Surface Reflectance Earth System Data Record/Climate Data Record White Paper

Vermote E.F., Nazmi Z. Saleous, Jeffrey L. Privette, et al.

1. Definition/Importance/Rationale/Requirements

Directional surface reflectance is defined as the ratio between the radiance measured in specific observation geometry (zenith and azimuth) and a direct source of illumination (zenith and azimuth) in an infinitely small solid angle. The directional surface reflectance is determined from satellite observations though the atmospheric correction process. When properly retrieved, the directional reflectance is fully decoupled from the atmospheric signal, and thus represents the value that would be measured by an ideal sensor held at the same sun-view geometry and located just above the Earth's surface if there was no atmosphere.

Directional surface reflectance is the most basic remotely sensed surface parameter in the solar reflective wavelengths. It therefore provides the primary input for essentially all higher-level surface geophysical parameters, including Vegetation Indices, Albedo, LAI/FPAR, Vegetation Indices, Burned Area, Land Cover and Land Cover Change. Directional surface reflectance is also used in various "imagery" applications to detect and monitor changes on the Earth's surface (e.g., anthropogenic impacts, red-green-blue images).

The accuracy requirements for directional surface reflectance typically are determined by the higher level products (e.g., Albedo: 0.02-0.05, NDVI: 0.03, etc.). Surface reflectance accuracy is primarily limited by the accuracies of: 1) the sensor calibration, 2) the atmospheric parameter inputs (e.g., aerosol optical depth), 3) the radiative transfer code used in the forward simulation, and 4) the operational implementation of the inverse problem or correction [1].

Downstream products also drive the spatial and temporal requirements for surface reflectance. For climate data records (CDRs), downstream products generally are analyzed on a monthly temporal basis, however the monthly values are most statistically significant when derived from as many satellite observations as possible (e.g., VI composite, BRDF/Albedo, LAI/FPAR synthesis).

Directional surface reflectance CDRs should be multi decadal datasets such that they allow decoupling of short term natural variations in the climate (periodicity of 2-7 years such as El Nino) and understanding of the impacts on the Land biosphere. This is required to fully understand and predict the anthropogenic dimension of the long term change.

In heritage processing efforts, the spatial requirement on the directional reflectance product has been established at 1 km and 0.05 deg., -- the former being the best resolution achievable with historical data (AVHRR LAC), the later the resolution of the longest data record (AVHHR-GAC) that could be easily aggregated to a coarser grid well suited for climate models. More recently, medium term land studies with a regional focus are emerging based on high spatial resolution surface reflectance products (Landsat ETM+ at 30m), such as **L**andsat **E**cosystem **D**isturbance **A**daptive **P**rocessing **S**ystem [2].

2. **Approach to generating the measurement (i.e., data product)**

2.1 Feasibility reliability of measurement

In practice, atmospheric correction is typically achieved by inverting a highly parameterized model of atmospheric radiative transfer coupled to a surface reflectance model. For speed and simplicity, the surface reflectance is often assumed to be Lambertian. As atmospheric radiative transfer modeling is relatively mature, several methods could be used to model the surface/atmosphere interaction (e.g., Successive Order of Scattering, Doubling adding, Monte Carlo simulation). The main challenges to the operational implementation of these models lies in the assignment of the atmospheric parameters and the a priori knowledge of the surface BRDF – strictly necessary for a full inversion. Approaches to operationally retrieving the atmospheric parameters have advanced considerably into the last 10 years as remote sensing instruments capable of retrieving atmospheric properties (aerosol, ozone, water vapor, etc..) have been put into operation. In the absence of operational retrievals, atmospheric climatology or forecasted values can be applied, although product accuracy degrades considerably. The determination of surface BRDF at the operational level is currently practical only for satellite sensors with single-pass multi-angular capability, such like MISR or POLDER. However, surface BRDF represents a second order effect and should introduce only a consistent bias and not influence inter-annual variability analysis.

2.2 Algorithm/Concept

The atmospheric "perturbation" of the directional surface reflectance signal depends on the type and characteristics of atmospheric particles interacting with the radiation. The gas molecules (N_2,O_2,O_3,H_2O,CO_2,…) scatter radiation according to Rayleigh's theory (i.e., molecular scattering). Gas molecules also absorb radiation in specific spectral bands with bandwidths varying by species, and the atmospheric pressure and temperature vertical profiles. Aerosols, which are suspended particles ranging from about 10^{-3} µm to about 20µm, scatter and absorb radiation according to the Mie and Geometric Optics theory. The former is used for aerosols with diameters on the order of the radiation wavelength; the latter assumes larger particles as individual spheres with given refractive real and imaginary refractive indices.

Atmospheric correction removes or reduces the effects of these atmospheric perturbations. In an idealized case of a Lambertian surface (angularly uniform reflectance) and in narrow spectral bands outside of the main absorption feature of water vapor, the top-of-atmosphere signal could be written [3] as:

$$\rho^i_{TOA}(\theta_s,\theta_v,\phi,P,\overbrace{\tau^i_A,\omega^i_0,P^i_A}^{Aer^i},U_{H_2O},U_{O_3}) = Tg^i_{OG}(m,P)Tg^i_{O_3}(m,U_{U_{O_3}})\left[\begin{array}{l}\rho^i_{atm}(\theta_s,\theta_v,\phi,P,Aer^i,U_{H_2O}) + \\ Tr^i_{atm}(\theta_s,\theta_v,P,Aer^i)\dfrac{\rho_s}{1-S^i_{atm}(P,Aer^i)\rho_s}Tg^i_{H_2O}(m,U_{U_{H_2O}})\end{array}\right] \quad (1)$$

Where:

ρ_{TOA} is the reflectance at the top of the atmosphere,

Tg is the gaseous transmission by water vapor, Tg_{H2O}, by ozone, Tg_{O3}, or other gases, Tg_{OG} (e.g. CO_2,…)

ρ_{atm} is the atmosphere intrinsic reflectance,

Tr_{atm} is the total atmosphere transmission (downward and upward)

S_{atm} is the atmosphere spherical albedo,

ρ_S is the surface reflectance to be retrieved by the atmospheric correction procedure,

The geometrical conditions are described by θ_s, the solar zenith angle, θ_v, the view zenith angle and φ, the difference between the solar and view azimuth angle,

P is the pressure which influences the number of molecules in the atmosphere and the concentration of absorbing gases.

τ_A, ω_0 and P_A describe the aerosol properties and are spectrally dependent,

τ_a is the aerosol optical thickness,

ω_0 is the aerosol single scattering albedo,

P_A is the aerosol phase function,

U_{H2O} is the integrated water vapor content ,

U_{O3} is the integrated ozone content ,

m, is the air-mass computed as $1/\cos(\theta_s)+1/\cos(\theta_v)$

The effect of the water vapor on the atmosphere intrinsic reflectance can be approximated as:

$$\rho^i_{atm}(\theta_s,\theta_v,\phi,P,Aer^i,U_{H_2O}) = \rho^i_R(\theta_s,\theta_v,\phi,P) + \left(\rho^i_{R+Aer}(\theta_s,\theta_v,\phi,P,Aer^i) - \rho^i_R(\theta_s,\theta_v,\phi,P)\right)Tg^i_{H_2O}(m,\frac{U_{U_{H_2O}}}{2}) \quad (2)$$

where ρ_R represent the reflectance of the atmosphere due to molecular (Rayleigh) scattering, and ρ_{R+Aer} represents the reflectance of the mixing molecules and aerosols. Accounting correctly for the mixing and the so-called coupling effect [4] is important for achieving high accuracy in the modeling of atmospheric effect. This approximation conserves the correct computation of the coupling, and supposes that the water vapor is mixed with aerosol and that the molecular scattering is not affected by the water vapor absorption.

2.3 Measurement / algorithm heritage and maturity

The surface directional reflectance product is generated as a standard product from the MODIS and MISR instruments. For MODIS, many of the atmospheric parameters listed above are estimated directly from the MODIS observations using the multispectral top-of-atmosphere observations and by applying assumptions on the land and atmospheric spectral signatures. Key to this approach is the "first guess" of land spectral reflectance, based on the MODIS mid-IR (2.1 micron) band observation. This band is minimally impacted by atmospheric effects. Surface reflectance products from Landsat, AVHRR, MERIS and SeaWiFS are currently in early stages of development (Beta). These types of algorithms are mature and documented.

2.4 Required inputs products and their traceability (including dependencies on other products)

As outlined in 2.1, the main inputs for the MODIS atmospheric correction are (by order of effect on standard products):

- **A**erosol **O**ptical **T**hickness, Size distribution, refractive indices and vertical distribution.
  - o Some of those parameters (**AOT**) are retrieved from the MODIS data itself; the others are assigned based on climatology. The spatial resolution required for AOT is 1 km and the values need to be nearly coincident with the observation (+/- 15mins). For other parameters, a much spatial coarser resolution can be used and a static model may be assumed with little loss of accuracy [5].
- Atmospheric pressure
  - o Obtained from a combination of a coarse resolution (1 deg, 6 hour time step) Weather Prediction model and a Digital Elevation Model at 1 km resolution.
- Ozone amount
  - o Usually determined from a UV/Longwave Sounder at a coarse spatial (1 deg) and temporal resolution (1d ay)
- Column-integrated water vapor content
  - o Determined from the MODIS data itself at 1km spatial resolution.

2.5 Processing / reprocessing requirements

The directional surface reflectance product can be generated in near-real time (example: VIIRS algorithm on NPP/NPOESS, Direct Broadcast algorithm on MODIS). The data should be re-processed as improvements in the algorithm become available (in particular to the aerosol estimation component), or if the calibration/level 1/Cloud mask products are substantially improved.

2.6 Calibration / validation

Algorithm validation should be conducted at two levels:

a) Validation of the radiative transfer model (http://rtcodes.ltdri.org), which is accomplished by intercomparing the parameterized radiative transfer model with a standard benchmark [1] and

b) Validation of the surface reflectance product, accomplished by comparing the product to other high quality reflectance products as determined by applying the radiative transfer model supported with high accuracy atmospheric parameters (e.g., those obtained at an AERONET site) to the level 1 data. Validation of high spatial resolution surface reflectance products (e.g., from IKONOS, QUICKBIRD, Landsat-ETM) is possible by comparing the satellite product to ground-level surface reflectance measurements.

It is useful to estimate the impact of the surface reflectance uncertainties directly on the downstream product itself as error are not spectrally independent, for example the error on the NDVI is always lower to the largest error possible considering the uncertainties on the individual bands (Red and Near-Infrared). This exercise can be achieved by comparing the standard downstream products to the one generated by using high quality reflectance product obtained on validation sites (see section 2.7).

2.7 Product accuracy, consistency, spatial and temporal resolutions, precision in terms of satisfying science requirements.

Product accuracy can be estimated by conducting the validation exercises described in 2.6.b over a statistically and globally representative set of field sites. This is most practically and accurately achieved using AERONET data. AERONET includes more than 200 sites globally. Each site hosts a ground-based sunphotometer which collects multispectral and multiangular samples of direct and diffuse irradiance throughout the day. These data are operationally processed into higher level aerosol and atmospheric gas products. An example of MODIS surface reflectance validation at 200 AERONET sites (>4000 cases) in 2003 is available at: http://mod09val.ltdri.org/mod09val.html

3. Intended sources for the measurement

The sensor source for the long term data record measurement includes: AVHRR, SeaWiFS, MERIS, MODIS, MISR, and VIIRS.

4. Necessary supporting activities, tasks

AERONET network needs to be supported. In addition, small dedicated validation campaigns, including ground-based surface reflectance measurements and high spatial resolution remote sensing measurements, need to be supported. Comparison and validation of radiative transfer codes need to be supported.

5. Relationships to other products and programs (of other agencies, international, etc.)

The surface reflectance product is the basis for the production of the land product suite and therefore it is at the center of interest of many programs, in particular the LDCM project, the REASON-CAN activities, and at the international level for the European Program. Collaboration can be firmly established in the context of CEOS-Cal/Val activities.

6. Key citations

[1] S. Y. Kotchenova, E. F. Vermote, R. Matarrese, & F. Klemm, 2006 Validation of a new vector version of the 6S radiative transfer code for atmospheric correction of MODIS data: Part I – Path Radiance, Applied Optics, in press. (ftp://papers.ltdri.org/papers/Kotchenova-etal-2006.pdf)

[2] Masek J.G., Vermote E.F., Saleous N.E., Wolfe R., Hall F.G., Huemmrich K.F., Gao F., Kutler J., Lim T.K., 2006, “A Lands at surface reflectance dataset for North America 1990-2000”, IEEE Geoscience and Remote Sensing Letters, 3, (1), 68-72.

[3] Vermote E.F., Tanré D., Deuzé J.L., Herman M., Morcrette J.J., 1997, Second Simulation of the Satellite Signal in the Solar Spectrum: an overview, *IEEE Transactions on Geoscience and Remote Sensing*, 35,3,675-686.

[4] Deschamps, P.Y., Herman, M. and Tanre, D. (1983). Modeling of the atmospheric effects and its applications to the remote sensing of ocean color. *Appl. Optics.,* **22:** 3751-3758.

[5] Remer L.A., Kaufman Y.J., Tanré D., Mattoo S., Chu D.A., Martins J.V., Li R-R., Ichoku C, Levy R. C., Kleidman R.G., Eck T.F., Vermote E., and B.N. Holben, 2005, “The MODIS Aerosol Algorithm, Products and Validation”, Journal of Atmospheric Sciences, 62 (4),947-973.