Temporal Repeat Frequency Needed to Achieve Cloud-Free Imagery from Landsat-Class Observatories:

An Analysis Based on 10 Years of MODIS TERRA Daily Coverage

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JACIE 2014

Background

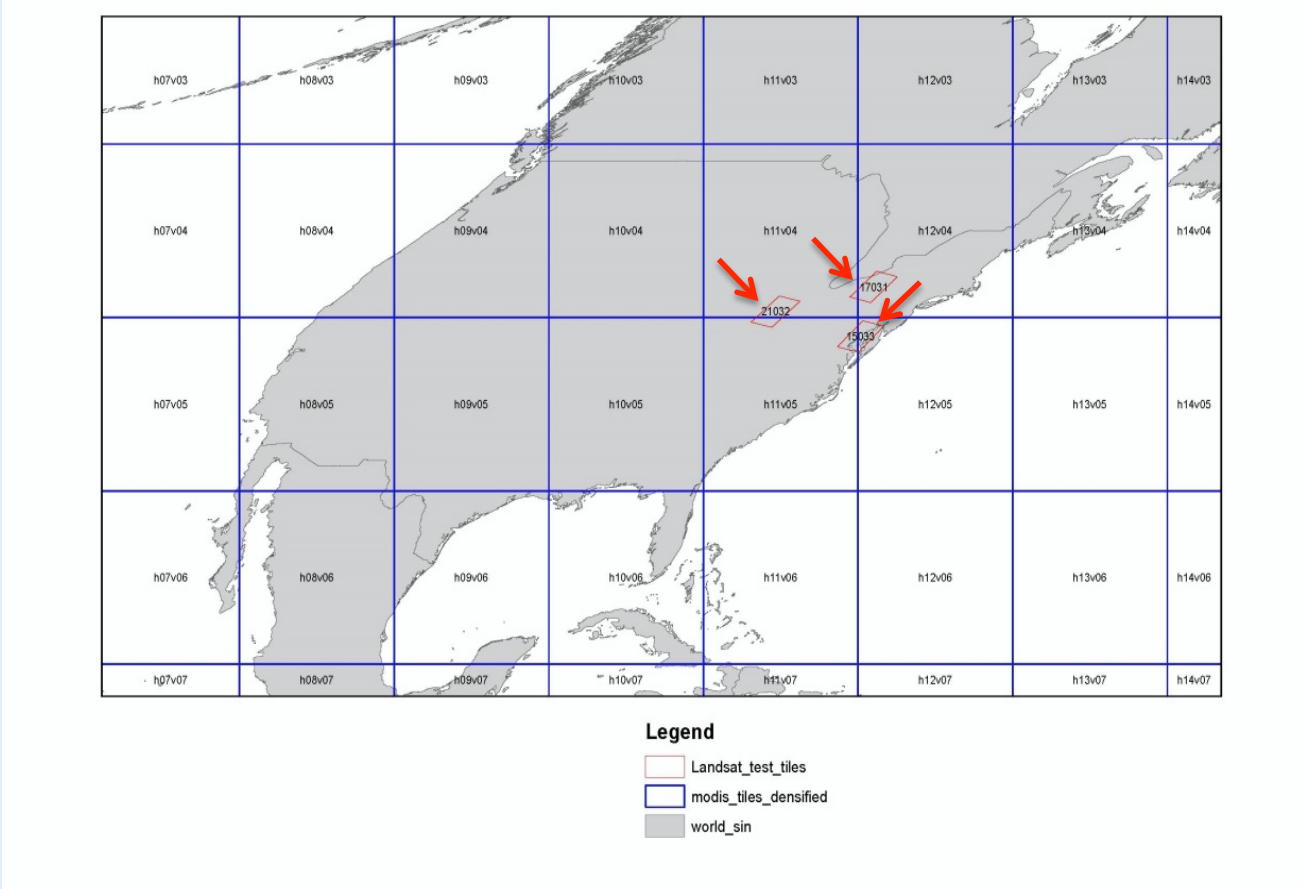
- A primary goal of the Landsat program is to "periodically refresh a global archive of Sun-lit, substantially cloud free, land images." ***Frequent repeat imaging is critical to achieve this mission***,
  - **Why?** because cloud contamination is the first order issue in passive optical land imaging.
- 4-day temporal repeat was the goal of Landsat visionaries (Pecora et al) => but hasn't been achieved
  - simultaneous op's of Landsat's 5 & 7 yielded 8-day repeat or ½ of original vision
  - 8-day repeat "kind of" continues with Landsat's 7 & 8, but Landsat 7 op's likely end in 2017 - 18.
- How visionaries estimated need for 4-day repeat in 1960's still not fully understood
  - maybe just a good guess?
  - question still being posed ***"What repeat frequency is, in fact, needed for successful imaging?"***
- We initiated a study to analyze 10 years of daily MODIS Terra observations to quantify Landsat repeat frequencies needed to overcome cloud contamination.
- **Our goal was to quantify the probability of acquiring "cloud-free" imagery, or creating a cloud-cleared composite, over specific time intervals** (e.g., weekly, biweekly, monthly, seasonally) by simulating observatory configurations with imaging repeat frequencies ranging from daily, to every 2 days, 4 days, 8 days, and 16 days.

Background (*cont*)

- @ mid-latitudes MODIS achieves daily coverage providing an effective source of daily cloud conditions.
- MODIS and Landsat 7 image the same geographical areas within 30 minutes of each other
- We examined cloud and shadow mask information contained within the MODIS daily surface reflectance product (MOD09GA) between Dec. 1, 2002 and Dec. 31, 2012.
  - intentionally omitted 2001 and most of '02 as there are substantial gaps in daily observations during this period
  - derived cloud mask includes quality bits for full cloud cover, mixed clouds, cirrus clouds, and clouds from the MOD09GA algorithm, as well as pixels affected by shadow.
- MODIS cloud cover estimates are derived at coarser spatial resolution (1 km vs 30 m) than Landsat.
  - coarser spatial res likely to produce cloud contamination results somewhat higher than might be achieved with Landsat @ 30m
    - particularly for summer convective cumulus conditions and associated shadows.

Three Study Sites Examined

- Three Landsat scene equivalents in Maryland (p15r33), Pennsylvania (p17r31), and Indiana (p31r/32) were examined as they are representative of humid, mid-latitude locations where ag and/or forestry land use practices dominate.



Map projection is MODIS equal area sinusoidal.

Study Definitions and Baseline Considerations

- **Cloud-Free Definition** - a ***"substantially cloud-free image"*** is defined as either a single image with less that 10% cloud cover or an image with < 10% cloud cover when composed of clear pixels that have been acquired over a specified period of time (e.g., weekly, biweekly, monthly, seasonally).

- **Temporal Repeat Cycle evaluated** was driven by historical Landsat orbital parameters including sun-synchronous near-polar orbit, 16-day repeat cycle and 185 km swath.

- **Historically, Landsat image acquisitions** occur when the imaging system is cycled on and off within each orbit to minimize imager heat buildup and power usage.
  - no Landsat imager has been operated "always on," except over the lower 48, where all opportunities to image have been exercised since the Landsat 5 mission
  - outside the US, Landsat 7 acquisitions are driven by the long-term acquisition plan (LTAP) which employs NOAA cloud cover forecasts, seasonal vegetation index measurements and other mission specific constraints to determine imaging operations
  - imaging "duty cycle" has averaged ~ 12 - 15% for past missions
    - note that 50% of an orbit is not Sun-lit
  - duty cycle / imaging constraints are less onerous for Landsat 8's pushbroom imager, and it is now being operated more frequently over sunlit land.

Baseline Considerations (*cont*)

- Temporal repeat metrics used were consistent with 185 km swath of current Landsat instruments; regularly spaced satellites in orbit were assumed (Table 1).
  - Same results could be achieved with ≤ ½ the satellites by doubling the swath width imaged (Table 2).

Table 1 Repeat Cycle Considerations @ **185 km** Swath

# Satellites	Repeat Frequency [1]
one	16 days
two	8 days
four	4 days
eight	2 days
sixteen	1 day

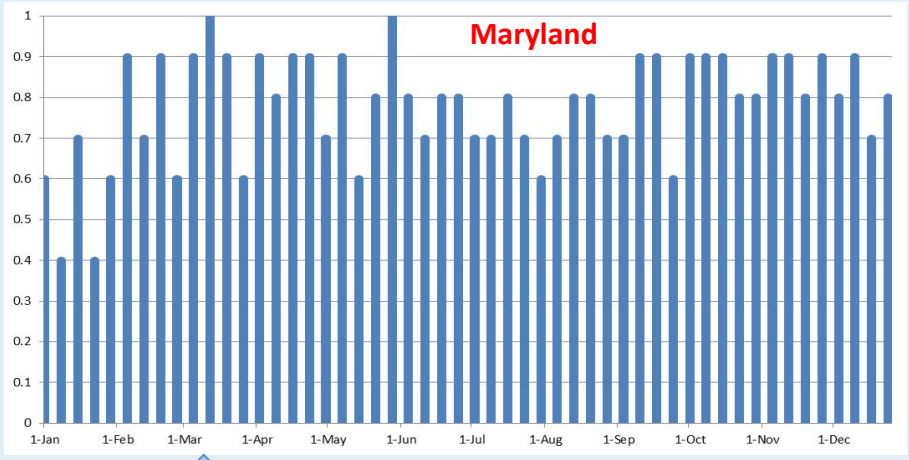
Table 2 Repeat Cycle Considerations **IF 370 km** Swath

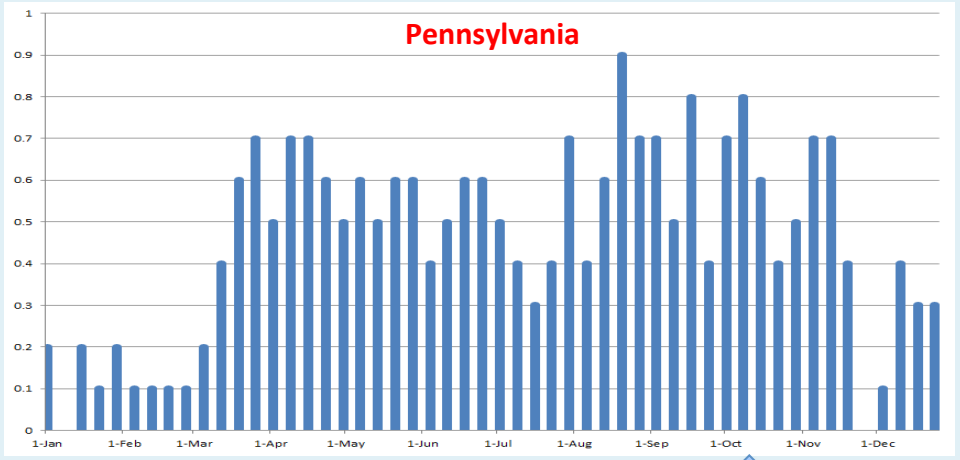
# Satellites	Repeat Frequency
one	8 days
two	4 days
four	2 days
~~eight~~ five	1 day
~~sixteen~~	~~1 day~~

[1] Assumes optimized spacing of orbits.

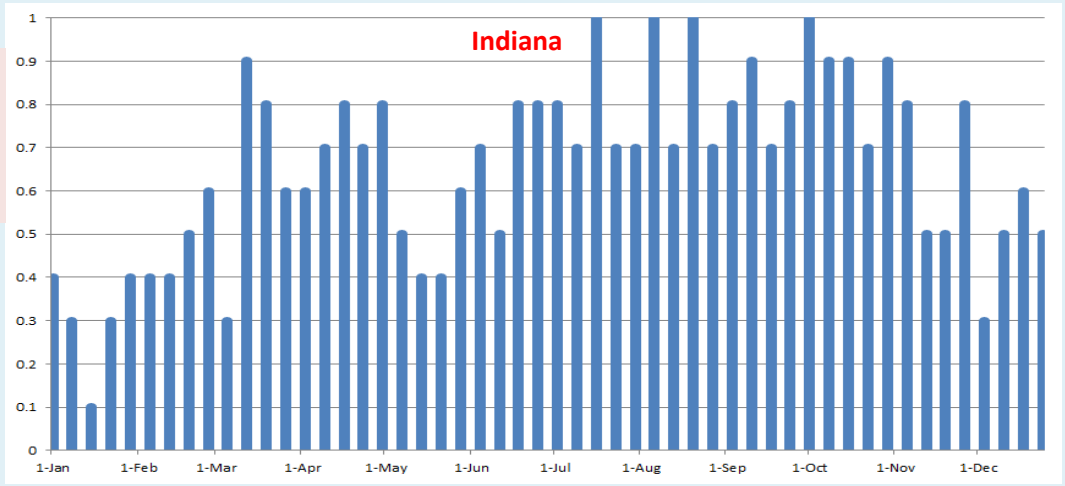
Probability of Weekly Clear View via Daily Observations

- The figure of merit is how often the satellite system achieves the desired observation metric of 90% or greater clear imagery (or image composite) for each week in the year.
  - this requires each year to be evaluated against this standard
  - the frequency with which this standard is achieved over 10 years is the metric shown in plots below



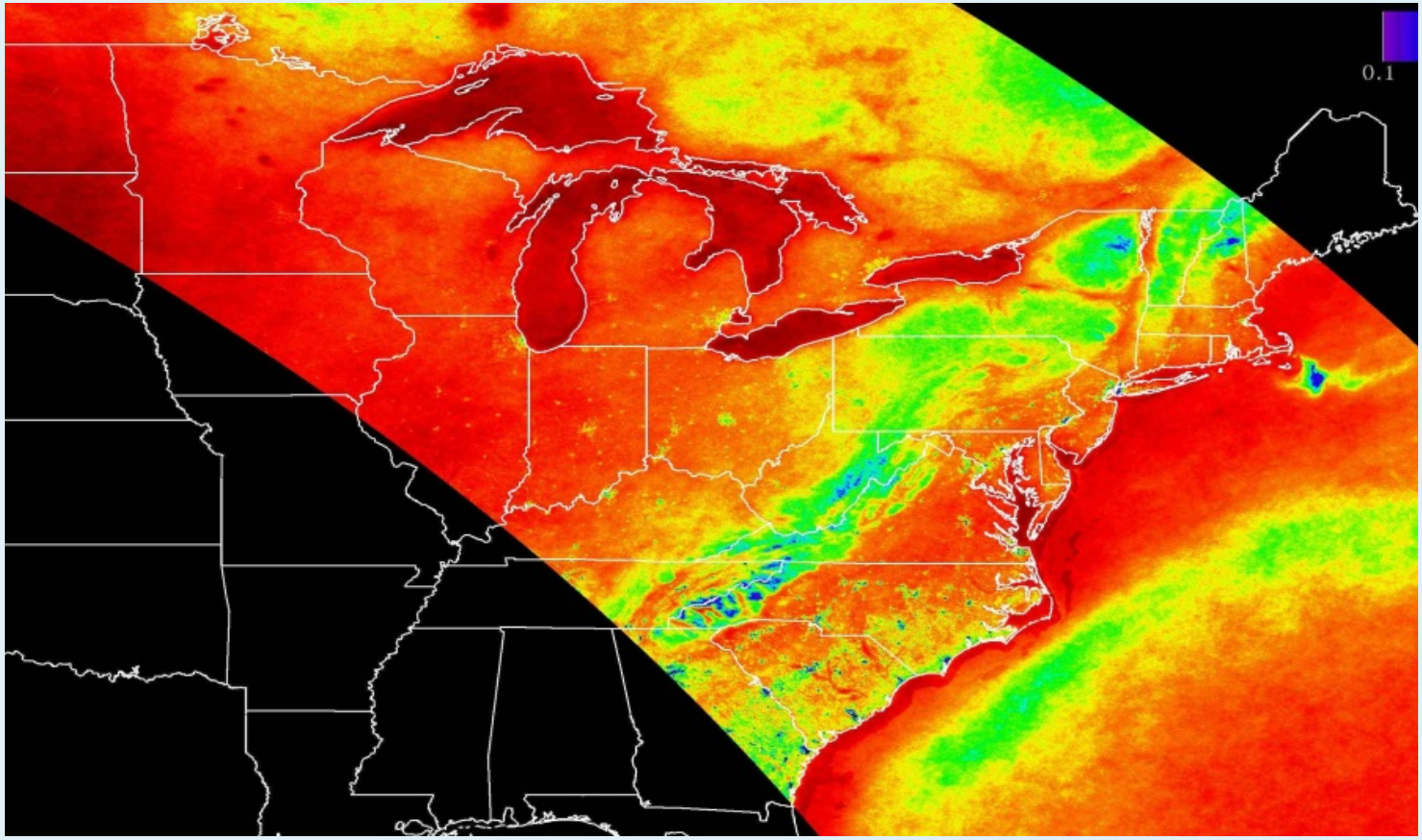


"Success" results for MD vary between 40% - 100%, with the worst outcome in winter months.



PA results are the worst of the three locales, showing no potential for clear views during some weeks of the winter, and ~50% success during the spring, summer and fall months.

Probability of Cloud-Cleared Views for the Summer "Season"



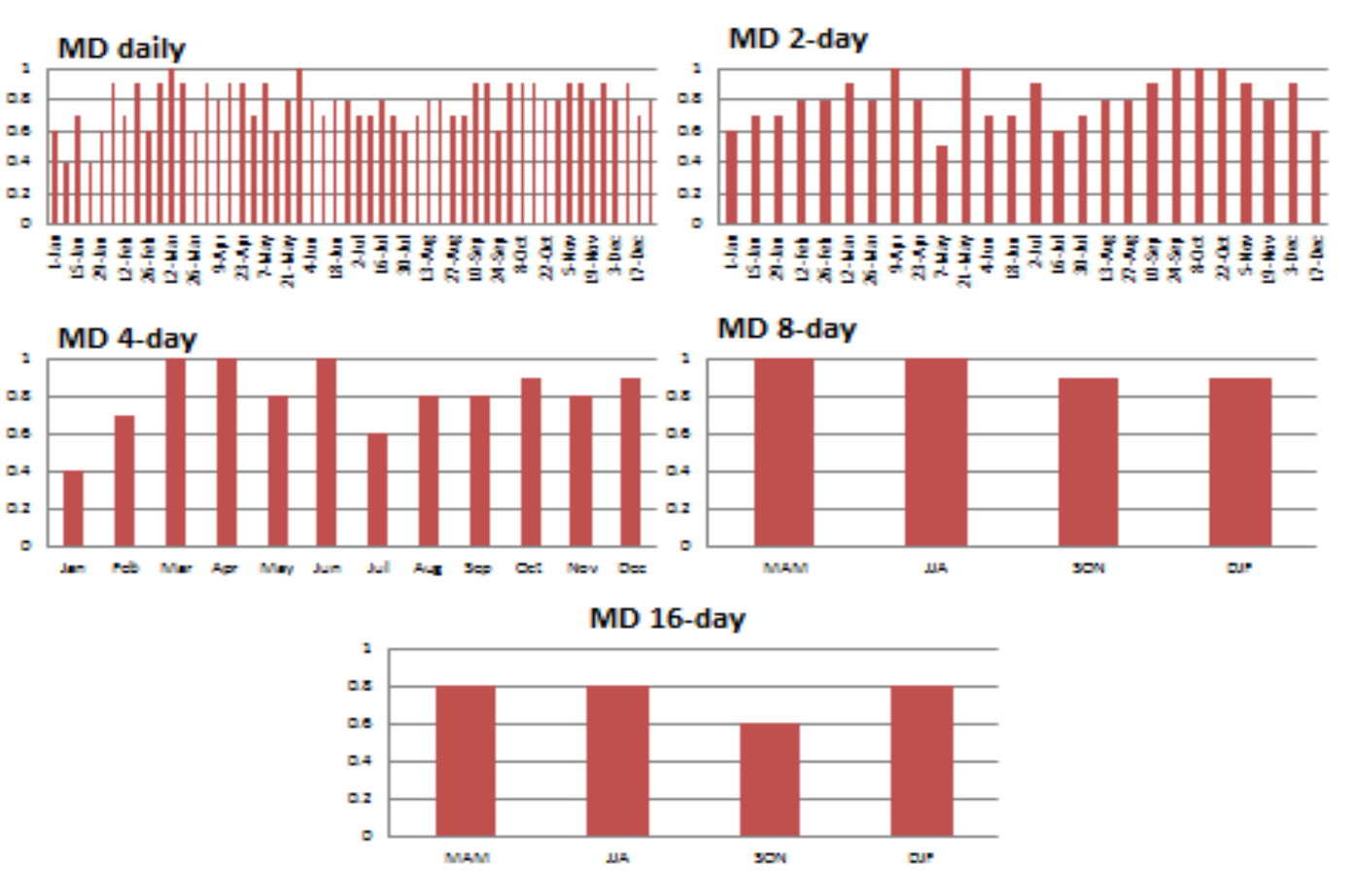
- Locations where the probabilities of cloud-cleared views are higher appear in shades of oranges and reds (≥ 30%). Lower probability areas are noted in yellows, greens, and blue (≤ 30%).
- Note the high probability of encountering clouds in mountainous regions, such as the Appalachians, Adirondacks, Green, and White Mountains.
- The Great Lakes water bodies are relatively cloud-free, along with western Illinois, eastern Iowa, southern Wisconsin and Minnesota, and into the Dakotas.

Probability of Cloud-Cleared Views for the Summer "Season" **(June, July, and August)** for Eastern U.S., summarized by "mining" a 10-Year MODIS Daily Observation Record. This visual reinforces the statistical patterns we observed at a weekly time step for the three study sites.

Results for Differing Temporal Repeat

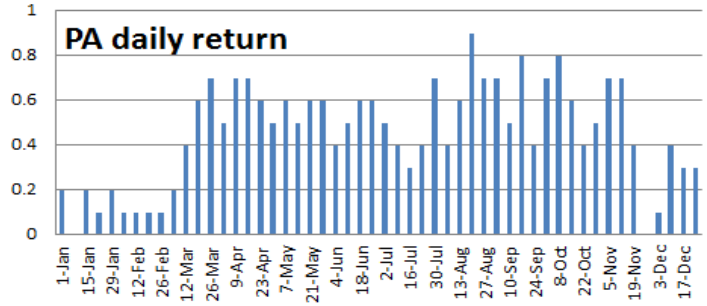
- Clear view probabilities decrease substantially with decreasing temporal frequency.
- For MD a 2-day repeat cycle (8 Landsat satellites) produces, on average, ~ 80% clear view frequency at a bi-weekly time step.
- 4-day repeat frequency (4 Landsat satellites) results in ~ 85% clear view at monthly time step.
- 8-day repeat produces a monthly repeat cycle with 95% seasonal clear view success.
- A single satellite having 16-day repeat produces at best 80% success for clear views on a seasonal basis.

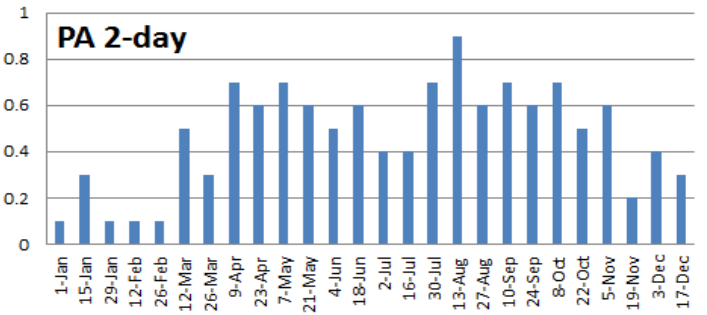
Maryland

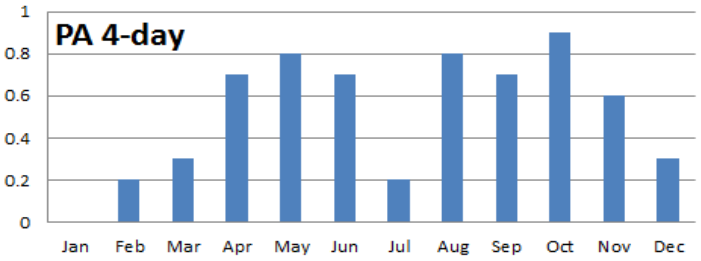


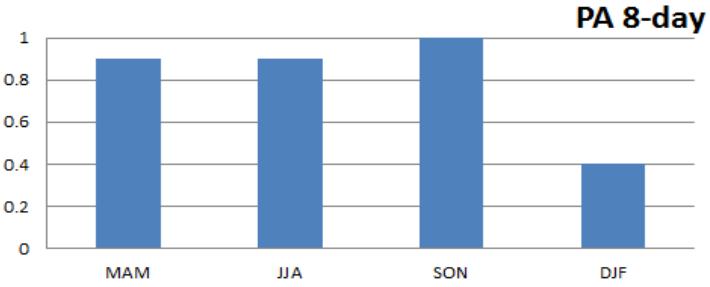
Results for Pennsylvania

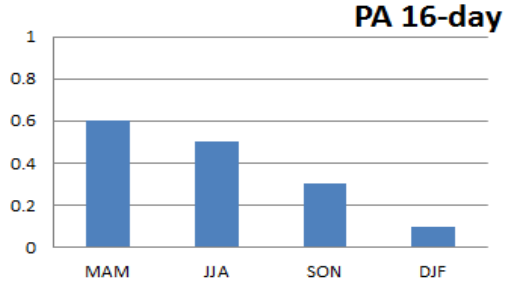
- Daily repeat should produce weekly clear views ~50% of the time in all seasons but winter.
- 8-day repeat would generally provide one clear view during each season of the year, except for winter when clear composites are achieved ~ 40% of time.
- 16-day repeat would produce marginal success (60%) in the spring, with ~50% chance of creating a clear composite during the summer; results for fall & winter are dismal.





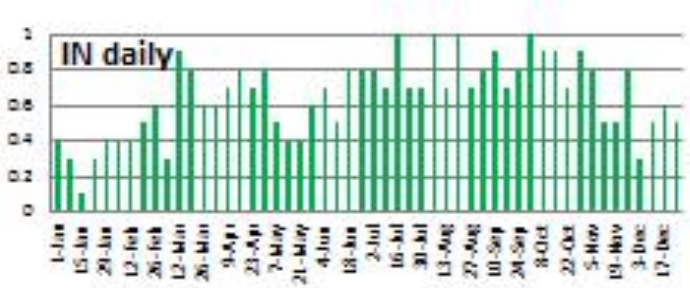


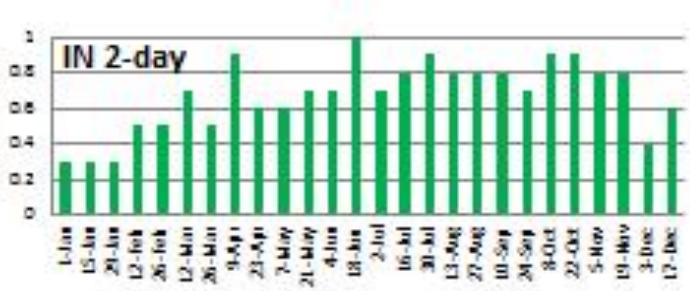


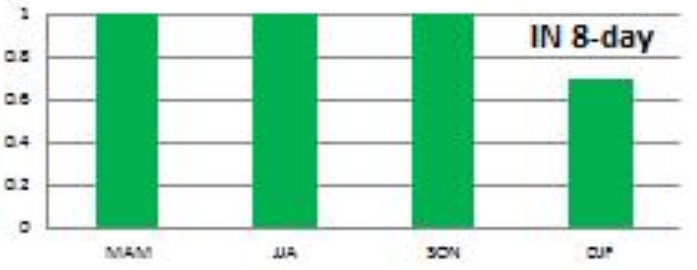


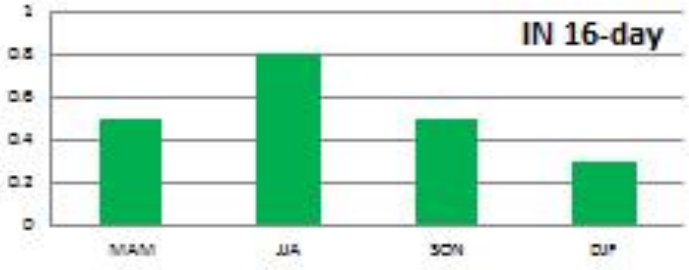
Results for Indiana

- A daily repeat cycle should reliably produce a weekly clear view throughout most of the growing season.
- 8-day repeat should generally provide reliable composited, clear views in spring, summer and fall with a drop in reliability in the winter.
- 16-day repeat should produce a successful clear composite ~80% of the time for the summer; probabilities fall below 60% during other seasons.



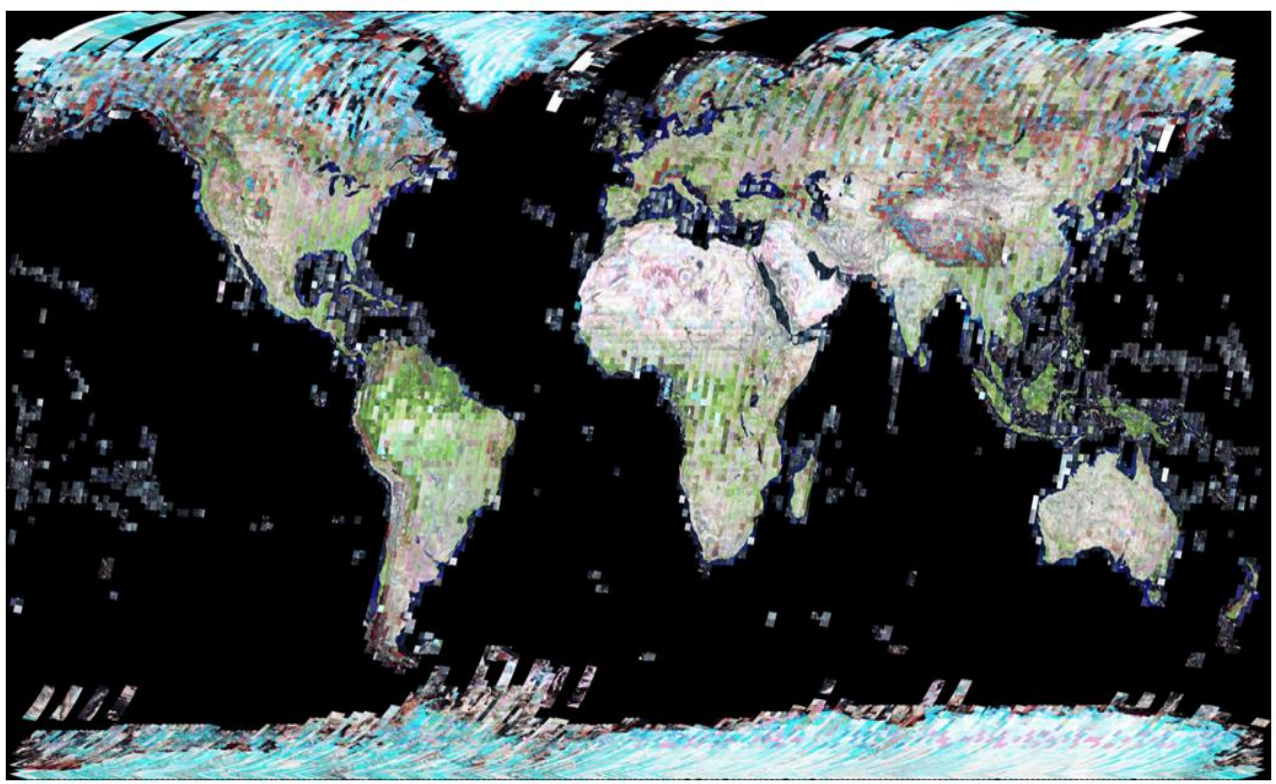




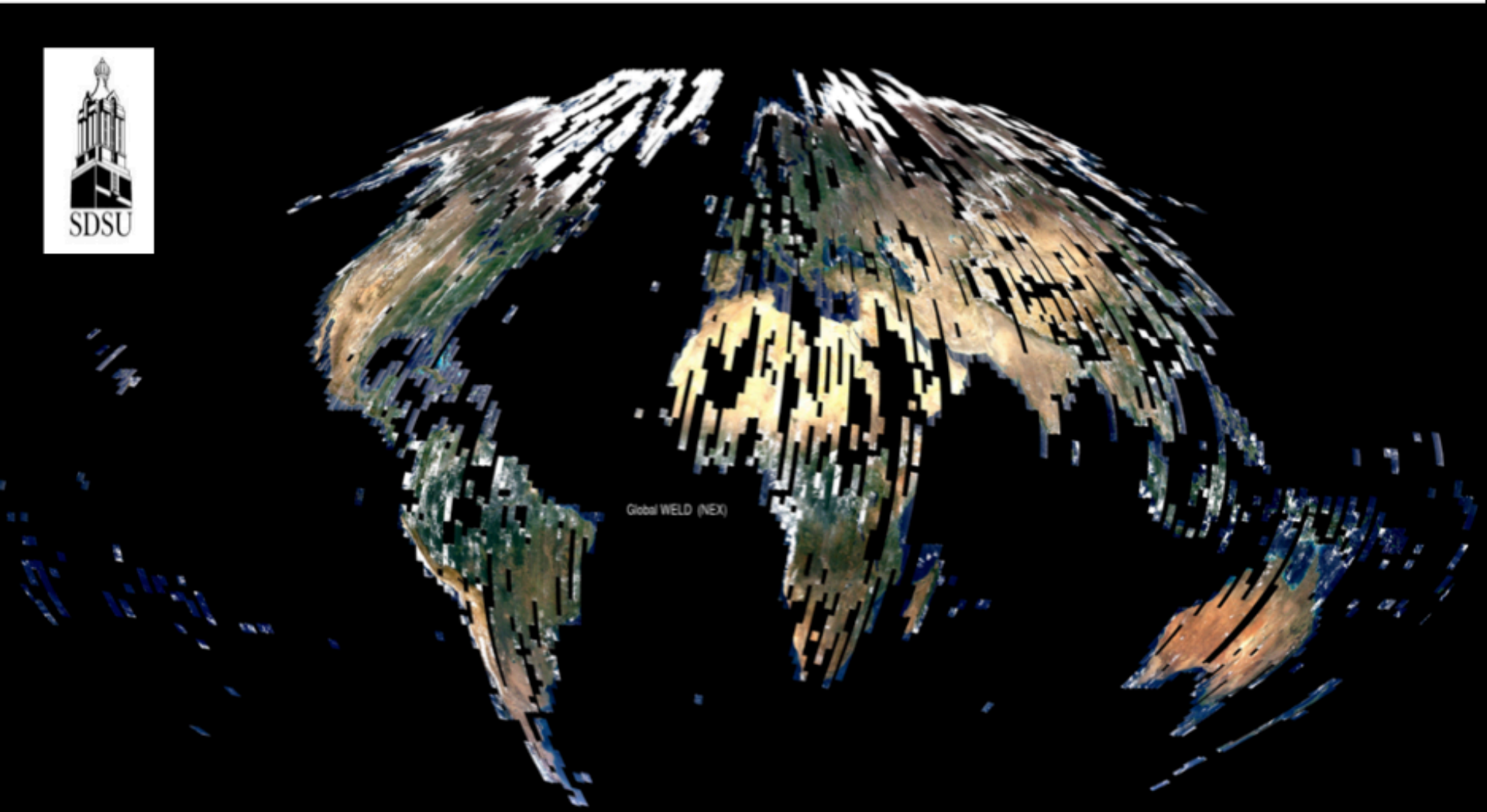


An interesting example of annual results

Landsat 7s 16-day repeat (driven by the long-term acquisition plan and ~15% duty cycle) yielded this year 2000 image mosaic created by Jay Feuquay. The best image acquired for each WRS-2 path/row during CY '00 was composited to produce this product. Detailed inspection of these "thumb nail" WRS images will reveal that many of the images, especially in humid tropical and boreal regions, are badly cloud contaminated. No attempt was made to combine images to produce clearer views.



Landsat 7 WELD Global Mosaic for May 2010



Developed by Dr. David Roy

Capability to generate this type of cloud-cleared global product @ 30m already exists, but we could do it routinely with more Landsat-like assets in orbit.

Overarching Conclusions

- In general our results indicate that the probability of acquiring clear views is a near-linear function of satellite / imaging repeat frequency.
- Some areas of the world are much clearer, but many important areas are much cloudier than our study areas.

Repeat Cycle	Reliable Clear Views
1 day	Weekly
2 days	Bi-weekly
4 days	Monthly
8 days	Seasonal (quarterly)
16 day	Annual (sometimes)

# Satellites Needed If Imaging a 370 – 400km Swath	Repeat Frequency
Five	1 day
Four	2 days
Two	4 days
One	8 days

- We need more Landsat-like observatories in orbit simultaneously.
- We say “Landsat-like” because at nearly $1B per copy, we will be lucky to get one mission approved every 10 - 15 years -- history has shown this to be true.
- There are much lower cost smallsat based solutions that should be used, at the very least, to augment Landsat “gold standard” observations.
- Constellation solutions also remove the ever present threat of a crippling gap in imaging capability.

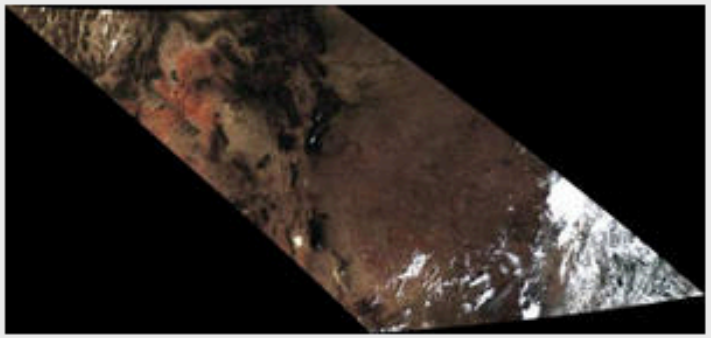
Surface Reflectance Daily L2G Global 1km

MOD09GA

The MODIS Surface Reflectance products provide an estimate of the surface spectral reflectance as it would be measured at ground level in the absence of atmospheric scattering or absorption. Low-level data are corrected for atmospheric gases and aerosols, yielding a level-2 basis for several higher-order gridded level-2 (L2G) and level-3 products.

MOD09GA provides Bands 1-7 in a daily gridded L2G product in the Sinusoidal projection, including 500-meter reflectance values and 1-kilometer observation and geolocation statistics. 500-m Science Data Sets provided for this product include reflectance for Bands 1-7, a quality rating, observation coverage, observation number, and 250-m scan information. 1-kilometer Science Data Sets provided include number of observations, quality state, sensor angles, solar angles, geolocation flags, and orbit pointers.

Short Name: MOD09GA



The above image was created by reprojecting Bands 1, 4, 3 from the MOD09GA product from their native Sinusoidal to Universal Transverse Mercator (UTM) coordinates using the MODIS Reprojection Tool (MRT). The data were acquired September 12, 2000 across the red rocks region of Southeastern Utah down through the heart of New Mexico (h09v06).

Version-5 MODIS/Terra Surface Reflectance products are Validated Stage 2, meaning that accuracy has been assessed over a widely distributed set of locations and time periods via several ground-truth and validation efforts.