



# **A surface reflectance scheme for retrieving aerosol optical**

- 2 depth over urban surfaces in MODIS dark target retrieval
- 3 algorithm
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## 13 Abstract

The MODerate resolution Imaging Spectroradiometer (MODIS) instruments, aboard two 14 15 Earth Observing Satellites (EOS) Terra and Aqua, provide aerosol information with nearly daily global coverage at moderate spatial resolution (10km and 3km). Almost 15 years of 16 aerosol data records are now available from MODIS that can be used for various climate and 17 air quality applications. However, the application of MODIS aerosol products for air quality 18 19 concerns is limited by a reduction in retrieval accuracy over urban surfaces. Here, in this study, we address the inaccuracies produced by the MODIS dark target algorithm (MDT) 20 Aerosol Optical Depth (AOD) retrievals over urban areas and suggest improvements by 21 22 modifying the surface reflectance scheme in the algorithm. By integrating MODIS land surface reflectance and land cover type information into the aerosol surface parameterization 23 scheme for urban areas, much of the issues associated with the standard algorithm have been 24 mitigated for our test region, the Continental United States (CONUS). The new surface 25 scheme takes into account the change in under lying surface type and is only applied for 26 MODIS pixels with urban percentage (UP) larger than 20%. Over the urban areas where the 27 new scheme has been applied (UP>20%), the number of AOD retrievals falling within 28 expected error (EE%) has increased by 20%, and the strong positive bias against ground-29





based sunphotometry has been eliminated. However, we note that the new retrieval introduces a small negative bias for AOD values less than 0.1, due to ultra sensitivity of the AOD retrieval to the surface parameterization under low atmospheric aerosol loadings. Global application of the new urban surface parameterization appears promising, but further research and analysis are required before global implementation.

6

#### 7 1 Introduction

In large concentrations, aerosols near the surface (also called particulate matter or PM) are air 8 pollutants. As urbanization and industrialization have amplified many folds during the last 9 few decades (United Nations, 2014), air quality has become a global public health concern, 10 especially in densely populated urban areas. In some cities, urban PM concentrations are at 11 dangerous levels, 5 to 10 times higher than World Health Organization (WHO) guidelines. 12 Although urban areas only represent about half a percentage of the total Earth's surface and 13 about 3% of Earth's land surface, half of the human population lives in these areas. According 14 to the new projections, two-thirds of the human population will live in urban areas by 2025; 15 therefore, it is critical to monitor air quality (aerosol or PM), especially as relating to human 16 exposure in populated regions around the world. 17

In economically developed countries such as the United States, and some European nations, surface PM concentrations and air quality is monitored by thousands of ground based monitoring stations (Cooper et al., 2012). While the density of measurements in the U.S. may be sufficient for metropolitan scale mapping, they are not dense enough for local or neighborhood scales. Also, about 30% of counties in the US are without any PM monitoring. On the other hand, most other countries, especially in developing nations, have few or no surface PM monitors and cannot measure the urban population's exposure to PM.

In the last few decades, satellites are increasingly being used to offer a global perspective on many atmospheric variables. One of these is aerosol optical depth (AOD), which is a measure of aerosol loading, integrated through the atmospheric column. As retrievals of AOD are increasing in their spatial resolution, coverage and accuracy, environmental monitoring agencies are increasingly looking to satellites to cover the gaps in aerosol monitoring. Although it is not straightforward, many studies (Wang and Christopher 2003; Gupta et al., 2006; Gupta and Christopher, 2009; Hoff and Christopher, 2009; van Donkelaar et al., 2010;





Liu et al., 2010; van Donkelaar et al., 2015) are trying to link satellites retrievals of AOD to
 surface concentrations of PM2.5 or PM10 (PM having aerodynamic diameters of 2.5 or 10
 micrometers, respectively).

In addition to its role in air quality and public health, aerosols are considered an essential 4 climate variable (e.g., IPCC, 2007), and remote sensing of AOD has evolved, primarily, to 5 address climate-related questions. Decisions on aerosol products, product resolution and 6 tolerance of poorer quality retrievals have been made to maximize the effectiveness of these 7 8 products for climate, not air quality applications. For example, poor quality retrievals over 9 urban surfaces that represent so little of the Earth's surface has negligible effect on the climate question, and so retrieval algorithms originally were tuned to ignore the special nature of the 10 urban environment. There are several satellite based AOD products and each combination of 11 satellite/retrieval algorithm has its own advantages and limitations. One satellite/algorithm 12 13 pair with a climate-oriented aerosol product is the Moderate-resolution Imaging Spectroradiometer (MODIS) dark-target algorithm (MDT). The MDT is mature, having being 14 developed twenty years ago (Kaufman et al. 1997b; Tanré et al., 1997) for retrieval of AOD 15 over primarily vegetated (e.g. dark) land surfaces and remote oceans. It is now running as 16 Collection 6 (Levy et al., 2007a, 2007b, 2013), and the standard AOD product (nominal 10 17 km spatial resolution) is generally unbiased over global land regions, a requirement for 18 19 climate applications.

20 The standard MDT product, while well suited to answer climate questions, has many shortcomings when used for air quality monitoring. The first, and most important, is that PM 21 is defined as the concentration of particles in the surface layer of the atmosphere where people 22 23 can be affected by the pollution, while the MDT product measures the aerosol loading (AOD), 24 integrated from this surface layer all the way to the top of the atmosphere. Correlation between column AOD and surface PM depends on the vertical profile of aerosol 25 concentration, which is not measured by MODIS. However, the other problem is that the 26 27 MDT retrieval, while nearly unbiased compared with the full set of sunphotometer measurements in the Aerosol Robotic Network (AERONET) database, has strong biases for 28 particular surface types. 29

MDT over land was designed for retrieval over vegetated and other "dark" surface regions.
MDT does not provide aerosol retrieval over very bright surface (i.e. desert) and over snow
and ice regions. In addition, several validation studies have shown that MDT AOD retrievals





over urban area are positively biased with respect to AERONET AODs (Levy et al., 2010;
 Jethva et al., 2007; Hyer et al., 2011; Gupta et al., 2013; Munchak et al., 2013). These studies
 have shown that the major source of bias in the MDT over cities is that the city surface does
 not behave as a vegetated "dark" target.

Several other research attempts have been made to change the surface scheme in the MDT for 5 particular urban regions; and produce better AOD retrievals for those specific cities (de 6 Almeida Castanho et al., 2007, 2008; Li et al., 2005; Wong et al., 2011; Zha et al., 2011; Li et 7 8 al., 2012; Escribano et al., 2014; Jakel et al., 2015). Instead of a retrieval focused on only one 9 city, we seek a surface parameterization that is valid for cities across the globe. This will lead to more accurate AOD retrievals, which can be utilized for air quality applications and 10 research, including estimating urban population exposure to aerosols. In this paper, we have 11 developed a surface characterization for cities in the CONUS region, applied it to the MDT 12 algorithm, and evaluated the results. In section 2 we introduce MODIS, the MDT algorithm 13 and its current limitations over cities. Section 3 discusses study region and various data sets 14 utilized in this study. Section 4 describes the new surface parameterization whereas results 15 and impact of new surface scheme on MDT AOD retrievals over CONUS regions are 16 discussed in section 5. Section 6 covers, implication of new surface scheme over global 17 regions and it limitations and challenges. We summarize the results and future directions in 18 19 the section 7.

20

## 21 2 MODIS and the Dark-Target Algorithm

MODIS sensors have been observing the Earth system (atmosphere, land and ocean) on board two satellites, since 1999 on Terra and since 2002 on Aqua. MODIS observes top-of-theatmosphere (TOA) radiance in 36 spectral bands, which are used to derive geophysical information about atmosphere, land and ocean. The spatial resolution varies from 250 meter to 1 km depending on spectral band. The large swath width of MODIS (~2300km) enables global coverage in 1-2 days. Data are separated into five-minute segments, known as granules.

Since MODIS measures the reflectance of the Earth's system, the measured radiation contains information about atmospheric properties as well as Earth's surface. In some spectral bands, the surface dominates the signal, whereas the atmosphere dominates in other bands. The strategy then is to use the right combinations of spectral bands to retrieve a particular aspect





of the combined Earth's system. Specifically, the MDT is used to derive global aerosol
 properties under cloud/snow/ice free conditions.

The theoretical basis of the MDT algorithm has remained constant from its original at-launch version, although individual sub-modules have been continuously evolving. While a summary of the algorithm is provided here, the reader is encouraged to read the references for details of the algorithm assumptions and structure, and its evolution through different versions over time (Remer et al., 2005; Levy et al., 2007a, 2007b, 2013).

The five main components of the MDT aerosol retrieval algorithm are: 1) pixel selection and 8 9 aggregation, including cloud masking and other filtering, 2) separating the surface from the atmosphere, and 3) assumptions about the aerosol (e.g. aerosol models), 4) matching observed 10 11 TOA spectral reflectance to lookup tables (LUTs), 5) and inferring the ambient aerosol conditions (model weightings and total AOD). There are two separate retrievals, one over 12 ocean and one over land, and the results of these retrievals and associated diagnostics are 13 available in a single data file. Each retrieval result and each diagnostic are independent 14 Science Data Sets (SDS) within the produced file. In production, collectively these SDSs 15 within the single file are known as the MxD04 product, where x depends on whether from 16 Terra ("O") or Aqua ("Y"), and the "04" denotes the level 2 aerosol products. Products 17 (SDSs) include the total AOD (at 0.55 µm), spectral AOD, and diagnostics describing the 18 choice of retrieval solutions, plus quality assurance criteria and expected confidence in the 19 retrieved AOD. The standard MxD04 product, known as MxD04 L2, is provided at a nominal 20 21 (nadir) spatial resolution of 10 km. In the recent release of MODIS collection 6 (C6) data version, there is also a MxD04 3K product, which is at 3km spatial resolution (nadir) and 22 available globally. The standard C6 products have gone through initial validation (e.g. Levy et 23 al., 2013; Munchak et al., 2013, Remer et al., 2013). 24

25 The MODIS retrieval codes are run in an operational environment to create C6 products. This includes infrastructure for managing file formats and also for processing entire granules of 26 MODIS data. In this work, we also make use of the so-called "standalone" version of the 27 MODIS dark target (S-MDT) retrieval code (e.g. Levy and Pinker 2007). The S-MDT is 28 stripped of all routines for cloud masking, pixel selection, and pixel aggregation, instead 29 operating on a pixel-by-pixel basis. Inputs are a single set of TOA spectral reflectance values, 30 plus sun-satellite geometry and geo-location. Outputs are the retrieved AOD, and most of the 31 diagnostics contained in the standard output. Since the standard C6 data (e.g. the 10 km 32





retrievals) include the TOA spectral reflectance used for each retrieved AOD value, the data provided in the C6 output file (e.g. MxD04\_L2) can be recycled through the S-MDT algorithm to retrieve the same AOD value as provided within the C6 product. Thus, the S-MDT can be easily modified to test different assumptions within the retrieval, including surface reflectance assumptions. The insights gleaned from the S-MDT exercises, can then be transferred back to modify the full (operational) retrieval code, and tests (and statistics) can be performed for global data.

8

## 9 2.1 MDT Surface Characterization and Urban Aerosol Retrievals

The land surface is too variable to apply an explicit model to describe its spectral optical 10 properties. Thus MDT uses an empirical parameterization based on only three MODIS bands. 11 Kaufman et al., (1997a, 2002) noted that for most vegetated and dark-soiled land surfaces, 12 observations showed that surface reflectance in a blue wavelength (0.47  $\mu$ m) and red 13 wavelength (0.65  $\mu$ m) were about <sup>1</sup>/<sub>4</sub> and <sup>1</sup>/<sub>2</sub> of the surface reflectance in a shortwave infrared 14 (SWIR - 2.1 µm) wavelength band, respectively. With such a SWIR to Visible (SWIR-VIS) 15 surface relationship theoretically existing on a global scale (e.g. Kaufman et al., 2002), one 16 can construct three equations and three unknowns using the satellite-measured reflectance at 17 18 the three wavelengths to separate the surface and aerosol contributions (Levy et al., 2007b).

The current operational version (C6) of the MDT algorithm is still based on the SWIR-VIS surface relationships, but also adjusts the relationship for vegetation amount and geometry as determined by a variant of the Normalized Difference Vegetation Index based on shortwave infrared bands (NDVI<sub>SWIR</sub>) and the Scattering Angle (SCA) of the solar/surface/satellite observing geometry. The NDVI<sub>SWIR</sub> is defined as,

$$NDVI_{SWIR} = \frac{(\rho_{1.24}^m - \rho_{2.12}^m)}{(\rho_{1.24}^m + \rho_{2.12}^m)}$$
(1)

Where  $\rho_{1.24}^{m}$  and  $\rho_{2.12}^{m}$  are the measured reflectances by MODIS at wavelengths 1.24 µm and 25 2.12 µm, respectively. NDVI<sub>SWIR</sub> is less affected by aerosols in the atmosphere than 26 traditional the NDVI based on red and near-IR channel (Levy et al., 2007b).

Although the SWIR-VIS assumption characterizes "dark" surfaces on a global scale, it fails to
 account for all surface types, especially for anthropogenic modifications to natural land





surfaces. As a land surface transitions from natural vegetation to manmade structures such as 1 buildings and roads, the global SWIR-VIS relationship is violated. This was noted in Levy et 2 al., (2007b, 2009). In addition, Castanho et al., 2007 analyzed the SWIR-VIS relationship 3 over Mexico City and found that the ratios of SWIR-red are much higher (0.73-0.76) than 4 what is assumed in the MDT global algorithm (0.50 - 0.55). They also found that the SWIR-5 VIS relationship strongly depends on differences in urbanization fraction. Using the global 6 values for surface ratio when the actual ratio is much higher will underestimate the visible 7 surface reflectance and the resulting aerosol contribution will be overestimated. Munchak et 8 al., (2013) used the dense AERONET Distributed Regional Aerosol Gridded Observation 9 10 Networks (DRAGON) (Holben et al., 2010) that operated in Washington DC - Maryland during 2011 to identify the urban high bias and link that bias to the urban percentage (UP) 11 around each AERONET site. While, there have been attempts to improve the MDT aerosol 12 retrieval on the local or even regional scale, no attempt has been made to date to develop a 13 14 general improved surface reflectance parameterization that can be applied to the global retrieval. In this study, we develop a new SWIR-VIS scheme that accounts for  $NDVI_{SWIR}$  and 15 16 scattering angle, but also accounts for the UP.

17

#### 18 3 Data and Study Region

We explore whether MDT surface parameterization can be modified to account for urban surface properties. We start with the research S-MDT version (Levy and Pinker, 2007; and <u>http://darktarget.gsfc.nasa.gov</u>), and develop a replacement SWIR-VIS parameterization that includes dependence on UP. To develop the replacement SWIR-VIS parameterization, we rely on two datasets. These are the MODIS Land Cover Type, and the MODIS Land Surface Reflectance Product. The MDT algorithm with the replacement SWIR-VIS parameterization, we denote as the C6-Urban, or C6U version.

To test the C6U retrieval, we compare the retrieved AOD with the sunphotometer measurements taken at standard AERONET sites, as well as AERONET's DRAGONs during the Maryland deployment of the 'Deriving Information on Surface conditions from Column and Vertically Resolved Observations Relevant to Air Quality' (i.e. DISCOVER-AQ) (Holben et al., 2010) experiment.





## 1 3.1 **AERONET**

The Aerosol Robotic Network (AERONET) is NASA's global ground network of sunphotometers that make measurement of direct transmitted solar light during daylight hours (Holben et al., 1998), and from that measurement derive spectral AOD. There are currently about 300 sites around the globe with more than one year of regular observations; in addition, there are dense DRAGON networks, while more limited in time, make dense measurements over urban/suburban areas. DRAGON networks have tended to be deployed in support of large field experiments, including DISCOVER-AQ.

The spectral measurements from the sun-photometers are used to derive AODs in respective 9 spectral bands. The typical frequency of measurements is every 15-minute and the spectral 10 bands are generally centered at 340, 380, 440, 500, 675, 870, and 1020 nm. Here we use the 11 Angstrom coefficient to interpolate AERONET AOD to 0.55 µm. AERONET data products 12 are available as unscreened (level 1.0), cloud screened (level 1.5) and cloud screened and 13 quality assured (level 2.0). In this study, Level 2.0 AERONET AOD data are considered as 14 ground truth to validate the satellite-retrieved AOD data. The reported uncertainty in 15 AERONET AOD is of the order of 0.01-0.02 (Eck et al., 1999). There are about 135 CONUS 16 AERONET stations collocated with MODIS-Aqua for the 2003 to 2012 time period. This 17 includes 39 DRAGON sites, permanent AERONET sites, and temporary AERONET sites 18 operated for different periods between 2003-2012. Only the sites located over land are 19 considered in this study. 20

The DRAGON sites in Maryland DISCOVER-AQ deployment were operated for about six weeks from July 1 to August 15, 2011. The sites were located in the Washington DC-Baltimore metropolitan area. The network provided useful AOD measurements over urban, agricultural, coastal and mountain landscapes over the Washington DC metro area.

#### 25 3.2 MODIS Land Cover Type

The MODIS land cover type product (MCD12Q1), at 500 m resolution, has been used to identify urban surfaces in the new surface scheme. This is a yearly product, based on a trained classification algorithm that uses five different classification schemes (Freidl et al., 2010), and is derived using observations from both MODIS sensors. There are 17 land cover classes as defined by the International Geosphere-Biosphere Program (IGBP). The land cover class defined as 'urban and built-up area' has been extracted and urban percentage (UP) at 0.1x0.1





- 1 degree resolution (approximately equivalent to the 10km MODIS AOD product resolution) is
- 2 calculated. Figure 1 shows the map of UP for the CONUS region. This map of UP has been
- 3 used in the C6U algorithm to define and apply the new surface scheme for each MODIS 10km
- 4 AOD retrieval.
- 5

## 6 3.3 MODIS Land Surface Reflectance

7 The surface parameterization in the MDT algorithm was based on performing atmospheric correction of MODIS-measured reflectance near AERONET sites, which led to formulation of 8 the empirical SWIR-VIS relationships (e.g., Levy et al., 2007b; 2013). Rather than repeating 9 this exercise, we rely on the MODIS-derived land spectral surface reflectance product because 10 it is available and has been validated with similar atmospheric correction exercises. 11 Specifically, we use the MODIS 8-day, clear-sky surface reflectance product 12 (MOD09A1/MYD09A1; Vermote and Kotchenova, 2008) for the first seven bands of 13 MODIS, which are gridded at 500 m resolution. These are same bands used for the MDT 14 aerosol retrieval. 15

The MxD09A1 product is created by identifying the "clearest" observations of a scene during 16 an 8-day period, and performing generic atmospheric corrections (estimating aerosol type and 17 AOD) to obtain surface reflectance values. These pixels are selected for low view angle, the 18 absence of clouds or cloud shadow, and low aerosol loading. Pixels identified as snow/ice, 19 adjacent to cloud, fire, cirrus, inland water, or high aerosols loading are excluded. This 20 surface reflectance product is officially validated as a stage 2 product. Validation of the 21 MxD09A1 product has been performed over 150 AERONET sites (http://modis-sr.ltdri.org), 22 by using AERONET measurements (spectral AOD, water vapor) to perform a detailed 23 atmospheric correction. Within an error bar of  $\pm$  (0.005+5%), 87% pixels of red band 24 25 reflectance are within the error bar and considered to be 'good' quality (http://landval.gsfc.nasa.gov/). Validation results show that the red and SWIR bands are more 26 accurate than the blue band. For example, over the CCNY (New York City) AERONET site, 27 uncertainty numbers for red, blue, and SWIR are 0.014, 0.029, and 0.0014, respectively 28 (http://landval.gsfc.nasa.gov/). 29

30

#### 31 4 Developing the New Surface Reflectance Scheme





- 1 Requirements for a new surface reflectance scheme in the MDT algorithm include:
- 2 (1) Reduce the known bias between MDT retrievals and sunphotometer measurements in
- 3 urban areas;
- 4 (2) No degradation of retrieval quality in non-urban areas;
- 5 (3) Must be an operational way to identify when to apply the new scheme and when not;

6 (4) It must slip into the structure of the standard operational algorithm without requiring7 extensive additional modifications to the existing algorithm;

The first step to meeting these requirements is to develop surface parameterizations 8 characteristics of urban surfaces. To do this we use the MODIS land product as described in 9 Section 3. The main advantage of using this product is its spatial coverage. Most previous 10 studies have used surface reflectance only over limited AERONET sites, where atmospheric 11 correction could be applied, but which may not represents actual variability in the SWIR-VIS 12 13 relationship over larger areas. Relationships derived in this limited database can be skewed towards surface characteristics of AERONET locations. The MODIS 500 m resolution surface 14 reflectance values are quality controlled and averaged into a 0.1x0.1 degree grid, roughly 15 16 equivalent to the MDT 10 km AOD retrieval. Thus instead of point measurements of surface 17 reflectance, we now have spatial maps of surface reflectance covering the entire study region.

We expect that different cities will exhibit different surface reflectance relationships for the 18 same UP, because the natural vegetation background is different. Therefore, we employ both 19 20 UP and NDVI<sub>SWIR</sub> to define four categories of surface type. For example Brooklyn (New York), with its sidewalk plantings of deciduous trees, may look different than Los Angeles 21 22 (California), that uses palm tree plantings for its sidewalks. These four categories are separated into low vegetation and high UP (NDVI<sub>SWIR</sub> < 0.20 and UP > 50%); low vegetation 23 and low UP (NDVI<sub>SWIR</sub> < 0.20 and 20% < UP < 50%); high vegetation and relatively low UP 24  $(NDVI_{SWIR} > 0.20 \text{ and } 20\% < UP < 70\%)$ ; and high vegetation and high UP  $(NDVI_{SWIR} > 1.0\%)$ 25 0.20 and UP >70%). These bin thresholds were chosen to optimize the correlation coefficient 26 between wavelengths in each bin. We have also restricted this analysis to only over the urban 27 areas by selecting pixels with UP larger than 20% so that the retrieval over natural surfaces 28 does not contribute to the formulation of the parameterization. For UP < 20%, we use the C6 29 assumptions for surface reflectance (using NDVI<sub>SWIR</sub> only). 30





Figure 2 provides the surface reflectance spectral relationships between SWIR and VIS, 1 defined for the four different categories based on the combinations of NDVI<sub>SWIR</sub> and UP. The 2 four regression lines in the figures are calculated for each of the four categories using bins of 3 equal number of points. We still derive the regression coefficients from the cloud of points 4 (shown as gray color), but bin the data to help visualize the differences from regime to 5 regime. We note that the slopes of the regression between the blue and red wavelengths are 6 not strongly dependent on differences in the UP or the NDVI<sub>SWIR</sub>, as long as UP > 20%. 7 However, the regressions between the red and SWIR wavelengths are indeed dependent on 8 the nuances of the urban surface. The values of the regression statistics (slope and yint) for 9 each of the four categories are given in the Table 1. Here slope and intercept are calculated 10 based on the least absolute deviation method to avoid the extreme outliers. Mean of the 11 absolute deviation (AbsStd) of the results and Y (result is calculated VIS reflectance and Y is 12 13 original VIS reflectance) is also provided in Table 1. This provides a quantitative indicator of uncertainties in surface reflectance of visible bands in the new surface scheme. 14

The regression statistics provide the information needed to relate the surface reflectance ( $\rho^{s}$ ) at 0.65 µm and 0.47 µm to that at 2.12 µm. We take into account the effects of geometry by relying on the Levy et al. (2007b) parameterization for scattering angle,  $\theta$ .

18 
$$\rho_{0.65}^{s} = \rho_{2.12}^{s} * M_{\frac{0.65}{2.12}} + b_{\frac{0.65}{2.12}}$$
 (2)

$$\rho_{0.47}^{s} = \rho_{0.65}^{s} * M_{\underline{0.47}} + b_{\underline{0.47}} + b_{\underline{0.47}}$$
(3)

19 where

20 
$$M_{0.65/2.12} = slope_{0.65/2.12}^{(NDVI,UP)} + 0.002 * \theta - 0.27,$$

21 
$$b_{0.65/2.12} = yint_{0.65/2.12}^{(NDVI,UP)} - 0.00025 * \theta - 0.033,$$

22 
$$M_{0.47/0.67} = slope_{0.47/0.67}^{(NDVI,UP)}$$
, and

23 
$$b_{0.47/0.67} = yint_{0.47/0.67}^{(NDVI,UP)}$$

and *slope* and *yint* are the regression constants for particular wavelengths, NDVI<sub>SWIR</sub> and UP,
 found in Table 1.





As shown in Table 1, the new slopes of SWIR-VIS over urban areas are significantly higher than those assumed in the C6 algorithm for global application, which is consistent with other studies (i.e. Levy et al., 2007b, Castanho et al., 2007, Min et al., 2010). The red-SWIR ratios are also higher for less vegetated areas (NDVI<sub>SWIR</sub> <0.2) than those with more vegetation areas (NDVI<sub>SWIR</sub> > 0.2).

The new surface scheme is expected to provide better surface reflectance estimates over urban 6 areas than the existing operational scheme (i.e. C6). Figure 2 shows very tight relationships 7 8 between SWIR-VIS reflectances, but even the presence of the small amount of scatter in the 9 correlation can cause errors in certain conditions and seasons. Bi-Directional Reflectance Function (BRDF) effects over urban surfaces and other factors as discussed in Levy et al., 10 2007 may also introduce error. Because, surface reflectance dominates the TOA signal for 11 low aerosol conditions (AOD<0.1) more so than for high aerosol loading (AOD>0.4), relative 12 13 uncertainties in retrieving AOD are larger under clean conditions.

UP is the only new parameter added to the surface scheme. This is a globally available parameter calculated from a standard MODIS Land product, and is updated annually. The C6U algorithm inputs UP and uses this parameter to decide whether to apply the old or the new surface parameterization. Dependence on UP assures that there will be no changes to the retrieved aerosol products for non-urban surfaces (UP < 20%).

We have developed this surface scheme using data from the continental U.S., expecting the scheme to be optimized for this region. Global implementation may be challenging and we discuss these challenges in Section 6.

22

## 23 5 Evaluation of C6U retrieval

## 24 5.1 Collocation and analysis strategies

The data from MODIS Aqua from 2003-2012 over the CONUS region is processed using the C6U algorithm, and compared against C6 retrievals and AERONET measurements. MODIS C6 and C6U AODs were collocated over AERONET sites in the CONUS region, using the same spatio-temporal technique (Ichoku et al., 2002) used for MODIS validation exercises (Levy et al., 2010). In this method, AOD values from all the pixels within a 0.5x0.5 degree latitude-longitude box centered over the AERONET location are averaged. This is equivalent





to approximately a 50x50 km<sup>2</sup> area or 5x5 pixels selection criteria as suggested (Ichoku et al., 1 2002) and used by (i.e. Levy et al., 2010). To represent the same air mass for the comparison, 2 AERONET AODs were averaged over ±0.5 hour centered at the satellite overpass time over a 3 particular AERONET station. As recommended by the MODIS science team (Levy et al., 4 2010; 2013) only AOD pixels with quality flag 'very good' were included in the spatial 5 average except if otherwise mentioned. Since, we are attempting a three-way comparison 6 between C6, C6U and AERONET simultaneously, exactly the same MODIS AOD retrieval 7 squares from the two algorithms were used in the averaging during the collocation with 8 AERONET. To be consistent with previous validation exercises (Levy et al., 2010), we have 9 10 retained the collocated data sets only when there were at least 5 MODIS AOD retrievals (out of a possible 25) and 2 AERONET measurements (out of 2-4) available from the collocation. 11 The C6-C6U-AERONET collocated validation data set consists of 14402 collocations from 12 134 AERONET stations. For the evaluation and comparison purpose, the S-MDT version has 13 been used and only collocated pixels are processed. In order to analyze the validation results 14 and uncertainties, the following statistical parameters were calculated (Hver et al., 2011): 15

16 Root mean square error (RMSE) and mean bias is estimated using equation 4 & 5

17 
$$RMSE = \sqrt{\frac{1}{n}\sum (AOD_{AERO} - AOD_{MODIS})^2}$$
(4)

 $Bias = Arithmatic Mean (AOD_{MODIS} - AOD_{AERO})$ (5)

Expected error (Remer et al., 2005) for AOD retrieved over land, as given by the MODISscience team through validation exercises is presented in equation 6.

$$EE = \pm (0.05 \pm 15\%) \tag{6}$$

20 The percentage of retrievals, falling within the envelope of EE, as compared to AERONET

AODs is given by equation 7.

$$EE\% = AOD_{AERO} - |EE| \le AOD_{MODIS} \le AOD_{AERO} + |EE|$$
(7)

22 where the AOD<sub>AERO</sub> is AOD from AERONET, and AOD<sub>MODIS</sub> is the retrieved value from

MODIS (either C6 or C6U version). Note the AOD is reported at 0.55 µm, which means that
 interpolation (quadratic on log-log scale) is performed for the AERONET data.

In addition, we have computed linear regression statistics, including correlation coefficient (R), regression coefficients (slope and intercepts) and number of data points (N).





## 1 5.2 Validation: Comparison with AERONET / DRAGON

Figure 3 shows 2-dimensional density scatter plots; representing all collocations of MODIS 2 retrieved AOD and AERONET sun-photometer (SP) measured AOD over CONUS urban 3 sites. Here, only retrievals where UP > 20% and the retrieval quality assurance flag indicates 4 'very good quality' (QAF =3; Levy et al., 2014) are shown. Figure 3 (left panel) represents 5 the MODIS C6 retrieval whereas Figure 3 (right panel) shows the same collocations, but for 6 C6U retrievals. Figure 3 (left panel) clearly shows positive bias (0.07) in C6 retrieved AODs 7 8 as compared to SP AODs. The bias is significantly reduced (to -0.01) when the C6U retrieval 9 is applied (right panel).

As discussed in section 4, aerosol retrieval from passive satellite measurements is sensitive to 10 11 underlying surface reflectance, and the relative uncertainty becomes greater for lower AOD conditions, when the surface reflectance dominates the signal. By improving the overall 12 urban surface reflectance parameterization, the bias is reduced. However, the small negative 13 bias indicates that there is still uncertainty in estimating visible reflectance. We note that most 14 of the negative AODs from the C6U retrieval are correctly identifying low values of AODs 15 (<0.1), such that a retrieval of "clean" conditions is correct. The other source of uncertainty in 16 AOD retrievals comes from selection of proper aerosol model, but this effect should be 17 minimal at such low optical depths. The number of retrievals within pre defined expected 18 19 error envelope (EE%) has also increased from 63 % for C6 to 85% for the C6U retrievals. 20 Most of the statistical parameters in comparing MODIS and SP AODs demonstrate improvement in C6U AODs as compared to C6 retrievals. 21

Previous validation and inter-comparison studies (Munchak et al., 2013) have pointed out the 22 positive correlation of C6 AOD biases with respect to urban land cover amount. The C6U 23 surface characterization accounts for change in urban area within each MODIS AOD pixel, 24 such that the positive correlation should be reduced in our dataset. We would expect that for 25 UP > 20% the bias should be flat with respect to UP if the new parameterization is doing its 26 27 job. Figure 4 shows bias in MODIS AOD (MODIS-AERONET) as a function of change in the UP. Again side-by-side comparisons for C6 in Fig 4a and C6U in the Fig4b are presented. 28 Here, we have considered all AOD pixels irrespective of urban percentage, which is different 29 from the source of Figure 3, which limited to cases having UP larger than 20%. Here the 30 31 objective is to evaluate the impact of new surface scheme on quality of the MDT retrieved AODs as a whole, beyond urban areas. We recall that the new surface scheme is applied only 32





on selective pixels (UP>20%), which consist of only about 3% of the total retrieved AODs in
the CONUS region. Red dots show the equal number of points bin averaged value with one
standard deviation in AOD error as vertical blue line. The biases in C6 AODs linearly
increase as land cover becomes more urbanized (larger UP), whereas biases in C6U AODs do
not show significant dependence on UP. This analysis indicates that the C6U surface
parameterization successfully removes AOD biases over cities, and should be applied to MDT
aerosol retrievals over the CONUS region.

8 The MODIS AOD data presented in Figures 3 and 4 represent collocations for where the 9 quality assurance flag identifies the retrieval as "science-quality" (QAF=3, 'very good'; Levy 10 et al., 2013). For some applications, including identifying large aerosol "events", there is 11 interest in analyzing retrievals with lower, but non-zero values of confidence flags (QAF>0).

In order to analyze and validate MODIS AODs with lower quality flags, we have grouped the data into several different ways to represent different retrieval conditions. Table 2 presents the statistical analysis of the two retrievals (C6 & C6U), for three categories of underlying surface type (i.e. UP). These are

- 16 1) ALL: all retrievals irrespective of UP
- 17 2) UP>0.0%: retrievals that have some urban fraction
- 18 3) UP>20%: retrievals with UP larger than 20%

For the third category (UP>20%) this includes only retrievals where C6U retrieval would be applied and different from C6, while the  $2^{nd}$  category includes retrievals that may be suburbs or small towns, and the  $1^{st}$  category (ALL) includes everything.

Each surface category in Table 2 is further broken down by QAF level. Note that the case of ALL and QAF=3 represents the data in Fig. 4, which are the MDT recommendations of "science quality" data. The correlation for C6U (R=0.86) is marginally higher than for C6 (R=0.85), but the bias is reduced to 0.006 from 0.022. The number of retrievals within expected error (EE%) increased by 4%. For the UP>20% cases (e.g. data shown in Fig. 3), there is a huge reduction in bias (from 0.075 to -0.007), and the EE% increases from 58.6% to 85.3%.

For the C6 data, there is a clear reduction in regression quality (decreased correlation, increased bias, %EE reduction) as QAF criteria are relaxed from 3 to 2 to 1. This is true for





the set of ALL retrievals, but especially when the retrieval is performed over even a small 1 fraction of urban surface type (UP>0). For C6U, the immediate effect is to cut bias to a 2 negligible value for QAF=3 for all categories including ALL. As QAF criteria are relaxed, 3 bias jumps up, correlation and %EE decrease, but not as drastically as for the C6 retrievals. In 4 fact, the statistics, including bias, for the QAF = 2 or 3 criteria are not much different than the 5 statistics for the current C6 retrievals for QAF=3 only. However, there is improved sampling 6 (50% more collocations with AERONET). If the currently recommended C6 retrieval at 7 QAF=3 is adequate, then it may make sense to recommend QAF= 2 and 3 for the C6U 8 algorithm and increase the number of available retrievals by 30%, 50% and 84% for ALL, 9 10 UP>0 and UP>20% categories, respectively.

The improved statistics for AOD retrievals with lower quality flags is encouraging and suggests opportunity for overall increase in high quality sampling with the MDT algorithm. This will definitely help characterize aerosol for air quality applications in densely populated areas. However, further research and dedicated evaluations of quality flag assignment criteria in the algorithm required before we suggest making use of lower quality data even in the C6U retrievals.

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#### 18 5.3 Evaluation over Selected Cities

The main reason of the development of the C6U retrieval algorithm is to reduce the biases in 19 AOD retrievals over cities where a large portion of the human populations lives. In this 20 section, we evaluate both C6 & C6U retrievals over selected cities where an AERONET 21 station is available. Figure 5 shows how C6 (red dots) and C6U (blue dots) compare with 22 23 AERONET AODs over eight selected AERONET stations covering various parts of the CONUS & Canada. Only MODIS AOD retrievals with QAF=3 are considered for this 24 25 analysis. These selected AERONET stations are marked (circles) in Figure 1. Table 3 provides statistical parameters corresponding to the scatter plots presented in Figure 5. All 26 AERONET stations show positive bias in C6 AOD, which, except for Fresno, is corrected in 27 the C6U retrievals. Over Fresno, the two retrievals have similar bias, which was near zero to 28 begin with. Both retrievals have high correlations (>0.9) with AERONET over all stations 29 except the Western US stations. 30





The lowest correlation is observed over CalTech with values of 0.42 & 0.58 for C6 and C6U, 1 respectively likely because of the complex terrain within the 0.5x0.5 degree box surrounding 2 the Caltech AERONET station. The CalTech AERONET site is located at the entrance of the 3 San Gabriel Valley, up against some very high mountains. There is a high possibility of 4 having pieces of the mountains, the San Gabriel Valley, the San Fernando Valley and the Los 5 Angeles coastal plain within that 0.5x0.5 degree box. Under these complex mix of terrain, it is 6 likely that AERONET and MODIS often sample different air masses and thus comparisons 7 can have large scatter. The largest improvement in EE%, Bias and RMSE is observed over the 8 New York City (CCNY) AERONET station. The number of retrievals within the uncertainty 9 10 window (EE%) at CCNY almost doubled from 46% in C6 to 83% in C6U, and the bias is reduced to zero from 0.09. The C6U results over CCNY observed a slight negative offset of -11 0.03 mainly due to a negative bias in low aerosol loading conditions (AOD<0.1). In general 12 the slope is larger than one for eastern US sites whereas it less than one for western US sites. 13

In Figure 6 we have evaluated the spatial distribution of AOD over the region covering two 14 large urban cities, Baltimore and Washington DC. The map shows averaged AODs for the 15 period of March-May, 2011. We would expect these AOD maps to represent the seasonal 16 aerosol distribution over the region, but due to limited sampling over certain parts of the 17 region, the seasonal distribution is skewed. Figure 6e, presents the number of averaging days 18 19 (or number of retrievals) for each grid box, and it is apparent that some grids near city centers, 20 have very limited sampling (1-3) days. Coincidently, these available days correspond to high aerosol loading days, creating an illusion of high seasonal mean aerosol loading in the city 21 centers. Similar high AODs with low sampling can also be seen along the shore of the 22 23 Chesapeake Bay on the map. The low number of retrievals in these squares is caused by a 24 combination of cloud/snow/ice during the period and the known issue of the algorithm choosing not to retrieve over very bright urban surfaces under low aerosol loading and at 25 certain Sun-satellite geometry. The new C6U algorithm will continue to be affected by this 26 limited sampling over highly urban surfaces, because the choice to retrieve or not retrieve 27 occurs during the algorithm's pixel selection process. Pixel selection occurs upstream of the 28 processes that are the focus of this paper, the parameterization the surface reflectance 29 relationships. Because, the purpose of the analysis is not to discuss seasonal variability but 30 more to emphasis that C6U retrievals are able to provide a more realistic (without bias) AOD 31 32 spatial distribution as compared to C6 retrievals where surface signal is enhancing urban AODs. Both Baltimore and Washington DC observed elevated AODs as compared with the 33





surrounding suburban and rural areas on the map in the C6 retrievals (Fig 6a). As noted in 1 Figure 5, MODIS C6 AODs are biased high over AERONET sites (GSFC and 2 MD\_Science\_Center) in the area. This suggests that those very high AOD values close to the 3 city center could be elevated due to the surface contamination in the aerosol signal. Indeed 4 application of C6U reduces the AOD in those cities by 0.08-0.12, leaving only a modest 5 elevated AOD there. The residual elevation in "seasonal" AOD could be an artifact of the 6 uneven sampling, or it could represent real elevation of aerosol from urban sources. We note 7 that in DISCOVER-AQ, multiple instruments on multiple platforms did find elevated 8 pollution and particles in the Baltimore-Washington corridor (Munchak et al., 2013). The 9 10 C6U AOD retrievals can be very helpful in studying these small scales features over large urban centers and their connection with urban pollution and population. Figure 5c shows the 11 difference between C6 and C6U AODs, which is correlated with UP (Fig 5d) and could be as 12 high as 0.12. 13

14

### 15 5.4 Regional Analysis over the DRAGON Network

Figures 7(a-h) show the evaluation statistics of the two algorithms over a dense network of 16 AERONET instruments in the Baltimore-Washington DC metro area (BALDCM) during 17 summer 2011. The DRAGON is a mesoscale network of sun/sky radiometers that 18 encompasses, urban, suburban, agricultural and hilly landscapes over the Washington DC 19 metro area. There were about 39 AERONET DRAGON stations operating during this 20 deployment. This dense SP network provides an excellent aerosol measurements data set 21 covering different types of landscapes. This AERONET DRAGON deployment also provides 22 an excellent opportunity to evaluate the high AOD values near the cities as observed in Figure 23 6. The data have been utilized to validate satellite aerosol retrievals and spatial variability in 24 the aerosol fields (Munchak et al., 2013). Munchak et al. (2013) reported that the MODIS C6 25 AOD retrievals were positively biased against AERONET values in (and near) urban areas 26 with a high degree of correlation with UP. We now revisit the Munchak et al., (2013) data sets 27 to verify whether the new C6U retrievals alleviate the issues noted by the previous study. 28

Figure 7 (a,c,e,g, i.e. left panels) and Figure 7(b,d,f,h, i.e right panels) represent comparisons
between MODIS C6 & C6U AOD validation statistics, respectively. The two scatter plots
show MODIS-retrieved AOD plotted against AERONET measurements. Each point is color-





coded with the UP estimated for each DRAGON site using the MODIS land cover type 1 information. The C6 AODs show (Fig 7a) positive biases specifically for AOD values larger 2 than 0.15, which results in an overall positive bias of 0.04 with very high correlation (R) of 3 0.95 suggesting consistent bias in AOD in the C6 retrieval. These statistics are very similar to 4 the Munchak et al., 2013 results where data from both Terra and Aqua MODIS were 5 analyzed. Here only data from MODIS Aqua are included. The UP color-coding hints that 6 most of the positively biased AOD pixels are located in a highly urbanized (UP >60%) area. 7 The two scatter plots (Fig a & e) very clearly show the improvement in AOD comparisons 8 against AERONET when the C6U algorithm is applied. The mean bias between MODIS and 9 10 AERONET is reduced to almost zero, and EE% has gone up to 93%. This implies that the RMSE and slope have also improved in the C6U retrievals, as compared with the C6 11 retrievals, but the offset (I) in C6U is now slightly negative (-0.02), which was zero in the C6 12 retrievals. A closer look at the scatter plot reveals that C6U has introduced some negative bias 13 14 at very low AOD cases (AOD<0.15), which is consistent with previous analysis over the CONUS region. Again, in order to remove these negative biases; more accurate estimation of 15 16 surface parameters is required. The remaining Figures show correlation, bias and EE% for the two algorithms over individual DRAGON sites. The outer color-coded circle in Fig. 7c 17 represents UP over each DRAGON site. The color-coding is done according to the scale 18 19 shown in the Fig 7a. In almost all statistical parameters, C6U outperformed C6 algorithm over each station. 20

21

#### 22 6 Global Implications and Challenges

The new surface scheme presented here is designed to work only over the Continental United 23 States (and perhaps other regions with similar surface properties). Implementing the new 24 scheme into the global algorithm may be challenging. In the CONUS we had a wealth of data 25 to work with: 135 AERONET stations with several in highly urban locations and a well-26 27 analyzed DRAGON network to evaluate the small-scale variability in the aerosol fields. We were able to parameterize the surface reflectance relationships by dividing the surfaces into 28 only four categories depending on UP and NDVI<sub>SWIR</sub>. The presence and varying amount (and 29 type) of vegetation in the urban areas and the different materials used in construction of 30 31 buildings and roads in other parts of the world will make accurate surface parameterization a more complex problem. However, because the results over CONUS have been so 32





encouraging, we decided to run the CONUS-derived C6U algorithm globally and to compare 1 the results with AERONET measurements. Figure 8 presents the difference between C6U 2 AOD with AERONET AOD as a function of UP over the entire global data set, excluding 3 AERONET stations from the CONUS region. The CONUS region has been excluded in order 4 to avoid weighting the results by the formulation data set. The results are surprisingly good. 5 The CONUS-derived C6U has reduced the positive bias over urban surfaces to nearly zero, 6 globally. This analysis is very encouraging, but more in depth analysis for specific 7 stations/regions will be required to better understand the new algorithm before applying it 8 operationally at global scale. 9

10

#### 11 7 Summary & Conclusions

The MODIS Dark Target aerosol retrieval algorithm, shaped by continuing research and 12 influenced by application needs, has been operating successfully for 15 years. The MODIS 13 C6U algorithm presented here reflects the MODIS science team's commitment to keeping the 14 algorithm updated and relevant. In this spirit, we address the AOD biases in the current 15 operational product related to improper surface parameterization over urban areas. We 16 develop a revised surface parameterization scheme over urban regions using the MODIS land 17 18 surface reflectance and land cover type products. The new parameterization parallels the current Collection 6 surface scheme, where visible surface reflectances are estimated for each 19 pixel using the value of the SWIR surface reflectances at that pixel, modified by NDVI<sub>SWIR</sub> 20 and scattering angle. The new scheme introduces one additional parameter, the percentage of 21 urban land type cover (UP) for each retrieval box. The new surface scheme is only applied for 22 MODIS retrieval boxes with UP larger than 20%. All other MODIS retrievals have been 23 treated exactly same as in the C6 algorithm. Initially, the surface parameterization has been 24 developed and implemented only for the Continental United States. 25

MODIS Aqua data sets from 2003 to 2012 over all AERONET stations in the US including a dense DRAGON network deployed during the DISCOVER-AQ field campaign in the Baltimore-Washington DC metro area have been utilized to evaluate the revised AOD retrievals. The side-by-side comparison of C6 and C6U retrieval against AERONET measurements provided quantitative estimates of improvements in the MODIS AOD retrievals. Over urban areas where the C6U retrieval has been applied (UP>20%), we find an





increase of more than 20% in the number of retrievals falling within the expected error 1 (EE%). The strong positive correlation between bias in AOD and amount of urban surface 2 near the AERONET site that was observed in C6 is gone in C6U. The C6U retrieval does 3 introduce a small negative bias in the retrieved AOD for AOD values less than 0.1, due to 4 ultra sensitivity of the AOD retrieval to the surface parameterization under low atmospheric 5 aerosol loadings. In general, the MODIS science team recommends using AOD data with the 6 best quality flag (QAF=3) for any over land quantitative purpose. But depending on 7 application and for qualitative purposes, lower quality flags (QA=1 & 2) can also be useful. 8 When we explored the effect of including C6U retrievals of lower quality we found a 9 10 significant reduction of error for lower quality AOD retrievals. On several occasions, C6U AOD with lower quality flags were of essentially the same accuracy of those C6 retrievals 11 with best quality flags. Relaxing the criteria could increase the number of useable retrievals 12 from 30 to 80%. It is too soon to change the recommendation and relax the QAF criteria for 13 14 quantitative purposes, but this analysis definitely gives sufficient motivation to revisit the quality flag assignment scheme in the MODIS DT algorithm if the C6U algorithm is 15 16 implemented operationally.

While the formulation of the C6U algorithm is based on surface characterization of stations in 17 the continental U.S., we tested the new algorithm on the global data set and compared with 18 19 AERONET AOD. Even when excluding the CONUS AERONET stations to avoid the 20 mistake of validating the formulation data set, the results show the elimination of AOD bias as a function of urban percentage. These are unexpected, but encouraging results that suggest 21 that the parameterization developed from the CONUS data may be implemented soon into the 22 23 global operational algorithm for a significant improvement over urban centers worldwide. 24 Additional testing will be necessary first.

As populations flock to urban centers causing the urban landscape around the world to grow 25 continuously, it becomes obvious that these regions can no longer be treated with second class 26 status by the MODIS Dark Target aerosol algorithm. It is crucial to have accurate retrievals 27 of AOD over the urban landscape, which translate into more accurate estimates of particulate 28 matter concentrations for air quality purposes over the regions where most people live. The 29 revised C6U algorithm improves the quality of MODIS AOD retrievals over urban regions, 30 which will be extremely useful for air quality applications. We expect that this improvement 31 32 will open up new opportunities for the research community to apply the MODIS Dark Target





- 1 AOD data to address other pressing issues such as urban scale spatial variability, gradients
- 2 between rural and urban areas, more accurate long-term trends and air quality-health links.
- 3

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- 1 Table 1. Regression coefficients for the new surface scheme introduced in C6U MDT
- 2 algorithm.

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	NDVI <sub>SWIR</sub> < 0.2	NDVI <sub>SWIR</sub> < 0.2	NDVI <sub>SWIR</sub> >0.2	NDVI <sub>SWIR</sub> >0.2
	& UP >50%	& 20% <up td="" ≤<=""><td>&amp; 20%<up< td=""><td>&amp; UP &gt;70%</td></up<></td></up>	& 20% <up< td=""><td>&amp; UP &gt;70%</td></up<>	& UP >70%
		50%	≤70%	
<i>slope</i> <sub>0.65/2.12</sub>	0.66	0.78	0.62	0.65
<i>yint</i> <sub>0.65/2.12</sub>	0.02	-0.02	0.00	0.00
<i>slope</i> <sub>0.47/0.65</sub>	0.52	0.51	0.47	0.48
<i>yint</i> <sub>0.47/0.65</sub>	0.00	0.00	0.01	0.01
R <sub>0.65/2.12</sub>	0.91	0.92	0.91	0.86
AbsStd <sub>0.65/2.12</sub>	0.013	0.013	0.008	0.008
R <sub>0.47/0.65</sub>	0.96	0.95	0.88	0.81
AbsStd <sub>0.47/0.65</sub>	0.003	0.003	0.004	0.006





Table 2. Statistics of MODIS and AERONET inter-comparisons using collocated data sets.
Comparisons are performed for different quality flags. Three different MODIS pixel selection
scheme based surface type are used, All: all MODIS pixels per considered irrespective of
underlying surface type, Urban % >0.0: MODIS pixels with urban surface were selected,
Urban % >20: MODIS pixels with urban percentage larger than 20% selected in collocation.
Statistical parameters, number of data points (N) linear correlation coefficient (R), mean bias
(Bias), and EE% are reported in this table.

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			R	R		Bias		EE%	
Data Set	QAF	Ν	C6	U6	C6	U6	C6	U6	
All	1	723	0.67	0.74	0.114	0.072	38.8	52.6	
	1, 2	6415	0.73	0.78	0.106	0.067	41.9	56.4	
	1, 2, 3	21842	0.80	0.83	0.051	0.029	65.0	72.5	
	2, 3	18995	0.81	0.84	0.041	0.020	69.1	76.0	
	3	14402	0.85	0.86	0.022	0.006	77.1	81.1	
Urban % >0.0	1	295	0.63	0.74	0.171	0.084	27.3	55.0	
	1, 2	3269	0.68	0.77	0.141	0.070	31.3	57.5	
	1, 2, 3	11258	0.78	0.84	0.071	0.028	59.1	74.6	
	2, 3	9455	0.79	0.85	0.062	0.020	63.8	78.1	
	3	6300	0.88	0.90	0.036	0.002	75.2	85.2	
Urban % >20.0	1	109	0.50	0.59	0.259	0.105	15.5	49.5	
	1, 2	1406	0.65	0.73	0.205	0.083	16.6	52.0	
	1, 2, 3	4301	0.75	0.83	0.128	0.032	37.4	73.2	
	2, 3	3451	0.78	0.85	0.115	0.021	42.2	76.8	
	3	1875	0.90	0.93	0.075	-0.007	58.6	85.3	





- 1 Table 3. Statistics of MODIS and AERONET inter-comparisons over selected urban sites
- 2 (Figure 5). Statistical parameters are number of coincident points (N), Linear Correlation
- 3 coefficient (R), Percentage of retrievals with uncertainty envelope (EE%), Root mean square
- 4 error (RMSE), Mean bias (Bias), Slope, and intercepts are reported in this table.

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AERONET Station	Version	Ν	R	EE%	RMSE	Bias	Slope	Intercept
Toronto	C6	222	0.92	78.83	0.08	0.04	1.28	-0.01
	C6U	222	0.94	89.64	0.06	0.01	1.20	-0.02
CCNY	C6	173	0.94	46.24	0.12	0.09	1.21	0.05
	C6U	173	0.95	83.24	0.07	0.00	1.15	-0.03
MD_Science_Center	C6	354	0.95	85.88	0.06	0.02	1.26	-0.01
	C6U	354	0.95	88.70	0.05	-0.02	1.18	-0.04
GSFC	C6	650	0.96	83.23	0.06	0.03	1.30	-0.01
	C6U	650	0.96	92.46	0.05	-0.01	1.18	-0.03
BSRN_BAO_Boulder	rC6	571	0.91	66.90	0.08	0.05	1.29	0.02
	C6U	571	0.92	83.01	0.06	0.03	1.25	0.00
Univ_of_Houston	C6	119	0.93	83.19	0.05	0.03	1.29	0.00
	C6U	119	0.93	94.96	0.03	-0.01	1.05	-0.02
CalTech	C6	165	0.42	51.52	0.13	0.06	0.76	0.08
	C6U	165	0.58	69.70	0.08	0.00	0.84	0.02
Fresno	C6	910	0.81	87.80	0.05	0.00	0.94	0.01
	C6U	910	0.81	88.24	0.05	-0.01	0.94	0.00







Figure 1. The urban percentage map for the continental United States derived from MODIS 3 land cover type product (MCD12Q1) at 0.1x0.1 degree resolution to be used in the new 4 surface characterization scheme inside the MODIS DT AOD retrieval algorithm. The circles 5 show individual AERONET stations for which results are presented in Figure 5 and table 3. 6 Dotted lines on the map show major highways. 7









2 Figure 2. The 0.65 µm versus 2.12 µm surface reflectance (top panel) and the 0.47 µm versus 0.65 µm surface reflectance (bottom) for four different combinations of NDVI<sub>SWIR</sub> and UP 3 values. Each combination of NDVISWIR and UP values are color coded and plotted as different 4 symbol. The standard regression using least absolute deviation method applied and resulted 5 regression lines are plotted. The regression parameters are presented in table 1 as linear 6 correlation coefficient (R) is presented in the figure corresponding each bin of NDVI<sub>SWIR</sub> and 7 UP. These four regression lines represent the new surface scheme for revised urban aerosol 8 9 retrieval in the MDT.







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Figure 3. The frequency scatter plot for AOD at 0.55 µm over AERONET locations in the CONUS region. This comparison between MODIS and AERONET consider only MODIS AODs pixels with UP larger than 20% with QAF=3. The side-by-side scatter plots of C6 (left) and C6U (right) AOD retrievals with AERONET are shown to analysis the impact of new surface scheme on the retrieved AOD values. The 1-to-1 lines and EE% envelopes are plotted as solid and dashed lines. The statistics of MODIS-AERONET comparisons are presented in top left corner of each scatter plot.







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Figure 4. Binned bias in MODIS AODs compared to AERONET AODs as a function of UP 3 4 using all collocated data sets with QAF=3. MODIS C6 retrieval on left and MODIS C6U retrievals on the right. Each bin represents 100 points and the error bars are ±1 standard 5 deviation in both directions. There are total 14402 MODIS-AERONET collocated points are 6 7 compared in the plot. C6 AODs shows increased in bias over urbanized land surfaces whereas C6U able to correct the bias over the CONUS region for QAF=3 data points. 8

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Figure 5. Inter-comparison of MODIS AODs at 0.55 µm with AERONET AODs over selected AERONET stations located in major cities in the US and Canada (see Fig 1). Each panel represents individual station, the red dots are AODs retrieved with C6 MDT and blue dots are AODs from C6U MDT algorithm. The 1-to-1 lines and EE% envelopes are plotted as solid black and dashed lines. The two regression lines for C6 and C6U comparisons are also plotted as solid red and blue lines respectively. These AERONET stations are selected to demonstrate the performance of C6U over varying surface and aerosol types.







Figure 6. Seasonal (March-April-May, 2011) maps of MODIS AOD at 0.55 µm as retrieved by C6 (a), C6U (b), C6-C6U (c) and urban % (d) covering Washington DC and Baltimore urban corridor (e) Number of AOD retrieval over the season. MODIS AODs with QAF=3 for three months have been averaged over 0.1x0.1 degree grids to generate these maps. C6U MDT retrieved AODs are lower over large cities as compared to C6 AODs, and the improvements are well correlated with UP.









Figure 7. Inter-comparison statistics of MODIS-AERONET AODs over DRAGON network 2 during DISCOVER-AQ field campaign (Jun-July 2011) in the Washington DC - Baltimore 3 area. This analysis used data from AERONET stations operated as part of DRAGON network. 4 5 Scatter plot between AERONET and MODIS for C6 (a), C6U (b), and each collocated point is color coded with UP corresponding to AERONET site. Other statistical parameter for each 6 7 AERONET stations are mapped in following order: c) Linear correlation coefficient (R) for 8 C6 and UP, d) R for C6U, e) mean bias in C6 AODs, f) mean bias in C6U AODs, g) EE% 9 from C6, and h) EE% from C6U.







4 Figure 8. Binned bias in MODIS AODs compared to AERONET AODs as a function of UP 5 using all collocated data sets with QAF=3. This analysis used data from global (excluding CONUS region) AERONET network for the period of January 2003- June 2013. MODIS C6 6 7 retrieval on left and MODIS C6U retrievals on the right. Each bin represents 100 points and the error bars are ±1 standard deviation in both directions. There are total 50948 MODIS-8 9 AERONET collocated points from 302 stations compared in this plot. C6 AODs shows increased in bias over urbanized land surfaces whereas C6U able to correct the bias over the 10 11 region for QAF=3 data points.