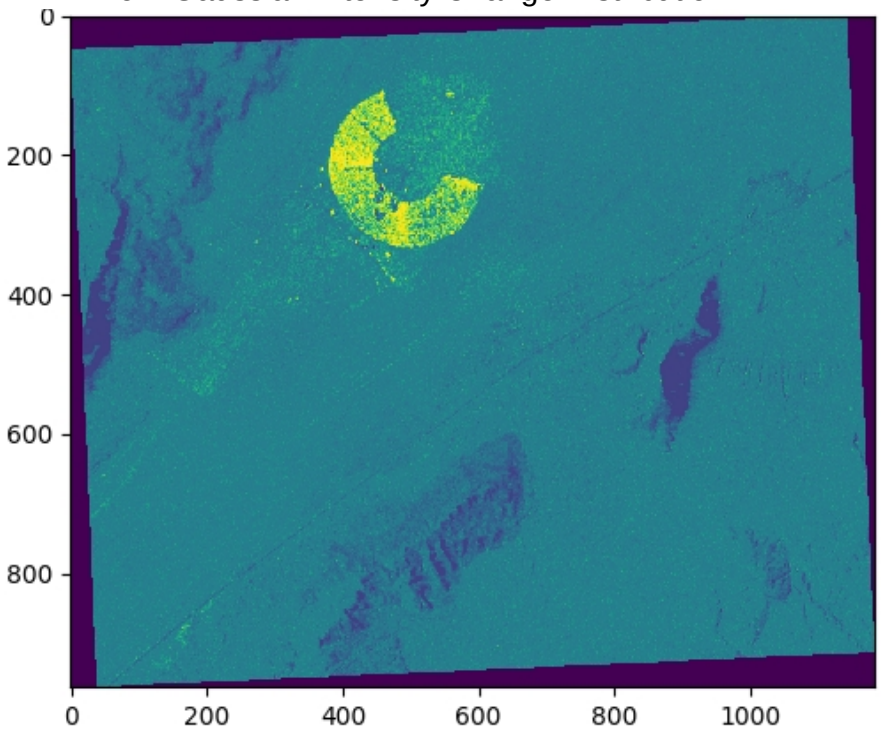
- $p(I_A, I_B)$ is lower (close to 0) for pixels in high-change regions of the distribution
- $p(I_A)$ and $p(I_B)$ remain largely unchanged
- Anomalous change is emphasized for regions of interest and unaffected near $y = x$

Anomalous Change Detection from Reconstructed Gaussian Distribution

From Original Intensity Change Distribution

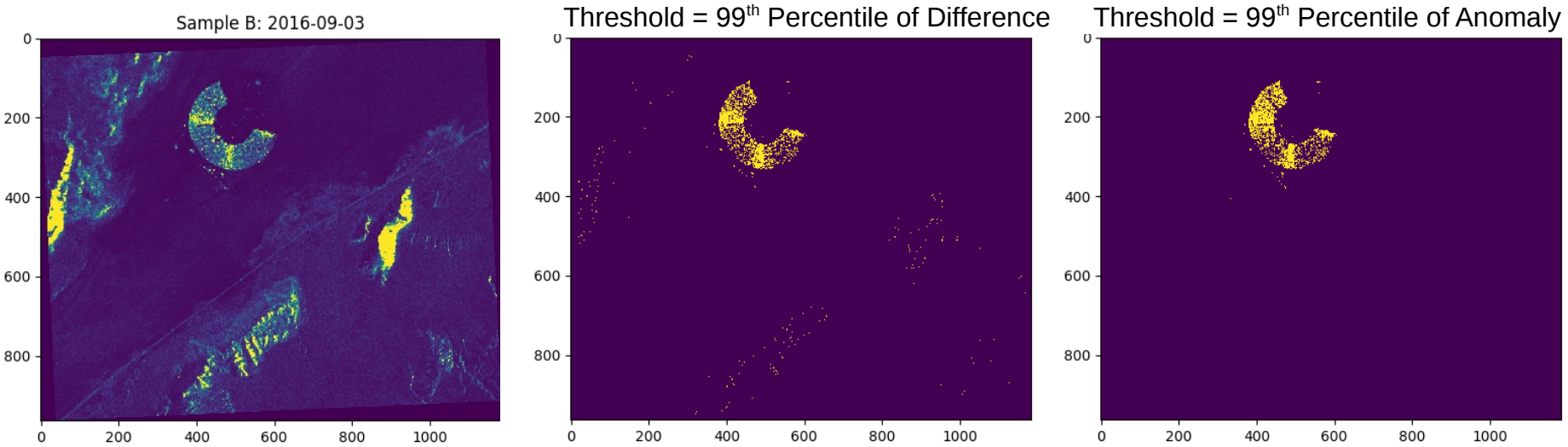


From Gaussian Intensity Change Distribution



- Reconstructed Gaussian distribution emphasizes pixels that both are anomalous and stand out from background
- Burning Man is much brighter than its background but still appears mostly uniform

Subtraction Compared to Anomalous Change Detection

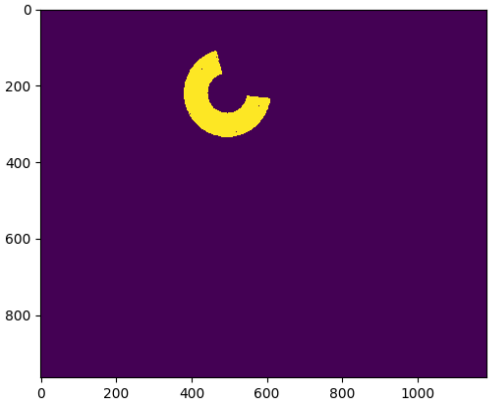


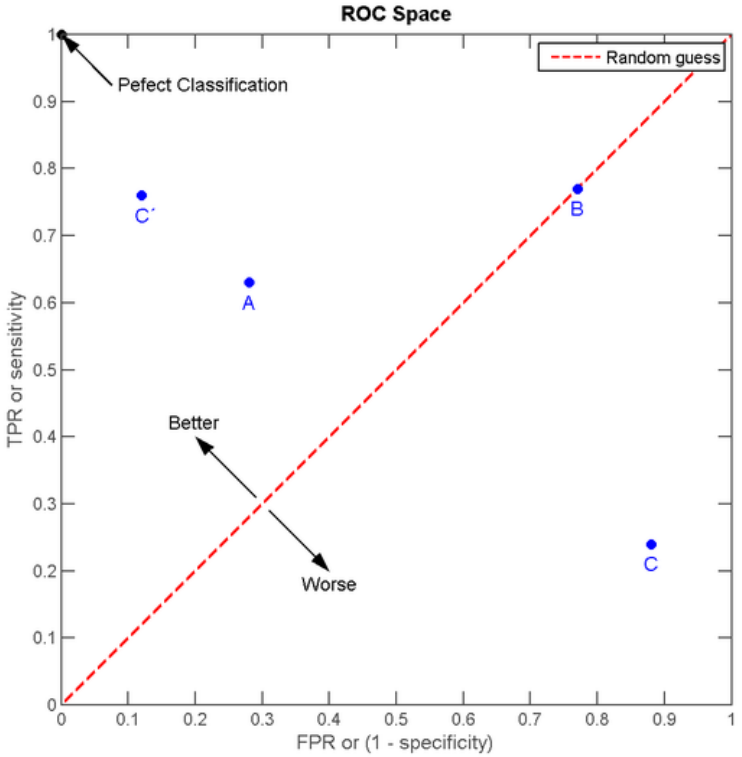
Pixels selected using anomalous change detection with Gaussian distribution.

- Detection algorithms are applied by flagging pixels above a chosen threshold
- The 99th percentile of difference values selects most of the Burning Man structure and some pixels in the mountains
- The 99th percentile of anomaly values selects most of the Burning Man structure and little else

Comparing Change Detection Methods: ROC Space

- **ROC** = Receiver Operating Characteristic
- Allows assessment of different detection algorithms at various detection thresholds
- Requires definition of “True Positive”
  - The algorithm needs to know what it is looking for.

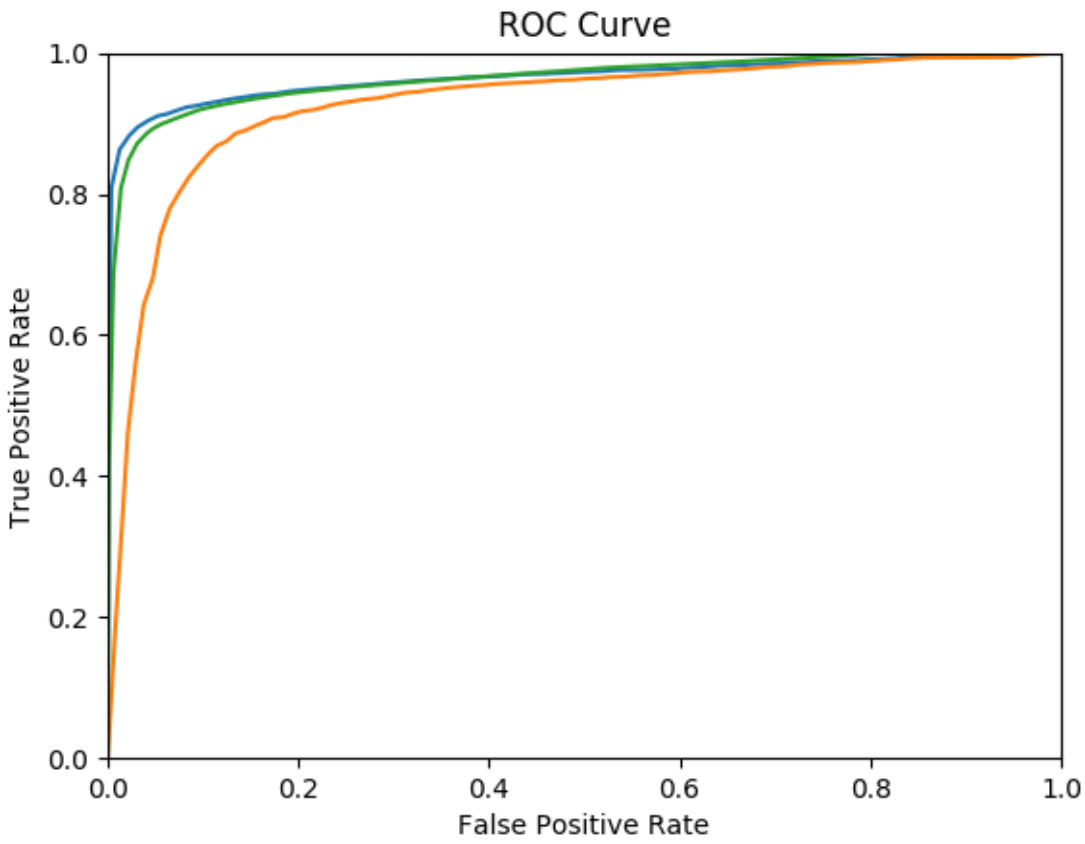




ROC Space Diagram (Wikimedia Commons)

Comparing Change Detection Methods: ROC Curves

- **Blue** = ACD from Gaussian Distribution
- **Orange** = ACD from Original Distribution
- **Green** = Subtraction Based Detection



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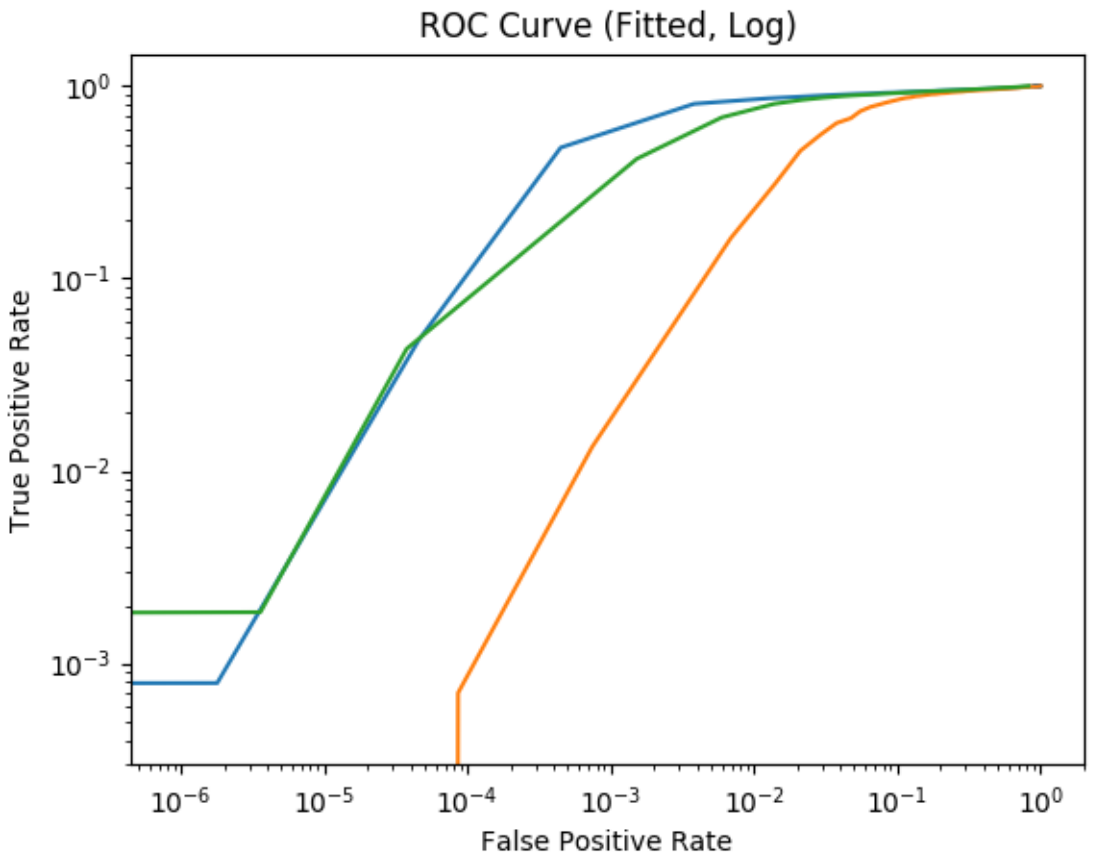


Conclusions and Further Studies

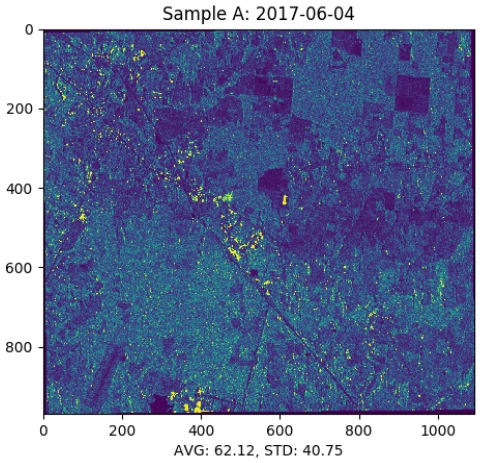
Conclusions:

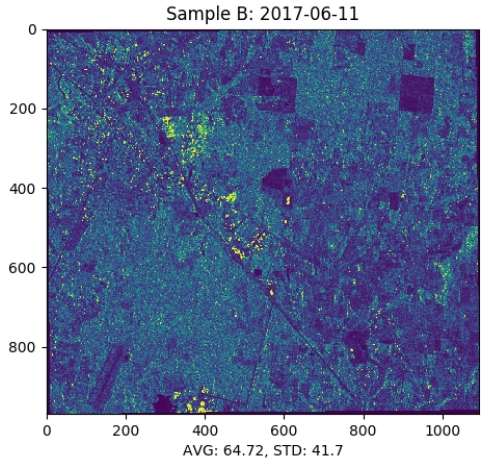
- Synthetic aperture radar imagery from Sentinel-1 provides an accessible platform for near real-time change detection on a global scale
- Methods are being explored to bolster the effectiveness of anomalous change detection
- Analysis of ROC curves can identify the most effective detection algorithms for large scale automation of change detection

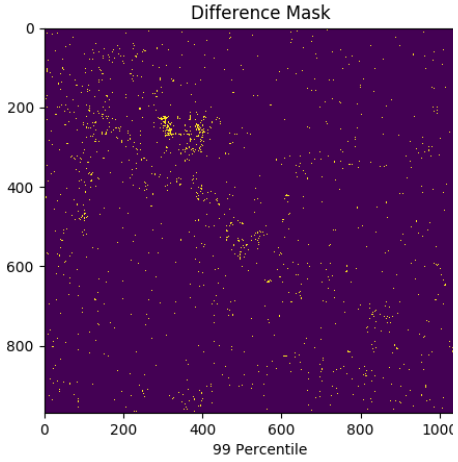
Further Studies:

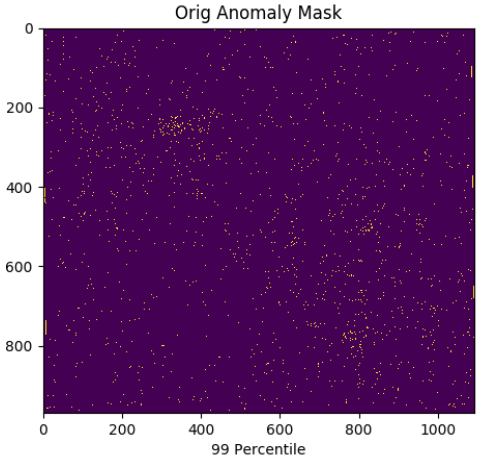
- Test algorithms with additional sites
- Investigate impact of spatial reasoning on performance
- Deploy in large-scale automated environment

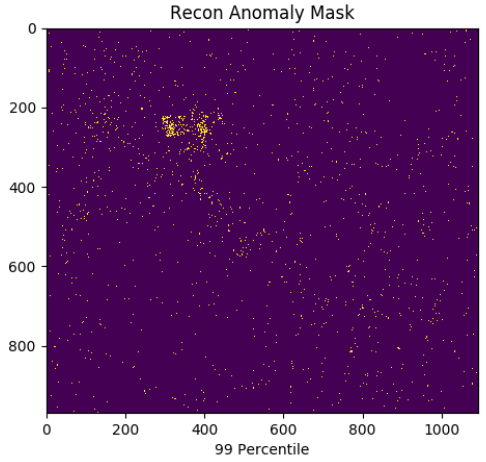
Appendix: Bonnaroo Music Festival Analysis











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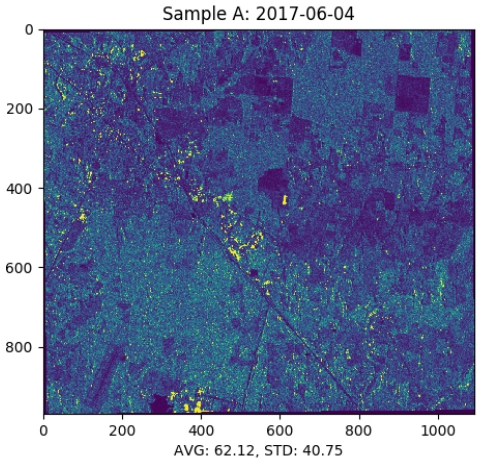

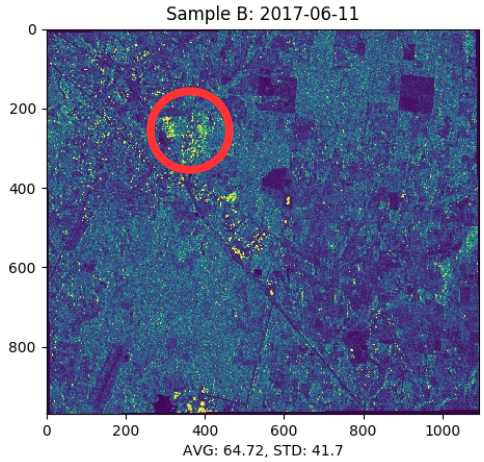

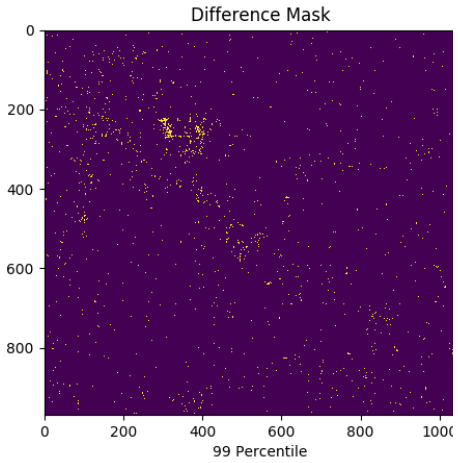

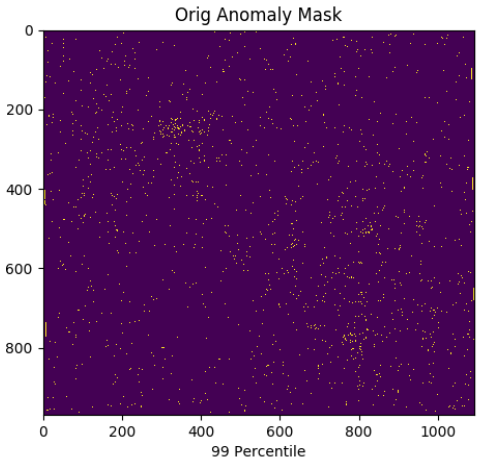

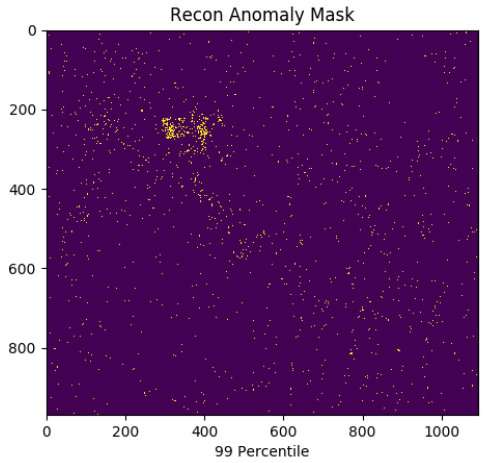

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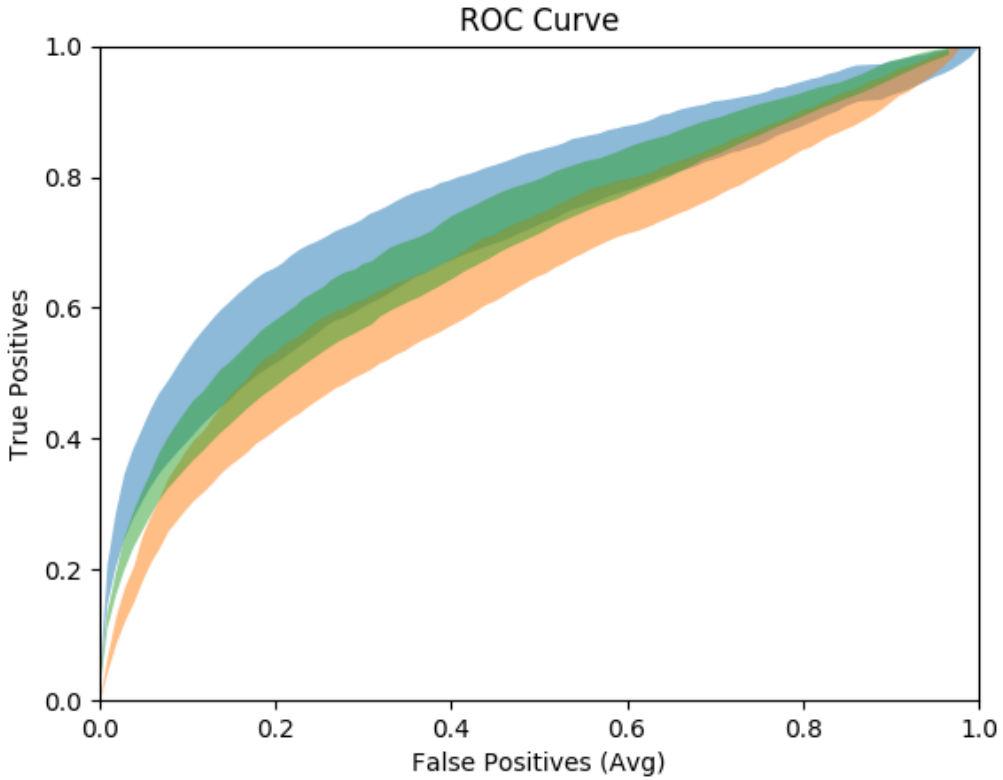

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Note: Error margin due to uncertainty of exact music festival boundaries

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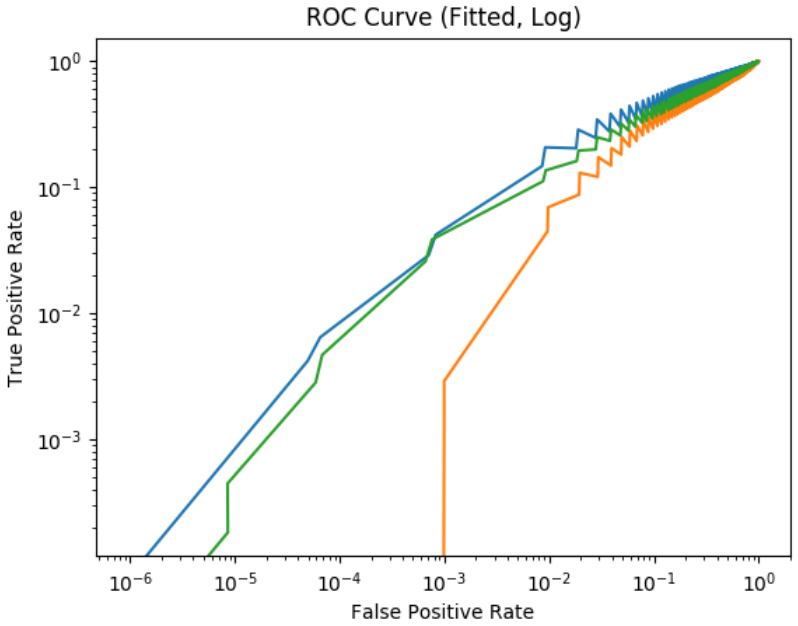

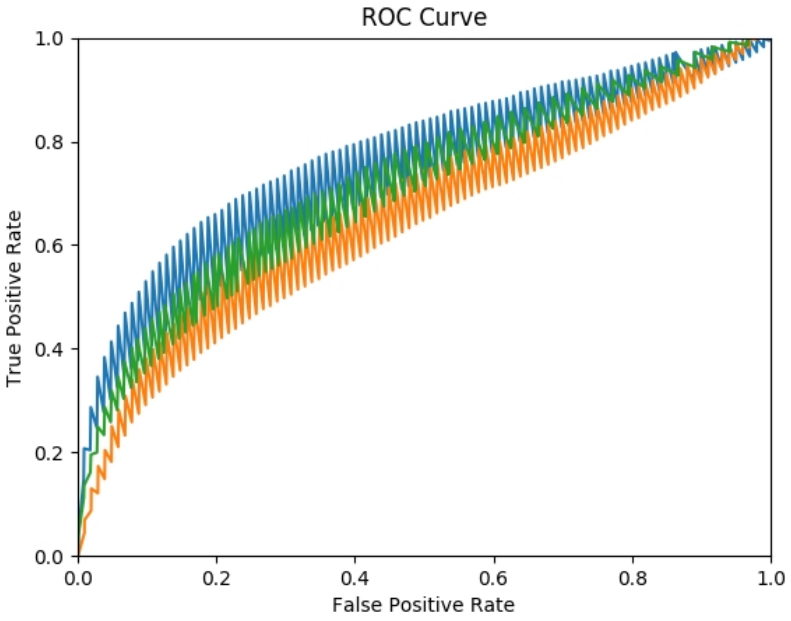

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