Development of Cloud and Aerosol Retrieval Algorithms for ADEOS-II/GLI Mission

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Abstract

This paper introduces algorithm development strategies for the ADEOS-II (Midori-II) GLI atmospheric mission, and presents the flow chart and the principle of each algorithm. During the GLI science mission, which operated between 1996 and 2008, the principal investigators and co-investigators of the atmospheric discipline were developing and improving algorithms which distinguish cloudy from clear pixels on GLI images, retrieve cloud and aerosol properties, retrieve the amount of precipitable water, and estimate the radiation budget from GLI multispectral radiance data in collaboration with the GAIT team managed by JAXA EORC. Despite the short lifetime of the GLI project, important scientific results in the atmospheric discipline were obtained from GLI multispectral imaging data by using the algorithms we developed. This legacy will be applied in future Japanese Earth observing missions in next decade.

Keywords: ADEOS-II, Global Imager (GLI), Cloud properties, Aerosol properties, Algorithm development, Signal simulation

1. Introduction

The Global Imager (GLI) is a satellite-borne multi-spectral crosstrack scanner with 36 channels in the near ultraviolet (380 nm) to thermal infrared (12 μm) range, which is located aboard the Advanced Earth Observing Satellite-II (ADEOS-II) together with another four different types of sensors. It has a 1600-km swath with a 1-km and/or 250-m Instantaneous Field of View (IFOV) at nadir from its 803-km high sun-synchronous orbit. GLI was launched in December 2002 and observed the Earth surface continuously between April and October 2003. The calibrated radiances (Level-1B) and several retrieved geophysical parameters (Level-2, -3) of atmosphere, ocean, land, and cryosphere have been released since December 2003. These results have been used for climate change studies, weather forecasting, and other general fundamental studies in the field of Earth sciences.

The primary objective of this paper is to introduce some unique strategies of the GLI algorithm development. It will also provide a description of the flow charts of the algorithms which retrieve the properties of clouds and aerosols in the atmosphere. Table 1 summarizes the “standard” products observed with GLI. Here, “standard” refers to the products and/or algorithms which were formally registered by JAXA and distributed to users by JAXA’s data center. Cloud and aerosol properties were retrieved from 1-km IFOV channels in the visible, near-infrared, short-wave infrared, and infrared wavelength regions. Precipitable water is also an important observation target for studying climate change, especially with respect to water cycle issues. The radiation budget was estimated by using the cloud and aerosol distributions and their optical and microphysical properties as retrieved from GLI (the radiation budget is not included in Table 1 since it is not a “standard” but a “research” product).

The strategy for the algorithm developments is introduced in Section 2, and the algorithm flow charts of the cloud and aerosol retrievals and the typical viewgraphs obtained from these algorithms are shown in Section 3. The significance of the GLI observations to atmospheric science and their possible application in future missions are summarized in Section 4. Since the primary goal of this paper is to introduce a draft description of the development of atmospheric algorithms, each section is composed of a brief outline of the respective topic. We recommend the reader turn to the reference articles for further details.
Table 1  Standard products obtained by the GLI data analysis system installed at JAXA.

<table>
<thead>
<tr>
<th>Product name</th>
<th>Global (4days)</th>
<th>Global (16days)</th>
<th>Global (1month)</th>
<th>Scene (Level-1b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clouds</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cloud flag</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Cloud fraction</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Cloud optical thickness (@500nm)</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Cloud particle effective radius</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Cloud top height</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Cloud top temperature</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Aerosols</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aerosol optical thickness (@500nm)</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Ångström exponent</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Water vapor</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Precipitable water</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
</tbody>
</table>

(○ stands for standard product)

2. Strategy for the development of GLI atmospheric algorithms

2.1 PI and GAIT collaboration

GLI retrieved atmospheric cloud and aerosol properties which are well known as two of the greatest uncertainties in the study of Earth climate change\(^1\). The standard algorithms for retrieving these properties were developed by principal investigators (PI), which were selected through ADEOS-II research announcements (RAs). These algorithms were implemented in the Japan Aerospace Exploration Agency (JAXA) Earth Observation Center (EOC) located in Saitama prefecture, Japan, under the unique framework of the JAXA Earth Observation Research Center (EORC). We refer to this framework as the GLI Algorithm Integration Team (GAIT). GAIT involves many individual scientists and engineers, and its members are engaged in algorithm implementation, system integration, validation of the observed results, and so on, thus creating strong connections with many researchers (PI and others) from outside JAXA as well as engineers from both inside and outside JAXA. It is very important to establish a framework which can act as a bridge between the hardware section and the science section in the case of large scientific missions such as GLI. Generally speaking, the motivation of most researchers is based on their strong interest in the research objectives and a good environment for writing scientific papers. Therefore, the GAIT framework was designed to match two different kinds of vectors, namely “promotion of the satellite mission” and “promotion of state-of-the-art science”. Table 2 summarizes the PI and co-investigators for each atmospheric algorithm of GLI and the successive GAIT members in the atmospheric discipline.

2.1 GLI signal simulator

We should not forget one of the other strategies for algorithm development in the GLI science mission, namely the development of the GLI Signal Simulator, which simulates realistic radiances observed with GLI by using computer resources. GLI was one of the path-breaking multi-spectral imaging sensors for comprehensive Earth observation. However, it implicitly included some uncertainties when we developed algorithms that involve “new combinations” and/or “new utilization” of spectral channels which have not been used before. It is obvious that we applied data from similar existing sensors aboard satellites and/or aircrafts in order to develop and test the GLI algorithms. In fact, data from the Advanced Very High Resolution Radiometer (AVHRR), the Coastal Zone Color Scanner (CZCS), the Ocean Color and Temperature Sensor (OCTS), and so on, have been used very often by PI and GAIT during the development phase. However, not only the center wavelengths and bandwidths but also the orbit (altitude, inclinations angle, local time) of these satellites and/or aircrafts were different from the real specifications of GLI. These differences can affect the development of GLI algorithms by introducing implicit and/or explicit
uncertainties. In order to overcome this problem, GAIT developed signal simulation software referred to as GLI Signal Simulator (GSS) with the help of many scientists. GSS was connected with the orbital calculation module, and as a result it calculated very realistic radiances observed with imaginary launched “GLI”. GSS was also used for the GLI sensor design\(^2\). Please refer to Nakajima T.Y. et al. (2003)\(^3\) for more detailed information about GSS and its efficient use. GSS data is publicly available via the Internet. (http://bishamon.eorc.jaxa.jp/ENTGSS/index.html).

### Table 2 Principal investigators and co-investigators for each algorithm and successive GAIT members in atmospheric science.

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Members</th>
<th>GAIT members, including successors (current position)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cloud screening</td>
<td>S. Ackerman (R. Frey)(^{10})</td>
<td>Y. Liu (Chinese Academy of Science, China)</td>
</tr>
<tr>
<td>Aerosol analysis</td>
<td>T. Nakajima (A. Higurashi)(^{11,12,13})</td>
<td>P. Zhang (China Meteorological Administration)</td>
</tr>
<tr>
<td></td>
<td>T. Nakajima (S. Fukuda)(^{14})</td>
<td>R. Höller (Federal Environment Agency, Austria)</td>
</tr>
<tr>
<td>Cloud analysis</td>
<td>T. Nakajima (T.Y. Nakajima)(^{4,5})</td>
<td>J. Nieke (University of Zurich, Switzerland)</td>
</tr>
<tr>
<td></td>
<td>T. Nakajima (S. Katagiri)(^{10})</td>
<td>N. Kikuchi (NIES, Tsukuba)</td>
</tr>
<tr>
<td>Cloud fraction/Radiation budget</td>
<td>T. Takamura(^{13}) (I. Okada, H. Takenaka)</td>
<td>N. Kikuchi (Fujitsu FIP, Tsukuba)</td>
</tr>
<tr>
<td></td>
<td>R. Pinker</td>
<td>S. Katagiri (JAXA, Tsukuba)</td>
</tr>
<tr>
<td>Cloud geometrical thickness</td>
<td>M. Kuji(^{18})</td>
<td>T. Y. Nakajima (Tokai University, Tokyo)</td>
</tr>
</tbody>
</table>

3. Data analysis flow of cloud and aerosol retrieval

#### 3.1 Clouds (Reflection method)

This is a standard algorithm of the GLI atmospheric mission. One of the proposed methods for retrieving cloud properties with GLI is the “Reflection method”\(^{4,5}\). This method was operated only during the daytime since it used the visible (0.678 \(\mu\)m) and short-wave infrared (3.715 \(\mu\)m) spectral channels, as well as one infrared channel (10.8 \(\mu\)m). The cloud optical thickness (CLOP), the cloud particle effective radius (CLER), the cloud top temperature (CLTT), the cloud liquid water path (CLWP), and the cloud top height (CLHT) were retrieved with this method for warm water-phase clouds, and the cloud optical thickness (CLOP) was retrieved for cold ice-phase clouds. The valid ranges of the retrieved properties are less than 70 for CLOP and less than 30 \(\mu\)m for CLER. Figure 2 shows CLOP and CLER averaged over one month (April 2003). The observed radiances of the visible and short-wave infrared channels includes unexpected radiative components. For example, the 3.715 \(\mu\)m channel contaminates the thermal radiative components emitted from the cloud top and the ground surface. Both the 0.678 \(\mu\)m and 3.715 \(\mu\)m channels contaminate the solar-origin radiative components, which penetrate the cloud layer and then become reflected from land surfaces. Some methods for eliminating these unexpected radiative components from the observed radiances have been suggested in many papers\(^4,5,9^\). The GLI algorithm utilizes the method proposed by Nakajima and Nakajima (1995)\(^4\) in combination with an extension to global-scale analysis proposed by Kawamoto et al. (2001)\(^8\). Please refer to Figure 1 and Nakajima T. Y. et al. (2008)\(^9\) in this issue for more details about the principle of retrieval based on radiative transfer and for methods for eliminating unexpected radiative components.

#### 3.2 Clouds (Emission method)

The other method for retrieving cloud properties is referred to as the “Emission method”. This is also a standard algorithm for the GLI atmospheric mission. It utilizes the 3.715 \(\mu\)m, 10.8 \(\mu\)m, and 12.0 \(\mu\)m channels of GLI and applies them to nighttime data. Using the 3.715 \(\mu\)m channel in order to normalize the split window arches obtained through the 10.8 \(\mu\)m and 12.0 \(\mu\)m channels is one of the unique features of this algorithm (Figure 3). The algorithm retrieves the cloud optical thickness (CLOP) and the cloud particle effective radius (CLER) of cirrus clouds. Please refer to Katagiri and Nakajima (2004)\(^10\) for more details about the algorithm. This algorithm utilizes the ATSEG dataset generated by the
GLI project. The ATSEG comprises the equal longitude and latitude gridded radiance dataset. Each segment is a grid box with dimensions of $0.25 \times 0.25$ degrees in longitude and latitude directions, so that the global dataset has $1440 \times 721$ boxes in total. $5 \times 5 = 25$ pixels of the GLI image are included in every segment element. Therefore, the results obtained with this algorithm were always map projected. Using the ATSEG data is mandatory in the emission method since the algorithm is based on statistical analysis from clustered pixels included in a given segment. Please refer to Nakajima T. Y. et al. (2008)\textsuperscript{10} for more detailed information regarding the ATSEG dataset.

3.3 Aerosols (2-channel method)

This is a standard algorithm of the GLI atmospheric mission. Three aerosol retrieval algorithms have been proposed for the GLI mission. One of them is the “2-channel method”, which is a promising and stable algorithm developed by Higurashi and Nakajima (1999)\textsuperscript{11} and Higurashi et al. (2000)\textsuperscript{12}. Two channels from the visible and near-infrared domains, namely 0.678 $\mu$m and 0.865 $\mu$m, are used for retrieving the aerosol optical thickness ($\tau_a$) and the Ångström exponent ($\alpha$). The Ångström exponent is a parameter related to
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Cloud optical thickness (CLOP) and cloud particle for models 1 and 2 were

\[ r_{m,1} = 0.17 \mu m, s_1 = 1.3 \]
\[ r_{m,2} = 3.44 \mu m, s_2 = 2.75 \]

The refractive index of the model aerosol which we used is 1.5–0.005i. Dark boundary limitations are imposed on the algorithm so that the aerosol properties are retrieved from only open ocean areas which have relatively low surface reflectance. Figure 5 shows \( \tau_a \) and \( \alpha \) averaged over one month (April 2003).

3.4 Aerosols (4-channel method)

This algorithm is a research algorithm developed by extending the 2-channel method. It was developed for the purpose of classifying aerosols into four groups by using the absorptivity and the particle size of the aerosol (Higurashi and Nakajima 2002)\(^{13}\). Aerosols are classified as sea salts, sulfates, dust, and soot. Figure 6 presents a chart of this algorithm and the aerosol classifications. The difference in reflectance between the 0.412-\( \mu \)m and 0.443-\( \mu \)m channels was used for selecting the aerosol model, after which the 2-channel method was operated under the selected non-absorbing or absorbing aerosol model. Non-absorbing aerosols with small and large particle size are classified as sulfates and sea salts, respectively, while absorbing aerosols with small and large particle size are classified as soot and dust, respectively. Dark boundary limitation is also applied in this algorithm.

3.5 Aerosols (+380 nm method)

We proposed a new research algorithm which uses the 380-nm channel of GLI in order to retrieve the aerosol properties over land areas\(^{44}\). Due to the fact that light with a wavelength of 380 nm is reflected poorly over land surface areas, aerosols can be identified by using this algorithm. Figure 7 illustrates the flow chart of the analysis. Meteorological data, National Center for Environment Prediction (NCEP) and Total Ozone Mapping Spectrometer (TOMS) ozone data were input into the system together with the satellite radiance and geolocation data. When the instantaneous Normalized Difference Vegetation Index (NDVI) is larger than the minimum value of the NDVI value obtained in advance, both the optical thickness and the Ångström exponents of the aerosol are retrieved, whereas if the NDVI is smaller than the minimum value, only the optical thickness is retrieved. Figure 8 shows the combined result for the aerosol optical thickness (\( \tau_a \)) and the Ångström exponent (\( \alpha \)) obtained with the 4-channel method for ocean areas and the +380 nm method for land areas.

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Fig. 2 Cloud optical thickness (CLOP) and cloud particle effective radius (CLER) as obtained with the reflection method of the GLI atmospheric algorithm and averaged over one month (April 2003).

the aerosol particle size. Large and small \( \alpha \) generally indicate small and large aerosol particles, respectively. Figure 4 illustrates the retrieval principle based on using two GLI channels. The curves illustrated in the figure show that the reflectance from 0.678-\( \mu \)m and 0.865-\( \mu \)m increases together with the optical thickness of the aerosol. The occurrence of this phenomenon is very understandable. The Ångström exponent (\( \alpha \)) modulates these curves so that \( \tau_a \) and \( \alpha \) can be retrieved upon comparison of a pair of GLI-derived reflectances and a pair of simulated radiances obtained from radiative transfer calculations. We used a fixed aerosol model which has two modes in radius defined by

\[
\frac{dV}{d\ln r} = \sum_{n=1}^{\infty} C_n \exp \left[ -0.5 \left( \frac{\ln r - \ln r_{m,n}}{S_n} \right)^2 \right]
\]

where the mode radius \( r_{m,n} \) and the log standard deviation \( S_n \).
atmosphere, oceans, land, and cryosphere were obtained from GLI multispectral imaging data. Two unique frameworks for developing data analysis algorithms were presented in this paper. One is GAIT, which is established and managed by JAXA (formerly NASDA) EORC, and the other is GSS. GAIT is a special team composed of many individual scientists and engineers who act as bridges between the GLI hardware section and the science section inside and outside JAXA. GSS is a software GLI signal simulator used for simulating observed radiances from a virtual orbit with a virtually operated GLI. The members of GAIT were engaged in algorithm implementation, system integration, and validation and have published many scientific papers in major journals. As a result, some of them received doctoral degrees while others were hired at important job positions inside and/or outside JAXA, at home or abroad. This constitutes indisputable evidence of the consistency of the GAIT framework.

We also presented two algorithms for retrieving cloud properties and three algorithms for aerosol properties. Most of the GLI data were analyzed by using these algorithms, and the results have been publicly released. Among these algorithms, the +380 nm method for aerosol retrievals is regarded as unique and state-of-the-art since GLI is the only global sensor which is equipped with a 380-nm channel with moder-
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Fig. 5 Aerosol optical thickness ($\tau_a$) and Ångström exponent ($\alpha$) as obtained with the 2-channel method of the GLI atmospheric algorithm and averaged over one month (April 2003).

Fig. 6 Simplified chart explaining the principle of classifying aerosol species from three visible and one near-infrared GLI channels.

Fig. 7 Aerosol Optical Thickness at 500 nm

Fig. 8 Aerosol Ångström Exponent

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The authors are grateful to all current and successive members of GAIT, including the contractors from Fujitsu, SED, RESTEC, and MSS, for their great effort in the development and operation of the algorithms. The authors are also grateful to the successive ADEOS-II project managers in JAXA (formerly NASDA), Mr. Ueno, Mr. Ito, and Mr. Matsuura, as well as to the ADEOS-II and/or GLI project coordinators, Mr. Uesugi, Dr. Saito, Mr. Nakagawa, Mr. Kurihara, Mr. Nasu, Mr. Tsuzurabara, Mr. Iwafune, Mr. Yamanashi, and Mr. Nakayama. Finally, we would like to thank to all successive ADEOS-II secretaries, Ms. Verenda, Ms. Haneda, Ms. Takahashi, Ms. Kadobayashi, and Ms. Miura. The GLI science team and the GAIT were established and managed by JAXA (NASA) EORC in the period 1996 to 2008. The data collected with the GLI hardware is still valuable, even though the project has finished.
Fig. 7  Flow chart of the process of retrieving aerosol properties (+380 nm method).

Fig. 8  Combined results for aerosol optical thickness ($\tau_a$) and Ångström exponent ($\alpha$) as obtained with the 4-channel method for ocean areas and +380 nm method for land areas. Results are averaged over one month (May 2003).
References


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