Observations of the downwelling far-infrared atmospheric emission at the Zugspitze observatory

Luca Palchetti[1], Marco Barucci[1], Claudio Belotti[1], Giovanni Bianchini[1], Bertrand Cluzet[4],
Francesco D'Amato[1], Samuele Del Bianco[5], Gianluca Di Natale[1], Marco Gai[5], Dina Khordakova[3],
Alessio Montori[1], Hilke Oetjen[7], Markus Rettinger[2], Christian Rolf[3], Dirk Schuettemeyer[7],
Ralf Sussmann[2], Silvia Viciani[1], Hannes Vogelmann[2], and Frank Gunther Wienhold[6]

[1]National Institute of Optics - CNR, Florence, Italy
[2]Karlsruhe Institute of Technology, IMK-IFU, Garmisch-Partenkirchen, Germany
[3]Forschungszentrum Jülich, Germany
[4]Univ. Grenoble Alpes, Université de Toulouse, Météo-France, CNRS, Centre d'Études de la Neige, Grenoble, France
[5]Institute of Applied Physics - CNR, Florence, Italy
[6]Institute for Atmospheric and Climate Science - ETH, Zürich, Switzerland
[7]ESA/ESTEC, Noordwijk, Netherlands

Correspondence: Luca Palchetti, (luca.palchetti@cnr.it)

Abstract.

Measurements of the spectrum of the atmospheric emission in the far-infrared (FIR) range, between 100 and 667 cm^{-1} (100–15 μm), are scarce because of the detection complexity and of the strong absorption of air at ground level, preventing the sounding of the FIR from low altitude. Consequently, FIR measurements need to be made from high-altitude sites or on

5   board airborne platforms or satellites. This paper describes the dataset of FIR spectral radiances of the atmosphere and snow surface emission, measured in the 100–1000 cm^{-1} range by the Far-Infrared Radiation Mobile Observation System (FIR-MOS) instrument, during a 2-month campaign carried out from ground at 3000 m of altitude, on the top of Mount Zugspitze in the German Alps, in 2018-2019. This campaign is part of the preparatory activity of a new space FIR mission, named Far-infrared-Outgoing-Radiation Understanding and Monitoring (FORUM), which is under development by the European Space

10   Agency (ESA). The dataset acquired during the campaign also includes all the additional measurements needed to provide a full characterisation of the observed atmospheric state and the local atmospheric and surface conditions. It includes co-located spectral measurements in the infrared range from 400 to 1800 cm^{-1}; lidar backscatter profiles; radiosoundings of temperature, humidity and aerosol backscatter profiles; local weather parameters; and snow/ice microphysical properties. These measurements provide a unique dataset that can be used to perform radiative closure experiments to improve modelling parameters

15   that in the FIR are not well characterised, such as water vapour spectroscopy, scattering properties of cirrus clouds and the FIR emissivity of the surface covered by snow. The consolidated dataset is freely available via the ESA campaign dataset website at https://doi.org/10.5270/ESA-38034ee (Palchetti et al., 2020a).

For the review process, the dataset is also available at https://fts.fi.ino.it/forum/firmos/zugspitze-dataset/

1 Introduction

20 The Far-InfraRed (FIR) is defined here as the longest wavelength region of the infrared spectrum covering the wavenumber range from 667 cm^{-1} (or equivalently 15 μm wavelength) down to 100 cm^{-1} (100 μm). The FIR contains more than 50% of the energy emitted by the Earth toward the space and it is modulated by the properties of the most relevant components of the climate system, such as water vapour, carbon dioxide, clouds, and snow surface emissivity (Harries et al., 2008). The characterisation of the FIR radiative properties of these components is therefore essential to improve FIR modelling of spectroscopy

25 (Mlawer et al., 2019), cirrus cloud radiative properties (Cox et al., 2010) and surface emissivity (Chen et al., 2014), which in turn will allow to better understand the Earth radiation budget and to reduce uncertainties in climate models (Huang et al., 2018; Baran et al., 2014; Huang et al., 2007). Nevertheless, due to technical challenges, systematic and global measurements of the FIR from space are still missing, and are scarce from ground and airborne platforms.

To fill this observational gap, a space mission, named Far-infrared-Outgoing-Radiation Understanding and Monitoring (FO-

30 RUM) (Palchetti et al., 2020b), is under development by the European Space Agency (ESA) as the ninth Earth Explorer mission to be launched in 2026 (https://www.forum-ee9.eu/). This mission will measure with high accuracy the spectrum of the outgoing infrared radiation from 100 to 1600 cm^{-1} (100–6.25 μm) covering, for the first time with high spectral resolution, the FIR portion of the spectrum. In preparation to this mission, an instrument demonstrator, named Far-Infrared Radiation Mobile Observation System (FIRMOS), was developed for field applications from ground-based (and in perspective airborne) platforms

35 to verify with real measurements the sounding capability provided by FIR observations.

At ground level the atmosphere in the FIR spectral region is very opaque because of the high concentration of water vapour. For this reason, sounding of the FIR with ground-based observations is possible only from high altitude sites where the water vapour content is sufficiently low to make the atmosphere transparent at frequencies below 667 cm^{-1}. This requires the deployment of FIR instrumentation on high mountain sites, around 3000 m asl or at higher altitude (Palchetti et al., 2015;

40 Mlynczak et al., 2016; Turner et al., 2012). Observations during the winter-time are preferred in order to have the water vapour content at its seasonal minimum, thus improving the capability to sound down to the lowest spectral region close to 250 cm^{-1}. The sounding of the wavenumber region of the FIR, below 250 cm^{-1}, is only possible from airborne platforms, high-altitude aircraft (Cox et al., 2007) or balloons (Mlynczak et al., 2006; Palchetti et al., 2006), flying in the upper troposphere or the lower stratosphere.

45 In this paper, we describe the measurements acquired during the first field deployment of FIRMOS, between the end of 2018 and the beginning of 2019 at the Alpine observatory of Mt. Zugspitze in the South of Germany at about 3000 m altitude, together with all the ancillary measurements needed to provide a complete characterisation of the observed atmospheric and surface states.

2 Zugspitze Observatory

50 The Zugspitze site was chosen because of the very dry atmospheric conditions, frequently encountered at the Summit Observatory, with values of the integrated water vapour (IWV) as low as 0.1 mm and median of 2.3 mm (see more details in Sussmann

et al., 2016). The minimum IWV is approximately a factor of 40 lower than at typical lowland mid-latitude sites. In this respect the Zugspitze is comparable to the driest sites in the world, i.e. remote locations like the Atacama desert or polar stations. In spite of that, the Zugspitze Observatory is reachable via cable car within 10 minutes from a car park and offered a suitable

55 infrastructure for the deployment of FIRMOS due to the presence of a complementary and comprehensive set of instruments. This provided independent information of the observed atmospheric and cloud states to be used as reference for the comparison with FIRMOS. The Zugspitze Observatory comprises two stations, the Summit station (47.421° N, 10.986° E, 2962 m asl) and the Environmental Research Station Schneefernerhaus (47.417° N, 10.980° E, 2675 m asl), which is located on the south slope of mountain, 300 m below and 680 m southwest from the Summit (see Fig. 1).

60 ## 3 Instrument description and performed measurements

During the campaign, measurements were carried out using instruments deployed at the Zugspitze Summit, at the Schneefernerhaus station, and at the Karlsruhe Institute of Technology (KIT) in Garmisch-Partenkirchen.

The emission spectrum was measured in the FIR with FIRMOS, which was developed at CNR-INO with the support of ESA, and installed in November 2018 on the terrace of the Summit station. The instrument is a Fourier Transform Spec-

65 trometer (FTS) designed on the base of the heritage of a similar instrument, named Radiation Explorer in the Far InfraRed – Prototype for Applications and Development (REFIR-PAD) (Bianchini et al., 2019), permanently installed in Antarctica since 2012 (Palchetti et al., 2015). The FTS consists in an interferometric layout with double-input and double-output ports in a Mach-Zehnder configuration, which increases the measurement reliability and the calibration precision (Carli et al., 1999). The instrument is able to cover the FIR radiation using wideband germanium-coated biaxially-oriented polyethylene tereph-

70 thalate beam-splitters and room-temperature pyroelectric detectors. It was mounted within a plastic box to protect optics and electronics from environmental conditions, such as wind and snowfall, when installed on the site.

At the Summit station, KIT operates an Extended-range Atmospheric Emitted Radiance Interferometer (E-AERI) system (Sussmann et al., 2016), manufactured by ABB Bomem Inc. (Quebec, Canada), which covers part of the far, mid and near infrared spectral regions. The spectrum of the Downwelling Longwave Radiation (DLR) was therefore measured in the FIR

75 and mid-infrared spectral ranges from 100 to 1800 cm^{-1} (100–3.3 μm) using both FIRMOS, covering the 100–1000 cm^{-1} spectral range with 0.3 cm^{-1} of resolution, and the E-AERI, covering the 400–1800 cm^{-1} range with 0.5 cm^{-1} of resolution. Fig. 2 shows FIRMOS installation close to the E-AERI instrument, which is permanently installed on the top of the shelter, 4 m above FIRMOS, and routinely performs measurements of spectral DLR, when the weather conditions allow the operation. An example of spectral measurements of the DLR performed simultaneously from FIRMOS and E-AERI is also shown in the

80 figure.

KIT also operates two lidar systems for aerosols/clouds (Vogelmann and Trickl, 2008), and water vapour and temperature (Klanner et al., 2020) profiling, installed at the Schneefernerhaus station. The advantage of mounting the lidar systems at Schneefernerhaus and the spectrometer at the Summit is that the onset of the measured lidar profiles is typically about 300 m above the laser, which coincides with the location of the spectrometers at the Summit. Cirrus cloud properties are detected

85 with the stratospheric aerosol lidar, which is a pure backscatter lidar operating at the wavelength of 532 nm. This system was operated in a semi-automatic mode, with a sequence of one profile every 4 or 10 minutes and an integration time of 1 min. Water vapour and temperature profiles were measured alternatively with a Raman lidar system using a XeCl-Laser at 308 nm for water vapour and with a Nd:YAG laser at 355 nm for temperature. The latter measurements were carried out manually in order to switch between one laser and the other. Water vapour profiles were recorded with 1 million laser shots, an integration

90 time of 1 hour and a vertical resolution of 30 m near ground (4 km asl) and 250 m at 15 km asl. Temperature profiles were derived from density profiles measured only in absolute clear-sky conditions with an integration time of typically 1 hour and a vertical resolution of 30 m near ground (4 km asl) and 2 km at 80 km asl. The lidar in operation at night and an example of measurements are shown in Fig. 3.

Specific balloon radiosoundings (Klanner et al., 2020) for in-situ water vapour profiles and cirrus cloud microphysics were

95 performed on two days (5–6 February 2019) under clear sky and thin cirrus cloud conditions during night time (Fig. 4). The antenna for communication with the balloon was built up on the Summit station and the preparation of the sonde payload and launch took place at KIT Campus Alpin, in Garmisch-Partenkirchen (47.476° N, 11.062° E, 730 m asl) about 8 km North-East of Mt. Zugspitze. The balloon sondes are equipped with a standard radiosonde (Vaisala RS41-SGP), a Cryogenic Frostpoint Hygrometer (CFH) for measuring water vapour profiles with high accuracy, an ozone sonde, and the Compact Op-

100 tical Backscatter Aerosol Detector (COBALD) (Brabec et al., 2012), developed at the Swiss Federal Institute of Technology in Zürich, that provides backscatter profiles at two wavelengths (455 nm and 940 nm) and color index within the cloud layers. The combined balloon payload is well tested and also regularly used by the Global Climate Observing System (GCOS) Reference Upper Air Network (GRUAN) (see e.g. Dirksen et al., 2014). The CFH has an uncertainty of about 2–3% in the troposphere and less than 10 % in the lower stratosphere. The CFH is especially suitable for measuring water vapour under the dry conditions

105 at the tropopause and in the stratosphere up to altitudes of 28 km. The accuracy of the backscatter ratio after post processing the COBALD raw data is better than 5 %, while the precision is smaller than 1 % in the upper troposphere / lower stratosphere (Vernier et al., 2015).

The Summit station is served with standard Pressure, Temperature, Relative Humidity (RH), and Wind (PTHW) meteo observations, provided by Deutscher Wetterdienst (DWD) at the website

110 https://opendata.dwd.de/climate_environment/CDC/observations_germany/climate/, that for completeness were also included in the available dataset for the period covered by the field campaign. Useful standard atmospheric soundings with operational radiosondes available near Zugspitze can be freely downloaded via the University of Wyoming website (http://weather.uwyo.edu/upperair/sounding.html) for the station of Muenchen-Oberschlssheim (Station No. 10868, daily soundings at 00 and 12 UTC), 100 km North the Summit, and the Innsbruck-Flughafen station (Station No. 11120, daily soundings

115 at 03 UTC), 33 km South-East.

Finally, the properties of snow samples were characterised in terms of snow grain type, density ($\mathrm{kg\ m^{-3}}$) and Specific Surface Area (SSA, $\mathrm{m^2\ kg^{-1}}$), using the DUal Frequency Integrating Sphere for Snow SSA measurement (DUFISSS) sensor, which retrieves the SSA by measuring the reflectance at 1310 nm (Gallet et al., 2009).

4 Field campaign

120 The aim of the Zugspitze field campaign was to collect FIR measurements of the DLR to be used to provide evidence of the FIR capability to retrieve vertical profiles of water vapour and temperature and cirrus cloud properties. as well as to perform a side-by-side validation of FIRMOS measurements with the instrumentation available on the site.

The campaign took place from 29 November to 18 December 2018 and from 21 January to 20 February 2019. Measurements were performed when the weather conditions allowed the operations; this occurred for a total of 33 days. The main

125 specifications of the collected measurements, which are available in the provided dataset, are summarized in Table 1.

During the first part of the campaign in November-December 2018, FIRMOS was installed and made operational. The weather conditions during that period were not very good and only a few days of clear sky for testing acquisitions occurred (only 43 useful sky observations). This first part is considered an engineering campaign for the deployment and preparation of the full suite of instruments. The second part of the campaign was dedicated to the acquisition of the DLR spectra both in clear

130 sky and in cirrus cloud conditions and all the ancillary information provided by lidars and radiosoundings.

Four days at the end of the campaign were finally devoted to measure snow and ice samples with the objective to characterize the FIR spectral emissivity, which is not well-characterized in the FIR range (Huang et al., 2016). We performed systematic snow measurements on 18 and 19 February 2019, FIRMOS was adapted to observe in a slant direction close to nadir (Fig. 5, left). In this way the main contributions to the measured radiance were by the surface emission and by the sky

135 reflection. To attain diversity in the snow properties, 8 samples of snow and 1 sample of ice were collected in the vicinity of the Zugspitze Summit and close to Zugspitzplatt station. One measurement with artificial patterns of surface roughness was also conducted. Each sample was measured by FIRMOS for roughly 90 minutes and successively characterized in terms of its surface properties. Figure 5 (right panel) shows the density and SSA values retrieved on the measured samples.

5 FIRMOS validation

140 The FIRMOS dataset includes calibrated spectra and noise estimates, calculated starting from the FTS acquired interferograms and following the procedure described in Bianchini and Palchetti (2008). Each spectrum is the average of 4 sky observations and it is calibrated with 4 calibration measurements (2 looking at a hot backbody reference source and 2 looking at a cold source). The noise is characterised by a spectrally-uncorrelated component (independent from one spectral channel to the other), called noise equivalent spectral radiance (NESR), due to the detector error, and a spectrally-correlated component,

145 called calibration error (CalErr), due to the temperature uncertainty of the calibration sources. The NESR is obtained from the error propagation through the calibration procedure of the 1σ detector random error, whereas the CalErr is calculated through the error propagation of the temperature accuracy error measured on each reference blackbodies. An example of the FIRMOS products is shown in Figure 6. In the figure, the NESR (red line) is compared with the standard deviation of 4 sky measurements (brown line) measured with constant sky conditions. The good agreement between the two curves gives an

150 assessment of procedure used for the NESR calculation.

FIRMOS spectral measurements were validated against E-AERI in order to qualify FIRMOS with a standard commercial spectrometer in the common spectral region. A measurable error of the spectral frequency scale, due to the uncertainty on the metrology laser, was found on both FIRMOS and E-AERI by fitting the measurements with synthetic spectra. FIRMOS shows a frequency scale error of about +50 ppm between simulations and observations ($\sigma_{real} = (1 + 5 \times 10^{-5}) \times \sigma_{firmos}$), whereas

155   E-AERI has the same error but with different sign (i.e. $\sigma_{real} = (1 - 5 \times 10^{-5}) \times \sigma_{e-aeri}$). The frequency scale of spectra was therefore recalibrated with this correction before the comparison. Only FIRMOS and E-AERI simultaneous measurements acquired within a 10-minutes of temporal distance were considered coincident and selected to calculate the average spectrum for the comparison. Both spectra are resampled at the common spectral resolution of 0.5 cm^{-1} by applying the same apodization function (Norton-Beer strong) (Norton and Beer, 1976, 1977). Figure 7 shows the comparison between the mean spectra of 420

160   simultaneous measurements. A good agreement between the two instruments is found in the common spectral range from 400 to 1000 cm^{-1} with the difference (shown in the bottom panel) that is within the average CalErr estimate, with the exception of few points where strong water vapour and CO_2 lines are present, caused by the different location of the two instruments, and the feature of the beam-splitter absorption around 730 cm^{-1}, which causes on FIRMOS measurements a not compensated phase error.

165   To make another assessment of FIRMOS measurements, an indirect approach was also used by comparing values of IWV retrieved from FIRMOS spectral measurements with the same parameter retrieved from E-AERI measurements. The IWV was calculated using the KIT algorithm that minimises the FIRMOS (or E-AERI) vs. LBLRTM (Line-By-Line Radiative Transfer Model) spectral residuals in the spectral range from 400 to 600 cm^{-1}. While details will be subject of an upcoming publication, we briefly state here that we found only a small overall bias (FIRMOS-AERI) = 0.0002 mm which is negligible compared to

170   the measured atmospheric IWV states, ranging form 0.2 to 2 mm. This proved that there are no indications of significant calibration errors in the FIR spectral domain of the water vapour rotational band.

6   Conclusions

In summary, the unique spectral measurements provided by the combination of FIRMOS and E-AERI covering the relevant spectral region of the thermal emission of the atmosphere from 100 to 1800 cm^{-1}, together with the other supporting lidars,

175   radiosoundings, atmospheric state, and surface properties measurements, provide a complete dataset that can be used to constrain radiative properties of water vapour, cirrus ice particles, and snow/ice emissivity over almost all the infrared emission, including the under-explored FIR spectral range.

7   Data availability

The full dataset of the 2-month campaign, including infrared spectra (FIRMOS and E-AERI) and all the additional information

180   (lidars, local PTHW, dedicated RS, snow SSA), is available via the ESA campaign dataset website

https://earth.esa.int/eogateway/campaigns/firmos (Palchetti et al., 2020a, https://doi.org/10.5270/ESA-38034ee). Information about the data formats are reported in README files within each data subdirectory.

For the review process, the dataset is also available at https://fts.fi.ino.it/forum/firmos/zugspitze-dataset/ (essd, F20z%sd)

Author contributions. LP designed the experiment and was chief scientist for the field campaign. RS was the responsible for the local deployment. LP, MB, GB, FDA, AM, SV, RS, MR, HV, CR, DK, BC run the instruments during the campaign. LP, CB, GDN, RS, MR, HV, CR, BC, SDB, MG, FGW carried out data analysis and measurement validation. DS and HO were responsible for the campaign organisation. LP prepared the manuscript with contributions from all co-authors.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. European Space Agency with the FIRMOS project (ESA–ESTEC Contract No. 4000123691/18/NL/LF) and the Italian Space Agency with the research projects SCIEF (Italian acronym of Development of the National Competences for the FORUM experiment - ASI contract No. 2016-010-U.0). The balloon activities were also partly supported by funding from the Helmholtz Association in the framework of MOSES (Modular Observation Solutions for Earth Systems).

References

Baran, A. J., Hill, P., Furtado, K., Field, P., and Manners, J.: A Coupled Cloud Physics–Radiation Parameterization of the Bulk Optical
Properties of Cirrus and Its Impact on the Met Office Unified Model Global Atmosphere 5.0 Configuration, Journal of Climate, 27,
7725–7752, https://doi.org/10.1175/JCLI-D-13-00700.1, https://doi.org/10.1175/JCLI-D-13-00700.1, 2014.

Bianchini, G. and Palchetti, L.: Technical Note: REFIR-PAD level 1 data analysis and performance characterization, Atmospheric Chemistry
and Physics, 8, 3817–3826, https://doi.org/10.5194/acp-8-3817-2008, https://acp.copernicus.org/articles/8/3817/2008/, 2008.

Bianchini, G., Castagnoli, F., Di Natale, G., and Palchetti, L.: A Fourier transform spectroradiometer for ground-based remote sensing of the
atmospheric downwelling long-wave radiance, Atmospheric Measurement Techniques, 12, 619–635, https://doi.org/10.5194/amt-12-619-
2019, https://www.atmos-meas-tech.net/12/619/2019/, 2019.

Brabec, M., Wienhold, F. G., Luo, B. P., Vömel, H., Immler, F., Steiner, P., Hausammann, E., Weers, U., and Peter, T.: Particle backscatter
and relative humidity measured across cirrus clouds and comparison with microphysical cirrus modelling, Atmospheric Chemistry and
Physics, 12, 9135–9148, https://doi.org/10.5194/acp-12-9135-2012, https://www.atmos-chem-phys.net/12/9135/2012/, 2012.

Carli, B., Barbis, A., Harries, J. E., and Palchetti, L.: Design of an efficient broadband far-infrared fourier-transform spectrometer, Appl.
Opt., 38, 3945–3950, https://doi.org/10.1364/AO.38.003945, http://ao.osa.org/abstract.cfm?URI=ao-38-18-3945, 1999.

Chen, X., Huang, X., and Flanner, M. G.: Sensitivity of modeled far-IR radiation budgets in polar continents to treatments of snow surface
and ice cloud radiative properties, Geophysical Research Letters, 41, 6530–6537, https://doi.org/10.1002/2014GL061216, https://agupubs.
onlinelibrary.wiley.com/doi/abs/10.1002/2014GL061216, 2014.

Cox, C., Harries, J., Taylor, J., Green, P., Baran, A., Pickering, J., Last, A., and Murray, J.: Measurement and simulation of
mid-and far-infrared spectra in the presence of cirrus, Quarterly Journal of the Royal Meteorological Society, 36, 718–739,
https://doi.org/10.1002/qj.596, 2010.

Cox, C. V., Murray, J. E., Taylor, J. P., Green, P. D., Pickering, J. C., Harries, J. E., and Last, A. E.: Clear-sky far-infrared measurements
observed with TAFTS during the EAQUATE campaign, September 2004, Quarterly Journal of the Royal Meteorological Society, 133,
273–283, https://doi.org/10.1002/qj.159, https://rmets.onlinelibrary.wiley.com/doi/abs/10.1002/qj.159, 2007.

Dirksen, R. J., Sommer, M., Immler, F. J., Hurst, D. F., Kivi, R., and Vömel, H.: Reference quality upper-air measurements: GRUAN data
processing for the Vaisala RS92 radiosonde, Atmospheric Measurement Techniques, 7, 4463–4490, https://doi.org/10.5194/amt-7-4463-
2014, https://www.atmos-meas-tech.net/7/4463/2014/, 2014.

Gallet, J.-C., Domine, F., Zender, C. S., and Picard, G.: Measurement of the specific surface area of snow using infrared reflectance in an
integrating sphere at 1310 and 1550 nm, The Cryosphere, 3, 167–182, https://doi.org/10.5194/tc-3-167-2009, 2009.

Harries, J., Carli, B., Rizzi, R., Serio, C., Mlynczak, M., Palchetti, L., Maestri, T., Brindley, H., and Masiello, G.: The Far-infrared
Earth, Reviews of Geophysics, 46, https://doi.org/10.1029/2007RG000233, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/
2007RG000233, 2008.

Huang, X., Chen, X., Zhou, D. K., and Liu, X.: An Observationally Based Global Band-by-Band Surface Emissivity Dataset for Climate and
Weather Simulations, Journal of the Atmospheric Sciences, 73, 3541–3555, https://doi.org/10.1175/JAS-D-15-0355.1, https://doi.org/10.
1175/JAS-D-15-0355.1, 2016.

Huang, X., Chen, X., Flanner, M., Yang, P., Feldman, D., and Kuo, C.: Improved Representation of Surface Spectral Emissivity in a Global
Climate Model and Its Impact on Simulated Climate, Journal of Climate, 31, 3711–3727, https://doi.org/10.1175/JCLI-D-17-0125.1,
https://doi.org/10.1175/JCLI-D-17-0125.1, 2018.

230   Huang, Y., Ramaswamy, V., Huang, X., Fu, Q., and Bardeen, C.: A strict test in climate modeling with spectrally resolved radiances: GCM simulation versus AIRS observations, Geophysical Research Letters, 34, https://doi.org/10.1029/2007GL031409, https://agupubs. onlinelibrary.wiley.com/doi/abs/10.1029/2007GL031409, 2007.

Klanner, L., Höveler, K., Khordakova, D., Perfahl, M., Rolf, C., Trickl, T., and Vogelmann, H.: A powerful lidar system capable of one-hour measurements of water vapour in the troposphere and the lower stratosphere as well as the temperature in the upper strato-
235   sphere and mesosphere, Atmospheric Measurement Techniques Discussions, 2020, 1–54, https://doi.org/10.5194/amt-2020-90, https: //amt.copernicus.org/preprints/amt-2020-90/, 2020.

Mlawer, E. J., Turner, D. D., Paine, S. N., Palchetti, L., Bianchini, G., Payne, V. H., Cady-Pereira, K. E., Pernak, R. L., Alvarado, M. J., Gombos, D., Delamere, J. S., Mlynczak, M. G., and Mast, J. C.: Analysis of Water Vapor Absorption in the Far-Infrared and Submillimeter Regions Using Surface Radiometric Measurements From Extremely Dry Locations, Journal of Geophysical Research: Atmospheres, 124,
240   8134–8160, https://doi.org/10.1029/2018JD029508, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2018JD029508, 2019.

Mlynczak, M. G., Johnson, D. G., Latvakoski, H., Jucks, K., Watson, M., Kratz, D. P., Bingham, G., Traub, W. A., Wellard, S. J., Hyde, C. R., et al.: First light from the Far-Infrared Spectroscopy of the Troposphere (FIRST) instrument, Geophys. Res. Lett., 33, 4569, https://doi.org/10.1029/2002JD003291, 2006.

Mlynczak, M. G., Cageao, R. P., Mast, J. C., Kratz, D. P., Latvakoski, H., and Johnson, D. G.: Observations of downwelling far-
245   infrared emission at Table Mountain California made by the FIRST instrument, Journal of Quantitative Spectroscopy and Radia- tive Transfer, 170, 90–105, https://doi.org/https://doi.org/10.1016/j.jqsrt.2015.10.017, http://www.sciencedirect.com/science/article/pii/ S0022407315300340, 2016.

Norton, R. H. and Beer, R.: New apodizing functions for Fourier spectrometry, J. Opt. Soc. Am., 66, 259–264, https://doi.org/10.1364/JOSA.66.000259, http://www.osapublishing.org/abstract.cfm?URI=josa-66-3-259, 1976.

250   Norton, R. H. and Beer, R.: Errata: New Apodizing Functions For Fourier Spectrometry, J. Opt. Soc. Am., 67, 419–419, https://doi.org/10.1364/JOSA.67.000419, http://www.osapublishing.org/abstract.cfm?URI=josa-67-3-419, 1977.

Palchetti, L., Belotti, C., Bianchini, G., Castagnoli, F., Carli, B., Cortesi, U., Pellegrini, M., Camy-Peyret, C., Jeseck, P., and Té, Y.: Technical note: First spectral measurement of the Earth's upwelling emission using an uncooled wideband Fourier transform spectrometer, Atmo- spheric Chemistry and Physics, 6, 5025–5030, https://doi.org/10.5194/acp-6-5025-2006, https://acp.copernicus.org/articles/6/5025/2006/,
255   2006.

Palchetti, L., Bianchini, G., Di Natale, G., and Del Guasta, M.: Far-Infrared Radiative Properties of Water Vapor and Clouds in Antarctica, Bulletin of the American Meteorological Society, 96, 1505–1518, https://doi.org/10.1175/BAMS-D-13-00286.1, https://doi.org/10.1175/ BAMS-D-13-00286.1, 2015.

Palchetti, L., Barucci, M., Belotti, C., Bianchini, G., Cluzet, B., D'Amato, F., Bianco, S. D., Natale, G. D., Gai, M., Khordakova, D.,
260   Montori, A., Oetjen, H., Rettinger, M., Rolf, C., Schuettemeyer, D., Sussmann, R., Viciani, S., Vogelmann, H., and Wienhold, F. G.: FIRMOS 2018-2019 Zugspitze campaign dataset, European Space Agency, https://doi.org/https://doi.org/10.5270/ESA-38034ee, https: //earth.esa.int/eogateway/campaigns/firmos, 2020a.

Palchetti, L., Brindley, H., Bantges, R., Buehler, S. A., Camy-Peyret, C., Carli, B., Cortesi, U., Del Bianco, S., Di Natale, G., Dinelli, B. M., Feldman, D., Huang, X. L., C.-Labonnote, L., Libois, Q., Maestri, T., Mlynczak, M. G., Murray, J. E., Oetjen, H., Ridolfi, M.,
265   Riese, M., Russell, J., Saunders, R., and Serio, C.: FORUM: unique far-infrared satellite observations to better understand how Earth radiates energy to space, Bulletin of the American Meteorological Society, pp. 1–52, https://doi.org/10.1175/BAMS-D-19-0322.1, https: //doi.org/10.1175/BAMS-D-19-0322.1, 2020b.

Sussmann, R., Reichert, A., and Rettinger, M.: The Zugspitze radiative closure experiment for quantifying water vapor absorption over the terrestrial and solar infrared – Part 1: Setup, uncertainty analysis, and assessment of far-infrared water vapor continuum, Atmospheric Chemistry and Physics, 16, 11 649–11 669, https://doi.org/10.5194/acp-16-11649-2016, https://www.atmos-chem-phys.net/16/11649/2016/, 2016.

Turner, D. D., Mlawer, E. J., Bianchini, G., Cadeddu, M. P., Crewell, S., Delamere, J. S., Knuteson, R. O., Maschwitz, G., Mlynczak, M., Paine, S., Palchetti, L., and Tobin, D. C.: Ground-based high spectral resolution observations of the entire terrestrial spectrum under extremely dry conditions, Geophysical Research Letters, 39, https://doi.org/10.1029/2012GL051542, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2012GL051542, 2012.

Vernier, J.-P., Fairlie, T. D., Natarajan, M., Wienhold, F. G., Bian, J., Martinsson, B. G., Crumeyrolle, S., Thomason, L. W., and Bedka, K. M.: Increase in upper tropospheric and lower stratospheric aerosol levels and its potential connection with Asian pollution, Journal of Geophysical Research: Atmospheres, 120, 1608–1619, https://doi.org/10.1002/2014JD022372, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2014JD022372, 2015.

Vogelmann, H. and Trickl, T.: Wide Range Sounding of Free Tropospheric Water Vapor with a Differential Absorption Lidar (DIAL) at a High Altitude Station, Appl. Opt., 47, 2116–2132, https://doi.org/10.1364/AO.47.002116, 2008.
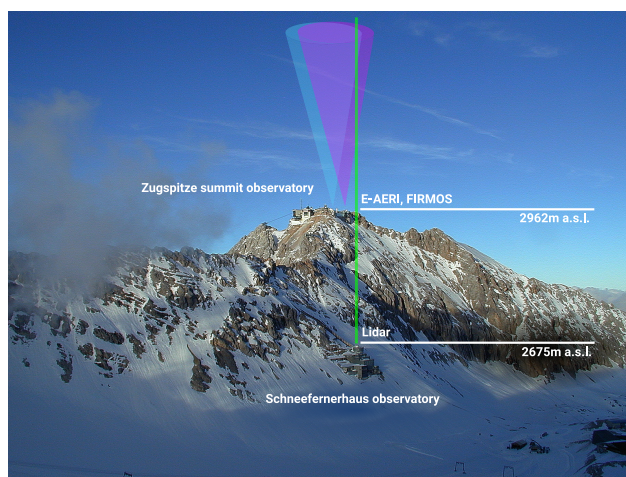
Figure 1. Summit and Schneefernerhaus stations at the Mt. Zugspitze, Germany.
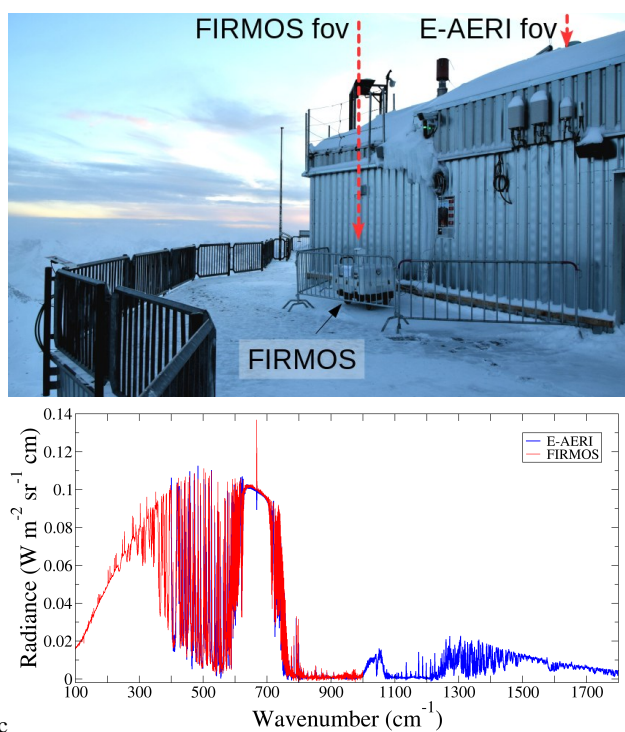
Figure 2. FIRMOS and E-AERI installed at the Summit station. The spectra comparison is shown for the average of 310 simultaneous observations in clear sky during 2019 campaign.
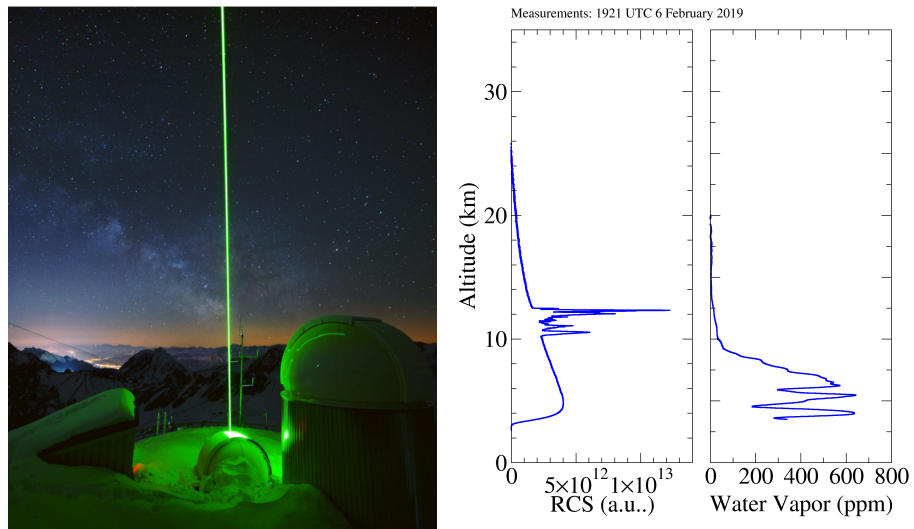
Figure 3. Lidar measurements at the Schneefernerhaus station. The plot shows an example of the Range Corrected Signal (RCS) of the backscatter lidar, detecting a cloud layer, and the water vapour profile of the Raman lidar measured on 6 February 2019 at 19:21 UTC.
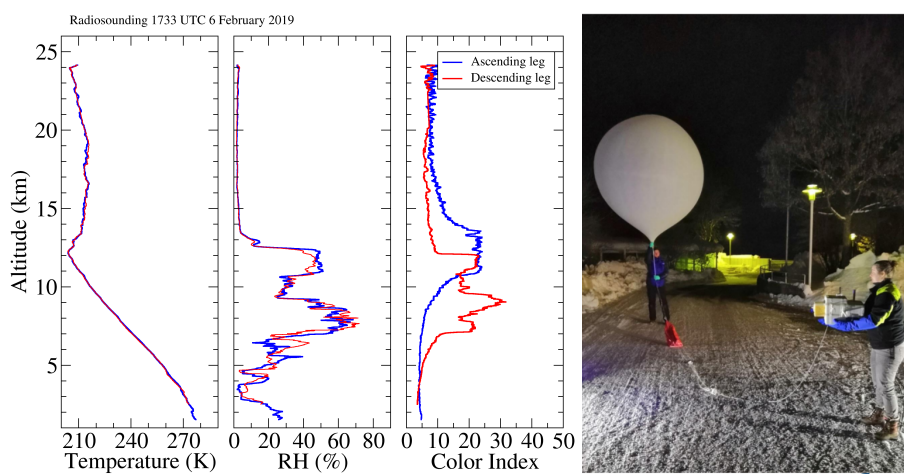
Figure 4. Radiosoundings from Garmisch-Partenkirchen of temperature, relative humidity (RH), and color index profiles. A single cloud layer during the ascending leg (blue curve) and a double layer during descending (red curve) for the launch on 6 February 2019 at 17:33 UTC is shown in the color index plot.
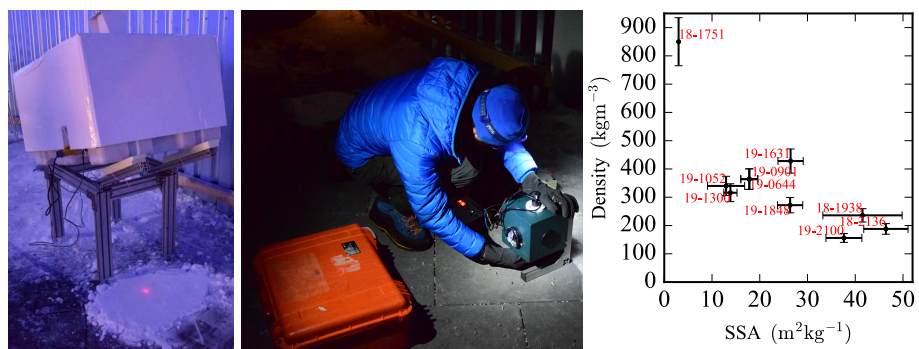
Figure 5. Snow measurements at Zugspitze Summit. FIRMOS in a slant angle during snow emissivity measurement (left), DUFISSS snow SSA measurement (center) and density-SSA properties of the snow samples (right, day-time of FIRMOS acquisition labelled in red).
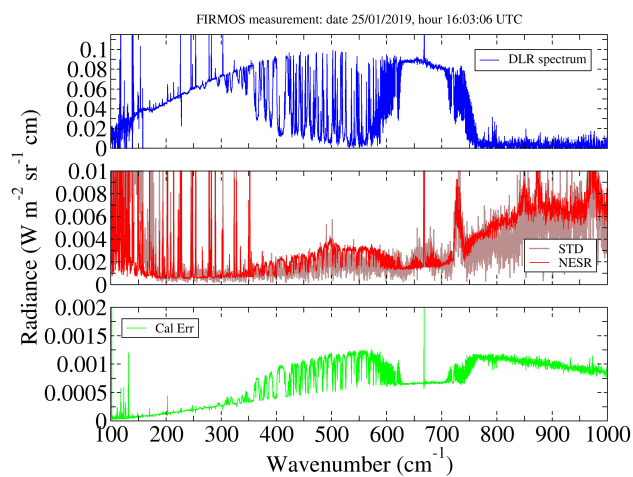
Figure 6. Example of FIRMOS DLR spectrum and the associated noise estimates acquired at on 25 January 2019 at 16:03 UTC.
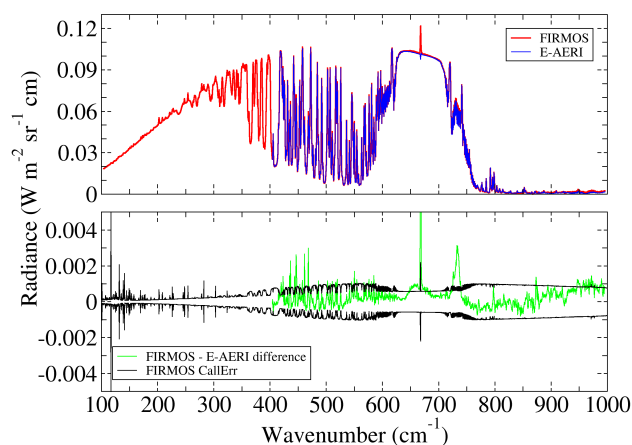
Figure 7. Comparison between FIRMOS and E-AERI averaged spectra of 420 simultaneous acquisitions for the 2019 campaign. Spectra were resampled to a common spectral resolution of 0.5 cm^{-1}. The bottom graph shows the difference between the average spectra (in green), compared with the calibration error (in black).

Table 1. Instrumentation deployed at Zugspitze and measurements performed during the FIRMOS campaign.

Instrument	Location	Type of measurement	Integration / repetition time	Date / No of measurements
FIRMOS	Zugspitze Summit station	DLR spectrum 100-1000 cm^{-1}		
		Res.= 0.4 cm^{-1}	128 s / 256 s	29/11/18–18/12/18 1197 spectra
		Res.= 0.3 cm^{-1}	210 s / 420 s	21/1/19–15/2/19 838 spectra
FIRMOS	Zugspitze Summit station	Ice/snow spectrum 100–1000 cm^{-1} Res.= 0.3 cm^{-1}	210 s / 420 s	16/2/19–20/2/19 152 snow + 283 sky spectra
E-AERI	Zugspitze Summit station	DLR spectrum 400-1800 cm^{-1} Res.= 0.5 cm^{-1}	214 s / 440 s	28/11/18–20/2/19 4987 spectra
Meteo station from DWD	Zugspitze Summit station	Local PTHW	every 10 min	Continuous
Backscatter lidar	Schneefernerhaus station	Extinction profile	1 min / 4-10 min	16 Nov 2018 to 19 Feb 2019
Raman lidar	Schneefernerhaus station	H$_2$O and T profiles	1 h	16 Nov 2018 to 19 Feb 2019
Dedicated RS	IMK-IFU, Garmisch-Partenkirchen	PTH, H$_2$O O$_3$, cloud extinction and color index profiles		4 launches on 5–6 Feb. under clear sky and thin cirrus cloud conditions during night time
DUFISSS	Zugspitze Summit station	snow SSA	-	Two measurements when possible, coinciding with FIRMOS acquisitions