



High resolution observations of small scale gravity waves and turbulence features in the OH airglow layer

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Abstract. A new version of the Fast Airglow Imager (FAIM) for the detection of atmospheric waves in the OH airglow layer has been set up at the German Remote Sensing Data Center (DFD) of the German Aerospace Center (DLR) at Oberpfaffenhofen (48.09° N, 11.28° E), Germany. The spatial resolution of the instrument is 17 m in zenith direction with a
10 field of view (FOV) of 11.1 km x 9.0 km at the OH layer height of ca. 87 km. Since November 2015, the system has been in operation in two different setups (zenith angles 46° and 0°) with a temporal resolution of 2.5 to 2.8 s.

In a first case study we present observations of two small wave-like features that might be attributed to gravity wave instabilities. In order to spectrally analyse harmonic structures even on small spatial scales down to 550 m horizontal wavelength, we made use of the Maximum Entropy Method (MEM) since this method exhibits an excellent wavelength
15 resolution. MEM further allows analysing relatively short data series, which considerably helps to reduce problems such as stationarity of the underlying data series from a statistical point of view. We present an observation of the subsequent decay of well-organized wave fronts into eddies, which we tentatively interpret in terms of an indication for the onset of turbulence.

Another remarkable event which demonstrates the technical capabilities of the instrument was observed during the night of
20 4th to 5th April 2016. It reveals the disintegration of a rather homogenous brightness variation into several filaments moving in different directions and with different speeds. It resembles the formation of a vortex with a horizontal axis of rotation



likely related to a vertical wind shear. This case shows a notable similarity to what is expected from theoretical modelling of Kelvin-Helmholtz instabilities (KHIs).

The comparatively high spatial resolution of the presented new version of the FAIM airglow imager provides new insights into the structure of atmospheric wave instability and turbulent processes. Infrared imaging of wave dynamics on the sub-kilometre scale in the airglow layer supports the findings of theoretical simulations and modellings.

1 Introduction

The reaction of hydrogen and ozone produces molecular oxygen and vibrational-rotationally excited hydroxyl (OH)*. OH* relaxes by emitting electromagnetic radiation, especially in the SWIR range (Bates and Nicolet, 1950). The hydroxyl forms a Chapman layer at the upper mesosphere / lower thermosphere and is one prominent component of the airglow phenomenon. The peak concentration of OH* is located at an altitude of ca. 87 km with a full half-width of about 8 km (Baker and Stair, 1988). The OH* mean emission altitude exhibits low annual variability (e.g. von Savigny, 2015). Since the density of the atmosphere decreases exponentially with increasing height, the amplitudes of upward propagating atmospheric waves considerably grow due to the conservation of energy. Once the waves reach the airglow layer, they influence the intensity of the airglow emission. This makes the airglow an established phenomenon for the investigation of atmospheric dynamics. Furthermore, based on temperature data derived from a Na-lidar, (Gardner et al., 2002) concluded that the vertical heat flux due to wave dissipation is maximum near the mesopause altitude region because of the reduced stability due to the large temperature lapse rate and the low buoyancy parameter below the mesopause. It is thus expected to frequently observe gravity wave breaking processes in this altitude region.

Gravity waves are an intensively investigated feature within atmospheric dynamics. Their ability to transport energy and momentum over long distances through the atmosphere makes them an important factor to be considered in climate studies and meteorology. It is well known that gravity wave spectra extend over a few magnitudes of the wavelength scale. Horizontal wavelengths from a few kilometres up to about thousand kilometres are usually observed.

Energy transported by atmospheric waves is released into the surrounding atmosphere when instabilities lead to turbulence. Atmospheric instability can either be of dynamical or of convective nature. Dynamical instabilities are caused by wind shear,



leading to formation of Kelvin-Helmholtz instabilities (KHI), whereas convective instabilities are induced when the temperature lapse rate gets superadiabatic (Fritts and Alexander, 2003).

Turbulent processes are characterized to cover several magnitudes of the length scale. The complete range of turbulence can be divided into three parts: within the largest regime, the so-called buoyancy subrange, energy is still carried by waves and the buoyancy force is dominating viscosity. Distortions on scales below the buoyancy subrange let the transported energy cascade to smaller and even smaller structures (inertial subrange) where energy is still conserved within the eddies until it is dissipated into the atmosphere due to viscous damping (viscous subrange) (e.g. Lübken et al., 1987). It must be noted that the scale limits between the three subranges are strongly dependent on the altitude. Within the abovementioned region of the OH* peak concentration at an altitude of about 87 km, the inertial subrange of turbulence is on a scale of a few hundreds of metres, starting just below 1 km and reaches the viscous subrange at about 30 m (Hocking, 1985).

Signatures of atmospheric gravity waves have already been extracted from time series of OH rotational temperatures which can be derived from airglow emission spectra (e.g. Scheer, 1987; Takahashi et al., 1999; Schmidt et al., 2013; Wüst et al., 2016).

In order to deduce horizontal information of atmospheric waves, infrared camera systems have come up as a highly promising remote sensing technique (see e.g. Peterson and Kieffaber, 1973; Herse et al., 1989; Moreels et al., 2008) as they allow obtaining images of atmospheric waves. Gravity wave activity at airglow altitude of the entire night sky can be imaged using all sky lenses (Taylor et al., 1997; Smith et al., 2009 and many others). Another application for airglow imagers is the investigation of small scale gravity wave structures, such as acoustic-gravity waves (e.g. Nakamura et al., 1999) or instability features (Hecht et al., 2014). A high spatio-temporal resolution is required for this purpose, which is achieved at the expense of the aperture angles of the imager. However, theoretical calculations especially in the spatial regime below 1 km are hardly supported by experimental observations yet, since a better spatial resolution than 500 m is needed to image structures on these scales (Hecht et al., 2014).

As it has been reported by (Hannawald et al., 2016), the infrared imaging system FAIM (Fast Airglow Imager) is currently being operated by the German Aerospace Center (DLR) in order to continuously observe gravity waves in the OH airglow each night with a temporal resolution of 0.5 s. Obtaining a mean spatial resolution of 200 m, small scale gravity wave



structures with a wavelength down to 2 km have already been discovered. Such instruments are currently operated at the
Sonnblick Observatory (47.05° N, 12.97° E) in Austria (FAIM 1) as well as at Oberpfaffenhofen (48.09° N, 11.28° E),
Germany (FAIM 4) for routine observations within the international Network for the Detection of Mesospheric Chance
(NDMC, <http://wdc.dlr.de/ndmc>). A third system of this kind, FAIM 2, is installed for air-craft based observations on the
75 DLR research aircraft FALCON.

In order to investigate even smaller scale gravity wave signatures and turbulent features within the inertial subrange at
mesopause heights a further developed FAIM system, FAIM 3, with a considerably improved spatial resolution is presented
in this paper.

2 Instrumentation

80 FAIM 3 is the second version of the already mentioned Fast Airglow Imagers established at DLR (Hannawald et al., 2016).
It is based on the SWIR camera CHEETAH CL developed by Xenics nv. Its 640 x 512 pixels InGaAs sensor array with a
pixel size of 20 μm x 20 μm is sensitive to the spectral range from 0.9 to 1.7 μm. The raw signal is converted into a 14 bit
digital stream, which is sent to a frame grabber via CameraLink. The sensor is thermoelectrically cooled down to an
operational temperature of 233 K. The dissipated heat is carried away by a closed circuit water cooling system. A schematic
85 drawing of the entire setup is shown in Figure 1.

All measurements presented here are performed at DLR at Oberpfaffenhofen (48.09° N, 11.28° E), Southern Germany. A
100 mm SWIR lens by Edmund Optics® is used. Its aperture angles have been determined to be 7.3° in horizontal direction
and 5.9° in vertical direction. In the first measurement configuration the camera was mounted on a fixed stage with a zenith
angle of 46°. Simple geometric considerations reveal that, using the above mentioned lens, the observed area corresponds to
90 a trapezium-shaped region of the airglow layer, with the height of the trapezium being 18.6 km and a width of 15.2 km to
16.9 km (see (Hannawald et al., 2016) for details of the calculation). We note that the curvature of the Earth has been
neglected within these considerations. Thus, horizontally an area of about 299 km² is observed with a mean spatial resolution
of 30 m. The camera is adjusted to an azimuth angle of 214°. In order to record a sufficiently strong airglow signal the
integration time of the camera is set to 2.5 s. The instrument in this configuration has been in operation from 18th to 30th



95 November 2015, corresponding to 12 measured nights. The data of the first shown case study was measured with this configuration.

In a second measurement configuration the FAIM 3 zenith angle is adjusted to 0° . Still using the 100 mm lens, a 11.1 km x 9.0 km rectangular area of the airglow layer is acquired. This leads to a mean spatial resolution of 17 m. The integration time has to be raised to 2.8 s since the airglow intensity decreases with decreasing zenith angle due to the van-Rhijn effect (van
100 Rhijn, 1921).

A flat field correction is applied in order to remove the fixed pattern noise and the vignetting of the acquired images.

As outlined above the section of the sky observed by the FAIM 3 instrument in zenith position is limited to an area of about 100 km². In order to better judge on the overall dynamical situation we operated the FAIM 3 zenith measurements simultaneously with the FAIM 4 instrument where FAIM 4 was allowed to sense the overall sky. The temporal resolution of
105 FAIM 4 in this case was 1.5 s while the horizontal resolution is roughly 400 m within the image centre.

3 Data Analysis

The horizontal wavelengths of gravity waves in an image can for example be estimated by analysing the data series of the pixel intensities along a cross section perpendicular to the wave fronts. The distortion resulting from the abovementioned trapezium-shaped FOV projected onto rectangular images has to be corrected prior to analysis, so that an equidistant metric
110 scale is provided. The images are mirrored and rotated into the proper azimuthal direction, so that they can be rendered true to scale onto a map (see Figure 2). This correction is performed using the same algorithm as described in (Hannawald et al., 2016). As a typical example, Figure 2a-f shows a sequence of such images taken on 18th November 2015, between 22:59:55 and 23:04:11 UTC.

In the image a wavelike structure reveals as more or less periodic brightness variations. This brightness variation clearly
115 appears in the series of pixel intensities along a direction perpendicular to the wave fronts in the image, as it is shown in Figure 3. Spectral analysis of the data series allows deducing the horizontal wavelengths. Since in our case the observed gravity waves are localized within a comparatively small area of the FOV and exhibit wavelengths of relatively small scales, the data series of pixel intensities extend over less than a hundred data points. Considering also the pronounced noise level,



the Maximum Entropy Method (MEM) turned out to be a powerful technique to estimate the spectral density of the data sets
120 (Ulrych and Bishop, 1975), even if the data series is so short. As an example, Figure 4 shows the MEM spectrum of the data
series shown in Figure 3.

The MEM provides an approach for estimating the spectral density of a time series with a high frequency resolution (e.g.
Bittner et al., 1994). While other methods like the wavelet analysis try to fit a predefined function to the data, the MEM does
not claim any assumptions about the theoretical shape of the signal but to be a stationary Gaussian process. According to
125 (Jaynes, 1963) the most probable of all possible spectra describing a dataset is the one which makes the least assumptions
about the information the data contain. This corresponds to the state of maximum entropy. The MEM derives the most
probable spectrum of a time series by fitting an autoregressive model (AR) of order N to the data. The AR coefficients are
determined using Burg's algorithm, which calculates them based on forward and backward predictions of the data. The
major issue of the MEM is to find the right order N of the underlying AR process. If the order is chosen too small several
130 frequency peaks may not be resolved, whereas an overestimated order will lead to further splitting of the peaks into spurious
subpeaks due to noise approximation (e.g. Wüst and Bittner, 2006).

4 Results

During the night from 18th to 19th November 2015 observations were performed at a zenith angle of 46° , leading to a
spatial resolution of approximately 30 m. In order to demonstrate the performance of the instrument, one interesting gravity
135 wave event, registered between 22:59:25 and 23:04:33 UTC, is presented. The relevant period is shown in parts by a series
of six images in Figure 2a–f and in its entirety in Video 1 in the supplemental material. First order difference images (that
means the temporal derivation of the original signal, here $\Delta t = 7.5$ s) are shown here to help better visualize wave structures.
The difference of two images acts as a high pass filter, suppressing long-period oscillations and highlighting the regions with
varying intensity between the two images. However, the original data is used, of course, for spectral analysis in order to
140 retrieve the correct spatial content. It is interesting to note that obviously a smaller scale wave packet is propagating from the
left corner of the FOV (West) to the right corner (East). The packet, which is marked by white circles in Figures 2a–e,
moves in the same direction as a second, larger wave structure but its wave fronts are tilted against each other horizontally



by an angle of about 45° . The larger wave structure extends nearly over the entire image from the lower left to the upper right corner of Figures 2a–f and the quite limited horizontal width of the wave fronts makes the wave appear to be trapped
145 in a narrow corridor in the airglow layer. Having nearly completely passed through the FOV the wave packet seems to decompose into some disordered features as time proceeds and is no longer visible in Figure 2f. This is best recognizable at the end of Video 1, starting at 23:03:20. Figure 3 shows in black the pixel intensities along a cross section perpendicular to the wave fronts of the small wave packet in the image acquired at 23:00:42 UTC (the position of the cross section is given in Figure 2b). Visual inspection of the image series and the cross section shows that the wavelength of the wave packet is about
150 half a kilometre. The wavelength of the larger wave structure can be visually estimated as about 1.7 km. For a more detailed analysis of the smaller structure the MEM is applied to the data series of Figure 3. An order of 20 is chosen as this corresponds to one third of the number of data points, which has turned out to be a good choice for analysing short data series with less than 100 values (Bittner et al., 1994). The MEM spectrum in Figure 4 exhibits a strong peak at about 550 m. It is clearly above the 99% level of statistical significance and fits to the small scale wave packet discovered in the images as
155 already mentioned above. It is interesting to note that the MEM spectrum also reveals four other significant peaks at wavelengths well below 200 m, which can also be found in the signal of Figure 3. In the following we will focus on the 550 m wave structure, as it is clearly recognizable in Video 1.

It can be seen in the image series that the 550 m wave signal is visible in the examined cross section from 23:00:17 to 23:00:55 UTC. In a next step the same cross section as above is analysed for each image to derive some insight about the
160 spatio-temporal evolution of the structure. Figure 5 shows the temporal development of the MEM spectrum. The order has been raised to 36 ensuring that signatures of wavelengths below 1 km are fully resolved. A stable maximum in the spectrogram (Figure 5) around a horizontal wavelength at about 550 m is obviously present over almost the entire time range. Another interesting event was observed during the night from 4th to 5th April 2016. The images (see Figures 6a–f) have been acquired at zenith position, ensuring a spatial resolution of about 17 m. The dimensions of each image are
165 approximately 11.1 km x 9.0 km. The zenith images show the sky as it is seen from the ground looking upwards. The upper image side corresponds to an azimuthal direction of 303° . Video 2 shows the entire event. A wave front, indicated by the dashed red line to guide the eye in Figure 6a, enters the FOV in the upper right corner. The straight red arrow shows the



direction of propagation. A new structure develops at 03:17:48 UTC (Figure 6b), marked by the ellipse in the upper right corner. At 03:18:27 UTC (Figure 6c) some filament-like structures of different velocities arise in the area of the dashed orange box. Video 2 shows what is hardly recognizable in the displayed snapshots of Figure 6: the filaments start forming a vortex structure (emphasized by the curved yellow arrows at 03:19:01 UTC, Figure 6d), which still moves in the direction of the straight red arrow. At 03:19:49 UTC (Figure 6e) the vortex structure begins to decompose into some disorganized features while the remaining structure continues following the initial direction (straight red arrows).

To put the observations into a larger spatial context, the FAIM 3 data are compared to simultaneous all sky measurements taken by the FAIM 4 instrument. Since the two cameras are deployed next to each other, the FOV of FAIM 3 is embedded in the centre of the FOV of FAIM 4 with a tilt of 19° . The FAIM 4 measurements are presented in Video 3. A snapshot is given in Figure 7. Besides the normal image (Figure 7a), the difference image (time difference of 60s) is displayed on the right side (Figure 7b). The approximate FOV of FAIM 3 is indicated by the green boxes in Video 3 and the white boxes in Figure 7. The all sky images reveal a clear and starry sky with high gravity wave activity, which can be determined on the basis of the characteristic patchy structures. The remarkable structure observed by FAIM 3 can be found again in Video 3 as a bright feature within the green box, propagating towards its lower left corner. It can be well recognized in the screenshot of Figure 7.

5 Discussion

The first of the two case studies presented here shows a wave packet with a horizontal wavelength of about 550m moving in the same direction as a 1.7km wave with the wave fronts being tilted about 45° against the other structure. We therefore tentatively interpret the wave packet as a ripple structure; see e.g. (Peterson, 1979). Ripples are spatially limited wave structures with a short life time (Adams et al., 1988) and are caused by atmospheric instabilities (Taylor and Hapgood, 1990). As the 550m wave packet does not form within the FOV, its lifetime cannot be estimated from our data. However, the appearance and disappearance of the 1.7km wave is located within the FOV, which allows estimating its lifetime to about 16min if our speculation holds. According to (Taylor and Hapgood, 1990) this feature can also be referred to as a ripple structure. The fact that the spatial extent of the wave fronts perpendicular to the direction motion is much smaller than



the extent of the wave packet in propagation direction is unusual (ratio approximately 1:6). Obviously, it cannot be described as a plane wave (of infinite extent), it may rather be trapped in a duct or the entire pattern, which appears to be a wave structure, may indeed be an instability feature itself, which is not unlikely given the small dimension with an apparent
195 wavelength of 1.7 km. It may be consequently speculated that the 1.7 km wave itself is a possible instability feature of a larger scale wave with a horizontal wavelength of several kilometres and decays into the 550 m wave packet as a subordinate instability structure. Such dynamics have already been observed on larger scales in (Hecht et al., 2014). Assuming the same scenario here, the ratio of primary to secondary wavelength is about 3.1. This number agrees quite well with earlier KHI models (Klaassen and Peltier, 1991). As described in section 1, KHIs are instabilities caused by wind shear. This could be a
200 possible explanation for the tilt of the wave fronts.

At around 23:03:30 UTC the 550 m wave packet starts to collapse into some disordered features, which we tentatively assign to turbulence. Following the considerations of (Hocking, 1985), observations on that scale are already situated in the inertial subrange at airglow altitudes. Similar turbulent-looking features resulting of atmospheric instabilities have been found in the measurements of (Hecht et al., 2014) in the buoyancy regime. Related Direct Numerical Simulations (DNS) (see Fritts et al.
205 2014) to that data have already predicted secondary instability features below 1 km, which had not been able to observe with an airglow imager so far. However, it must be stressed that these interpretations remain speculative at this stage as the focus of this paper is to demonstrate the performance of the FAIM 3 instrument in order to resolve smaller spatio-temporal scale dynamics in the mesopause altitude region. Alternatively, the periodic structures could simply be remarkably small scale gravity waves with wavelengths of 1.7 km and 550 m as well, without being results of atmospheric instability. As a possible
210 explanation for the narrow shape of the greater wave horizontal winds could then be considered to forbid wave propagation in the respective areas.

The second interesting event detected by FAIM 3 is a vortex-shaped structure, which develops out of filament-like features within a wave front and continues propagating in the initial direction before decaying into some disordered features. The formation of filament-like structures developing different velocities can possibly be led back to local instabilities of the
215 atmosphere due to wind shear. The filament structure decays into disorganized features, which resembles the turbulent collapse of the wave packet on 18th November 2015. Other airglow observations exhibit similar-looking breakdown events



of gravity wave fronts, like in (Hecht et al., 2014). The effects of KHI dynamics in the airglow layer have been modelled using DNSs and large eddy simulations in (Fritts et al. 2014). The vortex structure as well as the filament features turns out to be a typical manifestation of turbulence due to KHIs. The high gravity wave activity of the overall night sky, revealed by
220 FAIM 4 all sky measurements at the same time, possibly contributes to atmospheric instability by influencing the lapse rate. The aforementioned wave front is also visible in the all sky images. A close inspection of Video 3 shows that even with this system's coarse resolution indications for the separation of parts from the bright crest can be identified, which agrees with the turbulent looking decomposition of the wave crest found in the FAIM 3 measurements.

6 Summary and Conclusions

225 In order to observe smaller scale gravity wave events and instabilities or turbulence features in the metre regime, the established airglow imaging system FAIM (Hannawald et al., 2016) has been improved with regard to spatial resolution, using an InGaAs sensor array with the fourfold number of pixels (327680) and a 100mm SWIR lens manufactured by Edmund Optics[®]. The mean spatial resolution of 200m at a 45° zenith angle and 120m at zenith position achieved by the established FAIM system has been increased to 30m and 17m respectively. The observed scales are thus well within the
230 inertial subrange regime of turbulence at airglow altitudes. Measurements have been taken at Oberpfaffenhofen (48.09° N, 11.28° E), Southern Germany at a zenith angle of 46° and an azimuth angle of 214° as well as in zenith position.

Two case studies are presented. On 18th November 2015 from 22:59:25 to 23:04:33 UTC a wavelike structure with a wavelength of 1.7km and a smaller feature with a wavelength of 550m propagate in the same direction. Their wave fronts are tilted against each other by an angle of approximately 45°. The 1.7km wave is estimated having a lifetime of about
235 16 min, which leads to the presumption that it might be an instability feature of a larger gravity wave with a wavelength of several kilometres which cannot be seen in our small FOV. Following this hypothesis, the 550m structure could be the resulting subsequent instability feature. Another possibility is that the 550m wave packet could be the primary instability feature caused by a small 1.7km gravity wave. Both cases agree with the theory of turbulence: when atmospheric instabilities lead to the breakdown of waves, their transported energy is cascaded to smaller scale structures in the inertial



240 subrange. These considerations combined with the ratio of the wavelengths, which fits to values of earlier theoretical studies like (Klaassen and Peltier, 1991), suggest that the event of 18th November 2015 could be triggered by KHIs.

Zenith measurements on 5th April 2016 from 03:15:58 to 03:27:46 UTC exhibit the breakdown of a wave front into a vortex structure and the subsequent decay into disorganized features, probably due to turbulence. Characteristic dynamics of filament-like features indicate that instability could be generated by wind shear. The observations look similar to modellings
245 of KHI development and the consecutive turbulence dynamics of waves in the airglow layer (Fritts et al., 2014). Comparisons with parallel measurements of FAIM 4 obtaining all sky images reveal the high gravity wave activity all over the sky at that time, which might have contributed to increased atmospheric instability.

It has been demonstrated that FAIM 3 is able to image the dynamics of gravity waves on scales significantly below 1 km. This can provide experimental insight into processes like turbulent breakdown of waves or generation of smaller scale wave
250 structures due to atmospheric instabilities. FAIM 3 observations support earlier simulations of instability dynamics as presented in (Fritts et al., 2014). Apart from that, FAIM 3 is an ideal addition to all sky imagers, since it provides the opportunity to closer investigate specific airglow structures with a much higher spatial resolution, as it is demonstrated in the second case study in this paper.

Operational zenith measurements with a mean spatial resolution of 17 m and a temporal resolution of 2.8 s are being
255 performed automatically every night since 22th February 2016 at Oberpfaffenhofen, Germany. The data is archived at the WDC-RSAT (World Data Centre for Remote Sensing of the Atmosphere, <http://wdc.dlr.de>). FAIM 3 is part of the Network for the Detection of Mesospheric Change, NDMC (<http://wdc.dlr.de/ndmc>).

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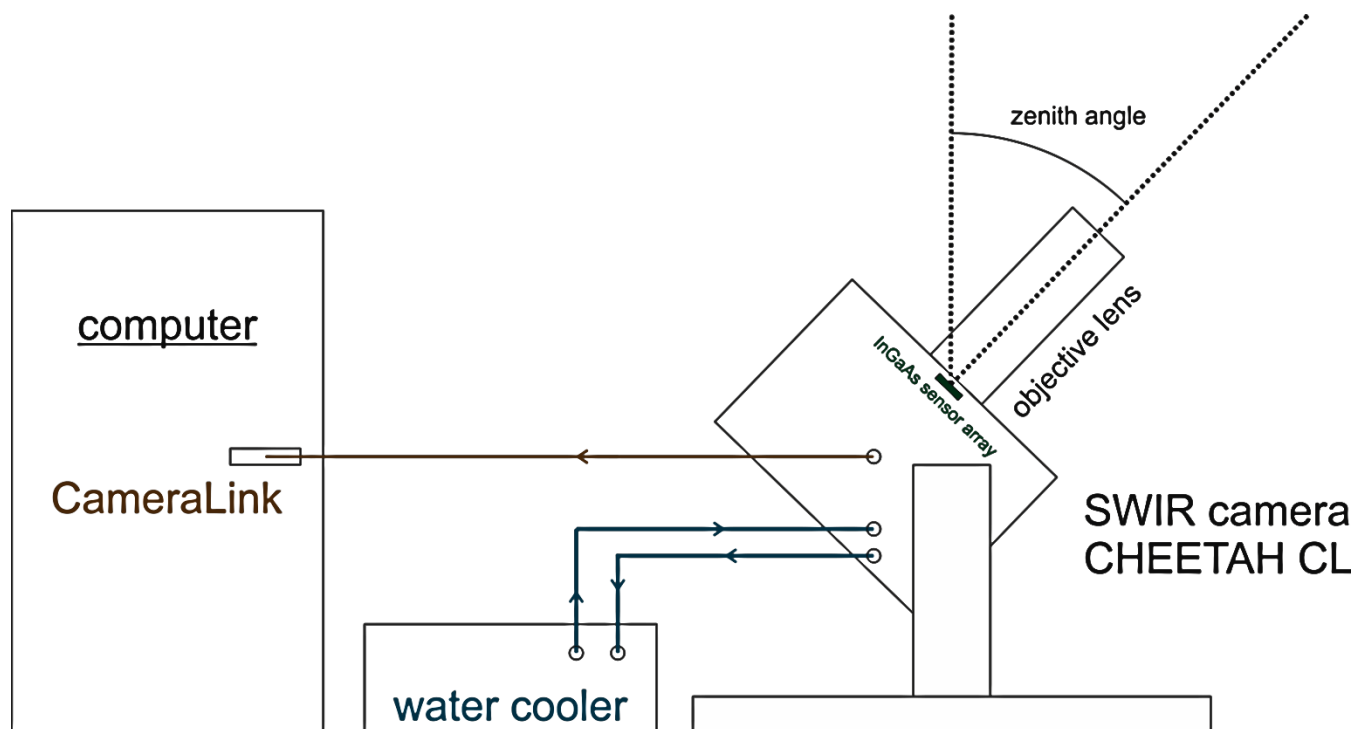
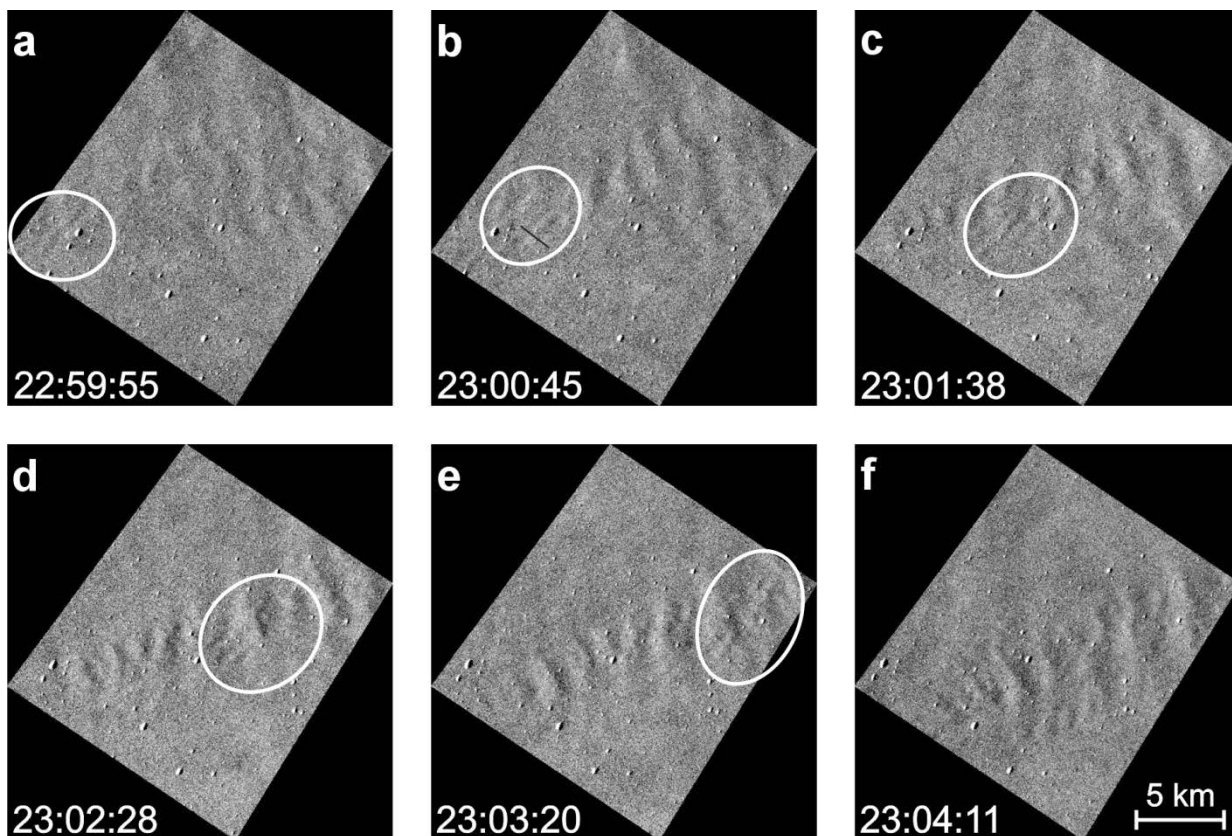


Figure 1. Schematic drawing of the FAIM 3 setup. The measurement configuration with a zenith angle of 46° is shown here.



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Figure 2. Image series of the case study of 18th November 2015 between 22:59:55 and 23:04:11 UTC. Difference images have been chosen for presentation purposes. The images are aligned to the North. The 1.7 km wave structure extends from the western to the eastern corner with several crests being arranged in a narrow corridor. The 550 m wave packet is framed in a white ellipse (images a - e). One may perceive the beginning decay at 23:03:20. The entire sequence is shown in Video 1. The black line, which is shown in image b, indicates the cross section along which the spectral analysis is performed in Figure 3 and 4.

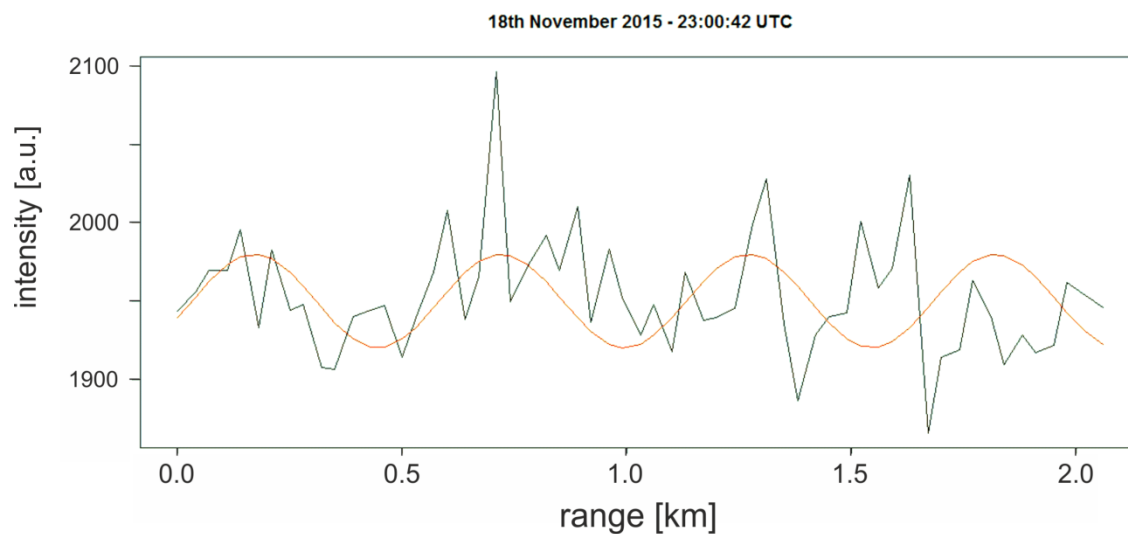
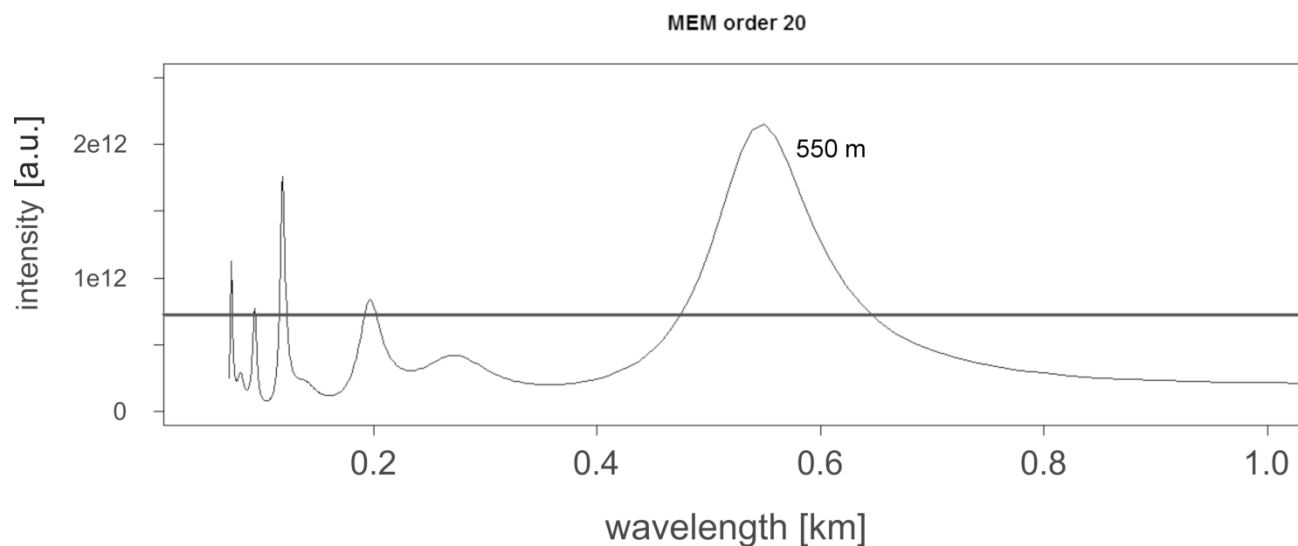
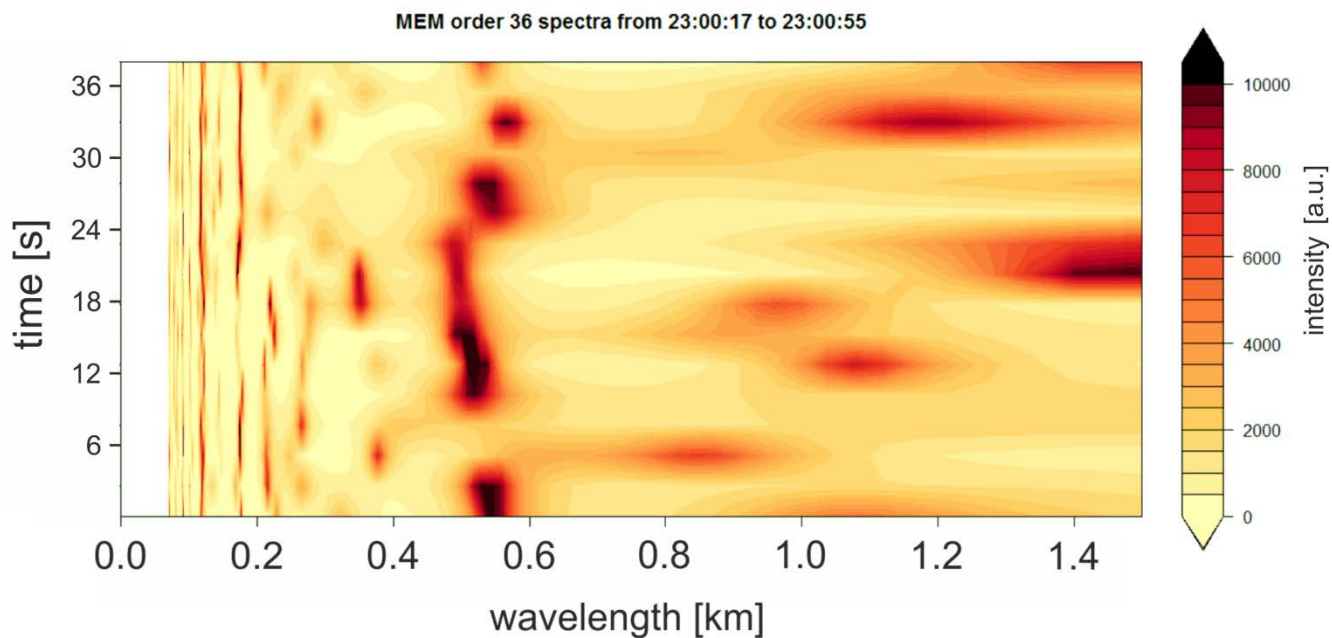


Figure 3. Measured intensities along a cross section perpendicular to the wavefronts (its position is indicated by the black line in Figure 2b) in the image of 18th November 2015, 23:00:42 UTC. The pixel range has been converted into kilometres. The orange line shows an ideal 550 m wave (fitted by hand). Only the first half of the data series shows this signal, too.

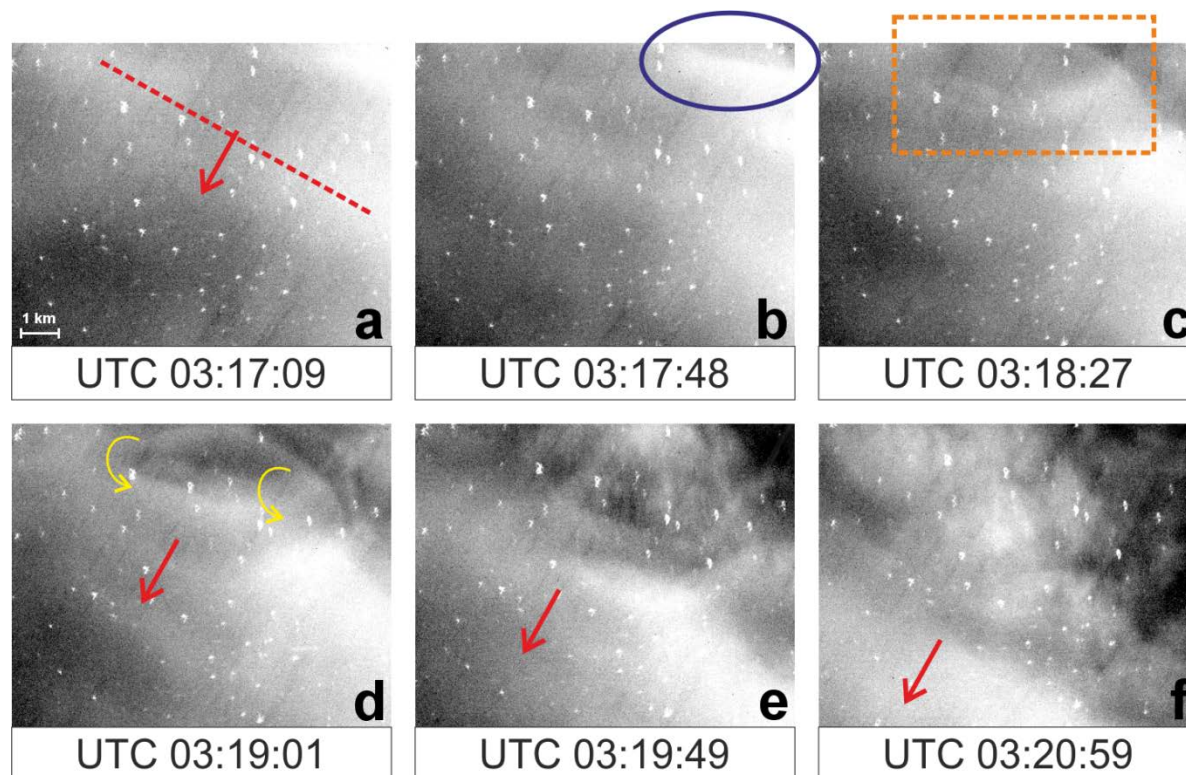


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Figure 4. MEM spectrum (order 20) of the data series shown in Figure 3. The horizontal line marks the 99 % level of significance. The peak of the 550 m wave packet is clearly recognizable.

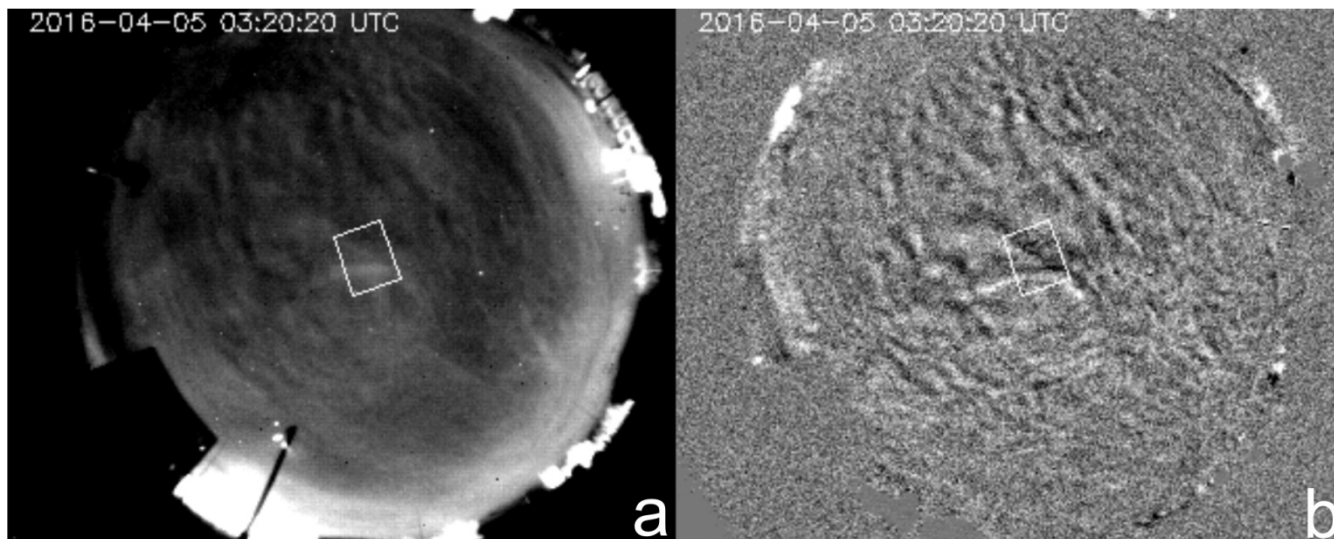


350 **Figure 5. MEM spectra of order 36 of pixel intensities along the abovementioned cross section (its position is indicated by the black line in Figure 2b) in every image taken between 23:00:17 and 23:00:55 UTC. The signature of the 550 m wave packet is found by the MEM nearly the entire period.**



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Figure 6. Image series of the second case study (5th April 2016 between 03:17:09 and 03:20:59 UTC). A wave front, indicated by the dashed red line, propagates into the direction of the straight red arrow (image a). At 03:17:48 UTC a new structure begins to develop in the elliptically shaped area (image b). Filament-like features arise (dashed orange box in image c) and form a vortex-like structure (curved yellow arrows in image d), which continues propagating into the direction of the initial wave front. The last two images show how the vortex structure decays into disorganized features while the remaining part of the wave front still follows the direction indicated by the straight red arrows (images e and f). The entire sequence is shown in Video 2.



360 **Figure 7.** FAIM 4 all sky image taken on 5th April 2016 at 03:20:20 UTC (left) and respective difference image with a time difference of 60s (right). The entire sequence is shown in Video 3. The FOV of FAIM 3 is indicated by the white box in the image centres. Due to their spatial structure and their wavelength, we interpret the patchy structures in the starry sky as gravity wave fronts in the airglow layer. The bright feature in the white box probably corresponds to the wave crest that propagates through the FAIM 3 image series at that time (see Video 2 and Figure 6).

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