NOAA NESDIS
CENTER for SATELLITE APPLICATIONS and RESEARCH

GOES-R Advanced Baseline Imager (ABI) Algorithm Theoretical Basis Document For Visibility

Version 1.0
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ACRONYMS

ABI - Advanced Baseline Imager
AIT - Algorithm Integration Team
ATBD - Algorithm Theoretical Basis Document
AWG – Algorithm Working Group
AWIPS - Advanced Weather Interactive Processing System
BT – brightness temperature
CMIP – Cloud and Moisture Imagery Product
CONUS – continental United States
FD – full disk
GRB – GOES ReBroadcast
GVAR – GOES Variable
IR - infrared
McIDAS – Man computer Interactive Data Access System
MTF – modulation transfer function
SNR – Signal-to-noise ratio
SRF – Spectral Response Function
TBD – To be determined
TBV – To be revised
TOA – top of atmosphere

1 INTRODUCTION

Visibility is the greatest horizontal distance at which selected objects can be seen and identified. Reduced visibility often occurs during periods of heavy rain and snow and also occurs when sunlight is scattered or absorbed by atmospheric particles. Visibility is a leading safety factor in determining aircraft flight rules, pilot certification and aircraft equipment required for taking off or landing. Federal Aviation Regulations require that aircraft operations at airports must be conducted under Instrument Flight Rules (IFR) when the prevailing visibility is below three statue miles (approximately 5km). In addition to these important safely considerations, reduced visibility due to regional haze also obscures the view in our nation's parks. The Clean Air Act authorizes the United States Environmental Protection Agency (EPA) to protect visibility, or visual air quality, through a number of different programs. The EPA's Regional Haze Rule calls for state and federal agencies to work together to improve visibility in national parks and wilderness areas such as the Grand Canyon, Yosemite, the Great Smokies and Shenandoah.

Fog droplets and haze particles are small enough to scatter and absorb sunlight, leading to reduced visibility. The meteorological definition of fog is a cloud (stratus) which has its cloud base on or close to ground, and reduces visibility to less than 1 km. Haze is caused when sunlight encounters tiny pollution particles in the air. More pollutants mean more absorption and scattering of light, which reduces visibility. The attenuation of light due to scattering and absorption by atmospheric particles is referred to as extinction. In general, scattering is the primary cause of light extinction and therefore visibility reduction. The smallest pollution particles (< 2.5microns) scatter sunlight more efficiently then larger particles. Haze is primarily composed of sulfate, organic, elemental carbon, and nitrate aerosols. Sulfur dioxide (SO2) emissions from power plants, nitrogen oxide (NOx) emissions from motor vehicles, and secondary organic aerosols of biogenic and wildfire origin contribute the most to regional haze events.

The GOES-R Advanced Baseline Imager (ABI) visibility retrieval will provide a satellite based estimate of boundary layer visibility to augment existing measurements from Automated Surface Observing System (ASOS) extinction measurements. The ability of ABI to continuously monitor visibility over the continental US will allow smoke and fog related transportation hazards to be monitored in real-time, providing valuable information to the Aviation Weather Center (AWC), National Weather Service (NWS), Federal Aviation Administration (FAA), and Department of Transportation (DOT). The ability of GOES-R to continuously monitor visibility in remote regions of the US will improve visibility monitoring within our National Parks and provide useful information to the regional planning offices responsible for developing mitigation strategies required under the EPA's Regional Haze Rule.

1.1 Purpose of This Document

The primary purpose of this algorithm theoretical basis document (ATBD) is to provide a high level description of the algorithms required by the visibility product from the Advanced Baseline Imager (ABI) onboard the GOES-R series of NOAA geostationary meteorological/environmental satellites.

1.2 Who Should Use This Document

The intended users of this document are those who are interested in understanding the theoretical basis of visibility product and how to use the product in a particular application. It provides information useful to anyone maintaining or modifying related algorithms and software systems.

1.3 Inside Each Section

This document consists of the following main sections:

- **Product Overview**: provides relevant details of the ABI and a brief description of the product generated by the algorithm.

- **Product Requirement Description**: provides the detailed requirements for the visibility algorithm and software system.

- **Algorithm Description**: provides the details for product processing outline, input/output parameters and key algorithms.

- **Test Data Sets, and Output**: provides a description of the test data sets used to characterize the performance of the algorithms and quality of the data products. It also describes the results using test data sets.

- **Practical Considerations**: provides a description of the issues involving the software system programming, quality assessment, diagnostics, and exception handling.

- **Assumptions and Limitations**: provides an overview of the current assumption and limitations of the approach and a plan for overcoming these limitations with further algorithm development.

1.4 Related Documents

The visibility retrieval uses ABI Aerosol Optical Depth (AOD), Cloud Optical Thickness (COT), fog/low cloud probability and thickness retrievals to estimate surface visibility. Readers should refer to Suspended Matter/Aerosol Optical Depth and Aerosol Size Parameter, Low Cloud and Fog, and Daytime Cloud Optical and Microphysical Properties (DCOMP) Algorithm Theoretical Basis Documents (ATBDs) for further discussion of the visibility input products. The GOES-R ABI Ground Segment (GS) Functional and Performance Specification (F&PS) document provides a summary of the GOES-R ABI visibility specifications.

1.5 Revision History

The first draft of this document (dated September 20, 2008) was created by Tim Schmit of NOAA/NESDIS/STAR, Wayne Feltz of CIMSS, and Brad Pierce NOAA/NESDIS/ STAR and was reviewed by Shobha Kondragunta NOAA/NESDIS/STAR. However, this was prior to any algorithm development. Significant progress has been made since this first draft and is included in this updated version. Its intent is to accompany the delivery of the version 1.0 algorithm to the GOES-R AWG Algorithm Integration Team (AIT).

2 PRODUCT OVERVIEW

This section describes the visibility product and the requirements it places on the system.

2.1 Product Generated

The visibility product is produced using a number of other ABI products. Other products include the low-cloud/fog probability and depth, aerosol optical depth (AOD), and cloud optical thickness (COT). It is important that the visibility algorithm obtain mature AOD/COT/fog derived products for robust testing and implementation. Fog detection is typically associated with a visibility of less than 1 km; while haze is associated with visibilities from 2-30 km. Heavy smoke or dust plumes may be associated with significantly lower visibilities. To determine the range of visibilities associated with haze the visibility product will use the ABI Aerosol Optical Depth (AOD) retrieval. AOD is the degree to which aerosols prevent the transmission of light at a particular wavelength and is the integrated extinction coefficient over a vertical column of unit cross section. The extinction coefficient is the fractional depletion of radiance per unit path length. Under haze conditions the visibility algorithm must be able to relate AOD (at a particular wavelength) to horizontal visibility within the planetary boundary layer. Primary auxiliary inputs (in addition to AOD) are boundary layer depth from a model analysis. Under low cloud and fog conditions the visibility algorithm must be able to relate visible COT to horizontal visibility within the low cloud or fog layer. Primary auxiliary inputs (in addition to COT) are fog probability and fog depth.

2.2 Instrument Characteristics

ABI has 16 spectral bands designed for a variety of application purposes. In fact, the ABI band 1 was added to the ABI to support aviation via an enhanced visibility product. Table 2-1 summarizes the instrument central wavelength, spatial resolution, and product characteristics. The instrument has two basic modes. One mode is that every 15 minutes ABI will scan the full disk (FD), plus continental United States (CONUS) 3 times, plus a selectable 1000 km × 1000 km mesoscale area every 30 seconds. The second mode is that the ABI can be programmed to scan the FD iteratively. The FD image can be acquired in approximately 5 minutes (Schmit et al. 2005).

Band Number	Central Wavelength (µm)	Spatial Resolution (km)	Product	Used in visibility product
1	0.47	1	aerosol	X
2	0.64	0.5	aerosol	X
3	0.86	1	-	X
4	1.38	2	clouds	X
5	1.61	1	snow	X
6	2.26	2	-	X
7	3.9	2	fog	X

8	6.15	2	clouds	X
9	7.0	2	clouds	X
10	7.4	2	clouds	X
11	8.5	2	-	X
12	9.7	2	ozone	X
13	10.35	2	surface	X
14	11.2	2	surface	X
15	12.3	2	surface	X
16	13.3	2	clouds	X

Table 2-1 GOES-R ABI instrument characteristics (the spatial resolution reflects the sub-point value).

The visibility product could be on three scales: CONUS, FD, and mesoscale. The performance of the product is sensitive to any imagery artifacts or instrument noise, calibration accuracy, and geolocation accuracy, as well as the quality of the intermediate products.

3 PRODUCT REQUIREMENT DESCRIPTION

The visibility requirements are summarized based on the GOES-R Series Ground Segment (GS) Functional and Performance Specification (F&PS) (NOAA/NASA 2008). The software system that generates routine CMIP shall meet the following requirements:

	Threshold		
Geographic Coverage/Conditions	FD	FD	
Primary Instrument	ABI		
Prioritization	O2		
Vertical Resolution	N/A		
Horizontal Resolution	10 km		
Measurement Accuracy	Clear (vis ≥ 30 km) Moderate (10 km ≤ Vis < 30 km) Low (2 km ≤ vis < 10 km); Poor (vis < 2 km)	under the conditions of clear up through clouds of only layer	Correct classification 80%
Refresh Rate/ Coverage Time	60 min	5 min	
Mapping Accuracy	5 km	5 km	-
Data Latency	806 sec	806 sec	-
Temporal Coverage Qualifier	Day		
Product Extent Qualifier	Quantitative out to at least 70 degrees LZA and qualitative at larger LZA		
Cloud Cover Conditions Qualifier	Clear conditions down to feature of interest associated with threshold accuracy		

Table 3-1 Visibility Requirements.

4 ALGORITHM DESCRIPTION

This section describes visibility software system processing outline, input/output parameters, and key algorithms at the current level of maturity (will be improved with each revision).

4.1 Overview

Visibility is the greatest horizontal distance at which selected objects can be seen and identified. Reduced visibility often occurs during periods of heavy rain and snow and also occurs when sunlight is scattered or absorbed by atmospheric particles. Fog droplets and haze particles are small enough to scatter and absorb sunlight, leading to reduced visibility. The meteorological definition of fog is a cloud (stratus) which has its cloud base on or close to ground, and reduces visibility to less than 1 km. Haze is caused when sunlight encounters tiny pollution particles in the air. More pollutants mean more absorption and scattering of light, which reduces visibility. The attenuation of light due to scattering and absorption by atmospheric particles is referred to as extinction. In general, scattering is the primary cause of light extinction and therefore visibility reduction. Visibility is inversely proportional to extinction which is a measure of attenuation of the light passing through the atmosphere due to the scattering and absorption by aerosol particles. For measurement of visibility in the daytime, Koschmieder's Law [Kaufman and Fraser, 1983] is used:

$$V = 3.9/\sigma \quad (1)$$

where V is the visibility (in km), and σ is the extinction coefficient (km^{-1}). The extinction coefficient (σ) relates the intensity (I) of light transmitted through a layer of material with thickness (x) relative to the incident intensity (I_0) according to the inverse exponential power law that is usually referred to as the Beer-Lambert Law:

$$I = I_0 e^{-\sigma x} \quad (2)$$

Optical depth τ is defined as σx. Expressing visibility in terms of τ gives:

$$V = 3.9/(\tau/x) \quad (3)$$

Equation (3) forms the theoretical basis for the GOES-R ABI Visibility algorithm. Equation (3) shows that visibility is inversely proportional to optical depth divided by the thickness of the material layer. No legacy algorithm exists relating satellite derived AOD/COT to boundary layer visibility measurements. However, feasibility studies have been conducted using ground based AOD measurements. Peterson et al. [1981] compared 6 years (August 1969-July 1975) of sunphotometer measurements of decadic turbidity at the Environmental Protection Agency (EPA) Research Triangle Park (RTP) Laboratory near Raleigh, NC with observer estimates of visibility from the Raleigh Durham airport (RDU). Decadic turbidity multiplied by a factor of 2.3 is equal to the aerosol optical depth. They considered four visibility classes ranging from <6, 7-8, 9-10, and >11 miles. Their primary conclusion was that there was a pronounced increase in turbidity for visibility < 7 miles. Monthly correlation coefficients between turbidity and visibility where large during the summer (-0.66 in June and -0.70 in July) and small during the winter (-0.02 in January and -0.03 in February). However, when RDU visibility exceeded 7 miles observers tended to report 10 or 12 miles visibility exclusively. This would tend to reduce the monthly correlation coefficients in the winter since mean turbidities are lowest during this time period. Kaufman and Fraser [1983] used correlations between transmissometer measurements of aerosol optical depth and nephelometer measurements of aerosol volume scattering coefficients [Charlson et al., 1969] to assess the feasibility of using satellite based AOD measurements to predict surface visibility. They compared inverse visibility (V^{-1}) measured at Baltimore, MD and Dulles airports with AOD measurements at Goddard Space Flight Center (GSFC) during 1980 and 1981. GSFC is 40 km south of Baltimore and 60 km northeast of Dulles. They found strong correlations between V^{-1} at Baltimore and Dulles in both 1980 and 1981 (0.96 and 0.91, respectively). They found good correlations between GSFC AOD and V^{-1} at Baltimore and Dulles during 1980 (0.85 and 0.84, respectively) but only moderate correlations during 1981 (0.51 and 0.58, respectively).

From Equation (3), the ABI Visibility uses retrieved Aerosol Optical Depth (AOD) to estimate τ under clear-sky conditions and uses retrieved Cloud Optical Thickness (COT) to estimate τ under cloudy conditions when Fog or Low Clouds have been detected. The ABI Visibility algorithm uses NWS Planetary Boundary Layer (PBL) depth to estimate x under clear-sky conditions and uses retrieved Fog and Low Cloud depth to estimate x under cloudy conditions when Fog or Low Clouds have been detected. Measurement requirements dictate the need to distinguish between; Clear (vis $\geq$ 30 km), Moderate (10 km $\leq$ Vis < 30 km); Low (2 km $\leq$ vis < 10 km); Poor (vis < 2 km). A "blended" retrieval approach is adapted. The blended visibility retrieval is constructed using a weighted combination of the non-bias corrected and bias corrected visibility estimates for both aerosol and low-cloud/Fog visibilities. The combination of blended aerosol and blended fog visibility estimates is referred to as the "merged" visibility product.

Bias correction look-up tables (LUT) for aerosol and fog/low cloud visibilities are obtained through statistical analysis of historical ASOS visibilities versus satellite based aerosol and fog/low cloud visibility estimates. In the Version 1.0 ABI aerosol visibility algorithm the LUTs are based on Version 5 MODIS AOD retrievals obtained from the NASA Earth Observing System Data and Information System (EOSDIS) archives and NOAA Global Forecasting System (GFS) Planetary Boundary Layer (PBL) depths obtained from the NOAA Comprehensive Large Array-data Stewardship System (CLASS) archive. Version 1.0 ABI fog/low cloud visibility algorithm LUTs are based on GOES Fog/Low Cloud Optical Depths (COT) and Fog/Low Cloud depth retrievals computed using the GOES-R AWG Cloud Team's GEOCAT framework. Optimal weighting between non-bias corrected and bias corrected visibility estimates for aerosol and fog/low cloud visibility is determined based on assessment of required categorical accuracy (percent correct classification), required precision (standard deviation of categorical error), Heidke Skill Score (fractional improvement relative to chance), and false alarm rate.

4.2 Processing Outline

Figure 4-1 provides a high level flowchart of the ABI visibility algorithm. For each pixel either aerosol or fog/low cloud retrievals are possible depending on whether clouds are present. If clouds are not present then a “first guess” non-bias corrected aerosol visibility is computed using Equation (3) and used to determine what visibility classification (Clear, Moderate, Low, Poor) should be used in the aerosol LUT to compute the bias-corrected aerosol visibility. The blended aerosol visibility is computed based on a weighted average of the first guess and bias corrected aerosol visibility estimates. If clouds are present an additional check is performed to determine if fog/low clouds are present using the fog/low cloud probability product. If fog/low clouds are present then a “first guess” non-bias corrected fog/low cloud visibility is computed using Equation (3) and used to determine what visibility classification (Clear, Moderate, Low, Poor) should be used in the fog/low cloud LUT to compute the bias-corrected fog/low cloud visibility. The blended fog/low cloud visibility is computed based on a weighted average of the first guess and bias corrected fog/low cloud visibility estimates. Finally, the aerosol and fog/low cloud visibility retrievals are combined to produce a final “merged” visibility retrieval.

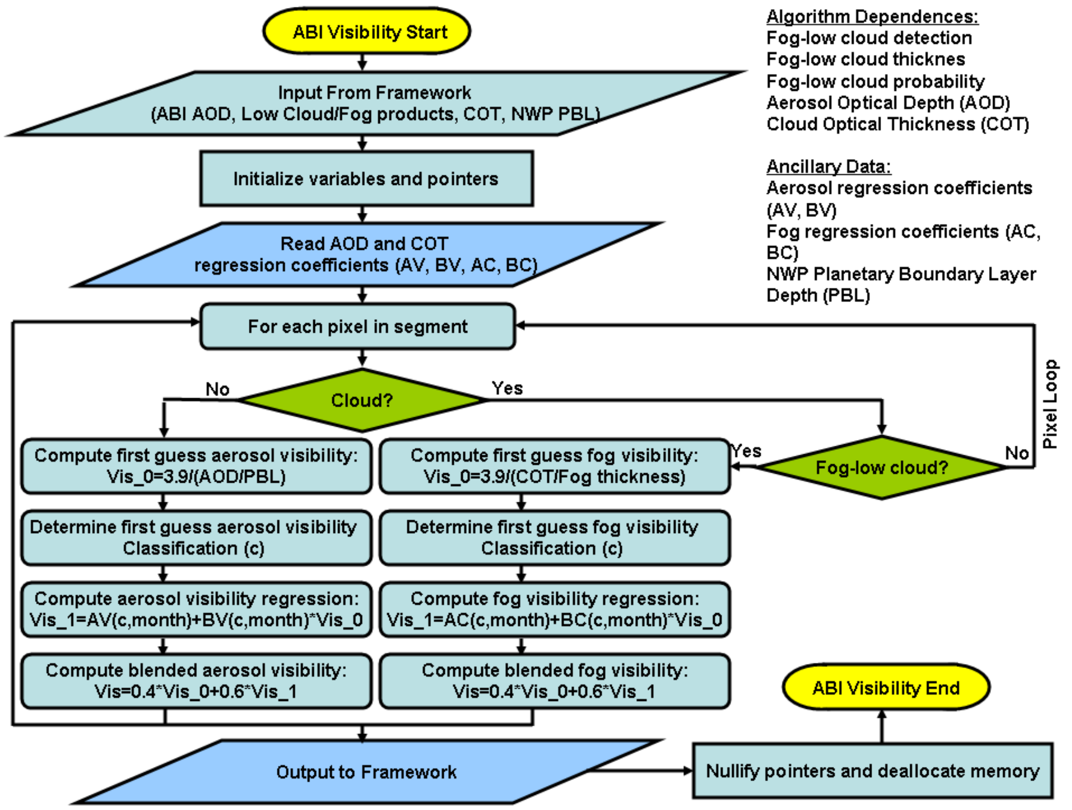

Figure 4-1 High level flowchart for generating visibility.

4.3 Algorithm Input

The ABI Visibility algorithm uses input products and other static and dynamic ancillary data. The input to the ABI Visibility algorithm includes the following ancillary data:

- ABI Dynamic Data: Cloud Mask, Cloud Optical Thickness, Aerosol Optical Depth, Fog and Low Cloud Probability, Fog and Low Cloud Depth

- Non-ABI Static Data: Aerosol and Fog/Low Cloud Visibility Bias LUT

- Non-ABI Dynamic Data: NWP planetary boundary layer depth

Geolocation information and view zenith and relative azimuth angles are extracted from the rebroadcast data stream. In Version 1.0 of the ABI Visibility algorithm the aerosol and fog/low Cloud LUTs include 12 monthly offset and scale factors for each of the 4 visibility categories for both aerosol and fog/low cloud visibility retrievals.

4.4 Key Algorithms Description

4.4.1 Aerosol Product

The first step in constructing the aerosol LUT involves collocation of raw (one-second) ASOS extinction measurements with Version 5 MODIS AOD and 12hr GFS forecasted PBL for 2007-2008. ASOS visibility sensors measure forward scattering of light in a mid-visible wavelength (550 nanometers) and convert the measured scattering to Sensor Equivalent Visibility using Koschmieder's Law. A total of 93,873 ASOS/MODIS coincident pairs were identified and used in subsequent statistical analysis. Figure 4-2 shows categorical histograms of the coincident ASOS and first guess MODIS aerosol visibility derived using Equation (3). The first guess MODIS aerosol visibility tends to overestimate the frequency of Poor and Low visibility classes resulting in a 58% categorical success rate for 2007-2008 ASOS coincident pairs. This overestimate of low and poor visibility relative to ASOS is most likely associated with increase in relative humidity (RH) at the top of the planetary boundary layer (PBL) under stable conditions. Increased RH leads to increased aerosol extinction due to hydroscopic growth of hydrophilic aerosols. Higher aerosol extinctions near the top of the PBL lead to overestimates in the frequency of Low and Poor visibility relative to ASOS since it measures surface visibility.

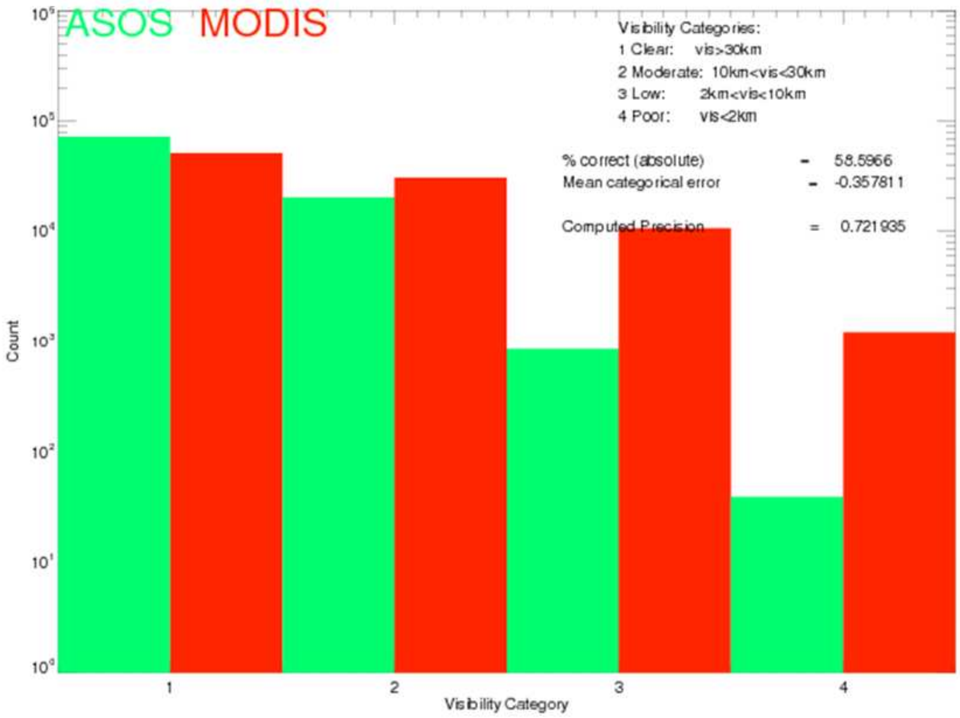

Figure 4-2 Categorical Histogram of non-bias corrected MODIS (red) and ASOS (green) aerosol visibility for 2007-2008 coincident pairs.

Linear regression was performed to determine offsets (bias) and scale factor (slope) for best estimate of ASOS visibility for each visibility category (clear, moderate, low, poor) and month using historical (2007-2008) ASOS/MODIS coincident pairs. This is referred to as “bias corrected” aerosol visibility. Figure 4-3 shows categorical histograms of the coincident ASOS and bias corrected MODIS aerosol visibilities. The bias corrected MODIS aerosol visibility tends to underestimate the frequency of Poor and Low visibility classes but the categorical success rate has increased to 78% for 2007-2008 ASOS coincident pairs.

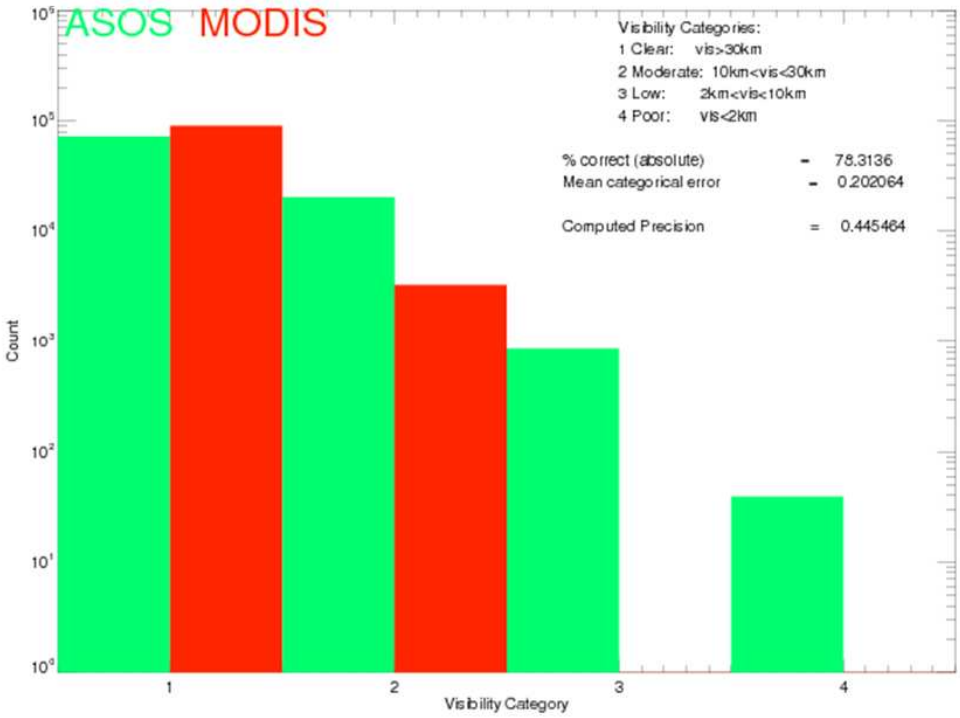

Figure 4-3 Categorical Histogram of bias corrected MODIS (red) and ASOS (green) aerosol visibility for 2007-2008 coincident pairs.

Heidke Skill scores [Brier and Allen, 1952] and False Alarm rates [Olson, 1962] were calculated for the non-bias corrected and bias corrected aerosol visibility for each visibility category using 2007-2008 coincident pairs. Heidke Skill scores measure the fractional improvement in skill relative to chance. Results are summarized in Tables 4-1 and 4-2. They show that while bias correction *reduces* false alarm rates for Moderate Low, and Poor aerosol visibility bias correction also *reduces* predictive skill for all classes.

Heidke Skill Score (Hit Rate) for MODIS aerosol visibility

Visibility Category	**Non-Bias Corrected**	**Bias Corrected**
1 (Clear)	0.260837	0.128602
2 (Moderate)	0.130284	0.111972
3 (Low)	0.0615632	0.00000
4 (Poor)	-0.000806477	0.00000

Table 4-1: Heidke Skill Scores for coincident ASOS and MODIS Non-Bias and Bias Corrected aerosol visibility during 2007-2008.

False Alarm Rate for MODIS aerosol visibility

Visibility Category	Non-Bias Corrected	Bias Corrected
1 (Clear)	0.113158	0.210274
2 (Moderate)	0.702888	0.400554
3 (Low)	0.958069	NA
4 (Poor)	1.00000	NA

Table 4-2: False Alarm Rate for coincident ASOS and MODIS Non-Bias and Bias Corrected aerosol visibility during 2007-2008.

The Heidke Skill Score tests show that while the bias correction results in the highest categorical success rates it results in a reduction in predictive skill. This points to the need to develop a “blended” aerosol visibility retrieval that is a weighted combination of the non-bias and bias corrected aerosol visibility estimates. Optimal weighting for the blended aerosol visibility retrieval is determined based on assessment of Heidke Skill Score (fractional improvement relative to chance), and false alarm rates.
Heidke Skill Score and False Alarm rates were calculated for each visibility category using the 2007-2008 coincident pairs. Weightings between the non-bias and bias corrected aerosol visibility estimates varied by 10% from 0% bias corrected to 100% bias corrected visibilities. Figure 4-4 shows Heidke Skill Scores and Figure 4-5 shows False Alarm rates verses the percentage of the bias corrected aerosol visibility for each visibility class. Results of Heidke Skill tests and False alarm rates show that a 60% bias corrected weighting resulted in the largest improvement relative to chance for both Clear and Moderate aerosol visibility and minimizes false detections for Low aerosol visibility. Based on these tests, the Version 1.0 ABI aerosol visibility blended retrieval uses a 40/60% weighting of the non-bias and bias corrected aerosol visibility estimates.

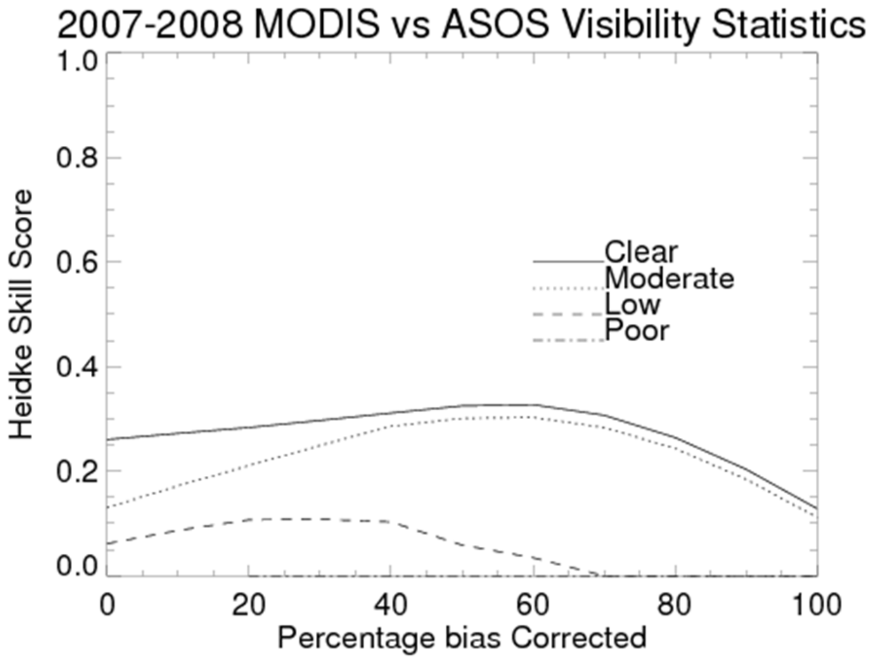

Figure 4-4: Results of Heidke Skill Score tests for aerosol visibility as a function of the percentage bias corrected for each visibility class.

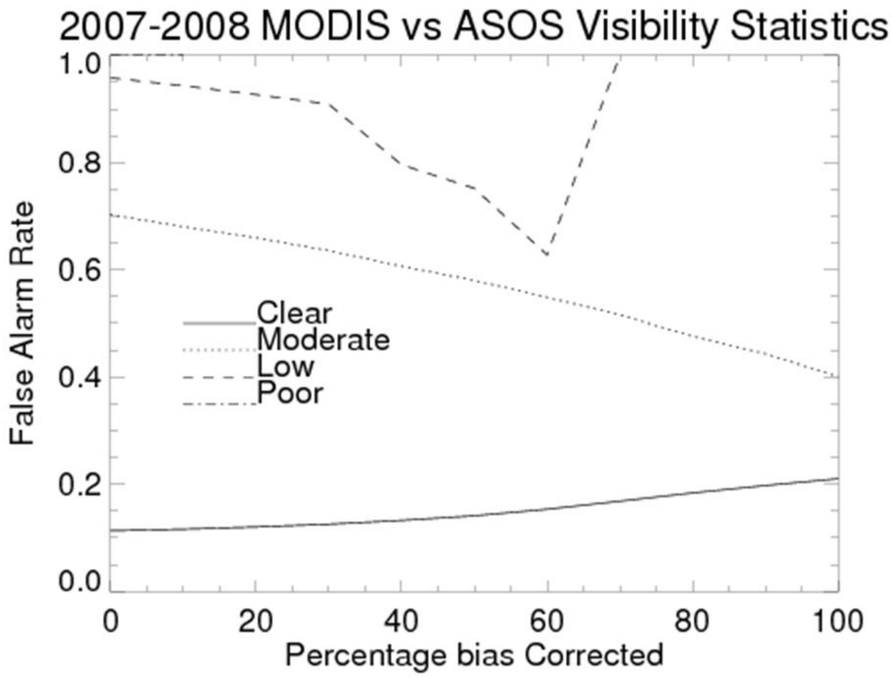

Figure 4-5: Results of False Alarm Rate tests for aerosol visibility as a function of the percentage bias corrected for each visibility class.

Figure 4-6 shows categorical histograms of the coincident ASOS and blended MODIS aerosol visibilities. The blended MODIS aerosol visibility improves the estimates of Low visibility but still tends to underestimate the frequency of Poor visibility classes. The categorical success rate of the blended aerosol visibility retrieval is 75% for 2007-2008 ASOS coincident pairs.

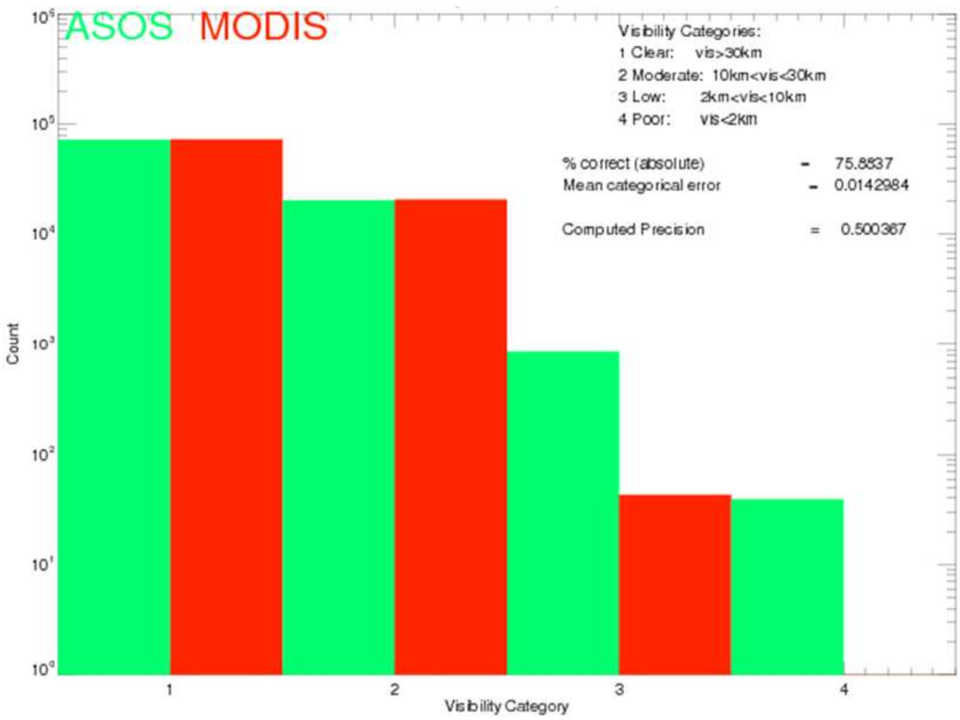

Figure 4-6 Categorical Histogram of blended MODIS (red) and ASOS (green) aerosol visibility for 2007-2008 coincident pairs.

4.4.2 Low cloud/fog Product

The first step in constructing the fog/low cloud LUT involves collocation of raw (one-second) ASOS extinction measurements with GOES fog/low cloud retrievals for 2007-2008. A total of 1532 coincident ASOS/GOES coincident pairs were identified and used in subsequent statistical analysis. GOES data was used as proxy data to generate the Version 1.0 fog/low cloud LUT since the ABI fog/low cloud algorithm has been implemented within the CIMSS GEOCAT framework and GEOCAT can not use MODIS proxy data at the time of this draft ATBD. Figure 4-7 shows categorical histograms of the coincident ASOS and first guess GOES fog/low cloud visibility derived using Equation (3). The first guess GOES fog/low cloud visibility falls exclusively within the Poor visibility class resulting in a 4.7% categorical success rate for 2007-2008 ASOS coincident pairs. This overestimate in the frequency of poor visibility relative to ASOS is due to a relatively high minimum COT within the GOES-R ABI cloud optical and microphysical retrieval when GOES proxy data is used. This overestimate is also likely to be associated with increase in relative humidity (RH) at the top of the planetary boundary layer (PBL) under stable conditions. Fog and low Clouds are more likely to form near the top of the PBL and may not reach surface.

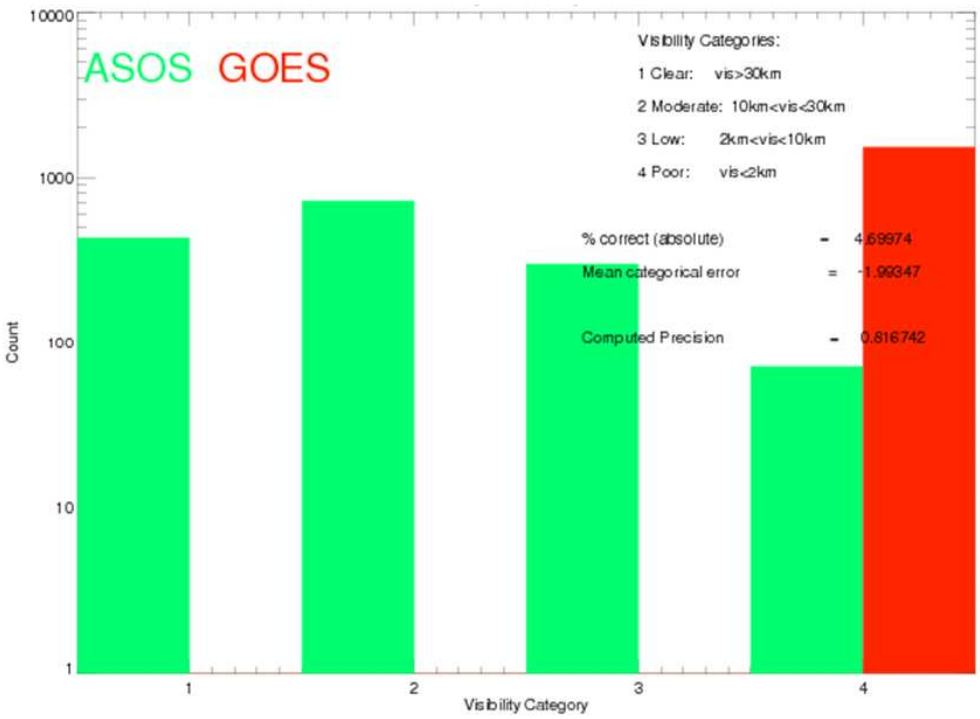

Figure 4-7 Categorical Histogram of non-bias corrected GOES (red) and ASOS (green) fog/low cloud visibility for 2007-2008 coincident pairs.

Linear regression was performed to determine offsets (bias) and scale factor (slope) for best estimate of ASOS visibility for each visibility category (clear, moderate, low, poor) and month using historical (2007-2008) ASOS/GOES coincident pairs. This is referred to as “bias corrected” fog/low cloud visibility. Since all of the first guess GOES fog/low cloud visibility retrievals fell within the Poor visibility category the offsets and scale factors for the Clear, Moderate and Low visibility classes are equal to zero in the Version 1.0 ABI visibility fog/low cloud LUT. Figure 4-8 shows categorical histograms of the coincident ASOS and bias corrected GOES fog/low cloud visibilities. The bias corrected GOES fog/low cloud visibility improves the prediction of Clear, Moderate, and Low visibility classes but now underestimates the frequency of Poor visibility. Categorical success rates have increased to 49% for 2007-2008 ASOS coincident pairs.

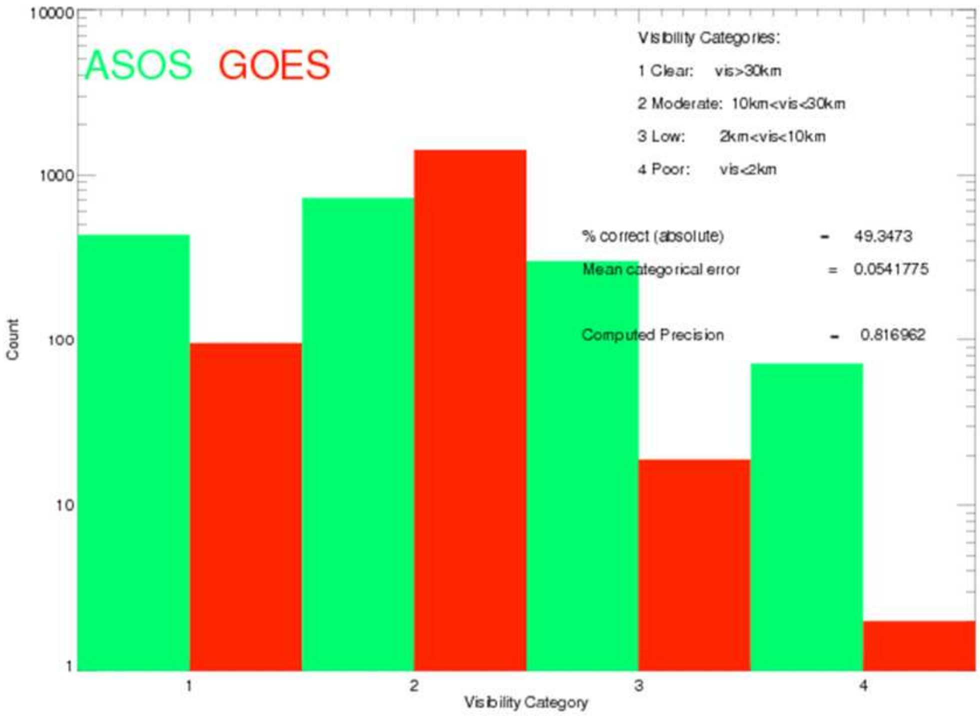

Figure 4-8 Categorical Histogram of bias corrected GOES (red) and ASOS (green) fog/low cloud visibility for 2007-2008 coincident pairs.

Heidke Skill scores and False Alarm rates were calculated for the non-bias corrected and bias corrected fog/low cloud visibility for each visibility category using 2007-2008 coincident pairs. Results are summarized in Tables 4-3 and 4-4. They show that without bias correction the GOES fog/low cloud visibility estimates have no skill relative to chance. Since all of the non-bias corrected GOES fog/low cloud visibility estimates fall into the Poor visibility class the False Alarm Rate for the non-bias corrected GOES fog/low cloud visibility is not applicable (NA). Bias correction *increases* predictive skill for all classes but also increases false alarm rates since other classes are now predicted.

Heidke Skill Score (Hit Rate) for GOES fog/low cloud visibility

Visibility Category	Non-Bias Corrected	Bias Corrected
1 (Clear)	**0.00000**	**0.137946**
2 (Moderate)	**0.00000**	**0.0436189**
3 (Low)	**0.00000**	**0.0274707**
4 (Poor)	**0.00000**	**-0.00254687**

Table 4-3: Heidke Skill Scores for coincident ASOS and GOES Non-Bias and Bias Corrected fog/low cloud visibility during 2007-2008.

False Alarm Rate for GOES fog/low cloud visibility

Visibility Category	Non-Bias Corrected	Bias Corrected
1 (Clear)	**NA**	**0.375000**
2 (Moderate)	**NA**	**0.513781**
3 (Low)	**NA**	**0.578947**
4 (Poor)	**0.953003**	**1.00000**

Table 4-4: False Alarm Rate for coincident ASOS and GOES Non-Bias and Bias Corrected fog/low cloud visibility during 2007-2008.

Following the same procedure used to construct the blended aerosol visibility retrieval we construct a "blended" fog/low cloud visibility retrieval using a weighted combination of the non-bias and bias corrected fog/low cloud visibility estimates. Optimal weighting for the blended fog/low cloud visibility retrieval is determined based on assessment of Heidke Skill Score (fractional improvement relative to chance), and false alarm rates. Heidke Skill Score and False Alarm rates were calculated for each visibility category using the 2007-2008 coincident pairs. Weightings between the non-bias and bias corrected fog/low cloud visibility estimates varied by 10% from 0% bias corrected to 100% bias corrected visibilities. Figure 4-9 shows Heidke Skill Scores and Figure 4-10 shows False Alarm rates versus the percentage of the bias corrected fog/low cloud visibility for each visibility class. Results of Heidke Skill tests showed that a 50% bias corrected weighting resulted in the largest improvement relative to chance. False alarm rates show that a 70% bias correction minimizes false detections for Low visibility. Based on these tests, the Version 1.0 ABI fog/low cloud visibility blended retrieval uses a 40/60% weighting of the non-bias and bias corrected fog/low cloud visibility estimates. This balances the improvement in Heidke Skill and False alarm rates under Low visibility conditions.

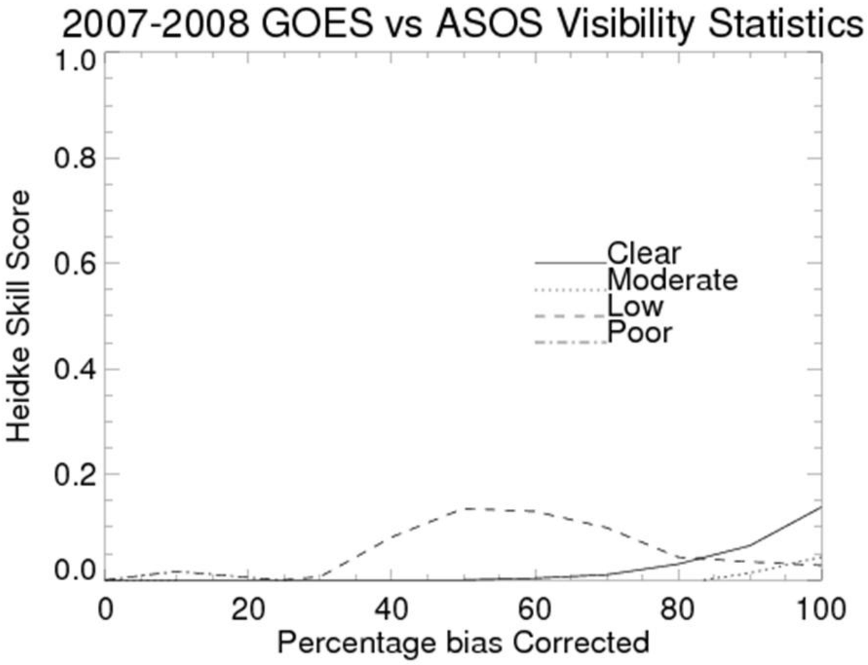

Figure 4-9: Results of Heidke Skill Score tests for fog/low cloud visibility as a function of the percentage bias corrected for each visibility class.

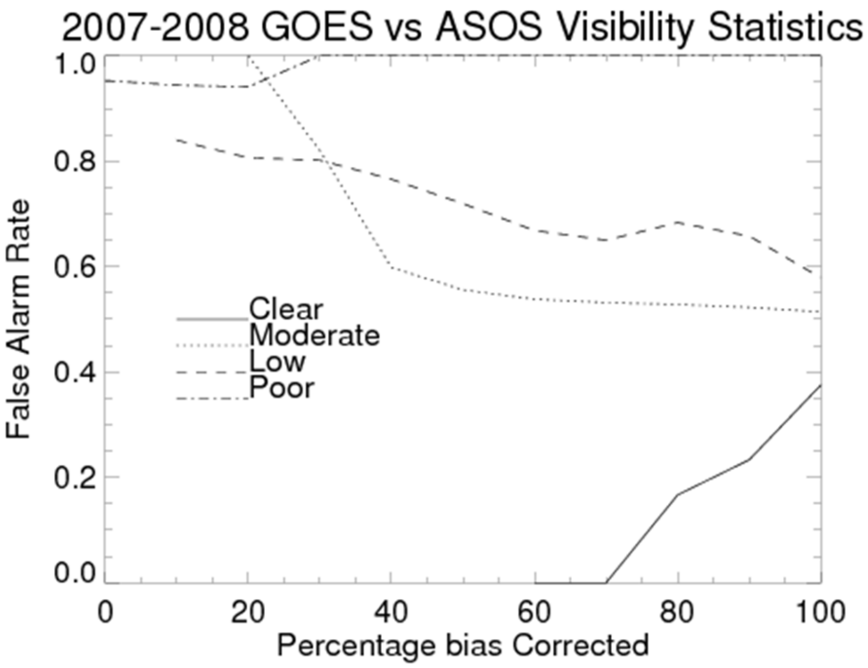

Figure 4-10: Results of False Alarm Rate tests for fog/low cloud visibility as a function of the percentage bias corrected for each visibility class.

Figure 4-11 shows categorical histograms of the coincident ASOS and blended GOES fog/low cloud visibilities. The blended GOES fog/low cloud visibility improves the estimates of Moderate and Low visibility but underestimates the frequency of Clear and Poor visibility classes. The categorical success rate of the blended fog visibility estimates is 44.5% for 2007-2008 ASOS coincident pairs.

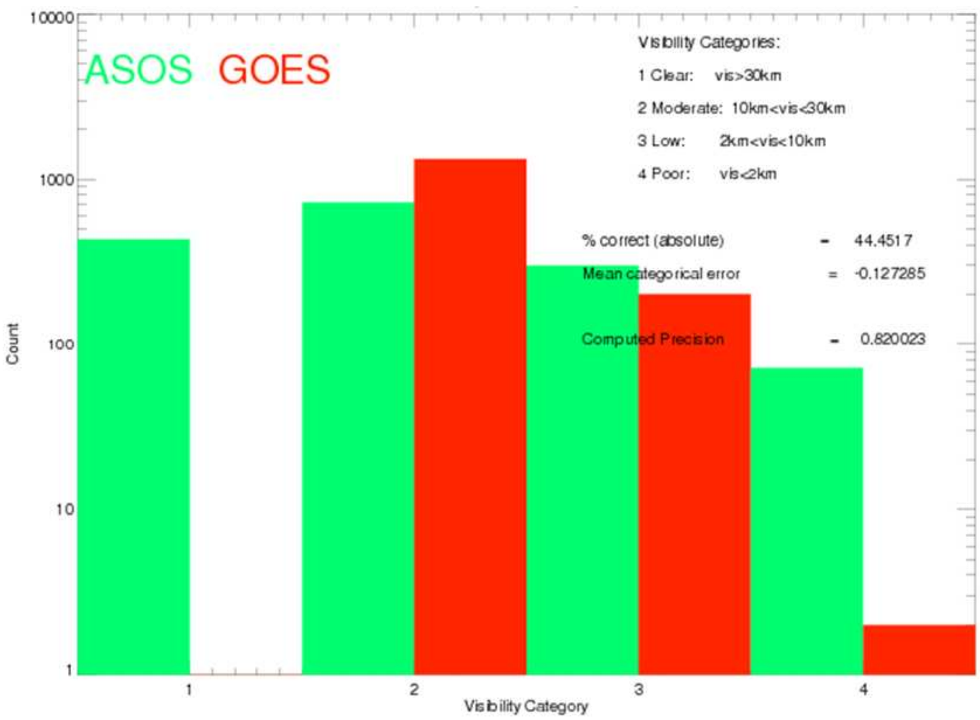

Figure 4-11: Categorical Histogram of blended GOES (red) and ASOS (green) fog/low cloud visibility for 2007-2008 coincident pairs.

4.4.3 Merged Aerosol and Fog/Low Cloud Product

The combination of blended aerosol and blended fog visibility estimates is referred to as the “merged” visibility product. Figure 4-12 shows categorical histograms of the coincident ASOS and merged MODIS aerosol and GOES fog/low cloud blended visibilities. A 40/60% non-bias/bias corrected weighting is used in both blended visibility estimates. The merged aerosol plus low-cloud/fog visibility retrieval results in a 75.4% categorical success rate for 2007-2008 coincident pairs. The merged aerosol plus low-cloud/fog visibility retrieval results captures the frequency of clear and moderate visibility very well but underestimates the frequency of low and poor visibility.

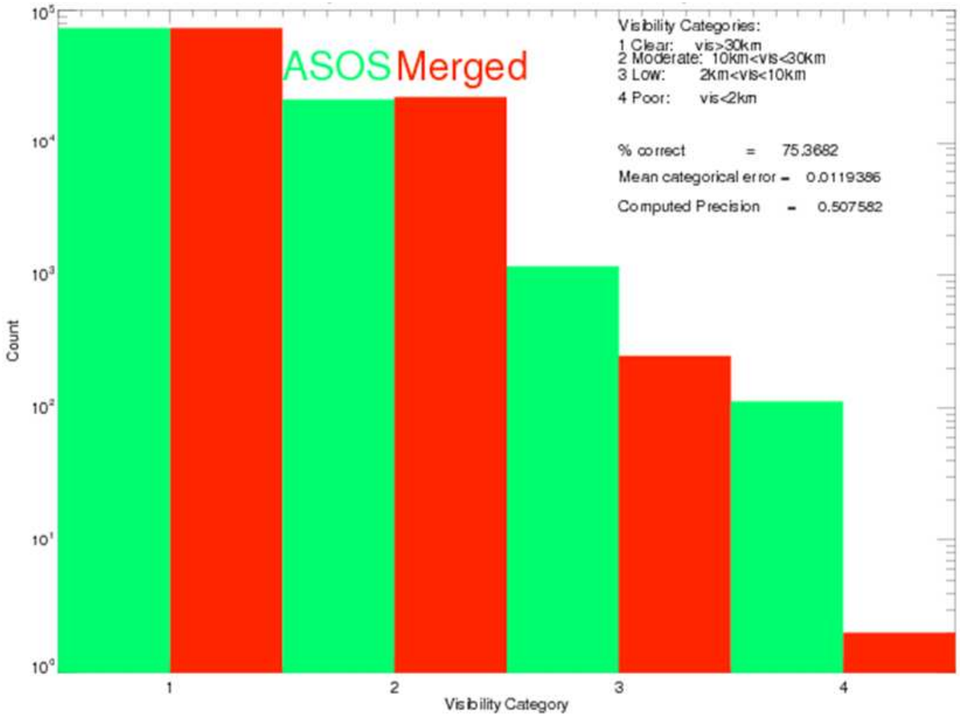

Figure 4-12: Categorical Histogram of Merged MODIS/GOES (red) and ASOS (green) aerosol plus fog/low cloud visibility for 2007-2008 coincident pairs.

Heidke Skill scores and False Alarm rates were calculated for the merged aerosol plus fog/low cloud visibility for each visibility category using 2007-2008 coincident pairs. Results are summarized in Tables 4-5 and 4-6. The GOES-R ABI merged visibility retrieval shows lower Skill and increased False alarm rates as visibility degrades from Clear to Poor.

Heidke Skill Score (Hit Rate) for merged aerosol plus fog/low cloud visibility

Visibility Category	Merged retrieval
1 (Clear)	**0.345980**
2 (Moderate)	**0.305405**
3 (Low)	**0.113883**
4 (Poor)	**-4.12233e-05**

Table 4-5: Heidke Skill Scores for coincident ASOS and merged MODIS aerosol and GOES fog/low cloud visibility during 2007-2008.

False Alarm Rate for merged aerosol plus fog/low cloud visibility

Visibility Category	**Merged retrieval**
1 (Clear)	**0.153365**
2 (Moderate)	**0.548148**
3 (Low)	**0.661224**
4 (Poor)	**1.00000**

Table 4-6: False Alarm Rate for coincident ASOS and merged MODIS aerosol and GOES fog/low cloud visibility during 2007-2008.

4.5 Algorithm Output

The primary output of this algorithm is an estimate of the visibility for a given pixel.

Output Name	Description
Visibility	The estimated visibility (km)
Aerosol Visibility	The blended visibility (km) due to aerosol extinction
Fog and Low Cloud Visibility	The blended visibility (km) due to fog and low cloud extinction
First Guess Aerosol Visibility	The first guess visibility (km) due to aerosol extinction
First Guess Fog and Low Cloud Visibility	The first guess visibility (km) due to fog and low cloud extinction
Quality Flags	Fog probability indicator, Aerosol Optical Depth and Cloud Optical Depth quality

Table 4-7 Fields in visibility output.

5 TEST DATA SETS AND OUTPUTS

5.1 Simulated/Proxy Input Data Sets

5.1.1 MODIS

The capabilities offered by ABI onboard GOES-R are similar to the multispectral observations currently provided by the Moderate Resolution Imaging Spectroradiometer (MODIS) flown on the NASA Earth Observing System (EOS) satellites Terra and Aqua and therefore MODIS Version 5 AOD retrievals are used as proxy data to generate the Version 1.0 aerosol visibility LUT. Figure 5-1 shows a composite of MODIS AOD (MOD04) and COT (MOD06) retrievals over the Continental US on August 31, 2009. Heavy aerosol loading (AOD> .5) extends throughout eastern Colorado, western Kansas and western Nebraska northward into eastern parts of Wyoming and central Montana due to transport of smoke from the Station Fire, near Los Angeles, CA.

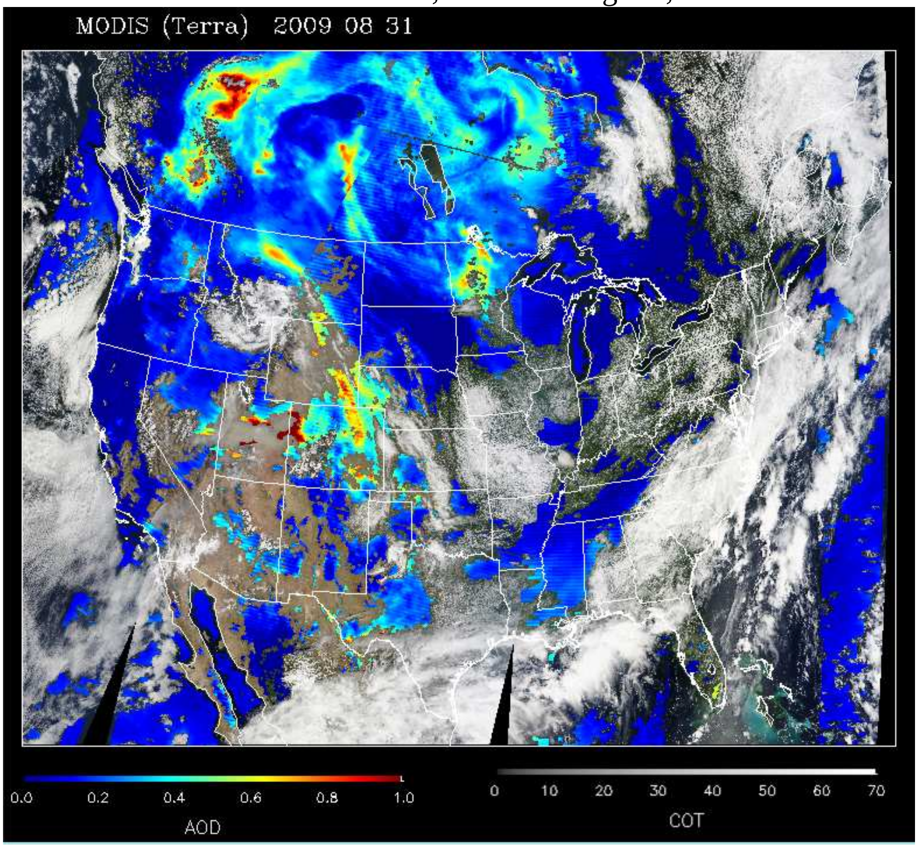

Figure 5-1: MODIS/TERRA on August 31, 2009. AOD: aerosol optical depth at 550nm, COT cloud optical thickness at 650 nm

5.1.2 Current GOES data

The fog product will be produced for each pixel observed by the ABI. The fog algorithm is designed to work when only a sub-set of the expected channels is provided. When running on GOES 12, the fog algorithm is able to utilize non-ABI cloud algorithms and account for the lack of Channel 11 (8.5 μm). Figure 5-2 shows an example of the fog probability product compared to ASOS surface visibility for 7:45 UTC December, 12, 2009. During early morning on December 13, 2009 a plane crashed while attempting to land at the Alva Municipal Airport in Alva, OK. Dense fog was reported limiting visibility to ~200 feet. The GOES-R fog algorithm shows with greater detail areas with the greatest threat for low visibility due to fog.

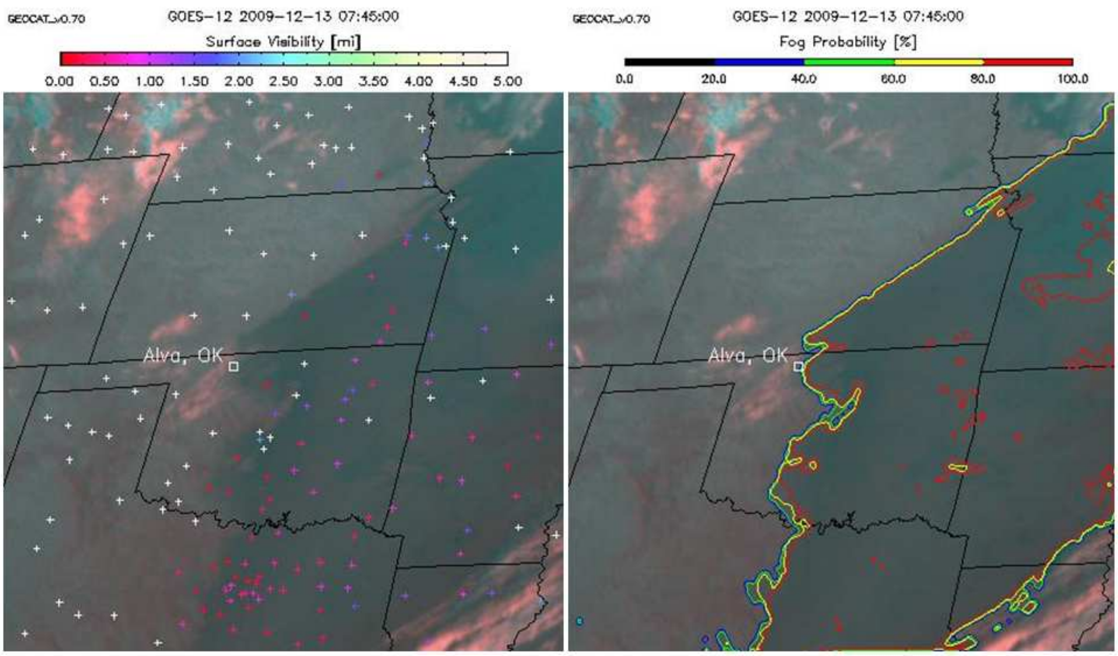

Figure 5-2: RGB image (R = 3.9 μm emissivity, G = 11 μm BT, B = 11 μm BT) of the US on December 13, 2009 at 7:45 UTC (1:45 am CST) with fog probability from the GOES-R fog algorithm contoured on top. (Figure provided by Corey Calvert, CIMSS - UW Madison and Michael Pavolonis, NOAA/NESDIS/STAR)

5.1.3 Simulated GOES-R ABI data

Currently extensive efforts are underway to develop, demonstrate, recommend and set standards for a broad range of capabilities designed to make optimal use of the GOES-R data when it becomes available. One of these efforts, addressed herein, involves the generation of high temporal and spatial resolution Advanced Baseline Imager (ABI) proxy datasets to be used by a variety of GOES-R team members for algorithm development and demonstration activities [Schaack et al, 2009]. High resolution aerosol and ozone data sets have been created over the continental US to augment the current GOES-R Algorithm Working Group Weather Research and Forecast (WRF) model [(Skamarock et al. 2001, 2005)] ABI proxy data capabilities. These data sets have been generated with WRF-Chem [Grell et al., 2005] air quality simulations coupled to global chemical and aerosol analyses from the Real-time Air Quality Modeling System (RAQMS) [Pierce et al., 2007]. Both WRF-Chem and RAQMS include on-line aerosol modules from the Goddard Global Ozone Chemistry Aerosol Radiation and Transport (GOCART) model [Chin et al., 2002]. The addition of aerosol and ozone distributions into the WRF proxy data set allows generation of more realistic synthetic (proxy) radiances for all ABI bands, using the forward visible and infrared radiance modeling capabilities from the Joint Center for Satellite Data Assimilation (JCSDA) Community Radiative Transfer Model (CRTM) [Han et al., 2006]. Synthetic WRF-CHEM radiances have been used as input into the GOES-R AOD algorithm to generate high horizontal and temporal resolution GOES-R ABI AOD retrievals for algorithm development. Figure 5-3 shows GOES-R ABI AOD retrievals based on WRF-CHEM/CRTM radiances at 15:30 UTC on August 24, 2006. The GOES-R ABI AOD retrieval is dominated by heavy aerosol loading associated with smoke in Northern Rocky Mountain states and regional haze in Mid-Atlantic, Southeast, and Mississippi Valley Regions

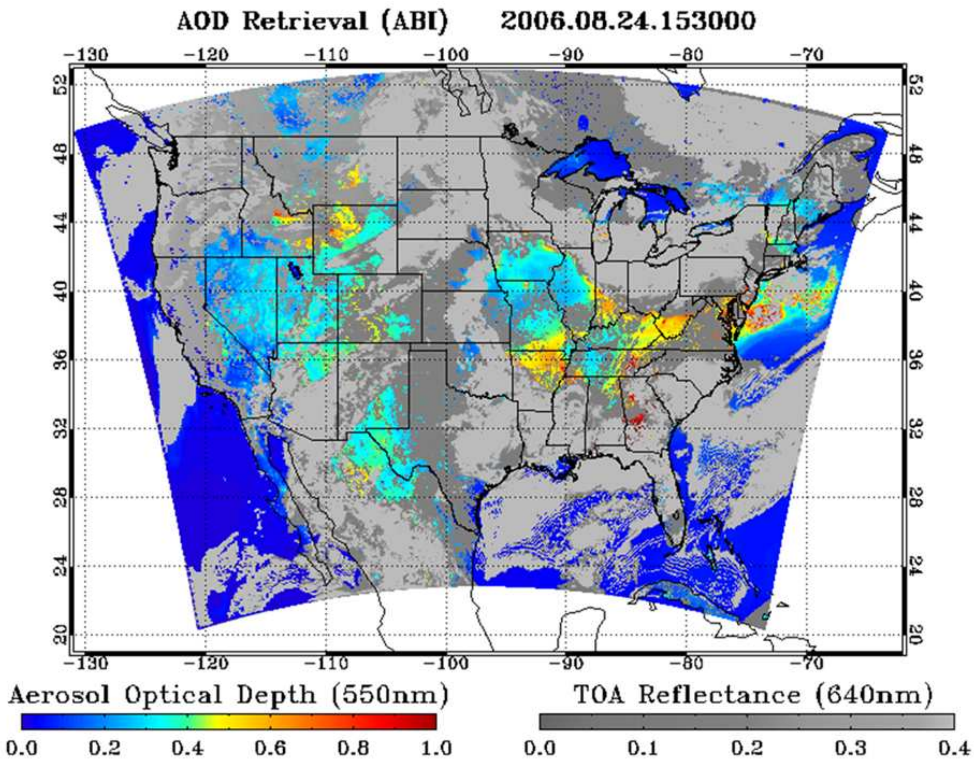

Figure 5-3: Simulated GOES-R ABI AOD 15:30 UTC August 24, 2006 (CONUS)

5.2 Output from Simulated/Proxy Inputs Data Sets

5.2.1 Visibility

August 31st, 2009 aerosol visibility retrievals based on MODIS AOD measurements (over Denver at 10:45am Mountain Standard Time) are shown in Figure 5-4. A broad area of reduced visibility extends throughout eastern Colorado, western Kansas and western Nebraska northward into eastern parts of Wyoming and central Montana and is associated with heavy aerosol loading from the Station Fire in California (see Figure 5-1).

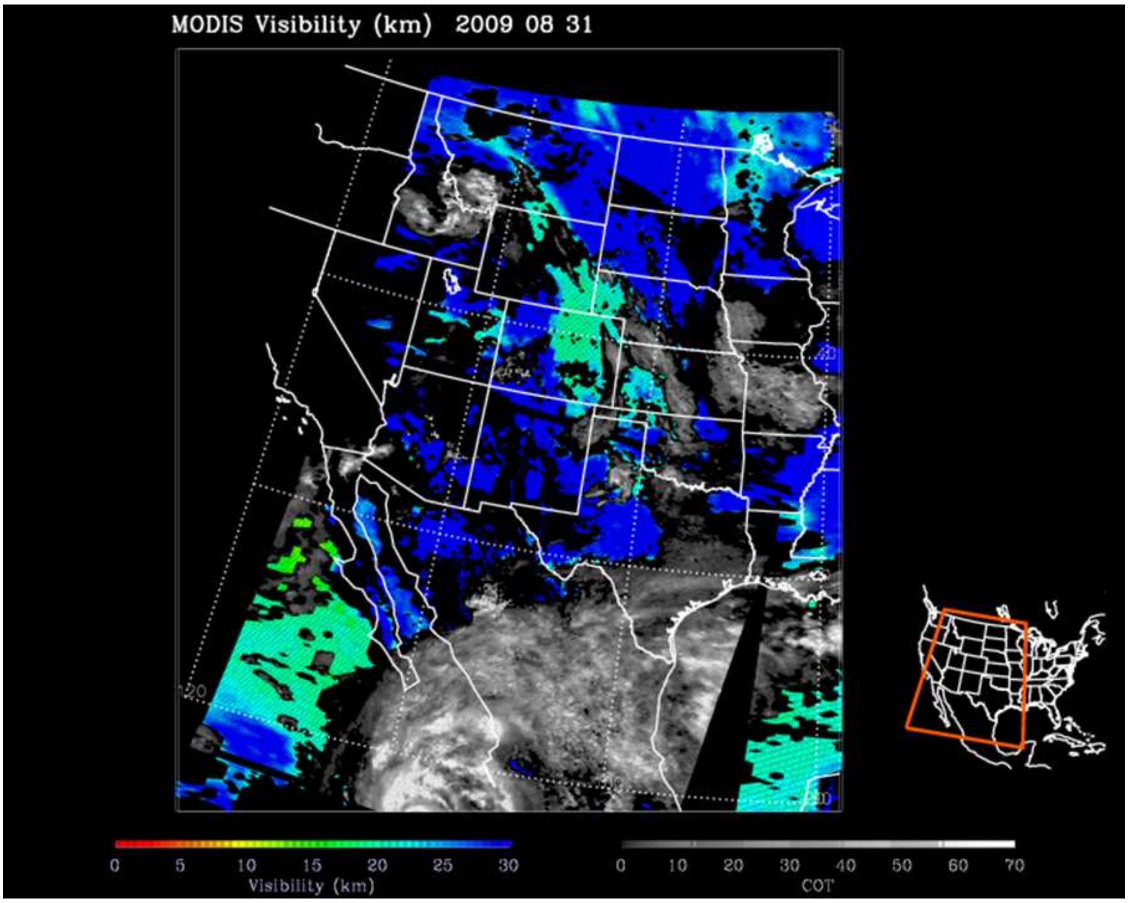

Figure 5-4: GOES-R ABI aerosol visibility (km) using MODIS Version 5 AOD retrievals on August, 31st, 2009. MODIS COT is indicated by the grey scale.

ASOS measurements show that visibility at the Denver International Airport (KDEN) was abruptly reduced from near 12 km to less than 3 km (~2 miles) at 4:00am and remained below 5 km until 7:00am due to smoke from the Station Fire (Figure 5-5). MODIS aerosol visibility estimates of 15 km are in good agreement with ASOS measurements at the Denver International Airport (KDEN) during the MODIS overpass at 10:45am.

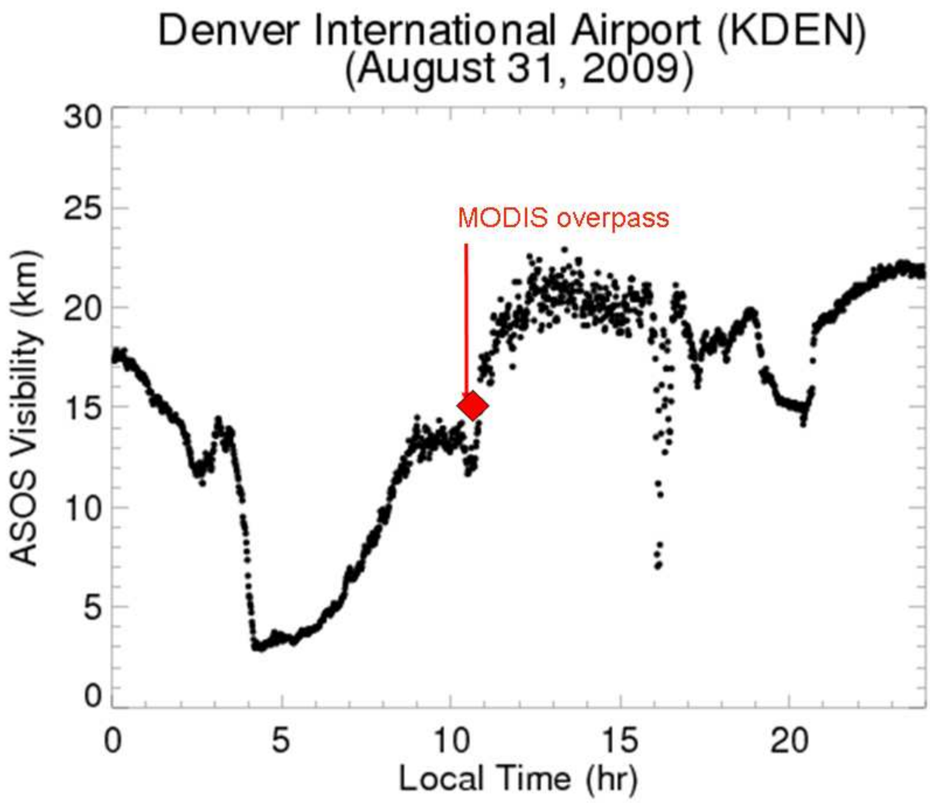

Figure 5-5: ASOS aerosol visibility (km) at Denver International Airport (KDEN) on August 31, 2009. The GOES-R ABI aerosol visibility retrieval at KDEN is indicated by the red diamond at the MODIS overpass time (10:45am).

6 PRACTICAL CONSIDERATIONS

6.1 Numerical Computation Considerations

The Visibility algorithm is implemented sequentially. Because it relies on the results of other algorithms, the cloud mask, cloud optical properties, the aerosol optical depth, and fog products must be run before the visibility algorithm. The computation time is very economic.

6.2 Programming and Procedural Considerations

The Visibility algorithm is run at the pixel level. Temporal information is not necessary.

6.3 Requirements

The GOES-R ABI visibility algorithm F&PS requirement is an 80% correct classification.

6.4 Other Issues

TBV.

6.5 Quality Assessment and Diagnostics

To be completed. This section describes how the quality of the output products is assessed, documented, and any anomalies diagnosed.

6.6 Exception Handling

If the retrieval is not performed, the retrieved parameters are set to a missing value and the quality flags are set to the lowest quality value. If the AOD or Fog products are not available, the retrieval is not performed.

6.7 Algorithm Validation

Algorithm is validated using independent (not used in the LUT regression) ASOS visibility measurements and available ground and space based cloud and aerosol extinction measurements. Merged GOES-R ABI visibility retrievals using MODIS (aerosol) and GOES (fog/low cloud) proxy data have been validated against ASOS visibility measurements during May-June 2010. Figure 6-1 shows categorical histograms of the coincident ASOS and merged MODIS aerosol and GOES fog/low cloud blended visibilities. The merged aerosol plus low-cloud/fog visibility retrieval results in a 72.8% categorical success rate for 3804 coincident ASOS/MODIS plus 202 coincident ASOS/GOES measurement pairs during May-June 2010.The merged aerosol plus low-cloud/fog visibility retrieval captures the frequency of clear, moderate and poor visibility relatively well but underestimates the frequency of low and poor visibility.

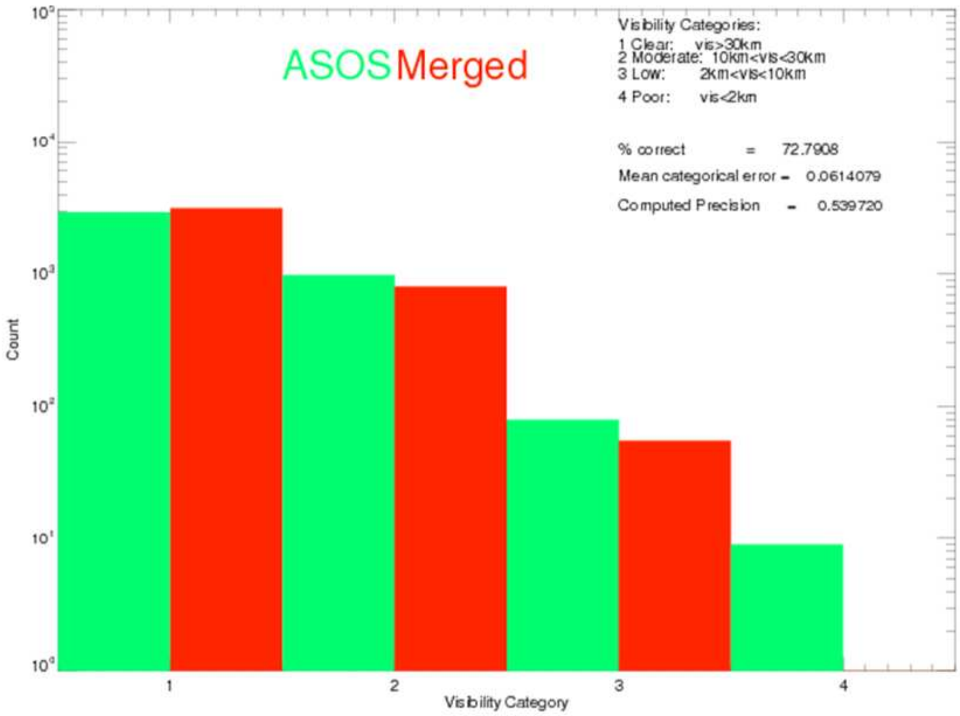

Figure 6-1: Categorical Histogram of Merged MODIS/GOES (red) and ASOS (green) aerosol plus fog/low cloud visibility for May-June 2010 coincident pairs.

Heidke Skill scores and False Alarm rates were calculated for the merged aerosol plus fog/low cloud visibility for each visibility category using May-June 2010 coincident pairs. Results are summarized in Tables 6-1 and 6-1. The GOES-R ABI merged visibility retrieval shows lower Skill and increased False alarm rates as visibility degrades from Clear to Poor.

Heidke Skill Score (Hit Rate) for merged aerosol plus fog/low cloud visibility

Visibility Category	**Merged retrieval**
1 (Clear)	**0.324869**
2 (Moderate)	**0.230516**
3 (Low)	**0.180768**
4 (Poor)	**-0.000449528**

Table 6-1: Heidke Skill Scores for coincident ASOS and merged MODIS aerosol and GOES fog/low cloud visibility during May-June 2010.

False Alarm Rate for merged aerosol plus fog/low cloud visibility

Visibility Category	Merged retrieval
1 (Clear)	**0.190461**
2 (Moderate)	**0.556522**
3 (Low)	**0.763636**
4 (Poor)	**1.00000**

Table 6-2: False Alarm Rate for coincident ASOS and merged MODIS aerosol and GOES fog/low cloud visibility during May-June 2010.

7 ASSUMPTIONS AND LIMITATIONS

7.1 Assumed Performance

Algorithm performance requires accurate aerosol optical depth and cloud optical thickness retrievals and accurate fog probability and fog depth retrievals. The aerosol visibility performance requires accurate NWP estimates of PBL heights and assumes that all aerosols are located within the PBL

7.2 Pre-Planned Product Improvements

To be completed.

ACKNOWLEDGEMENTS

8 REFERENCES

Brier, G. W., and R. A. Allen, 1952: Verification of weather forecasts. Compendium of Meteorology, Boston, Amer. Meteor. Soc., 841-848.

Bendix, J., B. Thies, J. Cermak, and T. Nauß, 2005: Ground Fog Detection from Space Based on MODIS Daytime Data—A Feasibility Study. Wea. Forecasting, 20, 989–1005.

Charlson, R. J., N. C. Ahlquist, H. Selvidge and P. B. MacCready, 1969: Monitoring atmospheric aerosol parameters with the integrating nephelometer, J. Air Pollut. Control Assoc., 19, 937-942.

Chin, M., et al., Tropospheric aerosol optical thickness from the GOCART model and comparisons with satellite and sunphotometer measurements, *J. Atmos. Sci. 59*, 461-483, 2002.

Ellrod, G. P., 2000: Using GOES and surface temperature data. Preprints, 9^th Conf. Aviation, Range, and Aerospace Meteorology, Amer. Meteor. Soc., Orlando, FL, 8.24, http://www.orbit.nesdis.noaa.gov/smcd/opdb/aviation/opdb_pubs/avn00fog.htm.

Grell, G. A., et al., Fully coupled online chemistry within the WRF model, Atmos. Environ., 39, 6957-6975, 2005.

Han, Y., et al., Community Radiative Transfer Model (CRTM) - Version 1. NOAA Technical *Report* 122, 2006.

Kaufman and Fraser, Light Extinction by aerosols during Summer Air Pollution, J. of Clim and Appl. Met, vol 22, pg 1694-1706, October 1983

Olson, R. H., 1965: On the Use of Bayes Theorm in Estimating False Alarm Rates, Mon. Wea. Rev., 93: 557-558.

Otkin, J. A., and T. J. Greenwald. 2008. Comparison of WRF model-simulated and MODIS-derived cloud data. *Mon. Wea. Rev.* 136:1957-1970.

Pierce, R. B., et al. (2007), Chemical data assimilation estimates of continental U.S. ozone and nitrogen budgets during the Intercontinental Chemical Transport Experiment–North America, J. Geophys. Res., 112, D12S21, doi:10.1029/2006JD007722.

Remer, L. A., Y. J. Kaufman, D. Tanr, S. Mattoo, D. A. Chu, J. V. Martins, R-R. Li, C. Ichoku, R. C. Levy, R. G. Kleidman, T. F. Eck, E. Vermote, & B. N. Holben, 2005: The MODIS Aerosol Algorithm, Products and Validation. Journal of the Atmospheric Sciences, Special Section. Vol 62, 947-973.

Schaack, T et al., (2009), High Resolution Coupled RAQMS/WRF-CHEM Ozone and aerosol simulations for GOES-R Research, 10th Annual WRF Users Workshop, the National Center for Atmospheric Research June 23 - 26, 2009. Extended abstract http://www.mmm.ucar.edu/wrf/users/workshops/WS2009/abstracts/5A-04.pdf

Schmit, T. J., M. M. Gunshor, W. P. Menzel, J. Li, S. Bachmeier, and J. J. Gurka. 2005. Introducing the next-generation Advanced Baseline Imager (ABI) on GOES-R. *Bull. Amer. Meteor. Soc.* 8:1079-1096.

Skamarock, W. C., J. B. Klemp and J. Dudhia, 2001: Prototypes for the WRF (Weather Research and Forecast) model. Preprints, *Ninth Conf. on Mesoscale Processes,* Fort Lauderdale, FL, Amer.Meteor. Soc., CD-ROM, J1.5.

Skamarock, W. C., J. B. Klemp, J. Dudhia Sh, D. O. Gill, D. M. Barker, W. Wang, and J. G. Powers, 2005: A description of the Advanced Research WRF Version 2. NCAR Tech. Note NCAR/TN-468&STR, 88 pp.

Vermote, E., S. Vibert, H. Kilcoyne, D. Hoyt, and T. Zhao, 2002: Suspended matter: Visible/infrared imager/radiometer suite algorithm theoretical basis document, Version 5. SBRS Document Y2390, Raytheon Systems Company, Lanham, MD, 49 pp.