3D reconstruction of atmospheric gravity waves with tomography applied to data from two ground-based cameras observing OH airglow above the Alpine region

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1. Motivation

Atmospheric gravity waves

- transport energy and momentum throughout the atmosphere
- can travel large horizontal and vertical distances from the troposphere up to the mesosphere and even above.
- They **contribute to atmospheric dynamics** and among others drive the meridional pole-to-pole circulation in the mesosphere leading to a cold summer pole in the middle atmosphere.
- Thus, **characterizing the gravity waves may allow further improvements in climate and even meteorological models**.

2. OH Airglow & Observations

The OH airglow layer is used to observe gravity waves in the upper mesosphere/lower thermosphere (UMLT)

- It is a chemiluminescent layer which can be observed at night times,
- emits light mainly in the **short-wave infrared** spectral range with the maximum emission at about 1.5 to 1.7µm,
- is in an altitude of about **87km** with half-width of about **4km**,
- is **modulated by traversing gravity waves**, e.g. by temperature changes, pressure changes, and by changing the composition of reactants which overall leads to local raising and declining of the layer.

Observations of the OH airglow layer with FAIM camera systems (Fast Airglow IMagers) and analyzing the acquired image series **normally only allow the derivation of horizontal wave parameters** (horizontal wavelength, horizontal angle of propagation, wave period, phase speed). However, **using two FAIM systems at different sites viewing the same area of airglow from two perspectives allows a 3D reconstruction** of traversing gravity waves by use of a novel tomography algorithm.

3. Data and Preprocessing

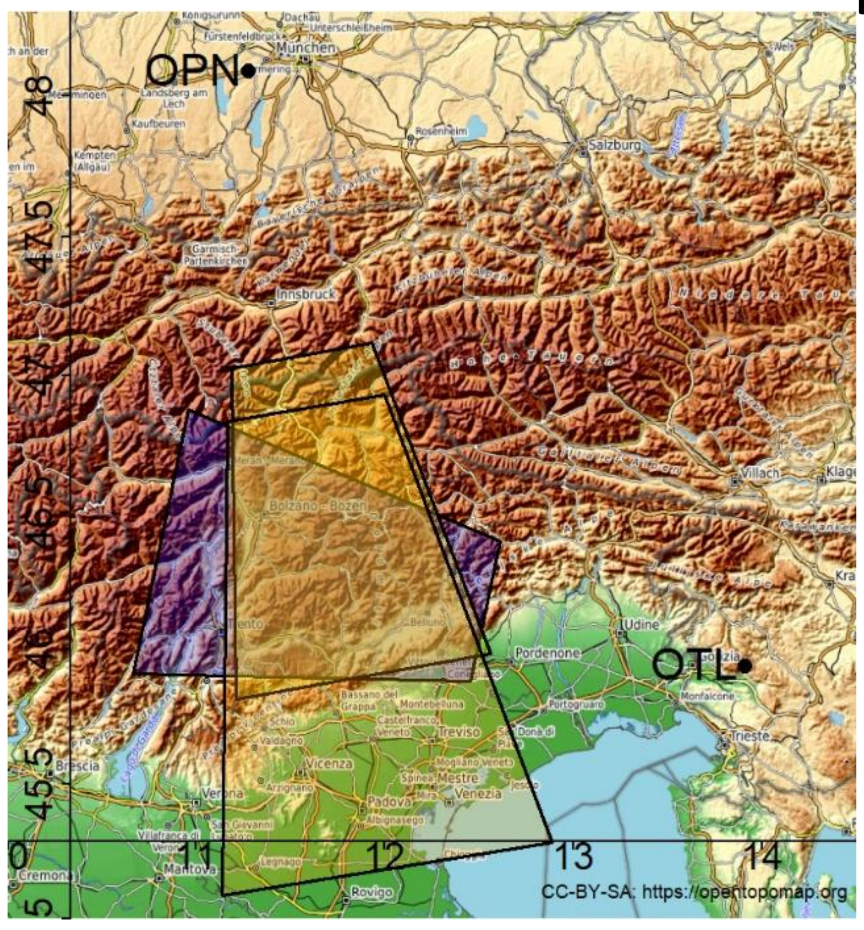


Figure 1: The two overlapping field-of-views at OH airglow layer height (87km).

- OPN = Oberpfaffenhofen, Germany
- OTL = Otlica, Slovenia

Both sides are about 300km apart.

The zenith angle of the OPN system changed from 61° (smaller yellow FOV) to 66° (larger yellow FOV) during the 1.5 years of airglow observations. The temporal resolution is 2 images per second.

- Only data without clouds, moon or similar sources of disturbance for the airglow observations are selected. For the here presented study a short 30min sequence is selected out of the whole set of observations.
- The precise orientation of the instruments is determined by alignment of the stars in the images with the known star positions for the site and respective time (using the 2MASS infrared star catalogue).
- The stars are then removed by means of image processing to avoid these non-airglow signals.
- Noise is reduced by applying a blur algorithm to the images.

4. Tomography algorithm

- A 3-dimensional grid (lon-lat-altitude) of size 160x160x24 is layed over the data.
- The contribution of each camera pixel to each grid cell is determined which leads to a highly underconstrained equation system.
- OH airglow vertical emission profiles from the TIMED-SABER satellite instrument are used on a statistical basis to reduce the 24 altitude layers to 8 basis functions.
- A Least-Squares algorithm (LSMR after Fong and Saunders 2011) is used for solving the equation system. A zeroth-order Tikhonov regularization is used to smooth the coefficients.

5. Case Study

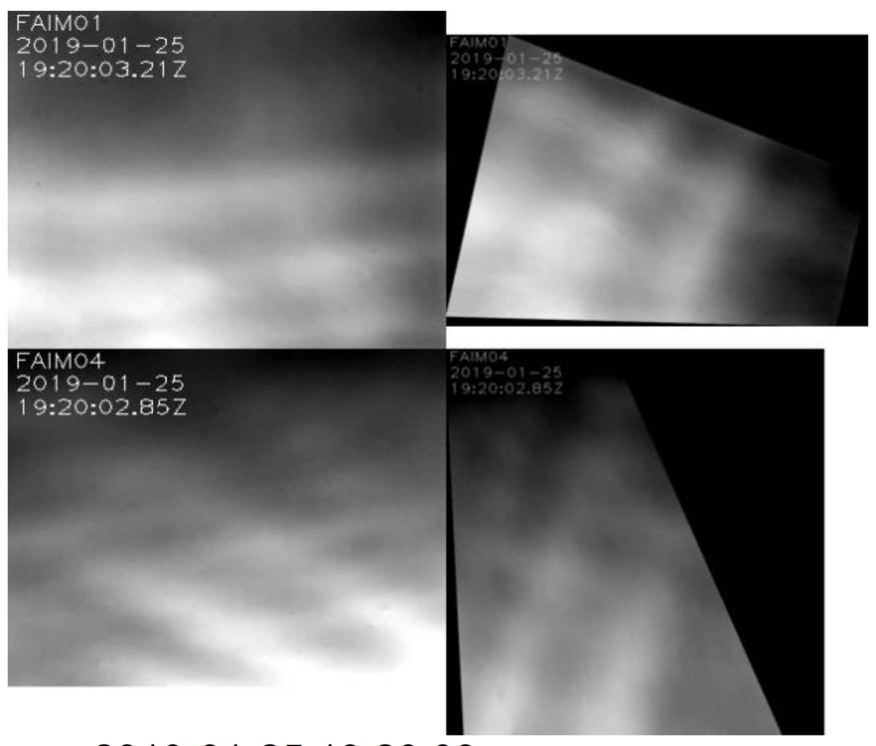


Figure 2:
Left column: One image of each FAIM system at the same time. Two overlapping wave structures with roughly a 90° horizontal propagation angle to each other are clearly visible.
Right column: The two images of the left side are georeferenced to correspond to the FOVs seen on the map (Figure 1).

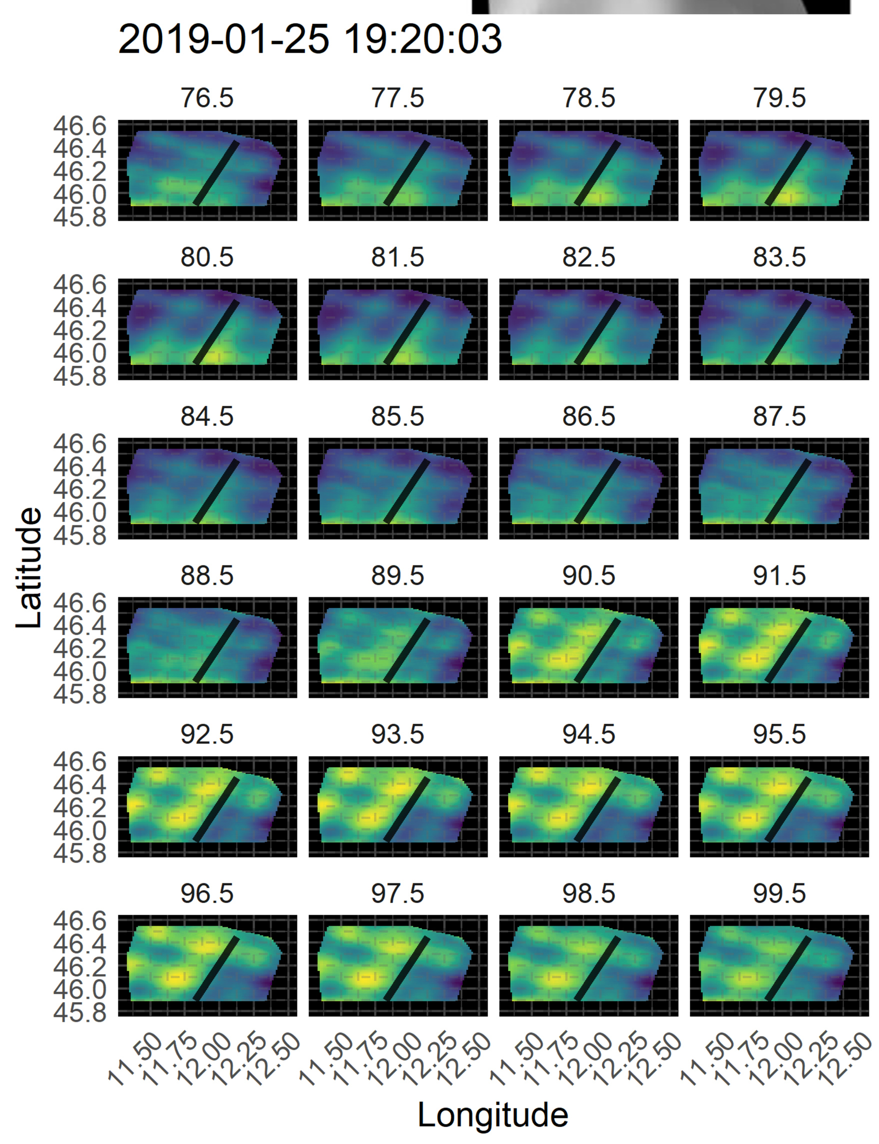
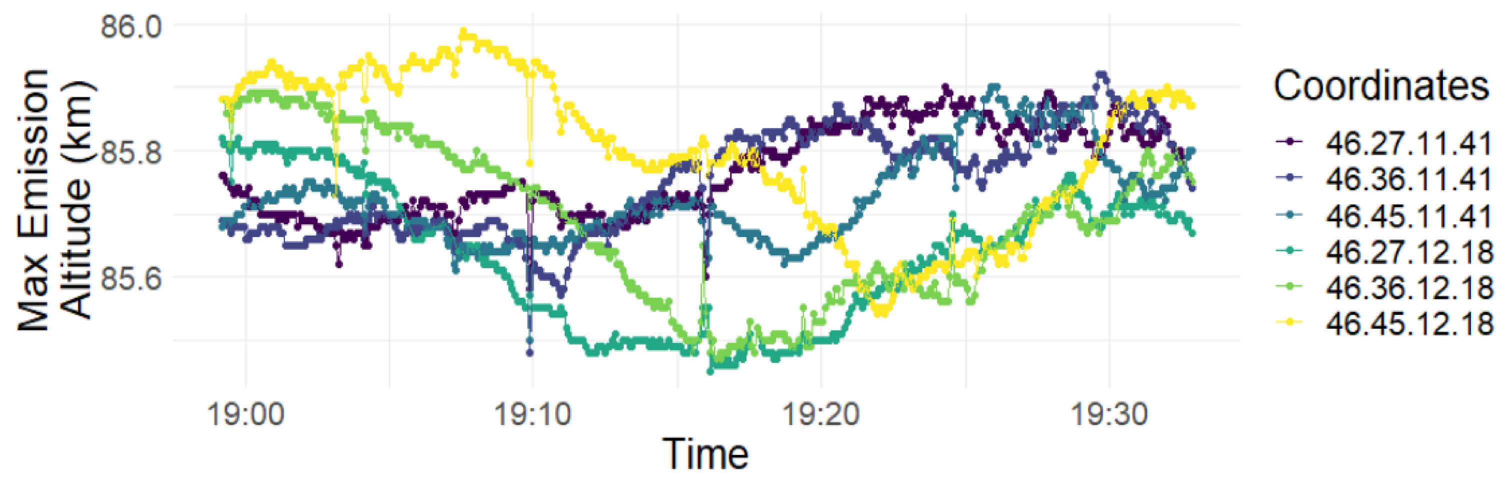


Figure 3 (Left): Airglow emission intensity for each grid height (76.5km to 99.5km) derived from tomographic reconstruction of two FAIM images. The color scale of arbitrary emission units is adjusted per subplot to better visualize the wave structures. In general the intensity maximizes at about 86-87km and falls off quickly to higher and lower altitudes. The black line is oriented on the wave maximum at 86.5km altitude to guide the eye and indicate the shift along the longitude direction at other altitudes. This shows the slant of the wave structure and allows the derivation of the vertical wavelength.

Figure 4 (Below): Time series of 6 selected horizontal grid points of maximum emission altitude (the given altitude values still have a large uncertainty and are preliminary, yet). From the difference between two maxima/minima the wave period can be derived.



The horizontal wavelength und propagation direction can be determined directly from the images (see Figure 2). The vertical wavelength can be calculated from the slant of the wave vector to the horizontal. The observed wave period/frequency can be extracted either from the time series of some image pixels (not shown) or the time series of the maximum emission altitude from the tomographic reconstruction (Figure 4). For estimating the intrinsic frequency of the wave using their dispersion relation (see Fritts et al. 2003), the characteristic Brunt-Väisälä-Frequency of the atmosphere has to be known. For the respective day-of-year and the location it can be taken from a climatology (see Wüst et al. 2020; here 0.024 Hz). Knowing the observed and (doppler-shifted) intrinsic wave period, even the wind along the direction of the wave vector can be estimated.

The investigated gravity wave has the following parameters:

- horizontal wavelength: 35 km
- slant to horizontal: 38°
- vertical wavelength: 27 km
- observed wave period / frequency: 18.4 min / 0.00090 Hz
- intrinsic wave period / frequency: 7.1 min / 0.0023 Hz
- background wind along wave vector: about 50 m/s towards wave propagation

Publications and Contact

FAIM systems: Hannawald et al., 2019, AMT, 10.5194/amt-12-457-2019
Brunt-Vaisala-Frequency: Wüst et al., 2020, AMT, 10.5194/amt-13-6067-2020
LSMR-Algorithm: Fong and Saunders, 2011, https://archive.org/details/arxiv-1006.0758/mode/2up
Dispersion relation: Fritts et al., 2003, 10.1029/2001RG000106
Tomography: Not peer-reviewed published, yet.

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Summary

Airglow is a well-suited way to observe gravity waves in the middle atmosphere altitude region. The gravity waves significantly contribute to atmospheric dynamics. Using two FAIM camera systems at different locations viewing the same volume of OH airglow emission (at about 87km altitude), a tomographic reconstruction is possible. By applying this novel approach not only the horizontal wave parameters, but all wave parameters can be derived from the observations. To solve the tomographic equation system, statistical background information of the OH airglow layer vertical emission profiles from the TIMED-SABER instrument is used. A case study with a fully characterized gravity wave is presented.

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