Issues in Data Fusion for Satellite Aerosol Measurements for applications with GIOVANNI System at NASA GES DISC

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Abstract

We look at issues, barriers and approaches for Data Fusion of satellite aerosol data as available from the GES DISC GIOVANNI Web Service. Daily Global Maps of AOT from a single satellite sensor alone contain gaps that arise due to various sources (sun glint regions, clouds, orbital swath gaps at low latitudes, bright underlying surfaces etc.). The goal is to develop a fast, accurate and efficient method to improve the spatial coverage of the Daily AOT data to facilitate comparisons with Global Models. Data Fusion may be supplemented by Optimal Interpolation (OI) as needed.

1. Motivation for Data Fusion

- Complementary Aerosol measurements from a variety of space-based sensors are archived and readily available to the Science User
- Community through GES DISC and other Data Centers. Each sensor's has strengths and weaknesses while making global aerosol measurements under a variety of conditions. (See Figures in Section 5).

- GES DISC Interactive Online Visualization and ANalysis aNd Infrastructure [1] can be used for the visualization and quick and easy exploration of these Aerosol Datasets. GIOVANNI is a value-added web-based service developed and deployed for efficient, convenient and rapid access to these datasets.

- Information or data about aerosol fields provided by any one sensor may be incomplete (as a result of gaps in spatial and temporal data coverage) and inadequate by itself to generate daily regional or global maps without gaps. For instance Melin et al. [2] have concluded that scientific and monitoring applications of aerosol products require the generation of long-term seamless data records with maximum spatial and temporal coverage and resolution.

- Fusing spatio-temporally co-located data obtained from identical or similar satellite sensors, followed by OI if necessary, has the potential of creating consistent and spatio-temporally complete data fields for easier and arguably more useful comparisons to Global Aerosol Model outputs. (See Figures in Section 5)

- In this work we consider various fusion (followed by OI if required) schemes for combining co-located Level-3 Daily Mean Aerosol Optical Depth Data as measured by the various NASA Earth Observing System Satellite Sensors (Viz. Terra/MODIS, Terra/MISR, Aqua/MODIS, Aura/OMI)

2. Simple approaches to Data Fusion

2.1) We use the standard validated [3] MODIS Terra (MOD08_D3.005) and Aqua (MYD08_D3.005), Terra-MISR (MIL3DAE.004) Level-3 Daily Global 1°X1° product. These products consists of Level-2 Swath data aggregated and binned into 1°X1° bins on an uniform Equal Area Lat-Lon grid. The Daily AOT maps will always contains gaps. (See Section 3).

2.2) Pure Merging Schemes without Interpolation:

2.2.1) SIMple Arithmetic Averaging (SIM)

$$\tau_i^{SIM} = \sum_{k=1}^{n_s} \tau_{i,k} / n_s$$

2.2.2) Maximum Likelihood Estimate (MLE)

$$\tau_i^{MLE} = \sum_{k=1}^{n_s} \frac{\tau_{i,k}}{\sigma_{i,k}^2} / \sum_{k=1}^{n_s} \frac{1}{\sigma_{i,k}^2}$$

2.2.3) Averaging with Weighting by Pixel Counts (WPC)

$$\tau_i^{WPC} = \sum_{k=1}^{n_s} \tau_{i,k} N_{i,k} / \sum_{k=1}^{n_s} N_{i,k}$$

$\tau_{i,k}$ is the AOT mean at the grid point i from sensor k, and is the number of sensors with data and $\sigma_{i,k}$ is the standard deviation of the mean at the grid point i from sensor k,

$N_{i,k}$ is the number of pixel counts at the grid point i from sensor k. All the above methods are quite simple, fast, random error-correcting and thus are suitable for incorporating into an interactive analysis system like Giovanni.

2.3) Optimal Interpolation (OI)

$$\tau_i^{OI} = \sum_{j=1}^{n} w_{ij} \tau_j$$

τ_i^{OI} is the estimate at analysis point i, $i = 1..n$ where n is the number of analysis points.
τ_j is the data value at point j, $j = 1..n$ where n is the number of points with available data.
w_{ij}: Co-efficients to be determined by minimizing the expected value of the sum of square - errors.
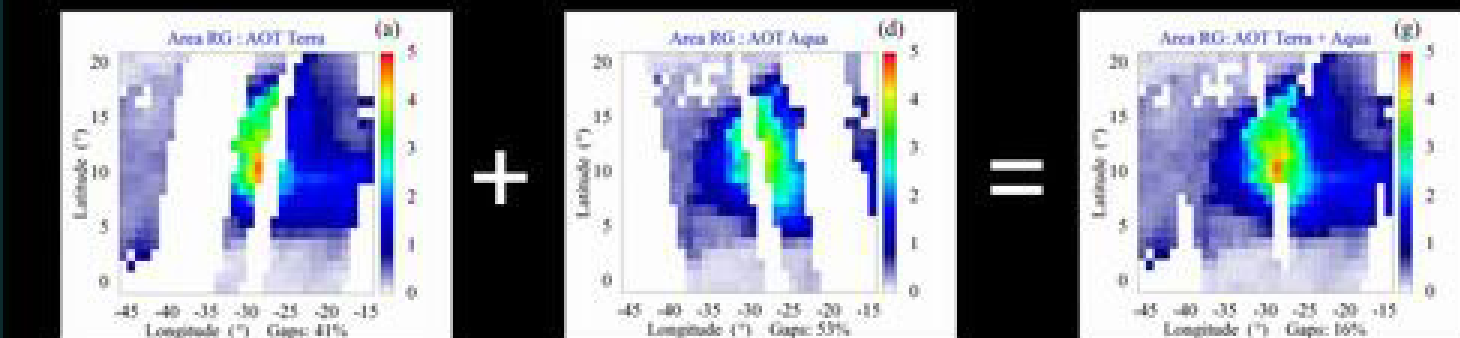
3. Experiments with Data Fusion

Fig. 1. Plates (a) and (d) represent maps of the original MODIS Terra and Aqua Level-3 AOTs for areas with mostly Regular Gaps (Area RG). These gaps (white areas in the maps) are due to sun-glint areas and gaps between orbital swaths. Plate (g) contains the map of the merged product created using the SIM method to combine the AOT values in Plates (a & d). (See Section 2)
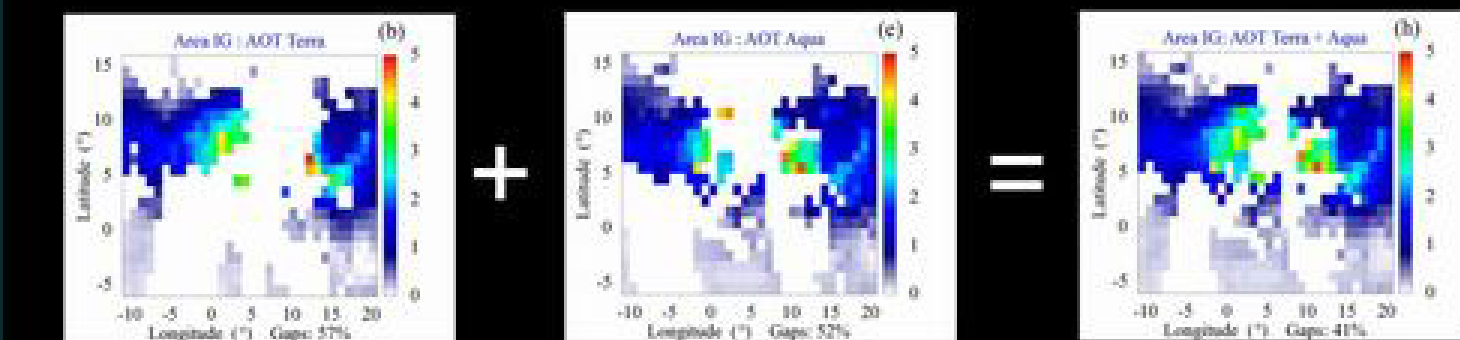

Fig. 2. Plates (b) and (e) also represent maps of original MODIS Terra and Aqua Level-3 AOTs for areas with mostly Irregular Gaps (Area IG). These gaps are due to clouds and bright land surfaces over which AOT is not retrieved. Plate (h) contains the map of the merged product created using SIM with AOT in Plates (b & e). Note the reduction but not elimination in gaps for the merged product for the case of Areas RG (Plate g) as opposed to the much lesser extent in reduction of gaps for the case of Areas IG (Plate h). Only 16% of the merged AOT map in Plate (g) contains gaps compared to 41% for Plate (h).
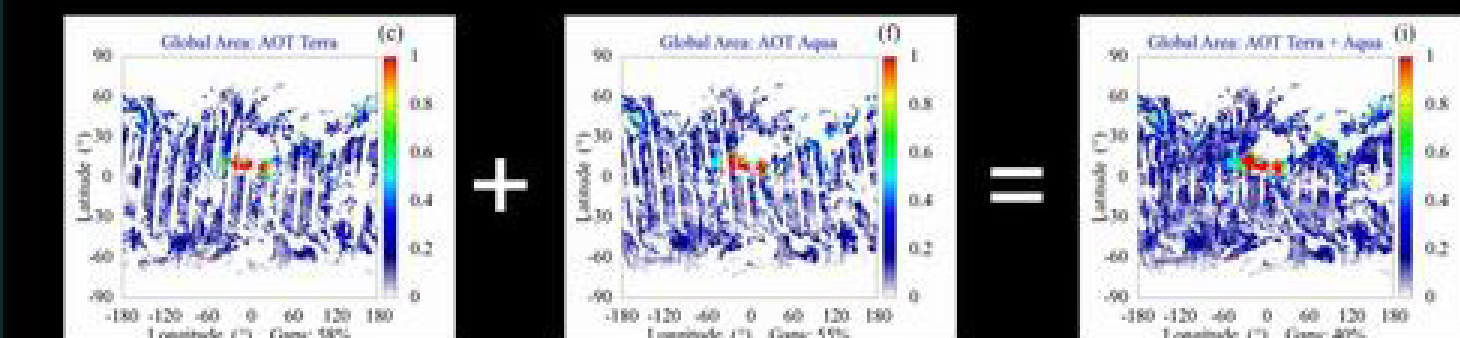

Fig. 3. On a global scale, AOT from Plates (c & f) were merged using SIM to create AOT map in Plate (i), about 40% of which is comprised of gaps. Note that the AOT on the global scale has been restricted to values below 1 owing to the large dynamic range of this parameter over a very small region.

4. Using Statistical Measures to Understand the Merged AOT

We introduce the notion of Merging Confidence Function (MCF) to understand the maps resulting from (A) merging of Terra and Aqua MODIS AOT (e.g. Plates g, h and i from Fig. 1-3 above) and (B) merging of Terra and Aqua AOT followed by OI for the gap regions. Broadly speaking MCF is a measure of the percentage of data values in the merged product whose deviation from the original Terra and Aqua AOT data are inside 3-Sigma.
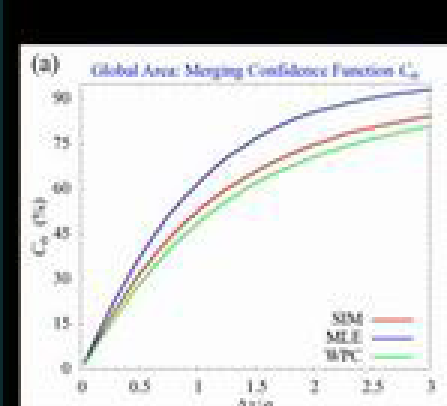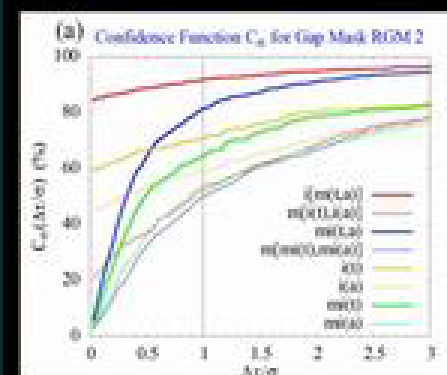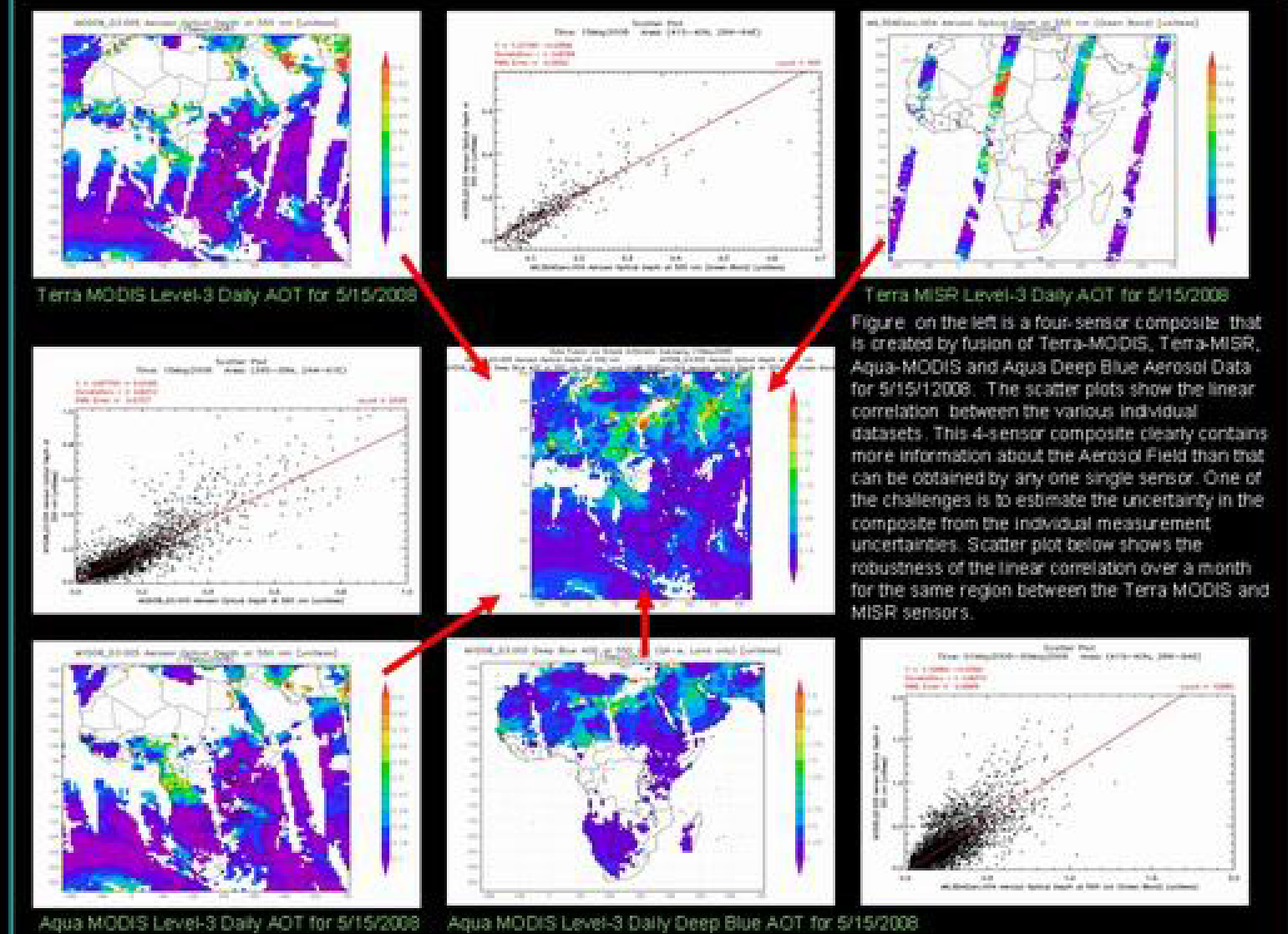

Figure 5

Fig. 5. The MCF for the merged data set using any of the pure merging schemes outlined in Section 2. All the methods produce merged data, 90% of whose deviation from the original AOT are inside 3-sigma.

Fig. 6. The MCF's for the merged and interpolated AOT product is shown for various combinations of merging and interpolation done in different orders. These curves essentially describe spatially complete reconstructed fields obtained using combinations of merging and OI. It is to be noted that i[m(t,a)] interpreted as merging of Terra and Aqua AOT data followed by OI for the gap areas, appears to be the best method as 80 – 90% of the merged and interpolated data deviates from the original data by less than 1-sigma.
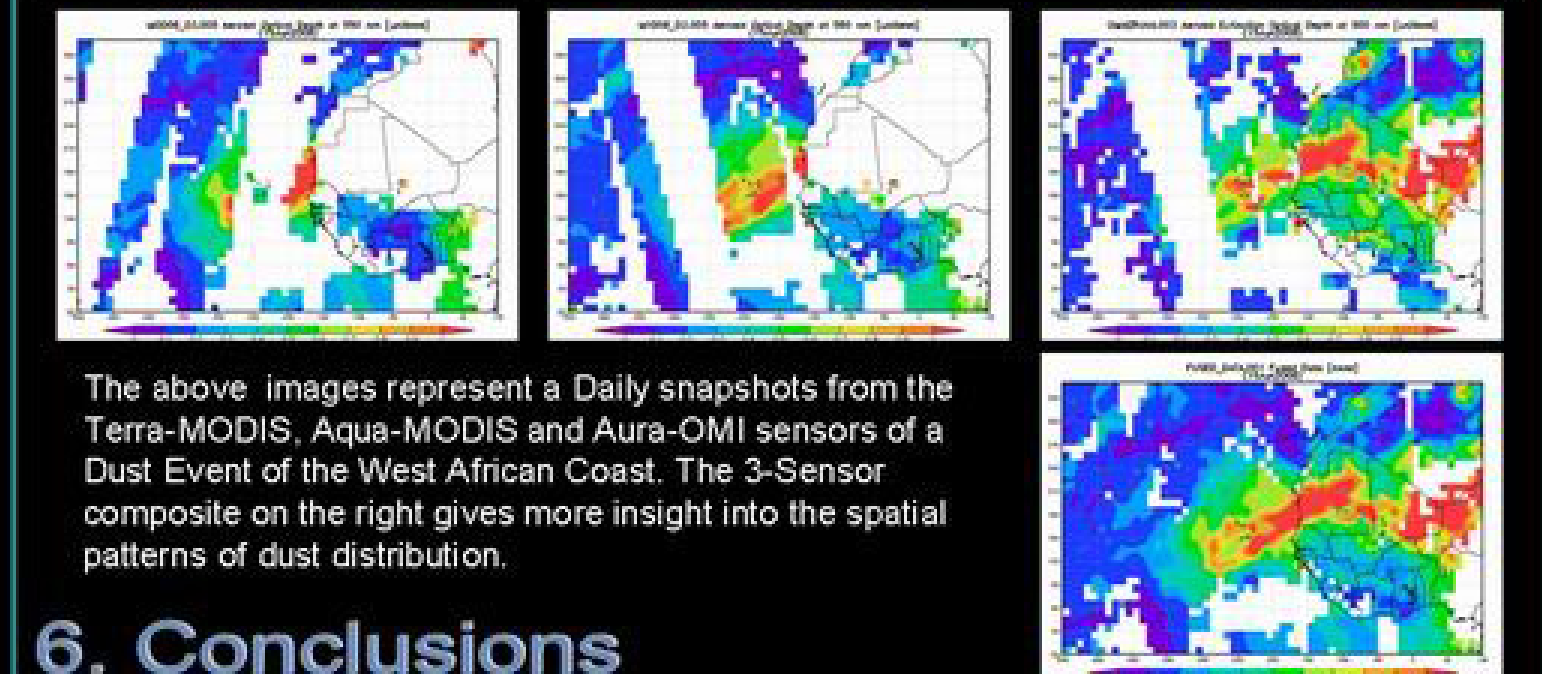

Figure 6

Fig. 7. The i[m(t,a)] method has been applied to number of Realistic simulations using both Regular (RGM) and Irregular Gap Masks (IGM). As is seen MCF's are sensitive to the gap fraction and pattern and about 68 -82% of the merged (& OI) data deviated from the original data by less than 1-sigma.

Figure 7

5. Issues and Challenges in Data Fusion as applied to Satellite Aerosol Measurements

Multi-sensor Aerosol Data Fusion can be performed at various levels in the satellite data processing chain from
- Level-1B Radiances
- Level-2 Retrieved Aerosol Data at Native Resolution [4]
- Level-3 Binned and Gridded Data

Multi-sensor Aerosol Data Fusion at any of the above levels has to consider:
- Measurement Uncertainties for the individual Sensors
- Differences in Spatial and Temporal Sampling between Sensors
- Bias between Sensors
- Error Analysis to evaluate the quality of the Fused product
- Validation of the Fused product

Terra MODIS Level-3 Daily AOT for 5/15/2008

Terra MISR Level-3 Daily AOT for 5/15/2008

Aqua MODIS Level-3 Daily AOT for 5/15/2008

Aqua MODIS Level-3 Daily Deep Blue AOT for 5/15/2008

Figure on the left is a four-sensor composite that is created by fusion of Terra-MODIS, Terra-MISR, Aqua-MODIS and Aqua Deep Blue Aerosol Data for 5/15/12008. The scatter plots show the linear correlation between the various individual datasets. This 4-sensor composite clearly contains more information about the Aerosol Field than that can be obtained by any one single sensor. One of the challenges is to estimate the uncertainty in the composite from the individual measurement uncertainties. Scatter plot below shows the robustness of the linear correlation over a month for the same region between the Terra MODIS and MISR sensors.

Dust storm of the West Coast of Africa: Three Sensor Individual and Composite View

The above images represent a Daily snapshots of the Terra-MODIS, Aqua-MODIS and Aura-OMI sensors of a Dust Event of the West African Coast. The 3-Sensor composite on the right gives more insight into the spatial patterns of dust distribution.

6. Conclusions

1. The data fusion experiments ranging from pure merging only to combinations of merging and optimal interpolation are able to take advantage of the complementary nature of Terra-MODIS, Terra-MISR and Aqua Daily Level-3 AOT Data to produce spatially contiguous Daily Mean AOT fields. As can be seen from Section 5, multi-sensor composite images are able to provide more insight into the spatial distribution patterns of the aerosol event.

2. Data fusion results will be sensitive to the parameter spatial homogeneity, temporal variability and sensor sampling considerations. Validation against independent measurements will be required to assess quality and accuracy of the fused data product.

7. References

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4. Pawan Gupta, Falguni Patadia and S. A Christopher, "Multisensor Data Product Fusion for Aerosol Research", IEEE Trans. Of Geosci. And Remote Sensing, Vol. 46, NO. 5, May 2008