# Development of Finer Spatial Resolution Optical Properties from MODIS

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## ABSTRACT

Typical MODIS ocean color products are at 1 kilometer (km) spatial resolution, although two 250 meter (m) and five 500 m bands are also available on the sensor. We couple these higher resolution bands with the 1km bands to produce pseudo-250m resolution MODIS bio-optical properties. Finer resolution bio-optical products from space significantly improve our capability for monitoring coastal ocean and estuarine processes. Additionally, increased resolution is required for validation of ocean color products in coastal regions due to the shorter spatial scales of coastal processes and greater variability compared to open-ocean regions. Using the 250m bands coupled with the 1km and 500m bands (which are bi-linearly interpolated to 250m resolution), we estimate remote sensing reflectances (Rrs) at 250m resolution following atmospheric correction. The aerosol correction makes use of the 1km near infrared (NIR) bands at 748 nanometers (nm) and 869 nm to determine aerosol type and concentration. The water leaving radiances in the NIR bands are modeled from retrieved water leaving radiances in the visible bands using the short wave infrared (SWIR) channels at 1240 nm and 2130 nm. The increased resolution spectral Rrs channels are input into bio-optical algorithms (Quasi-Analytical Algorithm (QAA), Water Mass Classification, OC2, etc.) that have traditionally used the 1 km reflectances resulting in finer resolution products. Finer resolution bio-optical properties are demonstrated in bays, estuaries, and coastal regions providing new capabilities for MODIS applications in coastal areas. The finer resolution products of total absorption (at), phytoplankton absorption (aph), Color-Dissolved Organic Matter (CDOM) absorption (ag) and backscattering (bb) are compared with the 1km products and *in situ* observations. We demonstrate that finer resolution is required for validation of coastal products in order to improve match ups of *in situ* data with the high spatial variability of satellite properties in coastal regions.

## INTRODUCTION

Ocean processes occurring in coastal regions require finer resolution satellite imagery for monitoring the ecology of our coastal waters. Bays and estuaries represent a dynamic environment as a result of changing tides, local winds and discharge of local rivers. These processes occur at time and space scales that are different than open ocean processes. Traditional ocean color monitoring that has been used to characterize the bio-geo-chemical properties of the global ocean is now being used for monitoring coastal processes. However, there are difficulties in resolving these coastal processes using 1 km satellite products. Improvements in the atmospheric correction process and increased ocean color signatures are required to help resolve these processes. Planned satellites at increased spatial and temporal scales have been discussed to resolve these processes, such as the Hyperspectral Environmental Suite on GOES-R which was planned for

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**14. ABSTRACT**

Typical MODIS ocean color products are at 1kilometer spatial resolution, although two 250 meter and five 500m bands are also available on the sensor. We couple these higher resolution bands with the 1 km bands to produce preudo-250m resolution MODIS bio-optical properties. Finer resolution bio-optical products from space significantly improve our capability for monitoring coastal ocean and estuarine processes. Additionally, increased resolution is required for validation of ocean color products in coastal regions due to the shorter spatial scales of coastal processes and greater variability compared to open-ocean regions. Using the 250m bands coupled with the 1km and 500m bands (which are bi-linearly interpolated to 250m resolution), we estimate remote sensing reflectances (Rrs) at 250m resolution following atmospheric correction. The aerosol correction makes use of the 1km near infrared..

**15. SUBJECT TERMS**

NIR, remote sensing reflectances, SWIR, optical properties

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300m resolution with high temporal coverage (every 2 hours). However, these sensors are not available at this time, and our objective is to demonstrate the advantages of finer scale coastal monitoring using the existing MODIS satellites.

As a result of the finer scale processes that occur in the coastal zone, the validation of satellite products as well as defining their uncertainty is more difficult. The spatial variability of the bio-optical products is significantly greater than what occurs in open ocean areas. Improving the resolution of the satellite products in coastal areas should reduce the uncertainty.

Ocean color products require accurate atmospheric correction estimates of aerosol concentrations which are extremely difficult in turbid/coastal waters. Within the past two years, improved methods of atmospheric correction for turbid coastal environments have been developed[1,2,14]. The Ocean Biology Processing Group (OBPG) at NASA's Goddard Space Flight Center (GSFC) has added the capability to produce the entire suite of MODIS Ocean, NIR, and SWIR channels at enhanced/higher resolution from MSL12 [2,3]. This capability permits use of these higher resolution channels to apply new atmospheric correction techniques and derive other "higher" resolution bio-optical properties from space. Note that the 645nm and 859nm channels (channel 1 and 2 on MODIS) are the only channels that are 250m. Wang and Shi [14] describe an atmospheric correction procedure using SWIR channels which has an advantage in coastal waters. Using the SWIR channels, where minimum remote sensing reflectance comes from the water, should be an improvement over the commonly used NIR atmospheric method[4]. We will compare satellite derived remote sensing reflectances (Rrs) using the old and new methods with *in situ* Rrs data to determine the "best" method in coastal regimes.

We demonstrate that finer resolution is required for validation of coastal products in order to improve match-ups of *in situ* data with the high spatial variability of bio-optics in coastal regions. We will use *in situ* remote sensing reflectance measurements to compare and validate different resolution and atmospheric correction methods and determine the uncertainty.

## FINER SCALE ALGORTIHMS FROM MODIS

Using the MSL12 software from GSFC as a basis, we improved the method by using the finer 250m high resolution optical properties from MODIS. This capability along with other software modifications was integrated into NRL's Automated Processing System (APS)[12], specifically the satellite data processing program, MSL12. We modified MSL12 to: 1) improve land detection using NDVI from 250m channels 1 and 2, and 2) use the 250m channel 1 Rrs in Quasi-analytical algorithm (QAA). The MODIS instrument was designed with 36 channels to support remotely sensed applications for land, atmosphere, ocean and clouds. The nine (9) channels used for ocean fall in the visible to NIR range from 412nm to 869nm at a spatial resolution of 1km. The 412, 443, 488, 531, 551, 667, 678, 748, and 869nm channels are highly sensitive in order to retrieve the ocean color contribution (<10%) of the total TOA radiance. The atmospheric radiance contributes ~ 90% of the TOA which makes the atmospheric correction procedure so critical. In coastal areas, it is possible for the dynamic range of certain bands of the ocean channels (such as 748nm) to be saturated due to high reflectivity from suspended sediment and result in a loss of signal. MODIS has higher resolution channels that extend into the SWIR from 469nm to 2130nm with less sensitivity which were designed for land and cloud observations and spectrally overlap the lower resolution ocean channels. These higher resolution channels have a ground pixel resolution of 250m (645nm and 859nm) and 500m (469, 555, 1240, 1640, and 2130nm) at nadir.

Initially, APS software exploited the two 250m channels at 645 nm and 859 nm to produce a beam attenuation coefficient ( c ) estimate at 645 nm [6] using aerosols derived from 1 km atmospheric correction. Later, a technique was developed in the APS version of MSL12 for enhancing the resolution of backscatter at 555 nm and absorption at 469 nm in coastal areas by using the 250 m 645nm channel[1]. MSL12 supports the processing of TOA radiances from a variety of sensors to Level-2 geophysical products. Two of the sensors supported are MODIS Aqua and Terra. The MODIS Level-1B format[8] produces the calibrated TOA radiances in three separate files corresponding to 250m, 500m and 1km resolution. MSL12 can now produce the entire ocean radiance channel suite at 250m resolution by bi-linearly interpolating the 500m and 1km channels to 250m resolution[2]. The additional spectral channels in the SWIR provide an opportunity to explore different atmospheric correction, land masking and cloud detection options that are important for turbid coastal waters. For ocean processing, the standard aerosol correction algorithm uses the NIR bands at 748nm and 869nm to determine aerosol type and concentration[4]. In addition, MSL12 applies an iteration to model and predict the water-leaving radiances in the NIR using the retrieved water-leaving radiances in the visible channels[1]. With the new modifications to MSL12 to use the entire channel suite[2], a new approach has been implemented using the SWIR channels to determine aerosol concentration and/or type using any combination of NIR and SWIR bands[14]. To determine the "best" approach to atmospherically correct the high-resolution bands, many combinations of the SWIR, NIR and 250m channels were examined for use in atmospheric correction. We determined that the optimal combination requires running the standard Gordon/Wang aerosol calculation twice for each pixel. In the first iteration, the SWIR bands are used in place of the standard 750/865nm NIR bands (the assumption here is that water-leaving radiance (Lw) at SWIR, not NIR, wavelengths is zero). From this initial aerosol calculation, the computed estimates of Lw at 750nm and 865nm are then used as the NIR correction in a second iteration of the Gordon/Wang aerosol correction, to further refine the Lw estimates[4,14].

Following this combined atmospheric correction approach (combined SWIR/NIR) using the high-resolution channels, we removed the aerosol contribution from the bi-linearly interpolated ocean channels and channel 1. We applied bio-optical algorithms (semi-analytical algorithms) using the resulting Rrs estimates to retrieve finer resolution optical products. These products include chlorophyll, spectral absorption coefficients with separately partitioned phytoplankton, sediment, detritus, and CDOM components, spectral backscattering coefficients, beam attenuation coefficients, diffuse attenuation coefficients, organic, inorganic and total suspended particulate concentrations , diver visibility (horizontal and vertical), and salinity.

More specifically, the QAA algorithm was improved by using the actual satellite derived 645nm Rrs at 250m along with bi-linearly interpolated 1km channels to a "pseudo" 250m resolution to compute the various coefficients for the computation of the 555nm total absorption coefficient. The higher resolution Rrs results in higher resolution optical products. Typically, the QAA is initialized by:

$$\text{Total absorption (555)} = f\left[(Rrs443+Rrs488) / (Rrs551 + (Rrs640/Rrs488) * Rrs640)\right] \tag{1}$$

The 443, 488, 551 and 640nm ocean channels were at 1km resolution. In the standard QAA processing, the 640nm Rrs is modeled from other 1km Rrs (488, 551, 667nm). The improved approach uses (1) the bi-linearly interpolated 1km Rrs at 443, 488, and 551nm to 250 m resolution[2] and (2) replaces the modeled Rrs 640nm with the measured 250m Rrs at 645nm. The use of these Rrs creates a "pseudo" 250m absorption product. The "pseudo" 250m absorption product is then used to estimate the backscattering coefficient at all ocean channels. The total absorption is decomposed into it's components see Lee et al., 2002 [10] and Gould, In Press[7] for details. The derived results are an improved finer resolution bio-optical product which is required for monitoring coastal areas. Follow-on algorithms to further separate the optical components are based on the results of the QAA.

## METHODS

We assembled a database of coincident Rrs from numerous cruises in the northern Gulf of Mexico (near the Texas, Louisiana and Mississippi coasts), the Chesapeake Bay, the Indian River Lagoon, the Potomac River, and the South Florida area for comparison with MODIS Aqua derived properties. Data were collected between April 2003 and September 2006 at 179 station locations for 39 cruise days in clear and turbid waters. Of the 179 stations, only 86 successful satellite/*in situ* match-ups were used for this validation effort. The unsuccessful match-ups were due in part to stations being collected too close to shore, where the image pixels were flagged as land. Other problems included cloud contamination; failures with the atmospheric correction algorithms in river, bay, estuary and coastal pixels; and invalid field spectra due to sun glint and/or surface roughness effects.

MODIS Aqua imagery was obtained from the NASA GSFC Archive. All successfully matched scenes corresponding to the dates of *in situ* data collection were obtained. The MODIS imagery was processed using different atmospheric correction techniques and resolutions. The scenes were processed using (1) the standard Gordon/Wang [4] atmospheric correction with the NIR iteration and Stumpf 412 iteration for absorbing aerosols [13] at 1km resolution, (2) combined SWIR/NIR atmospheric correction with the NIR iteration and Stumpf 412 iteration for absorbing aerosols at 1km and "pseudo" 250m resolution, and (3) SWIR atmospheric correction with NIR and Stumpf 412 iterations to produce Rrs at "pseudo" 250m resolution[14].

The Rrs values were extracted from the images for each station location. The MODIS-Aqua derived Rrs values processed using different atmospheric correction techniques and different resolutions from each station were compared to the measured values. The measured Rrs were collected with field Spectroradiometers developed by Analytical Spectral Devices (ASD) and Remote Optical Systems, Incorporated and processed with a Fresnel correction. The resulting Rrs is convolved using the MODIS spectral response files for visible bands.

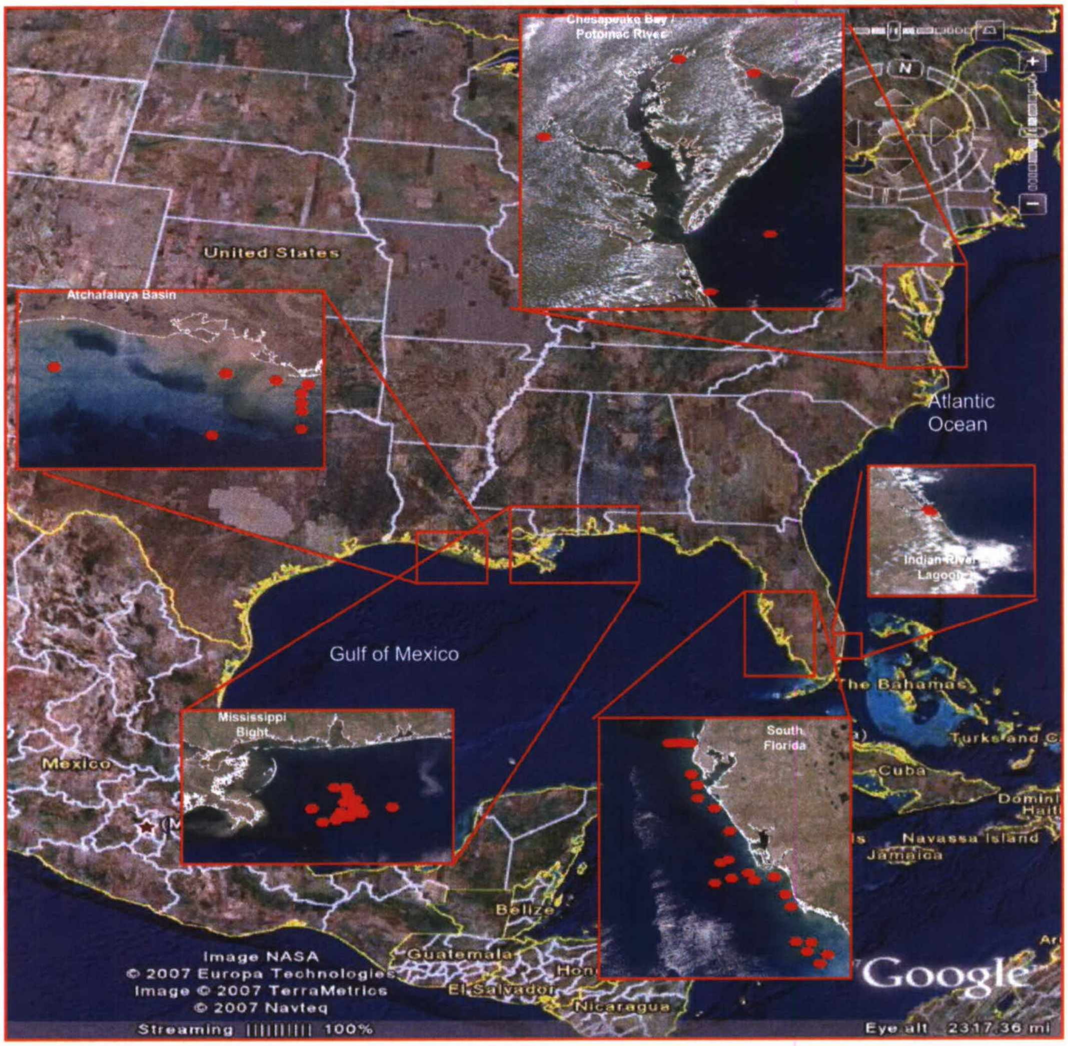


Figure 1: A map showing the station locations where *in situ* Rrs data was collected over 4 years (2003 to 2006). The availability of the high resolution processing now yields valid satellite and *in situ* match-ups in areas (near shore, estuaries, rivers, lakes, etc.) that in the past would not have been possible due to resolution and atmospheric failures.

## RESULTS

In-water optical property algorithms are highly sensitive to errors in Rrs, therefore, it is very important to retrieve the best Rrs possible when estimating inherent optical properties. The atmospheric correction process is very difficult in the coastal environment due to the non-zero water leaving radiance in the NIR and SWIR in addition to the rapid temporal and spatial changes, aerosol type, and concentration in the coastal zone. Comparisons between MODIS Rrs estimates derived using several different atmospheric correction techniques and coincident *in situ* Rrs data were examined. The "best" atmospheric correction method was determined and used to derive higher resolution Rrs estimates. These Rrs were then used to produce the "pseudo" 250m optical products.

The standard Gordon/Wang atmospheric correction uses the 1km NIR channels (748nm and 869nm) to determine aerosol contribution. We investigate using the higher resolution 250m channel 2 (859nm) in place of the 1km channel (869nm) to produce higher resolution aerosols. The comparisons of the estimated aerosol contributions are shown in figure 2 for the Northern Gulf of Mexico (NGOM) image from March 17, 2007. This scene represents a wide variety of water types ranging from high sediments to high CDOM. Comparisons show a slight offset in the aerosol contribution when using the 859nm channel in place of the 869nm channel. This offset does not significantly affect the resulting Rrs. Using the 250m channel to derive aerosols is feasible and generates Rrs estimates at an improved resolution.

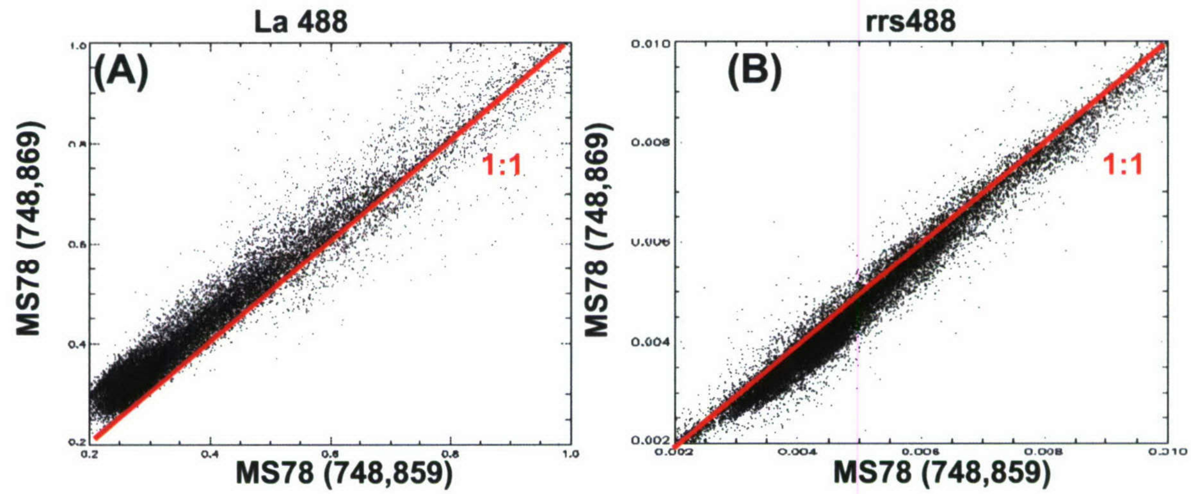


Figure 2: (A) Scatter plot showing the difference in aerosol contribution (La) at 488nm using the default 1km channel 8 (869nm) (y-axis) and the substitution of the 250m channel 2 (859nm) (x-axis) in the standard Gordon/Wang atmospheric correction. Note that there is a slight offset from the 1:1 line (red). (B) Scatter plot showing the difference in Rrs at 488nm using the default 1km channel 8 (869nm) (y-axis) and the substitution of the 250m channel 2 (859nm) (x-axis) in the standard Gordon/Wang atmospheric correction. Note that slight offset in La in Figure 2(A) does not significantly affect the resulting Rrs.

Based on the comparisons in Figure 2, we applied the standard Gordon/Wang algorithm to the March 17, 2007 NGOM image focusing on Lake Ponchartrain, LA. The image shows the difference between the standard 1km processing using all 1km channels for the atmospheric correction, and the substitution of the 250m channel (859nm) in the atmospheric correction. The results shown in Figure 3 indicate that by using the higher resolution channel, the atmospheric correction is able to better resolve coastal/land boundaries and give more detailed aerosol information. This will generate more detail/resolution in the forward products (Rrs, Optical, etc). Some problems still occur in the coastal region where the 748nm channel (1km) is saturated.

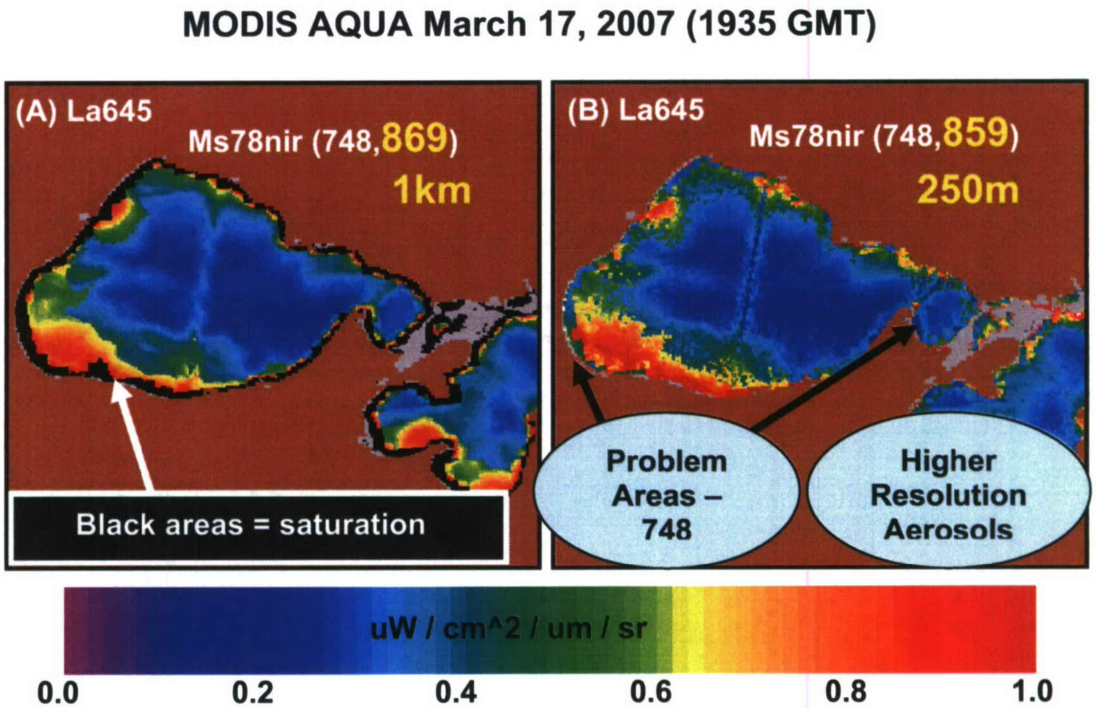


Figure 3: (A) MODIS Aqua "pseudo" 250m image of aerosol contribution (La) at 645nm using the standard Gordon/Wang (ms78nir) atmospheric correction with channel 7 set to 748nm (1km) and channel 8 set to 869 (1km). Note the black areas where the pixels are saturated due to land/water boundary problems. (B) MODIS Aqua "pseudo" 250m image of the aerosol contribution (La) at 645nm using the same atmospheric correction substituting the 250m channel (859nm) for the 1km channel (869nm). Note that land/water boundaries are better resolved.

Comparisons were made between MODIS Aqua derived and *in situ* Rrs using three atmospheric correction techniques (standard Gordon/Wang, combined SWIR/NIR, and SWIR). The results of these comparisons at 488nm and 551nm are shown in Figure 4. In both cases, (1) the combined SWIR/NIR approach is closest to the 1:1 line (dashed) and produces the best r-squared values, 0.67 for Rrs at 488nm and 0.83 for Rrs at 551nm, (2) using the SWIR channels (1240nm and 2130nm) for the atmospheric correction introduced more scatter (lower r-squared) but was still closer to the 1:1 line than the standard Gordan/Wang in both cases, and (3) the "best" estimate of Rrs at 488nm and 551nm was using the combined SWIR/NIR approach.

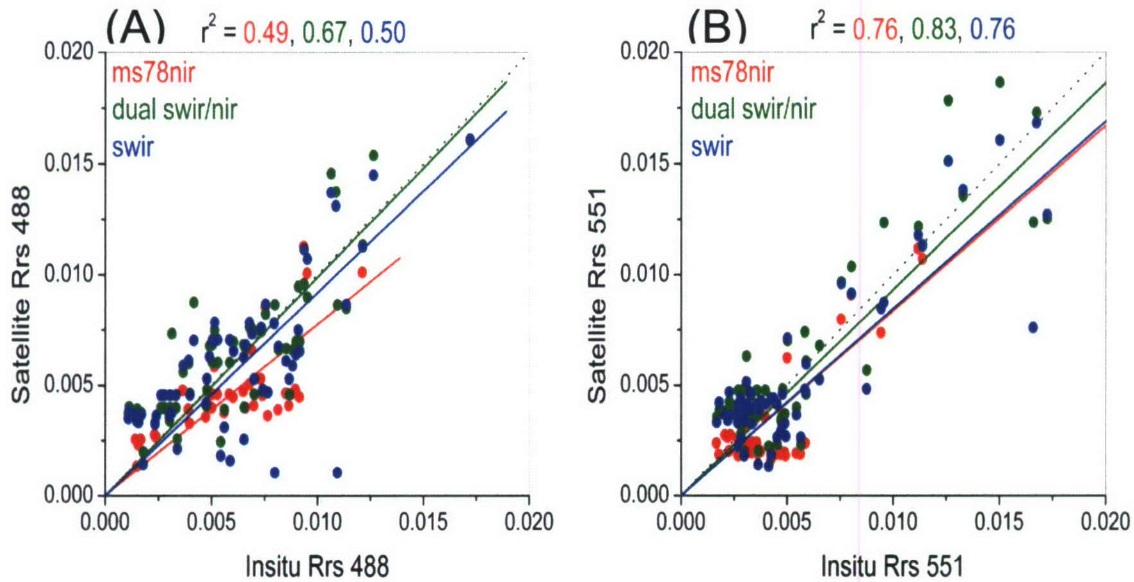


Figure 4: MODIS-derived versus *in situ* Rrs at 488nm (A) and 551nm (B) for three different atmospheric correction techniques: standard Gordon/Wang (red), combined SWIR/NIR (green), and SWIR (blue).

Following the atmospheric correction, the Rrs (1km and "pseudo" 250m) were input into the QAA algorithms to produce the bio-optical products for Lake Ponchartrain (Figure 5). The figure demonstrates the difference between the 1 km (standard Gordon/Wang) and "pseudo" 250m (combined SWIR/NIR) backscattering coefficient at 551nm. Note the significant increase in resolution and detail in the "pseudo" 250m resolution image (B) as compared to the 1km image (A).

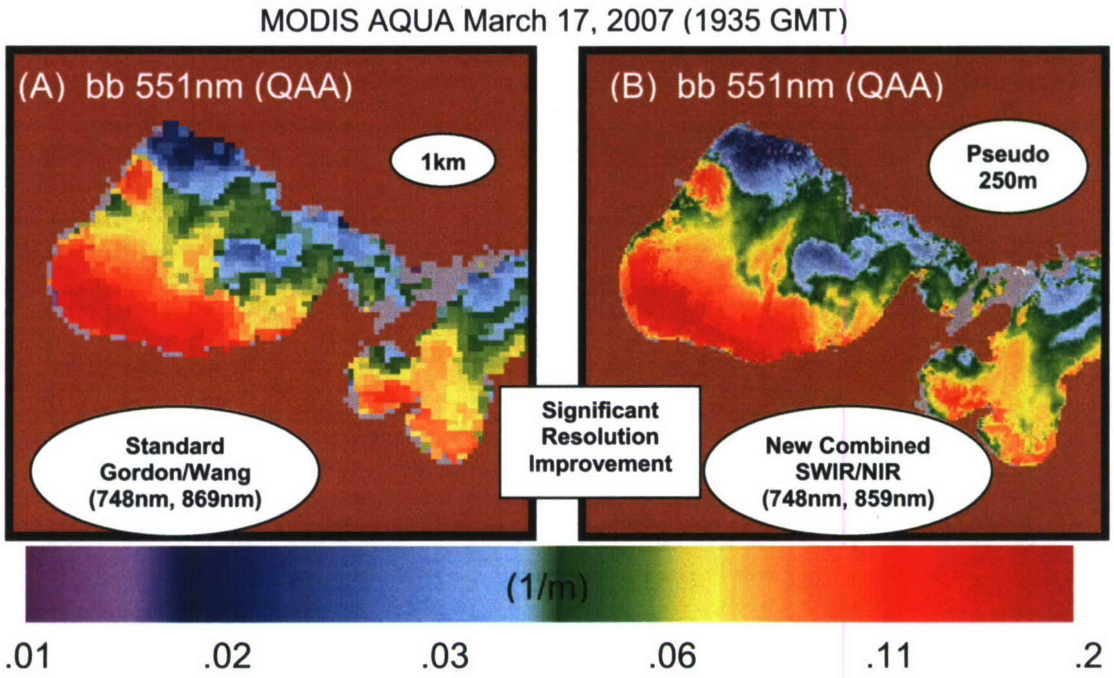


Figure 5: (A) MODIS Aqua backscattering coefficient at 551nm (1km) derived using Lee's Quasi-Analytical Algorithm (QAA) IOP algorithm [11] and the standard ms78nir (Gordon/Wang) atmospheric correction. (B) Same backscattering QAA product at 551nm as (A) but processed at 250m resolution with the combined SWIR/NIR atmospheric correction using the 250m resolution channel 2 (859) in place of the 1km channel 8 (869).

## CONCLUSION

The available high resolution bands originally designed for land and cloud applications were used to derive optical properties up to 250m resolution which is four times the resolution of the standard ocean properties. These additional channels extend into the SWIR and provide new methods for atmospheric correction. The effects of using the 250m channel at 859nm in place of the 1km 869nm in the standard Gordon/Wang atmospheric correction were examined. By using the 250m 859nm channel in place of the 1km 869 channel, the resolution of the resulting atmospheric radiance, Rrs, and optical properties were significantly improved. We demonstrated that the atmospheric correction using the higher resolution 250m channel produced valid aerosol estimates adjacent to the coast. The improved atmospheric correction near the coast provided valid Rrs values which could be used to retrieve bio-optical properties closer to the coastlines.

Results from three different atmospheric correction techniques were compared with *in situ* data: (1) the standard Gordon/Wang algorithm, (2) the SWIR correction with no NIR iteration, and (3) a combined SWIR/NIR correction using the 250m 859nm channel in place of the 1km 869nm channel. The best result was using the combined SWIR/NIR approach. This "best" atmospheric correction method significantly improved agreement between MODIS Aqua and *in situ* Rrs measurements in the case II waters with the least amount of atmospheric failures and negative radiances. This is a major advancement in being able to derive pseudo 250m high resolution properties in highly variable and turbid coastal locations (estuaries, bays, rivers, etc.) from space.

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