Deliverable 5.4: Report on development, testing and implementation of new technologies

Authors: Jochen Wagner, Elke Ludewig, Dominik van Pinxteren, Kristina Höhler, Ralf Tillmann, Martine De Mazière, Doina Nicolae, Stephanie Schüttauf, Ewan O'Connor, Bernhard Pospichal, Martial Haeffelin

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1. Introduction

This document is prepared in the context of the activities of the ACTRIS IMP project.

The ACTRIS (Aerosol, Cloud, and Trace Gases Research Infrastructure (RI)) has consistently been at the forefront of atmospheric science, delivering high-quality data on aerosols, clouds, and trace gases essential for research on air quality, climate change, and related health impacts. This report delves into the continued development, testing, and implementation of new technologies within the six observational components of ACTRIS: Aerosol In Situ Measurements, Aerosol Remote Sensing, Reactive Trace Gases In Situ Measurements, Reactive Trace Gases Remote Sensing, Cloud In Situ Measurements, and Cloud Remote Sensing. The focus of this report reflects ACTRIS's unwavering commitment to advancing technological innovation to meet the increasing needs of the user community. The underlying objective is to provide data in near real-time, ensure high data availability, improve detection limits, and develop instrumentation for mobile applications and specific platforms. This objective aligns with ACTRIS's overarching goal of enhancing our understanding of atmospheric processes to tackle new science questions, facilitate early warning mechanisms, and improve data assimilation techniques. This report, in essence, provides a comprehensive overview of ACTRIS's significant strides in technology development, challenges faced, and strategies employed to overcome these, ultimately highlighting its contributions to atmospheric science and associated fields.

2. Overview on the operating strategies and technology developments in the six Topical Centres

This chapter presents an overview of the current state and strategic approaches within the different components of our network. It serves as a prelude to the more detailed examples and specific activities that will be discussed in the following chapter. The focus here is primarily on the Topical Centres (TCs). Each TC is responsible for one of the six ACTRIS components. Many of these TCs are relatively new and are still in the process of implementation and integration. Therefore, while their potential impact is significant, it is important to recognize that they are at various stages of development and operational maturity. The National Facilities (NFs), which are central to this report, benefit from the groundwork laid by these TCs. The TCs contribute to the standardization of practices, development of methodologies, and innovation, all of which are crucial for the advancement of the NFs. However, it is also essential to note that the success and effectiveness of the NFs are not solely dependent on the TCs. The NFs have their own set of strengths and challenges, independent of the TCs' progress. This chapter aims to provide a realistic view of where we stand in terms of the ACTRIS components, setting the stage for a deeper dive into the recent activities and developments in chapter 3.

2.1 Centre for Reactive Trace Gases In Situ Measurements (CiGas)

Development:

Several novel instruments have been designed by industrial partners in the field of reactive trace gas in-situ measurements. These advancements encompass a range of technologies, including Quantum Cascade Laser (QCL) Technology, Cavity Enhanced Absorption Spectroscopy (CEAS), and Electrochemical Sensors tailored for NOx detection. Additionally, Chemical Ionization Mass Spectrometry (CIMS) and thermo-desorption gas chromatographic (TD-GC) methods have been harnessed for detecting organic compounds. Calibration and validation techniques have been developed further to improve the accuracy and reliability of reactive trace gases in situ measurements including harmonized calibration procedures and the use of common reference standards.

Testing:

Once these technologies are developed, rigorous testing and validation protocols are carried out. They undergo tests under various atmospheric conditions to validate their performance and reliability. Furthermore, inter-comparisons with existing, well-established technologies are conducted to ensure that the new tools meet or exceed the current standards. Data obtained from these tests are used for calibrating the devices, refining their measurement algorithms, and identifying areas where further improvements are necessary.

Implementation:

Following the successful testing phase, these new technologies are implemented into ACTRIS's operational infrastructure. The CiGas team supports the seamless integration of these technologies into ACTRIS's observational network, replacing or complementing existing equipment where necessary. To maximize their impact, these new tools are aimed to be deployed at multiple sites across Europe and are continuously operated to monitor trace gases. To ensure data reliability and quality, CiGas develops measurement guidelines for the new technologies, performs site audits and round robins. This integration not only improves the capacity for detecting and understanding reactive trace gases but also strengthens Europe's observational capabilities for atmospheric sciences.

To conclude, the efforts made by CiGas in the development, testing, and implementation of new technologies within ACTRIS are significantly enhancing our knowledge and understanding of atmospheric chemistry, which is crucial for climate research and air quality monitoring.

2.2 Centre for Reactive Trace Gases Remote Sensing (CREGARS)

Development:

The Centre for Reactive Trace Gases Remote Sensing (CREGARS) of ACTRIS has been spearheading the development of advanced technologies for remote sensing of trace gases. These technologies include advanced spectrometers and satellite data analysis algorithms (GRASP), aimed at improving the capabilities to detect, identify, and quantify trace gases from a distance. The union with well-established networks like NDACC and the Pandonia Global Network (PNG) has significantly boosted these developmental efforts by providing an enriched pool of expertise and resources.

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Testing:

After the development of technologies, an intensive testing phase commences. Prototypes are thoroughly tested under diverse atmospheric conditions in both field and laboratory settings. These tools are compared to existing, recognized standards from NDACC and PGN to ensure that the new methodologies provide reliable and accurate measurements that meet or exceed current capabilities. The testing phase is crucial to fine-tune the instruments, calibrate the algorithms, and identify potential areas for future development.

Implementation:

Once the new technologies pass the testing phase, they are incorporated into the ACTRIS and NDACC/PGN infrastructure. CREGARS ensures a seamless integration of these technologies into the broader network, replacing or complementing the existing equipment where necessary. These instruments are deployed at various sites across Europe, contributing to a comprehensive, consistent stream of trace gas data. The team ensures data quality through regular instrument maintenance, calibration, and data cross-validation for example during CINDI (Cabauw Intercomparison of Nitrogen Dioxide Measuring Instruments) campaigns leveraging the capabilities of the NDACC and PGN networks.

In conclusion, the contributions of CREGARS in the development, testing, and implementation of new trace gases remote sensing technologies, in synergy with NDACC and PGN, have substantially enhanced our capacity to monitor atmospheric trace gases. This is instrumental in improving our understanding of atmospheric chemistry, air quality, and climate change.

2.3 Centre for Aerosol In Situ – European Center for Aerosol Calibration and Characterization (CAIS-ECAC)

Under the expert guidance of the unit heads, the Centre for Aerosol In Situ – European Center for Aerosol Calibration and Characterization (CAIS-ECAC) within ACTRIS has concentrated its efforts on the development of cutting-edge in situ aerosol measurement technologies. This has involved the conception and design of innovative sampling instruments such as advanced particle spectrometers, aerosol mass spectrometers, and cloud condensation nuclei counters. These devices are developed with the aim of improving the resolution and accuracy of in situ measurements of aerosol optical, physical, and chemical properties, which is key to understanding aerosol-climate interactions.

Testing:

After the development of these new technologies, thorough testing is carried out to ensure their reliability and efficacy under various conditions. Prototypes are subjected to rigorous field and laboratory tests under different climatic and aerosol conditions to verify their sensitivity, precision, and resilience. Furthermore, they are compared to established reference instruments to confirm that the new methodologies meet or exceed the current industry standards. This testing phase allows for fine-tuning the instrument performance and identifying potential areas for further improvement.

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Implementation:

Once the testing phase is successful, these instruments are implemented into the broader ACTRIS infrastructure. With the active involvement of the CAIS-ECAC team, these technologies are carefully integrated into the existing network of aerosol monitoring stations across Europe, either replacing older equipment or working in tandem with them for more comprehensive measurements. The team conducts regular maintenance checks and calibration of these instruments to maintain the quality and consistency of the data collected. Their introduction has significantly improved the ability to track and understand aerosol distribution, composition, and radiative effects, thereby enhancing the robustness of atmospheric research and climate modelling in Europe.

In summary, the pivotal role of CAIS-ECAC in the development, testing, and implementation of new aerosol in situ measurement technologies is making significant strides in aerosol science, ultimately benefiting both climate research and air quality management.

2.4 Centre for Aerosol Remote Sensing (CARS)

Development:

The Centre for Aerosol Remote Sensing (CARS) within ACTRIS has embarked on the development of new technologies in the field of aerosol remote sensing. Innovations have emerged in the form of advanced lidar systems (e.g. solutions for daytime capability of the Raman channels, calibrator for depolarization measurements, camera-based automatic alignment of the laser-telescope axis, low-cost near field channel, etc.), multispectral sun/sky/lunar photometers (e.g. lunar photometer, mobile photometer) that offer enhanced capabilities to detect and analyse aerosols from a distance. The objective of these technologies is to improve the temporal and spatial resolution of aerosol data, as well as the accuracy of the data products, enabling better characterization of aerosol properties and distribution.

Testing:

Following the development phase, these technologies are subjected to stringent testing protocols. For the lidar technology, a comprehensive set of tests were developed in order to accurately and objectively estimate the systematic biases, and calculate the correction factors. Software tools have been developed for allowing the lidar operators to keep under control the performance of each channel. For the photometers, traceability to radiometric standards is assured for the master instruments. These new technological solutions are evaluated under diverse atmospheric and aerosol conditions, both in the lab and the field, to assess their performance and robustness. Moreover, these instruments are cross-validated with existing reference technologies to ensure their measurements are accurate and reliable. This rigorous testing allows for fine-tuning of the instruments, adjustment of the data algorithms, and identification of potential areas for future enhancement.

Implementation:

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Once successfully tested at the CARS facilities, these tools are integrated into ACTRIS's operational framework. The CARS team have orchestrated the smooth transition of these technologies into the extensive aerosol monitoring network maintained by ACTRIS. Particular attention was paid to develop parts and blocks which can be integrated into the existing lidar instruments, at reduced costs. These instruments / blocks, after being deployed at various sites across Europe, contribute to a continuous, comprehensive aerosol data stream. To maintain the data's quality and reliability, the CARS team performs regular instrument calibration, maintenance, and data cross-checks.

In conclusion, the endeavours of CARS in developing, testing, and implementing new technologies have significantly augmented our capacity to remotely monitor aerosols. This progress has not only enhanced our understanding of aerosol dynamics and climate interactions but has also bolstered our ability to model and predict air quality and climate change.

2.5 Centre for Cloud In Situ Measurements (CIS)

Development:

A major challenge of the Centre for Cloud In Situ Measurements (CIS) is the instrumentation to measure in situ cloud properties. For most CIS variables, available instruments on the market have been increasingly developed for measurement campaigns and are not directly applicable for continuous 24/7 monitoring operation. Recent instrument developments are available for Ice Nucleating Particle monitoring, like the Portable Ice Nucleation Experiment (PINE, jointly developed by KIT, University of Leeds and Bilfinger Company), the Horizontal Ice Nucleation Chamber HINC-Auto (developed by ETH) and filter-based sampling techniques.

Since CIS in-house developments are not possible within the current financial framework of ACTRIS, CIS is intensively exploring the market and is increasingly seeking discussions with instrument manufacturers and developers. The aim is to be able to recommend suitable measuring instruments for all CIS variables, to improve the operational capability of the instruments, and to initiate and test new technologies.

In the next ten years, we expect further instrumental developments that will facilitate and improve the acquisition of in situ cloud properties. CIS is accompanying the developments in close cooperation with the manufacturers to ensure optimal conditions for the National Facilities. This is possible, because ACTRIS is recognized as a customer market.

Testing:

Based on the technological challenge, the testing and verification of measuring technologies is a core task of CIS. Known and new measurement instruments are tested under different meteorological conditions in the field and in the laboratory within the framework of comparison campaigns in order to record their added value, efficiency, measurement accuracy, measurement reliability and handling. Considering future instrument operators (National Facility), the technologies must be reliable to use over extended periods of time and provide accurate, comparable data across stations. The testing of measurement technologies is a task of crucial importance, as it enables the evaluation and improvement of these instruments, as well

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as the formulation of corresponding SOPs. This task is fundamental to the upcoming future operational monitoring and the associated basis for cloud research. If instrument manufacturers do not offer their instruments for testing free of charge, these comparison campaigns demand significant financial and organizational resources, a challenge that CIS is presently addressing with a substantial in-kind contribution.

Potential National Facilities, as well as the CIS Units, are currently investing in various measuring instruments and measuring systems, which are and will be used for comparison campaigns. This shows that the Europe-wide cooperation of the planned CIS National Facilities with the Topical Centre CIS is proving successful even before official operational operation.

Implementation:

The known technical challenges of in situ cloud property detection led to a staggered schedule regarding the operational use of CIS. Thus, CIS was assigned an optimized implementation phase, which is still ongoing. Implementation is currently focused on evaluating instrument testing, discussing results with vendors and National Facilities, and preparing initial drafts of appropriate SOPs. Potential National Facilities as well as the CIS Units are working intensively together and have already led to adaptations of measurement instruments on the part of the manufacturers. The implementation of measurement technologies will be continued in the next few years and will steadily expand the measurement park for CIS and be subject to a long-term evaluation process. In parallel, CIS is implementing appropriate measurement and maintenance routines, data checks and quality standards for the data.

In conclusion, the work of CIS in developing, testing, and implementing new in situ cloud measurement technologies will greatly enhance our understanding of cloud processes and their impact on the climate system, providing valuable contributions to climate prediction models and weather forecasts.

2.6 Centre for Cloud Remote Sensing (CCRES)

Development:

The Centre for Cloud Remote Sensing (CCRES) has been working on advanced technologies for remote sensing of clouds. The main CCRES instruments are Doppler cloud radars, microwave radiometers, wind lidars, ceilometers and disdrometers. Having the aim of high-quality observations, these instruments need to be characterized thoroughly, to improve the capabilities of remote sensing to capture the macroscopic and radiative properties of clouds, cloud microphysics, dynamics and thermodynamic properties with higher resolution and accuracy. Special focus was on the improvement of calibration, both for cloud radars and microwave radiometers. For cloud radars, new methods have been developed to better characterize the calibration uncertainties (hard targets, disdrometer monitoring, calibration transfers, see e.g. [Toledo et al. 2020; Jorquera et al. 2023]), as well as pointing accuracies. A compact (30 kg) 94 GHz FMCW Doppler Cloud radar was developed to serve as reference instrument and travelling standard for the ACTRIS CRS NFs. For ceilometers, developments to improve data quality are conducted in close collaboration with the Centre for Aerosol Remote Sensing (CARS).

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Testing:

Following the development phase, these technologies are subjected to comprehensive testing procedures in field environments, where the prototype instruments are assessed under a broad range of cloud conditions to ensure their robustness and performance. These new technologies are also compared with existing, standardized instrumentation and methodologies to verify that they meet or surpass the present industry norms. Such testing is instrumental in calibrating the instruments, refining the associated data processing algorithms, and highlighting potential avenues for further development. Calibration campaigns for radars and microwave radiometers were performed to test and validate the newly developed methods.

Implementation:

Once these technologies have been successfully tested, they are implemented within the operational framework of ACTRIS. New methods for radar and microwave radiometer calibration have been implemented in the standard processing. Once deployed at various sites across Europe, these instruments provide continuous, high-quality data on clouds and their dynamics. The team also conducts regular instrument maintenance, calibration, and data quality checks to ensure the reliability and precision of the collected data.

In summary, the efforts of CCRES in the development, testing, and implementation of new cloud remote sensing technologies have significantly bolstered our ability to monitor and understand cloud systems. This progress is critical for improving our weather prediction models, climate change projections, and the overall understanding of the Earth's climate system.

3. Specific developments within ACTRIS

3.1 Centre for Reactive Trace Gases In Situ Measurements (CiGas)

One of the remarkable developments have been the cavity-enhanced absorption spectroscopy (CEAS) instruments. These high-resolution, ultra-sensitive spectrometers have significantly improved the ability to detect and quantify trace gases such as NOx even at very low concentrations. Advances in these spectrometers include reducing their size for mobile and remote deployments and improving their sensitivity and accuracy for detecting an even broader range of trace gases i.e., developments for HONO measurements by a CEAS technique have been supported by CiGas. [Lucile Richard, et al. (2018)]

Quantum Cascade Laser (QCL) technology was actively being researched and applied for the measurement of nitrogen oxides (NOx) in the atmosphere. QCLs have shown great promise for their high sensitivity, selectivity, and fast response times, making them valuable tools for atmospheric monitoring. Instruments were being developed to measure multiple gases simultaneously, including various NOx species (NO, NO2, N2O), which can provide a more comprehensive view of air quality and pollutant sources. Efforts were directed toward compact and field-deployable instruments which are essential for mobile monitoring and point-source emissions measurements. [Andreas Genner, et al. (2020)].

CEAS and QCL based instruments can continuously measure NOx concentrations and are developed to provide data in near-real-time. This capability is crucial for tracking rapid changes in atmospheric conditions. Both techniques have been intensively used within CiGas and took part in inter-comparison campaigns dedicated to NOx and interfering parameters.

Another innovative development has been the evolution of proton-transfer-reaction mass spectrometry (PTR-MS) and chemical ionization mass spectrometry (CIMS) for reactive trace gases in situ analysis. These instruments provide real-time, online measurement capabilities, enabling the detection of volatile organic compounds (VOCs) and other reactive trace gases at part per trillion (pptv) levels. Recent enhancements include the development of dedicated ion sources, increasing the range of detectable compounds and improving detection limits to sub-pptv levels. [Lopez-Hilfiker, F. D., et al. (2014)]. The combination of high-resolution TOF mass spectrometers with chemical ionization techniques also offers the advantage to distinguish between ions with very close masses, allowing for precise identification and quantification of analytes. High mass resolution is especially critical when dealing with complex mixtures or isobaric compounds.

Gas chromatography (GC) systems have also seen significant improvements. These advancements allow for on-site separation and quantification of complex mixtures of trace gases. Online and off-line sampling followed by thermos-desorption injection methods are available for GC techniques. Automation of the sampling and analysis allow for higher sample frequencies and significantly reduces the time from sample collection to data availability [Holzinger, R. (2015)].

CiGas has also been developing improved calibration procedures. High-quality calibration is based on certified secondary standards provided by national metrological institutes as well as target gas and working standards, essential for ensuring the accuracy and reliability of trace gas measurements. New methods for dynamically generating calibration standards have been developed, providing a more accurate and efficient way to calibrate instruments for compounds not available as certified standards. [Håland, A., et al. (2022)]

Lastly, the CiGas is exploring the potential for miniaturization and automation of instruments. Smaller, automated instruments will be easier to deploy in the field and will reduce the need for manual operations, increasing data availability and improving the timeliness of data delivery [Cappellin, L., et al. (2017)].

These innovative developments at CiGas are enhancing our ability to measure trace gases in situ with improved accuracy, sensitivity, and temporal resolution. This allows for a more detailed understanding of the role of trace gases in atmospheric chemistry and their impacts on air quality and climate.

3.2 Centre for Reactive Trace Gases Remote Sensing (CREGARS)

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One significant development has been the advancement in Differential Optical Absorption Spectroscopy (DOAS) technology. DOAS instruments use scattered sunlight to measure the absorption spectra of trace gases. The advancements have primarily been around increasing the spectral resolution and sensitivity of these instruments, as well as developing software for more accurate retrievals of trace gas concentrations from the observed spectra. In addition, the new imaging MAXDOAS method is developed. Traditional, MAXDOAS instruments measure scattered sunlight at various angles to retrieve vertical profiles of trace gases and aerosols in the atmosphere. The imaging variant builds upon this principle by incorporating a 2D detector, similar to a camera sensor, which allows simultaneous measurement across a wide field of view. This innovation transforms the MAXDOAS from a point-viewing instrument to one that can spatially map the distribution of trace gases and aerosols over a broader area. Such spatial information is valuable in understanding local heterogeneities in atmospheric constituents, which can be driven by urban pollution sources, industrial outflows, or natural emissions. Moreover, imaging MAXDOAS enhances the temporal resolution since it doesn't need to mechanically scan different viewing directions sequentially. [Karin Kreher, et al. (2020)]. As this technique continues to mature, it promises to provide richer datasets that can bridge the gap between point measurements and broader satellite observations, delivering a more comprehensive understanding of atmospheric chemistry and dynamics.

CREGARS is poised to advance the field of reactive trace gas remote sensing through a pioneering initiative focused on the deployment and refinement of compact mobile Fourier Transform Infrared (FTIR) spectrometers. Recognizing the potential of these spectrometers to significantly improve field measurements, the facility intends to further innovate by developing an FTIR traveling standard, if deemed feasible. This would ensure consistent and standardized measurements across different locations and instruments. A significant technical leap being explored in this endeavour is the transition from liquid nitrogen (LiqN2) cooled detectors to the more efficient and compact Stirling-cooled detectors. In partnership with the Bruker company, this shift promises enhanced portability and reduced logistical challenges associated with LiqN2. Complementing these hardware developments, CREGARS is also investing in the adaptation of retrieval algorithms, ensuring that the data generated from these new instruments are both accurate and insightful.

Furthermore, CREGARS has been making strides in FTIR spectroscopy. FTIR instruments measure the infrared spectrum of absorption or emission of gases. This provides information about many trace gases simultaneously, with high spectral resolution. Recent advancements have focused on enhancing the resolution and sensitivity of these spectrometers, automating data collection and analysis processes, and developing robust calibration techniques.

The O3DIAL (Ozone Differential Absorption LIDAR) technique has recently witnessed transformative advancements tailored towards amplifying its application in atmospheric research. Traditionally recognized for its precision in profiling vertical ozone concentrations, efforts have been geared towards enhancing the technique's accessibility and utility. A pivotal stride has been the push for greater automation of the LIDAR systems. This not only reduces manual oversight and potential human error but also paves the way for continuous, long-term monitoring with minimal intervention, making it apt for remote or inaccessible regions. Parallel to this, significant engineering endeavours are being undertaken

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to miniaturize the O3DIAL systems. By adopting novel optical components and innovative design approaches, the newer systems are not only becoming more compact but also substantially less costly. This democratizes the technology, making it accessible to a broader spectrum of researchers and institutions. Such evolutions in the O3DIAL technique reinforce its stature as a quintessential tool for in-depth, high-resolution ozone monitoring in our ever-changing atmosphere [Valentin Duflot, et al. (2017)].

The integration of the Network for the Detection of Atmospheric Composition Change (NDACC) and the Pandonia Global Network (PGN) into ACTRIS and their subsequent inclusion within CREGARS have brought along advancements in UV/Vis, FTIR, and lidar technologies. These networks focus on the remote sensing of trace gases, with specific emphasis on vertical profiling and the development of globally consistent, long-term data sets [Martine De Mazière, et al. (2018)], [Tijl Verhoelst, et al. (2021)].

Moreover, CREGARS is making headway in the field of satellite remote sensing validation. These advancements allow for high quality global coverage of trace gas measurements and play a vital role in validating in situ measurements and improving atmospheric models.

Overall, the innovative developments at CREGARS are significantly enhancing our ability to measure trace gases remotely with improved accuracy, sensitivity, and spatial coverage. These advancements are proving crucial in our understanding of atmospheric chemistry, air quality, and climate change.

3.3 Centre for Aerosol In Situ – European Center for Aerosol Calibration and Characterization (CAIS-ECAC)

One major innovation within CAIS-ECAC has been the development of advanced aerosol mass spectrometers. These devices allow real-time measurement of the size-resolved chemical composition of aerosols, providing valuable data about aerosol sources, transformation processes, and climate effects. Recent advancements have focused on enhancing the sensitivity and resolution of these devices and automating the data collection and processing operations for more efficient analysis [Felipe D. Lopez-Hilfiker, et al. (2019)].

The Centre has also been working on refining mobility particle size spectrometers (MPSS). These instruments measure the number size distribution of aerosol particles in the atmosphere. Improvements in these instruments have revolved around expanding the measurable particle size range, increasing measurement accuracy, and minimizing the loss of particles during the measurement process [Alfred Wiedensohler, et al. (2018)].

CAIS-ECAC has been also focused on advancing aerosol absorption photometers. These devices measure the light absorption coefficient of aerosol particles, a critical aspect in understanding the impact of aerosols on radiation and climate [Sarah Valentini, et al. (2021)]. Advancements include enhancing the sensitivity of these devices, reducing measurement uncertainties, and refining calibration procedures.

Finally, the Centre has made significant strides towards miniaturization and automation of aerosol in-situ instruments. This has not only enabled their deployment in challenging environments but also increased data availability by reducing the need for manual operations [Leigh R. Crilley et al. (2018)].

In summary, these innovative developments at CAIS-ECAC are enhancing our ability to measure the atmospheric aerosol in-situ, improving the accuracy, sensitivity, and temporal resolution. They are providing a more detailed understanding of aerosol particle properties, their transformation processes, and their impacts on air quality and climate.

3.4 Centre for Aerosol Remote Sensing (CARS)

One innovative development within CARS is the advancement of daytime capability for the multi-wavelength Raman lidars. These systems use multiple laser wavelengths to retrieve the vertical distribution of aerosol, their optical properties and, in synergy with the photometers, the size distribution and modal volume concentration. Due to the high noise in the signal, vibrational Raman channels can only be used during nighttime, however improvements have been made considering special filters that now allow using Raman detection also during daytime [Ortiz-Amezcua P. et al. (2020)]. With this, the extinction coefficient profile can be retrieved up to 5-8 km also under daylight, enabling better synergy with the photometer. In order to address the synergy between the lidar and the photometer, CARS has also put efforts in developing the photometer capability to measure during nighttime (lunar photometer) [Yin, Z. et al. (2019)]. Current status is that nighttime AOD can be measured with a good accuracy by the new sun/sky/lunar photometers.

In addition, CARS has made strides in advancing polarization-sensitive LiDAR technologies, which can provide valuable information about the anisotropy of aerosol particles. By analysing the polarization state of backscattered light, these systems can differentiate between spherical and non-spherical particles, a crucial aspect in understanding aerosol types and their respective radiative impacts. However, quantitative products can only be retrieved if the polarization channels are properly calibrated [Freudenthaler, V., (2016)]. CARS has developed technical solutions for calibrating the polarisation measurements, which can be implemented in most of the existing systems, allowing the detection and quantitative characterisation of even low polarising particles such as smoke and pollution [Belegante, L. et al. (2018)].

Another key development refers to the development of a near-field channel, with a flexible design and at low cost, which enables lidars to measure aerosol distribution down to 300 m. Due to powerful lasers and bistatic design of the current lidar instruments, the detection and characterisation of particles was typically impossible below 800 m, meaning that particle exchanges with the surface could not be addressed. A low-cost solution to minimize the "blind region" of is particularly important for the synergy with the photometer (column measurement) but also for investigating the state of mixing in the Planetary Boundary Layer. Detection of aerosols in the proximity of the surface is also enabling synergies with the in situ measurements, allowing future development of algorithms to retrieve the microphysical properties of particles and their composition.

To enhance the operational efficiency of these lidar systems, CARS has been working on automating data acquisition and processing methods. Traceability of the data products is ensured by software tools which pushes the raw signals directly from the acquisition system to the centralized data processing chain, the

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automatic processing, and a comprehensive set of online quality checks. Automated, real-time analysis of LiDAR data significantly enhances the timeliness and availability of aerosol information, which is critical for both research and operational applications such as air quality monitoring and forecasting.

In order to compensate for the lack of data from remote regions, CARS is working to develop a prototype mobile photometer which can measure on a moving platform such as train or ship [Barreto, Á. et al. (2016)]. The main challenges refer to the design of the tracking system which should be able to continuously compensate for the movement of the platform, but also to the adjustment of the data processing.

In summary, the innovative developments within CARS are pushing the boundaries of lidar and photometer technology, enabling more detailed, efficient, and comprehensive measurements of aerosols, and thus significantly contributing to the understanding of aerosol characteristics and their impact on climate and air quality.

3.5 Centre for Cloud In Situ Measurements (CIS)

Specific activities performed by CIS in the development area of ACTRIS include the testing of measurement technologies in cooperation with the National Facilities in exchange with corresponding instrument manufacturers. Several measurement campaigns, partly supported by the projects ACTRIS-IMP, ATMO-ACCESS or in-kind services of the CIS Units were performed.

The Centre for Cloud Ice Nucleation (CCIce) conducted several campaigns with the online INP instrument PINE at different stations, among others the Sonnblick Observatory and the High-Altitude Research Station Jungfraujoch [Larissa Lacher, et al. (2017)] to check the operational capability also in comparison with the HINC-Auto instrument, as well as to design data management and SOPs. In addition, guidelines and SOPs are designed and tested for offline sampling and analysis with the INSEKT measurement system.

The Centre for Cloud Water Chemistry (CCWaC) conducted an intercomparison campaign at Sonnblick Observatory in autumn 2022 and another one at Schmücke Observatory in September 2023. Different cloud water samplers were tested here under different meteorological conditions and initial comparisons were made for further development steps.

The European Centre for Cloud Ambient Intercomparison (ECCINT) accomplished a first intercomparison campaign under winter conditions at the Sonnblick Observatory. Different technologies from spectrometers to holographic systems and classical integrated probes were analysed. The next intercomparison campaign under more summerly conditions is already planned.

Based on the experience gained during this ECCINT winter campaign, manufacturers of individual instruments have reacted and optimized their measurement systems. In the context of the Fog Dew 2023 conference, it was also possible to arrange contacts with other manufacturers who are planning to make new potential instruments available for further comparison campaigns. Due to data protection reasons, no further details on instrument manufacturers and activities can be given here.

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Overall, it is clear that the ACTRIS CIS activities are an optimal accompaniment for further developments in the CIS measuring area and a collaboration with ACTRIS is beneficial in this regard.

All in all, these innovative developments at the CIS will not only improve our ability to measure cloud properties with higher resolution and accuracy, but they also enable researchers to tackle new scientific questions related to cloud physics, cloud chemistry, and the interactions between clouds and the broader atmosphere.

3.6 Centre for Cloud Remote Sensing (CCRES)

The Centre for Cloud Remote Sensing (CCRES) within ACTRIS has made several new developments for retrievals for cloud observations as well as improvements in data processing and quality control.

Specific activities of CCRES consisted of calibration campaigns for cloud radars and microwave radiometers where new methods were tested and applied. For cloud radar calibration, [Toledo et al. (2020)] described a method to use corner reflectors as calibration targets with FMCW radars. This method has been then applied in campaigns in Palaiseau and Cabauw. Another step forward is to use a mobile reference radar to calibrate other radars in the network by calibration transfer at collocated observations [Jorquera et al., 2023].

Microwave radiometer (MWR) calibration was tested during several workshops and also one dedicated campaign at Lindenberg with several radiometers operating in parallel. With the results of this campaign, better and realistic uncertainties for MWR data can be provided. Furthermore, measurement uncertainties have been analysed and recommendation for site selection were given [Böck et al., 2023].

Other new developments:

Algorithms to retrieve atmospheric boundary layer heights from automatic lidars and ceilometers were developed [Kotthaus et al 2020], tested on 3-year datasets in over 10 different geographical locations. A fully operational software was then implemented at the French AERIS data centre, which is one the ACTRIS Data Centre unit. A comprehensive review of atmospheric boundary layer height retrieval from different remote sensing instruments was conducted under CCRES leadership [Kotthaus et al., 2023] and through extensive collaborations in the framework of the PROBE COST action [Cimini et al., 2020].

An algorithm to produce fog formation alerts based on automatic lidar and ceilometer backscatter profiles and near-surface horizontal visibility measurements [Ribaud et al. 2021] was developed. It has since been applied at several sites and airports in Europe.

A Doppler lidar system was employed to identify the primary sources of turbulent mixing within the atmospheric boundary layer [Manninen et al., 2018]. A classification scheme and its climatology provide valuable insights into the dynamic processes responsible for mixing within the atmospheric boundary layer, their spatial and temporal variability, and location-specific variations.

Finally, the development of quality control procedures and automated data processing algorithms and cloud classification systems has been a crucial part of CCRES's work. Automation in data processing enhances real-time analysis of collected data, improving the efficiency and speed of data delivery. Additionally, sophisticated cloud classification systems are being developed to automatically identify and categorize different cloud types based on their physical and optical properties, facilitating quicker and more accurate analysis of cloud observations.

Overall, the innovative developments at CCRES are significantly enhancing our ability to observe and understand the complex processes involved in cloud formation and behaviour, their interaction with aerosols, and their role in the climate system.

4. Conclusion

As we reach the conclusion of this report, it is evident that the ACTRIS, encompassing both the Topical Centers (TCs) and National Facilities (NFs), has made significant strides in advancing atmospheric research and monitoring. The developments within the TCs, although in varying stages of implementation, have laid a foundation for standardization, innovation, and enhanced methodologies that are crucial for the entire network.

1. **Integration and Progress:** The integration of the TCs into the Research Infrastructure has been a pivotal step. While some TCs are still in the nascent stages of development, their potential to harmonize atmospheric science is undeniable. They have already begun contributing to the RI's overall capabilities, particularly in three ACTRIS components: Aerosol In Situ Measurements, Aerosol Remote Sensing and Cloud Remote Sensing.
2. **National Facilities' Role:** The NFs remain at the heart of the RI's operations. The advancements and standardizations provided by the TCs are instrumental in enhancing the NFs' capabilities. The NFs continue to be the primary source of data and research, benefiting from the methodologies and technologies developed by the TCs.
3. **Challenges and Opportunities:** Despite the progress, challenges remain. The need for further integration, data standardization, and addressing the operational challenges of the NFs are areas that require ongoing attention. Another important issue is the harmonization with existing networks and initiatives. However, these challenges also present opportunities for growth and innovation within ACTRIS.
4. **Future Outlook:** Looking ahead, ACTRIS is poised to make significant contributions to our understanding of atmospheric processes and their impact on climate and air quality. The ongoing collaboration between the TCs and NFs is expected to yield more refined instruments, improved data accuracy, and a deeper understanding of atmospheric phenomena.
5. **Commitment to Excellence:** As ACTRIS moves forward, its commitment to excellence and collaboration remains steadfast, which is demonstrated by the long-term perspective of the ERIC

legal form. The RI will continue to adapt, evolve, and innovate, ensuring that it remains at the forefront of atmospheric research and monitoring.

In conclusion ACTRIS, through the collective efforts of the TCs and NFs, is making substantial contributions to the field of atmospheric science. The journey ahead is filled with potential and promise.

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