NOAA NESDIS
CENTER for SATELLITE APPLICATIONS and RESEARCH

ALGORITHM THEORETICAL BASIS DOCUMENT

Snow Cover

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ACRONYMS AND ABBREVIATIONS

ABI	**A**dvanced **B**aseline **I**mager
ACM	**A**BI **C**loud **M**ask
AIT	**A**lgorithm **I**ntegration **T**eam
ATBD	**A**lgorithm **T**heoretical **B**asis **D**ocument
AVHRR	**A**dvanced **V**ery **H**igh **R**esolution **R**adiometer
AVIRIS	**A**irborne **V**isible/**I**nfrared **I**maging **S**pectrometer
AWG	**A**lgorithm **W**orking **G**roup
F&PS	**F**unction and **P**erformance **S**pecification
FSC	**F**ractional **S**now **C**over
GOES-R	**G**eostationary **O**perational **E**nvironmental **S**atellite, **R** series
GOESRSCAG	**GOES-R** **S**now **c**over **a**nd **g**rain size
MODIS	**Mod**erate-resolution **I**maging **S**pectrometer
MRD	**M**ission **R**equirements **D**ocument
NEDT	**N**oise **E**quivalent **D**elta **T**emperature
NDVI	**N**ormalized **D**ifference **V**egetation **I**ndex
NOAA	**N**ational **O**ceanic and **A**tmospheric **A**dministration
NWS	**N**ational **W**eather **S**ervice
QA	**Q**uality **A**ssurance
RMSE	**R**oot **M**ean **S**quared **E**rror
RTM	**R**adiative **T**ransfer **M**odel
SCAG	**S**now **c**over **a**nd **g**rain size
SNR	**S**ignal-to-**n**oise **R**atio
TM	**T**hematic **M**apper

ABSTRACT

This Algorithm Theoretical Basis Document (ATBD) provides a high-level description of the physical/mathematical basis and operational implementation of the Snow Cover (FSC) product from the Advanced Baseline Imager (ABI) to be flown onboard NOAA Geostationary Environmental Operational Satellite R series (GOES-R). Currently, prior to launch of GOES-R, the FSC algorithm is being prototyped with available satellite data, specifically NASA Moderate Resolution Imaging Spectroradiometer (MODIS) due to its spectral range, spectral sampling, and spatial resolution. The FSC algorithm, GOESRSCAG – GOES-R Snow Covered Area and Grain size, requires as its input reflectance from optical channels, brightness temperature from thermal infrared channels, and observational/illumination geometry. FSC uses a coupled multiple endmember spectral mixture analysis (MESMA) with a radiative transfer model of snow's spectral reflectance (DISORT) to estimate fractional snow cover per pixel and grain size/snow albedo of that fractional snow cover. It also estimates the fractional cover of green vegetation and soil and rock. Spectral libraries of snow account for changes in grain size, solar geometry, and view geometry. The combination of the geographically meaningful determination of fractional cover from MESMA and directionally explicit snow spectral endmembers results in a direct, physical retrieval of fractional snow cover as opposed to previous empirical approaches. The validation and testing of the FSC algorithm will be carried out with (a) retrievals of FSC from proxy ABI data (five bands) compared with retrievals of FSC for the same data but with the full band space of MODIS (seven bands – MODIS Snow Covered Area and Grain size model - MODSCAG) and with (b) comparisons of FSC from proxy ABI data with high spatial resolution retrievals of FSC from Thematic Mapper data. FSC will also be monitored with *in situ* determinations of snow presence from broad networks in the CONUS, Canada, and Alaska. Ultimately, before GOES-R ABI data are available but after the NASA MODIS on Terra and/or Aqua have failed, we will use fractional snow cover retrievals from the NOAA National Polar Orbiting Environmental Satellite System (NPOESS) analogue instrument Visible Infrared Imaging Radiometer Suite (VIIRS). Compared with MODSCAG retrievals that have an uncertainty of 0.05, the FSC from proxy ABI data have no bias (mean difference = 0.02) and a one-sigma standard deviation of 0.08 in snow cover across the range 0.00 to 1.00. These results of prototyping and validation of the ABI FSC product show that its accuracy/precision are well within existing GOES-R ABI specifications for FSC.

1. INTRODUCTION

1.1 Purpose of This Document

The Fractional Snow Cover (FSC) Algorithm Theoretical Basis Document (ATBD) provides a) a high level description of and b) the physical basis for the retrieval of the fraction of each pixel covered by snow from image data acquired by the Advanced Baseline Imager (ABI) instrument proposed for the GOES-R series of NOAA geostationary meteorological satellites. The FSC product will provide estimates of snow cover, as a fraction of each ABI pixel area, for image regions not obscured by clouds or heavy forest cover. The FSC product will be made available to variety of Algorithm Working Group (AWG) products that have indicated a dependency on *a priori* knowledge of the presence of snow. FSC, a GOES-R program office option 1 (baseline) product, has also been identified as a critical GOES-R end user product.

1.2 Who Should Use This Document

The intended users of this document are those interested in understanding the physical and mathematical basis of the spectral mixture analysis, as applied to fractional snow cover retrievals, and how to utilize the outputs of fractional snow cover for a particular application. This document also provides information useful to anyone involved with maintaining or modifying the original algorithm.

1.3 Inside Each Section

This document is broken down into the following main sections:

- **Observing System Overview**: Provides relevant details of the GOES-R ABI instrument and provides a brief description of the products generated by the Fractional Snow Cover algorithm (FSC).

- **Algorithm Description**: Provides a detailed description of the FSC including its physical and mathematical basis, its inputs and its outputs.

- **Test Data Sets and Validation**: Provides a description of the proxy GOES-R ABI data sets used to assess the performance of the FSC and the quality of its output products. It also describes the results from the FSC processing using the simulated GOES-R ABI input data.

- **Practical Considerations**: Provides an overview of the issues involved in the FSC numerical computation, programming and procedures, quality assessment and diagnostics, exception handling, and continuing validation efforts.

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

1.4 Related Documents

This document currently does not relate to any other document outside of the specifications of the GOES-R Ground Segment Functional and Performance Specification (F&PS), the GOES-R Mission Requirements Document (MRD) 3 and to the specific documents referenced in following sections. We anticipate that the FSC ATBD may ultimately relate to other GOES-R AWG ATBDs, especially the ACM ATBD.

This document has an appendix (Appendix 1) which contains additional information for programmers. Programmers should consult the appendix to learn about the formats and data types of, among other things, the configuration files.

1.5 Revision History

Version 0.1 of this document was created by Donald Cline, NOAA/NWS/NOHRSC; Thomas Painter, UCAR/UCLA; Milan Allen, NOAA/NWS/NOHRSC; Christopher Bovitz, UCAR/NOHRSC; Kelley Eicher, UCAR/NOHRSC; and Andrew Rost, NOAA/NWS/NOHRSC. Its intent is to accompany the delivery of version 0.1 of the FSC code set to the GOES-R AWG Algorithm Integration Team (AIT).

Version 1.0 of this document was created by Thomas H. Painter, UCAR/UCLA; Andrew Rost, NOAA/NWS/NOHRSC; Donald Cline, NOAA/NWS/NOHRSC. Its intent is to accompany the delivery of version 3 of the FSC code sent to the GOES-R AWG Algorithm Integration Team (AIT) and it considered the 80% delivery. Revision date is 10 August, 2009.

Version 2.0 of this document was created by Thomas H. Painter, UCAR/UCLA; Andrew Rost, NOAA/NWS/NOHRSC, and Christopher Bovitz, UCAR/NOHRSC. Its intent is to accompany the delivery of version 5 of the FSC code sent to the GOES-R AWG Algorithm Integration Team (AIT) and it considered the 100% delivery. Revision date is 30 June 2010.

Version 2.1 of this document was created by Thomas H. Painter, UCAR/UCLA; Andrew Rost, NOAA/NWS/NOHRSC, and Christopher Bovitz, UCAR/NOHRSC. Its intent is to accompany the September 2010 of version 5 of the FSC code sent to the GOES-R AWG Algorithm Integration Team (AIT) and it considered an update to the 100% delivery. Revision date is 30 September 2010.

All revisions to this ATBD include author of the revision, description of the revision, motivation for the revision, and revision number and date.

2. Observing System Overview

This section will describe the products generated by the FSC and the requirements it places upon the GOES-R ABI instrument. Where appropriate, throughout the remainder of this document, the FSC may also be referred to as GOESRSCAG (GOES-R Snow Cover And Grain size), which is the formal name of the FSC code set.

2.1 Products Generated

The FSC is responsible for calculating subpixel estimates of snow cover. FSC retrievals are expressed as the fraction of the ABI pixel covered by snow (0.0 = no snow cover continuously through 1.0 = total snow cover). FSC is often referred to in the literature as sub-pixel snow cover. Since the FSC is based upon the spectral reflectance of snow in the visible and near-visible wavelengths of the electromagnetic radiation spectrum that varies by the changes in grain size of the snow pack's surface, the FSC also retrieves snow grain size. Among other uses, rapid changes in snow grain size in the temporal domain can be used to infer the presence of clouds in ABI imagery.

In terms of the F&PS, the FSC is not directly responsible for other products. However, several AWG teams have identified a dependency upon *a priori* knowledge of snow cover. Additionally, since the ABI Cloud Mask (ACM) is dependent upon an ABI derived snow mask, any AWG product dependent upon the ACM may also be indirectly dependent upon the FSC.

The specific products generated by the FSC include:

- Fraction of pixel covered by snow (0.0 – 1.0) (primary),
- Fraction of pixel covered by non-snow surface and its land surface type (e.g., vegetation, bare soil, rock, etc. 0.0 – 1.0) (intermediate),
- Snow grain size (Sphere radii 10 to 1,100 μm) (intermediate),
- Binary (snow/not snow) coverage (intermediate)
- Quality values (intermediate)
- Quality flags (intermediate)
- RMSE retrieval confidence (intermediate).

Updates to the F&PS requirements for fractional snow state that the measurement accuracy for the FSC is 0.15 fractional and the measurement precision for FSC is 0.30 fractional (Table 1).

Table 1. Snow Cover product requirements from F&PS.

Region	Horizontal Resolution	Refresh Rate	Product Range	Product Accuracy	Product Precision	Product Type	Product Sub-type
Hemispheric	2 km	60 min	Fraction 0 – 1	0.15	0.30	Land	Land
Coterminous U.S.	2 km	60 min	Fraction 0 – 1	0.15	0.30	Land	Land
Mesoscale	2 km	60 min	Fraction 0 – 1	0.15	0.30	Land	Land

2.2 Instrument Characteristics

FSC will be produced for each noncloud pixel observed by the ABI. The GOESRSCAG model is dependent upon the spectral surface characteristics of the snow pack, as a function of snow grain size, in the visible and near-visible portion of the energy spectrum. Table 2 summarizes the ABI channel subset used by GOESRSCAG. Unless the design specification of the GOES-R ABI instrument changes, the final delivery channel subset used by the FSC has not changed as the algorithm is developed and validated.

It should be noted that since the FSC is based on the spectral signature of snow at the surface, the algorithm is designed to perform using surface reflectance corrected data generated by a rigorous Radiative Transfer Model (RTM). However, the algorithm can be modified to work with top of atmosphere (TOA) reflectances as well if a common spectral surface reflectance product is not available. As of this writing the common spectral surface reflectance product is under development with contributions primarily from the radiation/albedo team but also the cryosphere team. It is hoped that the development of an RTM for the GOES-R ground segment will benefit more than just the FSC algorithm's results.

Table 2. GOES-R ABI bands required in algorithm.

ABI Channel	Wavelength (μm)	Upper Limit of Dynamic Range	NEDT/SNR	Used in FSC?
1	0.45 – 0.49	625 W m^{-2} sr^{-1} μm^{-1}	300:1	✓
2	0.59 – 0.69	515 W m^{-2} sr^{-1} μm^{-1}	300:1	✓
3	0.8455 – 0.8845	305 W m^{-2} sr^{-1} μm^{-1}	300:1	✓
4	1.3075 – 1.3855	114 W m^{-2} sr^{-1} μm^{-1}	300:1	
5	1.58 – 1.64	77 W m^{-2} sr^{-1} μm^{-1}	300:1	✓
6	2.225 – 2.275	24 W m^{-2} sr^{-1} μm^{-1}	300:1	✓
7	3.8 – 4.0	400 K	0.1 K	*
13	10.1 – 10.6	330 K	0.1 K	*

* Use of thermal bands use is a planned enhancement

Secondly, since snow is a highly reflective material in the visible portion of the electromagnetic spectrum, the FSC may be sensitive to detector saturation and damping. Thirdly, since the FSC relies on spectral mixture analysis, imagery artifacts and instrument noise will negatively impact its performance.

The geometric fidelity of the GOES-R ABI may have an impact on the GOESRSCAG performance. If image-to-image pixel registration can be counted on (either mechanically or via software image navigation) the efficiency of the FSC's implementation can be enhanced by "buffering" certain GOESRSCAG calculations between temporally sequential data sets. This in particular will serve to enhance cloud/snow discrimination.

Finally, since FSC is an Earth surface feature, it is important to consider horizontal displacement distortions in the GOES-R ABI image data. While the end user may remove these distortions, it is preferable that parallax corrections be applied in the ground segment prior to product distribution. Correction of this distortion prior to the application of the FSC will nontrivially improve the algorithm's performance.

3. ALGORITHM DESCRIPTION

Complete description of the FSC at the current level of maturity (which will improve with each revision).

3.1 Algorithm Overview

The FSC retrievals serve a critical role in the GOES-R ABI processing system. It is a fundamental physical property but also serves to determine which pixels can be used for atmosphere and land cover applications (ACM, NDVI etc). The FSC is based on spectral mixing analysis. The implementation of the FSC, GOESRSCAG, has lineage directly from:

- HYPSCAG (Hyperion-based fractional snow cover and grain size) (Painter, 2002)
- MEMSCAG (AVIRIS-based fractional snow cover and grain size) (Painter et al., 2003)
- MODSCAG (MODIS-based fractional snow cover and grain size) (Painter et al., 2009)
- TMSCAG (Thematic Mapper-based fractional snow cover and grain size) (Painter et al., 2010b).

GOESRSCAG uses

- calculated (not directly measured) surface reflectance values
- calculated (not directly measured) cloud mask values.

Briefly stated, spectral mixture algorithms extract from the spectrum measured for a single pixel the proportions of individual spectra of the constituent materials (endmembers) observed by the instrument. The measured spectrum is proportionally decomposed into individual spectra by straightforward matrix inversion between the instrument observed spectrum and a library of *a priori* known, pure spectra.

GOESRSCAG, the implementation of the FSC for the GOES-R ABI, can be characterized as being a *Multiple Endmember Spectral Mixture Analysis* (Roberts et al., 1998a) wherein the

- Number of endmembers may vary pixel-by-pixel
- Endmembers themselves may vary pixel-by-pixel
- Snow endmembers are generated with radiative transfer model DISORT

which retrieves the following products

- Fraction of each pixel covered by snow (0.0 – 1.0) (primary)
- Fraction of each pixel covered by non-snow surfaces (e.g., vegetation, bare soil, etc.) (intermediate)
- Effective snow grain size of the per-pixel snow cover fraction (intermediate)
- Binary (snow/not snow) coverage (intermediate)
- Per-pixel RMSE retrieval confidence (intermediate)

In general, the fractional snow cover products can be used for clear conditions (snow mapping), cloudy conditions (cloud mapping), and as a pre-processing step for land cover pixel product generation for use by other applications.

3.2 Processing Outline

The processing outline of the core elements of the FSC, as expressed in the GOESRSCAG code set, is presented in Figure 1. The code set is designed to run on entire GOES-R ABI image sets. For processing efficiency, GOESRSCAG is implemented as a multi-threaded application with the number of threads being configurable.

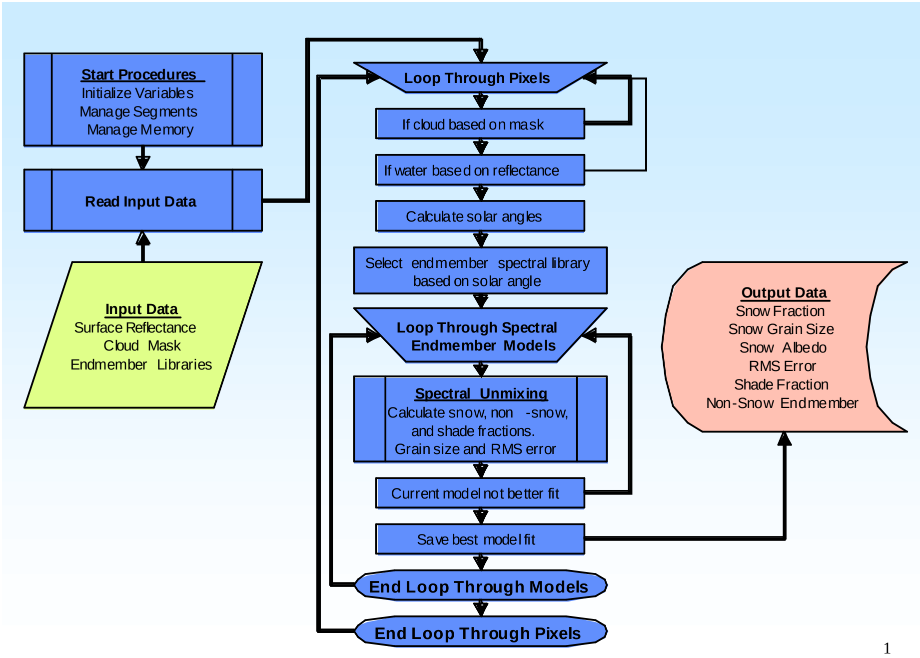

Figure 1. Basic flowchart of core snow cover elements in GOESSCAG implementation.

Two items should be noted. First, under certain circumstances GOESRSCAG is capable of making it own determination of cloud cover. GOESRSCAG cloud cover could augment the AWG Cloud Team ACM product.

Second, GOESRSCAG processing efficiency is enhanced by buffering certain calculations (e.g. previous FSC retrieval, pixel specific nonsnow endmembers) between time-sequential GOES-R ABI image sets. This aspect of the GOESRSCAG processing stream is not represented in Figure 1.

This section describes the input needed to process the FSC. The FSC is derived for each ABI pixel, and requires knowledge of clouds and surface reflectance. In its current implementation, we run the GOESRSCAG on each pixel.

Code will be described in much greater detail in Appendix 1 with important code sections detailed in subsequent appendices.

3.3 Algorithm Input

3.3.1 Primary Sensor Data

The list below contains the primary sensor data used by GOESRSCAG. By primary sensor data, we mean information that is derived solely from the ABI observations and geolocation information.

- GOES-R ABI surface reflectance band passes (preferably parallax corrected for horizontal displacement distortions)
- As per the Algorithm Working Group meeting, a common spectral surface reflectance product will be available for all GOES-R product streams.
- Quality flags for surface reflectance bands
- Quality flags for general pixel utility
- View zenith θ_v and azimuth ϕ_v angles for each GOES-R pixel (fixed by satellite position – each is predictable)
- Solar zenith θ_0 and azimuth ϕ_0 angles for each GOES-R pixel (variable – each is predictable)
- First estimate of clouds generated locally or by the GOES-R Cloud Team. A snow-specific final cloud mask will be determined by the GOESRSCAG model using the grain size retrievals coupled with persistence metrics for changes in grain size.

3.3.2 Ancillary Data

The following data lists and briefly describes the ancillary data required to run GOESRSCAG. By ancillary data, we mean data that requires information not included in the ABI observations or geolocation data.

- Interpolated spectral libraries calculated ahead of time in five-degree increments of angles of solar zenith, view zenith, and relative azimuth (solar azimuth – view azimuth). These libraries are used to de-mix the spectral signature from a pixel. The various calculated spectra are used alone or in pairs to determine the best fit to the spectral response in the pixel.
- Model types are used to direct the algorithm on how to attempt to unmix a pixel's spectral signature. Currently, there are spectral libraries for many variations of snow, vegetation, rock, and ice.
- Dynamically-updated (by GOESRSCAG) non-snow endmember per pixel. The most-prominent non-snow endmember for each pixel is stored in a file, and on subsequent runs, the nonsnow endmember which corresponds to this ground covering is used to calculate the snow fraction. This field is recalculated for pixels which are close to solar noon (for best solar illumination).
- Land-Water Mask. GOESRSCAG will skip non-land pixels identified in a common product land-water mask

3.4 Theoretical Description

GOESRSCAG spectral mixture analysis derives from heritage algorithms that work on AVIRIS, AVHRR, and MODIS, retrieving subpixel fractional snow cover and grain size estimates via multiple endmember spectral mixture analysis. This physically based retrieval model is well-established and proven with MODIS (Painter et al., 2009) and AVIRIS (Painter et al., 2003) data. As is the case with any algorithm that uses optical data such as the reflectance bands of ABI, GOESRSCAG is unable to make snow retrievals under cloudy and heavily forested conditions. Implemented with MODIS surface reflectance data, the model has fractional snow cover uncertainty of < 0.05 and implemented with AVIRIS data has fractional snow cover uncertainty of < 0.04 (Painter et al., 2003; Painter et al., 2009).

3.4.1 *Physics of the Problem*

The current MODIS snow cover product, MOD10, is a “binary” map, whereby each pixel is classified as either “snow” or “not snow” (Hall, 2002). The algorithm’s heritage traces back to retrieval of snow-covered area and qualitative grain size from the Landsat Thematic Mapper using normalized band differences (Dozier, 1989).

In contrast to the binary product, the GOESRSCAG model estimates the fraction of each pixel that is covered by snow, along with the grain size of that snow, using spectral mixture analysis and a radiative transfer model. Their simultaneous solution is necessary because the spectral reflectance of snow is sensitive to grain size (Warren, 1982) and the spectrum of the mixed pixel is sensitive to the spectral reflectance of the snow fraction (Painter et al., 1998). Therefore, we allow the snow’s spectral reflectance to vary pixel-by-pixel and thereby address the spatial heterogeneity that characterizes snow cover in rough terrain (Painter et al., 2003; Painter et al., 2009).

3.4.1.1 Snow Endmembers

In spectral mixture analysis, an endmember is the spectral reflectance of a pure surface cover. GOESRSCAG uses a snow spectral library generated with model calculations of snow reflectance for monodispersions of spheres of radii 10 to 1,100 µm and solar zenith angles ranging from 0 degrees to 75 degrees of arc to accommodate changes in solar zenith angles during GOES-R ABI acquisitions. We calculate their single-scattering properties over each ABI band with Mie theory (Mie, 1908; Nussenzveig and Wiscombe, 1980; Wiscombe, 1980) and the hemispherical-directional reflectance factor R_λ (Schaepman-Strub et al., 2006) with a discrete-ordinates RTM (DISORT, Stamnes et al., 1988).

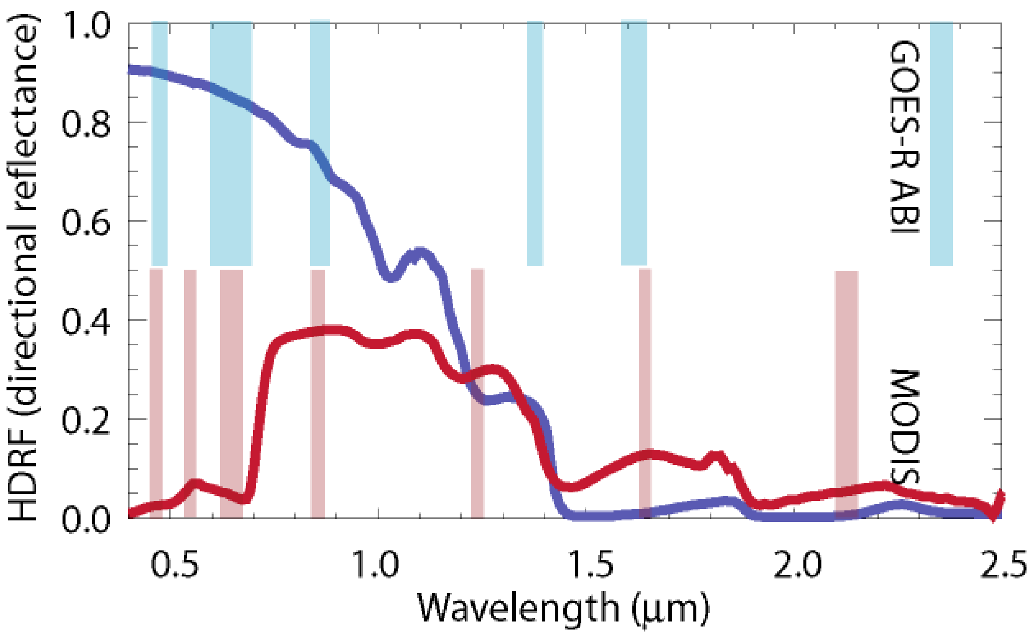

Figure 2. Snow (blue spectrum) and vegetation (red spectrum) endmembers with GOES-R ABI (blue bars) and MODIS (red bars) implementations.

3.4.1.2 Rock, Soil, Vegetation, and Lake Ice Endmembers

The spectral library of vegetation, rock, soil, and lake ice comes from hyperspectral reflectance measurements made in the field and laboratory with an Analytical Spectral Devices field spectroradiometer (http://www.asdi.com). These spectra were convolved from 1 nm spectral resolution to the ABI bandpasses. **Error! Reference source not found.** Figure 2 shows snow (blue) and vegetation (red) endmembers contained in a spectral library with the GOES-R ABI and MODIS bandpasses indicated.

3.4.2 Mathematical Description

Linear spectral mixture analysis is based on the assumption that the radiance or reflectance measured at the sensor is a linear combination of radiances reflected from individual surfaces. The technique has been used to infer the fractional cover of vegetation cover (Roberts et al., 1998b; Okin, 2007), soils and rock cover (Asner and Heidebrecht, 2002; Ballantine et al., 2005), urban landscapes (Powell et al., 2007), and snow cover (Nolin et al., 1993; Rosenthal and Dozier, 1996; Painter et al., 1998; Painter et al., 2003; Painter et al., 2009). By contrast, Salomonson and Appel (2004; 2006) used a regression approach with the Normalized Difference Snow Index to infer fractional snow cover but with FSC uncertainties greater than 0.30 due to the tremendous scatter in the relationship between coarsened Thematic Mapper data and the NDSI (Painter et al., 2009a).

The linear assumption for spectral mixture analysis is appropriate for spatial scenarios such as snow and rock cover above timberline where the surface is near planar. Nonlinear analysis, which accounts for multiple scattering between surfaces, is necessary when the surface has a structure, such as vegetation that reflects and transmits radiation to the snow or soil substrate and other vegetation (Roberts et al., 1993). However, nonlinear mixtures can be linearized through the use of canopy-level endmembers. The vegetation endmembers in the spectral library are canopy-level measurements.

Spectral mixture analysis is based on a set of simultaneous linear equations that make up the components of the pixel-averaged ABI surface reflectance:

$$R_{S,\lambda} = \sum_{i=1}^{N} F_i R_{\lambda,i} + \varepsilon_\lambda \qquad (1)$$

where F_i is the fraction of endmember i, $R_{\lambda,i}$ is the hemispherical-directional reflectance factor of endmember i at wavelength λ, N is the number of spectral endmembers, and ε_λ is the residual error at λ for the fit of the N endmembers. The least squares fit arriving at F_i can be solved by several standard methods. The residual error is a rearrangement of the linear mixture model:

$$\varepsilon_\lambda = R_{S,\lambda} - \sum_{i=1}^{N} F_i R_{\lambda,i} \qquad (2)$$

The root mean squared error provides a spectrum-wide measure of fit for a mixture model:

$$RMSE = \left(\frac{1}{M} \sum_{\lambda=1}^{M} \varepsilon_\lambda^2 \right)^{1/2} \qquad (3)$$

where M is the number of imaging spectrometer bands used. The *RMSE* is a useful fundamental metric for optimizing selection of model results in the multiple endmember spectral mixture analysis (Dennison and Roberts, 2003).

The estimate of subpixel snow-covered area comes from the shade-normalized snow fraction f_S:

$$f_S = \frac{F_S}{\sum_{p \in S,v,r} F_p} = \frac{F_S}{1 - F_{shade}} \quad (4)$$

where F_s is the snow spectral fraction, F_p are the physical spectral fractions (non-shade), and F_{shade} is the spectral fraction of photometric shade (Gillespie et al., 1990). Normalizing by the additive complement of the shade fraction accounts for topographic effects on irradiance. The estimates of subpixel vegetation cover, rock cover, and other surface cover are determined with equation (4) as well.

3.4.2.1 GOESRSCAG Model

GOESRSCAG analyzes individual linear spectral mixtures for each permutation of two or more endmembers of the spectral library, in which no more than one endmember from a surface cover class is present (i.e., at most one snow endmember). For example, a potential model would consist of snow endmember of grain radius, coniferous forest, and photometric shade. A model is considered valid if: (a) spectral fractions are in the range [-0.01, 1.01], (b) overall RMSE is less than 2.5%, and (c) no three residuals exceed 2.5%.

For each *n*-endmember suite of models that meet the constraints for a pixel, GOESRSCAG selects the snow fraction and grain size values associated with the smallest error and the tighter constraints. GOESRSCAG then attributes to the pixel the snow fraction and snow grain size of the valid model that has the fewest endmembers because a solution with more endmembers is mathematically trivial relative to that with fewer. The data flow of GOESRSCAG is exhibited in Figure 1.

GOESRSCAG incorporates the following assumptions: (a) the variability in the hemispherical-directional reflectance factor for the solar geometry and atmospheric conditions at the time of each GOES-R ABI acquisition is negligible, i.e., $R_\lambda(\theta_0, \phi_0, 0, 0) \approx R_\lambda(\theta_0, \phi_0, \theta_r, \phi_r)$ within the range of angles $[\theta_r, \phi_r]$ observed from GOES-R ABI; (b) the effects of impurities and the effects of thin snow on snow spectral reflectance are not separable and these effects do not impact retrievals of snow area and grain

Table 3. Snow cover (GOESRSCAG) algorithm outputs

FSC Output	Description	Category
Snow Fraction	Fraction of pixel covered by snow endmember (0.0 to 1.0)	Product
Non-Snow Fraction	Fraction of pixel covered by non-snow endmember (0.0 to 1.0)	Intermediate
Vegetation fraction	Fraction of pixel covered by vegetation (0.0 to 1.0)	Intermediate
Rock/soil fraction	Fraction of pixel covered by rock or bare soil (0.0 to 1.0)	Intermediate
Snow Grain Size	Sphere radii ranging from 10 to 1,100 μm	Intermediate
Binary snow	Pixel is covered/not covered by snow (0 or 1)	Intermediate
RMSE	Retrieval confidence (0.0 to 1.0)	Diagnostic
Quality values	Number which represents reasons why pixel was modeled or not modeled.	Quality
Quality flags	Logical bit flags which represent reasons why pixel was or was not modeled.	Quality

size; (c) linear spectral mixture analysis is valid for multispectral scenes of alpine terrain; and (d) liquid water in the snow does not affect the retrievals of snow-covered area and grain size. Painter et al. (2003) and Painter and Dozier (2004) specifically confirmed the validity of these assumptions for spectral mixture analysis of FSC.

3.4.3 Algorithm Output

There are three types of final output that are produced by the algorithm: products (snow fraction), quality information (quality values, quality flags), diagnostic/intermediate information (non-snow fraction, snow grain size, binary snow, vegetation fraction, soil fraction), and metadata (RMSE). Table 3 gives information about each of these outputs.

The primary output of the algorithm is (fractional) snow cover. Along with the header file that will accompany the data file, there will be additional metadata produced for the image. For the entire image and for specified subregions, the algorithm will provide the RMS, maximum, and minimum values for those areas in an ASCII list. The following is an example of this metadata for the entire image ("Full Disk") and each region ["Region #", where # is the region number and ranges from 1 to the number of regions (specified by "M")]:

Region name: Full Disk
Minimum fraction: <maximum value>
Maximum fraction: <minimum value>
Mean faction: <mean value>
Mean of RMS: <RMS value>
Standard deviation of RMS: <stddev value>
Number of QA flags: <value>
Flag 0 QA description: <string>
Flag 0 % of retrievals: <value>
Flag 1 QA description: <string>
Flag 1 % of retrievals: <value>
…
Flag 7 QA description: <string>
Flag 7 % of retrievals: <value>

Number of snow regions: <value>

Region 1 name: <string>
Minimum fraction: <maximum value>
Maximum fraction: <minimum value>
Mean fraction: <mean value>
Mean of RMS: <RMS value>
Standard deviation of RMS: <stddev value>
Number of QA flags: <value>
Flag 0 QA description: <string>
Flag 0 % of retrievals: <value>
Flag 1 QA description: <string>
Flag 1 % of retrievals: <value>
…

Flag 7 QA description: <string>
Flag 7 % of retrievals: <value>

…

Region M name: <string>
Minimum fraction: <maximum value>
Maximum fraction: <minimum value>
Mean fraction: <mean value>
Mean of RMS: <RMS value>
Standard deviation of RMS: <stddev value>
Number of QA flags: <number of flags>
Flag 0 QA description: <string>
Flag 0 % of retrievals: <value>
Flag 1 QA description: <string>
Flag 1 % of retrievals: <value>
…
Flag 7 QA description: <string>
Flag 7 % of retrievals: <value>

Quality assurance (QA) values will be tracked for each pixel in both the entire image and for specified subregions. These values (in the quality_bits file) will be composed of eight bits that can be interpreted as an integer. If all bits are "turned off" (i.e., the QA value is 0), a good snow-fraction retrieval was performed. This can also include a successful retrieval of no snow (0%). If a pixel is not modeled, or is modeled but the snow fraction value should be used with caution, its QA value will not be 0. Table 4 interprets the use of the quality bits. Bit 0 is the least-significant bit of the QA value; bit 7 is its most significant bit.

The format of these data will be of the form "variable: value", where "variable" will be the name of the datum (such as "whole image RMS" or "region 1 maximum") and "value" will be the value of that particular item.

The GOESRSCAG algorithm has a 60 minute refresh, therefore it should be run once an hour.

The product quality information associated with each FCSA retrieval is defined as follows:

0.00: if the no data value was encountered in any of the inputs, or

1.00: if the pixel falls on water, or

2.00: if the solar zenith angle is too small, or

Table 4. Interpretation of QA bits in quality bits field.

QA bit	Meaning if bit is set
0	No-data value in band data
1	Missing data in band data
2	Modeled cloudy
3	Salt water
4	Solar zenith angle out of acceptable range
5	Sensor zenith angle out of acceptable range
6	Bad metadata or ancillary data
7	Other reason

3.00: if the solar zenith angle is too large, or

4.00: if the pixel could not be modeled, or

5.00: if the pixel had bad source data, or

6.00: if the pixel has bad horizontal location (latitude or longitude) metadata, or

7.00: if the pixel has an unreasonable sensor angle value, or

8.00: if the pixel has an unreasonable solar zenith angle, or

10.00: if the pixel could be modeled but is snow free, or

2f.ff: if the pixel could be modeled and has snow (where fife is the snow fraction), or

3f.ff: if the pixel could be modeled and has shaded snow (zero grain size) (should be physically impossible but is mathematically feasible) (where f.ff is the snow fraction), or

4f.ff: if the pixel could be modeled and has cloud by grain size (where f.ff is the cloud fraction).

The flags may be modified by the FSCA for cloud masking as follows:

Add 100.00 if cloud masked, or

Add 200.00 if probably cloud masked, or

Add 300.00 the cloud mask is undetermined,

The flags may be modified by the FSCA for the following second-most prominent non-snow endmember in a modeled pixel:

Add 1,000.00 if the most prominent non-snow endmember is vegetation, or

Add 2,000.00 if the most prominent non-snow endmember is vegetation, or

Add 8,000.00 if the most prominent non-snow endmember is other, or

Add 9,000.00 if the most prominent non-snow endmember is photometric shade

The flags may be modified by the FSCA for the following condition:

Add 10,000 if the pixel was modeled but beyond the sensor angle threshold

4. TEST DATA SETS AND OUTPUTS

GOESRSCAG requires as input the spectrum measured by the Advanced Baseline Imager. Because ABI is a quantum step forward in geostationary sampling, no data exist from GOES or SEVERI to serve as proxy data. Therefore, in order to perform validation in the Pre-launch Phase, we must use proxy data from the current MODIS instruments on Terra and Aqua while still available, and, once no longer available, data from the Visible Infrared Imaging Radiometer Suite (VIIRS) in the NPOESS Preparatory Project and the NPOESS. In the Post-launch Phase, we will perform validation of the algorithm directly from the ABI data and with the VIIRS data in order to assess how accurately proxy data had represented the ABI data in the Pre-launch Phase.

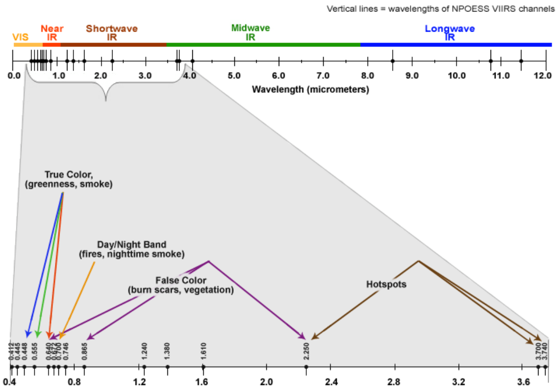

Figure 3. VIIRS bandpasses. Note these include some bands that are not included in the surface reflectance products.

4.1 Input Data Sets

Proxy data will be created with MODIS data for as long as the Terra and Aqua MODIS instruments are functional. As of Spring 2009, both have exceeded their design lives of six years (Terra in 2006, Aqua in 2008), so it is likely that no MODIS acquisitions will be available by the 2015 launch of GOES-R. However, radiance and surface reflectance data from the NPOESS Preparatory Project (NPP) Visible/Infrared Imager Radiometer Suite (VIIRS) will be available from the NOAA Comprehensive Large Array-data Stewardship System (CLASS) and NASA EOSDIS (Figure 3). Launch as of this writing is scheduled for 2010. Data from the NPOESS VIIRS should be available in 2013 according to present launch schedule but this date may well slip if NPP is an indication of readiness for NPOESS. While input data from MODIS data has been thoroughly tested regarding its use in the algorithm, it is expected that the other aforementioned data sources will be compatible with the algorithm or could be made so with minimal adjustments to the data.

Proxy and simulated ABI data will be made available by the GOES-R proxy data team. During Pre- and Post-launch periods, the NOHRSC will be running MODSCAG/VIIRSSCAG operationally. Therefore, we can ship the either the raw data or the FSC retrievals to the AWG proxy data team for most teams to use as proxy FSC for their algorithms. The FSC team requires proxy data that mimic the ABI spectrum of bands 1 through 3 and 5 through 6. MODIS bands 1, 3, 4, 6, and 7 and the VIIRS bands M3, M5, M7, M10, and M11 are analogues for the required bands in the ABI spectrum (Table 4).

Already we have begun collections of MODIS calibrated radiance data (Level 2) at the National Operational Hydrologic Remote Sensing Center (NOHRSC). We download MOD02IKM, MOD02HKM, MOD02QKM and MOD03 level 1b data and convert them to surface reflectance with the MOD09_SPA program that is made available by the NASA Direct Readout Laboratory (http://directreadout.sci.gsfc.nasa.gov - version V5.3.18). The MOD09_SPA code converts the radiance data to surface reflectance with a sparser ancillary dataset that characterizes the atmosphere so that surface reflectance is available with latency of less than 1 day rather than the approximately four-day latency of delivery of the MODIS MOD09GA Surface Reflectance Product. MOD09_SPA uses the Global Data Assimilation

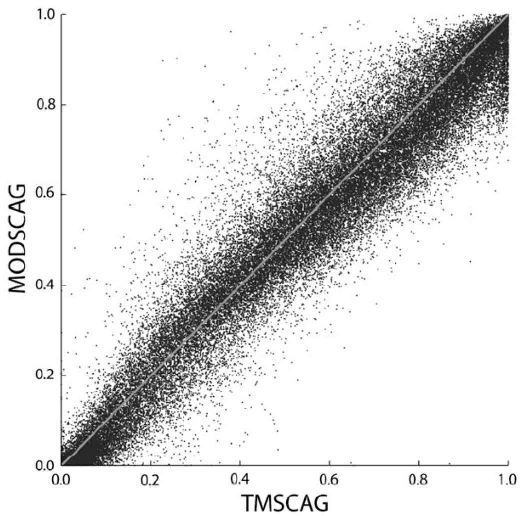

Figure 4. Aggregated comparison of MODSCAG and TMSCAG.

Group (GDAS) numerical weather prediction model. NOHRSC has a bent-pipe feed of MODIS radiance data (MOD02x, MOD03x) from NASA EOSDIS and GDAS data from the Goddard Space Flight Center so that we can access these data at sub-day latency. The greatest lag comes in the delivery of GDAS data with latencies as great as six hours.

Table 4. FSC GOES-R ABI proxy data for pre-launch (MODIS, VIIRS) and post-launch

GOES-R ABI Channel Number	GOES-R ABI Wavelength (µm)	Used in FSC	MODIS proxy Channel	VIIRS Proxy Channel
1	0.47	✓	1	M3
2	0.64	✓	3	M5
3	0.8655	✓	4	M7
5	1.61	✓	6	M10
6	2.25	✓	7	M11
7	3.9	*	21	M12
13	10.35	*	31	M15

* Use of thermal bands use is a planned enhancement

We will use the MODSCAG model to retrieve FSC for validation from the seven band MODIS surface reflectance data (Painter et al., 2009). In parallel, the MODIS data will be reduced in band space to that of ABI as shown above. Given that MODSCAG has an FSC accuracy of -0.005 and precision of 0.049 as shown in **Error! Reference source not found.** and in Error! Reference source not found. (Painter et al., 2009), 7-band FSC retrievals from MODIS will represent a validation set that addresses the model uncertainty that is related to the changes in band space at native resolution of 500 m and then coarsened to 2 km.

Upon the availability of NPP and NPOESS VIIRS reflectance data, we will use ABI proxy data from NPP VIIRS and NPOESS VIIRS data. As is done with MODIS data, we will initially run the new model (VIIRSSCAG) with the 11 VIIRS reflectance bands M1-M11, which span 0.412 to 2.25 µm wavelength, at 742 m spatial resolution, for validation. Subsequently, we will compare the 5-band proxy ABI retrievals with the full VIIRSSCAG retrievals at the native resolution of 742 m and then coarsened to 2 km. Note that Investigator Painter is discussing with the Northrup-Grumman team in charge of algorithms for VIIRS the adoption of VIIRSSCAG as the standard snow cover product for NPOESS VIIRS. NPP VIIRS already has adopted the more simplistic binary snow cover model based on poor implementation of the original ATBD for snow cover for VIIRS. Table 4 describes the GOES-R channels used in the GOESRSCAG algorithm and their corresponding bands in proxy data from other satellites.

Validation of the 5-band proxy ABI data against the MODSCAG 7-band results has been performed with several years' data for the coterminous US (2008 – 2010). Merging of all of these scenes including 38 full CONUS retrievals from weekly reflectance composites in 2010 from MODIS showed that FSC (GOESRSCAG) has accuracy well within specification. These results are described below.

4.2 Output from Input Data Sets

The output data from the proxy ABI data from MODIS have the same general formats as those that will come from the operational ABI processing. These will be represented as continuous fractional snow cover (as well as fractional green vegetation, fractional soil/rock/senesced vegetation) as shown in **Error! Reference source not found.** for the north-central coterminous US into southern Canada. These output data match the content of the algorithm package delivery.

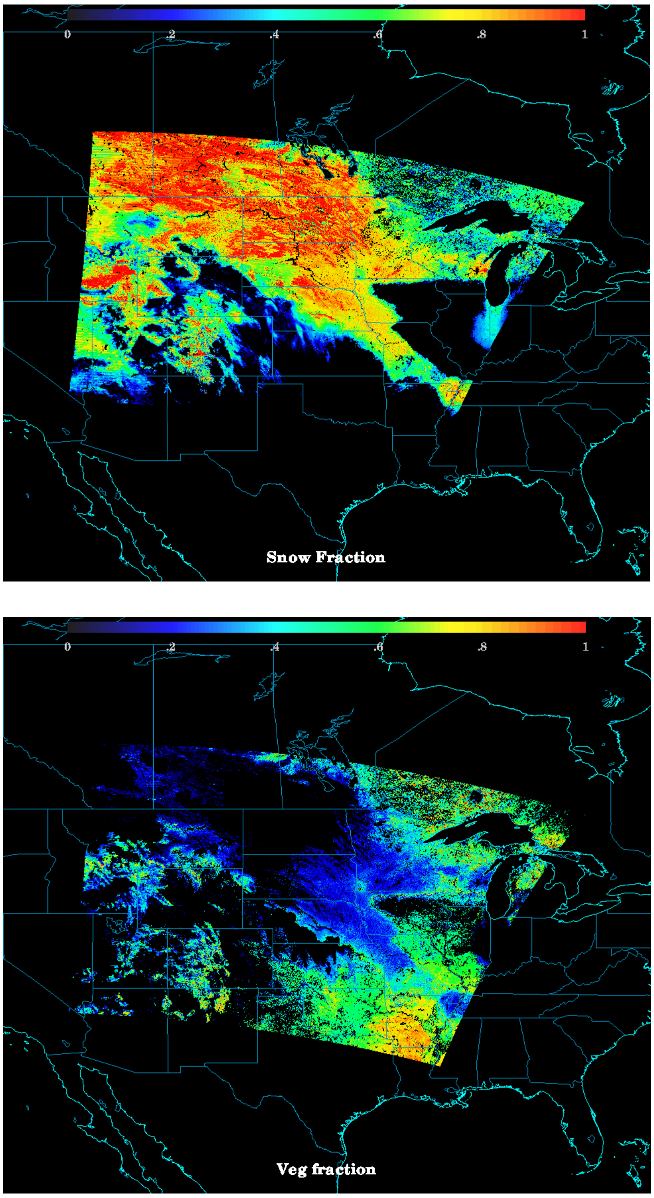

Figure 5. Simulated GOES-R ABI snow fraction (top) and green vegetation fraction (bottom) from GOESRSCAG processing of proxy ABI data from MODIS, 1 March 2009.

4.2.1 Accuracy and Precision Estimates

The mean difference between the five bandpass GOESRSCAG outputs and the seven bandpass MODSCAG outputs were calculated where both algorithms identified snow on the same pixel (Table 5). Calculation of difference for all regions that also include no snow was calculated and establishes a better estimate of the detection of snow than the quantification of snow covered area (Table 5).

4.2.2 Error Budget

Using the requirements shown in Table 1, the snow cover algorithm meets the F & PS 100% requirements.

The text has described the first two rows of Table 5 in describing the MODSCAG 7 band model. For the comparison of the 5-band ABI proxy version relative to MODSCAG, we now give the results. The overall accuracy (pixel-weighted, mean difference) shown in this phase of testing and validation was 0.023 (snow and snow-free) and 0.037 (snow only) across all scenes described above. Therefore, FSC (GOESRSCAG) meets the specification of 0.15 with a buffer of ~0.12. It is highly unlikely that any algorithm modifications would push the accuracy into that buffer. Given the accuracy result of the MODSCAG algorithm, the greatest composite accuracy value for FSC (GOESRSCAG) is 0.018 (snow and snow-free) and 0.027 (snow only), again well within specification of 0.15.

The overall precision for the 5-band ABI proxy data in this phase of testing and validation was 0.077 (snow and snow-free) and 0.119 (snow only) across all scenes described above (Table 5). Therefore, FSC (GOESRSCAG) meets the specification of 0.30 with a buffer of ~0.20. It is highly unlikely again that any algorithm refinement would increase precision values through that buffer. Given the precision result of the MODSCAG algorithm, the worst-

Table 5. Validation results of FSC (GOESRSCAG) under various scenarios.

Validation Configuration	Accuracy (Spec)	Precision (Spec)
Fractional snow cover MODSCAG vs. Landsat (snow only)	-0.010 (0.15)	0.089 (0.30)
Fractional Snow Cover MODSCAG vs. Landsat (snow and snow-free)	-0.005 (0.15)	0.049 (0.30)
Fractional Snow Cover 5-band ABI proxy vs. 7-band MODSCAG (snow only)	0.037 (0.15)	0.119 (0.30)
Fractional Snow Cover 5-band vs. 7-band ABI proxy (snow and snow-free)	0.023 (0.15)	0.077 (0.30)

case composite precision values for FSC (GOESRSCAG) lie < 0.20, again well within F&PS requirements of 0.30.

In addition, in Table 6 are the errors of omission and commission from the tests. Two hundred forty-three MODIS granules were processed with the SCAG algorithm. These granules covered an area bounded by parallels of latitude 24ºN and 60ºN and meridians of latitude from 65ºW to 126ºW, covering the coterminous U.S. and southern and central Canada. The time period used was from 2009 October 1 to 2010 June 30. This area is where all testing of the algorithm has taken place.

4.3 Numerical Computation Considerations

The FSC relies on two primary inputs:

- Surface reflectance values for GOES-R ABI channels 1, 2, 3, 5 and 6 (and eventually 7 and 13)
- An *a priori* calculated cloud mask

Some would argue that snow, from a spectral analysis perspective, behaves like a low-altitude, large-particle cloud. Using this supposition, it is possible to leverage the spectral mixture analysis for FSC and the rapid GOES-R image acquisition schedule to assist the AWG Cloud Team's ACM product. Temporal signatures of grain size can provide an additional capability for cloud masking as short terms changes in grain size indicate cloud presence. Since the FSC (which depends on a cloud mask) and the ACM (which depends on a snow mask) are interdependent, it seems reasonable to pursue synergies between the two algorithms.

FSC as expressed in GOESRSCAG relies on linear transformations to decompose a pixel's spectral signature into its constituent spectra. GOESRSCAG employs (or will employ) several strategies to reduce its computational load:

- Limit the number of possible endmembers to two (snow and a single non-snow endmember from a limited list of possibilities) plus shade. GOESRSCAG retrieves, for example, combinations of snow and

Table 6. Raw counts of errors in test data.

Statistic	Value
Number of pixels processed	668 million
Number of errors of commission	3.02 million (0.045%)
Number of errors of omission	2.92 million (0.045%)

vegetation or snow and bare ground. Since the primary aim is the determination of FSC (as opposed to the identity and proportion of the non-snow constituents), this limit minimizes the dimensions of the matrices. However, GOESRSCAG has the full capacity to map combinations of vegetation and soil, and as such, can act as a robust cross-validation of other vegetation retrievals. (Status: done)

- Limit the number of possible snow grain size spectra (Status: done)
- Limit the number of spectra within a possible non-snow endmember spectrum library (Status: done)
- Integrate (and then optimize) spectrum mixing analysis modeling with the final endmember sorting/selection logic execute a FSC retrieval with as few matrix operations as possible (Status: done)
- Buffer repetitive, intermediate calculations between time sequential GOES-R ABI images (e.g., the identity of the non-snow endmember for a given pixel). (Status: in progress)

4.4 Programming and Procedural Considerations

The GOESRSCAG FSC is a pixel-by-pixel algorithm that will benefit by running on time-sequential images. The algorithm relies on matrix operations that impact program design and implementation. While this reliance impacts programming considerations, we addressed strategies for its mitigation above.

Additionally, we recognize that the GOES-R satellite will not be deployed for several years. With that in mind, rather than adopting a more traditional single-threaded architecture, we have implemented the GOESRSCAG FSC as a multi-threaded application more suitable to the multiprocessor computers anticipated for the near future.

4.5 Quality Assessment and Diagnostics

The following procedures are recommended for diagnosing the performance of the FSC.

- Monitor the percentage of specific endmembers in regional areas where these values should be nearly constant after snow cover reaches 100 percent during accumulation in the fall or snow cover reaches 0 percent during ablation in the spring.
- Assess persistence/consistency of fractional snow cover by pixel. There should be no rapid oscillations in FSC and grain size for a given pixel. FSC for a given pixel should vary smoothly in the temporal domain except immediately after cloud cover that has produced snowfall.
- Assess errors of confusion between cloud cover and snow cover.
- Assess fractional snow cover retrievals with high spatial resolution, polar-orbiting sensors such as the Landsat Thematic Mapper.
- Assess fractional snow cover retrievals with physically based, energy- and mass-balanced snow models.
- Periodically review the individual test results for artifacts or non-physical behaviors.
- Maintain close collaboration with other teams using the FSC in their product generation.
- Maintain a close collaboration with the cloud teams to resolve issues associated with snow/cloud discrimination.

4.6 Exception Handling

The GOESRSCAG FSC will include checking the validity of each required channel before executing its retrievals. The GOESRSCAG FSC also expects the Level 1b processing to flag any pixels with missing geolocation or viewing geometry information. The following additional pixel-by-pixel exceptions will be identified and flagged by the FSC in its output:

- Clouds identified by ACM and/or grain size
- Pixels below the solar zenith angle threshold
- Pixels that are saturated
- Pixels missing surface reflectance RTM correction
- Pixels too close to limb.

In these cases, appropriate flags will indicate that no FSC retrieval was made for that pixel.

4.7 Algorithm Validation

FSC is a quantitative, area representation of snow cover rather than a simple detection of presence somewhere in the area. Therefore, it is necessary to assess the spatial heterogeneity in the algorithm errors with validation data that have the capacity to reveal the distribution of snow cover at a scale finer than that of GOES-R and that can be coarsened to the distribution at the scale of GOES-R. The retrievals from GOESRSCAG will be assessed in terms of their fractional accuracy, fractional precision, and stability over space and time. We will also assess their binary accuracy for those users who may be interested in simple detection of snow presence. The validation of GOESRSCAG with the ABI proxy data from MODIS and VIIRS will address the accuracy and precision of the model. The validation of GOESRSCAG with the high spatial resolution data will facilitate understanding the subpixel drivers of uncertainty in FSC retrievals such as anisotropic distribution of vegetation and topographic variation that affects irradiance and snow grain size distributions.

In either of the pre-launch or post-launch periods, the primary validation datasets will be retrievals of

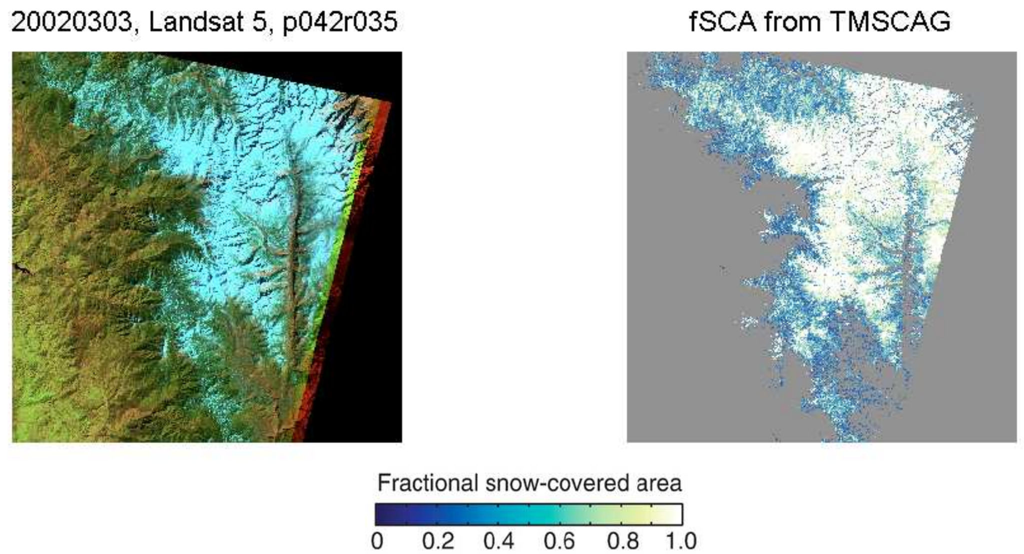

Figure 6 TMSCAG results for the southern Sierra Nevada (Sequoia and Kings Canyon National Parks), California. (left) Color composite of TM5 bands. (right) FSC for the same scene.

snow cover from medium and high spatial resolution polar orbiting data, the scales of which are greater than that of GOES-R ABI (2 km). In the Pre-launch Phase, the medium resolution data will come from MODIS (500 m) and the high-resolution data from the Landsat-5 Thematic Mapper and Landsat-7 Enhanced Thematic Mapper Plus (ETM+) (29 m) (Figure 6Figure 7). In the Post-launch period, the medium resolution data will come from VIIRS (370 m) and the high-resolution data from Landsat Data Continuity Mission (LDCM) (29 m). Secondary validation will come in the form of binary validation with in situ measurements from cooperative observer networks and snow pillows and courses, numerical snow model state variables, as well as from the higher resolution satellite instruments.

The GOESRSCAG algorithm will be evaluated with two levels of data sets; MODIS and VIIRS proxy data at 500 m and 2 km spatial resolution and coincident high spatial resolution data from the Landsat Thematic Mapper (TM). The model will be assessed based on its FSC accuracy and precision. Accuracy and precision will be evaluated according to the F&PS (Table 1).

The sensitivities of the algorithm will be assessed with the high-resolution fractional snow cover data and ancillary data. The dependent variables will be per pixel FSC errors and the independent variables will be solar zenith angle, local zenith angle, sensor azimuth angle (relative to solar principal plane), uncertainty in surface reflectance retrieval, elevation, aspect, topographic variance, land cover, vegetation type, and snow grain size. Perfect success of the algorithm would be shown by insignificance in the relationships above with near zero errors in FSC. However, perfect success is highly unlikely given the chain of uncertainties from sensor radiance response through atmospheric characterization and surface reflectance retrieval to model uncertainties. While the regressed relationship between RMSE

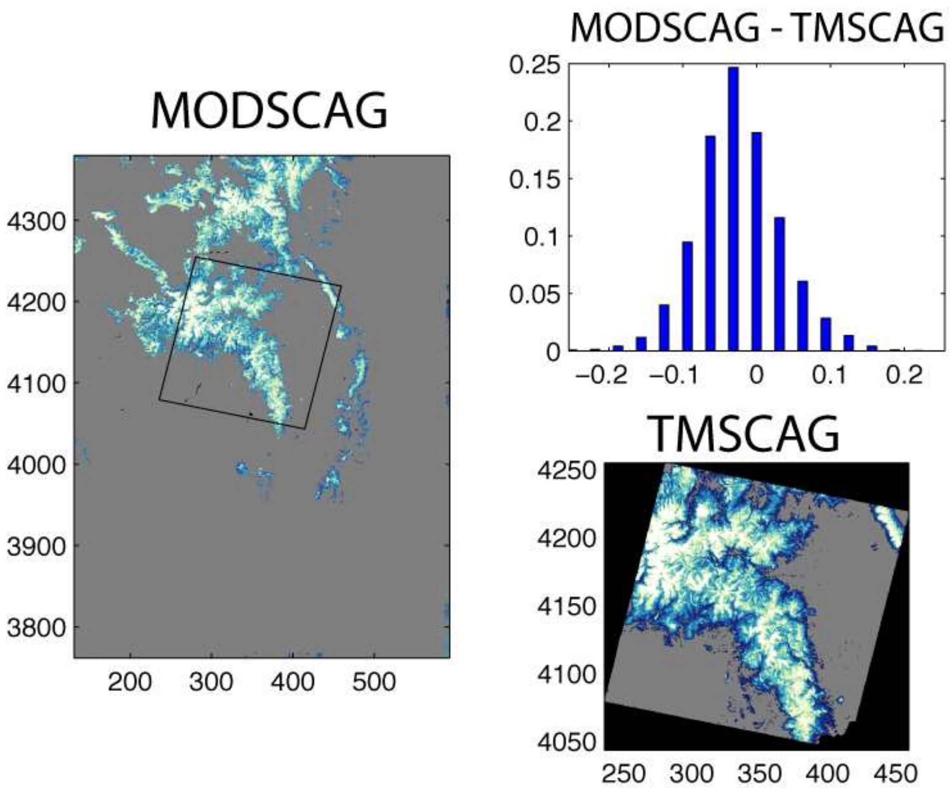

Figure 7. MODSCAG validation with TMSCAG. This scene shows the Upper Rio Grande basin of Colorado and New Mexico, on 17 April, 2001. The histogram presents the distribution of errors.

error and solar zenith angle is positive (consistent with our hypothesis), the errors are relatively insensitive with the $R^2 = 0.22$. The reader at this point is most likely considering algorithm stability in time. This will be described in detail below and treated during the Post-launch Phase.

The full details of the algorithm validation are handled in the **Product Validation Plan Document: *Fractional Snow Cover***. Below we describe the pre-launch phase activities and post-launch phase activities.

4.7.1 Pre-launch Phase Activities

The NOHRSC will continuously ingest and correct MODIS (VIIRS when available) level 1B data for the CONUS, Canada, and Alaska in real time. Both 7-band (validation) and 5-band (ABI proxy) FSC retrievals will be produced and analyzed as described above. A time series of validation statistics, computed daily, will characterize the accuracy, precision, and spatiotemporal-stability of the FSC. In addition to these moderate resolution validation efforts, ancillary validation efforts will conducted (as described above) using high resolution Landsat data, the NOHRSC's numerical snow model, and the NOHRSC's comprehensive collective of ground-based snow observations. Modifications to the FSC will be made by Painter/Rost/Bovitz as necessary during the pre-launch phase.

4.7.2 Post-launch Phase Activities

As described above, the post-launch allows us an opportunity to replace proxy ABI with real ABI data. Early post-launch activities will consist of the same activities conducted during the pre-launch phase with the replacement of proxy data with real data. Once validated (and adjusted as needed) the FSC will be considered deployed. A subset of the pre-launch validation activities will be continued by the NOHRSC in post-launch and beyond as part of its operational mission. These results can be fed forward to the GOES-R FSC deployment to serve as a real time cross validation dataset. It should be noted the FSC uses external spectral signature files to drive its numerical analysis. Refinements to the model's performance can be easily affected by replacing these files. Efforts at the NOHRSC to improve its MODIS/VIIRS implementation of the FSC can be leveraged by GOES-R by this means. Critical to validation in the Post-launch Phase will also be the extensive stability testing at the daily scale and sub-day scale.

5. ASSUMPTIONS AND LIMITATIONS

The following sections describe the current limitations and assumptions in the current version of the GOESRSCAG FSC.

5.1 Performance

The following assumptions have been made in developing and estimating the performance of the FSC. The following list contains the current assumptions and proposed mitigation strategies:

- Background snow-free surface reflectances will be available based on our preprocessing.
- Horizontal displacement distortions removed by parallax correction. Otherwise relax constraints on solar angle-geometry calculations
- The processing systems allows for ingest of previous output for application of the temporal tests. Otherwise allow for reduced performance of GOESRSCAG and give up GOESRSCAG cloud analysis
- High-quality cloud maps are available. Otherwise calculate cloud mask within the FSC

Note that FSC retrievals can only be made where snow is visible to the sensor. Snow under trees cannot be retrieved once snow falls off of the canopy. This can be partially mitigated by keeping track of forested areas during the snow-free season and tracking canopy intercepted snow and carrying it through subsequent images.

The algorithm depends solely on data from GOES-R; there is currently no plan to incorporate data from degraded or missing source layers from other data sources. Degraded data – such as a "noisy" band – will cause degraded products; missing data, including ancillary or metadata, will cause the algorithm to not produce output but fail gracefully.

5.2 Assumed Sensor Performance

We assume the sensor will meet its current specifications. However, the GOESRSCAG will be dependent on the following instrumental characteristics:

- Unknown spectral shifts in some channels will cause biases in the clear-sky surface reflectance calculations that may impact the performance of GOESRSCAG.
- Errors in navigation from image to image will affect the performance of the temporal tests.
- Any saturation in the visible wavelength channels will effect performance of mixture analysis
- Loss of a band can degrade performance of GOESRSCAG. In particular, loss of ABI band 5 would lose leverage for grain size retrieval and, in turn, cause the loss of cloud-masking capability.
- Temporal analysis in FSC will be critically dependent on the amount of striping in the data.

5.3 Pre-Planned Product Improvements

The FSC performance must be optimized for the Land Application Team, Cloud Team and Hydrology Team algorithms. We therefore intend to allow for feedback and to incorporate any suggestions from them to improve the FSC. In particular, we feel that the interdependence between the FSC and the ACM requires special attention and coordination, perhaps through the AIT.

The FSC serves many other applications. Its development is therefore tied to the development and feedback from the other algorithms. At this point, it is therefore difficult to predict what the future modifications will be. However, the following list contains our current best guess of the future FSC modifications:

- Temporal signatures of snow cover and grain size for cloud mapping applications and quality control
- Unless addressed elsewhere (e.g., by the AIT), some of the performance mitigations addressed above.

Additionally, we will continue to cooperate with the AIT to pursue

- RTM-driven surface-reflectance correction
- Parallax correction for horizontal displacement distortions.

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APPENDIX 1: COMMON ANCILLARY DATA SETS

1. LAND_MASK_NASA_1KM

a. Data description

Description: Global 1km land/water used for MODIS collection 5
Filename: lw_geo_2001001_v03m.nc
Origin: Created by SSEC/CIMSS based on NASA MODIS collection 5
Size: 890 MB.
Static/Dynamic: Static

b. Interpolation description

The closest point is used for each satellite pixel:

1) Given ancillary grid of large size than satellite grid
2) In Latitude / Longitude space, use the ancillary data closest to the satellite pixel.

2. MDS_L2_CLD_MASK_FILE

a. Data description

Description: MODIS L2 cloud mask 1km
Filename: MOD35_L2.AYYYYDDD.HHMM.005.yyyydddhhmmss.nc /
MYD35_L2.AYYYYDDD.HHMM.005.yyyydddhhmmss.nc.
Where,
MOD35_L2/ MYD35_L2 – Level 2 Cloud Mask from TERRA (MOD) / AQUA (MYD)
A – Nothing to do here
YYYYDDD – 4 digit year plus 3 digit of Julian day
HHMM – 2 digit of hour and 2 digit of minutes in GMT
005 – Processing system version
yyyydddhhmmss – processing date/time
Origin: NASA DAAC
Size: 45 MB
Static/Dynamic: Dynamic

b. Interpolation description

The closest point is used for each satellite pixel:

In Latitude / Longitude space, use the ancillary data closest to the satellite pixel.

APPENDIX 2

1 INTRODUCTION

1.1 Implementation Concepts: Models and Model Types

As stated above, the FSCA is based on a least squares fit between the mixed spectra observed by the sensor instrument and solar-zenith-angle-specific libraries of *a priori* measured pure endmember spectra. Each of the spectral libraries delivered with SCAG include the spectra for 110 snow endmembers (by grain size radii from 10 to 1,100 microns) and 54 additional spectra for various vegetation, rock/bare-ground and ice/other endmember types.

Given enough bands of input data (and raw processing power) it is technically possible to calculate any desired number of endmember fractions for a given pixel. However, this implementation of the FSCA is constrained by the relative small number of available spectral bands on the GOES-R ABI instrument and the execution-time performance requirements set forth in the MRD. Consequently, this implementation of the FSCA is limited to a maximum of two endmembers.

The easiest and perhaps most important FSCA solution is the pure pixel case (i.e., the entire pixel is covered by a single endmember). Therefore, while we are limited to two endmembers per pixel, we also test the one-endmember solutions.

For practicality’s sake, we’ve grouped the 164 endmembers into four groups: snow, vegetation, rock (including bare ground) and other. While the FSCA keeps track of the specific endmember combinations, the output is generalized into one of these four endmember groups. Working with these limitations the outputs from this implementation are generalized into endmember group combinations as follows:

- Pure snow;
- Pure vegetation;
- Pure rock;
- Pure other;
- Snow fraction plus vegetation fraction;
- Snow fraction plus rock fraction;
- Snow fraction plus other fraction;
- Vegetation fraction plus rock fraction;
- Vegetation fraction plus other fraction and
- Rock fraction plus other fraction.

Currently, “other” is interpreted as ice.

Both physically and mathematically, the FCSA has to account for photometric shade (zero reflectance for each band in the spectrum). For each of the 10 generalized endmember group combinations listed above there is actually an implicit additional endmember (expressed explicitly in the computations, of course) to account for shade. The calculated shade fraction is normalized out of the final solution by dividing the non-shade endmember fractions by one minus the shade fraction.

At this point it is appropriate to introduce the concept of models and model types. In order to calculate the FSC solution we have to compare the spectrum measured by the sensor instrument at the pixel against each possible one and two endmember fractional combinations of the 164 spectral library spectra. These combinations are referred to as models. The model (combination of endmember spectra) yielding the best least squared fit is selected as the optimal solution for that pixel.

The concept of model types addresses two issues. Firstly, as mentioned above, the 164 specific endmembers are generalized into one of four general endmember groups and 10 combinations of those groups. The concept of model types is used to order the large number of possible individual endmember combinations into the 10 generalized endmember group combinations listed above.

The second purpose of model types is to address the issue of model constraints. Only in the very rarest of circumstances will the measured spectrum perfectly match a specific model. Normally there are model residuals to consider. Only when the model residuals and RMSE fall below threshold levels is a model considered acceptable. In addition to grouping and combining models, model types are used to associate varying levels of model fit constraints to each combination of endmember groups. In this FSCA implementation we consider two levels of model fit constraints: loose and tight. The tight constraints are characterized by small acceptable model RMSE and model residual requirements, while the loose constraints relax these requirements.

In the FSCA the model types are ordered by priority as follows:

1. One-endmember model with tight constraints;
2. Two-endmember model with tight constraints;
3. One-endmember model with loose constraints and
4. Two-endmember model with loose constraints.

One should quickly realize that each endmember model has the potential for being calculated twice: once with tight constraints and once with loose constraints.

When retrieving the FSC for a given pixel the algorithm loops through the potential models (endmember combinations) by model type in the order of priority listed above. As mentioned above, the optimal model for a given pixel is that which mostly closely meets the model constraints (smallest RMSE and residuals). In order to limit needless calculations, once we discover an acceptable solution for a given pixel at given priority level we exhaustively examine the remaining models for that priority level but skip all of the models associated with lower priority levels. For instance, if a pixel meets the constraints for priority one, there is no point in examining the models associated with priorities two, three, or four.

2 FILES

2.1 Overview

The FSCA is expressed in a program named “scag.” There are four types of files associated with the SCAG program, other than the program code itself:

- Configuration files;
- Input files;
- Output files and
- Endmember memory file.

Their purpose, content and format are described in the following sections. The configuration and endmember memory files are of interest primarily to the FSCA programmers. The input files are of interest primarily to the FSCA program operators. And the output files are of interest primarily to the FSCA product users. The following sections will attempt to be sensitive to the needs of these various audiences.

2.2 Configuration Files

2.2.1 Overview

The purpose of this section is to describe the files intrinsic to the design of the FSCA as expressed in the SCAG source code.

The FSCA configuration files contain data that either a) control the flow of the FSCA execution, or b) contain static data required by the FSCA. It is through these files that future modification of many of the performance characteristics associated with the algorithm can be altered without modifying the source code itself. All configuration files are expected by the SCAG program to reside in a single directory. Under no circumstances should these files be altered by the FSCA program operators. Their content not only directs the flow of the FSCA program, but also affects its results. Under certain circumstances, incorrect modification of their content could either a) yield unpredictable erroneous results or b) result in runtime errors. Consequently, the contents of these files should fall within the domain of the FSCA programmers. All configuration parameters that are of interest to the FSCA operators are contained in the program’s command-line arguments and can be captured within script files.

2.2.2 SPECLIBS

2.2.2.1 Purpose

The purpose of the SPECLIBS file is to define the configuration of the FSCA’s spectral library input files (see `#define FILE_SPECLIBS` in the SCAG source code). This file is read once by scag to determine the location and characteristics of the spectral libraries available to the FSCA.

2.2.2.2 Content

This file identifies:

- The name of each spectral library file;

- The nominal solar zenith angle for which the file's contents are valid;
- The number of endmember spectra contained in the file;
- The number of spectra wavelengths contained in the file;
- The gain applied to each spectrum value and
- The endmember location in the file for the photometric spectrum.

The gain value is the divisor to be applied to the library spectrum data to align them with the expected range of sensor input data. The current range of library spectrum data is 0 to 10,000. The expected range of sensor input data is 0 to 1,000. Hence the gain value should be set to 10.0 for each entry in the SPECLIBS file. The gain value is closely related to the scag `#defined` variable `DATA_SCALAR`. The current value of `DATA_SCALAR` is 1,000.0, which scales the range of the input sensor data from 0 to 1 to 0 to 1,000. When altering either the gain or the `DATA_SCALAR`, make sure the other is altered appropriately.

2.2.3 speclib.z##.sli

Where ## refers to the solar zenith angle.

2.2.3.1 Purpose

The purpose of the speclib.z##.sli files is to store the *a priori* measured solar-zenith-angle-specific pure spectral signature for each possible endmember. These files are read once by scag and held in memory.

2.2.3.2 Content

These files contain:

1. The spectral signature for the photometric shade endmember;
2. The spectral signatures for the snow endmembers by ascending grain size and
3. The spectral signatures for the non-snow endmembers.

All of these files should contain the same number of spectra and bands. The location of endmember spectra should be the same in each file.

The current library files contain spectra for the following wavelengths:

- 0.469 µm;
- 0.555 µm;
- 0.645 µm;
- 0.858 µm;
- 1.240 µm;
- 1.640 µm; and
- 2.130 µm.

2.2.4 MODELTYPES

2.2.4.1 Purpose

The purpose of the MODELTYPES file is to define the configuration of the FSCA's workflow by defining the model types (see `#define FILE_MODEL_TYPES` in the scag source code). This file identifies the files containing the definitions of endmember group combinations, identifies the two and three endmember (including photometric shade) model types and their model file constraint levels, and defines the prioritized order that the model types should be executed. This file is read once by scag to determine the order in which the other FSCA configuration files should be read into memory and subsequently processed.

2.2.4.2 Content

This file identifies:

1. The name of the model type;
2. The number of endmembers (including photometric shade) in the model type;
3. The number of models defined by the model type;
4. The priority of the model type [from 0 (the highest) to n (the lowest)] and
5. The model type model fit constraint level [0 (tight) or 1 [loose)].

Note that each model type is listed twice: once with a tight constraint level and once with a loose constraint level. Relative to order of priority, for a given model type, the tight constraints should precede the loose constraints. Relative to order of priority, the two-endmember model types should precede the three-endmember model types.

2.2.5 #em.name.models

Where # refers to the number of end members and name refers the model type name.

2.2.5.1 Purpose

The purpose of the #em.name.models files is to define the FSCA's retrieval models and the endmember group combination component of the model type definitions (the other component being the model constraints; see section 2.2.6 below). These files are read once by scag and held in memory.

2.2.5.2 Content

These files contain the two-endmember model endmembers and the three-endmember model endmember pairings as part of the model type definitions. Recall that the FSCA model type definitions are comprised of two parts: the combining of endmember groups and the assignment of model fit constraints.

2.2.6 CONSTRAINTS

2.2.6.1 Purpose

The purpose of the CONSTRAINTS file is to assign model good of fit thresholds to the loose and tight two- and three-endmember model types (see `#define FILE_CONSTRAINTS` in scag.h). This file is read once by scag held in memory.

2.2.6.2 Content

This file contains:

- The number of endmembers in the model type for which the constraints apply
- The constraint level - either loose or tight
- The minimum and maximum acceptable calculated endmember fraction
- The threshold maximum model RMSE
- The threshold maximum residual for a spectral signature band
- The maximum number of successive wavelength-ordered bands that are allowed to exceed the threshold maximum residual.

If, for any model, any of these constraints are exceeded, that model is rejected. The accepted model is that which meets these constraints with the minimum RMSE after all models within its priority level have been tested. Once all models within a priority level have been tested **and** an acceptable model has been identified, further modeling for a pixel is unnecessary (i.e., lower priority models are ignored).

2.2.7 EMTYPES

2.2.7.1 Purpose

The purpose of the EMTYPES file is to assign endmembers to an endmember group (see #define FILE_EMTYPES in the SCAG source code). This file is read once by scag held in memory.

2.2.7.2 Content

This file contains the endmember group associated with each endmember as follows

0: Snow
1: Vegetation
2: Rock/bare ground
3: Other (lake ice)

2.2.8 GSTABLE

2.2.8.1 Purpose

The purpose of the GSTABLE file is to assign a snow grain size radius (in microns) to each endmember (see `#define FILE_GSTABLE` in scag.h). This file is read once by scag held in memory.

2.2.8.2 Content

This file defines the snow grain size radius (in radians) for each endmember. This file differs from many of the other configuration files in that it includes an entry for the photometric shade endmember.