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Retrieval of polar mesospheric cloud properties from CIPS: Algorithm description, error analysis and cloud detection sensitivity

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ABSTRACT

The Cloud Imaging and Particle Size (CIPS) instrument has been in operation on the NASA Aeronomy of Ice in the Mesosphere (AIM) satellite since May 2007. CIPS is a multi-camera UV imager that makes unprecedented hemispheric-scale measurements of polar mesospheric clouds (PMC). The primary CIPS data products are cloud frequency, albedo, mean particle radius, ice water content and vertical column particle density. These quantities are retrieved at 25 km^2 resolution at latitudes between $\sim 55°$ and $84°$ over a range of local times in the summer hemisphere. CIPS has obtained data for six Northern Hemisphere and five Southern Hemisphere PMC seasons to date and is still in operation and performing flawlessly. The CIPS data are made available to the scientific community in a variety of formats and spatial and temporal resolution, including full-resolution single-orbit level 2 data files and images, daily (hemispheric) albedo maps and images, and full-season latitude-binned summary files. In this paper we describe the CIPS measurement strategy and sampling characteristics, calibration and the Version 4.20 processing algorithms and retrievals. We also provide a quantitative evaluation of the CIPS cloud detection sensitivity and estimated random and systematic errors of the V4.20 cloud data products.

1. Introduction

The Cloud Imaging and Particle Size (CIPS) instrument was launched onboard the Aeronomy of Ice in the Mesosphere (AIM) satellite into a circular, sun-synchronous, 600-km orbit on April 25, 2007. AIM is the first satellite mission dedicated solely to the study of polar mesospheric clouds (PMC), and has provided unique measurements that directly address the issues of PMC formation, morphology and variability, and their connection to the meteorology of the polar mesosphere (Russell et al., 2009). CIPS is one of three instruments on the AIM satellite, along with the Solar Occultation for Ice Experiment (SOFIE) (Gordley et al., 2009) and the Cosmic Dust Experiment (CDE) in-situ dust detector (Poppe et al., 2011).

CIPS is a nadir-imaging instrument that utilizes a unique four-camera design to discriminate the scattering of ultraviolet (UV) solar photons from PMC ice particles against the background sunlit atmosphere. Cloud single-scatter albedo is measured at high spatial resolution over a range of scattering angles, thus providing a direct measurement of the PMC ice scattering phase function. Through analysis of the measured phase function it is possible to retrieve fundamental microphysical properties of the cloud particles. CIPS began routine measurements on May 24, 2007 and has operated flawlessly since that time. To date it has observed six full PMC seasons in the Northern hemisphere (NH) and five in the Southern hemisphere (SH). Approximately 97% of all possible data has been successfully downloaded and processed.

PMCs have been studied from numerous satellite-borne instruments over the past 30 years, using a variety of remote sensing techniques. These include both nadir- and limb-viewing geometries, measurements of extinction (via solar and stellar occultation) as well as scattered solar radiance, and utilizing spectral bands from the UV through the infrared (IR). DeLand et al. (2006) provides a comprehensive overview of satellite PMC measurements in the pre-AIM era. Two primary methods are available for deriving information on the PMC ice particle size parameters.

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The majority of measurements employ a spectral approach, where the wavelength dependence of the PMC scattering or extinction signal is used to constrain the particle size via comparison to optical model calculations. The alternative approach, employed by CIPS, is to measure the angular dependence of PMC scattering, e.g., the scattering phase function. A small number of direct measurements of the PMC phase function have been previously obtained from rocket experiments (Gumbel et al., 2001) while the satellite-born Student Nitric Oxide Explorer (SNOE) (Bailey et al., 2005) and Solar Mesosphere Explorer (SME) (Thomas, 1984) instruments both made limited (bidirectional) measurements of the phase function, from which particle size information was inferred (Thomas and McKay, 1985; Rusch et al., 2008). CIPS represents the first comprehensive space-based measurements of the PMC phase function over the entire polar summer hemisphere.

The scientific validity of the CIPS data has already been established through its use in a variety of scientific and validation analyses. Comparison of CIPS cloud frequency and albedo to measurements from the solar backscatter ultraviolet (SBUV/2) instrument on NOAA-17 show consistent agreement between these two nadir-viewing datasets when the CIPS data are degraded to the SBUV resolution (Benze et al., 2009, 2011). Baumgarten et al. (2012) have analyzed CIPS data obtained in close coincidence with ground-based lidar measurements and found good agreement in the cloud brightness observed by these two very different methods. The detailed spatial structures observed by CIPS have been used to study mesospheric gravity waves (Chandran et al., 2009, 2010, 2012) and planetary waves (Merkel et al., 2009), while the CIPS ice water content has been used by Stevens et al. (2010) to analyze the effect of tidal signatures on PMC. CIPS cloud frequencies were used in Karlsson et al. (2011) to connect SH PMC variability with the breakdown of the wintertime SH stratospheric polar vortex. The SH intra-seasonal PMC variability observed by CIPS was also used to investigate inter-hemispheric coupling in Karlsson et al. (2009). Stevens et al. (2012) used the CIPS observations of PMC frequency and albedo in July 2011 to help demonstrate a causal link between the occurrence of very bright clouds and the main engine exhaust from the space shuttle's final flight. A more extensive list of publications based on CIPS data can be found at http://lasp.colorado.edu/aim/publications.html. Two closely related companion papers in this issue complement the current paper in addressing CIPS data quality and validation from different perspectives. Bailey et al. (in this issue) presents a detailed analysis of coincident CIPS and SOFIE measurements in the AIM common volume while Carstens et al. (in this issue) provides a theoretical analysis of the information content and error characteristics of the CIPS measurements.

Bailey et al. (2009) provided a brief description of an early CIPS data version and associated algorithms. This paper addresses the current CIPS V4.20 data version. The goals of the paper are: (1) to describe the key features of the CIPS instrument, measurement technique, and sampling characteristics, (2) to provide a thorough description of the V4.20 data processing and retrieval algorithms, (3) to summarize the available CIPS data products, and (4) to provide quantitative error estimates for those products. The paper is organized as follows. Section 2 summarizes the basic instrument design, measurement technique, and sampling characteristics of the CIPS instrument. Section 3 describes the level 1 data processing, summarizing the key steps used to calibrate the level 1a images and then merge data from the four cameras to produce the critical level 1b data. In Section 4 we present a comprehensive description of the CIPS level 2 algorithms used to separate the cloud signal from the Rayleigh background and retrieve PMC data products. In Section 5, we present an analysis of the CIPS out-of-season data to quantify the false cloud detection rate in the dataset. Section 6 presents results from a detailed retrieval simulation study, yielding quantitative estimates of the CIPS cloud detection sensitivity and retrieval errors. In Section 7, we briefly describe the publicly released CIPS data products and give examples of each, followed by a summary and conclusions in Section 8.

2. CIPS measurement technique and sampling

McClintock et al. (2009) describes the CIPS instrument in detail. CIPS consists of four nadir-viewing UV sensitive cameras that together provide an instantaneous field of view of 120° (along-track) by 80° (cross-track). The spectral passband is centered at 265 nm with a width of ~15 nm (full-width half-maximum). Fig. 1 illustrates the orientation of the cameras, which are arranged in a cross pattern with overlapping pixels along the inner edges. We define a spacecraft-centered coordinate system with *X*–*Y*–*Z* axes corresponding to the roll (along-track), pitch (cross-track) axis and yaw (nadir) directions, respectively. The PX and MX cameras are pointed in the +*X* and –*X* direction, with similar convention for the *Y* cameras. The *Y* cameras are offset ±19° along the pitch axis and thus are primarily nadir-pointed. The *X* cameras are offset ±39° along the roll axis and therefore project out to larger off-nadir view angles along the orbit track. Fig. 2 illustrates the distribution of offset angles across the four cameras, relative to the spacecraft nadir (*Z*) axis. The resulting geometric footprint, when projected to the nominal 83-km cloud deck altitude, is characterized by the along-track and cross-track distance scales shown in Fig. 1. During routine science data operations the AIM satellite is always oriented such that the PX camera is facing the sunward direction. This corresponds to the forward (ram) direction for NH measurements and the backward (anti-ram) direction in the SH. The yaw (*Z*) axis is nominally aligned with satellite nadir during the science image sequence, with the notable exception of the CIPS common volume measurements, which are described later in this section.

AIM is in a sun-synchronous orbit with a noon/midnight (descending/ascending node) equator crossing time. CIPS operates only in the summer hemisphere, switching between NH and SH measurement modes at the equinoxes. The data sequences executed in the two hemispheres are essentially mirror images of one another. On each orbit, measurements are obtained over a solar zenith angle (SZA) range from approximately 20° to 105° (well past the terminator). The NH measurement sequence starts with three "first-light" images taken by the forward-looking PX camera as it leads the transition from darkness into the sunlit portion of the orbit. The sequence begins approximately 6 min after completion of the SOFIE sunrise occultation, with the first image taken at a solar zenith angle of ~105°. 27 full CIPS scenes follow the first-light images. A scene is comprised of simultaneous images from all four cameras and spans an area approximately 2000 km

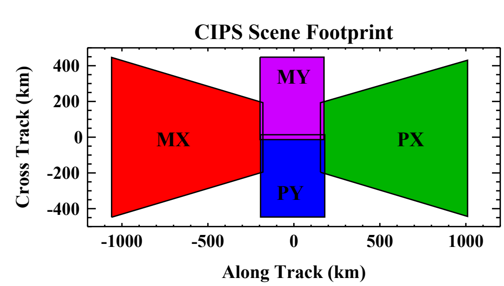

Fig. 1. This diagram illustrates the relative alignment of the four CIPS cameras. The two "*X*" cameras point in the forward and aft direction, while the "*Y*" cameras have a primarily nadir orientation. The distance scales indicate the geometric footprint of a CIPS scene at the nominal PMC cloud deck altitude of 83 km. The PX camera always points in the sunward direction, which corresponds to the satellite ram (anti-ram) for Northern (Southern) Hemisphere measurements. Note that the color-coding used here for the four cameras is preserved in all figures to follow.