Journal of Atmospheric and Solar-Terrestrial Physics 95-96 (2013) 41–50

Contents lists available at SciVerse ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

Retrieval of the three-dimensional wave structure of gravity waves from multi-position airglow measurements

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ARTICLE INFO

Article history:
Received 28 March 2012
Received in revised form
28 December 2012
Accepted 31 December 2012
Available online 17 January 2013

Keywords:
Gravity wave
Emission layer
Airglow imager
Satellite

ABSTRACT

The aim of this work is to develop mathematical foundation of a method which can be used to infer the three-dimensional gravity wave characteristics from multi position airglow observations from space. This work derives a one-dimensional Fredholm integral equation of the first kind, which describes the relations between the gravity wave spectrum and spatial structure of wave perturbations registered by a space-based airglow imager. It is shown that the solution of this equation belongs to the central slice through a three-dimensional gravity wave spectrum, whose plane is perpendicular to the optical axis of the airglow imager. Thus, in order to retrieve the three-dimensional gravity wave characteristics from the airglow observations performed from space, it is needed to obtain the set of images of a local emission layer area from different imager positions. Then this data must be processed using the developed mathematical techniques to obtain a set of the central slices of the three-dimensional gravity wave spectrum. Applying the technique, for a superposition of three individual waves, amplitude and wave vector can be determined.

1. Introduction

Atmospheric gravity waves (GWs) have been a subject of intense research activity in recent decades. One chief reason is the large GW contribution to the energy and momentum balance in the mesosphere and the low thermosphere (Fritts and Alexander, 2003). The changes of the Brewer–Dobson circulation and QBO are also bound with atmospheric GWs. However, estimates of the momentum and energy fluxes carried by GWs still rely more on models then on measurements, and have a large ambiguity (Ern et al., 2005; Alexander and Barnet, 2007; Frödlich et al., 2007; Alexander et al., 2010). All measurement techniques employed for assessing atmosphere GWs are now far from being perfect and may be divided into three groups: in-situ, ground- and space-based measurements (Preusse et al., 2009). In-situ measurements use radiosondes (Wang and Geller, 2003; Tsuda et al., 2004), rocketsondes (Hamilton, 1991; Schöch et al., 2004), research aircrafts (Doyle et al., 2002; Lu et al.,2005), and super-pressure balloons (Vincent et al., 2007; Hertzog et al., 2008). These techniques allow in situ measurements of the vertical momentum fluxes carried by atmospheric GWs. Besides in situ measurements, the momentum and energy fluxes may be derived from simultaneous registration of amplitude, vertical and horizontal wavelength of the atmospheric GWs (Ern et al., 2004). However, the conventional ground-based instruments are usually unable to measure horizontal and vertical wavelengths simultaneously. So, in order to estimate the energy and momentum fluxes, a combination of the airglow- and radar/lidar-measurements is used (Manson and Meek, 1988; Tsuda et al., 1990; Taylor et al., 1995; Gardner and Taylor, 1998; Nastrom et al., 2000).

Among space based measurements there are limb, sub-limb and nadir GW measurements from space research platforms (Wu et al., 2006). GWs are generally detected in satellite observations as temperature fluctuations of the atmosphere air. The limb sounders—Limb Infrared Monitor of the Stratosphere (LIMS) (Fetzer and Gille, 1994), Cryogenic Infrared Spectrometers and Telescopes for the Atmosphere (CRISTA) (Preusse et al.,1999, 2001, 2002; Ern et al., 2004), and High Resolution Dynamics Limb Sounder (HIRDLS) (Gille et al., 2008; Alexander et al., 2008), all have a high vertical resolution ($\approx$ 1 km), and low horizontal one ($\approx$ 200 km). On the contrary, sub-limb and nadir satellite instruments, such as Atmospheric Emissions Photometric Imager (AEPI) (Mende et al., 1994), the Tether Optical Phenomena (TOP) airglow imager (Mende et al., 1998), Upper Atmosphere Research Satellite (UARS) Microwave Limb Sounder (MLS) (Armstrong et al., 1995; Wu and Waters 1996a,b; McLandress et al., 2000), Midcourse Space Experiment (MSX) (Dewan et al., 1998), Advanced Microwave Sounding Unit (AMSU) (Wu, 2001), and Atmospheric Infrared Sounder (AIRS) (Aumann et al., 2003) are characterized by a nice horizontal resolution (up to several hundred meters) and a

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1364-6826/$ - see front matter
http://dx.doi.org/10.1016/j.jastp.2012.12.022

low vertical resolution ($\approx$10 km and more). These two types of instruments can only see different limited portions of the GW spectrum because of their resolution, footprint, and sampling limitations. Nevertheless, the simultaneous measurement of horizontal and vertical wave structure by limb infrared sounder technically feasible for GWs with horizontal wavelengths longer than ~200 km (Ern et al., 2004; Alexander et al., 2008). In the nearest future, the advances in detector technology will allow measuring vertical temperature profiles separated from each other by 50 km and 24 km distances along and across the orbital track, respectively, with vertical resolution of about 500 m. As a result, the GWs with vertical and horizontal wavelengths larger than, respectively, 1 km and 100 km, could be captured by this instrument (Friedl-Vallon et al., 2006; Preusse et al., 2009).

To assess GWs, which can convey momentum from the troposphere to the low thermosphere, the waves with horizontal wavelengths λ_H between 10 km and a few thousand kilometers, and vertical wavelength λ_V between one and a few tens of kilometers should be monitored. Currently, the important short wavelength part ($\lambda_H < 100$ km, $\lambda_V < 15$ km) of the GW spectrum still remains unresolved. The importance of one has been determined through extensive radar measurements, which demonstrated that 70% of the energy transported through the mesosphere is carried by GWs with horizontal wavelength of only tens of kilometers (Fritts and Vincent, 1987; Vincent, 1984). Most of these waves have horizontal wavelength between 10 and 40 km (Anderson et al., 2009; Taylor et al., 1997; Swenson et al., 1999; Hecht, 2004). Conventional airglow imaging can measure such values of horizontal wavelengths, but cannot measure the vertical wavelengths at all. To overcome this limitation, a method of airglow tomographic reconstruction has been tested (Nygren et al., 1998; Nygren et al., 2000; Anderson et al., 2008). However, because the reconstruction quality strongly depends on the number of imagers and on the mutual orientation of the wave front and the chain of the measurement positions, it had been recognized that this method is not robust enough to reconstruct all the wave events.

Recently it was justified that no complete cycle of the tomographic reconstruction is needed to determine the vertical wavelength of the wavelike airglow perturbation. It was shown that with the proper technique the values of the vertical and horizontal wavelengths can be estimated directly from data obtained by simultaneous observations from several airglow imagers without tomographic inversion (Anderson et al., 2009). A similar approach is developed in this paper with respect to airglow measurements of atmospheric GWs from space. It is expected to be used with space based CCD imagers under nadir and sub-limb measurement geometries. In Section 2 we shortly reproduce the derivation of the spectral expansion of the spatial structure of the observed brightness field of the emission layer (Belyaev, 2009). This expansion determines the relation between the 3D GW Fourier spectrum of the temperature field in a vicinity of the emission layer and the 2D brightness field of the emission layer registered by the space based airglow imager. Section 3 is devoted to the proof of the theorem, which associates each image of the emission layer with the corresponding central slice of the 3D GW spectrum. In Section 4 we present the algorithm of retrieving the GW spectrum, and describe the numerical experiment, which illustrates how parameters of a few plane GWs can be inferred from a set of emission layer images captured by a space based airglow imager.

2. The spectral expansion of the observed brightness field

Hereafter, we shall suppose that the space based airglow imager has a spatial limited field of view (FOV). Let us assume that the sizes of FOV are such that the spatial domain of the emission layer observed by this imager may be considered as a plane-parallel horizontal formation. Based on this assumption, we can solve the problem under a plane-parallel geometry using the Cartesian coordinate system, such as: (i) the airglow imager is situated at point (0,0,h) and (ii) FOV is centered in the point (x_0,0,0) (see Fig. 1). In this case, the certain foreshortening, under which the orbital airglow imager 'sees' the observed area of the emission layer, will be defined by two parameters, h and x_0. For example, the limb measurements will be realized at $h=0$ and the cases with $x_0=0$ will correspond to the nadir viewing (see Fig. 1). The plane (x,y,0) marks the altitude for which the wave field will be reconstructed, and we call this plane "image plane", and the direction of LOS may be defined by Cartesian coordinates (x,y).

We will examine some hypothetical emission layer whose volume emission rate can be approximated by the linear term in a perturbation series expansion

$$\varepsilon = \varepsilon_u(z) + \varepsilon'(z)(T'/T_u), \quad (1)$$

where the temperature fluctuations (T'/T_u) in the vicinity of the emission layer are attributed to the passage of the gravity wave (hereafter index u corresponds to the unperturbed values of atmospheric parameters), ε_u is the unperturbed value of volume emission rate, and $\varepsilon'(z)$ is the amplitude of linear perturbation. It was shown by Belyaev (2009) that in case of the O_2 atmospheric (0,0) nightglow, the expansion coefficients can be approximated by Gaussian functions. To analyze the airglow perturbations induced by GWs in the hypothetical emission layer we also assume that Gaussian function $\varepsilon'(z) = B_1/\sqrt{2\pi}\sigma_1 \exp(-(z-h_1)^2/2\sigma_1^2)$ may be used for the approximations of the expansion coefficient $\varepsilon'(z)$ in Eq. (1). B_1, h_1, and σ_1 are the parameters of the Gaussian functions: magnitude, height and full width at half maximum of $\varepsilon'(z)$, respectively. The observed geometry is illustrated in Fig. 1b. It is assumed that the origin of Cartesian coordinate system (x,y,z) coincides with the centroid of the ε'-layer, z_1 . Thus the vertical coordinate of the space based airglow imager is $h = R_{sat}\cos\chi - R_1$

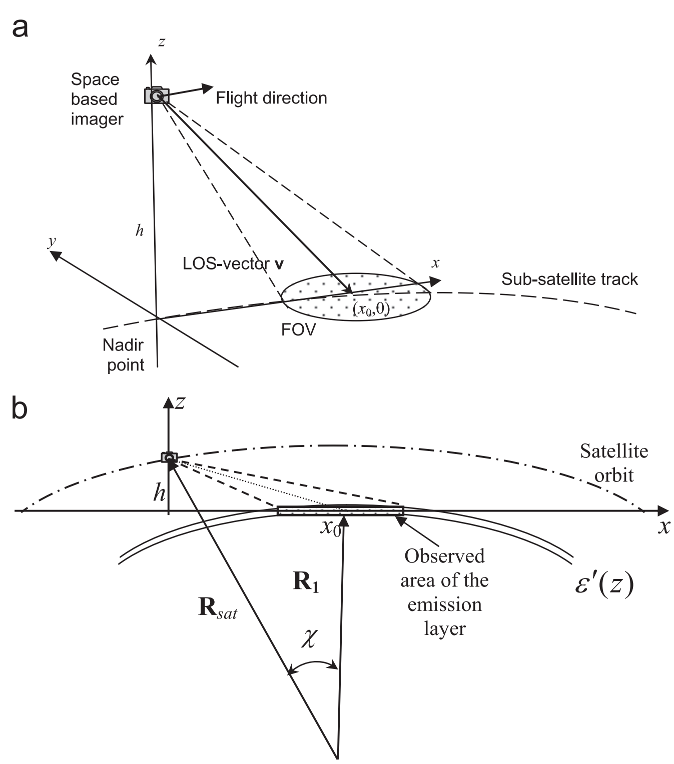

Fig. 1. Viewing geometry for the space-based airglow measurements. (x,y) is the image-plane. (a) 3D illustration and (b) 2D illustration.