WORLD METEOROLOGICAL ORGANIZATION

COMMISSION FOR INSTRUMENTS
AND METHODS OF OBSERVATION

# EXPERT TEAM ON NEW TECHNOLOGIES AND TESTBEDS

## First session

**Geneva, Switzerland**
**4 – 7 March 2013**

# FINAL REPORT

# CONTENTS

## EXECUTIVE SUMMARY

This first session of the CIMO Expert Team on New Technologies and Testbeds was held from 4 to 7 March 2013 at the WMO Headquarters in Geneva, Switzerland.

The status and use of (new) remote-sensing technologies was reviewed towards assessing which of them could be considered as mature enough to be used operationally by National Meteorological and Hydrological Services. The meeting agreed on actions required to properly reflect and describe these techniques in the CIMO Guide, in IOM reports and on the WMO website.

The meeting reviewed the outcomes of CIMO Testbeds and Lead Centres with a view of cooperating with them on subjects of common interest. It recognized the potential that testbeds and lead centres could have in the implementation of WIGOS to test the performances of instruments and systems prior to their deployment within WIGOS. It therefore decided to develop of proposal for expanding their Terms of Reference and specifying the role they should play in WIGOS for the consideration of the Management Group, and ICG-WIGOS, if appropriate.

The meeting also addressed the matter of the traceability of remote-sensing observations.

# AGENDA

**1. ORGANIZATION OF THE SESSION**

1.1 Opening of the Session

1.2 Adoption of the Agenda

1.3 Working Arrangements for the Session

**2. REPORT OF CHAIRPERSON**

**3. WIGOS FRAMEWORK IMPLEMENTATION**

3.1 Update on progress in WMO

3.2 Proposed Expert Team contributions to WIGOS Framework Implementation

**4. GUIDANCE ON METEOROLOGICAL USE OF GNSS**

4.1 Status of development of IOM Report on GNSS

**5. GUIDANCE ON OPERATIONAL USE OF PASSIVE MICROWAVE PROFILERS**

5.1 Status of development of guidance material on operational use of passive microwave profilers

5.2 Status of review of CIMO Guide chapter

**6. STANDARDS ON LIDARS**

6.1 Status of development of ISO standards

6.2 Status of development of other standards

**7. DEVELOPMENT AND IMPLEMENTATION OF NEW REMOTE-SENSING TECHNOLOGIES AND THEIR OPERATIONAL APPLICATION**

7.1 Microwave Radiometers (MWR)

7.2 Global Navigation Satellite System (GNSS)

7.3 Water-Vapor LIDARs

7.4 Wind-finding

7.5 Cloud Radars

7.6 Aerosol and volcanic ash detection

7.7 Other

**8. MONITORING OF CIMO TESTBEDS**

8.1 Status of testbed monitoring

8.2 Status report on examination of need for update to CIMO Guide

**9. SI TRACEABILITY OF REMOTELY SENSED ATMOSPHERIC VERTICAL PROFILES**

9.1 Status report

**10. OTHER ACTIVITIES OF THE EXPERT TEAM**

10.1 Remote sensing of snow depth by airborne and spaceborne systems

10.2 Reliability and consistency of wind profiler measurements

10.3 Wind and temperature observations from aircraft surveillance data

**11. ANY OTHER BUSINESS**

**12. WORK PLAN REVIEW**

**13. CLOSURE OF THE SESSION**

# GENERAL SUMMARY

## 1. ORGANIZATION OF THE SESSION

### 1.1 Opening of the Session

1.1.1 The first session of the CIMO Expert Team (ET) on New Technologies and Testbeds (NTTB) was opened on Monday, 4 March 2013 at 9:00, by Mr Arkadiy Koldaev, Chairman of ET-NTTB.

1.1.2 The list of participants is given in Annex I.

1.1.3 Dr Miroslav Ondras, Chief of the WMO Observing Systems Division, welcomed the participants. He noted that most experts from the team were from Europe and Asia, which have a lot of expertise on remote-sensing observations and thanked the experts for their willingness to share that expertise with WMO Members. He stressed the need to ensure the activities of the team support the development of WIGOS, particularly in the areas of standardization, interoperability and data compatibility and to include their outcomes in the appropriate WMO regulatory documents, such as the CIMO Guide and/or to publish them in IOM reports.

### 1.2 Adoption of the Agenda

The meeting adopted the Agenda as reproduced at the beginning of this report.

### 1.3 Working Arrangements for the Session

The working hours and tentative timetable for the meeting were agreed upon.

## 2. REPORT OF THE CHAIRPERSON

2.1 Mr Arkadyi Koldaev presented a summary of the activities of the CIMO ET-NTTB since April 2011, when the workplan of the team was agreed among members. He highlighted the progress and problems in each individual topic. He stressed some areas that would require particular attention. These included the monitoring of the outcomes of CIMO Testbeds, the traceability of vertical profiles in the atmosphere by various remote-sensing technologies, and strengthening the contribution of ET-NTTB to the implementation of WIGOS.

2.2 He proposed some new activities that ET-NTTB should consider addressing before the next CIMO session meeting in 2014:

- Testing of instruments in CIMO testbeds before their use in WIGOS,
- Elaboration of quality control (QC) procedures for new technology instruments involved in WIGOS,
- Sharing of information about potential operational use of new technologies in NMHSs, and
- Possible simplification of the mechanism to include information on new technologies in the CIMO Guide.

These topics will be discussed in further details in the relevant agenda items.

## 3. WIGOS FRAMEWORK IMPLEMENTATION

### 3.1 Update on progress in WMO

3.1.1 The meeting was informed about the status of development of WIGOS, which is one of the priority areas of WMO. It was also informed in more details about the WIGOS Implementation Plan

(WIP), which identifies 10 key activity areas and activities needed to be carried out in the coming years to support the development of WIGOS. The ET was invited to identify which of the WIP activities it could support, and to align its workplan accordingly. It was stressed that Congress had requested all Technical Commissions to realign their workplans to support WIGOS activities.

3.1.2 The general approach used in developing the WIGOS section of the WMO Technical Regulations was presented to the meeting. It assumes:

- Phasing out of the Manual on the GOS (WMO-No. 544) and
- No separate Manuals on WIGOS, GAW, GCW, WHYCOS or CIMO.

The key principles to be applied in developing the WIGOS sections of the WMO Technical Regulations accordingly were highlighted.

3.1.3 The meeting noted that some countries had made positive progress with integration, while others were struggling with various operators applying totally different standards, or no standards, for example, for the siting of instruments. It noted that sharing “success stories” on integration would be very valuable to motivate various entities to adhere to the WIGOS principles and recommended that such experience be published in relevant WIGOS outreach documents so that they could be easily accessible and shared.

3.1.4 New technologies tend to be associated with increasingly expensive instrumentation, which are not always easy to put into operational use as they require personnel with relatively high qualifications to operate and maintain them. However, the meeting recognized that it could play an important role in providing information on simpler and cheaper new instrumentation that can be easily used and maintained, and decided to address this when reviewing its workplan.

3.1.5 The meeting reviewed the WIP and its workplan to verify whether its activities were in-line with the WIP and to identify other possible activities that it should engage in. The meeting clarified the wording of some of its tasks to better reflect their link to WIGOS and identified to which WIP activities each of its tasks are contributing. (see revised ET Workplan in Annex V).

### 3.2 **Proposed Expert Team contributions to WIGOS Framework Implementation**

3.2.1 Mr Koldaev presented his views on how ET-NTTB could contribute with new/enhanced activities to achieving the goals of WIGOS. The meeting addressed each of them and the relevant decisions are listed below.

3.2.2 Mr Koldaev proposed that a formal approval procedure should be established for instruments which are going to be implemented in WIGOS through the testing of these instruments at WMO CIMO nominated testbeds. The meeting recognized that this would be very valuable for testing the performance of new instrumentation and would possibly also reduce the need for other instrument intercomparisons. However, the meeting noted that this was beyond the present scope of CIMO Testbeds and also that additional testbeds would be required to be able to cope with all types of instruments to test and to cover all relevant climatic conditions. Also, it might be difficult to find appropriate ways to test specific instrumentation, like radars or lightning detection systems. The consequences of such a procedure would have to be carefully assessed and it should be made sure that it would be sustainable, not depending on the willingness of single persons, nor single NMHSs. The meeting decided to develop a discussion paper on this subject, addressing potential problems, including possible impact on existing centres (like RICs), which would be submitted to the next session of the CIMO Management Group for consideration and later possibly proposed to ICG-WIGOS for inclusion in the WIGOS Framework. The meeting included this new activity in its workplan (see Annex V).

3.2.3 The meeting agreed with the need to develop requirements and quality control procedures for new technologies in WIGOS. It recognized that this could be achieved within its existing workplan.

3.2.4 Mr Koldaev proposed that a way to collect and share “success stories” on the early implementation of new technologies and new instruments types should be considered. The meeting agreed that such information would be very valuable and could be shared through the

CIMO Newsletter when it is revived. It would require a push-mechanism to ensure a large number of WMO Members and NMHS experts get this information rather then to rely on them checking a website. The meeting noted that this would require additional support from the WMO Secretariat. The meeting recommended to the Management Group to consider:

- Creating an area on the CIMO website, where links to such experience published elsewhere could be collected,
- Consider options to revive the CIMO newsletter, possibly by including a “News Editor” in the future CIMO structure that would be responsible for collecting information from all ETs, editing it and forwarding it to all CIMO experts and other interested persons.

3.2.5 The meeting considered possibilities to simplify the incorporation of information on new technologies into the CIMO Guide. However, it noted that the CIMO Guide should be used to share information on new technologies that are mature enough for operational use, and that it would not be appropriate for new technologies that still require additional testing/development before they would be easily deployed operationally. The meeting felt that information on new technologies still in development could be shared through the CIMO website.

## 4. GUIDANCE ON METEOROLOGICAL USE OF GNSS

### 4.1 **Status of development of IOM Report on GNSS**

4.1.1 Mr Siebren de Haan presented a document on “Guidelines on the operational use and data exchange protocols for GNSS water vapor”. An earlier version of that document had been presented to an earlier CIMO ET session. It was further developed in collaboration with GRUAN experts, as it was expected that it could also serve as a reference document within GRUAN. In its present state, the document is targeted to operational use, but would still require some amendments to meet the needs of climate applications which require reprocessing of the data from time to time.

4.1.2 The meeting agreed that this document was very valuable and should be published as an IOM report. It requested all ET members to make a final review of the document (together with other relevant experts from their services) and provide their final comments to Mr de Haan by Mid-April 2013, so that he can finalize it by mid-2013, including the part on climate applications.

4.1.3 Most GNSS stations are operated by geodetic surveys, while NMHSs operate only very few stations. The meeting recognized that the data processing is the core issue of the system.

4.1.4 The noise level of real-time data is fairly high, but it can be improved using a larger number of satellites and/or waiting for more precise orbit information, which takes typically two weeks, as larger statistics need to be accumulated.

4.1.5 It was recognized that it would be valuable if the software used for GNSS water vapor retrieval could be standardized, though the data from different systems tend to agree within 10%. However, the meeting noted that it would be difficult to achieve such a standardization as the geodetic services are providing that information at no cost to NMHSs and that it would not be worth pursuing at this time.

4.1.6 The meeting noted that the main meteorological application for GNSS data is NWP which assimilates the total time delay, while the integrated water content is used for verifying model outputs.

### 4.2 **Status of review of CIMO Guide chapter**

4.2.1 The meeting agreed that GNSS water vapour retrieval is a technique that is mature enough for operational use and that it is essential to properly cover it in the CIMO Guide. However, the meeting agreed that the information that would have to be included in the CIMO Guide would differ somewhat from the IOM report, requiring for example information on where to site GNSS stations, etc.

## 5. GUIDANCE ON OPERATIONAL USE OF PASSIVE MICROWAVE PROFILERS

### 5.1 Status of development of guidance material on operational use of passive microwave profilers

5.1.1 Mr Arkady Koldaev presented a draft document named "Guidance material on passive microwave profilers and proposed update for the CIMO guide", which is intended to provide an introduction on this technology. This document provides information on the practical utilization of Ground Based Microwave Profilers. It describes theoretical principles of operation for angle scanning mode of operation, areas of applications, practical recommendations for installations, regular operation and data quality control, maintenance instructions and data utilizations. He noted that microwave radiometers profiles can be used to complement the data obtained at most twice a day by radiosondes. These instruments can be operated continuously and provide information up to a height of 10 km. They cannot be operated during precipitation events without the uncertainty of the measurements being dramatically increased.

5.1.2 The meeting recommended that the document be expanded somewhat to cover additional aspects of this technique, including an analysis of the uncertainties of such measurements, height resolution estimation and how these estimates are obtained. It requested all ET members to review the document (together with other relevant experts from their services) and provide their comments and suggestions to Mr Koldaev by end of April 2013, so that he could further develop the document towards publishing it as an IOM report.

### 5.2 Status of review of CIMO Guide chapter

5.2.1 The meeting noted that microwave radiometry was already succinctly addressed in the CIMO Guide. In view of the very limited operational implementation of ground based microwave radiometers world wide, the meeting felt that it would be premature to include the content of the document mentioned above into the CIMO Guide.

## 6. STANDARDS ON LIDARS

### 6.1 Status of development of ISO standards

6.1.1 The meeting was informed on the development of ISO standards relevant to its work, which are under the responsibility of ISO Technical Committee 146 "Air Quality", Sub-Committee 5 "Meteorology" (ISO TC146/SC5). One standard has been published: ISO 28902-1:2012 Air quality -- Environmental meteorology -- Part 1: Ground-based remote sensing of visual range by lidar. Another standard, ISO/WD 28902-2 Air quality -- Environmental meteorology -- Part 2: Ground-based remote sensing by Doppler wind lidar, is presently under development. Furthermore, the activity of the ISO working group dealing with backscatter aerosol lidar has been withdrawn in 2010.

6.1.2 A working group was set-up by ISO a year ago to develop the second standard and has monthly meetings. The meeting recommended that more wind lidar experts (and members of ET-NTTB) actively participate in this activity.

6.1.3 The meeting noted that there is a very strong demand for Doppler wind lidar systems, in particular for applications such as wind energy, airport weather, meteorology and climate monitoring. It recommended that the standard also includes a complete uncertainty analysis of the system and the validation of the system.

6.1.4 The meeting was informed that the WMO Secretary-General approached ISO to seek its concurrence to further develop two standards as common ISO-WMO standards. One of them is the standard on Ground-based Remote Sensing by Doppler Wind Lidars mentioned above. ISO responded positively to this request. Mr Arnoud Apituley is taking part in this work, representing CIMO and more generally WMO. The meeting therefore recommended that WMO formally nominates him as WMO liaison person for this task, as well as Dirk Klugmann and Masahisa Nakazato.

6.1.5 The meeting noted that in the context of the Working Arrangements between WMO and ISO, the word "standard" is meant as defined by ISO/IEC Guide 2:2004[1]. In this context, a standard is a document describing a procedure to be followed and does not have the meaning of a WMO standard practice, which requires Members to implement it. ISO standards are voluntary, as long as they are not specified as mandatory in regulatory documents, such as the WMO Technical Regulations and Manuals.

### 6.2 Status of development of other standards

6.2.1 There are many standardization activities for wind Doppler lidars. IEC (International Electrotechnical Commission) has an expert group which is finalizing the IEC standard entitled "IEC 61400-12-1: Power performances measurements with remote sensing" for the end of 2013. IEA (International Energy Agency) has an expert group which has been established to work on wind resource assessment. The activities of both IEC and IEA are dedicated to wind energy and are more focused on short range (0 – 200m) vertical wind Doppler lidars, while the activities of ISO are more relevant for broader scale meteorology.

## 7. DEVELOPMENT AND IMPLEMENTATION OF NEW REMOTE-SENSING TECHNOLOGIES AND THEIR OPERATIONAL APPLICATION

### 7.1 Microwave Radiometers (MWR)

7.1.1 The meeting was informed about some operational deployments of microwave radiometers. These include a private network in USA for meso-scale prediction and storm warning, a network in India targeted at operational weather forecasting and nowcasting, in Russian Federation for monitoring of fast global changes like consequences of catastrophes, and some individual instruments used for specific purposes, such as in support of the winter Olympic games in Sochi (Russian Federation). Another network has been deployed in Republic of Korea targeted at heavy rainfall conditions, which is proving very challenging in view of the limited performances of MWR in such conditions.

7.1.2 Though numerous manufacturers commercialize microwave radiometers for satellite applications, only few companies have serial production of microware radiometers for ground-based meteorological applications.

7.1.3 Scientific use of these instruments is possible however they require considerable maintenance/support. More validation of MWR data will be required to better assess their quality so that they could be assimilated in NWP.

7.1.4 The meeting recognized that MWR technology could not yet be considered as mature enough for operational use by NMHSs.

### 7.2 Global Navigation Satellite System (GNSS)

7.2.1 At present, NOAA is processing over 400 GNSS sites in the United States and Pacific on an hourly basis. This data is exchanged through the EUMETNET programme E-GVAP.

7.2.2 In Europe, the E-GVAP coordinates the processing and distribution of GNSS observables for meteorology. The data produced through this facility are distributed on the GTS.

---

[1] According to ISO/IEC Guide 2:2004 a standard is a document, established by consensus and approved by a recognized body, that provides, for common and repeated use, rules, guidelines or characteristics for activities or their results, aimed at the achievement of the optimum degree of order in a given context
NOTE Standards should be based on the consolidated results of science, technology and experience, and aimed at the promotion of optimum community benefits.

7.2.3 Other regions have GNSS receivers and networks installed. The meeting recognized that access to this data would be beneficial for regional and global meteorological applications,

7.2.4 At present the GNSS observables are used in Numerical Weather Prediction models at least at NOAA-ESRL, the MetOffice, MeteoFrance and KNMI. Forecasters at the MetOffice use the GNSS maps to validate the models.

7.2.5 The meeting recognized that access to GNSS raw data alone is not enough but that processing is essential for acquiring meteorological observables. Access to global GNSS data, on the other hand, has the potential to be very valuable for global NWP models. Exchange of raw GNSS data and processing at one of the global GNSS processing centres might be helpful.

7.2.6 The current use of the GNSS network data is focused on (near) real time. Close collaboration with GRUAN is needed in order to acquire consistent climate data from GNSS.

## 7.3 Water-vapor LIDARs

7.3.1 It has been demonstrated that water vapor Raman lidar can be operationally deployed during daytime and nighttime (see technology status provided in Annex II). However, since the instrumental requirements are demanding, these instruments are sizeable and expensive (> 1 Million USD). The number of instruments that are available is small and these tend to be located at atmospheric supersites, such as the ARM sites, Payerne, and Lindenberg Testbeds.

7.3.2 Calibration (SI traceability) is an important issue for this technology, in particular for climate monitoring applications.

7.3.3 The Differential Absorption Lidar (DIAL) technique is an alternative technique for water vapor measurements that is self calibrated. Up to now, the required laser technology has prevented wide spread application beyond the research domain. However, recent developments in laser technology will enable the deployment of small autonomously operated water vapor DIAL systems for profiling the lowest few kilometres of the atmosphere. Commercial developments of such instruments are ongoing. Such systems may become available for operational use in e.g. NWP data assimilation.

7.3.4 The meeting recommended that:

- Traceability for water vapor Raman lidar is undertaken by the GRUAN community and that ET-NTTB collaborates with GRUAN to ensure the transfer of knowledge.
- The development of the ceilometer-style water vapour DIAL systems should be closely monitored by ET-NTTB. Information about the status of the developments should be sourced with the (US) groups involved in the developments.
- Manufacturers be encouraged to develop robust instruments of both (Raman and DIAL) technologies with stable calibration for operational applications.

## 7.4 Wind-finding

7.4.1 Several wind finding technologies were discussed. It was observed that an overlap exists between ET-NTTB and the CIMO Expert Team on Operational Remote Sensing dealing with wind profiling. Care should be taken to harmonise recommendations between both ETs.

7.4.2 No new developments are known in SODAR. SODARs are widely used for security matters (nuclear power plant monitoring).

7.4.3 The meeting was informed that several campaigns have been performed in the framework of various projects in USA (ARM project) and in Europe (COST Action 0702-EGCLIMET) in order to evaluate the operation rate and the accuracy of Wind Doppler lidars in terms of horizontal wind speed and wind direction. These results showed that during those campaigns the Doppler lidars had operation rate higher than 90% and they worked in various conditions from summer to winter and even with rain and snow. This data analysis showed that the measurement range is linked with cloud height when looking vertically and with visibility when looking in the PBL. During these campaigns, compared to radiosoundings and radar wind profilers, the Doppler lidars had a typical bias of less than 0.5 m/s for the wind speed and less than 2° for the wind direction.

7.4.4 The fields of application of these techniques are very diverse and there is a growing interest for the Wind Doppler lidar technology for the following domain: wind energy for wind resource assessment of a given region, meteorology for the vertical profiling of PBL, industrial impact like nuclear power plants, and also wind hazards for the air traffic management like wind shears and wake vortices. Over the world, there are roughly 500 Doppler lidars that are deployed mostly for wind energy applications. Several operational deployments have also been performed for wind shear detection and a lot of research studies in ATM projects like SESAR in Europe are on-going whose purpose is to handle the risk of wake vortices.

7.4.5 With regard to Doppler wind lidar (see above paragraphs). It should be noted that other wind lidar techniques exist, but these were not discussed in details by the meeting.

7.4.6 The meeting recommended that:

- For windprofilers, ET-NTTB harmonises its recommendations with those of CIMO ET-ORS.
- ET-NTTB monitor properties and progress of wind lidar technologies and other new developments in these domains.

## 7.5 Cloud Radars

7.5.1 Millimeter wave radars have been used for meteorological research since the late 1950s, when a large number of combined Ka and X band radars were introduced in the former USSR. The first Ka band radar exclusively used for meteorological research was operated by NOAA / WPL – later NOAA / ETL – in the USA. The first W band radar for meteorological research was operated by Miami University in the USA. All of these systems were based on vacuum tube technology. The first semiconductor based millimetre wave radars were put in service by Hamburg University in Germany (W band) and Rutherford Appleton Laboratories in the UK (Y band, later converted to W band) in the second half of the 1990s.

7.5.2 Millimeter wave radars have been and are applied successfully for many different research topics. These include projects on aircraft icing hazard, climate change monitoring (e.g. ARM) and understanding atmospheric processes and aerosol-cloud interactions (e.g. CLOUDNET). The main benefits of millimeter wave radars over optical remote sensing instruments (e.g. lidar, ceilometer) are their ability to penetrate optically dense clouds and to detect multiple cloud layers. Doppler radars also allow direct assessment of information about cloud droplet size distribution and contribute information on precipitation. Currently roughly a dozen millimeter wave radars – both Ka and W band – are in use for meteorological research. These are either operated at fixed sites or on mobile platforms for specific research campaigns.

7.5.3 To the participants' knowledge four types of millimeter wave radars are commercially available currently, all of these operated in Ka band. An additional type of radar operated at W band has been announced recently by one manufacturer. To the participants' knowledge there is no operational application by any National Meteorological and Hydrological Service (NMHS) globally, though some of the aforementioned research systems are operated by research branches of NMHSs. Potential future operational applications at NHMSs include Numerical Weather Prediction (NWP) model verification (cloud output), data assimilation into NWP models and provision of cloud information for forecasters.

## 7.6 Aerosol and volcanic ash detection

7.6.1 Mr Arnoud Apituley presented a document providing an overview of techniques available for aerosol and volcanic ash detection. It covered both active and passive techniques, some of them being new developments while others are more mature (see Annex III).

7.6.2 Multi-Axis Differential Optical Absorption Spectroscopy (MAX-DOAS) is a technique to measure trace gas amounts in the lower troposphere from ground-based scattered sunlight observations. MAX-DOAS observations have a representative range of several kilometers, both in the horizontal and in the vertical dimension. A two-step retrieval scheme was developed to derive aerosol corrected tropospheric $NO_2$ columns from MAX-DOAS observations. In a first step, boundary layer aerosols, characterized in terms of aerosol optical depth (AOD), are estimated from relative intensity observations, which are defined as the ratio of the sky radiance at elevation α and the sky radiance in the zenith. Relative intensity measurements have the advantage of a strong dependence on boundary layer AOD and almost no dependence on boundary layer height. In a second step, tropospheric $NO_2$ columns are derived from differential slant columns, based on AOD-dependent air mass factors.

7.6.3 Used in a slightly different way, MAX-DOAS allows derivation of information on the aerosol extinction profile and optical/microphysical properties by passive remote sensing. While established passive remote sensing techniques using sun photometers only provide the total optical depth, information on the aerosol vertical distribution is derived from measurements of the optical depth of the oxygen dimer ($O_4$) in addition to the (relative) intensity of diffuse skylight at different viewing directions and wavelengths by MAX-DOAS. The comparison to established techniques measuring aerosol optical properties like the extinction profile and the total optical depth demonstrates that MAX-DOAS has the capability to derive information on atmospheric aerosols. The MAX-DOAS instrumentation has the advantage that relatively simple set-ups can be built at affordable cost. The retrieval, however, in particular when vertical profiles are derived, are indirect and have been known to diverge.

7.6.4 Mr Ludovic Thobois made a presentation on automatic operational lidars equipped with nitrogen Raman and dual polarized lidar that are now commercially available. This kind of sensor combines the benefits of both ceilometer (low cost, hardiness and networking) and lidar systems (low overlap and high measurement range, accuracy on optical properties, capabilities in aerosols detection and classification). These sensors are working at 355 nm wavelength.

7.6.5 The demonstrated technical performance of these sensors is a radial range for elastic channels of between 13 and 20 km for day and nighttime respectively. The range of the Nitrogen Raman channel is 15 km during nighttime and 2 to 3 km during daytime. The common overlap is 150 m. Structure detection based on the two depolarization channels is essential to be able to detect any type of clouds and aerosol layers. The optical properties are retrieved in an accurate way (AOD error less than 10% demonstrated compared to sun photometers) thanks to the Raman channel which allows to determine the lidar ratio and which acts as an auto-calibration and real-time method. Some instrumental and post-processing comparisons have been performed between these systems and their post-processing chains to an Earlinet lidar and the SCC. They showed a good correlation on extinction and backscatter coefficients. These results have been presented in the COST EG-CLIMET group and at the ISTP, ILRC, ISARS and AMS conferences in 2012 and will be published this year in peer-reviewed literature.

7.6.6 Aerosol classification can be performed in an accurate way by using depolarization and lidar ratios in 5 different classes (maritime, continental, dust, ash and ice crystals). An automatic algorithm has been able to determine structure detection, optical properties and clouds and aerosols classification. Several cases of clouds, Saharan dust observed in 2012, and ash during the 2011 eruption have been presented. The classification method performs quite well when looking at back-trajectory models.

***Volcanic Ash Detection***

7.6.7 A special case of atmospheric aerosols is volcanic ash, in the event that they are present after major volcanic eruptions. Recent major volcanic eruptions have caused disruption of air traffic. In particular, the eruption of the Eyjafjallajökull, Iceland in 2010, the Grimsvötn, Iceland in 2011 and the Puyeheye, Chili in 2011.

7.6.8 According to the Volcanic Ash Advisory Centres (VAAC) the criteria for the decision for safe use of the airspace are:

a) The location of the volcanic ash plume,
b) The height of the volcanic ash plume,
c) The mass concentration of volcanic ash in the plume.

7.6.9 Passive remote sensing techniques, such as satellite imagery are able to detect the location of the ash plume, provided the visibility of the plume is not hampered by presence of clouds. However, these passive techniques rely on indirect and therefore uncertain means to derive information related to the ash plume altitude. For the ash layer height, the contribution of lidar measurements, which provides direct range-resolved information, is invaluable, particularly the networked observations, from which spatio-temporal information can be obtained.

7.6.10 No present remote sensing method is capable of directly estimating ash mass density. All present remote-sensing approaches rely on first estimating the ash optical properties and then using a model of some sort to convert to mass density. High-performance Raman or High-Spectral-Resolution (HSRL) systems are best suited for the accurate estimation of aerosol optical properties such as extinction and backscatter. However, such systems are relatively large and expensive and, with few exceptions, do not operate in continuous (24/7) mode. A few types of smaller sized Raman lidars are commercially available that are capable of operating around the clock. However, daytime capabilities are restricted to the elastic wavelengths, while Raman capabilities during daytime are limited. On the other hand, given suitable circumstances, simpler polarization sensitive backscatter lidars that do routinely operate continuously can provide near real-time estimates of ash optical properties. These estimates are more indirect than those derived using Raman or HSRL lidar data. However, this is largely out-weighted for the purposes of air safety since quantitative estimates of ash mass loading are provided in near real-time. The uncertainty in this parameter is likely dominated by the uncertainty associated with the conversion from the ash optical properties to mass. Therefore, an automated procedure using continuous measurements is useful for operational purposes even if the accuracy is less than that which can be delivered by e.g. a Raman system.

7.6.11 In response to the eruption of the Eyjafjallajökull, a lidar technique has been developed that is able to autonomously estimate the volcanic ash concentration on the ash layer based on depolarization lidar measurements (Donovan, Appl. Opt, accepted for publication, 2013).

7.6.12 In order to successfully employ this technique in a near real-time fashion to a depolarization lidar (or lidar network) specifically for ash quantification then the following example set of high-level requirements can be formulated.

- The system must be appropriately reliable and capable of 24/7 unattended all-weather operation. Recently, automatic operational lidars equipped with nitrogen Raman and dual polarized lidar are now commercially available. This kind of sensor combines the benefits of both ceilometer (low cost, hardiness and networking) and lidar systems (low overlap and high measurement range, accuracy on optical properties, capabilities in aerosols detection and classification). These sensors should be eye-safe and satisfy local regulations. Special attention must be paid to laser technologies which must ensure a 24/7 operation and a minimum operation costs.
- The system should be able to detect clear air scattering (Rayleigh scattering).
- The depolarization inter-channel calibration and cross-talk coefficient should be well characterized and stable with accuracy better than 5%. The cross-talk should ideally be minimized, which leads to reduced errors in the derived extinction and therefore reduced error in the mass estimates.
- The power levels, system collection efficiency etc. should be such that a volume depolarization ratio of 30% at 7 km can be measured with a precision of better than 5% for a spatial/temporal resolution of on the order of 100 m and 15 min. This would enable the quantification of aerosol backscatter at 7 km (corresponding roughly to a mass density on the order of 2 mg/m$^{-3}$) to within about 50 %.

7.6.13 The remaining significant source of uncertainty is the conversion of the optical extinction measurements into mass estimates. Significantly different conversion factors can be found in the recent literature for the recent volcanic events. Looking ahead to any hypothetical future eruption, this uncertainty could result in inconsistent mass estimates being generated by different institutions/agencies/research groups. It is recommended that work be done that leads to consistent guidelines regarding appropriate conversion factors and associated uncertainty ranges.

7.6.14 It would seem feasible to deploy such depolarization lidars in a volcanic ash surveillance system.

- These lidars should be put in strategic locations, covering the most sensitive infrastructures, e.g. upwind from aerodromes and major air corridors. The density of the network should depend on the location and geographic extent of the sensitive areas.
- The lidars should be taken up in the (largely existing) networks of lidar ceilometers, to improve spatial coverage. The ceilometer data can be used to interpolate the location and properties of the ash plume.
- Satellite data is the most important source of observations of the spatial (horizontal) distribution of ash. Various satellite products are available to distinguish ash from other aerosols and clouds, but the satellite data needs to be corroborated by active (ground based) remote sensing techniques, e.g. lidar, and to provide reliable and usefully accurate estimates of the mass concentration.
- Particle dispersion models are invaluable for the prediction of the spreading of the ash plume in the event of an eruption. Remote sensing data, both active and passive, is needed for the correct interpretation of the model results.

7.6.15 The meeting noted that during daytime sunphotometers collocated with lidar systems can increase the accuracy of volcanic ash detection. The data has to be processed rapidly (almost real-time). This prevents NMHSs needing to rely on a centrally managed network, like Aeronet in the case of sunphotometers, which provides the processed data with a significant delay, but requires them to do the processing themselves.

7.6.16 The meeting recognized that it would be very valuable to carry out an instrument intercomparison targeted at the detection and measure of volcanic ashes. It therefore decided to develop a concept paper/feasibility study that could be presented to the next CIMO session for consideration/approval.

7.6.17 Mr Pablo Ristori provided a presentation on a LIDAR network project that was developed and implemented in a very short time following a major volcanic eruption in Argentina. Due to the proximity of the volcano, the ash fell on the ground and could be lifted again by wind, even months after the event. A short summary of the project is provided in Annex IV.

***LOAC***

7.6.18 Mr Jean-Baptiste Renard provided a presentation on the LOAC (Light Optical Aerosol Counter), which is a new generation of aerosol counter/sizer that can be carried by all kinds of balloons. The instrument has a weight of ~250 grams and a low electric consumption. The measurements are conducted at two scattering angles: the first one, at 12°, is used to determine the aerosol particle concentrations in 19 size classes within a diameter range of 0.3-100 µm. With such an angle close to forward scattering, the signal is much more intense and the measurements are not strongly sensitive to the nature of the particles. The second angle is at 60°, where the scattered light is strongly dependent on the particle refractive index and thus on the nature of the aerosols. The ratio of the measurements at the two angles is used to discriminate between the different types of particles dominating in the different size classes (liquids, carbons, minerals).

7.6.19 Since 2011, several copies of LOAC were flown under zero pressure stratospheric balloons, low altitude pressured balloons and meteorological balloons. For the meteorological balloons flights, the total weight of the gondola including batteries, PTU sensors and the telemetry is 1 kg. Tens of LOAC units are already involved in different scientific projects: AEROWAVE (Zero pressure and meteo balloons) for the study of aerosol nature in the stratosphere, VOLTAIRE labex (meteo balloons) for the study of volcanic plumes and of aerosols trend in the stratosphere, ChArMEx, (low altitude pressured balloons) for the transport of sand and pollution aerosols above Mediterranean Sea), and STRATEOLE (long duration flights) for the study of low stratosphere aerosols in the tropical stratosphere.

7.6.20 The meeting recommended that intercomparison campaigns with other well-established techniques be carried out to further demonstrate the capabilities of the system, before it could be considered for operational use.

## 7.7 Other

***Rainfall maps from cellular communication networks***

7.7.1 A new method has been developed to construct country-wide rainfall maps from cellular communication networks. This demonstrates the potential of such networks for real-time rainfall monitoring, in particular in those parts of the world where networks of dedicated ground-based rainfall sensors are often virtually absent.

7.7.2 The meeting noted the need to investigate the feasibility of implementing such methods in various countries around the world, in particular with respect to access to (privately owned) data for this purpose.

***Opportunistic use of DAB-T signals***

7.7.3 Bath University recently finished a feasibility study on the application of terrestrial Digital Audio Broadcasting (DAB-T) signals for assessing atmospheric parameters. Identical DAB-T signals are transmitted by various transmitters at the same time. As the location of the DAB-T transmitters is well known, the expected travel time of signals from individual transmitters to a receiver at a well known location can be calculated very precisely. From this the travel time difference of signals from different stations to any receiver can be calculated. Any change of the expected time difference can be attributed to the change of the atmospheric refractive index (and hence the speed of electromagnetic waves in that medium) due to atmospheric parameters (humidity, temperature, turbulence).

7.7.4 A similar approach is possible by using a single transmitter and a number of receivers. The only additional requirement is that signals at all receivers are time stamped with high accuracy (e.g. GNSS timing) to allow for exact calculation of the DAB-T signal's travel time differences. Combining multiple transmitters with multiple receivers will eventually allow for a 2-dimensional tomographic approach. The meeting was informed that the Met Office has agreed on starting a project to assess the operational applicability of this method in the Financial Year 2013/14.

***Additional information from Radar Profilers (aka Radar Wind Profilers)***

7.7.5 Currently only wind profiles (wind speed and direction) are used for data assimilation into and verification of output from Numerical Weather Prediction (NWP) models. These wind profiles are derived from the more basic moments profiles, which are not utilised to date. The zeroth moment profile provides the backscatter power with height, the first moment provides the (backscatter power weighted) average velocity and the second moment provides information about the turbulent spectral width. These moments are derived from the even more basic Doppler spectra at each height.

7.7.6 The zeroth moment profile is influenced by the gradient of temperature and humidity with height, and the presence of turbulence and dedicated layers (humidity or temperature) in the atmosphere. Due to the ambiguity introduced by this complex dependency on multiple atmospheric parameters, the retrieval of these parameters is not possible. But verification of NWP model output or assimilation into NWP models by means of a forward operator could provide significant benefits.

7.7.7 The first moment profile is influenced by vertical wind velocity and the presence of precipitation. The second moment profile is influenced by atmospheric turbulence and – as the first moment profile – by the presence of precipitation. For both moments, it again is difficult to discriminate between the contributing atmospheric parameters without additional information or a-priory assumptions. But as with the zeroth moment profile verification of NWP model output or assimilation into NWP models by means of a forward operator could provide significant benefits.

7.7.8 Utilisation of the full Doppler spectra profiles would allow assessing some atmospheric parameters without additional assumptions. These would be the vertical wind velocity and the drop size distribution in rain. From these information additional parameters like rain rate and liquid water content could be derived. Furthermore, utilisation of the full Doppler spectra profiles would allow assessing the melting / freezing level height above the radar profiler. This method is based on the significant change of the Doppler spectrum from frozen to liquid precipitation, which occurs at that height in the atmosphere, and on the temporary significant increase of the reflectivity while frozen hydrometeors are covered by liquid water during the melting process.

7.7.9 The meeting was informed that the Met Office will investigate the utilisation of additional information form cm wave Radar profilers (aka Radar Wind Profilers) starting with the Financial Year 2013/14.

## 8. MONITORING OF CIMO TESTBEDS

### 8.1 Status of testbed monitoring

8.1.1 Mr Won presented a report in which he had summarized the main outcomes of three CIMO Testbeds (TB) and two CIMO Lead Centres (LC) based on the activity reports they provided at the beginning of 2013. (The reports from one testbed and one lead centre were still not available at the time of this meeting.) Most of these TB and LC were nominated a year ago, which explains that they have not had time to carry out numerous activities.

8.1.2 The meeting was informed that there is a CIMO Task Team that has been tasked with the nomination and evaluation of the TB and LC, while the task of ET-NTTB is to review the outcomes of TB and LC towards coordinating the inclusion of relevant guidance material in IOM reports and in the CIMO Guide concerning the performance of surface-based remote-sensing technologies and the principles for an optimal mix of surface-based in-situ and remote-sensing systems.

8.1.3 The meeting recognized the value of testbeds to perform instrument intercomparisons and testing and therefore recommended that testbeds be further developed to be able to serve as “secondary standards” for remote-sensing instrument intercomparisons. In order to be able to assess the potential of TB to test and/or intercompare specific instruments, a list of the TB instruments and of their specifications would be needed. The meeting recommended that each TB provides such information and that the WMO Secretariat should endeavour to make it available through the CIMO website, possibly establishing a page for each TB and LC.

8.1.4 A proposal to expand the role of testbeds to perform a formal and mandatory testing of instruments which are going to be implemented in WIGOS was included in Section 3.2. The meeting encouraged WMO Members to submit additional proposals of CIMO Testbeds and Lead Centres.

### 8.2 Status report on examination of need for update to CIMO Guide

8.2.1 The meeting did not identify any need to update specific part of the CIMO Guide based on the present outcomes of CIMO Testbeds and Lead Centres.

## 9. SI TRACEABILITY OF REMOTELY SENSED ATMOSPHERIC VERTICAL PROFILES

### 9.1 Status report

9.1.1 The meeting recalled that traceability means the property of a measurement or the value of a standard where it can be related to a stated reference, usually national or international standards through an unbroken chain of comparison all having stated uncertainties.

9.1.2 Mr. Masahisa Nakazato presented a report of investigation related to SI traceability of the remote sensing instruments. For ensuring traceability of remote sensing instruments, it is necessary to obtain the calibration certificates issued by the National Metrology Institute (NMI) or other calibration authorities. As reference instruments traceable to SI, the in-situ instruments and radiosondes are usually available although there are some exceptions.

9.1.3 The meeting recognized that the calibration of the remote sensing instruments should be considered as consisting of two parts, namely the internal calibration and the external calibration (inter-comparison). The theory-based instruments such as that measuring the Doppler velocity and the self-calibrated instruments such as (water vapor) DIAL would be useful as a reference instrument suitable for SI traceability.

9.1.4 The meeting noted that for each remote sensing instrument further details about technical aspects should be explored such as measurable range, accuracy as a function of range, etc. New technologies related to calibration for respective instruments should further be developed.

9.1.5 Even though there are several ways to identify the traceability to SI of the remote sensing techniques in the laboratory, especially for the lidar systems as presented by Mr. Nakazato, it is still necessary to organize further field intercomparison experiments to validate the traceability of meteorological data under the real physical environment. CIMO Testbeds facilities should be encouraged to carry out such intercomparison and to consider the use of DIAL as a secondary standard, as it is a self-calibrated instrument.

9.1.6 The meeting recognized that there were some fundamental problems in ensuring the full traceability of some remote-sensing systems, because they are inferring atmospheric variables from other parameters, such as radiances.

9.1.7 The meeting supported the idea to make an intercomparison campaign of available operational ceilometers and lidars in focusing on accuracy of optical properties retrieval, on the sensitivity to detect aerosol layers, on the aerosol classification and on the maintenance and unmanned operations.

## 10. OTHER ACTIVITIES OF THE EXPERT TEAM

### 10.1 Remote sensing of snow depth by airborne and spaceborne systems

10.1.1 Mr Koldaev reported about first operational application of the passive microwave sounding of snow depth and snow water equivalent on board of snow mobile. The system consists of two radiometers operating at 0.8 cm and 21 cm wavelength, which are identical to the space-born instruments and are used for determining the same snow parameters. First results of the field experiments demonstrate very promising perspectives of operational application of the proposed technology. However, statistically valuable data about intercomparisons with manual measurements are highly necessary to validate the proposed technology.

### 10.2 Reliability and consistency of wind profiler measurements

10.2.1 Mr Koldaev presented a preliminary proposal on the “calibration” of wind profilers using in situ measurements, such as high tower measurements and tethersonde data. During the discussion, the meeting agreed in principal with the proposed ideas. The meeting agreed that this should be further investigated, possibly using the facilities of CIMO Testbeds and Lead Centres.

### 10.3 Wind and temperature observations from aircraft surveillance data

10.3.1 Wind and temperature observations can be inferred from data links established for air traffic control (ATC) purposes.

10.3.2 Mode-S Enhanced Surveillance (Mode-S EHS) and Mode-S Meteorological Routine Air Report (MRAR) require an interrogation of aircraft by a certified aeronautical agency. Automatic Dependent Surveillance Contract (ADS-C) information is triggered by for example airlines.

10.3.3 Mode-S EHS wind information has good quality (comparable to AMDAR) when appropriate corrections and calibration are applied. Temperature information from Mode-S EHS is of lower quality.

10.3.4 Mode-S MRAR and ADS-C wind and temperature information are of high quality.

10.3.5 KNMI is collecting in real time Mode-S EHS surveillance data from the dutch ATC (LVNL) and EUROCONTROL within the framework of SESAR WP 11.2. This data is operationally used in NWP. Mode-S MRAR is received by the Slovenian Met Service.

10.3.6 Mode-S EHS and Mode-S MRAR information can be locally received. The information content is equal to that received through ATC. The total amount is dependent on the quality of the antenna and receiver.

10.3.7 The Met Office is currently working on two projects for assessing the utilisation of MODE-S messages. One project investigates the use of MODE-S data received by the UK Civil Aviation Authority (CAA). The other project investigates the utilisation of the direct interception of the MODE-S messages transmitted by aircrafts upon interrogation by the Air Traffic Control.

## 11. ANY OTHER BUSINESS

11.1.1 The CIMO Guide has a number of chapters that are "parameter-oriented", while some others are "technology-oriented". The meeting recognized that there will be a need for properly linking the information provided in both types of chapters. The meeting recognized the need to ensure the guide provides guidance on how to use, operate and properly site all types of instruments.

11.2 The meeting reviewed the draft report of the session and decided to finalize it by correspondence.

## 12. WORK PLAN REVIEW

12.1 The meeting revised its workplan to incorporate the decisions taken during this meeting, as provided in Annex V.

## 13. CLOSURE OF THE SESSION

The session closed on Thursday, 7 March 2013 at 16:15 hours.

**ANNEX I**

## LIST OF PARTICIPANTS

| | |
|---|---|
| ***Chairman***<br><br>Arkadiy KOLDAEV | Roshydromet<br>RPA “TYPHOON”<br>3, Pervomayskaya Street<br>141700 DOLGOPRUDNY<br>Moscow Region<br>Russian Federation<br>tel.: +7 915 356 7252<br>fax: +7 495 562 39 59<br>avk425@mail.ru |
| ***Vice-chair***<br><br>Arnoud APITULEY | Royal Netherlands Meteorological Institute<br>Wilhelminalaan 10<br>P.O. Box 201<br>NL-3730 AE DE BILT<br>Netherlands<br>tel.: +31 30 220 6418<br>fax: +31 30 221 0407<br>apituley@knmi.nl |
| Pablo RISTORI | Laser and Applications Centre – Lidar Division<br>Ciudad Autonoma de Buenos Aires<br>Argentina<br>Tel : +54 9 11 61 77 2526<br>Fax : +54 11 4709 81 22<br>Pablo.ristori@gmail.com |
| GAO Yuchun | Meteorological Observation Centre<br>China Meteorological Administration<br>No. 46 Zhongguacun, Nandajie<br>BEIJING 100081<br>China<br>tel.: +86 10 6840 6966<br>fax: +86 10 6840 6956<br>gycaoc@cma.gov.cn |
| Dirk KLUGMANN | Met Office<br>FitzRoy Road<br>EXETER<br>Devon EX1 3PB<br>United Kingdom<br>tel.: +44 1392 88 56 44<br>fax: +44 1392 88 56 81<br>dirk.klugmann@metoffice.gov.uk |
| Siebren DE HAAN | Royal Netherlands Meteorological Institute<br>Wilhelminalaan 10<br>P.O. Box 201<br>NL-3730 AE DE BILT<br>Netherlands<br>tel.: +31 30 2206 745<br>fax: +31 30 2210 407<br>siebren.de.haan@knmi.nl |

| | |
|---|---|
| Masahisa NAKAZATO | Japan Meteorological Agency<br>1-3-4 Otemachi, Chiyoda-ku,<br>Tokyo 100-8122<br>Japan<br>tel.: 81-3-3212-8341(ext. 2157)<br>fax: +81-3-3211-7066<br>masahisa.nakazato-a@met.kishou.go.jp |
| Jae Gwang WON | Observation Infrastructure Bureau<br>Korea Meteorological Administration<br>45 Gisangcheong-gil<br>Dongjak-gu<br>SEOUL 156-720<br>Republic of Korea<br>tel.: +82 2 2181 0694<br>fax: +82 2 2181 0709<br>wonjg@kma.go.kr, ecotus37@korea.kr |
| Henk KLEIN BALTINK<br>(by teleconference) | Royal Netherlands Meteorological Institute<br>Wilhelminalaan 10<br>P.O. Box 201<br>NL-3730 AE DE BILT<br>Netherlands<br>tel.: +31 30 2206 476<br>fax: +31 30 2210 407<br>henk.klein.baltink@knmi.nl |
| ***HMEI Representative***<br><br>Rémy PEPIN | Modem<br>Rue de Bessonville<br>77760 URY<br>France<br>tel.: +33 1 60 74 74 60<br>fax: +33 1 60 74 74 19<br>rpepin@meteomodem.com |
| ***HMEI Representative***<br><br>Jean Baptiste RENARD | Laboratoire de Physique et Chimie de l'Environnement et de l'Espace (LPC2E)<br>34, avenue de la Recherche Scientifique<br>45071 Orléans Cedex 02<br>France<br>tel: +33 238 25 53 01<br>fax: +33 238 63 12 34<br>jbrenard@cnrs-orleans.fr |
| ***HMEI Representative***<br><br>Ludovic THOBOIS | LEOSPHERE<br>Lidar Environmental Observations<br>14/16 rue Jean Rostand<br>91400 Orsay<br>France<br>tel. : +33 6 62 26 01 98<br>lthobois@leosphere.com |

| **WMO SECRETARIAT**<br>7 bis, avenue de la Paix<br>Case postale 2300<br>CH 1211 Geneva 2<br>Switzerland | **IMOP website**<br><br>http://www.wmo.int/pages/prog/www/IMOP/IMOP-home.html |
|---|---|
| **Observing and Information Systems Department (OBS)** | |
| Isabelle RUEDI<br>Head, Instruments and Methods of Observation Unit (IMO) | Tel: +(41 22) 730 8278<br>Fax: +(41 22) 730 8021<br>E-mail iruedi@wmo.int |
| Roger ATKINSON<br>Scientific Officer, Instruments and Methods of Observation Unit (IMO) | Tel: +(41 22) 730 8011<br>Fax: +(41 22) 730 8021<br>E-mail ratkinson@wmo.int |
| Miroslav ONDRÁŠ<br>Chief, WMO Observing Systems Division | Tel.: +41 22 730 8409<br>Fax: +41 22 730 8021<br>E-mail: mondras@wmo.int |
| Dean LOCKETT<br>Scientific Officer, Aircraft Observation Unit | Tel: +(41 22) 730 8323<br>Fax: +(41 22) 730 8021<br>E-mail dlockett@wmo.int |
| Jerome LAFEUILLE<br><br>Chief, Space-based Observing System Division | Tel: +41 22 730 8228<br>Fax: +(41 22) 730 8021<br>Email: jlafeuille@wmo.int |


_______________

**ANNEX II**

# RAMAN WATER VAPOUR TECHNOLOGY STATUS

## Introduction

The Raman lidar technique is based on the lidar (light detection and ranging) principle, and utilizes the in-elastic Raman scattering by atmospheric molecules for the detection of these species. Water vapor has a sufficient Raman scattering cross section to be able to detect the Raman scattering by water vapor molecules using the lidar technique when the scattering is exited by laser ration at UV or visible wavelengths. The Raman lidar technique for water vapor (WVRL) measurements has been in development since (Melfi) and is now (semi) operationally used in a number of locations (ARM, MeteoSwiss, Lindenberg).

In order to develop WVRL for practical application a number of critical issues need to be addressed. These will be mentioned here briefly. A list of references is provided for further details.

This document currently restricts itself to ground based lidar techniques.

### *WVRL Calibration*

The water vapor Raman signal is proportional to the number concentration of water vapor molecules. A second lidar signal proportional to the air density is needed to convert the WV Raman signal to the WV mixing ratio. The Raman signal from atmospheric nitrogen gas molecules is usually taken for this, since this gas is uniformly mixed. Finally, this mixing ratio needs to be calibrated to obtain the measurement of the water vapor mixing ratio.

The calibration usually relies on an external, independent source of water vapor data. This can be for instance:

- Radio sonde data
- Microwave radiometer data
- GNSS data
- In situ sensor

Reliable calibration using these external sources relies on its turn on the calibration of those sources.

Then, the long-term stability of the calibration constant relies on the stability of the Raman lidar instrument. For instance, a change in the alignment or a change in the sensitivity of a detector sue to ageing will have an influence. This is one of the main points of concern for the viable application of this technique. There are solutions to monitor the stability of the calibration constant by means of a lamp (McDermid, LeBlanc). This again relies on the stability of the lamp emission and spectral stability.

Also, a technique has been developed to use a calibration lamp to calibrate the WVRL instrument without an external source (Venable). To date this approach has not been adopted in many locations.

### *Daytime performance*

Since the Raman lidar technique depends on relatively weak optical scattering, a relatively high power laser and large aperture receiving optics are needed. A large receiver is collecting more sky background illumination than a small aperture receiver. So, when measurements during daytime need to be taken, the WVRL benefits from a narrow field of view (i.e. the size of the disc in the sky that is observed by the receiving telescope) and narrow spectral band detection, as well as a powerful laser. These requirements make the stability of the system more critical. These requirements have been met for several WVRL systems, however, in order to measure the dry conditions at the top of the troposphere, the daylight background will always add noise to the measurement. Therefore, the WVRL technique is most powerful during nighttime conditions.

*Biases*

It has been reported that certain elements in a WVRL operating at UV wavelengths may be impeded by fluorescence issues, if not properly addressed. The fluorescence will induce a wet-bias in situations where very dry atmospheric conditions are measured (McDermid, LeBlanc). There is some debate whether or not these effects can be appropriately corrected for (depending also on the application), or that fundamental solutions should be applied (McDermid, LeBlanc, Whiteman).

*Operational application*

For the operational application of WVRL, a fully automated system is needed. This was first accomplished by Goldsmith et al. for the ARM CART Raman lidar. A couple of other examples have been put to operation (MeteoSwiss, Lindenberg). The full automation of a large scale Raman lidar, especially containing a high-power laser source, remains a challenging task. But in principle this remains a purely technical task that can be solved with proper sensors and software to handle conditions of exception that require instrument adjustment or, in ultimate cases, shutdown.

***Alternative techniques***

A few words could be said about alternatives to WVRL. For certain applications – for instance climate monitoring (i.e. trend detection) – the unbiased detection of dry conditions at the top of the tropopause and lower stratosphere (UTLS) are needed. This means the lidar system needs a large range as well as high accuracy. This is in general in contradiction with optimal daytime operation. On the other hand, numerical weather prediction (NWP) and studies of convective conditions using Large Eddy Simulations (LES) require also daytime operation, while demands on accuracy are somewhat relaxed due to the combination of the measurements with modeling. And NWP and LES benefit more from information about moisture in the boundary layer and lower free troposphere.

*Differential Absorption Lidar (DIAL)*

The differential Absorption Lidar technique relies lidar measurements at two wavelengths, one more absorbed by a certain species than the other. If the absorption cross sections of the species of interest are accurately known, and little or negligible interference can be assumed from other atmospheric trace gases, the DIAL technique is a self calibrating technique for measuring trace gases. For ground based application of the DIAL technique for UTLS WV the general shape of the vertical water vapor profile has the disadvantage that most WV is close to the Earths' surface so that most laser light is absorbed and no high accuracy measurements can be taken in the UTLS due to signal to noise constraints. However, high accuracy measurements can be taken, also during daytime, in the lower troposphere. This is attractive for NWP and LES applications. Moreover, the highly accurate low altitude profile could be used as a calibration source for high altitude WVRL measurements.

***Enabling (laser) technology developments***

The reliable long term operation of WVRL systems could benefit greatly from a new generation of high power (Nd:YAG) laser sources. Nowadays, the vast majority of these lasers is driven by fashlamps. These impose thermal stress on the lasing medium and require a very reliable cooling system for the safe operation of the laser – and therefore the lidar. In recent years, diode pumped Nd:YAG lasers that relieve some of these burdens, have become available, albeit at a relatively high cost. In case this diode pumped technology becomes available at a lower initial cost, more WVRL systems could become available for (networked) application of high accuracy, high altitude water vapour measurements.

With regard to the laser sources for DIAL techniques, recent developments in laser technology have enabled the construction of relatively low-cost WV-DIAL systems for application in the lower 5 km of the atmosphere that would be well suited for NWP and LES applications (Nehrir). These laser developments are presently under development for application in commercial lidar systems, that have the potential of a ‘Water Vapor Ceilometer’, i.e. a small trurn-key lidar for water vapor.

***References***

Melfi, S. H.: Remote Measurements of the Atmosphere Using Ra- man Scattering, Appl. Opt., 11, 1605–1610,

Goldsmith, J., Blair, F., Bisson, S., and Turner, D.: Turn-key Raman lidar for profiling atmospheric water vapor, clouds and aerosols, Applied Optics, 37, 4979–4990, 1998.

Leblanc, T. and McDermid, I. S.: Accuracy of Raman lidar water vapor calibration and its applicability to long-term measurements, Appl. Opt., 47, 5592–5603, 2008.

D. Venable, D. Whiteman, M. Calhoun, A. Dirisu, R. Connell, and E. Landulfo, "Lamp mapping technique for independent determination of the water vapor mixing ratio calibration factor for a Raman lidar system," Appl. Opt. 50, 4622-4632 (2011).

D. Whiteman, D. Venable, and E. Landulfo, "Comments on ``Accuracy of Raman lidar water vapor calibration and its applicability to long-term measurements’’," Appl. Opt. 50, 2170-2176 (2011).

Amin R. Nehrir, Kevin S. Repasky, and John L. Carlsten, Micropulse water vapor differential absorption lidar: transmitter design and performance, Optics Express, Vol. 20, Issue 22, pp. 25137-25151 (2012)

**ANNEX III**

# AEROSOL AND VOLCANIC ASH DETECTION TECHNOLOGY STATUS

***Introduction***

Aerosols play an important role in atmospheric pollution and as modulators of the radiation balance of the Earth's atmosphere. The atmospheric pollution is emitted essentially at the Earth's surface and is transported by atmospheric dynamical processes and modified over time through atmospheric chemical processes. Sources of aerosols can be natural (e.g. sea spray, desert dust) and of anthropogenic origin (air pollution, sometimes mineral dust is also regarded as anthropogenic if it is related to human activity). A special case of atmospheric aerosols is volcanic ash, in the event that they are present after major volcanic eruptions.

For aerosol detection, various remote sensing techniques exist, that can be divided in active and passive remote sensing techniques. In active remote sensing, the measuring instrument carries its own source of radiation that is emitted into the atmosphere, while the atmospheric response to the excitation by the emitted radiation is measured. From the response, atmospheric properties are inferred. Excitation sources are e.g. continuous wave or pulsed optical sources (lasers) or continuous wave or pulsed microwave sources. Passive remote sensing relies on an external, uncontrolled, source of radiation, such as the sun or microwave emissivity of the atmosphere. Again, from the response of the atmosphere to the radiation sources, atmospheric properties are inferred.

## 1. Passive aerosol remote sensing techniques

### 1.1 Mature techniques

#### 1.1.1 The sunphotometer (SPM)

The sunphotometer (SPM) is a photometer that tracks the sun and measures direct radiation. The measurements can be calibrated to yield the aerosol optical depth (AOD), that is the integrated attenuation by aerosols in a certain wavelength band. Usually, SPMs are equipped with multiple wavelength bands, so that wavelength dependence of the AOD can be obtained. The wavelength dependence is related to e.g. the size of the aerosols in the vertical column between the sun and the SPM. For a sufficiently equipped SPM, the total AOD observed can be split between a fine and course mode fraction (O'Neill). The SPM technique is applied in the Aerosol Robotic Network (AERONET). AERONET provides AOD information for a wide range of stations distributed over the globe.

### 1.2 New developments in passive aerosol remote sensing

#### 1.2.1 MaxDOAS

Multi-Axis Differential Optical Absorption Spectroscopy (MAX-DOAS) is a technique to measure trace gas amounts in the lower troposphere from ground-based scattered sunlight observations. MAX-DOAS observations have a representative range of several kilometers, both in the horizontal and in the vertical dimension. A two-step retrieval scheme was presented by Vlemmix (Vlemmix), to derive aerosol corrected tropospheric $NO_2$ columns from MAX- DOAS observations. In a first step, boundary layer aerosols, characterized in terms of aerosol optical depth (AOD), are estimated from relative intensity observations, which are defined as the ratio of the sky radiance at elevation $\alpha$ and the sky radiance in the zenith. Relative intensity measurements have the advantage of a strong dependence on boundary layer AOD and almost no dependence on boundary layer height. In a second step, tropospheric $NO_2$ columns are derived from differential slant columns, based on AOD-dependent air mass factors.

Multi-Axis Differential Optical Absorption Spectroscopy (MAX-DOAS) used in a slightly different way, allows to derive information on the aerosol extinction profile and optical/microphysical properties by passive remote sensing. While established passive remote sensing techniques using sun photometers only provide the total optical depth, information on the aerosol vertical distribution is derived from measurements of the optical depth of the oxygen dimer ($O_4$) in addition to the (relative) intensity of diffuse skylight at different viewing directions and wavelengths by MAX-DOAS (Zieger). The comparison to established techniques measuring aerosol optical properties like the extinction profile and the total optical depth demonstrates that MAX-DOAS has the capability to derive information on atmospheric aerosols. The MAX-DOAS instrumentation has the advantage that relatively simple set-ups can be built at affordable cost. The retrieval, however, in particular when vertical profiles are derived are indirect and have been known to diverge (various refs.).

#### 1.2.2 SPEX

An important challenge remote sensing is the retrieval of aerosol properties under cloudy conditions. Hasekamp describes the possibilities of multi-angle photo-polarimetry to perform a simultaneous retrieval of aerosol and cloud properties for partly cloudy scenes and for fully cloudy scenes from a satellite perspective where the aerosol layer is located above the cloud, using multi-angle photo-polarimetric measurements. Hasekamp shows that already for clear sky conditions polarization measurements are highly important for the retrieval of aerosol optical and microphysical properties from space over land surfaces with unknown reflection properties. Furthermore, it is shown that multi-angle photo-polarimetric measurements have the capability to distinguish between aerosols and clouds, and thus facilitate a simultaneous retrieval of aerosol and cloud properties. High accuracy (0.002–0.004) of the polarimetric measurements plays an essential role here. These techniques will now be applied for ground-based instrumentation capable of providing multi-angle photo-polarimetric data. In particular, the spectral modulation for full linear polarimetry technique, under the name of Spectropolarimetry for Exoplanet Exploration (SPEX) (Snik), is a new instrumental development that provides the possibilities of spectral modulation for full linear polarimetry using a device that contains no moving optical elements. The accuracy of the instrument is up to an order of magnitude higher than current techniques, and therefore gives access to the aerosol retrievals needed (Hasekamp, Stammes) to provide aerosol microphysical properties such as particle size, number density and refractive index. Currently, a ground based prototype of a SPEX instrument is in field-testing at Cabauw.

## 2. Active aerosol remote sensing techniques

The light detection and ranging (lidar) technique is an active remote sensing technique that is capable of unambiguous detection of the spatial distribution of aerosol particles in the atmosphere. Generally, a pulsed laser is emitted, and the range resolved atmospheric return is captured by an optical receiver system, detected by fast response photo detectors and subsequently recorded by transient digitizing equipment and/or photon counters. The basic lidar technique has been enhanced to be used fro many purposes, including trace gas detection, temperature measurements and atmospheric dynamics. However, it is true to say that any of the lidar techniques is capable of detecting aerosols. Below the lidar techniques specifically used for aerosol measurements are briefly highlighted.

### 2.1 Ceilometers

Ceilometers are small scale lidar instruments that are mainly designed for cloud base detection in e.g. airports. The aerosol information from this type of lidar is confined to the planetary boundary layer (PBL) since generally the signal to noise ratio of the atmospheric returns are insufficient to detect very tenuous aerosol layers on the free troposphere. The advantage of the ceilometers is that they are eye-safe under all conditions, and that useful information of atmospheric layering becomes available (Haeffelin, de Haij). Furthermore, ceilometer can be networked, so that vertical information about the build up of the atmosphere can be obtained (Thomas).

Recently, more powerful versions of ceilometers have become available, that are more capable of detecting aerosols in the free troposphere. Specific actions are under way to validate ceilometer data against more capable backscatter and Raman lidar instruments. (Thomas).

The fundamental limitation of ceilometers with respect to quantitative aerosol measurements is that critical assumptions need to be made for quantitative retrieval, and that SNR in the free troposphere is too low to detect clear air scattering, so that a proper calibration cannot be made.

Ceilometers networks are currently used for detecting cloud layers in the first kilometers of the atmosphere and for providing the cloud base height mainly for Air traffic control. Developments in the recent years showed the potential use of last generation ceilometers for PBL height detection and aerosol backscattering at least in the first kilometers of the atmosphere, under certain atmospheric conditions and with specific calibration procedures [3, 4, 5]. These new functionalities need to be carefully assessed in term of accuracy, quality check, bias, and operational capability, in order to confirm this potential and determine the limitations for operational use.

Suggested action: As suggested in Thomas, CIMO MG-10, October 2012, CIMO intercomparison of mature ceilometers and automatic lidars (Vaisala, Jenoptik and Leosphere types) are necessary due to the strong demand of the NMHS to propose an independent and accurate evaluation of the capabilities of each sensor : range of measurement (lower and higher ranges), sensitivity of each instrument by day and night to the aerosol detection in upper troposphere, cloud base detection, accuracy of backscattering retrieval, AOD accurary, stability over time under various weather conditions, real time and automatic calibration capability). A first intercomparison campaign has been conducted by Meteo-France during Summer 2012, using these various sensors. It could be use as a first reference.

### 2.2 Backscatter lidars

Backscatter lidars differ from ceilometers in general due to the high-average power. Therefore much better SNR can be obtained, but they are not always eye-safe, which is a limiting factor for autonomous unattended operation in general. High SNR can be obtained up to high altitudes, as high up as the stratosphere. However, as to the quantitative retrieval of aerosol properties similar limitations exist as for the ceilometers in the sense of unambiguous calibration. In case the backscatter lidar is able to detect clear air (Rayleigh) scattering, e.g. by using visible or UV wavelengths, a better calibration can be performed. Still, critical assumptions about the aerosol properties have to be made in the retrieval to the optical properties. This is a limiting factor for e.g. climate studies. Aerosol layering etc., can however be studied adequately. Also, in case multiple wavelengths are used from the UV to visible wavelengths, useful backscatter color ratios can be obtained. Backscatter lidars are commercially available, but operational use is still limited.

### 2.3 Scanning lidars

In order to solve the ill-posed problem that exist in backscatter lidar, scanning the lidar over a number of azimuthal angles can be performed, so as to generate more equations to solve multiple variables. It has been shown that under the assumption that the atmosphere is horizontally reasonably homogeneous, vertical aerosol backscatter and extinction profiles can be obtained at similar accuracies as from Raman lidars (Adam). However, the scanning backscatter lidar in general poses safety issues, limiting their operational use.

### 2.4 Aerosol Raman lidar

The Raman lidar technique utilizes rotational-vibrational Raman scattering off a homogeneously mixed gas such as nitrogen or oxygen. It therefore is able to separate backscatter and extinction information. A dataset consisting of an elastic lidar signal measured simultaneously with a Raman scattered signal (Ansmann, Whiteman) is needed. The technique has the advantage that a robust instrument can be built that does not require tedious wavelength tuning. In principle, an elastic backscatter lidar can be expanded to incorporate a Raman channel matched to the emitted wavelength of the backscatter lidar. A limitation of the Raman lidar technique is the relatively weak Raman scattering. For Raman lidar measurements a high power-aperture product (the laser power multiplied by the receiver collecting area) is required. It is therefore challenging to perform tropospheric aerosol measurements during daytime. A number of daytime capable aerosol Raman lidars is currently limited and are mainly in the research domain. Various manufacturers offer Raman capable lidars, although the Raman capability is mainly limited to night conditions. The aerosol Raman lidar technique is currently the backbone of quantitative aerosol research lidar networks, e.g. EARLINET, ADNET, GALION.

### 2.5 High spectral resolution lidar (HSRL)

The High Spectral Resolution lidar technique separated the molecular lidar return from the particulate lidar return by a high spectral resolution filter. The fact that particles are heavier than molecules provide the possibility to do this. Once the signals are separated, very similar possibilities become available for aerosol optical property retrieval as for aerosol Raman lidar (Shipley). However, HSRL has the advantage that only elastic scattering is used, so that sufficient signal can be obtained during daytime. This makes HSRL also suitable for airborne application (DLR, NASA). HSRL is also prepared for space application (ESA/Aeolus, ESA/EarthCARE). HSRL can be used in 24/7 operation, also in hash conditions such as in the arctic (Eloranta). HSRL has great potential for operational use, but the complexity of the instrumental requirements (laser technology), seems to be the limiting factor at the moment. Currently, no commercial versions of HSRL is available. Application is mainly limited to research applications (ARM).

### 2.6 Pure Rotational Raman lidar (PRRL) for temperature and aerosols

The pure rotational Raman lidar technique ulitizes the narrowly spaced pure rotational transitions close to the central Chabannes line of elastic scattering. The PRRL technique is mainly used for temperature profiling (Behrendt, Arshinov), but if the temperature sensitive channels are numerically added, the temperature dependence of the signals are virtually cancelled. What then remains is again similar to aerosol Raman lidar and HSRL. PRRL has also the advantage that stronger scattering is used, so that better daytime performance is obtained than with aerosol Raman lidar based on rotational-vibrational transitions. However, the stability of the instrument (laser, mechanincal, temperature) is more demanding. This technology is currently only in the research phase, but operational application has been demonstrated in Barbados (MPI, Serikov). This particular implementation uses fiber optic techniques and disperisive gratings, that a provide more robust instrument compared to the dichroic mirror approach. No commercial versions are available, but this technique may be further developed for PRRL systems that are smaller and more robust than rotational-vibrational Raman lidars, with comparable (daytime) performance.

### 2.7 New developments

#### 2.7.1 Aerosol Microphysical Property Rertieval

*Multi-wavelength Raman lidar*

Multi-wavelength Raman lidars have been able to provide aerosol optical property (backscatter and extinction) measurements at various wavelengths form the UV to the near infrared. It has been shown that from a minimum set of backscatter profiles at three wavelengths and extinction profiles at two wavelengths, vertical profiles of aerosol microphysical properties can be derived (Müller, Veselovski). A lidar that can provide such a dataset is referred to as a 3+2 lidar. These techniques, however, are very sensitive to the statistical and systematic errors in the lidar data, and results should always be generated with sufficient expertise during manual data interpretation. Recently, new algorithms have been developed based on the same 3+2 dataset, to derive aerosol microphysical properties using a principle component analysis (PCA) (de Graaf), or, an interesting recent approach is to also retrieve the refractive index from inversion of lidar measurements using 'linear estimation' (Veselovski). In the latter approach a fast inversion scheme, similar to the PCA technique, is performed for a large number of complex refractive index values. A best estimate of the complex refractive index is then found as a function of height and time by minimizing a cost function.

In summary, a number of muli-wavelength Raman lidar retrieval algorithms have been developed to obtain aerosol microphysical properties. These techniques could also be applied to multi-wavelength HSRL data sets (Burton).

*Simultaneous Lidar and SPM retrievals*

Active and passive remote sensing techniques for aerosols can be combined in a synergistic way. For instance, a lidar-SPM technique has been developed that is capable of merging the information from both instruments in an optimal way, so that vertically resolved profiles of the fine and course mode of the aerosols can be given, rather than a vertical backscatter profile and an integrated column that is divided in a fine and a course mode fraction (Chaikovsky). Where the LIRIC algorithm uses single or multi-wavelength elastic backscatter lidar data, new algorithms are currently under development that use advanced lidar data from (multi-wavelength) Raman lidars in addition to the SPM data. Depolarisation information from both the lidar and SPM can be taken into account. These algorithms are under development, mainly in the EC FP7-ACTRIS project.

## 3. Volcanic Ash detection

The continuous hazardous aerosol detection (dust, ash, forest fires, accidents) over the vertical in the troposphere requires networks of operational lidars or ceilometers that can observe the layers of interest at any altitude up to the maximum flying level, i.e. above 13km, and especially above 5 kilometers according to recommendations from VAAC (cruise level surveillance). The question of the sensitivity, and its evolution against height, to aerosol layers of the ceilometers or lidars deployed in a network is crucial for ensuring the detection capability of the network at any height, in case of need for immediate decision and for validation of the forecasting models outputs.

Moreover, these lidars and ceilometers must be capable to work automatically 24/7 mode and to provide reliable products. This tricky compromise can lead to the strategy of having two levels of networks, raising the risk not to be able to provide the needed met products. As many projects of establishing networks for aerosol and ash detection are going to start over the world, inter-comparison campaigns with accurate comparison protocol and specific data check must be proposed.

The volcanic ash resulting from the 2010 April-May eruptions of the Icelandic Eyjafjallajökull volcano caused widespread disruption to European air traffic. During the events, the spread of the ash was monitored by various ground-based, air-borne and space-borne remote-sensing systems and techniques. Also, dedicated flights were made to collect in-situ samples of the ash. The spread of the ash and analyses of the optical and physical properties has been documented in previous studies (various refs.). Since passive remote sensing techniques, such as visible imagery, must rely on indirect (and uncertain) means in order to derive information related to the ash plume altitude, the contribution of lidar measurements, which provide direct range-resolved information, was invaluable, particularly the networked observations (e.g. Pappalardo, Flentje), from which spatio-temporal information could be obtained.

The main driver for the closure of airspace was not the lack of information on the location of the ash, but rather on the quantitative mass concentration. No present remote sensing method is capable of directly estimating ash mass density and all present remote-sensing approaches rely on first estimating the ash optical properties and then using a model of some sort to convert to mass density. Given the present state-of-the-art of lidars in widespread operation there is little question that high-performance Raman or High-Spectral-Resolution (HSRL) systems are best suited for the accurate estimation of aerosol (including volcanic ash) optical properties such as extinction and backscatter. However, such systems are relatively large and expensive and, with few exceptions (e.g. ARM, MeteoSwiss), do not operate in continuous (24/7) mode. A few types of smaller sized Raman lidars are available that are capable of operating around the clock. However, daytime capabilities are restricted to the elastic wavelengths, while Raman capabilities during daytime are limited (PollyXT, Raymetrics). On the other hand, given suitable circumstances, simpler polarization sensitive backscatter lidars that do routinely operate continuously can provide timely useful estimates of ash optical properties, which is the subject of this paper. These estimates are more indirect than those derived using Raman or HSRL lidar data. However, this may not be a serious issue given that the for the purposes of, for example, air safety, quantitative estimates of ash mass loading are required in near-real-time (NRT) and the uncertainty in this parameter can be dominated by the uncertainty associated with the conversion from the ash optical properties to mass. Therefore, an automated procedure using continuous measurements is useful for operational purpose even if the accuracy is less than that that could be delivered by e.g. a Raman system. To be clear, within this context we talk of an ``automated procedure'' as a robust automated processing of lidar data and the generation of output, as opposed to manual inversions that usually still needed for Raman and HSRL techniques while unattended processing for Raman lidar data is still under way (d'Amico). The output from our technique must then be evaluated in a larger context together with other data streams (e.g. satellite observation and ash transport forecasts and cloud data) by appropriately experienced or trained personnel. Similar multi-data-stream synthesis evaluations are routinely carried within various meteorological agencies and the Volcanic Ash Advisory Center (VAAC).

When limited to single-wavelength visible or ultraviolet backscatter lidar data, traditional approaches for estimating the aerosol extinction profile typically involve (either explicitly or implicitly by e.g. choosing a reference range and a corresponding extinction boundary value) calibrating the lidar signal on a profile-by-profile basis. In this paper, we present a new technique for estimating optical backscatter and extinction profiles using the observed volume depolarization ratio and uncalibrated lidar backscatter signals. The depolarization calibration is not affected by e.g. laser power variations or variations in the near-field atmospheric transmittance and other such factors. Thus, the relevant depolarization calibration does not have to be performed on a profile-by-profile basis and hence a retrieval based on the depolarization ratio is well-suited to being applied in an automatic fashion.

The technique described in Donovan 2013, is specific to targets where the particulate depolarization ratio can be reasonably constrained a priori. It is demonstrated that the technique can be successfully applied to the particular case of volcanic ash layers even in the case where the ash may be mixed with non-depolarizing aerosol. The approach described here shares similar underlying concepts with approaches recently described by e.g. Ansmann (Ansmann.JGR.2011), Marenco and Hogan (Marenco.JGR.2011b) and Miffre et al. (Miffre.GRL.2011), which, in turn, are based on concepts previously described by e.g. Sugimoto et al. (Sugimoto.GRL.2003) and Tesche et al. (Tesche.JGR.2009). All of the aforementioned approaches exploit the difference between the observed volume (aerosol+Rayleigh) depolarization ratio and the expected particle depolarization ratio to help determine the aerosol backscatter profile and/or the degree of mixing between depolarizing and any non-depolarizing aerosol which may be present. The method presented in this paper unifies some of these concepts and extends upon them to not only estimate backscatter but to also extinction profiles in a self-consistent manner. Further, the implementation of a practical inversion procedure well-suited to automated operation is described.

For volcaninc ash measurements, depolarisation techiniques are essential. Obtaining mass estimates depends on extinction to mass conversion, that introduces the main source of uncertainties. It is proposed to obtain extinction estimates automatically, using the technique outlined above. Development of networks of affordable systems is necessary and possible using this technique. The network should be augmented with stations of high-performance and high accuracy instruments. This should be embedded in a wider surveillance system consisting of (atmospheric transport models (explicit particle dynamics), space borne remote sensing (large scale overview and dynamics).

***References***

O'Neill, N. T.,T. F., Eck, , A. Smirnov, B. N.Holben, S. Thulasiraman, 2003: Spectral discrimination of coarse and fine mode optical depth, 108, J. Geophys. Res., No. D17, 4559-4573, 10.1029/2002JD002975.

Vlemmix, T., Piters, A. J. M., Stammes, P., Wang, P., and Levelt, P. F.: Retrieval of tropospheric NO2 using the MAX-DOAS method combined with relative intensity measurements for aerosol correction, Atmos. Meas. Tech., 3, 1287-1305, doi:10.5194/amt-3-1287-2010, 2010.

Zieger, P., Weingartner, E., Henzing, J., Moerman, M., de Leeuw, G., Mikkilä, J., Ehn, M., Petäjä, T., Clémer, K., van Roozendael, M., Yilmaz, S., Frieß, U., Irie, H., Wagner, T., Shaiganfar, R., Beirle, S., Apituley, A., Wilson, K., and Baltensperger, U.: Comparison of ambient aerosol extinction coefficients obtained from in-situ, MAX-DOAS and LIDAR measurements at Cabauw, Atmos. Chem. Phys., 11, 2603-2624, doi:10.5194/acp-11-2603-2011, 2011

F. Snik, T. Karalidi, and C. Keller, "Spectral modulation for full linear polarimetry," Appl. Opt. 48, 1337-1346 (2009).

Haeffelin, M. and Angelini, F. and Morille, Y. and Martucci, G. and Frey, S. and Gobbi, G. and Lolli, S. and O'Dowd, C. and Sauvage, L. and Xueref-Rémy, I. and Wastine, B. and Feist, D. “Evaluation of Mixing-Height Retrievals from Automatic Profiling Lidars and Ceilometers in View of Future Integrated Networks in Europe” Boundary-Layer Meteorology, , 2012, 143:1, pp 49-75, doi: 10.1007/s10546-011-9643-z

M.J. de Haij and W.M.F. Wauben and H. Klein Baltink and A. Apituley, “Determination of the mixing layer height by a ceilometer”, Proceedings of the 8th International Symposium on Tropospheric Profiling, 19--23 Oct. 2009, Delft, the Netherlands, A. Apituley and H.W.J. Russchenberg and W.A.A. Monna (Eds.), S03-P01

Thomas, W., “DWD - Ceilometer-Viewer”, http://www.dwd.de/ceilomap, 2013.

Thomas, W., “INTERCOMPARISONS, CEILOMETER AND AUTOMATIC LIDARS INTERCOMPARISON CAMPAIGN”, CIMO/MG-10/Doc. 6(2) (8.X.2012)

M. Adam, "Vertical versus scanning lidar measurements in a horizontally homogeneous atmosphere," Appl. Opt. 51, 4491-4500 (2012).

A. Ansmann, U. Wandinger, M. Riebesell, C. Weitkamp, and W. Michaelis, "Independent measurement of extinction and backscatter profiles in cirrus clouds by using a combined Raman elastic-backscatter lidar," Appl. Opt. 31, 7113-7131 (1992).

D. Whiteman, "Examination of the Traditional Raman Lidar Technique. I. Evaluating the Temperature-Dependent Lidar Equations," Appl. Opt. 42, 2571-2592 (2003).

D. Whiteman, "Examination of the Traditional Raman Lidar Technique. II. Evaluating the Ratios for Water Vapor and Aerosols," Appl. Opt. 42, 2593-2608 (2003).

S. Shipley, D. Tracy, E. Eloranta, J. Trauger, J. Sroga, F. Roesler, and J. Weinman, "High spectral resolution lidar to measure optical scattering properties of atmospheric aerosols. 1: Theory and instrumentation," Appl. Opt. 22, 3716-3724 (1983).

Eloranta, E. W., High Spectral Resolution Lidar in Lidar: Range-Resolved Optical Remote Sensing of the Atmosphere, Klaus Weitkamp editor, Springer Series in Optical Sciences, Springer-Verlag, New York, 2005.

A. Behrendt and J. Reichardt, "Atmospheric temperature profiling in the presence of clouds with a pure rotational Raman lidar by use of an interference-filter-based polychromator," Appl. Opt. 39, 1372-1378 (2000).

Y. Arshinov, S. Bobrovnikov, I. Serikov, A. Ansmann, U. Wandinger, D. Althausen, I. Mattis, and D. M¸ller, "Daytime operation of a pure rotational Raman lidar by use of a Fabry-Perot interferometer," Appl. Opt. 44, 3593-3603 (2005).

D. Müller, U. Wandinger, and A. Ansmann, "Microphysical Particle Parameters from Extinction and Backscatter Lidar Data by Inversion with Regularization: Theory," Appl. Opt. 38, 2346-2357 (1999).

D. Müller, U. Wandinger, and A. Ansmann, "Microphysical Particle Parameters from Extinction and Backscatter Lidar Data by Inversion With Regularization: Simulation," Appl. Opt. 38, 2358-2368 (1999).

D. Müller, F. Wagner, U. Wandinger, A. Ansmann, M. Wendisch, D. Althausen, and W. von Hoyningen-Huene, "Microphysical Particle Parameters from Extinction and Backscatter Lidar Data by Inversion with Regularization: Experiment," Appl. Opt. 39, 1879-1892 (2000).

I. Veselovskii, A. Kolgotin, V. Griaznov, D. M¸ller, K. Franke, and D. Whiteman, "Inversion of multiwavelength Raman lidar data for retrieval of bimodal aerosol size distribution," Appl. Opt. 43, 1180-1195 (2004).

Martin de Graaf, Arnoud Apituley, and David Donovan, Feasibility study of integral property retrieval for tropospheric aerosol from Raman lidar data using principle component analysis, Applied Optics, accepted 02/20/2013; Doc. ID 176498

Veselovskii, I., Dubovik, O., Kolgotin, A., Korenskiy, M., Whiteman, D. N., Allakhverdiev, K., and Huseyinoglu, F.: Linear estimation of particle bulk parameters from multi-wavelength lidar measurements, Atmos. Meas. Tech., 5, 1135-1145, doi:10.5194/amt-5-1135-2012, 2012

Burton, S. P., Ferrare, R. A., Hostetler, C. A., Hair, J. W., Rogers, R. R., Obland, M. D., Butler, C. F., Cook, A. L., Harper, D. B., and Froyd, K. D.: Aerosol classification using airborne High Spectral Resolution Lidar measurements – methodology and examples, Atmos. Meas. Tech., 5, 73-98, doi:10.5194/amt-5-73-2012, 2012

Chaikovsky, A., et. al., “Algorithm and software for the retrieval of vertical aerosol properties using combined lidar/radiometric data: dissemination in EARLINET”, Proceedings 26th ILRC, A. Papayannis and D. Balis (Eds.), Porto Heli, Greece, 2012.

---

**ANNEX IV**

# ARGENTINEAN LIDAR NETWORK FOR VOLCANIC ASH DETECTION

## Introduction

About 60 of the 125 active volcanoes in Chile had some kind of eruptive activity on the last 450 years. Volcanic activity in Los Andes Mountain Range was important during the last 20 years due to eruption of volcanoes like Mount Hudson (1991, close in time to the eruption of Mount Pinatubo), Lascar (2006), Chaitén (2008) and Puyehue (2011).

The last eruption occurred on the Puyehue – Cordón  Caulle volcanic complex the 4th June 2011 generating alert level of 4 with ash clouds reaching 12 km height and forcing the evacuation of adjacent areas. Prevailing westerly winds made the tephra reach and cover the surface of the Bariloche and Neuquén Airports in Argentina. Some other airports where closed like the ones at Buenos Aires, Argentina (Ezeiza and Aeroparque) or in Melboune, Australia, showing the extent of this eruption.

Most of the flights over the affected region were grounded due to the volcanic activity for a period of time of about 6 months. The European experience with the Eyjafjallajökull eruption showed that operational conditions should be restricted to regions with concentrations lower than $2\times10^{-3}$ $g.m^{-3}$. The lack of confidence in the volcanic ash/dust model initialization and the lack of measurements, created a total restriction of flights in presence of volcanic plume or dust at whichever concentration over the affected region. The solely presence of volcanic dust lifted from the ground was enough to close the airports until the end of the episode.

Argentina, having almost on third of the European surface, had at that moment only one aerosol Raman lidar station from the Lidar Division at CEILAP to perform routine tropospheric measurements and it was at Buenos Aires.

## Lidar project description

During the last quarter of 2011 a Project intending to develop lidar stations over the ash cloud and ash dust affected regions was accepted by the Country Defense Department. Its main goal is to enrich the National Weather Service (NWS) observations in Patagonia with multi wavelength Lidar technology developed at the Lidar Division of CEILAP.

These lidar stations were built in a 20 feet container, having enough space to place additional instrumentation as well as a small office for the NWS observer at the site, uninterrupted power supply systems and network connectivity instrumentation.

The lidar was designed to emit and receive three elastic wavelengths (fundamental, second and third harmonic of a Nd:YAG laser), two Raman channels to collect the inelastic Raman backscattered radiation from the ultraviolet and green laser pulses as well as an additional Raman channel to measure water vapor vertical distribution. Finally a seventh channel is used to measure depolarization.

Other instrumentation will complement the lidar retrievals:

I. A CIMEL sunphotometer to link with AERONET/NASA Network
II. A nephelometer to measure aerosol size distribution
III. An automatic weather station
IV. Three solar radiation sensors UVA, UVB, piranometer
V. A ground temperature sensor

For the operation training and maintenance of this network, two high level technical service projects (STAN) were accepted for this project. Basic training to operate the existing lidar stations was done in situ when the systems were installed for the local observing NWS team.

Actually there are two lidar station of this network being operated by the NWS at Bariloche and Comodoro Rivadavia. These stations communicate directly to the VAAC when a possible volcanic ash event is detected. The real time observations are accessible online, however raw and processed data is only accessible by request. One of the goals to be achieved during 2013 is the reinforcement of online data processing, network capabilities as well as an improvement of the lidar network website.

As the main parts of the lidars were already bought, the next three lidars at Río Gallegos, Trelew and Ezeiza are expected to be installed before the end of 2013. A Science and Technology Research Partnership with Japan for Sustainable Development (SATREPS) is going to be signed on the next month between Argentina, Chile and Japan for the "Development of the Social Management System for Atmospheric Environmental Risks in South America". During this five-year collaboration the project has as an overall goal that "Relevant ministries and agencies use the Atmospheric Environmental Risk Management System to minimize the risks and damages into the society due to UV rays, aerosols, and others". This project strengthens the Country Defense Department Lidar Project by reinforcing the existing lidar station instrumentation and adding to this network three new high spectral resolution lidars to the network.

**ANNEX V**

## REVISED WORKPLAN

### WorkPlan of CIMO Expert Team on New Technologies and Testbeds (2011-2014)

| No. | **Task description** | Person responsible | Action | Deliverable | Deadline for deliv. | Status [%] | Comments |
|---|---|---|---|---|---|---|---|
| 1. | **Guidance on meteorological use of GNSS2** | **S. de Haan**<br>R. Ware | 1. Finalize development of guidance document on theory and operational use of GNSS for meteorology, incl. comparison with other systems such MWR and radiosondes, guideline on operational use of WP, recommendations on data exchange protocols, if appropriate<br>2. Develop update for CIMO Guide chapter | 1. IOM report<br>2. Updated CIMO Guide | 2011<br><br>July 2013 | 100%<br><br>20% | Advanced draft completed end 2012. Now undergoing CIMO MG review and approval process.<br><br>Commenced, having completed first deliverable<br><br>(Contributes to WIGOS Actions: 1.1.1, 4.1.2, 5.1, **6.1.1**) |
| 2. | **Guidance on operational use of passive microwave profilers1** | **A. Koldaev**<br>R. Ware<br>P.W.Chan<br>D.Klugmann<br>J. Won | 1. Develop guidance material on operational use of passive microwave profilers (with emphasis on PBL performance)<br>2. Review relevant CIMO Guide chapter and develop update if appropriate.<br>3. Prepare IOM Report | 1. Document with guidance material<br>2. Updated CIMO Guide Chapter<br>3. IOM Report prepared | 2011<br>2012<br>Dec 2013 | 70%<br>100%<br>30% | Preliminary draft completed. Undergoing refinement.<br><br>CIMO Guide Chapter reviewed. ET recommends not to update Guide at this stage but publish in an IOM report.<br><br>(Contributes to WIGOS Actions: 1.1.1, 4.1.2, 5.1, **6.1.1**)<br><br>ET-RSUT&T, para 4.1.19 |
| 3. | **Standard on LIDARs1** | **D.Klugmann**<br><br>M. Nakazato<br>A. Apituley<br>L. Sauvage<br>L. Thobois | 1. Inform ET and MG on status of development of ISO standards (incl. recommendation & justification on whether WMO should approach ISO to develop them | 1. Document to CIMO MG | 2012 (MG-10) | 100%<br><br>Ongoin | WMO has approached ISO and ISO has replied positively. |

[2] Note: This activity contributes directly to WIGOS Regulatory Material and/or the WIGOS Information Resource.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | as ISO-WMO standards)<br>2. Collaborate with ISO working group on development of standards on lidars<br>a. Wind<br>b. Visual Range<br>c. Other | 2. Input to ISO standards | In phase with ISO development process | g | (Contributes to WIGOS Actions: 1.1.1, 5.1, **6.1.1**) |
| 4. | **Monitor, evaluate and report on development and implementation of new remote-sensing technologies and their operational application, with a focus on implementation of WIGOS** | MWR-<br>**A. Koldaev**<br>R. Ware<br><br>GNSS-<br>**S. de Haan**<br>R. Ware<br>J. Won<br><br>WV Lidar<br>**A.Apituley**<br>P. Ristori<br><br>Wind-finding<br>**H. Klein-Baltink**<br><br>Cloud radars<br>**D. Klugmann**<br>A. Koldaev<br>Y. Gao<br><br>Aersol&volca-nic ash detection<br>**A. Apituley**<br>J. Won<br>**P. Ristori**<br>L. Sauvage<br>L. Thobois<br>Other:<br>**R. Kivi**<br>Y. Gao | 1. Review and evaluate development and implementation of various new remote-sensing technologies and their potential/readiness for operational application, including path to operation use and traceability to SI (MWR, GNSS, WV lidar, wind-finding systems, cloud radars, aerosol & volcanic ash detection, etc…)<br>2. Prepare reports on performance and use of those systems<br>3. If appropriate, compile IOM report out of report on the various systems<br>Responsibilites for various subdocuments:<br>- MWR,<br>- GNSS<br>- WV lidar<br>- wind-finding systems<br>- cloud radars<br>- aerosol & volcanic ash detection<br>- other (incl. Precipitation mapping by microwave comms links, and ATC Mode-S and DAB-T) | 1. Report on performance, implementation and operational use of various systems to the attention of WMO Members<br><br>2. IOM report on new RS technologies or CIMO website contribution, as appropriate<br><br>3. IOM Report on Aerosol and Volcanic Ash including Argentinian network. | March 2012<br><br>2013<br><br>Oct 2013 | 80%<br><br>20% | Reports on individual technologies prepared and to be published with ET session report and on CIMO website as opposed to IOM Report because information contained therein too perishable for IOM report.<br><br>(Contributes to WIGOS Actions: 1.1.1, 2.3.1, 5.1, **6.1.1**) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | Microwave comms:<br>A. Apituley<br><br>ATC Mode-S<br>S de Haan<br><br>DAB-T<br>D. Klugmann | | | | | |
| 5. | **Monitoring of CIMO testbeds** | **J.G. Won**<br>D. Klugmann (4)<br>A. Apituley (3)<br>A. Koldaev | 1. Monitor and review outcomes of all CIMO Testbeds and Lead Centres in liaison with test bed site representatives (with focus on performance & limits of new surface-based RS technologies)2 Assess need to, and develop, up-date for relevant part of CIMO Guide, as necessary.3. Develop principles for optimal mix of surface-based in-situ & RS technologies (incl. satellites)<br><br>4 Update concept for the future of testbeds | 1. Document summarizing main outcomes of testbeds relevant to ET Terms of Reference<br>2.1 Report to OPAG-A Chair if update required<br>1.2 Revised CIMO Guide Chapter<br>3 Report listing principles for optimal mix of various technologies (incl. justification)<br>4. Document on future concept of testbeds | 2012 (MG-10)<br><br>Dec. 2013<br><br>Dec 2013<br><br>Dec 2013 | 100%<br><br>100% | Awaiting Lindenberg input.<br><br>Re 2, no need for this.<br><br>Will take longer than originally anticipated so delivery date revised to end of 2013.<br><br>New task<br><br>ET-RSUT&T, para 4.1.20 (Contributes to WIGOS Actions: 4.1.2, 6.1.1, 9.1.1) |
| 6. | **Assessment of the uncertainty and traceability to SI of vertical profiles in the atmosphere by various remote-sensing technologies** | All ET Members<br>**M. Nakazato (1)**<br>**J.G. Won (2)**<br>**D. Klugmann** | 1. Identify tools and techniques to ensure that remote-sensing observations aretraceable to SI<br>2. Develop recommendations on how to improve traceability of various RS observations | Document on findings of 1 and 2..<br><br>Report on intercomparison feasibility (3). | Dec 2013<br><br>July 2013 (3) | Started | CIMO-XV, para 5.20<br><br>Re 1. Where applicable, identify tools of measurement which are accepted by national standard |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | **(3)**<br>**A. Apituley (4)**<br><br>(linking with GRUAN) | 3. Examine and report on the feasibility of an intercomparison of selected RS observing technologies (with W Thomas).<br>4. Investigate the feasibility and requirements for certification of selected RS technologies. | Document on feasibility of certification (4) | Nov 2013 (4) | | organizations, in each case specifying the technical parameters of that tool.<br><br>(Contributes to WIGOS Actions: 5.1.1, 6.1.1) |
| 7. | **Contribute to the implementation of WIGOS and provide relevant advice and support to the CIMO-MG** | All ET Members | 1. Address relevant items of WIGOS Implementation Strategy approved by Cg-XVI and subsequent WIGOS IP<br>2. Modify ET Workplan to better support WIGOS WIP | 1 Revised ET Work Plan better addressing WIGOS activities.<br>2. New activities identified that explicitly address WIGOS activities | 2012<br><br>2012 | 100%<br><br>100% | Work plan revised.<br><br>(Fulfills WIGOS Action 1.1.2) |
| **Lower priority** | | | | | | | |
| 8. | **Report on modern possibility of remote sensing of snow depth by means of passive and active radar airborne and spaceborne systems** | **A. Koldaev**<br><br>Y. Gao | 1. Study the latest results of different research groups in Canada, Europe, Russia and Japan concerning the space born and aircraft remote measurements of the snow pack. | 1. Preliminary report on remote sensing of snow depth provided.<br>2. General recommendations for the implementation of the remote sensing tools into the program of international inter - comparisons of snow precipitation measurements | 2012/13<br><br>Nov 2013 | 100% | In cooperation with A3 (SPICE Intercomparison) |
| 9. | **Examine the reliability and consistency of wind measurements by wind profilers towards the development of an ISO-WMO standard** | **P.W. Chan** | 1. Study the different possibilities of the validation of the remote sensing wind profiler data by means of high meteorological towers, unmanned airplanes, tethered balloons and others | 1. Report to CIMO-MG on potential for development of a CIMO standard | 2013/14 | | In close cooperation with A1 and B1 and Task 6. |

---