NOAA NESDIS
CENTER for SATELLITE APPLICATIONS and RESEARCH

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

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GOES-R ABI NDVI ALGORITHM THEORETICAL BASIS DOCUMENT
VERSION HISTORY SUMMARY

Version	Description	Revised Sections	Date
0.0	New ATBD Document according to NOAA /NESDIS/STAR Document Guideline		6/21/2008
0.1	Comments/modifications by N. R. Nalli (AWG/SAT)		9/18/2008
1.0	ATBD Document with 80% readiness of algorithm development software improvement		6/26/2009
1.1	Modification made reflecting the responses to AIT and other reviewer's comments, together with some results from the NDVI test plan.		9/23/2009
2.0	Revision reflecting changes made since Version 1.1, mainly represented by the addition of QC flags and validation of NDVI algorithm on common test data.		06/28/2010
2.1	Modification and improvement have been made in response to reviewer's comments/suggestions on Version 2.0.		08/27/2010

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LIST OF ACRONYMS

ABI	Advanced Baseline Imager
ACM	ABI Cloud Mask
ADEB	Algorithm Development Executive Board
AIADDD	Algorithm Interface and Ancillary Data Description Document
AIT	Algorithm Integration Team
ATBD	Algorithm Theoretical Basis Document
AVHRR	Advanced Very High Resolution Radiometer
AWG	Algorithm Working Group
CDR	Critical Design Review
CICS	Cooperative Institute for Climate Studies
CIMSS	Cooperative Institute for Meteorological Satellite Studies
CM	Configuration Management
DG	Document Guideline
EPL	Enterprise Product Lifecycle
GS-F&PS	Ground Segment Functional and Performance Specification
IFOV	Instantaneous Field of View
IMS	Interactive Multi-sensor snow and ice mapping System
LZA	Local Zenith Angle
MSG	Meteosat Second Generation
NDVI	Normalized Difference Vegetation Index
NESDIS	National Environmental Satellite, Data, and Information Service
NIR	Near Infrared wavelength
NOAA	National Oceanic and Atmospheric Administration
OCD	Operations Concept Document
OSDPD	Office of Satellite Data Processing and Distribution
QA	Quality Assurance
QC	Quality Control
RED	Red wavelength
SEVIRI	Spinning Enhanced Visible and Infrared Imager
SSEC	Space Science and Engineering Center
SSMI	Special Sensor Microwave Imager
STAR	Center for Satellite Applications and Research
SZA	Satellite Zenith Angle
TOA	Top of Atmosphere
TOC	Top of Canopy
TVDI	Temperature Vegetation Dryness Index
VIS	Visible wavelength
VVP	Verification and Validation Plan
WDRVI	Wide Dynamic Range Vegetation Index

ABSTRACT

Vegetation indices have long been used to measure and monitor plant growth, vegetation cover and biomass production from multispectral satellite data. The idea of these indices is to enhance the vegetation signal by combining reflectances observed in different spectral bands, most often in the visible and in the near-infrared spectral range. The Normalized Difference Vegetation Index (NDVI) presents the most widely used index characterizing the state of vegetation. It is calculated as the difference between the observed near infrared and visible red reflectances divided by their sum.

This document presents the theoretical basis for the development and implementation of the algorithm to derive Top of the Atmosphere (TOA) NDVI from observations of Advanced Baseline Imager (ABI) instrument onboard GOES-R. It also describes the process for ABI TOA NDVI product validation and characterizes algorithm performance and uncertainties.

INTRODUCTION

1.1 Purpose of This Document

The GOES-R ABI NDVI algorithm theoretical basis document (ATBD) provides a high level description of the physical basis (scientific and mathematical) for the derivation of the GOES-R Normalized Difference Vegetation Index (NDVI) products using observations from the Advanced Baseline Imager (ABI) flown on the GOES-R series of NOAA geostationary meteorological satellites. GOES-R ABI will be the first GOES imaging instrument providing observations in both the visible and the near infrared spectral bands and therefore can be used to generate NDVI values for monitoring the state of the vegetation cover as well as identifying areas of vegetation stress and drought.

This version of ATBD for GOES-R ABI top of the atmosphere (TOA) NDVI product includes improvement and validation in the algorithm development, in subsequence to the ATBD prepared in September 2009.

1.2 Who Should Use This Document

The intended users of this document are those interested in understanding the physical basis of the NDVI algorithm and how to use the output of the TOA NDVI algorithm for a particular application. This document also provides information useful to anyone maintaining or modifying the original algorithm.

1.3 Inside Each Section

This document includes the following main sections.

- **Observing System Overview**: Provides relevant details of ABI and provides a brief description of products generated by the algorithm.

- **Algorithm Description**: Provides a detailed description of the algorithm including the physical basis, input and output.

- **Test Data Sets and Outputs**: Provides the description of the input data sets used for the algorithm development and testing, together with the test output to demonstrate the assessment of precision and accuracy.

- **Practical Consideration**: Provides information on issues involving numerical computation, programming and procedures, assessment and diagnostics and exception handling at a level of detail appropriate for the current algorithm maturity.

- **Assumptions and Limitations**: Provides an overview of current limitations of the approach and the plan to overcome these limitations by the further algorithm improvement.

1.4 Related Documents

This document currently does not relate to any other document other than the GOES-R Ground Segment Functional and Performance Specification (GS-F&PS). In addition, information on ancillary data may be found in the relevant AIT document "Algorithm Interface and Ancillary Data Description Document (AIADDD)".

Other related references are listed in the Reference Section.

1.5 Revision History

Version 0.0 of this document was created to accompany the delivery of the version 0.1 algorithm to the GOES-R AWG Algorithm Integration Team (AIT).

Version 1.0 of this document was created upon modification of the draft ATBD to reflect changes/improvement made for the 80% readiness document, including some additions/changes conducted from the algorithm Critical Design Review (CDR) and the Test Readiness Review (TRR).

Version 1.0 also includes modifications made in response to AIT and other reviewer's comments, together with some results from the NDVI test plan.

In Version 2.0, validation of the NDVI algorithm and product using common test data is presented in Section 4. Also, QC flags and metadata description are included in the Version 2.0 ATBD.

Since NDVI is an Option 2 product, no review comments from the AIT, ADEB and Harris group were available at the initial delivery of Version 2.0 in June 2010. The latest Version 2.1 includes responses to the reviewer's comments which have been received recently.

OBSERVING SYSTEM OVERVIEW

This section describes the products generated by the ABI NDVI algorithm and the related sensor requirements.

1.6 Products Generated

The GOES-R Normalized Difference Vegetation Index product is the top of the atmosphere land surface product. It is derived from satellite observed reflectances with no correction for the atmosphere and for angular anisotropy. The NDVI algorithm will be used to derive the operational NDVI product on an hourly basis for all day time cloud free and snow free land pixels within the ABI full disk domain. Following the GOES-R Ground Segment Functional and Performance Specification (GS-F&PS) shown in Table 2.1, NDVI should be provided at a spatial horizontal resolution of 2 km with the measurement accuracy of 0.04 NDVI unit. The temporal coverage qualifiers are defined by the Sun at 67° solar zenith angle and below for the full sun illumination. The product extent qualifiers are defined as quantitative out to at least 70° local zenith angle (LZA) or local zenith angle (SZA). The NDVI product refresh rate is defined as 60 minutes. Instantaneous GOES-R ABI data will be used to generate the TOA NDVI product every 60 minutes. There is no image composition for the hourly product since changes in the cloud cover distribution during the hour are expected to be small, even though the ABI data will be available every 5 minutes. Concurring to the characteristics of observations from a geostationary satellite, across a single image, there will be simultaneous and co-varying sun angle and view angles. Over time, there will be shifts in the sun angle but no shift in the view angle for a given location. The TOA NDVI with no atmospheric and geometric angle corrections will then be used as one of the inputs to generate green vegetation fraction for each pixel.

Table 2.1 – Functional & Performance Specification (GS-F&PS) for ABI NDVI

Name	User & Priority	Geographic Coverage (G, H, C, M)	Vertical Res.	Horiz. Res.	Mapping Accuracy	Msmnt. Range	Msmnt. Accuracy	Refresh Rate/Coverage Time Option (Mode 3)	Refresh Rate Option (Mode 4)	Data Latency	Product Measurement Precision	Temporal Coverage Qualifiers	Product Extent Qualifier	Cloud Cover Conditions Qualifier	Product Statistics Qualifier
Vegetation Index	GOES-R	H	N/A	2 km	1 km	0 to 1 (NDVI units)	0.04 NDVI units	60 min	60 min	3236 sec	0.04 NDVI units	Sun at 67° solar zenith angle	Quantitative out to at least 70° LZA and qualitative beyond	Clear conditions associated with threshold accuracy	Over specified geographic area

1.7 Instrument Characteristics

The NDVI will be produced for each pixel observed by the ABI using the visible red and near infrared channels. Table 2.2 identifies the ABI channels and marks those used for the NDVI algorithm.

Table 2.2 – Channel numbers and wavelengths for the ABI

Channel Number	*Central Wavelength (μm)*	*Bandwidth (μm)*	*Spatial Resolution*	*Used in NDVI*
1	0.47	0.45 – 0.49	1 km	
2	0.64	0.59 – 0.69	0.5 km	✓
3	0.86	0.8455 – 0.8845	1 km	✓
4	1.38	1.3705 – 1.3855	2 km	
5	1.61	1.58 – 1.64	1 km	
6	2.26	2.225 – 2.275	2 km	
7	3.90	3.8 – 4.0	2 km	
8	6.15	5.77 – 6.60	2 km	
9	7.00	6.75 – 7.15	2 km	
10	7.40	7.24 – 7.44	2 km	
11	8.50	8.30 – 8.70	2 km	
12	9.70	9.42 – 9.80	2 km	
13	10.35	10.10 – 10.60	2 km	
14	11.20	10.80 – 11.60	2 km	
15	12.30	11.80 – 12.80	2 km	
16	13.30	13.0 – 13.6	2 km	

The NDVI algorithm is simple and straightforward but it relies on the effective elimination of cloud contaminated pixels to ensure product quality.

ALGORITHM DESCRIPTION

This section presents a complete description of the algorithm at the current level of maturity (which may improve with each revision).

1.8 Algorithm Overview

Normalized Difference Vegetation Index (NDVI) is an important land surface characteristic derived from satellite data. It is widely used to characterize the density and vigor of the given vegetation cover as well as to identify vegetation stress and drought. The GOES-R ABI will be the first GOES imaging instrument that provides observations both in the visible and in the near infrared spectral bands that can be used to estimate and monitor NDVI. According to the updated GOES-R Ground Segment Functional and Performance Specification (GS-F&PS) as shown in Table 2.1, ABI-based Vegetation Index products should be generated for the full disk area at 2 km horizontal resolution every 60 minutes with both the product accuracy and precision of 0.04 vegetation index units.

Vegetation Index is an option-2 product in the GOES-R ABI processing system. It relies on the high quality cloud mask to determine which pixels can be used for clear-sky applications. The ABI NDVI is defined as the difference of the near infrared and visible red reflectance divided by their sum. The ABI NDVI for clear sky land pixels is derived from the following expression

$$NDVI = \frac{R_{NIR} - R_{RED}}{R_{NIR} + R_{RED}} ,$$

where R_{NIR} is the reflectance observed in ABI channel 3 at 0.86 μm, and R_{RED} is the reflectance in ABI channel 2 at 0.64 μm.

Both the red and near-infrared reflectances are top of the atmosphere values. They depend not only on the reflective properties of the land surface but also on the properties of the atmosphere and thus vary with the viewing-illumination geometry of observations. Therefore, the GOES-R ABI NDVI is effectively the bidirectional TOA NDVI.

NDVI was first introduced by Rouse, *et al* (1973), and has been widely used in vegetation/climate monitoring ever since (e.g., Tucker, 1979; Holben, 1986; Myneni *et al*., 1995; Kogan, 2001). Gao *et al* (2002) studied the bidirectional NDVI characteristics and presented the benefit of using a bidirectional NDVI in an atmospherically resistant inversion process for retrieval of surface BRDF and albedos. A more recent study by Fensholt *et al* (2006) examined the NDVI for the African continent using the atmospherically corrected reflectance in the RED and NIR channels of MSG SEVIRI instruments. Other studies have extended the application of NDVI calculated from the red and near-infrared Top-of-Atmosphere (TOA) reflectance to Temperature Vegetation Dryness Index (TVDI) for assessment of surface moisture (Stisen *et al*, 2004), and the Wide Dynamic Range Vegetation Index (WDRVI) for sensitivity enhancement (Vina *et al*, 2004).

GS-F&PS defines the range of possible NDVI values as 0 to 1. Vegetated areas generally yield high NDVI values of 0.5-0.7 because of their relatively high near-IR reflectance and low visible red reflectance. Rock and bare soil areas have similar reflectances in the two spectral bands and result in NDVI values close zero. Negative values of NDVI are associated with clouds, water, and snow which have larger visible RED reflectance than near-IR reflectance. Inundated land can exhibit small or even negative values of NDVI, similar to water surfaces. To adequately characterize these latter surfaces in the NDVI map, the range of possible NDVI values may be extended to -0.2 to 1. Until a request for change is granted in the GS-F&PS, the valid range for NDVI remains 0 - 1 in the ATBD and the associated codes.

Satellite-observed reflectances in the visible and infrared demonstrate a strong dependence on the viewing and illumination geometry of observations. Application of NDVI as a ratio of the difference of reflectances in the two spectral bands to its sum is partially reasoned by the fact that it may reduce variation in images caused by surface topography (Holben and Justice, 1981). NDVI values are also reported to be less sensitive to viewing and solar geometries as compared to the spectral surface reflectance (Gao *et al.*, 2002).

1.9 Processing Outline

The processing outline of the NDVI is summarized in Figure 3.1 with the high level flowchart and Figure 3.2 showing detailed data flow diagrams consistent with the software architecture. As required by the GS-F&PS, NDVI products are derived from ABI instantaneous images every 60 minutes. Although ABI images will be available at 5 minutes interval, no cloud clear compositing of images is assumed to generate an hourly NDVI product. Changes in the cloud cover distribution during a one hour time interval are small and image compositing does not help to substantially reduce cloud-caused gaps in the hourly NDVI product.

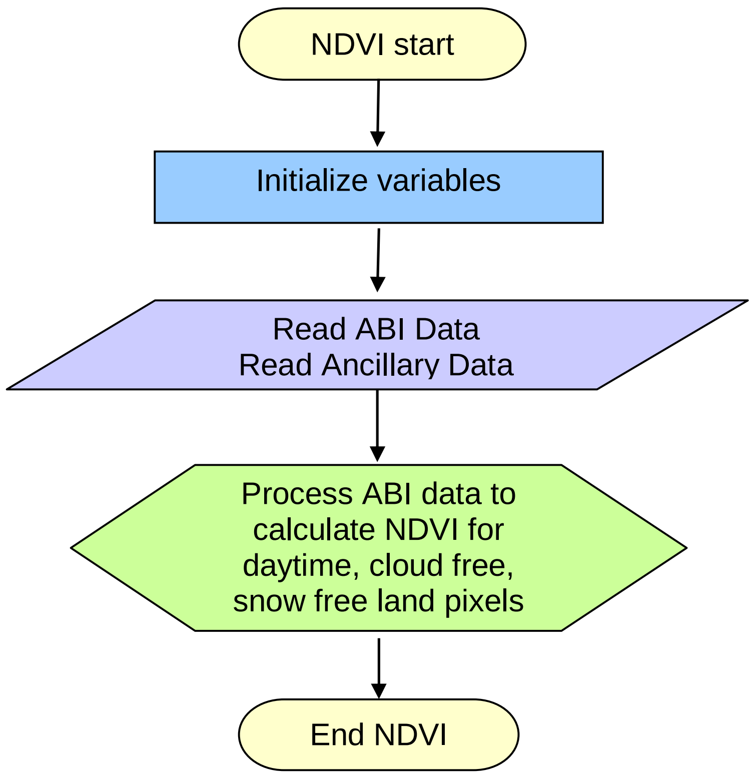


Figure 3.1 – High Level Flowchart of NDVI.

The process starts with extracting ABI sensor data which include visible red and near infrared reflectances, solar-target-sensor geometry, pixel geolocation and the sensor data quality control flags. Since the ABI sensor data come at different spatial resolution, data aggregation and averaging is performed first within 2km grid cells. Aggregation is included in the algorithm to match the spatial resolution of ABI reflectances to the spatial resolution of other ABI-derived data that are also used by the algorithm and to satisfy the requirement to the spatial resolution of the output product (2 km). This is then followed by the extraction of ancillary datasets which can be categorized as ABI and non-ABI related datasets. The ABI-derived datasets include the ABI cloud mask and the snow mask. The snow mask may be supplied either as ABI derived ancillary data, if available, or as non-ABI derived ancillary data. Currently the ABI snow product is the fractional snow coverage, from which the snow mask can be derived. The non-ABI related datasets include the land/sea mask and the snow/ice map generated within NOAA Interactive Multisensor Snow and Ice Mapping System (IMS). The IMS product will be used in the algorithm as a substitute for the ABI snow cover product if the latter is not available.

After the land/sea and snow masks are acquired, they are mapped (or remapped) to the ABI 2km grid. The cloud mask is available at 2 km spatial resolution and does not need additional remapping. Pixels with at least some fraction of water or snow are labeled as mixed pixels. No NDVI retrievals are performed over mixed pixels. The cloud mask assigns every pixel to one of four categories, “confidently clear”, “probably clear”, “probably cloudy” and “confidently cloudy". NDVI estimates are performed only for pixels classified as "confidently clear". All other pixels are labeled as cloudy. The geometric conditions of each pixel are also checked prior to the calculation of NDVI. Pixels beyond the geographic extent qualifier, i.e. LZA ≥70° are excluded from NDVI calculation and given a specific QC flag. Solar zenith angle is used as the criteria for day/night identification. NDVI is only calculated for pixels with a solar zenith angle of less than 67° for full sun illumination.

Finally, the calculated NDVI values and their associated quality control flags, which were generated in each of the aforementioned steps, are combined with the NDVI product package and are saved to files for user access. Figure 3.2 presents the sequence of operations towards generation of the NDVI product.

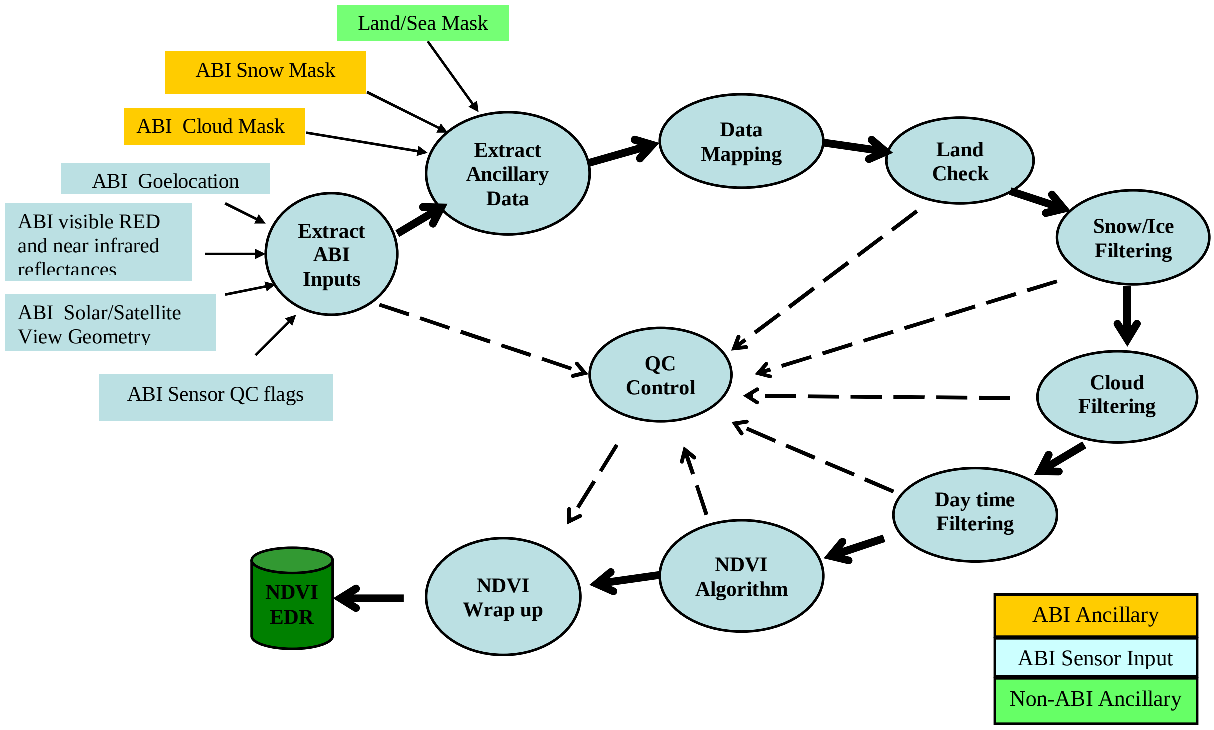


Figure 3.2 – Processing line of NDVI production.

1.10 Algorithm Input

This section describes the input needed to generate the NDVI product. The TOA NDVI product is derived once an hour for all cloud clear and snow free land pixels getting sufficient solar illumination.

1.10.1 Primary Sensor Data

The primary sensor data is information that is derived solely from the ABI observations, geolocation and viewing geometry information. The primary sensor data used to derive NDVI include the calibrated reflectances in channel 2 (0.64 µm, 0.5 km IFOV) and in channel 3 (0.86 µm, 1 km IFOV) along with the solar zenith angle. The local zenith angle and relative the azimuth angle are also acquired to allow for bidirectional correction of surface reflectance if needed in the future. Since the ABI visible red and near infrared channels provide observations at different spatial resolution, data aggregation will be carried out so that each aggregated pixel has a horizontal resolution of 2 km, matching the spatial resolution of the ABI cloud mask. NDVI will be calculated using the mean reflectance of each aggregated pixel in the near infrared and the average reflectance for the corresponding pixels in the visible red spectral band.

- **ABI channel input**

  The GOES-R ABI channel reflectance at 0.64 µm and 0.86 µm are used for NDVI calculation directly. The pixel size is 0.5 km for the visible red and 1 km for the near infrared channel.

- **Geolocation data**

  Latitude and longitude information for each pixel is needed for mapping the sensor data to ancillary data applied. They should be part of the Level 1 ABI data and the unit used for calculation should be in degrees.

- **Viewing geometry information**

  Solar zenith angle is needed to identify observations having sufficient daylight for NDVI retrievals. The satellite local zenith angle and the relative azimuthal angle may be used for potential bidirectional correction of surface reflectance.

- **QC flags in the level 1 ABI data**

  Any inherent QC flags in the level 1 ABI data will be read and applied before generating NDVI using the selected algorithm. Any missing/bad pixels will be skipped for generating vegetation index.

1.10.2 Derived Data

GOES-R products required as input data to run the NDVI algorithm are as follows:

- **Snow mask**

  The GOES-R ABI snow mask developed by the GOES-R Algorithm Working Group (AWG) will be used if available. According to the GOES-R GS-F&PS, the fractional snow cover product will be available at 2 km resolution and refreshed every 60 minutes. A byproduct of the snow mask will be generated from the fractional snow cover based on input data requirements from other AWG groups. An alternative snow cover mask is the output of NOAA Interactive Multi-sensor Snow and Ice Mapping System (IMS) produced operationally by the National Ice Center (http://www.natice.noaa.gov/ims/). The IMS map is available in a polar projection and is generated daily over the Northern Hemisphere at 4 km spatial resolution. Every grid cell in the map is assigned one of the five categories: “snow”, “ice”, “snow-free land surface”, “ice-free water” and “no data (outside the area)”. To use IMS data in NDVI retrievals daily IMS map will be regridded to the GOES-R natural grid at 2 km spatial resolution.

- **Cloud mask**

  The initial TOA NDVI is only generated for the cloud free pixels. The GOES-R AWG ABI cloud mask (ACM) will be used to eliminate cloud contaminated pixels. The cloud mask assigns every pixel to one of four categories, “confidently clear”, “probably clear”, “probably cloudy” and “confidently cloudy”. The probably cloud-clear pixels are not used in NDVI retrievals but may be included for generating NDVI products upon further study. Cloud shadows are currently not filtered or masked in the ACM product.

1.10.3 Ancillary Data

Ancillary data are the non-GOES-R data that provide information not included in the primary sensor (ABI) data or products. For the GOES-R NDVI product, the land/sea mask is the main ancillary data input.

- **Land/Sea mask**

  The University of Maryland Department of Geography generated the global land cover classification collection in 1998 (Hansen *et al*. 1998, 2000). Imagery from the AVHRR satellites acquired between 1981 and 1994 were analyzed to distinguish fourteen land cover classes (http://glcf.umiacs.umd.edu/data/landcover/). This product is available at three spatial scales: 1 degree, 8 kilometer and 1 kilometer pixel resolutions. The 1 km resolution product was used for GOES-R ABI NDVI products in the early development stage.

  To be consistent with other GOES-R product development in term of common ancillary data input, the 1 km resolution land/sea mask to be used in the framework for GOES-R ABI products is created by SSEC/CIMSS based on NASA MODIS collection 5. Several categories are available in the land/sea mask, including shallow, moderate and deep oceans, land, shoreline, shallow, ephemeral, and deep inland water. This mask is remapped using the Latitude/Longitude information to the same 2 km grid as the NDVI output. The TOA NDVI will be calculated for all pixels classified as “land”.

- **Snow/Ice mask**

  In case the ABI snow mask is not available as input for NDVI algorithm, the IMS snow and ice product can be used as an alternative. The IMS snow and ice product is available daily for Northern Hemisphere. It incorporates a wide variety of satellite imagery (AVHRR, GOES, SSMI, etc.) as well as derived mapped products (USAF Snow/Ice Analysis, AMSU, AMSR-E, NCEP models, etc.) and surface observations. The product is presently used as an operational input into several NWS computer weather prediction models as well as several other governmental agencies. Currently it is available at about 4 km grid (6144x6144 pixels in total) from NSIDC with a slight delay. Near real-time gridded data is available in ASCII format by request (http://www.natice.noaa.gov/ims/).

Details on the derivation of ancillary data can be referred to in the relevant AIT document "Algorithm Interface and Ancillary Data Description Document (AIADDD)".

1.11 Theoretical Description

The spectral reflectance of green vegetation in the visible and near infrared has a specific spectral structure, which can be used to distinguish it from "dead" or dry vegetation and from non-vegetated land surface. Figure 3.3 shows typical surface spectral reflectance curves for green grass (shown in green color), dead grass (in brown) and dry soil (in gray) in the visible and near infrared portion of the electromagnetic spectrum. The difference between the spectral reflectance of "dead" and green grass is caused primarily by two factors. First, chlorophyll absorbs solar radiation and thus reduces the solar reflectance of green leaves in the visible-red region of the spectrum. Second, mesophyll structure of green leaves increases their reflectance in the near infrared.

The difference between spectral reflectance pattern of green and dry grass has been widely used in monitoring vegetation condition from remote sensing data and in particular from satellite observations. To simplify discrimination between green and dry grass, to assess the "greenness" of the scene or to determine the fraction of green vegetation within the instrument field of view, a large number of spectral indices have been proposed that utilized the observed spectral reflectance in the visible red and in the near infrared spectral band.

The Normalized Difference Vegetation Index, or NDVI is the most well known and the most frequently used spectral index. It is expressed as

$$NDVI = \frac{R_{NIR} - R_{RED}}{R_{NIR} + R_{RED}} ,$$

where R_{NIR} and R_{RED} are the reflectances observed correspondingly in the near infrared and in the visible red spectral bands.

Larger NDVI means "greener," denser or more vigorous vegetation. In particular, NDVI values, in the range of 0.5-0.7 are frequently observed over dense tropical and boreal forests. Non-vegetated land surfaces, in particular, desert areas, exhibit small NDVI values of 0.05-0.08. Clouds and snow exhibit low-positive or low-negative NDVI values. Therefore NDVI is often used to identify cloud-clear and snow free land surface in satellite imagery.

The top-of atmosphere NDVI products derived from satellite RED and NIR measurements often demonstrate angular anisotropy, with added atmospheric effects mostly from atmospheric path scattering (Gao *et al*, 2002). The effect of atmospheric conditions on NDVI data continuity has been studied in van Leeuwen *et al*'s study (2006). They concluded that insufficient knowledge of the atmospheric conditions may introduce additional uncertainty in NDVI products. A more advanced, but more complicated approach to calculate NDVI consists of using reflectances that have been atmospherically corrected and normalized to certain viewing and illumination geometry. This approach is utilized for generating the top-of-canopy (TOC) vegetation indices from observations of MODIS instrument onboard Terra and Aqua satellites (Huete *et al*, 2002).

Concerns and planned improvements for the current ABI TOA NDVI are stated in Section 5 and Section 6 of this ATBD.

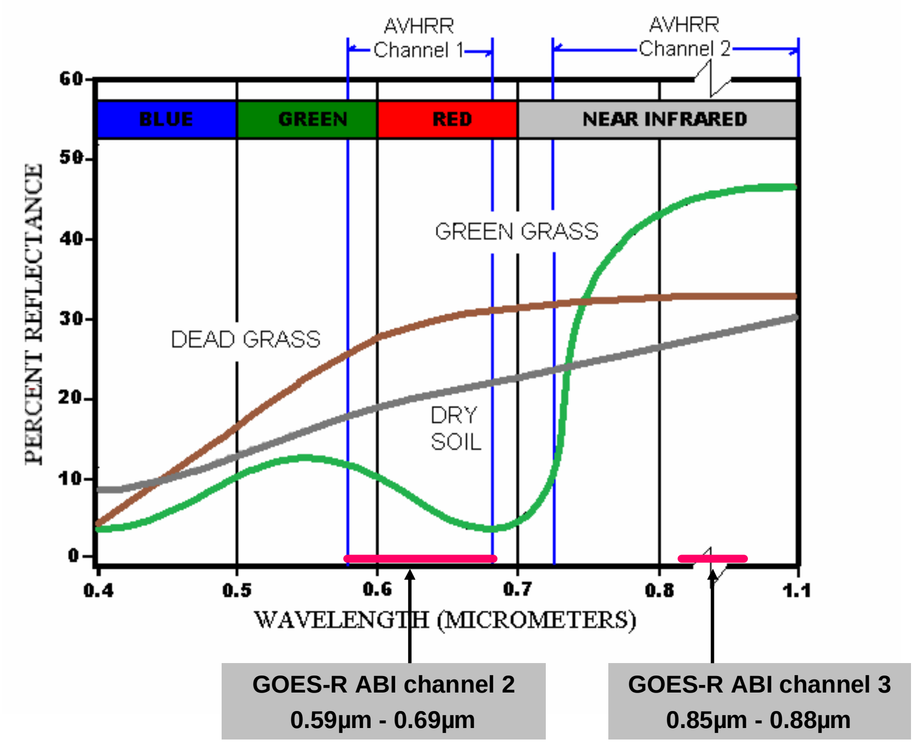


Figure 3.3 – Typical spectral reflectance curves for green grass, dead grass and dry soil in the visible and near infrared channels.

1.12 Algorithm Output

The final output of this algorithm is an array of scaled NDVI values together with quality control flags for each pixel (Table 3.2). Scaled NDVI values are saved as a 2-byte integer with a fill value of -999.

Some users/reviewers have suggested including the original reflectance values at the aggregated 2 km spatial resolution along with NDVI values in the product output. This suggestion cannot be adopted at present without the official change in the GS-F&PS.

Table 3.2 – Output table for the NDVI product

Name	Type	Description	Dimension
ABI NDVI	Integer	Scaled NDVI values: (NDVI+1)*100=100*NDVI+100	grid (xsize, ysize)
QC flags	Integer	Quality control flags for each pixel of the scanning mode: Land, cloudiness, sensor data quality, day/night, product extent qualifier etc.	grid (xsize, ysize)

It is proposed to reserve a two byte quality control flag for each pixel, which may be comprised of a total of 16 bits holding the test results (yes/no) for each of the various tests and flags.

Table 3.3 – Quality Control (QC) flags explained

Byte	Bit	Flag	Source	Effect
1	0	Empty		Reserved for future use
	1	Availability	SDR	0=normal, 1=out of space, bad data, or missing data
	2	View angle	SDR	0= (LZA<70°), 1= (LZA≥70°)
	3	Surface Type	Land/sea Mask	0=land, 1= water
	4	Cloud index	Cloud Mask	0=clear, 1= cloudy
	5	Day/night	SDR	0=day (solar zenith ≤ 67°), 1=night
	6	Snow/Ice	Snow/ice mask	0=normal, 1=snow/ice
	7	NDVI quality	NDVI	0=normal, 1= out of range (0 - 1)
2	0	Empty		Reserved for future use
	1			
	2			
	3			
	4			
	5			
	6			
	7			

In addition, the NDVI retrieval procedure will also generate metadata characterizing the processing information (e.g. date/time stamps). Some additional metadata will be inherited from the sensor input data. The GOES-R AWG and the Land Team recommends that the following metadata (Table 3.4) is provided for the ABI TOA NDVI products.

Table 3.4 - Metadata defined for the ABI TOA NDVI product.

Metadata	Type	Definition
Date	common	Beginning and end dates of the product
Time	common	Beginning and end times of the product
Bounding Box 1	common	Resolution, number of rows, number of columns
Bounding Box 2	common	Byte per pixel, data type, byte order information, location of box relative to nadir
Product Name	common	The ABI NDVI product name
Ancillary Data Used	common	Ancillary data name, version
Satellite	common	GOES-R satellite name
Instrument	common	ABI
Altitude	common	Altitude of the satellite
Position	common	Latitude and longitude of the satellite position
Version	common	Product version number
Compression	common	Data compression type (method) used
Location	common	Location where the product is produced
Contact	common	Contact information of the producer/scientific supporter
Number of QC flags	NDVI	7
For each QC flag value, the following information is required: • Percent of retrievals with the QC flag value • Definition of QC flag		
Availability	NDVI	Valid ABI input excluding any pixel that is out of space, bad data, or missing data
Cloud Index	NDVI	Good if ACM indicates clear, bad if ACM indicates probably clear, probably cloudy, or cloudy
View Angle	NDVI	Good if LZA is <70°, bad if view angle is beyond product extent qualifier (LZA≥70°)
Surface Type	NDVI	Good if it is land, bad if it is not land
Day/night	NDVI	Good for day time if solar zenith ≤ 67° for full illumination, bad if solar zenith angle >67°
Snow/Ice	NDVI	Good for areas free of snow/ice, No NDVI will be generated for snow/ice pixels
NDVI Quality	NDVI	Valid range for NDVI product (0 - 1)
Product Unit	NDVI	Scaled unitless
Scaling Factor	NDVI	100
Offset	NDVI	100
Land Types	NDVI	Number of land surface types (Land, snow/ice)
Statistics	NDVI	Mean and standard deviation of all the available NDVIs
Good pixels	NDVI	Number of pixels in valid NDVI range (0 - 1)
Total Pixels	NDVI	Total pixels NDVI is retrieved (cloudless, snow free, daytime land

		surface pixels)

2 TEST DATASETS AND OUTPUTS

2.1 Simulated/Proxy Input Datasets

Observations from the Spinning Enhanced Visible and Infra-red Imager (SEVIRI), onboard the European Meteosat Second Generation (MSG) satellite, Meteosat-8, are used as a proxy for GOES-R ABI in the NDVI algorithm verification/validation. SEVIRI spectral channels in the visible RED and the near infrared part of spectrum are similar to GOES-R ABI channels. This section describes the proxy and validation datasets used in assessing the performance of the NDVI.

Table 4.1 provides a channel comparison of the visible RED and near infrared channels on GOES-R ABI and MSG SEVIRI instruments. Figure 4.1 shows an example of false color composite and Figure 4.2 presents the derived TOA NDVI map of SEVIRI full disk image for April 9, 2008, 12:15 UTC.

Table 4.1 – Channel comparison of ABI vs. SEVIRI as a proxy

Sensor	Channel No.	Wavelength Center (μm)	Band width (μm)	Sensor Noise (SNR)	Spatial Resolution (km)
GOES-R ABI	2	0.640	0.59 – 0.69	300:1@100% albedo	0.5
	3	0.865	0.846 – 0.885	300:1@100% albedo	1
MSG SEVIRI	1	0.635	0.56 – 0.71	10.1 @ 1% albedo	3
	2	0.810	0.74 – 0.88	7.28 @ 1% albedo	3

2.1.1 SEVIRI Data

MSG SEVIRI provides observations in 11 spectral channels at a spatial resolution of 3 km and a temporal resolution of 15 minutes. SEVIRI offers the best source of geostationary data currently available for testing and developing the NDVI. Figure 4.1 is a full-disk SEVIRI image from 12:15 UTC on April 9, 2008. The SEVIRI data are routinely provided by the University of Wisconsin Space Science and Engineering Center (SSEC) Data Center through the Man-computer Interactive Data Access System (McIDAS).

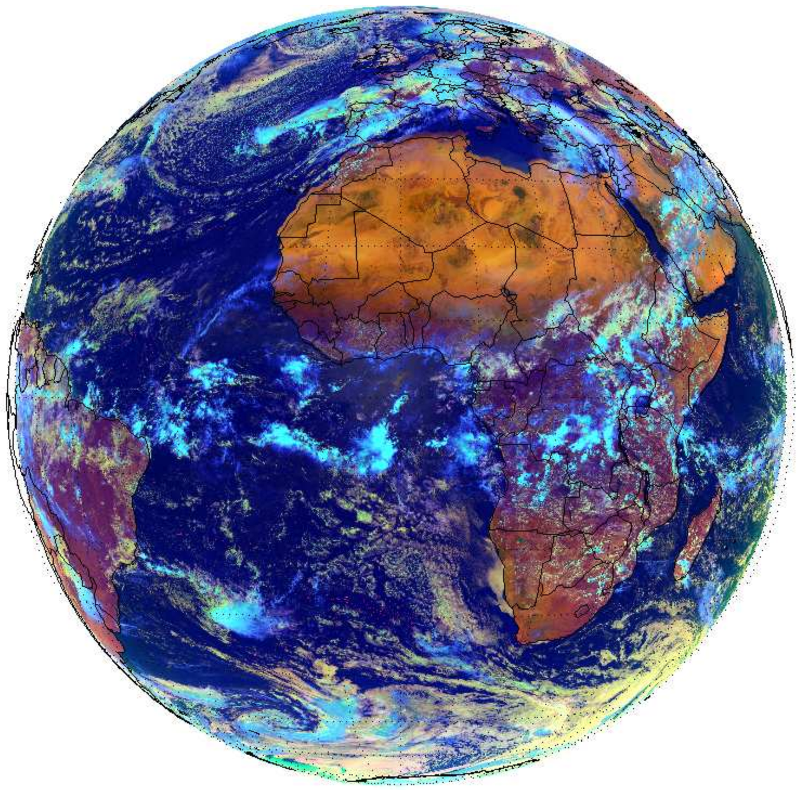


Figure 4.1 – Full disk false color image from SEVIRI for 12:15 UTC on April 9, 2008. The image is composed of channel 3 reflectance at 1.61 µm (in red), channel 1 reflectance at 0.63 µm (in green) and inverted channel 9 at 10.8 µm brightness temperature (in blue).

2.1.2 SEVIRI data for algorithm and product validation

To support the development and off-line validation of the ABI NDVI algorithm, we have collected a three-year set of MSG SEVIRI data. The dataset covers the time period since March 2007 and includes half-hourly observations from SEVIRI in spectral bands 1 (visible red, 0.63µm), 2 (near infrared, 0.81µm), 3 (shortwave infrared, 1.6µm), 4 (middle infrared, 3.9µm) and in split-window bands 9 and 10 (10.8µm and 12.0µm, respectively). Another MSG SEVIRI dataset has been prepared by AIT and ingested into the mainframe system. The latter dataset includes SEVIRI data at 15 minutes interval for the time periods Aug. 1-31, 2006; Feb.1-14, 2007; Apr. 1-13, 2007; and Oct. 1-13, 2007.

The collections of MSG SEVIRI data described above are used for both the offline and framework validation of the NDVI algorithm and products. While the accuracy of NDVI algorithm is determined only by the accuracy of reflectance measured in ABI channels 2 and 3, NDVI product accuracy depends on the accuracy of external datasets, e.g. cloud mask, snow mask, and navigation data. It may also be affected by variable aerosol concentration. Since NDVI is not measured on the ground, no real truth data is available. NDVI estimates from different satellite data are sensor-specific and cannot be quantitatively compared either. Therefore, the spatial and temporal change in NDVI consistent with variation of the state of the vegetation cover will be used as a "surrogate" truth. In addition, "smoothness" of NDVI temporal change can be considered as an indirect indication of the product validity.

2.2 Output from Simulated/Proxy Inputs Datasets

The near real time NDVI image products have been generated using the full disk SEVIRI data since March 2007. Figure 4.2 shows an example of the NDVI product over cloud free land areas. This image is for 12:15 UTC on April 9, 2008 and corresponds to the false-color image in Figure 4.1.

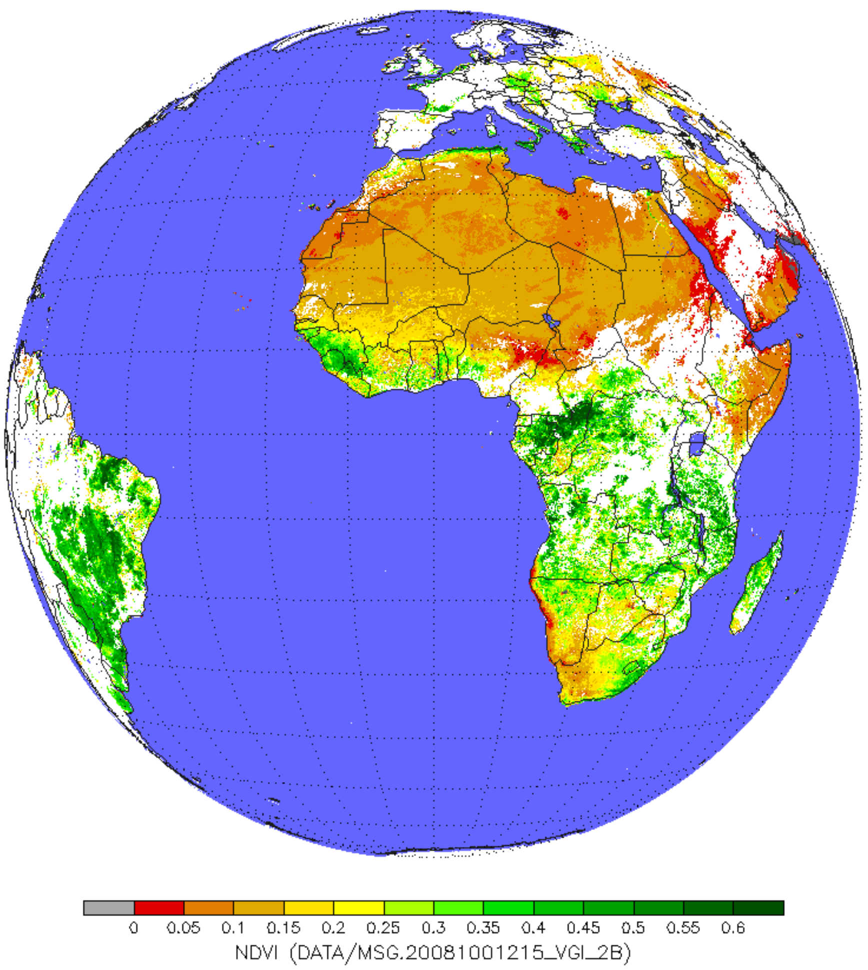


Figure 4.2 – Example NDVI map for 12:15 UTC April 9, 2008 produced from SEVIRI on Meteosat-8. A cloud mask and the land/sea mask have been applied; the derived NDVI is shown where a land pixel is cloud free.

2.2.1 Precisions and Accuracy Estimates

No problems are expected in the NDVI algorithm performance for meeting the accuracy requirement of 0.04 NDVI units. NDVI is a radiance-based parameter and NDVI accuracy is defined by radiance measurement accuracy. Simple estimates have shown that if the instrument noise in ABI spectral bands 2 and 3 satisfies specifications and remains below 0.3%, the NDVI error should not exceed 0.012 and thus should also be within the ground segment functional and performance specifications (GS-F&PS).

Direct quantitative validation of the NDVI product is not possible since there are no *in situ* observations of NDVI available for "ground truth." To overcome this problem in the precision assessment, evaluation of individual products will be based on the analysis of NDVI spatial distribution and temporal change. Spatial and temporal change in NDVI should be consistent with variation of the state of the vegetation cover. To achieve a high precision, it is desirable to see a low (lack of) high-frequency (day-to-day) changes in NDVI. To meet the NDVI precision specification of 0.04, NDVI estimates made in cloud-clear conditions at the same time of the day (same geometry) on two consecutive days are compared to derive quantitative measurements of the daily RMS change of NDVI. A validity criterion is established and achieved if the daily RMS change of NDVI is kept below 0.04.

It is identified that major risks in the NDVI product quality may be associated with the following aspects:

- Inaccurate cloud identification (missed clouds);
- Cloud shadows;
- Large aerosol variations which can cause shifts in the TOA NDVI;
- Reflectance anisotropy (not accounted for in the NDVI formulation);
- Sensor calibration, image navigation, and channel co-registration.

Validation results for accuracy and precision assessment can be found in Section 4.2.3. The results demonstrate that the NDVI algorithm generates products that meet the GS-F&PS specifications.

2.2.2 Error Budget

As stated in the previous section, requirements for both NDVI accuracy and precision are set at 0.04 NDVI unit. This should be met without problems provided that GOES-R instruments are meeting performance requirement and the channel reflectance values are within the specified error limits of below 0.3%.

2.2.3 Validation result from the SEVIRI test data

2.2.3.1 Software verification

To test the software readiness, SEVIRI data, plus cloud mask and snow mask for 12:00 UTC August 1, 2006 have been used to generate NDVI on AWG developer's Linux machine using research code and on a Linux machine in the collaborative environment using the AIT's Framework. The results were compared and confirmed on the pixel by pixel basis for all snow/cloud free land area. The results between the Framework and the offline code are identical using the same compiler. The resultant TOA NDVI values are reasonable and the spatial distribution of the NDVI is consistent with our understanding of the region, as shown in Figure 4.3.

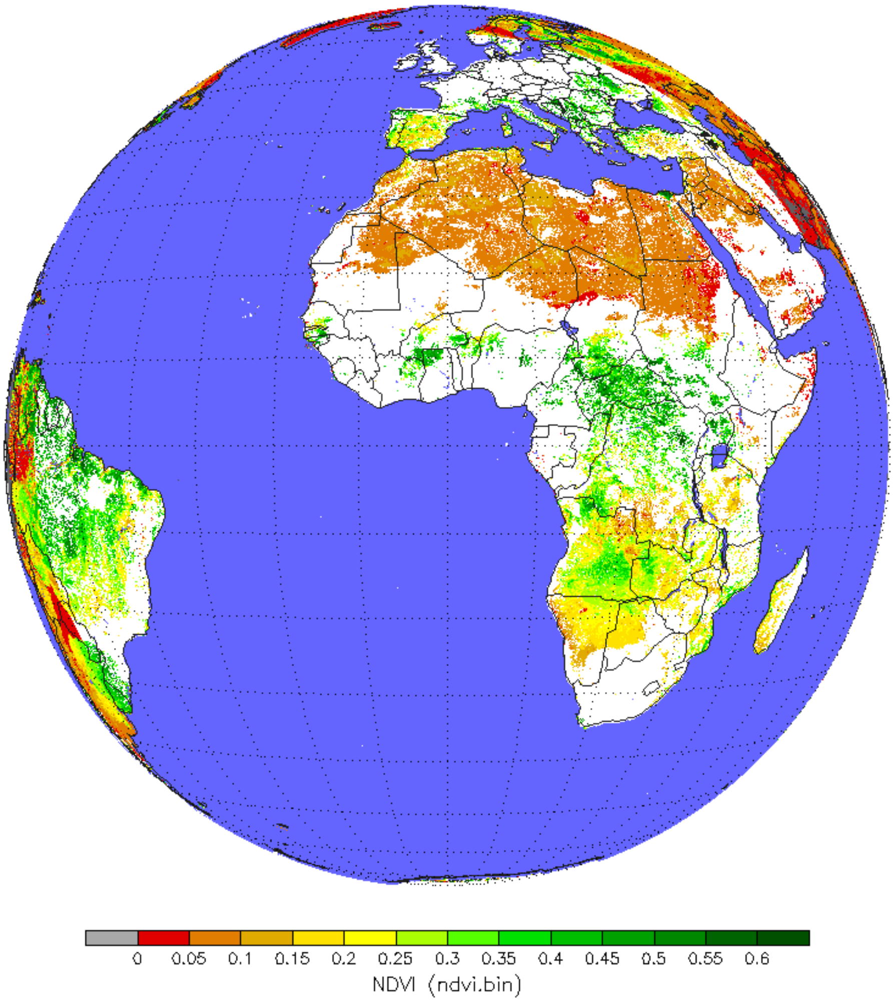
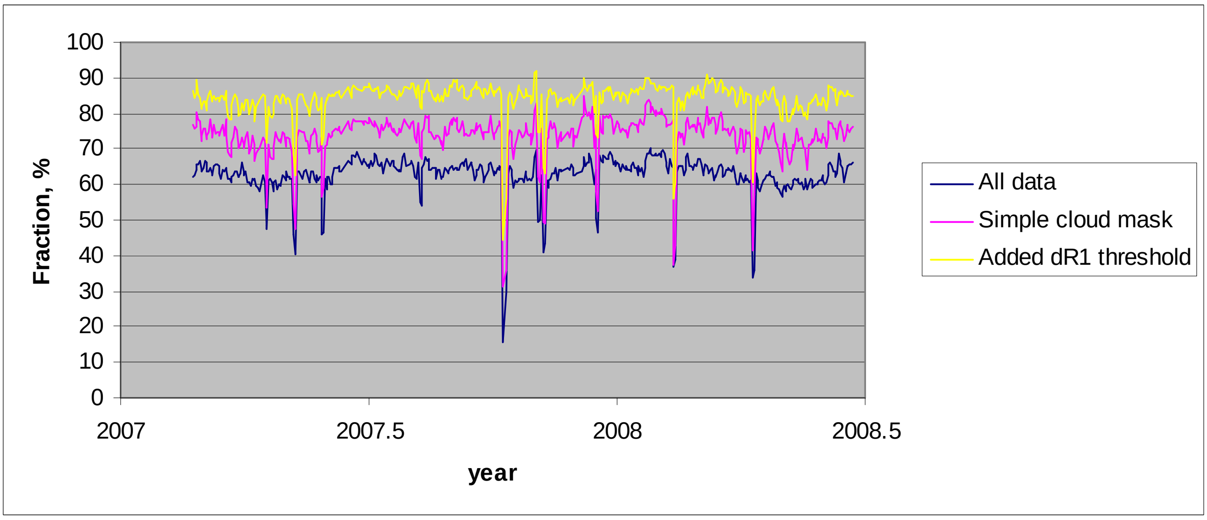


Figure 4.3 – MSG-8 SEVIRI data at 1200Z on August 1, 2006 are used to test NDVI software readiness.

2.2.3.2 Offline product validation

The method for the offline product validation is to evaluate daily change of derived NDVI. NDVI daily change of over 0.05 is considered excessive. It indicates external effects on NDVI (undetected clouds, inaccurate navigation, large variation in aerosol concentration, etc.). Thus, the NDVI estimates made in cloud-clear conditions at the same time of the day on two consecutive days will be compared and a fraction of pixels with NDVI daily change less than 0.05 would indicate good performance. It is expected that NDVI product should have less than 20% of cases with excessive (over 0.05) daily change in NDVI at 80% readiness, and less than 5% of cases with over 0.05 NDVI daily change at 100% readiness. Figure 4.4 shows an example of such comparison of daily changes for 11:45 UTC. It can be seen that a relatively simple cloud mask reduces the fraction of cases with excessive NDVI daily change to 10-20%. With more advanced cloud mask, the percentage of cases with large NDVI daily change may further decrease.



"All data": No cloud mask applied, ϴsat < 70°, ϴsol < 70°
"Simple cloud mask": T_9>285K, R_1<60%, NDVI>0.05
"Added dR1 threshold": Cloud mask consisting of "Simple cloud mask" and 10% max daily change in R_1

Figure 4.4 – Fraction of cases with over 0.05 NDVI diurnal variations for MSG SEVIRI full disk data at 11:45UTC.

2.2.3.3 Framework validation

Framework validation technique is the same as the offline technique. AIT members have done 10 week runs of MSG SEVIRI data to generate NDVI and other products. The GOES-R ABI Cloud Team's cloud masks are used to evaluate daily change of NDVI for pixels identified as cloud clear for observations made at the same time of the day. The percentage of pixels with excessive (over 0.05) NDVI daily change can then be calculated. It should correspond to those obtained offline with the same test dataset.

Figure 4.5 shows an example of NDVI output from the framework with the GOES-R ABI cloud team's cloud mask applied. It seems that negative NDVI values shown in red most probably correspond to missed clouds.

Table 4.2 presents the estimates of the fraction of cloud clear pixels that exhibit and excessive (over 0.05) daily change in NDVI for August 2006. ABI cloud mask (code 4 = completely clear) has been used. The fraction of land pixels with excessive NDVI daily variation ranges from 4.7% to 8.2%, which is quite reasonable and should meet the performance requirement.

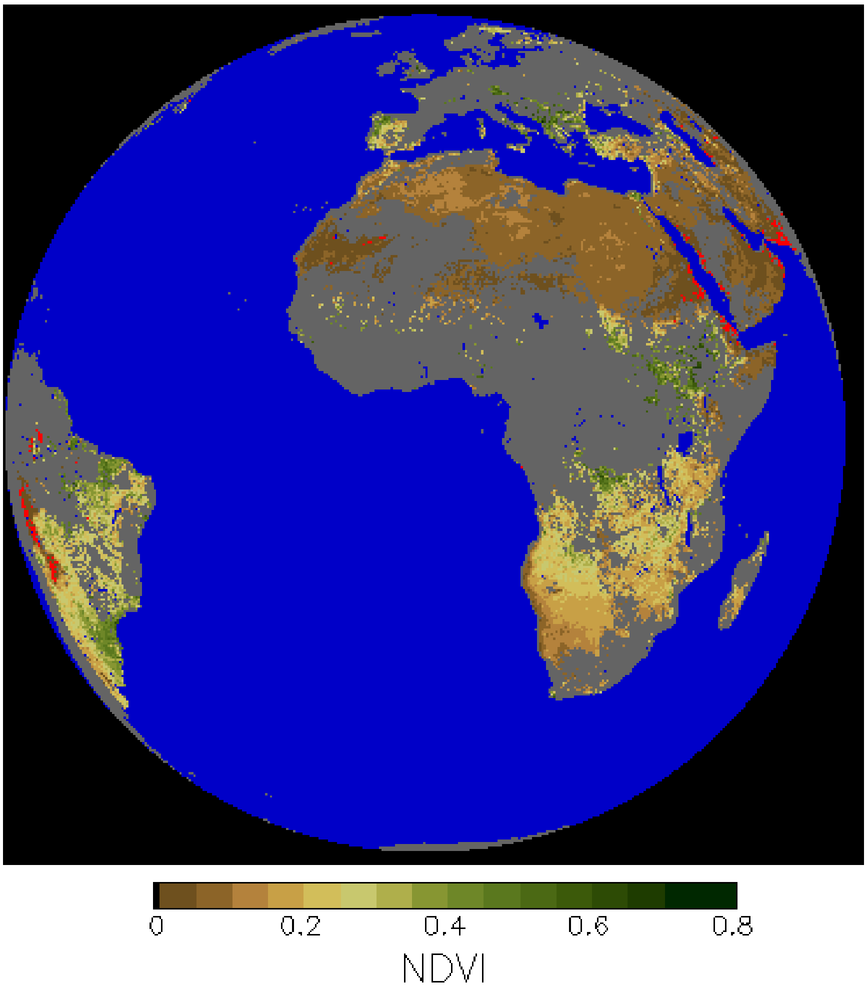


Figure 4.5 – NDVI map with cloud mask overlaid for 11:45 UTC on August 24, 2006. NDVI is shown for pixels identified as completely cloud-clear (cloud mask code 4). Clouds are shown in gray. Negative NDVI values are shown in reds.

Table 4.2 – Estimates of the fraction of cloud clear pixels that exhibit an excessive (over 0.05) daily change in NDVI.

Date (YYYYDDD)	Total Clear Land Pixels	Pixels with Excessive Variation (>5%)	Fraction (%)
2006213	13468	788	5.9
2006214	13939	922	6.6
2006215	13701	744	5.4
2006216	13602	688	5.1
2006217	14180	874	6.2
2006218	14586	881	6.0
2006219	14567	848	5.8
2006220	13874	897	6.5
2006221	13383	624	4.7
2006222	13364	805	6.0
2006223	13542	790	5.8
2006224	13709	847	6.2
2006225	12443	1022	8.2
2006226	12495	1061	8.5
2006227	13227	722	5.5
2006228	13623	731	5.4
2006229	13146	871	6.6
2006230	13221	877	6.6
2006231	14303	1026	7.2
2006232	13330	930	7.0
2006233	12454	868	7.0
2006234	10914	677	6.2
2006235	10980	574	5.2
2006236	10968	896	8.2
2006237	11197	693	6.2
2006238	11331	651	5.7
2006239	11785	729	6.2
2006240	12030	740	6.2
2006241	11967	729	6.1
2006242	12148	973	8.0

To further understand the validation results, NDVI time series for selected locations are plotted for August, 2006 using the common test data as shown in Figure 4.6. Large day-to-day variation in derived NDVI values at some locations may be due to undetected clouds/cloud shadows or other factors such as navigation, co-registration, variable aerosol.

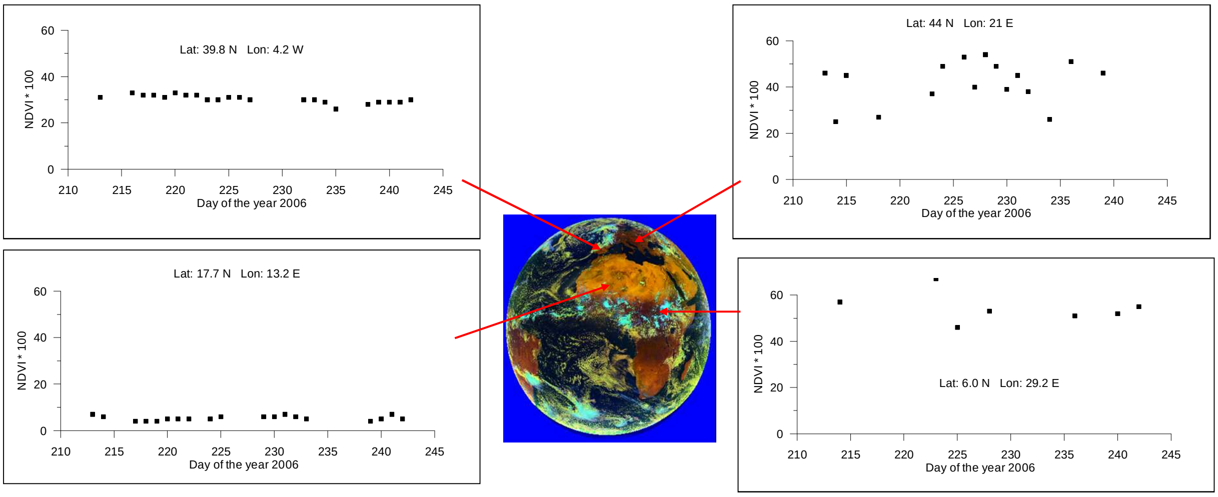


Figure 4.6 – NDVI time series for selected locations with cloud mask overlaid for 11:45 UTC on August 2006.

In addition, NDVI temporal variation for different regions is presented in Figure 4.7. It is encouraging that the mean daily change of NDVI over full disk is below 0.04. It also reveals that NDVI estimates over deserts are more consistent than over densely vegetated areas.

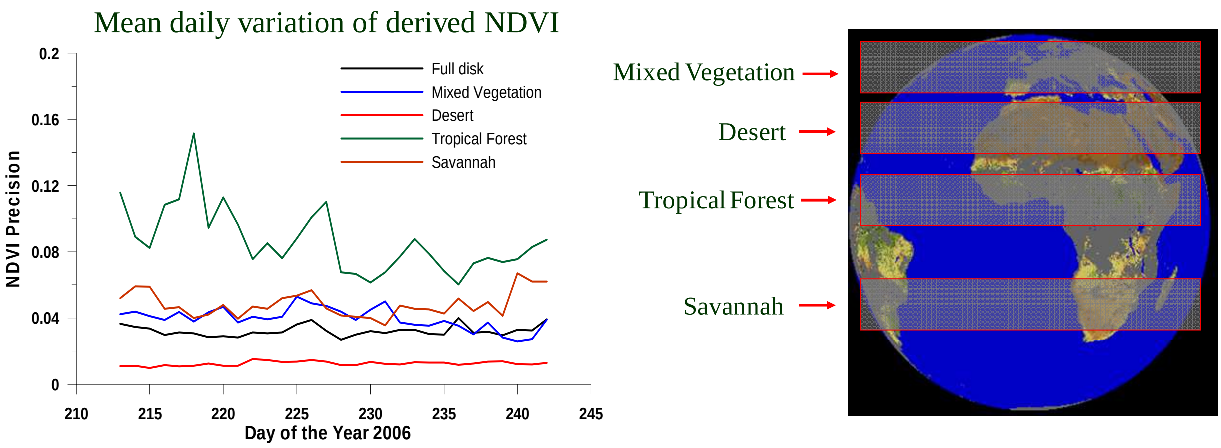


Figure 4.7 – NDVI temporal variation for selected regions with cloud mask overlaid for 11:45 UTC in August 2006.

Overall NDVI product is close to meeting the accuracy and precision specifications. More conservative cloud mask over densely vegetated areas may further improve NDVI precision.

3 PRACTICAL CONSIDERATIONS

3.1 Numerical Computation Considerations

The NDVI is implemented through simple computation. Some ancillary data flags need to be applied to identify valid land pixels before the computation of NDVI. Array computation for the full disk image may require large memory storage. It is recommended to loop through all pixels and compute NDVI for pixels that are over land, snow free, cloud free, and under “full illumination” (“full illumination condition” is defined by the product qualifier of < 67° solar zenith angle).

3.2 Programming and Procedural Considerations

The GOES-R ABI NDVI is a pixel by pixel algorithm, with NDVI being computed when a pixel is identified as snow and cloud-free land pixel in full illumination condition.

3.3 Quality Assessment and Diagnostics

The following procedures are recommended for diagnosing the performance of the NDVI retrieval.

- Monitor individual NDVI values periodically. Qualitative analysis of NDVI spatial distribution and temporal change. These values should be quasi-constant over a large area.
- Abnormally low NDVI absolute values, lack of spatial uniformity, excessive short-term variations are indicative of cloud contamination.
- Maintain a close collaboration with the other teams/users using the NDVI in their product generation.

3.4 Exception Handling

All GOES-R algorithms will check the status of the required input data, including primary sensor data, AWG product precedence, and ancillary data. If the input data are of poor quality and could not be used to generate the GOES-R products, quality control (QC) flags will be set and the particular algorithm will exit. The QC flags will be sent back to the framework and the processing will continue to other algorithms.

The NDVI algorithm includes checking the validity of each required channel (ABI channels 2 and 3) before applying the appropriate test. The NDVI algorithm also expects the main processing system to flag any pixels with missing geolocation or viewing geometry information.

In addition, the NDVI algorithm checks for conditions where the NDVI should not be performed. These conditions include high solar zenith angles >67° not meeting the full illumination condition or missing reflectance values. In such cases, the appropriate quality flag is set to indicate that no NDVI was produced for that pixel.

Availability of required previously computed GOES-R products and ancillary data is also checked. If the standard ABI snow mask is not available, the interactive multi-sensor snow and Ice Mapping System (IMS) snow/ice mask from NOAA/NESDIS/STAR/NIC will be used to identify snow/ice pixels. Table 5.1 lists the exception handling needs for NDVI retrievals in the case of missing/bad data.

Table 5.1 – Exception handling needs for ABI NDVI algorithm

Situation of missing/bad data	What will be generated
Pixel is identified as cloudy	"Invalid NDVI" flag in the NDVI file "Cloud" flag in the control file
Pixel is over water	"Invalid NDVI" flag in the NDVI file "Water" flag in the control file
Insufficient solar illumination (solar zenith angle > 67°)	"Invalid NDVI" flag in the NDVI file "Dark" flag in the control file
Derived NDVI value is beyond the [0.0, 1.0] interval	"Invalid NDVI" flag in the NDVI file "Value outside limits" flag in the control file
Corrupted reflectance values (RED or NIR outside of [0%:100%] range	"Invalid NDVI" flag in the NDVI file "Reflectance value outside limits" flag in the control file

3.5 Algorithm Validation

This section provides a brief overview of pre- and post-launch activities to validate the GOES-R NDVI product. A complete description of the NDVI validation plan is provided in the "GOES-R NDVI Validation Plan" document.

Top-of-atmosphere NDVI is derived with a deterministic equation relating NDVI to satellite-observed reflectances. Therefore the algorithm itself does not require validation. The NDVI product however may be affected by undetected clouds, variable aerosol loading, navigation/registration inaccuracy and some other factors. These factors may cause inconsistency in GOES-R ABI NDVI estimates.

No routine NDVI observations are performed on the ground. As a result, direct evaluation of the accuracy of NDVI estimates is impossible. Consistency of NDVI estimates will be assessed indirectly by examining temporal variations in the observed NDVI. Large short-term variability in the derived NDVI cannot be caused by vegetation cover changes and is typically an indicator of cloud contamination of the time series.

Over vegetated land areas with a pronounced seasonal vegetation cycle, NDVI changes from about 0.1 in spring to maximum values of 0.5-0.6 in the middle of the growing season. This increase from minimum to maximum values typically occurs within a period from one to two months and therefore corresponds to a maximum NDVI daily change rate of about 0.01-0.015. According to the GS-F&PS document, NDVI should be derived with an error of less than 0.04. Therefore diurnal change in the observed NDVI exceeding 0.05 should be considered excessive. Corresponding cases should be properly identified to flag NDVI estimates that are most probably erroneous.

The fraction of cases where derived NDVI at two consecutive days exceeded 0.05 will be used as a parameter characterizing the overall accuracy and consistency of the NDVI product. It is important, that since NDVI depends on the viewing and illumination geometry, estimates of the diurnal NDVI change will be made using images taken at the same time of the day.

Validation of the NDVI product will be conducted on a daily basis by evaluating daily changes in the derived NDVI for each land pixel of the full disk image. Two hourly images obtained at the same time of the day with one day apart will be compared. Pixels identified as clear in both images will be used. The statistics of the difference in estimated NDVI in these pairs of pixels will be generated. The fraction of pixels with the NDVI daily difference of over 0.05 will be presented as the fraction of invalid NDVI retrievals or as the accuracy of the current NDVI product.

3.6 Other Considerations

Several other considerations are listed below with regard to the current NDVI products:

- Instantaneous NDVI products have little chance to satisfy the user community.
- Daily and weekly composite and mostly cloud-free NDVI products are needed and have to be developed.
- Daily and weekly products will involve image compositing and will thus provide better area coverage (less cloud gaps) compared to the instantaneous products.
- With the current approach, NDVI correction for the atmosphere and the angular anisotropy is left to the users.
- The standard cloud mask may have to be modified or replaced with the mask developed specifically for the NDVI product.

4 ASSUMPTIONS AND LIMITATIONS

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

4.1 Performance

The following assumptions have been made in developing and estimating the performance of the NDVI, including proposed mitigation strategies in parentheses.

- High quality snow maps are available. (Use snow information from NWP).
- The ABI cloud mask is available at the time of NDVI estimate. (Use alternative built-in algorithm to identify cloudy pixels).
- ABI reflectance data in channels 2 and 3 are available, calibrated and navigated, and are not distorted (set quality flag to bad pixels and no NDVI is produced).
- All of the static ancillary data are available at the pixel level. (Reduce the spatial resolution of the surface type, land/sea mask).
- The processing system allows for ingest of previous output for application of the temporal tests/maximum NDVI compositing. (Make temporal tests optional).

The product is extremely sensitive to degradation of the sensor data and ancillary products. There is no alternative method to calculate NDVI if any one of ABI spectral channels 2 and 3 becomes inoperative. Unavailability of the cloud mask will cause the product to degrade to an unusable level. Unavailability of geometrical configuration files and in particular the solar zenith angle data file will cause invalid NDVI retrievals over areas with insufficient daylight.

4.2 Assumed Sensor Performance

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

- Unknown spectral shifts in some channels will cause biases in the performance of the NDVI.
- Errors in navigation from image to image will affect the performance of the temporal tests or future daily/weekly NDVI compositing.

4.3 Limitations

The following limitations are identified and cautioned for the NDVI algorithm and products:

- No NDVI retrievals will be conducted in cloudy or nighttime conditions.
- Derived NDVI varies depending on the viewing and illumination geometry (no angular correction).
- Possible variations of the atmospheric composition (e.g., aerosol) affect NDVI estimates.

4.4 Pre-Planned Product Improvements

Plans for NDVI product improvements and overcoming identified limitations fall into the following three areas:

- Daily and weekly products
  - Compositing of half-hourly NDVI retrievals
  - Less cloud gaps than in the polar product due to high frequency of observations
  - Weekly products are mostly used by climatologists

- Angular correction
  - Required to allow for comparison and compositing of NDVI estimates made at different viewing and illumination geometry
  - Semi-empirical kernel-driven BRDF models will be used for correction

- Atmospheric correction
  - Required to estimate top-of-canopy NDVI
  - 6S or similar code will be used to calculate corrective factors
  - Lookup tables will be developed to perform operational correction

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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. SNOW_MASK_IMS_SSMI

a. *Data description*

Description: Snow/Ice mask, IMS – Northern Hemisphere, SSM/I – Southern Hemisphere
4km resolution – the 25 km SSM/I has been oversampled to 4km
Filename: snow_map_4km_YYMMDD.nc
Origin: CIMSS/SSEC
Size: 39 MB.
Static/Dynamic: Dynamic

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.