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Investigating Gravity Waves in Polar Mesospheric Clouds Using Tomographic Reconstructions of AIM Satellite Imagery

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Key Points:
• First application of tomography for studying polar mesospheric cloud structures imaged by the CIPS instrument on the NASA AIM satellite.
• Used an intensity-weighted centroid profile and PMC surface maps to determine gravity wave-induced altitude variability in the PMC layer.
• New tomographic analyses reveal a spatial anti-correlation between albedo and wave-induced altitude, consistent with current theories.

Abstract

This research presents the first application of tomographic techniques for investigating gravity wave structures in Polar Mesospheric Clouds (PMCs) imaged by the Cloud Imaging and Particle Size (CIPS) instrument on the NASA AIM satellite. Albedo data comprising consecutive PMC scenes were used to tomographically reconstruct a 3D layer using the Partially Constrained Algebraic Reconstruction Technique (PCART) algorithm and a previously developed “fanning” technique [Hart et al., 2012]. For this pilot study, a large region (760 x 148 km) of the PMC layer (altitude ~83 km) was sampled with a ~2 km horizontal resolution and an intensity weighted centroid technique was developed to create novel 2D surface maps, characterizing the
individual gravity waves as well as their altitude variability. Spectral analysis of seven selected wave events observed during the Northern Hemisphere 2007 PMC season exhibited dominant horizontal wavelengths of ~60-90 km, consistent with previous studies [Chandran et al., 2009; Taylor et al., 2011]. These tomographic analyses have enabled a broad range of new investigations. For example, a clear spatial anti-correlation was observed between the PMC albedo and wave-induced altitude changes; with higher-albedo structures aligning well with wave troughs, while low-intensity regions aligned with wave crests. This result appears to be consistent with current theories of PMC development in the mesopause region. This new tomographic imaging technique also provides valuable wave amplitude information enabling further mesospheric gravity wave investigations, including quantitative analysis of their hemispheric and inter-annual characteristics and variations.

**Keywords:** Aeronomy of Ice in the Mesosphere (AIM), Cloud Imaging and Particle Size (CIPS) experiment, Algebraic Tomography, Atmospheric Gravity Waves, ANGWIN

1 Introduction

Polar Mesospheric Clouds (PMCs), originally known as Noctilucent clouds (NLCs), are the highest, driest, coldest, and rarest clouds on Earth. Ever since the first NLC sightings in the summertime twilight skies over Northern Europe [Leslie, 1885; Backhouse, 1885; Jesse, 1885], their extreme altitude and the unusual conditions under which they occur continue to inspire and challenge new observations, theory, and modeling studies.

It is now well established that PMCs are formed by water-ice nucleation primarily onto cosmic dust [e.g., Hervig et al., 2009] in the tenuous summer mesopause region (altitude ~85 km) where the summertime temperatures can fall below 130-150 K [Gadsden and Schroder, 1989; Bailey et al., 2009]. The anomalously cold mesopause temperatures provide a conducive environment for the formation of microscopic ice crystals that nucleate and grow to detectable sizes (few 10’s of nm), over periods of typically several hours to a few days [Gadsden, 1982; Jensen and Thomas, 1988; Rapp et al., 2002; Rapp and Thomas, 2006; Baumgarten et al., 2008; Hervig et al., 2009; Cho and Rottger, 1997; Merkel et al., 2009].

Atmospheric gravity waves (GWs) play two key roles in the formation, visibility, and structure observed in PMCs. The first is through their ability to transport large amounts of energy and momentum upwards from copious tropospheric sources. On a global scale the
resultant deposition of GW momentum flux acts to close the mesospheric jets and drives a residual meridional inter-hemispheric circulation \cite{Lindzen1973, Holton1983, Garcia1985, McIntyre2001}, resulting in strong upwelling in the summer polar region. Consequent strong adiabatic cooling creates the remarkably cold summer mesopause region at polar latitudes \cite{Fritts2003, Lübken1999, Fritts2003}. The second role of GWs is their local effect on the PMC particles acting to alter their sedimentation, growth, and sublimation via wave-induced vertical displacement and by impressing their characteristic spatial structures onto the cloud field \cite{Witt1962, Klostermeyer2001, Chu2003, Rusch2009, Chandran2010}.

From the ground, these ‘night shining’ mesospheric ice clouds often appear as a geographically extensive, thin (few km) visual cloud layer seen at twilight by strong forward scattering of sunlight off the ice particles. They are frequently characterized by a variety of spatially periodic wave structures. Indeed, observations over the past ~120 years have established a standard NLC classification with large-scale ‘bands’ and small-scale ‘billows’ as two of the primary categories for describing the clouds’ appearance \cite{Witt1962, Fogle1969, Taylor1984, Gadsden1989, Gadsden1995}.

Observations, mainly from the northern hemisphere, have provided important information on the most commonly occurring wave structures in the mesopause region during the summer. This has enabled high-quality investigations of their spatial properties, dynamics, and associated instability processes at high-latitudes \cite{Fogle1969, Gadsden1989, Taylor2011, Fritts1993, Dalin2004, Pautet2011, Fritts2014}. For example, Type II bands are signatures of extensive propagating small to medium-scale gravity waves exhibiting horizontal wavelengths of ~10-100 km, with lifetimes of up to several hours. In contrast, Type III billow events are spatially limited, exhibit short horizontal wavelengths (typically 5-10 km), and are signatures of transient convective or dynamical instabilities generated in situ by strong wind and temperature gradients \cite{Gadsden1989, Fritts1993, Fritts2014}.

Ground-based optical, rocket-borne, and more recently, active lidar soundings of these clouds have provided a wealth of information on their evolution, particle size, wave
dynamics, and altitude structure essential for quantifying their variability [Semeter et al., 1997; Rapp et al., 2002; Chu et al., 2003]. They have also established the remarkably consistent and stable altitude of the NLCs in the upper mesosphere over the past century, occurring at a mean height of 83 ± 2.5 km [Jesse, 1896; Störmer, 1933; Paton, 1964; Taylor et al., 1984; Gadsden and Taylor, 1994; von Zahn et al., 1998; Chu et al., 2004; Collins et al., 2009; Thayer et al., 2003; Baumgarten et al., 2009; Gerding et al., 2007]. However, most of these measurements are from isolated sites and are naturally limited by the prevailing weather conditions [Gadsden and Schroder, 1989]. In contrast, space-based observations of PMCs have revolutionized our understanding of their global-scale spatial and temporal variability.

The earliest space-based human observations began with Soyuz 9 [Vasil’yev et al., 1987] and were later conducted from Skylab [Packer et al., 1977]. Such observations continue today from the International Space Station [www.nasa.gov/mission_pages/aim/multimedia/ISS031-E-116058.html]. The earliest satellite measurements by the OGO-6 satellite [Donahue et al., 1972], and by the Solar Mesosphere Explorer (SME) satellite [Thomas et al., 1984] established the near continuous presence of a PMC layer in the perpetually sunlit summer polar regions over the Arctic (May–August) and Antarctic (November–February) [Jensen et al., 1988; Thomas, 1991; Evans et al., 1995; Carbary et al., 2000; von Savigny et al., 2004; Bailey et al., 2005; Russell et al., 2007; 2008].

The first satellite image measurements of the PMC layer were obtained by the WINDII limb viewing interferometer aboard the Upper Atmosphere Research Satellite (UARS), which recorded patchy structures in the cloud layer as observed in the Earth's limb at ~83 km [Evans et al., 1995]. Subsequent measurements by the Ultraviolet and Visible Imaging and Spectrographic Imaging (UVISI) instrument on the Mid-Course Space Experiment (MSX) satellite provided the first evidence of large-scale “transpolar wave structures” in the PMCs as imaged in the earth's sub-limb, exhibiting horizontal wavelengths of 500-1000 km over both the northern and southern summer polar regions [Carbary et al., 2000]. Ensuing analyses of these data also revealed smaller-scale structures with horizontal wavelengths <100 km, typical of the band-type waves frequently observed in ground-based NLC imagery [Carbary et al., 2003; Gadsden and Schroder, 1989; Dalin et al., 2004; Pautet et al., 2011].
The Optical Spectrograph and Infrared Imaging System (OSIRIS) on the Odin satellite (launched in 2001) has been used to collect atmospheric limb-scans from 7-107 km altitudes over the spectral range 275-810 nm [Gattinger et al., 2009]. These line-of-sight brightness measurements provide accurate multiple-angle views of the PMC layer suitable for tomographic imaging studies. Degenstein et al. [2003] initially used the near infrared data to investigate the feasibility of retrieving structure from a series of limb images using a likelihood expectation maximization algorithm and succeeded in mapping volume emission rates of the oxygen infrared atmospheric (OIRA) band [Degenstein et al., 2004]. Most recently, Hultgren et al. [2013] have utilized OSIRIS in a special “tomographic mode” focusing the line-of-sight scans over a restricted altitude range (~73-88 km), thereby increasing the number of scans through the PMC layer. Using 180 orbits of ultraviolet (<310 nm) data obtained during the northern hemisphere summers of 2010 and 2011, they successfully retrieved two-dimensional distributions of volume emission rate as a function of altitude and horizontal range through the PMC region. This novel tomographic study demonstrated new capabilities for investigating the vertical structure and particle size composition of PMCs [Hultgren et al., 2013; 2014].

The NASA Aeronomy of Ice in the Mesosphere (AIM) satellite (launched in 2007) is the first satellite mission with the primary objective of studying PMCs and their variability [Russell et al., 2009]. The Cloud Imaging and Particle Size (CIPS) instrument onboard AIM comprises four wide-field UV imagers that map the PMC field with high spatial and temporal resolution. As the satellite traverses over the summer polar region, it provides unprecedented observations of the PMC layer and the embedded mesospheric gravity wave structure [Rusch et al., 2009; McClintock et al., 2009; Lumpe et al., 2013]. These data have enabled several novel investigations of the broad spectrum of gravity waves present over the summer polar regions. Early CIPS data were utilized to investigate the characteristics of the frequently observed small-scale (horizontal wavelength < 100 km) gravity waves in the high Arctic and their relationship to those generally observed in lower-latitude NLCs [Chandran et al., 2009; Taylor et al., 2011]. Chandran et al. [2010] and more recently Zhao et al. [2015] have utilized several seasons of CIPS data to investigate the spectrum of larger scale gravity waves (horizontal wavelengths up to 800 km) and their inter-seasonal and inter-hemispheric similarities and differences.
This paper presents the first results of applying tomographic techniques to the CIPS imagery to investigate the potential of the extensive AIM data set (2017 marks 10 years of continuous measurements in the northern and southern polar summer mesosphere) to quantify horizontal and vertical wave structures and amplitudes in the PMC field, and their variability induced by the ever-present gravity waves.

2 PMC Reconstructions

2.1 Tomography

Tomographic data are acquired as a signal is emitted by, projected through, or reflected from a surface and measured by a sensor or camera. As the number of available sensors increases, more viewing angles become available which enhances the quality and accuracy of reconstructions. Sparse tomography is a process in which an imaging region is reconstructed using non-ideal projections. Such data are often limited by the geometry of the imaging region, allowing for a restricted range of viewing angles while offering a limited number of viewing locations. This reduces the amount of data available for processing and can degrade image quality.

Large-scale tomographic measurements, such as those commonly used in atmospheric imaging, are naturally limited in their range of viewing angles and result in a sparse ray distribution. Despite these limitations, tomography has proven to be a powerful imaging tool for a variety of atmospheric phenomena (e.g., airglow, aurora, and ionospheric disturbances) [Bernhardt et al., 1998; Bernhardt et al., 2006; Pryse et al., 2003; Kamalabadi et al., 2002; Kamalabadi et al., 1999; Semeter et al., 1997; Semeter et al., 1999; Hart et al., 2012; Nygren et al., 2000]. This can be attributed primarily to a specific class of algorithms, known as matrix methods, which have been developed and implemented for yielding practical solutions to ill-conditioned imaging problems.

In matrix tomography, the low density of the projected rays necessitates the use of a quantized representation. A grid is overlayed on the imaged object to produce a discrete structure through division into pixels, as shown in Figure 1a). This quantization of the imaging region and the corresponding projections gives rise to a linear description and a matrix formalism. A single projection $p$ is equal to the product of the weighting factor $w$, 
which quantifies the effect of a pixel on a ray, and the pixel $f$ through which the ray is
projected:

$$ p = wf. $$

In this study, the weight $w_{mn}$ of the $n^{th}$ pixel in the $m^{th}$ projection is defined as the area
of intersection between the pixel and the two rays constituting the projection (see Figure 1). The total projection $p_m$ is given by the sum of the weights of each intersected pixel. The total measured signal along a given angle resulting from an interaction with $N$ pixels can be expressed as the following sum:

$$ p = \sum_{n=1}^{N} w_n f_n. $$

The projection of the $m^{th}$ ray through the imaging region is then given by:

$$ p_m = \sum_{n=1}^{N} w_{mn} f_n. $$

These projected rays constitute a vector which contains the combined contribution of each pixel. The resulting system of equations can be expressed as a matrix:

$$ \begin{bmatrix} w_{11} & w_{12} & \cdots & w_{1N} \\
 w_{21} & w_{22} & \cdots & w_{2N} \\
 \vdots & \vdots & \ddots & \vdots \\
 w_{M1} & w_{M2} & \cdots & w_{MN} \end{bmatrix} \begin{bmatrix} f_1 \\
 f_2 \\
 \vdots \\
 f_N \end{bmatrix} = \begin{bmatrix} p_1 \\
 p_2 \\
 \vdots \\
 p_M \end{bmatrix}. $$

This matrix equation is difficult to solve in practical applications. The primary reason being that most imaging geometries produce underdetermined systems for which no unique solution exists. Additionally, arrays with large numbers of elements can make accurate approximations difficult. Finding sufficiently accurate solutions to this system is the primary objective of sparse tomography. The most common approach utilizes a set of tomographic methods known as algebraic reconstruction techniques (ARTs). ARTs are a set of correction algorithms in which an initial image is gradually improved as successive iterations are carried out. An initial approximation of the object’s structure is provided to the algorithm as a vector and a correction factor is iteratively added. This correction term is calculated by comparing the tomographic projections of the previous image in the iteration with the measured projections.

Various ART algorithms have been developed, including constrained or totally constrained ART (TCART), multiplicative ART (MART), the simultaneous iterative
reconstruction technique (SIRT), simultaneous ART (SART), and memory ART. These various ART algorithms have been successfully implemented in prior studies [Bender et al., 2011; Tsai et al., 2002; Padmanabhan et al., 2009; Vecherin et al., 2007; Hobiger et al., 2008]. The performance of each algorithm was tested using synthetic data and the resulting images exhibited a high degree of similarity. We ultimately selected to use PCART because it was slightly more consistent, though in most cases the difference was small (particularly for multiplicative ART which performed well).

The PCART algorithm is given by [Kak and Slaney, 2001]:

\[
f_{mn} = f_{m-1,n} + \lambda \left( \frac{p_m - p^l_m}{N_m} \right) w_{mn},
\]

(5)

where \( f_{mn} \) is the discrete value of the reconstructed image for the \( m^{th} \) ray and the \( n^{th} \) pixel. The addition of a correction factor to previous image values \( f_{m-1,n} \) provides the iterative step. Elements of the weighting matrix are given by \( w_{mn} \) and convergence of the corrections can be controlled by the relaxation parameter \( \lambda \). The measured projections correspond to \( p_m \) and the computed projections to \( p^l_m \). The \( N_m \) term is the total weight of the \( m^{th} \) ray and can be expressed as the sum of each individual weighting factor for the \( N \) pixels in the imaging area:

\[
N_m = \sum_{n=1}^{N} w_{mn}.
\]

The limitations of atmospheric tomography require an initialization of the algorithm, which is iteratively corrected. We previously used the PCART algorithm to reconstruct mesospheric airglow wave signatures [Hart et al., 2012]. In that study, the algorithm was well tested using synthetically generated profiles and a range of different initializations (e.g., binary, Gaussian, and Chapman functions) [Hart et al., 2012]. Both the Chapman and Gaussian functions performed well, but the Gaussian profile was ultimately selected due to its frequent use in the literature to quantify the airglow emission layer profiles (peak height and fullwidth at half maximum (FWHM) thickness) as observed by limb viewing satellites [e.g., Zhao et al., 2005].

PMCs naturally occur in a well-defined, relatively thin continuous cloud layer with a typical mean altitude centered around 83 km. Lidar measurements now provide excellent observations of the optical thickness of this layer (typically 1-3 km) and local variability in
altitude induced by gravity waves and other perturbations \cite{vonZahn2003, Chu2004, Collins2009, Thayer2003, Gerding2007}. The choice of an initialization is determined by the shape of the structures being imaged. As PMCs reside in thin localized layers, a narrow Gaussian band was selected to represent the expected shape of the reconstructed PMCs. This Gaussian profile was used as the initial term \( f_{m-1,n} \) in the PCART algorithm and was successively modified with each iteration. It was centered at 83 km with a FWHM of 4 km, providing good extension over an \( \sim8 \) km altitude range encompassing the PMC layer. During reconstruction, this initial profile successfully converged to a width of \( \sim2\) - 3 km, consistent with prior PMC observations. We used Gaussian profiles of varying sizes along with Chapman and box functions to prevent the initialization from biasing reconstructed images. The results of synthetic testing showed these reconstructions became more accurate as the initialization more closely approximated the physical shape of the layer being imaged. This provided a rationale for a Gaussian initialization, as LIDAR data have confirmed the shape of such layers. As part of our analyses we have also utilized a novel ‘fanning’ technique that was introduced in our airglow study to generate the 3D PMC volume retrievals \cite{Hart2012}. This method is illustrated in Figure 1 and described in the following sections.

2.2 Imaging Configuration

AIM was launched into a sun-synchronous 600 km altitude circular orbit. The CIPS experiment uses four intensified cameras filtered to observe UV emissions at 265 nm. The four cameras are aimed towards the nadir and are tilted to observe the forward, aft, port, and starboard directions, such that their fields of view overlap slightly. Together, these four cameras comprise a wide-angle imager with a field of view spanning 120° along track and 80° across track, resulting in an \( \sim2000 \times 1000 \) km field of view at the PMC layer altitude \cite{Rusch2009, McClintock2009}.

Snapshot images (\( \sim0.75 \) s exposure) were acquired by each of the four cameras simultaneously at 43 second intervals along the polar track with a nadir pixel resolution of 2 km, that reduces to \( \sim5 \) km at the edges of the forward and aft cameras. When merged together, these four images create a “bowtie” shaped map of the PMC layer which is often
referred to as a “scene” [Rusch et al., 2009]. Figure 2 shows the utilization of several consecutive scenes for the tomographic reconstruction (discussed in more detail below).

CIPS data comprising the scene information are routinely combined together to form an ~1000 km wide by up to 8000 km long composite image of the PMC layer over the summer polar region. This is a standard CIPS level 2 data product, which is available at http://lasp.colorado.edu/aim/index.html and provides measurements of the cloud presence, spatial morphology, and microphysical parameters, re-binned to a uniform pixel resolution of 25 km². However, for this initial tomographic investigation, we have utilized the original, higher-resolution CIPS bowtie scenes [Chandran et al., 2009; Rusch et al., 2009], which are not a standard AIM/CIPS data product but can be made available upon request.

Similar studies conducted with OSIRIS data from the Odin satellite have established the required preprocessing of images for tomographic inversion. Specifically, cloud radiance must be separated from background radiation due to molecular Rayleigh scattering and instrumental effects [Hultgren et al., 2014]. This process was implemented with the CIPS imagery as each scene was first flat-fielded and then normalized to albedo units. The flat fielding involved two main processes as described in detail by Rusch et al. [2009]: a) correction for Rayleigh scattered sunlight from the atmosphere observed by CIPS at different viewing angles due to its wide field of view, and b) compensation for the strong forward scattering behavior when viewing the PMC ice particles at small scattering angles as CIPS encounters each sunrise and sunset. The layer was also assumed to be optically thin and tenuous. As a result, multiple-scattering and diffusion were ignored in the tomographic reconstruction process.

The forward scattering correction was well modeled by a phase function comprising a Gaussian distribution of spherical water-ice particles with a mode radius of 60 nm and a width of 12 nm (applicable to bright PMCs as reported herein). The cloud albedo, defined as the ratio of the scattered radiance (after the background correction) to the incoming solar irradiance averaged over the band pass of the CIPS instrument, was then normalized to a 90° solar scattering angle [McClintock et al., 2009]. For our pilot tomographic analysis, data from five consecutive scenes were combined to create a “common PMC volume” sampled by CIPS as the satellite transited overhead. This process comprised two parts as illustrated in Figures 1 and 2.
Figure 2 shows the five flat-fielded scenes displaced vertically (for illustrative purposes). The scene at time $t_1$ is superimposed on a geographic grid, showing its field of view, orientation, and location in the vicinity of the North Pole. As the satellite passed over the PMC layer, images of the same region were sequentially acquired at five different orbital positions. The extended dashed black lines plot the orbital track of the satellite. Subsequent scenes $t_2 - t_5$ (displaced vertically) show the progression of the “common intensity” profile (white line) with time. The resultant profile has a length of 762 km, enabling quantitative investigations of a broad range of gravity wave perturbations evident in the CIPS data.
Figure 1. a) The definition of projections in discrete matrix tomography. b) An illustration of the fanning technique used in this study to acquire projection data from multiple grids within a 3D volume. c) The application of this technique to the AIM imaging configuration using five consecutive observation sites. As the satellite passed over the PMC layer, CIPS acquired albedo images of the same region but from varying angles away from the zenith.

The extension of the common intensity profile into a “common volume” measurement is illustrated in Figure 1 b), which shows a “fanning” technique that we effectively implemented to investigate gravity waves in the OH emission layer using limited field image data [Hart et al., 2012]. Instead of using a single nadir common profile, a set of intensity profiles were collected. A common volume viewing area was obtained by ‘fanning’
across the PMC layer over a range of angles away from the nadir, as depicted by the red lines in Figure 1 b). Each of the yellow lines in Figure 1 c) represents a 1D albedo profile which were used as projection data in the PCART algorithm. From each 1D projection profile, a 2D image could be reconstructed representing a cross-section of the PMC layer. By combining multiple adjacent cross-sectional images, a 3D PMC layer was established. This process is described as fanning because subsequent 1D albedo profiles were acquired at varying angles increasing away from the nadir, forming the fan-like geometry shown in Figure 1 c).

Figure 2. An illustration of the method used to generate the tomographic projection data. Each of the five consecutive flat-fielded PMC albedo scenes (t1-t5) were acquired at a different time, position, and angle. The common intensity profile (white line) is indicated in each scene. The dashed line shows the track of the AIM satellite. Note the subsequent scenes are displaced vertically for illustrative purposes. These data were acquired from CIPS Orbit 1393, scenes 12-16, taken on day 209 of 2007.
2.3 Synthetic Data and Validation

The accuracy of the presented tomographic technique was verified using an artificially generated PMC layer. Known pixel values inside this layer were multiplied by corresponding weighting values of rays within the image grid. This produced synthetic projection data which simulated a physical albedo measurement. These data were then reconstructed and the resulting image was compared with the synthetic layer. This approach provides a ground truth which can be used to assess the accuracy of reconstructed images. The results of this process are shown in Figure 3, which includes the a) synthetic layer and b) corresponding reconstruction.

Figure 3. The results of synthetic testing used to validate the presented tomographic technique. a) A synthetic layer was used to produce synthetic projection data, which were then reconstructed to produce a b) 2D image. The effect of imaging geometry on this
method was also analyzed using various other altitudes and spacing factors (distance between imaging sites). c) The average pixel difference was calculated as a function of the number of receivers used to collect projection data.

While edge effects are present in the reconstruction (as to be expected), the overall structure and variability in thickness has been preserved. These results were produced using the same Gaussian initialization and PCART algorithm applied to the CIPS data and provide confidence in the presented technique.

We were also interested in determining the effect which imaging geometry had on reconstruction accuracy. The AIM satellite transited over the PMC layer at an altitude of 600 km. The average height of the layer above the surface was 83 km. As such, the altitude of the receiver was assumed to be 517 km. The CIPS cameras acquired images every 43 seconds, resulting in a physical separation of ~130 km (hereafter referred to as a spacing factor). This combination of distances constituted the AIM imaging geometry in which CIPS observation angles ranged from 0° (directly overhead) to 41.1° at the far edges of the bowtie albedo images. In a previous study involving OH airglow emissions (~83 km altitude), two ground-based cameras were included, separated by a distance of 100 km [Hart et al., 2012]. As such, this study included a spacing factor of 100 km and an altitude of 83 km.

Five additional geometries were evaluated, including spacing factors ranging from 100-400 km and altitudes ranging from 83-662 km. These combinations are shown in Figure 3 c), which includes plots of the average pixel difference (APD) calculated between the synthetic layer and the corresponding reconstruction. The CIPS data included five receivers and the AIM geometry is represented by the blue line in the figure. This plot demonstrates the AIM geometry resulted in lower errors than several others included in the study, notably the configuration from our previous OH airglow study (black line). There is also an obvious downward trend as increasing the number of imaging sites resulted in lower errors and more accurate image reconstructions.

2.4 Centroid Method

The CIPS albedo data were used as projections ($p_m$) in the PCART algorithm. These projections were reconstructed to produce 2D PMC images (an example of which is shown in Figure 4 b)). By fanning away from the zenith, multiple 2D reconstructions could be produced inside of the physical 3D space from which the albedo data were collected. The 2D reconstructions were...
observed to converge to a thickness of 2-3 km, consistent with the physical PMC cloud layer. They were then smoothed using an isotropic Gaussian filter with a kernel size of $\sigma = 10$ pixels to better identify the dominant spatial features. When these adjacent 2D reconstructions were aligned (Figure 4a), they formed a 3D volume representing the physical PMC layer. This is referred to hereafter as the 3D PMC volume.

As the CIPS data were collected with a nadir spatial resolution of 2 km, which is comparable to the depth of the PMC layer, the resultant 3D reconstruction was physically too narrow to investigate gravity wave variations within the layer using classical tomographic cross-sectional views (e.g., as employed by Hultgren et al. [2014]). Instead, we utilized a novel intensity-weighted centroid technique to enhance the visibility of the overall structure of the reconstructed PMC layer and to hence determine the horizontal dimensions and vertical variations at various locations. The vector position $\vec{R}$ of this centroid is given by:

$$\vec{R} = \frac{1}{A} \sum_{i=1}^{N} a_i \vec{r}_i$$

where $a_i$ represents the albedo of the $i_{th}$ pixel, $A$ the total albedo along a vertical column of $N$ pixels, and $\vec{r}_i$ the altitude of the $i_{th}$ pixel. During processing of the CIPS data, a constant particle size of 60 nm was assumed. This prevents the use of this equation for studying altitude variability as a function of particle size.

Figure 4b) shows an end-on view of the 3D PMC layer in which horizontal structuring in the layer is identified by colored contours. The calculation of this centroid along all columns in a 2D image slice through the 3D layer is represented by the black dots shown in the figure. These data result in a 1D horizontal perturbation height vs. distance profile, as shown in Figure 4c).

Calculation of the centroid for multiple slices constituting the entire 3D volume results in a 2D surface plot, as shown in Figure 4d), which is our working data product. These 2D centroid surface plots (hereafter referred to as “surface maps”) are rich in structure and exhibit strong periodicities identifying the dominant gravity wave structures evident in the original albedo data.
Figure 4. Development of the PMC surface plot from the 3D tomographic reconstructed PMC layer after smoothing. a) Depicts the computed 3D PMC volume, b) shows an end-on 2D slice through the 3D volume identifying internal structure, c) displays the 1D intensity-weighted centroid analysis plot (also depicted by the black dots in ‘b’), and d) shows the derived 2D horizontal surface map. Note the three dashed vertical arrows identify the relation between structure in the 2D slice and the 1D plot. The colorbar corresponds to vertical displacement in d) and c), whereas the interior color in b) and a) represents relative albedo.

In order to assess the viability of this proposed centroid technique, a synthetic wave perturbation was induced in an artificial PMC layer. In a process similar to the synthetic testing described in Section 2.3, this artificial layer (containing the synthetic wave) was used to generate projection data which were then input to the PCART algorithm. The proposed centroid technique was then applied to this reconstructed layer and the resulting centroid was compared to the induced (ground truth) wave structure. An example of this testing is shown in Figure 5. As is evident in the figure, the induced wave (top) and reconstructed wave (bottom) exhibit a high degree of
similarity, with an APD of 0.0821. This result supports the use of the proposed centroid technique as a viable imaging tool for quantifying small-scale vertical structures in sparse tomography images. In the following results section, we compare and contrast the gravity wave surface maps (reconstructed from CIPS data) with the original PMC albedo imagery from AIM and use these new results to further investigate the vertical as well as horizontal structure of waves perturbing the PMC layer.

Figure 5. The results of synthetic centroid testing. A wave pattern (top) was induced in an artificial PMC layer, which was used to generate synthetic projection data. The PCART algorithm was then used to reconstruct a layer from these data. Finally, the centroid technique was applied to measure vertical structures in the resulting image. This centroid (bottom) exhibits a high degree of similarity to the induced wave (top), a result which supports the viability of the proposed method.

3 Results

3.1 Gravity Wave Structures
CIPS albedo data from five different AIM orbital tracks were selected from the first Northern Hemisphere season in 2007, when the original flat-fielded bowtie scenes were available as an initial data product [e.g., Rusch et al., 2009]. Our criteria were to select orbits and scenes with a variety of well-defined gravity waves visible in the PMC albedo imagery. The five orbits used in this study were Orbits 01242_199, 01243_199, 01244_199, 01245_199, and 01299_202, of which four were consecutive. In the case of Orbits 01244_199 and 01245_199, two different sets of scenes were acquired on the same orbital path. In total, seven sets of PMC scenes were acquired and processed for this pilot study. These data were then reconstructed and the results combined to form 3D PMC volumes, as depicted in Figure 4 a). The intensity weighted centroid method was then applied to each of the seven volumes resulting in series of 2D PMC surface maps as shown in Figure 6.
Figure 6. Example results of the intensity-weighted centroid analysis applied to the seven reconstructed PMC volumes. Each 2D surface map shows strong evidence of short-period gravity wave perturbations. The corresponding AIM orbital numbers are included on the left of each profile. For visibility, the surface plots are canted to reveal their constituent wave structure, coherence, and amplitude/altitude variations.

Each of these surface maps shows clear evidence of well-developed wave patterns perturbing the PMC layer. For example, several surface maps exhibit strong wave features comprising large amplitude (>1-1.5 km) wave crests and adjacent troughs (e.g., Orbits 01243_199 and 01245_199, #6), which extend laterally across the surface maps indicating extended (>150 km) coherent
wave crests. Some of the surface maps also suggest a systematic change in altitude (1.5-2 km) along the spacecraft track (e.g., Orbits 01242_199, 01244_199 (#3), and 01299_202). These changes in height are due to a change in altitude of the intensity-weighted mean albedo at various locations along the reconstructed 3D profiles. As such, they are similar to what would be observed, for example, by ground-based observers measuring the height of the often continuous NLC layer (and its perturbing wave structures) using two-station line-of-sight triangulation or stereographic methods (compared further in discussion section) [Witt, 1962; Taylor et al., 2011]. The sharp reduction in structure near the left end of Orbit 01245_199 (#5) also suggests the edge of a wave packet or a “mesospheric front”. Such features are characteristic of short-period (<1 hour) gravity waves as frequently observed in the mesospheric airglow emissions [Ejiri et al., 2003; Snively et al., 2005] and in NLCs [Chandran et al., 2009; 2010; Pautet et al., 2011; Thayer et al., 2003].

3.2 Spectral Analysis of Surface Maps
To investigate the spatial properties of wave patterns evident in the PMC layer, the data were analyzed quantitatively using a fast Fourier transform (FFT) applied to 1-D plots of altitude vs. distance along the center of each surface map. Figure 7 a) shows two examples of centroid albedo vs. altitude profiles for Orbits 01242_199 and 01245_199, spanning the length of the PMC layer, while Figure 7 b) shows their computed FFT power spectra. These two events were dominated by gravity waves with horizontal wavelengths of ~63 km and ~87 km, respectively. The primary contributing waves for the other five cases were determined to vary between ~43 and ~98 km. These individual results are fully consistent with the reported horizontal spectra of gravity waves by Chandran et al. [2009] and Taylor et al. [2011], using the same CIPS Northern Hemisphere 2007 data set.
Figure 7. Example data and FFT power spectra for two of the seven PMC surface profiles. a) The midplane altitude profile for orbit maps 01242-199 and 01245-199, and b) the corresponding FFT power spectra identifying strong wave events with horizontal wavelengths of 63 and 87 km, respectively.

4 Discussion

Figure 8 presents a pictorial summary of our research method comparing the initial data input and the tomographic results. The CIPS bowtie scene in Figure 8 a) was one of five sequential scenes used to generate surface map #1 (Orbit 01242_199) in Figure 6. In Figure 8 b), the area of the original scene used for the reconstruction (yellow rectangle) is outlined. For this investigative study, we chose to apply the fanning technique to only one-half of the available area for the tomographic analysis. The resultant surface map was 760 km by 148 km as depicted in Figure 8 c), which presents a false-color map where blue indicates lower altitudes and red higher altitudes, with a scale ranging over ±1.2 km. The 3D format of this plot provides a new viewing perspective helping to interpret the “planar” CIPS albedo imagery and its constituent data. In
particular, the tomographic results reveal new information on the relative amplitudes of the differing wave crests and troughs and their extended spatial coherence.

Figure 8. Illustrates the enhanced visibility of the wave structure using the new tomographic analysis technique. a) shows the original CIPS overhead scene with the common imaging volume highlighted by the yellow box, b) an enlarged view of the common volume showing wave structure in the PMC layer albedo, and c) an angled view of the resultant surface map. Note the additional altitudinal information on the wave pattern provided by the tomographic analysis centroid method.

4.1 Spatial Correlations

These comparative results depict a high spatial correlation between the horizontal wave structures in the tomographic reconstructions and the original albedo data establishing their potential for more in-depth studies of the selected gravity wave data. In particular, the new
tomographic surface perspective that these data provide and the clarity of the resolved waves open the door to a range of possible studies involving the relative altitude distribution of the structures. For example, a visual inspection of the enlarged CIPS albedo scene shown in Figure 8 b) and the computed surface PMC map suggests that dark (low-altitude/blue) regions in the centroid profile directly coincide with the bright (high-intensity/red) regions in the albedo data of Figure 8 a). This apparent relationship is demonstrated more clearly in Figure 9, which visually compares four examples of our albedo-centroid image pairs where the CIPS albedo and the derived tomographic surface maps are both presented as nadir views to facilitate the comparison. Results from a broad (whole field) view and also from selected one-to-one PMC structure comparisons clearly suggest that the lower altitude (blue) regions generally align well with the higher PMC albedo (white) regions. Conversely, the lower albedo regions tend to be associated with comparatively higher altitude regions and wave structures. The black arrows point to examples to illustrate this finding.
Figure 9. Four examples comparing PMC albedo and centroid image pairs. A strong correlation is visually evident in all of these data suggesting that low-altitude (blue) regions in the centroid correspond well with high-intensity (white) regions in the PMC albedo.

To provide a more quantitative assessment of this visual correlation, we have employed the Pearson Correlation Coefficient (PCC), a similarity metric commonly used to measure spatial overlap in medical tomography. Each of the seven example CIPS albedo images (e.g., Figure 8 b)) was normalized and the data then squared to provide sufficient separation between high and median albedos (a form of histogram equalization). The derived centroid profile was also normalized in the same way but not squared as its histogram distribution was comparable to that
of the CIPS imagery. This procedure was done to test our hypothesis that low altitude centroid data generally correlates with high PMC albedo. The normalized centroid images were then inverted to compare bright regions with bright regions and dark with dark. The PCC ranges from 0 (no overlap) to 1 (identical images) and is calculated as:

\[
PCC = \frac{\sum_{i=1}^{n} (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n} (X_i - \bar{X})^2} \sqrt{\sum_{i=1}^{n} (Y_i - \bar{Y})^2}}
\]

where \(X_i\) represents each pixel in the first image and \(Y_i\) represents the corresponding pixels in the second image. The average pixel value of the first and second image is given by \(\bar{X}\) and \(\bar{Y}\), respectively.

Uncertainty in these values was quantified using the results of synthetic testing described earlier. Each pixel in the centroid image was assigned a random error ranging from 0 to 0.1642, resulting in an average of 0.0821, as calculated in the synthetic centroid simulation. We also included errors resulting from typical wind speeds (30-60 m/s) occurring at mesospheric altitudes. Although these values are lower in the summer than in the winter, over the 43 second CIPS image intervals, they can result in motion ranging from 1-2 km. The results are shown in Table 1, where a consistent high correlation was found in each case. Though it varies between different applications, values exceeding 0.8 are typically considered to indicate good agreement and strongly support the hypothesis relating high PMC albedo with lower PMC altitude.
Table 1. Results of the PCC analysis for each of the seven PMC scenes used in this study. The high degree of similarity indicated by each of the PCC values (max =1) strongly support an inverse relationship between centroid altitude and PMC albedo.

<table>
<thead>
<tr>
<th>#</th>
<th>Orbit Number</th>
<th>PCC Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>01242_2007-199</td>
<td>0.76 ± 0.03</td>
</tr>
<tr>
<td>2</td>
<td>01243_2007-199</td>
<td>0.81 ± 0.02</td>
</tr>
<tr>
<td>3</td>
<td>01244_2007-199</td>
<td>0.77 ± 0.02</td>
</tr>
<tr>
<td>4</td>
<td>01244_2007-199</td>
<td>0.79 ± 0.03</td>
</tr>
<tr>
<td>5</td>
<td>01245_2007-199</td>
<td>0.77 ± 0.03</td>
</tr>
<tr>
<td>6</td>
<td>01245_2007-199</td>
<td>0.76 ± 0.04</td>
</tr>
<tr>
<td>7</td>
<td>01299_2007-202</td>
<td>0.82 ± 0.03</td>
</tr>
</tbody>
</table>

This analysis can be taken a step further by correlating our tomographic results with other available CIPS data products ([http://lasp.colorado.edu/aim/index.html](http://lasp.colorado.edu/aim/index.html)). For example, the CIPS data and other satellite measurements [e.g., Hultgren et al., 2014] have previously established that ice-water content (IWC) is directly related to cloud albedo. This is illustrated in Figure 10 which compares level 2 IWC data from the AIM database (available on the mission websites). The figure comprises multiple images showing a) the overhead CIPS albedo scene for orbit 01245_199 (#6), identifying the tomographic region, b) an enlarged view of this region showing high cloud albedo to the left side, c) the tomographic reconstruction surface map for this region, d) part of a larger field CIPS level 2 orbital swath comprising data from multiple scenes along the orbital track, and e) the CIPS level 2 derived ice-water content map.

The common area is identified in these latter two images which clearly show a high visual correlation between the PMC albedo and the IWC. In comparison, our tomographic analyses derived independently from the original bowtie scene albedo data suggest that high albedo (and hence high IWC) regions occur mainly where the PMC layer has a lower centroid altitude. This finding is qualitatively consistent with current theories of PMC nucleation, growth, and
sedimentation processes in the mesopause region [e.g., Rapp and Thomas, 2006], which result in the development of high IWC and high albedo levels in the lower levels of the PMC cloud layer, where the largest ice particle are also found to occur. Indeed, a key observation of the recent tomographic study by Hultgren et al., [2014] was the detection of large ice particles (> 70 nm) apparently falling through the base of the PMC layer. (Note isolated “raining out” events have also been reported in ground-based NLC observations [e.g. Witt, 1962]). This said, a very recent study by Rusch et al., [2016] using other CIPS data has occasionally detected an anti-correlation between mean particle size and cloud albedo in isolated cloud regions (typically < 100 km) usually associated with strong GW activity. While they found that very large particles (> 60-100 nm) occurred mainly in the troughs of the GW they also determined that these regions unexpectedly exhibited reduced IWC. An accompanying modeling study suggested that sporadic downward winds heating the upper PMC levels may have enhanced the detection of the lower lying larger particles, but at the same time also reduced the total IWC. Specific conditions are required for such warming to occur and the absence of PMC voids in our data would suggest they were not present at the time of image acquisition. The occurrence rates for these large particle events need to be studied in more detail.

These pilot tomographic results establish a general relationship between height and brightness for PMCs, apparently consistent with current knowledge, supporting the validity of the proposed centroid technique as a tool for investigating small-scale gravity waves in sparse tomography images. They also provide compelling new views of structures perturbing the layer and a new ability to quantify induced altitude variations, enabling future in-depth wave investigations.
Figure 10. A composite image demonstrating the relationship between the overhead CIPS scene, the centroid profile, and the ice-water content map for AIM Orbit 01245_199 (#6). It is evident from the common analysis areas (rectangles) in each image that lower altitudes correspond well with high albedo and high IWC.

4.2 Gravity wave structures and amplitudes

Another notable result is the differences which exist between each of the seven example surface maps. Coherent variations can be seen in the occurrence and amount of wave activity and in their maximum and minimum amplitudes. Adopting a median altitude of 83 km, the average altitude for each map was calculated by summing over the entire region to determine their variability.
Figure 11 shows the calculated values for each map. The plot displays the mean value (central line), upper and lower quartile (box edges), and total span (border lines) of the data. Average changes in PMC layer height across the >750 km fields of view were small (<0.2 km), while average wave amplitudes within the PMC layer were relatively large, varying from 0.6-1.2 km. This suggests that the smaller-scale (<100 km) gravity waves tend to dominate the PMC layer structuring at any given location. In contrast, much larger horizontal scale gravity waves and tidal perturbations could also be investigated using continuous PMC tomographic measurements along full orbital tracks (typically >2000-6000 km) to determine their amplitudes and variability.

Figure 11. A box-and-whisker plot showing the altitude distribution for each of the seven centroid profiles included in this study. The data reveal differences in the range of altitudes as well as in the mean altitude for each profile.

Finally, Figure 12 shows two examples of wave measurements of the vertical displacements of the PMC layer caused by gravity waves. The upper plot a) reproduces a famous NLC measurement by Witt [1962] who made two-station photogrammetric measurements of a magnificent NLC display observed from Torsta (63° N) in central Sweden on 10-11 August, 1958 during the International Geophysical Year. The vertical coordinates are computed heights (above sea level), while horizontal coordinates are distances to mapped NLC structures at cloud...
The figure shows a time sequence of 3 consecutive 1D vertical cross sections through the NLC layer separated by five min. The clouds were observed at low elevations of 10-15° and the bottom of each (black) plot delineates the measured wave-induced undulations in the underside of the cloud layer, while the top of the layer indicates the estimated thickness of the layer also as determined from the stereo photogrammetry. The horizontal wavelength of the dominant NLC bands was 50 km, while their measured wave amplitudes varied from 0.5-4 km. Figure 12 b) shows a canted side view of one of our tomographic surface maps, 01245 (#5), calculated using the new intensity-weighted centroid technique. This surface map also displays altitude vs. distance across the PMC layer but, in addition, provides a 2D measure of the gravity wave perturbations with alternating crests and troughs separated by ~90 km intervals. The similarity in these two figures is striking, both of which identify significant and variable undulations in the PMC layer induced by similar horizontal scale gravity waves. In comparison, lidar measurements of PMCs show that these amplitude variations are typical [Chu et al., 2003; Collins et al., 2009] but are limited to a single measurement in the zenith vs. time.
**Figure 12.** a) Height vs. distance plotted for an NLC layer observed from the ground, modified from Figure 9 in Witt [1962]. The data show NLCs of varying heights across the field of view characterized by their constituent wave structures [Gadsden and Schroder, 1989]. b) An elevated side view of surface map 01245 (#5) showing a well-defined wave event. Troughs and crests are easily identified which are separated by ~90 km intervals. Note the strong similarity in wave structures between these two figures.

Limited-angle tomography with our chosen reconstruction algorithms has proven effective for gleaning new information from albedo measurements and furthering our understanding of the effect of gravity waves seen in PMCs. Notably, our new ability to quantify and compare centroid heights provides additional opportunities for future in-depth seasonal and hemispheric investigations. The assumption of a constant particle size (60 nm), used in the procurement of the flat-fielded bowtie data precludes further quantitative comparisons at this time.

We were, however, interested in the effect this assumption may have on the proposed tomography algorithm. As such, a Mie scattering simulation was conducted using parameters from the CIPS data, including a particle size of 60 nm, an index of refraction of 1.3 (ice), and a wavelength of 256 nm. The total scattered intensity (normalized to unity over 4π steradians) for particle diameters ranging from 30 nm to 90 nm is shown in Figure 13.

**Figure 13.** The result of a Mie scattering simulation for varying particles sizes, ranging from 30 nm to 90 nm. Other parameters were assumed to agree with CIPS conditions, including a

![Normalized Intensity vs. Angle](image-url)
wavelength of 256 nm and an index of refraction equal to 1.3. The data have been normalized to unity over a complete solid angle.

The angle of observation for the CIPS cameras varied from $0^\circ$ (overhead) to $\sim 41.1^\circ$ at the edge of the bowtie scenes. AIM acquired images in the summer hemisphere between the terminator and a dayside latitude of about 40 degrees [http://lasp.colorado.edu/aim/]. At higher latitudes, the angle between incident and scattered light can reside in the region of the graph where the curves intersect and the difference between scattered intensities is small for varying particle sizes. As such, the effect of particle size on scattered intensity depends largely on the latitude at which the images were acquired.

5 Conclusion

A key result of the early CIPS data was the sheer abundance of gravity waves evident throughout the summer polar mesosphere [e.g., Rusch et al., 2009]. Satellite data are inherently sparse due to the limited number of available viewing angles. We examined the imaging configuration of the CIPS data and the favorable use of limited-angle PCART tomography for application to a geometrically thin (1-3 km) PMC layer. Algorithm validation was conducted using synthetic data based on an earlier study of mesospheric OH airglow emissions. As part of our analyses, we utilized a previously-developed ‘fanning’ technique to generate the 3D PMC volume retrievals [Hart et al., 2012]. A novel imaging technique was also introduced for measuring wave-induced structures in the tomographic reconstructions of the PMC layer. An intensity-weighted centroid was then calculated along vertical columns of the derived 3D layer to generate novel 2D surface maps containing prominent gravity wave perturbations. These patterns were found to comprise waves with horizontal wavelengths ranging from 43-98 km, confirming previous studies by Chandran et al. [2009] and Taylor et al. [2011], using the same CIPS 2007 data set, and paving the way forward for further detailed wave studies.

In particular, the new tomographic surface perspective that these data provide have revealed a marked spatial correlation between CIPS albedo imagery and the derived tomographic surface map altitudes. Observations across a broad field of view suggest that lower altitude regions generally aligned well with the higher PMC albedo regions, while selected one-to-one PMC wave comparisons clearly showed deep wave troughs coinciding with strong albedo wave
structures. This hypothesis was tested with a correlation metric and image pairs were found to be in high agreement with an average PCC value near 0.8 calculated across seven profiles from five AIM/CIPS orbits. This new finding appears to agree with current theories of PMC growth and ice particle sedimentation in the mesopause region. However, our study, and that of Rusch et al., [2016], were both based on limited samples of the CIPS data set and require further investigation.

As of 2017, the AIM mission has far exceeded its originally planned two-year operational period, which began in 2007, and has acquired 10 years of extensive CIPS instrument imagery available for mapping the geographical extent, structure, and seasonal variability of PMCs over the summer polar regions. This pilot tomographic study demonstrates a valuable new capability for investigating a broad range of mesospheric gravity waves (and other dynamical features) in both the northern and southern summer polar regions, important for investigating their longitudinal, inter-hemispheric, and inter-annual characteristics and variability.

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Data

CIPS level 2 PMC data products are available on the AIM website (http://lasp.colorado.edu/aim/index.html). Individual ‘scene’ data are not provided as a standard data product but the limited data used herein are available upon request.

Conflicts
The authors declare no conflicts of interest.

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