OSCAR: Online Services for Correction of Atmosphere in Radar

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1. Introduction

Interferometric Synthetic Aperture Radar (InSAR) is used to measure the deformation of Earth's surface by computing the interference of two radar images taken at different times. The phase of a SAR image is affected by propagation delays in the atmosphere and constitutes the largest source of error in InSAR measurements. While both the ionosphere and the troposphere contribute to the propagation delays, the majority of SAR archives is in the C-band (wavelength 6 cm) and is only weakly affected by the ionosphere. OSCAR concentrates on web services for locating, collecting and processing atmospheric data to correct the InSAR propagation delays caused by the wet atmosphere.

InSAR-based corrections have historically used single atmospheric data sets and ad hoc methodologies that cannot be applied to all situations. One can distinguish four methods to correct for atmospheric delays, which are using ancillary data:

a. *Continuous Global Positioning Systems:* Global Navigation Satellite Systems signals have propagation delays similar to those of InSAR. The ground receivers can measure both ionospheric and tropospheric delays. The ionospheric delay is estimated from the multiple frequencies of the GPS signal by using the property that delays are dispersive in the ionosphere but not in the troposphere. The remaining delay of the GPS signal is the tropospheric component. The total tropospheric delay can be estimated as random walk processes and then be interpolated spatially and temporally to the grid of the InSAR images.

b. *Near IR absorption and reflection data:* The MODIS instrument (on both the NASA Terra and Aqua satellites) provides a water vapor product that can be calibrated to agree with GPS data by using one continuous GPS station within a 2,030 km x 1,354 km MODIS scene. The MERIS instrument is collocated with the radar ASAR on the European platform ENVISAT. It produces a water vapor product that closely agrees with GPS data. Both MODIS near IR and MERIS near IR measure the absorption of reflected sunlight by water vapor in the troposphere. This means that they can only make measurements during the day. In addition,
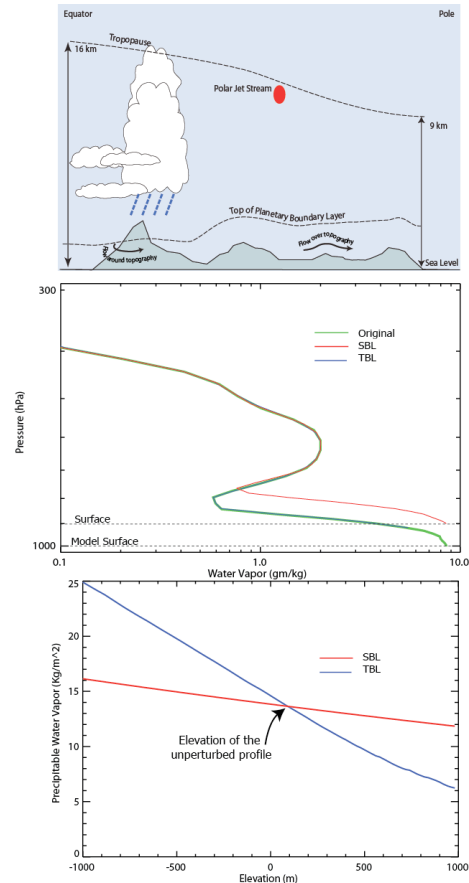

Figure 1. Stretched Boundary Layer and Truncated Boundary Layer algorithms for the extrapolation of the specific humidity as a function of altitude. The top panel illustrates the tropospheric model and the air flow patterns near obstacles. The middle panel shows the original ECMWF model (green), the TBL (blue) and SBL (red) precipitable water vapor profiles. The lower panel shows the elevation of the unperturbed profile.

radiation at near IR wavelengths is reflected by clouds, with the consequence that these instruments only measure the water vapor above any clouds that are present.

c.   *Thermal IR:* MODIS provides thermal IR measurements of water vapor, but we found this to be insufficiently accurate for our purposes. We will consider AIRS data at later stage.

d.   *Numerical Weather Models (NWF):* GPS and near-IR data are complementary but not globally available at all times. Weather forecast models like those from the European Center for Medium Range Weather Forecasting (ECMWF) and the NOAA NCEP North American Mesoscale Model (NAM) fill this gap but care has to be taken to correct for low spatial resolution in the model, as compared to the high resolution of InSAR. Corrections from NWF are greatly improved if local topographic corrections are applied.

We developed the Stretched Boundary Layer (SBL) and the Truncated Boundary Layer (TBL) algorithms to modulate the coarse fields of the weather model data with the high resolution topography of the SAR (Figure 1).

The TBL algorithm truncates the model profile at the correct elevation obtained from a Digital Elevation Model (DEM) when the DEM surface is above the model surface, and linearly extrapolates the logarithm of the water vapor as a function of the logarithm of the elevation when the DEM surface is below the model surface. TBL is expected to be most accurate when the air flows around obstacles.

The SBL algorithm linearly expands or contracts the model tropospheric elevation grid to match the DEM surface elevation. SBL is expected to be most accurate when the air flows along the slopes.

2.   Information technology architecture

OSCAR consists of a set of services that help the clients generate atmospheric corrections. The diagram above depicts the functional architecture diagram (Fig. 2).
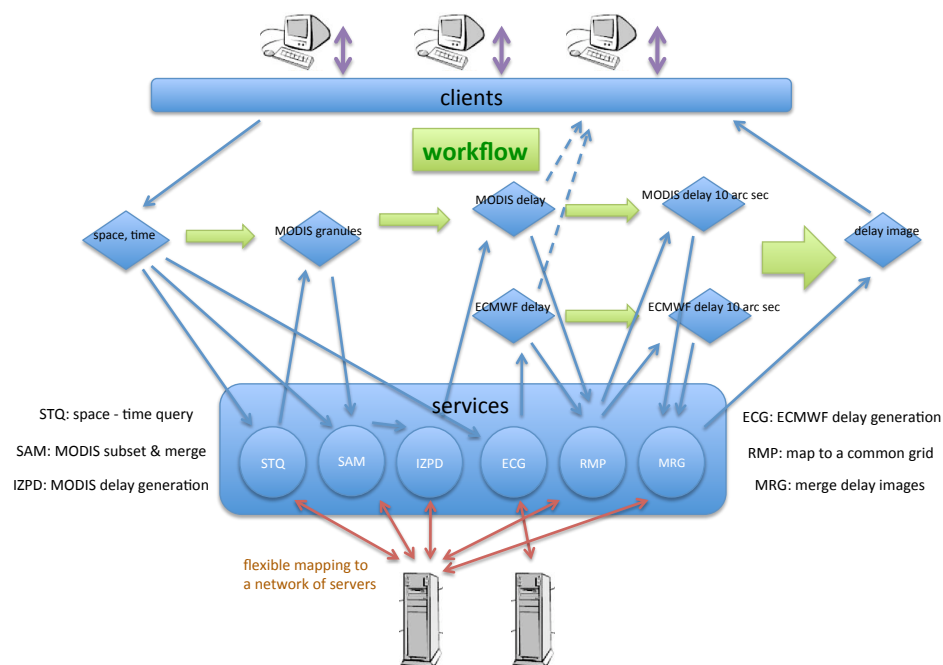

Figure 2. Functional architecture diagram for OSCAR.

Data processing "smarts" are distributed among services. The design principles are outlined as follows: (1) Each service is responsible for a single task. (2) Communications between clients and services, and among services use concise RESTful Web APIs. This approach provides flexibility for

building complex applications like OSCAR and establishes a new foundation, on which future Earth science applications can leverage.

OSCAR includes 6 services, of which the first 4 are functional: (1) the Space and Time Query (STQ) service, (2) the Subset And Merge (SAM) service, (3) the Interpolated Zenith Path Delay (IZPD) service, (4) the ECMWF delay Generation (ECG) service, (5) the ReMaPping service (RMP), and (6) the MeRGe (MRG) service.

A typical use case is described by the following 8 steps.

1. User selects InSAR scenes, where OSCAR will compute tropospheric delays
2. User selects data to use for corrections (MODIS, MERIS, AIRS, ECMWF, NAM)
3. User provides OSCAR client with spatial bounding box and temporal constraints
4. OSCAR retrieves the URL of data granules corresponding to spatio-temporal constraints
5. OSCAR merges granules and subsets the data
6. OSCAR returns the delays on a latitude-longitude grid
7. User applies gridded delays to InSAR scenes in data processing package (e.g., ROI_pac)
8. User retrieves scientific analysis from InSAR package (ROI_pac or ISCE)

3. Merging Remote Sensing and Weather Forecast Data

One of the key objectives of OSCAR is to combine remote sensing data from for example MODIS with weather forecast data from for example ECMWF. We have developed a merging method based on Bayesian statistics that requires the following elements for the data sets. MODIS near-IR total precipitable water vapor needs quality control, error characterization, bias correction and remapping to a uniform latitude-longitude grid. ECMWF global analysis data requires bias and topography corrections, and remapping.

MODIS Quality Control Model

The quality of the data is also assessed from 5 parameters directly available from the MODIS data: Water_Vapor_Near_Infrared, Cloud_Mask_QA, surface type flag, Quality_Assurance_Near_Infrared, and the total precipitable water (NIR) usefulness flag. We define a single quality control mask that takes the value 1 if all the MODIS quality parameters are satisfactory and 0 otherwise.

ECMWF Topography Correction

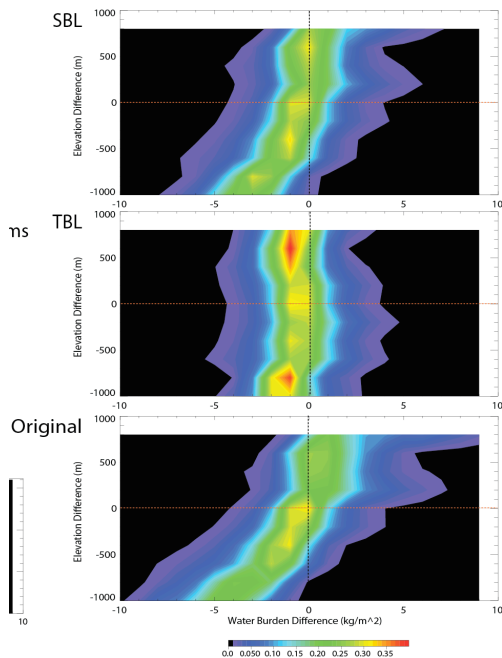The topography correction is applied using the TBL or the SBL algorithms described in section 1.2.

The validity of the correction algorithms is assessed by comparing with water vapor burden data from a set of GPS stations equipped with a meteorological package, obtained from A. Moore of the Bock et al. AIST project on real-time GPS processing.

Figure 3 shows histograms for the water burden difference for the original model data and the SBL and TBL corrected data, conditional on the elevation difference between the model and the GPS station. This statistical analysis shows that the SBL and TBL algorithms lead to better corrections when the surface is above and below the model surface, respectively. We use this result to choose which algorithm to apply for a given InSAR scene.

ECMWF Bias Correction

Validation studies show that ECMWF data includes a 5.5% dry bias and a regional and seasonal water vapor bias when compared with MODIS or GPS data. Since water vapor is modulated by topography and affected by large seasonal variations, we selected a bias correction that is dynamic and derived from coincident and collocated ECMWF and MODIS data.

Figure 3. Histogram of the water vapor burden difference conditional on elevation difference.

The topographically corrected ECMWF and MODIS data are collocated on a uniform latitude-longitude grid and a scaling factor is computed as the ratio of the median ECMWF to the median MODIS water vapor data in the regions where the quality control flag for MODIS (see section 3.1) is 1. An annealing algorithm extends the bias correction to the empty bins.

Merging Algorithm

A Bayesian merging algorithm gives the combined water vapor as the average of the MODIS and the ECMWF data weighted by the inverse of the square of the errors. As neither product provides error covariance matrices, ad hoc point error estimates are inferred. The Mesoscale Alpine Experiment, Special Observing Period (MAP-SOP) 1999 using GPS over Europe gives an error for ECMWF of 2.6 kg/m^2 (13% RMS) at a spatial resolution of 0.25° (O. Bock et al. 2005). The accuracy of MODIS NIR data was estimated in the literature to be 5.44 kg/m^2 at 1 km resolution by comparison with GPS, radiosondes and AERONET Sun photometer data (Prasad et al. 2009). While the MODIS and ECMWF have comparable errors, at the same spatial resolution (for uncorrelated errors) the MODIS data is about 25 times more precise than the ECMWF data. The ECMWF error is spatially correlated over roughly 25 MODIS pixels. Therefore in transitioning smoothly from a region of poor MODIS data to good, the transition should be smoothed over the ECMWF correlation length.
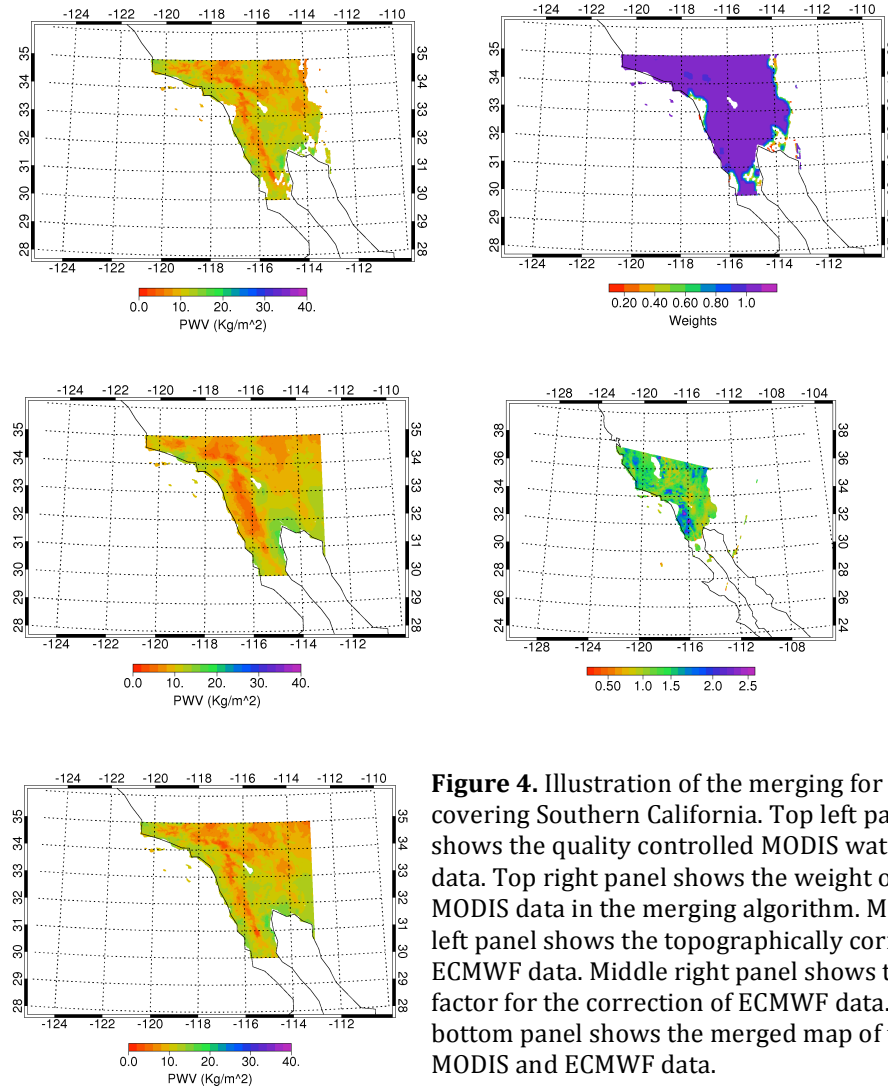

Figure 4. Illustration of the merging for a scene covering Southern California. Top left panel shows the quality controlled MODIS water vapor data. Top right panel shows the weight of the MODIS data in the merging algorithm. Middle left panel shows the topographically corrected ECMWF data. Middle right panel shows the bias factor for the correction of ECMWF data. The bottom panel shows the merged map of the MODIS and ECMWF data.

The quality control mask for MODIS data (see section 3.1) is used in the merging algorithm to weight the MODIS and the ECMWF errors according to the following expression.

$$\frac{\sigma^2_{ECMWF}}{\sigma^2_{MODIS}} = \frac{\text{smoothed\_qc\_mask}}{1 - \text{smoothed\_qc\_mask}}$$

where the smoothed quanlity control map is obtained by mapping the mask for each of the relevant MODIS granules to a uniform grid and apply a box car smoothing.

The result of the merging algorithm is illustrated in Figure 3. The success of the merging algorithm is demonstrated by the fact that the map of the merged data at the bottom of the figure uniformly covers the scene, smoothly integrating the ECMWF data in the regions where MODIS data is not available, as shown in the top left panel in Fig. 4. We have tested the algorithm for several other spatial and temporal conditions and have not yet found an case where the algorithm fails.

4. Conclusion

Algorithms were presented and validated for correcting the effect of tropospheric water vapor on InSAR images using merged total water vapor contents from MODIS and from ECMWF numerical weather forecast. A web service architecture was developed and implemented using RESTful services to present the correction algorithms to the user.

5. Acknowledgments

6. References

O. Bock et al. 2005, Q J Roy. Meteor. Soc., 131, 3013.
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