Three-dimensional tomographic reconstruction of mesospheric airglow structures using two-station ground-based image measurements

Vern P. Hart,^{1,*} Timothy E. Doyle,² Michael J. Taylor,^{1,4} Brent L. Carruth,³
Pierre-Dominique Pautet,⁴ and Yucheng Zhao⁴

¹Department of Physics, Utah State University, 4415 Old Main Hill, Logan, Utah 84322, USA

²Department of Physics, Utah Valley University, 800 West University Parkway, MS 179, Orem, Utah 84058, USA

³Department of Electrical and Computer Engineering, Utah State University, 4120 Old Main Hill, Logan, Utah 84322, USA

⁴Center for Atmospheric and Space Sciences, Utah State University, 4405 Old Main Hill, Logan, Utah 84322, USA

*Corresponding author: vern.hart@aggiemail.usu.edu

Received 15 June 2011; revised 4 November 2011; accepted 14 December 2011;
posted 16 December 2011 (Doc. ID 149292); published 29 February 2012

A new methodology is presented to create two-dimensional (2D) and three-dimensional (3D) tomographic reconstructions of mesospheric airglow layer structure using two-station all-sky image measurements. A fanning technique is presented that produces a series of cross-sectional 2D reconstructions, which are combined to create a 3D mapping of the airglow volume. The imaging configuration is discussed and the inherent challenges of using limited-angle data in tomographic reconstructions have been analyzed using artificially generated imaging objects. An iterative reconstruction method, the partially constrained algebraic reconstruction technique (PCART), was used in conjunction with *a priori* information of the airglow emission profile to constrain the height of the imaged region, thereby reducing the indeterminacy of the inverse problem. Synthetic projection data were acquired from the imaging objects and the forward problem to validate the tomographic method and to demonstrate the ability of this technique to accurately reconstruct information using only two ground-based sites. Reconstructions of the OH airglow layer were created using data recorded by all-sky CCD cameras located at Bear Lake Observatory, Utah, and at Star Valley, Wyoming, with an optimal site separation of ~100 km. The ability to extend powerful 2D and 3D tomographic methods to two-station ground-based measurements offers obvious practical advantages for new measurement programs. The importance and applications of mesospheric tomographic reconstructions in airglow studies, as well as the need for future measurements and continued development of techniques of this type, are discussed. © 2012 Optical Society of America

OCIS codes: 100.6950, 010.1290.

1. Introduction

Ground-based spectrometric and imaging methods were first developed for studying the aurora and later the fainter airglow emissions. Some of the first scientific measurements of airglow emissions were conducted in the Soviet Union by using a spectro-

graph as early as 1933 [1]. Subsequent observations and additional spectrographic measurements were more widely performed in the years that followed [1].

Although ground-based imaging is easily accessible, it inevitably encounters some difficulties arising from the limited angular views available from the ground. Another problem is the amount of background light captured in the images, leading to a noisy signal [2]. This complication is commonly countered by performing measurements at night or

occasionally during the twilight hours [3]. A total solar eclipse has also been used to accommodate daytime observation of airglow [4]. The absence of sunlight makes such measurements possible but restricts the times when the airglow observations can be made.

As the technology available for airglow measurements improved, many of these restrictions have been reduced or eliminated. The need to observe emissions at night can be negated by conducting observations at higher altitudes [2]. The feasibility of using near-infrared (NIR) cameras onboard high-altitude balloons to study daytime auroral and airglow emissions has also been investigated [5]. In addition to ground-based studies, detailed observations of the airglow emissions have now been obtained using sounding rockets, as well as remote-sensing satellite measurements [6,7]. Importantly, auroral brightness measurements have been made from sounding rockets and used to tomographically reconstruct two-dimensional (2D) distributions of auroral volume emission rates [8,9]. Tomographic inversion of the mesospheric airglow layer has also been conducted using satellite-based limb scans [10,11]. Developments in atmospheric imaging have further aided the study of other phenomena, such as ozone [12,13] and polar mesospheric clouds [14].

Advances made in data acquisition, particularly for space-based measurements, have provided a means for understanding the chemical and physical processes responsible for producing airglow emissions [2]. For example, satellite information has been used for the OI (557.7 nm) airglow emission during the early ISIS II mission [15], while a broad dayglow spectrum was obtained from instruments onboard the space shuttle [16]. Significant contributions to the early development of space-based atmospheric imaging were also made by Anger and colleagues, who published a series of papers detailing results from the Ultraviolet Imager onboard the Viking Spacecraft [17]. These studies focused on understanding auroral dynamics, while more recent studies using the OSIRIS instrument onboard the Odin spacecraft have investigated the airglow emissions and have included tomographic techniques [18–20].

While advanced techniques provide novel opportunities for observing the airglow layer, they often lack the accessibility of ground-based measurements. Technological advances have eliminated most of the difficulties associated with observing airglow from the ground [21]. The application of tomography methods in atmospheric science is proving to be a powerful tool for investigating structure and dynamics of the airglow emissions using relatively sparse image data. On this note, Nygrén *et al.* examined the use of a stochastic inversion algorithm for reconstructing 2D tomographic images of aurora using two cameras separated by 200 km [22]. Because of the large distance between the sites, reconstructions were obtained only from an area close to one of the sites. This stochastic inversion technique

was later applied to 2D tomographic reconstructions of gravity wave structure in the hydroxyl (OH) airglow layer; the study was, however, limited to simulated reconstructions and a linear chain of five camera sites [23]. A subsequent airglow study compared the performance of a five-camera chain to a two-camera configuration with simulations, and also presented reconstructions from two-camera measurements of the OI (557.7 nm) emission layer from Hawaii [24]. However, the large site separation (152 km) provided a poor range of projection angles for reconstruction and it was concluded that three or more stations were necessary to provide reasonably good results, and that a linear chain of sites could not image specific gravity wave features, such as wave fronts that are parallel to the chain [24].

Recently, a virtual chain was created by collecting a sequence of all-sky OH images for 2D tomographic imaging using a single camera on an airplane [25]. However, the motion of the aircraft combined with the integration time of the imagers limited the resolution of the data to 8 km for an assumed stationary gravity wave. The reconstructions were obtained by performing a least-squares minimization of a weighted vector norm, and were constrained using a vertical envelop function for the airglow layer estimated from the experimental data. In contrast, Semeter and Mendillo conducted simulation studies of tomographic imaging of upper-atmospheric airglow emissions using a nonlinear optimization technique, and constrained the reconstructions using Chapman profiles for the vertical emission profiles [26]. Their work, however, was limited to 2D reconstructions and focused on measurements from a chain of four equally spaced cameras.

Although significant progress has been achieved in airglow tomography with three or more stations, considerably less progress has been reported for advancing the possibilities of two-station tomography [22,24]. This paper examines the capabilities and potential of using sparse ground-based imaging measurements from only two stations for tomographic studies of the airglow emission structures. The abilities of two-station data are demonstrated using both synthetically created imaging objects (modeled data) and OH airglow data. For modeled data, synthetic projections are created from the object and used to create a reconstruction. The synthetic reconstruction was then compared to the original object in order to validate the tomography methods and algorithms. The working hypothesis for this research was that two viewing stations are sufficient for creating accurate tomographic reconstructions when provided with *a priori* knowledge of the layer's vertical distribution. The typical extent or thickness of this layer was provided by altitude studies of OH airglow using rocket measurements and suggested a layer thickness of 8.6 ± 3.1 km [27] as well as recent measurements of the OH emission layer made by the SABER instrument onboard NASA's TIMED satellite. This value is sufficiently larger than the resolution of

our cameras at mesospheric altitudes and allows for the delineation of fine vertical structure in the images. The ability to resolve vertical variations is of significant interest to mesospheric studies because of its relevance to the propagation of gravity waves and the formation of certain cloud layers [28].

Images of the OH airglow layer were reconstructed using the partially constrained algebraic reconstruction technique (PCART) algorithm from data recorded by all-sky CCD cameras located at the Bear Lake and Star Valley observatories, operated by the airglow group at Utah State University (USU). These reconstructions were generated using projection data measured along linear profiles common to images obtained at each viewing site. A novel three-dimensional (3D) fanning technique was developed that combines multiple 2D reconstructions to form a 3D mapping of the OH airglow structure from which detailed investigations of the thickness, height, and internal structure of the layer were possible. The results presented here promote the use of 3D tomographic imaging capabilities, using two-station arrays optimized for airglow emissions, to investigate mesospheric gravity wave structure and propagation in unprecedented detail.

2. Methods

A. Imaging Configuration

A number of parameters affect the choice of location for ground-based imaging instrumentation. Although proximity provides researchers with greater accessibility to equipment, ambient light pollution often necessitates the placement of imaging systems in sparsely populated areas. While methods exist that can account for “background noise” in atmospheric imaging [29], the limited nature of two-station data is further complicated by such inclusions.

The objective of this project was to test the capability of tomographically reconstructing airglow emission data collected from only two viewing stations. The locations of the two stations were, therefore, optimized to ensure that the data were of the highest quality possible to create accurate reconstructions. Several low-population areas are in close proximity to the USU campus in Logan, Utah. The university-owned Bear Lake Observatory (BLO) was a prime location for one of the all-sky CCD cameras used to acquire the airglow measurements. The BLO is located on a mountainside a few miles west of Bear Lake, Utah (41.95° N 111.49° W) and provides a superior night-sky viewing capability.

The viewing conditions of the two sites needed to be as similar as possible so that simultaneous observations of events could provide consistent data from each location. In addition to this requirement, the distance between the two cameras is important for providing a tomographically conducive imaging configuration. In order to provide sufficient angular coverage, the distance between the two viewing stations

should be on the same order of magnitude as the height of the OH airglow emission layer. As described in Section 1, measurements of median OH layer altitudes have been conducted using a number of remote-sensing techniques, including rockets, satellites, and ground-based imaging systems in which volume emission profiles were estimated using tomographic techniques [27,30,31]. These measurements suggest a mean altitude of 87 ± 3.0 km for the OH M band [27,32]. A search for a suitable site for the second camera identified Afton, Wyoming, which is located ~ 100 km almost due north of BLO. A mobile observatory was constructed and located on the playing field of Afton’s Star Valley High School (42.74° N 110.95° W), which was located at a similar altitude to BLO and provided good viewing conditions. This second station is hereafter referred to as the Star Valley Observatory (SVO).

An all-sky imager was operated at each site during the winter period of 2009–2010. Each imager utilized a sensitive back-thinned 1024×1024 pixel CCD of high quantum efficiency ($\sim 80\%$ at visible, 50% at NIR wavelengths) to measure the mesospheric NIR OH Meinel broadband emission (710–930 nm). The large dynamic range and low noise characteristics (dark current $< 0.5e^-/\text{pixel}/\text{s}$) of these devices provided an exceptional capability for quantitative measurements of faint, low contrast ($< 5\%$) gravity waves. The exposure time for each camera, synchronized using GPS, was 15 s with an image acquired every 30 s. The data were 2×2 binned on the chip, down to 512×512 pixels, resulting in a zenith horizontal resolution of ~ 0.5 km, suitable for short-period gravity wave measurements [33].

Figure 1 is an example of two coincident CCD images recorded from BLO and SVO on the night of 15 February 2009 at 07:51:32 UT. The displacement of prominent wave structures in these two images is evident. The images were calibrated using the known star background to accurately determine each camera’s orientation and pixel scale size. They were then filtered to remove stars and “unwarped” to correct for the all-sky observing geometry and

Fig. 1. Synchronous OH airglow images from BLO and SVO recorded on 15 February 15 2009 at 07:51:32 UT showing gravity wave structures. Images have been flat fielded and processed to remove the star background and projected onto a $256 \text{ km} \times 256 \text{ km}$ grid.

projected onto a rectangular geographical grid of dimensions $256 \text{ km} \times 256 \text{ km}$ for an assumed OH emission altitude of 87 km [34,35]. A time sequence of these images at 7.5 min intervals is shown in Fig. 2, which illustrates the coherent motion of the wave structures. The top two images were used to create the airglow reconstructions presented in this paper.

To process these data for tomographic reconstruction, simultaneous image pairs were geographically aligned and then overlapped, creating a common measurement area as shown in Fig. 3. From these composite images, projection data were calculated that represented the intensity of the emissions measured at a given angle for each viewing location. These data constituted the tomographic projections used to create the airglow reconstructions. The yellow line in the figure represents the emission profile common to both images from which the projection data were extracted as described below.

Once the projection data were extracted from the common imaging profile, large-scale intensity fluctuations were filtered out to compensate for light from nonairglow sources and any differences in the spatial responses of the two cameras. Figure 4 shows this process. The upper two plots show the OH signal with fitted background curves, which were used to remove the large-scale amplitude variations. The

Fig. 2. Time sequence of OH airglow images from the BLO (left) and SVO (right) with a 7.5 min difference between successive images, illustrating coherent wave motion (indicated by arrows). The top two images were used for the tomographic reconstructions in this article.

Fig. 3. (Color online) An example of the overlapping technique used to align simultaneous images from BLO and SVO. The solid yellow line represents a common imaging profile from which projection data were extracted and used to create tomographic reconstructions of the OH structures.

lower plot shows the resultant excellent agreement between the relative intensities of the BLO and SVO data. The similarity of the relative magnitudes of projection data acquired at each imaging location is an important element of creating accurate tomographic reconstructions.

B. Tomographic Theory

Large-scale tomographic measurements, such as the airglow measurements described here, are often naturally limited in their range of viewing angles, resulting in a sparse ray distribution. This limitation creates an ill-conditioned inverse problem that is most appropriately solved by using a class of reconstruction algorithms known as matrix methods. This is in contrast to the set of transform methods in which the object to be reconstructed can be approximated as continuous because of the dense ray distribution (e.g., medical imaging). With matrix methods, the low density of the projected rays necessitates the use of a quantized representation for the imaged object. The assumed continuity of the imaged object and its projections is, therefore, replaced by a discretized description. The grid overlaid on the imaged object is also given a discontinuous structure through division into pixels. The quantization of the imaging object and its projections gives rise to a linear (algebraic) description and a matrix formalism.

The projection of a ray through a pixel is given by the direct relationship

$$p = wf. \quad (1)$$

The single pixel projection p is equal to the product of the weighting factor w and the functional pixel value f . The weighting factor expresses the area of the pixel that is intersected by the ray. This convention is

Fig. 4. (Color online) Plots of OH emission brightness for BLO (top) and SVO (center) along a common 120 km profile (indicated by the yellow line in Fig. 1). The fitted background curves were used to remove large-scale brightness variations across these profiles. The bottom image demonstrates the excellent agreement between the two intensity profiles once these variations are removed.

shown in Fig. 5. The weight $w_{m,n}$ of the n th pixel in the m th projection is defined as the area of intersection between the pixel and the two rays (lines) constituting the projection. This common area is represented by the two red shaded regions in the diagram. 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 the ray's interaction with N pixels can be expressed as the sum

$$p = \sum_{n=1}^N w_n f_n. \quad (2)$$

In matrix methods, as used here, the number of constructed rays from a given site is finite and the projection of the m th ray through the imaging region is given by

Fig. 5. (Color online) Illustration of the discretized imaging region used in algebraic tomography. The contribution of a given pixel to a measured projection is defined by the weighting factor w represented by the shaded region showing the intersection of a ray with a pixel. The lightly shaded region represents the imaging object.

$$p_m = \sum_{n=1}^N w_{m,n} f_n. \quad (3)$$

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

$$\begin{bmatrix} w_{11} & w_{12} & w_{13} & \cdots & w_{1N} \\ w_{21} & w_{22} & w_{23} & \cdots & w_{2N} \\ w_{31} & w_{32} & w_{33} & \cdots & w_{3N} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ w_{M1} & w_{M2} & w_{M3} & \cdots & w_{MN} \end{bmatrix} \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ \vdots \\ f_N \end{bmatrix} = \begin{bmatrix} p_1 \\ p_2 \\ p_3 \\ \vdots \\ p_M \end{bmatrix}. \quad (4)$$

This matrix equation, $\bar{W}\mathbf{f} = \mathbf{p}$, is in practice difficult to solve. The primary reason for this is that most applications of matrix methods generate underdetermined systems for which no unique solution exists [36]. Additionally, arrays with large numbers of elements can make accurate approximations difficult. Finding sufficiently accurate solutions to this system forms the foundation of algebraic tomography. The most common approach to finding solutions of this system utilizes a set of tomographic methods known as algebraic reconstruction techniques (ARTs) [36]. ARTs are a set of correction algorithms in which an initial image is gradually improved upon as successive iterations are carried out. An initial approximation of the object's structure (e.g., nominal OH layer profile) is provided to the algorithm as a vector and a correction factor is repetitively added. This correction term is calculated by comparing the tomographic projections of the previous image in the iteration with the measured projections. The way in

which this correction term is computed defines the reconstruction technique used here.

The fundamental algorithm upon which the set of ARTs is based is called the algebraic reconstruction technique (ART). Subsequent modifications to this technique have been developed, each designed for optimizing certain aspects of the data in order to create more accurate reconstructions. Among them are the constrained or totally constrained ART (TCART), the multiplicative ART (MART), the simultaneous iterative technique (SIRT), the simultaneous ART (SART), and the memory ART [36]. Using both synthetic and measured data, these and other algorithms were tested and assessed on the basis of their ability to accurately reconstruct airglowlite images from limited tomographic projection data. The testing determined that the PCART provided accurate and reliable reconstruction capabilities for our two-station imaging configuration. However, reconstructions formed using the MART algorithm were essentially indistinguishable from the PCART results described here.

The correction algorithm for PCART is

$$f_{m,n} = f_{m-1,n} + \lambda \frac{(p_m - p_m^i)w_{m,n}}{N_m}, \quad (5)$$

where $f_{m,n}$ 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 for this iterative reconstruction technique. The elements of the weighting matrix are given by $w_{m,n}$ and the convergence of the corrections can be controlled by the relaxation parameter λ . The measured projections correspond to p_m and the computed projections to p_m^i . The N_m term in the denominator 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:

$$N_m = \sum_{n=1}^N w_{m,n}. \quad (6)$$

The initial value of f can also have a significant impact on the convergence of iterative algorithms. This basis value, sometimes called the initial guess, was found to be of critical importance to the synthetic testing and method validation used for this project. Varying initial guesses were used in combination with specific artificial imaging objects in order to test the influence of the initial guess on the converged image. This synthetic testing provided an important means of validation for the algorithms used to reconstruct the airglow emission structure.

3. Results

The results of this study are divided into two parts that use synthetic and measured data. The synthetic data are first discussed as a means of validating the

PCART tomographic method used here. OH data and their corresponding reconstructions are then presented to demonstrate the capability of this technique for future airglow imaging studies.

A. Synthetic Data and Validation

Synthetic imaging objects were generated by artificially specifying the values of f corresponding to a terminal iteration value. The weighting matrix was then utilized in a forward modeling approach to create synthetic projections of the artificial object. These synthetic projections were then processed by the tomographic (inverse) algorithm to generate reconstructed images. The validity of these images was assessed by comparison with the original artificial imaging objects. Through successive testing, an understanding of the behavior of the reconstruction algorithm under conditions appropriate to the airglow measurements was acquired. The combination of these assessments provided a good qualitative assessment of the accuracy of the tomographic algorithm. Confidence in the reconstructions was obtained through synthetic testing of artificial imaging objects that closely resembled the airglow structure. In this study, typical synthetic objects were constructed using a vertical profile and periodic wave structure to simulate gravity waves propagating through the OH layer.

As two-station airglow tomography involves an imaging configuration which restricts the ray coverage, an assumed vertical profile or some other form of height constraint is necessary in the inversion process. This need for an *a priori* initialization of the correction algorithm has been previously described in the literature. The rocket-based tomography reported by McDade *et al.* as part of the ARIES campaign included a careful selection of pixel elements that were allowed to contribute to line-of-sight brightness measurements. The imaging region was restricted to a rectangular grid that conservatively enclosed the primary auroral form as determined separately from ground-based observations [9]. Similarly, Semeter and Mendillo regularized the ill-posed tomographic problem of reconstructing atmospheric emissions observed from the ground by constraining the vertical profile to a Chapman function. The resulting nonlinear optimization problem was minimized and used as the initial guess in a MART algorithm [26]. Of particular relevance to our OH airglow study, Anderson *et al.* used a Gaussian function as the vertical profile for their atmospheric gravity wave parameter estimation method [37].

During the synthetic testing, the algorithm's independence from ray geometries and sensitivity to various vertical profiles were examined. The effects of different ray-tracing geometries on the PCART algorithm were studied using a range of imaging grids that were varied independently between the forward problem (synthetic data) and inverse problem (tomographic reconstructions). For example, the synthetic object shown at the top of Fig. 7 was generated using

a 50×200 pixel grid. This differs from the 60×160 pixel grid used in the three reconstructed images shown in the figure (bottom). The algorithm's ability to reconstruct the object when provided with a different projection matrix, resulting from varied ray coverage, demonstrates a robustness that provides confidence in the tomographic algorithm and the Gaussian initialization.

As part of the synthetic testing, various vertical profiles were used to initialize the reconstruction algorithm in order to study its behavior. These distributions were characterized by their width (Γ), vertical position (μ), and maximum value (P^m), which are described as follows. The square or constant profile (Fig. 6 upper panel) is defined by

$$P_S(z) = \begin{cases} P_S^m & \text{if } \mu - \frac{\Gamma}{2} < z < \mu + \frac{\Gamma}{2}, \\ 0 & \text{otherwise} \end{cases}, \quad (7)$$

which is the simplest assumption and includes the least *a priori* information. The maximum value (P^m) is not unique to any single altitude. The value of μ is the center of the distribution as opposed to a maximum or peak value.

A common asymmetric profile frequently encountered in aeronomy is the Chapman function. It is defined by [26]

$$P_C(z) = P_C^m e^{\frac{1}{2}(1 - \tilde{z} - e^{-\tilde{z}})}, \quad (8)$$

where

$$\tilde{z} = \frac{z - \mu}{\Gamma}. \quad (9)$$

The Chapman profile can be seen in Fig. 6. Because of asymmetry, the value of μ defines the altitude of the maximum emission rate as opposed to the function centroid. The characteristic width (Γ) is less intuitive in this case. However, it is analogous to the parameterized width of a Gaussian defined by

$$P_G(z) = P_G^m e^{-\frac{(z-\mu)^2}{\Gamma^2}}. \quad (10)$$

The Gaussian profile (Fig. 6) has been used in prior studies to represent the stratified form of cloud or emission layers in atmospheric imaging [37]. It is simpler than the Chapman function and is symmetric. These three functions were used to initialize the reconstruction algorithm during synthetic testing.

Figure 7 shows one example of an artificial airglow imaging object representing a vertical cross section through several wave crests. The three profiles discussed above were used to initialize the algorithm in an attempt to reconstruct the artificial object. The resulting reconstructions are also shown in Fig. 7. The use of a square initial guess prevents the reconstruction from localizing and a broader square initialization causes it to wash out completely. Using this imaging configuration, there is not enough projection data to reconstruct an image with-

Fig. 6. (Color online) Three of the profiles used to initialize the reconstruction algorithm during synthetic testing. The (a) square, (b) Chapman, and (c) Gaussian profiles are shown along with their vertical cross sections (left).

out the use of a height constraint. In contrast, the accuracy of the reconstruction using the Gaussian and Chapman profiles is evident in both cases (Fig. 7). Minor effects and artifacts are visible but the overall integrity of the reconstructed images is apparent. The reconstructions are shown for 20 iterations; by which point the value of the sum of each pixel in the image changed by less than 1% during an iteration.

A more detailed comparison between the reconstructions using the Gaussian and Chapman profiles shows that, although the Chapman initialization contains more information on the layer's assumed vertical profile, it did not significantly alter the resulting structure along the bottom edge. Asymmetries and height variations were also included in the synthetic object to test the capabilities of the Chapman function as well as the performance of a symmetric Gaussian under these same conditions. The Gaussian initialization proved capable of reconstructing these asymmetric objects while the Chapman profile caused some distortion along the top edge and exhibited a higher occurrence of imaging artifacts. Furthermore, the use of a slightly wider Gaussian (as much as twice the width of the synthetic object) did not significantly alter the reconstructions.

Fig. 7. (Color online) Results of synthetic testing performed using the three initial profiles shown in Fig. 6. (a) The synthetic object was designed to include asymmetries and height variation in order to test the robustness of the algorithm and compare initial guesses. The reconstructions resulting from (b) square, (c) Chapman, and (d) Gaussian initializations are shown.

The choice of a Gaussian structure in simulating airglow layer emission profiles is also supported by previous ground-based measurements that used combinations of Na lidar, radar, imaging, and interferometric measurements of different airglow layers [32,38,37]. Additional support is provided by the SABER instrument onboard NASA's TIMED satellite. SABER was designed to measure the vertical distribution of infrared radiation emitted by various atmospheric gases. The graph in Fig. 8 displays an average volume emission rate (VER) for the $1.64\ \mu\text{m}$ band (channel 9) as a function of altitude. These data comprise an average of 35 nighttime measurements made as the satellite passed within 10° longitude and 10° latitude of BLO in February of 2009, spanning the time period when the tomographic measurements were made. The average OH VER exhibits a Gaussian-like response with a peak emission altitude of 87.3 km and a FWHM of 9.8 km, in good agreement with previous OH emission measurements [27]. This channel is dominated by the OH (4,2) and (5,3) band emissions, which typically originate at a slightly lower peak altitude (approximately 1.5 km) than the broadband (710–930 nm) OH emissions, primarily the OH (6,2) and (7,3) bands, imaged by both cameras [39].

In summary, the simplicity of the Gaussian and its success in reconstructing the synthetic imaging object when compared to more sophisticated

Fig. 8. Average VER profile of the OH emission determined from SABER observations onboard NASA's TIMED satellite. The data were collected in February of 2009 and correspond to instances when the satellite passed within the vicinity of BLO. The profile exhibits a Gaussian-like shape of FWHM 9.8 km and a peak height of 87.3 km.

(Chapman-like) initializations has made it a natural choice for an initial guess in this study. It also assumes less *a priori* information than the Chapman profile and has proven to be sufficiently independent of ray configurations. Furthermore, the Gaussian initialization also proved superior to backprojection and other forms of distributive initializations (not discussed here). As accurate tomographic imaging of airglow from a limited number of viewing angles requires the use of a height constraint, a SABER-like Gaussian profile conveniently centered at 85 km has been used in the OH airglow reconstructions. This is well within the nominal height range of the OH layer [27].

B. Airglow Layer Reconstructions

The synthetic testing results support the use of the PCART algorithm for the two-station tomographic airglow study, while the tests conducted using different emission profiles support the use of a symmetric Gaussian and provide confidence that the resulting structures are authentic and not artificially introduced by the initial guess. Emission data were uniformly sampled along a line joining the two camera sites (Fig. 3) and processed using the presented tomographic technique to reconstruct a 2D cross-sectional view of the airglow layer and its structure, as shown in Fig. 9. The reconstruction was made over a height range of 70–100 km and a horizontal ground range of

Fig. 9. (Color online) Cross-sectional tomographic reconstruction of the OH layer using data from two ground-based CCD cameras and constrained using a Gaussian profile. Note the change in structure, content, and apparent layer depth along the line joining BLO and SVO.

Fig. 10. Sketch showing the fanning configuration applied to the airglow data. Images were acquired by all-sky cameras at BLO and SVO (sites 1 and 2 in the figure) and tomographically reconstructed to create a 3D mapping of the OH layer.

80 km by using a Gaussian centered at 85 km with a FWHM of 10 km. The reconstruction yielded information on the airglow layer over the altitude range of 82–88 km. As expected, the structured region between the 40 and 80 km range coincides with the wave pattern, comprising three main crests evident near BLO in Fig. 3 while the structureless region closer to SVO appears to be thinner. As the upper and lower boundaries of the reconstruction were created by the tomography algorithm and not artificially introduced, they appear to represent significant changes in the bottom-side altitude of the OH layer. Furthermore, several finer wave structures within the vicinity of BLO are also evident in the reconstruction. These are more easily seen in the later images of the time series of Fig. 2.

C. Three-Dimensional Mapping of Airglow

While a standard 2D reconstruction of the airglow layer provides information on the structure within the zenith plane, it is clearly limited and does not utilize the full 3D imaging volume for quantitative studies of the wave evolution and propagation. To do this, we have developed a novel tomographic fanning technique to create a true 3D mapping of the airglow layer and its structure. In this method, a series of 2D reconstructions are acquired at varying angles away from the zenith plane and combined together to form a 3D reconstruction. This concept is illustrated in Fig. 10. The two horizontal planes

Fig. 11. (Color online) Composite 3D rendering of the airglow layer formed by combining 180 individual 2D reconstructions using the fanning geometry of Fig. 10.

Fig. 12. (Color online) Expanded view of the 3D airglow mapping shown in Fig. 11. The 3D rendering has been divided into six horizontal slices, each separated by 1.2 km. The ability to observe individual wavelike structures within the airglow layer demonstrates the advantage of using the 3D fanning technique.

shown represent the upper and lower boundaries of the tomographic imaging region.

Successive 2D reconstructions (totalling 180 slices) were generated at viewing angles incremented at 0.33° (limited by CCD pixel resolution) up to $\pm 30^\circ$ from the zenith. These images were then combined using volume-rendering software to create a 3D mapping of the airglow layer as shown in Fig. 11. The spatial extent of the 3D imaging volume is illustrated by the dashed rectangle in Fig. 3.

The 3D surface provides information about the structure and extent of the wave features that is not accessible in 2D reconstructions. For example, the three primary wave crests (horizontal wavelength ~ 20 – 30 km) are clearly seen extending across the top of the airglow mapping as surface undulations with significant peak-to-peak variations >1 km. These correspond to the short-period waves seen in Fig. 2. Further information can be obtained by slicing the 3D mapping at selected altitudes, creating several horizontal 2D cross-sectional segments. An example of this process is presented in Fig. 12, which is an expanded view of Fig. 11. In this case, the 3D rendering has been divided into six

Fig. 13. (Color online) Lower portion of the 3D airglow mapping shown in Fig. 11 segmented normal to the wave crests.

slices, each separated by 1.2 km and spanning the altitude range 82–88 km. The fingerlike wave structures are seen in each level, establishing the coherence of the wave throughout the airglow layer. However, the structure in adjacent levels shows significant difference in the fine-scale structures. This new fanning technique clearly provides additional detailed structural information that is not readily available using current limited tomographic methods applied to atmospheric data.

4. Discussion

The ability to perform detailed tomographic processing of airglow image data from only two stations has major practical advantages. This is because high-quality imaging instrumentation is relatively sparse and the placement and maintenance of three or more such instruments can be logistically difficult. Previously, 3D tomographic reconstruction of the airglow layer was thought to require at least three cameras, with one of the sites not in line with the other two [24]. However, it has been demonstrated here that the fanning technique can provide robust 3D reconstructions using data from only two stations. This was achieved by combining a number of adjacent 2D slices reconstructed from projection planes that are incrementally tilted from the zenith (Fig. 10). The resultant 3D airglow reconstructions exhibited consistent and well-defined variations in layer height, thickness, and internal structure (Figs. 11 and 12).

This study has been restricted to the development and demonstration of the fanning technique using suitable *a priori* knowledge of the layer to investigate 3D wave structure in the OH layer. Multiple 3D renderings constructed from time sequences of image pairs would provide important new information on the wave propagation, evolution, and possibly even its dissipation during the course of a night. Frequently, more than one wave pattern is observed in the airglow layers (as is evident in the time sequence of Fig. 2) and the 3D data can be used to investigate different structures along various angled planes. The potential to view the 3D mapping along specific axes of interest is illustrated in Fig. 13, which plots the lower half of Fig. 11 along a plane normal to the wave crests (i.e., orthogonal to the direction of the wave propagation). Such data can provide clearer structural information on the individual wave events.

Airglow imagery is frequently used to obtain key parameters of the gravity waves in the mesosphere–lower-thermosphere (MLT) to define their characteristics and to better understand how they transfer momentum and generate turbulence at these altitudes [25]. One of these parameters is the intrinsic phase speed of the wave (i.e., speed relative to the background wind field at that altitude). This can be obtained with *a priori* knowledge of the wave's vertical and horizontal wave components, which usually requires coincident measurements of

the wind field. Alternatively, this information may be obtained directly from the observed pitch angle of the wave front. The ability to acquire 3D reconstructions containing information on the wave tilt significantly broadens the range of information that can be acquired, as well as the types of wave phenomena that can be studied. For example, horizontal variations in the pitch of the wave front can be determined across the wave field over distances significantly larger than the wavelength of short-period, small-scale (5–50 km) waves (Figs. 11 and 12). The structure and dynamics of more complex phenomena can be studied as well, such as mesospheric bore events that are characterized by sharp leading wave fronts and undular trailing waves that increase in number with time. Additionally, 3D tomography may be used to investigate interfering wave patterns and embedded instabilities called ripples that are associated with gravity wave breaking. The ability to image the scale of these features, as well as to render their 3D structures as they evolve in time, will lead to new and unprecedented models for upper-atmospheric dynamics.

Although the studies reported in this paper were limited to only the NIR OH emissions at 87 km, they are also applicable to other MLT airglow emission layers, such as the Na (589.2 nm line centered at 90 km), the O₂ (0,1 band at 94 km), and the OI (557.7 nm green line emission at 96 km) [33]. One intriguing possibility is the simultaneous acquisition of tomographic data from several emission bands spanning the 80–100 km region of the MLT. Combining the separate emission band reconstructions would extend the vertical range of the tomographic imaging, thereby allowing the observation of phenomena, such as the upward or downward propagation of gravity waves or other dynamic phenomena, across a wide altitude range.

Finally, the tomographic methods presented in this paper may also be applicable to other upper-atmospheric features, such as ionospheric F-region airglow, auroral emissions, meteor trails, and polar mesospheric clouds. The ability to collect tomographic data from only two stations is particularly well suited to temporary or campaign-style studies where the cost, availability, or access to equipment is a key issue.

5. Conclusion

A new method has been presented for creating 3D tomographic reconstructions of the upper-mesospheric OH airglow emission using only two-station image data. Through synthetic testing, the potential of the fanning method has been demonstrated. The accuracy of the tomographic reconstructions was greatest with the use of the PCART algorithm in conjunction with a height constraint. When the initialization was assumed to have a Gaussian-like structure, the algorithm proved capable of reconstructing asymmetries present in the imaged object. This *a priori* knowledge localized the

initialization and ensured that it was vertically coincident with the imaging object. This technique is especially well suited to airglow tomography because the altitudes of the MLT emission layers are well measured and relatively stable, especially the OH emission layer [27], with wave-induced changes of only a few kilometers [32]. Opportune satellite measurements of some of these emissions are also currently available (e.g., TIMED satellite). The method was applied to OH airglow data taken by two all-sky cameras located at BLO and SVO with an optimal line-of-sight separation of 100 km. Cross-sectional reconstructions of the layer structure have been presented and analyzed. Multiple reconstructions from a range of angles measured from the zenith were combined to create a 3D mapping of the airglow layer displaying variations in layer thickness, height, and internal structure. The results presented here support the future use of this method for detailed tomographic studies of MLT structure and dynamics.

This work was funded by Grant No. ATM 0536876 from the National Science Foundation. The authors thank the students and faculty of Star Valley High School in Afton, Wyoming, for their permission to locate the Star Valley Observatory on their campus and their help in maintaining the observatory.

References

1. V. Y. Khomich, A. I. Semenov, and N. N. Shefov, "Introduction," in *Airglow as an Indicator of Upper Atmospheric Structure and Dynamics* (Springer, 2008), pp. 1–5.
2. S. Chakrabarti, "Ground based spectroscopic studies of sunlit airglow and aurora," *J. Atmos. Sol. Terr. Phys.* **60**, 1403–1423 (1998).
3. D. M. Hunten, "Spectroscopic studies of the twilight airglow," *Space Sci. Rev.* **6**, 493–573 (1967).
4. W. E. Sharp, J. W. F. Lloyd, and S. M. Silverman, "Zenith sky-light intensity and color during the total solar eclipse of 20 July 1963," *Appl. Opt.* **5**, 787–792 (1966).
5. X. Y. Zhou, D. Lummerzheim, R. Gladstone, and S. Gunapala, "Feasibility of observing dayside aurora using NIR camera on-board high-altitude balloons," *Geophys. Res. Lett.* **34**, L03105 (2007).
6. K. Kita, N. Iwagami, and T. Ogawa, "Rocket observations of oxygen night airglows: excitation mechanisms and oxygen atom concentration," *Planet. Space Sci.* **40**, 1269–1288 (1992).
7. G. Schmidtke, P. Seidl, and C. Wita, "Airglow-solar spectrometer instrument (20700 nm) aboard the San Marco D/L satellite," *Appl. Opt.* **24**, 3206–3213 (1985).
8. I. C. McDade and E. J. Llewellyn, "Inversion techniques for recovering two-dimensional distributions of auroral emission rates from tomographic rocket photometer measurements," *Can. J. Phys.* **69**, 1059–1068 (1991).
9. I. C. McDade, N. D. Lloyd, and E. J. Llewellyn, "A rocket tomography measurement of the N_2^+ 3914 Å emission rates within an auroral arc," *Planet. Space Sci.* **39**, 895–906 (1991).
10. I. C. McDade and E. J. Llewellyn, "Satellite airglow limb tomography: methods for recovering structured emission rates in the mesospheric airglow layer," *Can. J. Phys.* **71**, 552–563 (1993).
11. E. J. Llewellyn, W. S. C. Brooks, I. C. McDade, and D. W. Johnson, "Tomography from a Canadian small satellite in low Earth orbit," *Can. Aeronaut. Space J.* **37**, 72–76 (1994).
12. D. A. Degenstein, R. L. Gattinger, N. D. Lloyd, A. E. Bourassa, J. T. Wiensz, and E. J. Llewellyn, "Observations of an extended mesospheric tertiary ozone peak," *J. Atmos. Sol. Terr. Phys.* **67**, 1395–1402 (2005).
13. D. A. Degenstein, A. E. Bourassa, C. Z. Roth, and E. J. Llewellyn, "Limb scatter ozone retrieval from 10 to 60 km using a multiplicative algebraic reconstruction technique," *Atmos. Chem. Phys.* **9**, 6521–6529 (2009).
14. P. E. Sheese, E. J. Llewellyn, R. L. Gattinger, A. E. Bourassa, D. A. Degenstein, N. D. Lloyd, and I. C. McDade, "Mesopause temperatures during the polar mesospheric cloud season," *Geophys. Res. Lett.* **38**, L11803 (2011).
15. L. L. Cogger and C. D. Anger, "The OI 5577 Å airglow experiment on the ISIS 2 satellite," *J. Atmos. Terr. Phys.* **35**, 2081–2084 (1973).
16. A. L. Broadfoot, D. B. Hatfield, E. R. Anderson, T. C. Stone, B. R. Sandel, J. A. Gardner, E. Murad, D. J. Knecht, C. P. Pike, and R. A. Viereck, " N_2 triplet band systems and atomic oxygen in the dayglow," *J. Geophys. Res.* **102**, 11567–11584 (1997).
17. C. D. Anger, J. S. Murphree, A. V. Jones, R. A. King, A. L. Broadfoot, L. L. Cogger, F. Creutzberg, R. L. Gattinger, G. Gustafsson, F. R. Harris, J. W. Haslett, E. J. Llewellyn, D. J. McConnell, D. J. McEwen, E. H. Richardson, G. Rostoker, B. R. Sandel, G. G. Shepherd, D. Venkatesan, D. D. Wallis, and G. Witt, "Scientific results from the Viking ultraviolet imager: an introduction," *Geophys. Res. Lett.* **14**, 383–386 (1987).
18. D. A. Degenstein, E. J. Llewellyn, and N. D. Lloyd, "Tomographic retrieval of the oxygen infrared atmospheric band with the OSIRIS infrared imager," *Can. J. Phys.* **82**, 501–515 (2004).
19. Z. Wang and S. Chen, "Effective solution algorithm for tomographic inversion of volume emission rate from satellite-based limb measurement," *Chin. Geograph. Sci.* **21**, 554–562 (2011).
20. P. E. Sheese, E. J. Llewellyn, R. L. Gattinger, A. E. Bourassa, D. A. Degenstein, N. D. Lloyd, and I. C. McDade, "Temperatures in the upper mesosphere and lower thermosphere from OSIRIS observations of O_2 A-band emission spectra," *Can. J. Phys.* **88**, 919–925 (2010).
21. M. J. Taylor, "A review of advances in imaging techniques for measuring short period gravity waves in the mesosphere and lower thermosphere," *Adv. Space Res.* **19**, 667–676 (1997).
22. T. Nygrén, M. Markkanen, M. Lehtinen, and K. Kaila, "Application of stochastic inversion in auroral tomography," *Ann. Geophys.* **14**, 1124–1133 (1996).
23. T. Nygrén, M. J. Taylor, M. S. Lehtinen, and M. Markkanen, "Application of tomographic inversion in studying airglow in the mesopause region," *Ann. Geophys.* **16**, 1180–1189 (1998).
24. T. Nygrén, M. J. Taylor, G. R. Swenson, and M. S. Lehtinen, "Observing gravity wave activity in the mesopause region by means of airglow tomography," *Adv. Space Res.* **26**, 903–906 (2000).
25. D. S. Anderson, G. Swenson, F. Kamalabadi, and A. Liu, "Tomographic imaging of airglow from airborne spectroscopic measurements," *Appl. Opt.* **47**, 2510–2519 (2008).
26. J. Semeter and M. Mendillo, "A nonlinear optimization technique for ground-based atmospheric emission tomography," *IEEE Trans. Geosci. Remote Sens.* **35**, 1105–1116 (1997).
27. D. J. Baker and A. T. Stair, "Rocket measurements of the altitude distributions of the hydroxyl airglow," *Phys. Scr.* **37**, 611 (1988).
28. M. J. Taylor, D. C. Fritts, and J. R. Isler, "Determination of horizontal and vertical structure of an unusual pattern of short-period gravity waves imaged during ALOHA-93," *Geophys. Res. Lett.* **22**, 2837–2840 (1995).
29. R. A. Bernstein, W. L. Freedman, and B. F. Madore, "The first detections of the extragalactic background light at 3000, 5500, and 8000 Å. I. Results," *Astrophys. J.* **571**, 56–84 (2002).
30. E. E. Remsberg, B. T. Marshall, M. Garcia-Comas, D. Krueger, G. S. Lingenfelter, J. Martin-Torres, M. G. Mlynarczyk, J. M. Russell III, A. K. Smith, Y. Zhao, C. Brown, L. L. Gordley, M. J. Lopez-Gonzalez, M. Lopez-Puertas, C.-Y. She, M. J. Taylor, and R. E. Thompson, "Assessment of the quality of the Version 1.07 temperature-versus-pressure profiles of the middle atmosphere from TIMED/SABER," *J. Geophys. Res.* **113**, D17101 (2008).
31. B. Gustavsson, T. Sergienko, M. T. Rietveld, F. Honary, Å. Steen, B. U. E. Brändström, T. B. Leyser, A. L. Aruliah, T. Aso, M. Ejiri, and S. Marple, "First tomographic estimate of

- volume distribution of HF-pump enhanced airglow emission," *J. Geophys. Res.* **106**, 29105–29123 (2001).
32. Y. M. Zhao, M. J. Taylor, and X. Chu, "Comparison of simultaneous Na lidar and mesospheric nightglow temperature measurements and the effects of tides on the emission layer heights," *J. Geophys. Res.* **110**, D09S07 (2005).
 33. M. J. Taylor, M. B. Bishop, and V. Taylor, "All-sky measurements of short period waves imaged in the OI (557.7 nm), Na (589.2 nm) and near infrared OH and O₂ (0,1) nightglow emissions during the ALOHA-93 campaign," *Geophys. Res. Lett.* **22**, 2833 (1995).
 34. F. J. Garcia, M. J. Taylor, and M. C. Kelley, "Two-dimensional spectral analysis of mesospheric airglow image data," *Appl. Opt.* **36**, 7374–7385 (1997).
 35. D. Pautet and G. Moreels, "Ground-based satellite-type images of the upper-atmosphere emissive layer," *Appl. Opt.* **41**, 823–831 (2002).
 36. A. C. Kak and M. Slaney, *Principles of Computerized Tomographic Imaging* (Society for Industrial and Applied Mathematics, 2001), pp. 49–68, 275–292.
 37. D. S. Anderson, F. Kamalabadi, and G. R. Swenson, "Estimation of three-dimensional atmospheric wave parameters from ground-based spectroscopic airglow image data," *IEEE Trans. Geosci. Remote Sens.* **47**, 2427–2435 (2009).
 38. J. Fujii, T. Nakamura, T. Tsuda, and K. Shiokawa, "Comparisons of winds measured by MU radar and Fabry-Perot interferometer and effect of OI5577 airglow height variations," *J. Atmos. Sol. Terr. Phys.* **66**, 573–583 (2004).
 39. S. Adler-Golden, "Kinetic parameters for OH nightglow modeling consistent with recent laboratory measurements," *J. Geophys. Res.* **102**, 19969–19976 (1997).