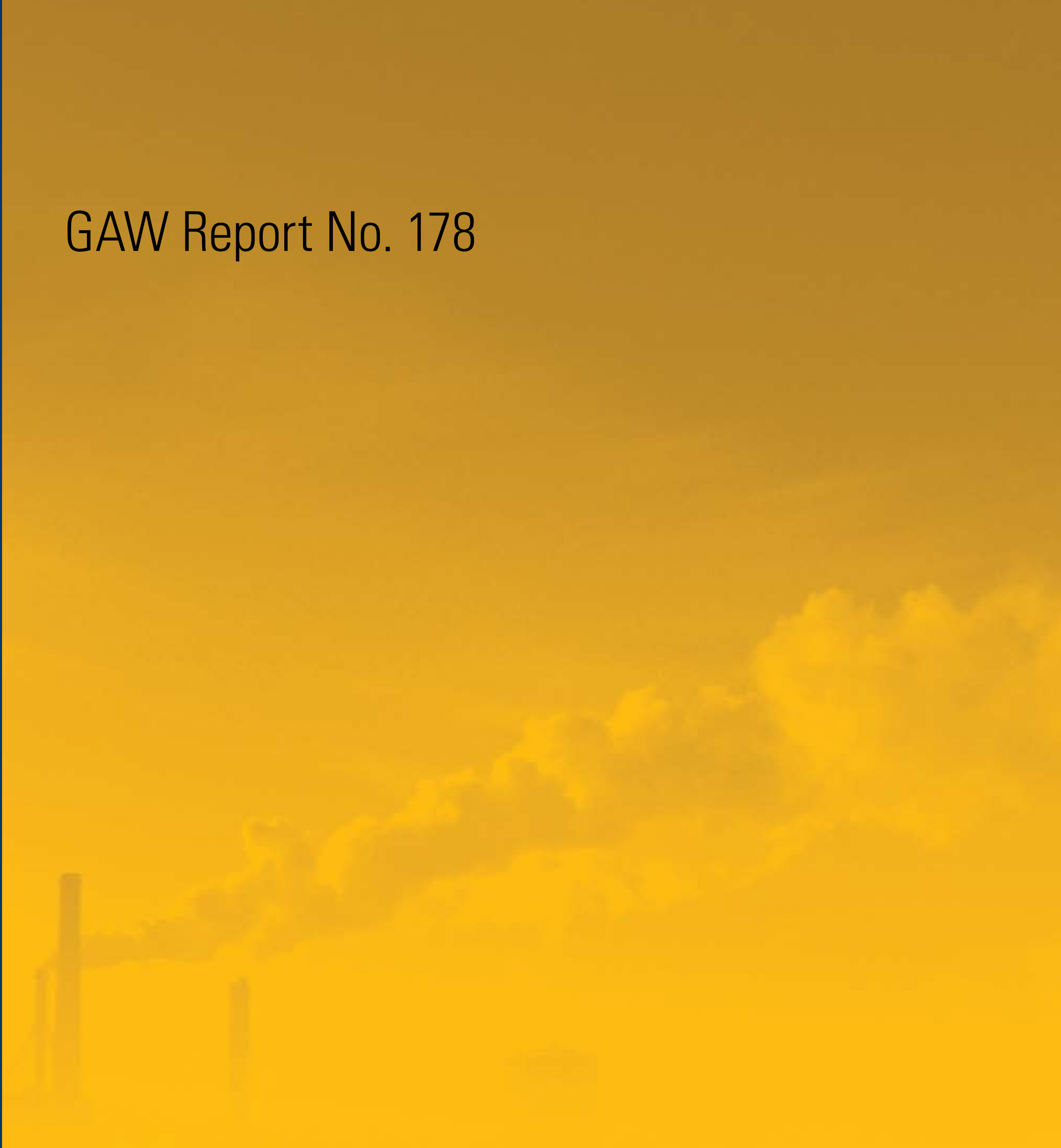
GAW Report No. 178



Plan for the implementation of the GAW Aerosol Lidar Observation Network GALION

(Hamburg, Germany, 27 to 29 March 2007)

World
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Weather • Climate • Water

WORLD METEOROLOGICAL ORGANIZATION
GLOBAL ATMOSPHERE WATCH

GAW No. 178

Plan for the implementation of the

GAW Aerosol Lidar Observation Network GALION

(Hamburg, Germany, 27 - 29 March 2007)

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FOREWORD

FOREWORD

Suspended particulate matter in the atmosphere, commonly known as aerosol plays an important role in climate change, air quality/human health, sand and dust storms, ozone depletion and the long-range transport and deposition of toxics and nutrients. Aerosols have many sources ranging from sea spray and mineral dust that are mechanically generated by wind at the Earth's surface to sulphates, nitrates and organics produced primarily by chemical reaction of gases in the atmosphere producing non-volatile products that condense to form particulate mass. The complexity of aerosol processes in our environment is so great that it leads to large uncertainties in quantitative understanding of their role in many of the major environmental issues listed above. For instance, the last report of the Intergovernmental Panel on Climate Change (IPCC, 2007) has identified aerosol radiative forcing and associated feedbacks as one of the greatest unknowns in our understanding of climate change.

In the first decade of the 21st century, a revolution is taking place in the approach to managing and utilizing global Earth observations coupled with weather and climate models to address societal needs. A single type of observational platform cannot, by itself, provide sufficient data to fulfil our current observational needs. A combination of surface-based (in situ and remote sensing), suborbital (aircraft and balloons), and satellite observations are needed. One of the roles of WMO as a separate operating organization of the United Nations serving the collective needs of 180 Member countries for over fifty years is to fill gaps in the global aerosol observing and assessment activities through international coordination and cooperation. A strategy for this is given in the internationally recognized report on Integrated Global Atmospheric Chemistry Observations (IGACO) strategy (GAW, 2004) and in the strategic plan of the WMO Global Atmosphere Watch (GAW, 2007) programme which is leading the implementation of IGACO. Through the leadership and guidelines documents of the Scientific Advisory Group for Aerosols (GAW, 2003) and within the context of a WMO Integrated Global Observing System (WIGOS), GAW is systematically addressing the recommendations of IGACO (GAW, 2004) for aerosols.

In March 2004, an international "Experts Workshop on a Global Surface-Based Network for Long Term Observations of Column Aerosol Optical Properties" was organized by WMO-GAW at the World Optical Depth Research and Calibration Centre, Davos, Switzerland. The global network of systematic aerosol optical depth observations using surface-based, sun-tracking photometers was identified and recommendations were made on ways to standardize and coordinate activities as well as to ensure that observations are of known quality (GAW, 2005). It was recognized that while vertical profiling of aerosols by LIDAR is a natural complement to total column aerosol observations made by surface sun photometers and satellites efforts world wide lacked a coordinating mechanism. Therefore, a second international "Experts Workshop on the Implementation of a GAW Aerosol Lidar Observation Network: GALION" was organized by the WMO-GAW at the Max-Planck-Institut für Meteorologie, Hamburg, Germany from 27 to 29 March 2007. The meeting was attended by 26 international LIDAR experts from 11 countries representing most of the major LIDAR networks and observatories of the world.

On behalf of the World Meteorological Organization and its many partners, we would like to thank Dr Raymond Hoff and Dr Jens Bösenberg for leading this meeting and the production of this road map for GALION. In addition, thanks are due to the contributing authors and participants. This report provides a clear justification and strong recommendations for advancing the LIDAR component of an integrated global aerosol network.

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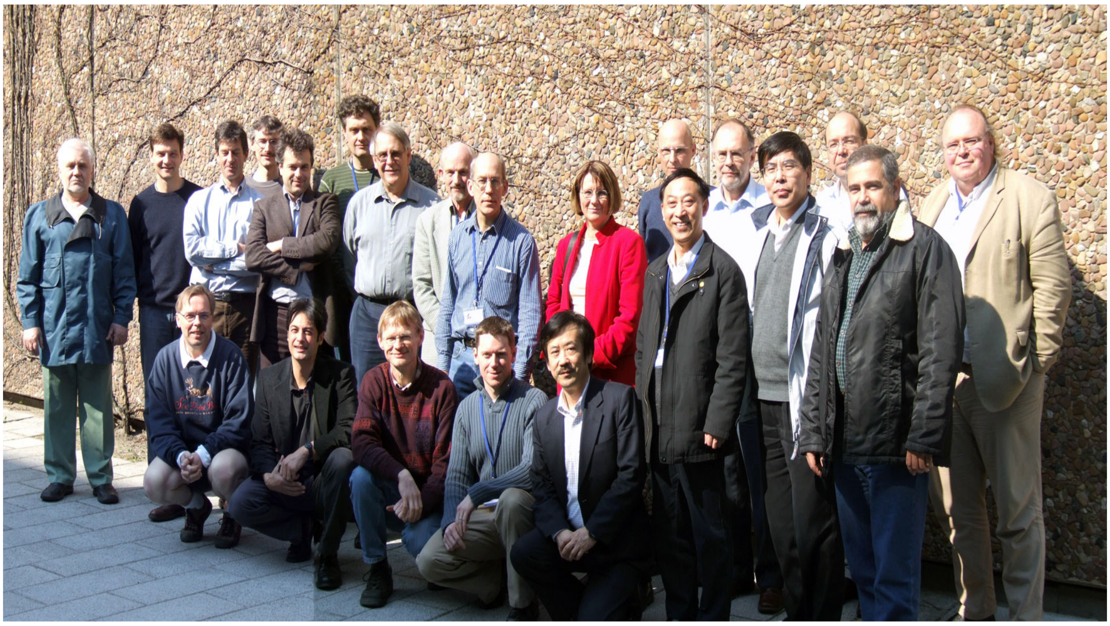

Participants: (kneeling, left to right) Stefan Kinne, Arnoud Apituley, Albert Ansmann, Judd Welton, Nobuo Sugimoto (standing, left to right) Anatoli Chaikovsky, Oleg Dubovik, Julian Wilson, Detlef Müller, Alberto Maurizi, Igor Veselovskii, Ray Hoff, Jens Boesenberg, David Winker, Christine Böckmann, Volker Freudenthaler, Jun Zhou, Slobodan Nickovic, Pucai Wang. Michael Schulz, Juan-Carlos Antuña and Holger Linne.

1. OBJECTIVE

The Global Atmosphere Watch (GAW) aerosol programme (GAW, 2007) strives "to determine the spatio-temporal distribution of aerosol properties related to climate forcing and air quality up to multidecadal time scales". The specific objective of the GAW Atmospheric Lidar Observation Network (GALION) is to provide the vertical component of this distribution through advanced laser remote sensing in a network of ground-based stations. The aerosol properties to be observed include the identification of aerosol layers, profiles of optical properties with known and specified precision (backscatter and extinction coefficients at selected wavelengths, lidar ratio, Ångström coefficients), aerosol type (e.g. dust, maritime, fire smoke, urban haze), and microphysical properties (e.g., volume and surface concentrations, size distribution parameters, refractive index). Observations will be made with sufficient coverage, resolution, and accuracy to establish comprehensive aerosol climatology, to evaluate model performance, to assist and complement space-borne observations, and to provide input to forecast models of "chemical weather".

2. THE RATIONALE FOR GROUND-BASED AEROSOL PROFILING

All main long-term objectives of GAW, as stated in the WMO Global Atmospheric Watch (GAW) Strategic Plan: 2008-2015 (GAW, 2007), are related to the 4-dimensional space-time distribution of aerosols, with different demands on measurement characteristics:

1. Detection of long-term man-made trends in the concentration of greenhouse gases and aerosols related to climate change above natural variability; *(requires a long-term climatology for aerosols including the vertical distribution for identification of sources and impact on radiation as well as cloud formation)*
2. Better environmental assessments related to climate, air quality, ozone depletion and the long-range transport of pollution between regions; (*aerosols in elevated layers are excellent tracers for long range transport of pollution*)
3. Better quantification of pollution sources and their atmospheric pathways to sensitive downwind receptors; (*significant long-range transport occurs at elevated layers, precise arrival heights are needed to trace substances back to the source)*
4. Reliable global concentration fields of selected chemical variables and aerosols at various altitudes for the study of outstanding problems in atmospheric chemistry; (advanced profiling is needed at a number of anchor stations to support and improve space-borne observations*)*
5. Better prediction of UV intensities at the Earth's surface both in populated and remote regions; (*aerosols have a significant impact on UV radiation, radiative transfer calculations require the vertical distribution of constituents)*
6. Direct observation of plumes from major events such as forest fires, dust storms and volcanic eruptions; (*these plumes are associated with characteristic aerosol emissions, large parts of the plumes are within elevated layers)*
7. Improved regional forecasts of both weather and air quality, and to provide forecasts in regions where these are unobtainable at the moment; *(understanding transport of pollutants at elevated layers and down mixing into the boundary layer is essential for air quality forecasts, aerosols are among the most important pollutants and are excellent tracers for other components).*

In view of these objectives the present observations of the vertical distribution of aerosols are far from adequate. While within GAW an observing network for aerosol properties at ground level is well established and a programme has been initiated for the coordination of sun-photometer networks (GAW, 2005) measuring column integrated aerosol optical properties, the vertical component is not yet covered. The implementation principles of the GAW strategic plan recommend filling gaps like this by "working with the GAW observational community and Contributing Partners that have substantive networks to complete the global network, and improve collaboration between National Hydrological and Meteorological Services, environmental agencies and research organizations in filling gaps in GAW networks and projects." It is the mission of GALION to organize such observational capability for the 4-dimensional distribution of key aerosol parameters.

2.1 Scientific background

Aerosols are important constituents of the atmosphere, playing a major role in weather, climate, water and environmental issues. Here we examine in particular the impact of GALION in climate and air quality studies.

2.1.1 Climate

The importance for the climate system is evident from the IPCC-4 report (IPCC, 2007), where the indirect and the direct effect of aerosols make the two largest contributions to the total uncertainty of the radiative forcing. Obviously the present understanding of the aerosol properties and distribution is far from adequate, observations of the 4D-aerosol field are urgently required to improve the situation. The requirement for improved observations of the aerosol vertical distribution is related to the facts that:

- Practically all long-range transport occurs at elevated layers, decoupled from the ground.
- Ground-level observations are in many cases disturbed by local effects exhibiting large temporal and spatial variability.
- Major sources are not sufficiently well known, e.g., the formation of secondary aerosols from trace substances or the generation of dust in remote desert areas.
- No global climatology of the aerosol vertical distribution exists.

For an assessment of the impact of aerosols on climate, it is necessary, although not sufficient, to establish a climatology of the aerosol distribution. Because most effects of aerosols on climate occur at elevated layers, e.g., the direct modification of the radiation field through scattering and absorption or the indirect effect through modification of the cloud condensation nuclei, the long-term climatology needs to cover the vertical as well as the horizontal properties of the aerosol field. The sampling requirements include spatial coverage of regions with occurrence of the most important types of aerosols, temporal coverage that includes all major temporal cycles, and fixed observation times to avoid bias through "blue sky only" measurements.

The aerosol vertical distribution depends on the distributions of the emissions, on chemical production for secondary aerosols (secondary particulate matter and sulphate), on the distribution of clouds and precipitation (that determine aqueous chemistry aerosol production and wet deposition), on the parameterization of wet deposition processes, and on the transport characteristics determined by the flow field. The complexity of the aerosol interaction with the climate system makes it necessary to estimate its impact and possible future changes through the use of numerical models of the whole system. Simulation results of global aerosol models and observations of aerosols in the atmosphere have been assembled in the framework of the AEROsol model interCOMparison initiative AeroCom. Further information can be found in the AeroCom publications [Guibert et al., 2005; Kinne et al., 2006; Schulz et al., 2006; Textor et al., 2007; Textor et al., 2006] and at the project web site: http://nansen.ipsl.jussieu.fr/AEROCOM/aerocomhome.html. The AeroCom results have shown that very little agreement exists among the various models for the vertical aerosol distribution. As an example, for the annually and zonally averaged aerosol concentration, all models show two maxima of aerosol concentration, where the northern hemisphere maximum results mainly from desert dust, and that in the Southern Hemisphere is caused by sea salt emissions in the “roaring forties” of the South Pacific. But there are remarkable discrepancies: in some models the aerosol is quite dispersed both in the vertical and in the horizontal direction, in others it is confined to the source regions. The height of the aerosol plumes differs considerably, and this in turn has important implications on the transport patterns and atmospheric residence time of aerosol particles. This demonstrates that comprehensive and reliable data are needed to evaluate the performance of numerical models and to improve the representation of aerosols and their effects in such models. Only sufficiently validated models can assess the impact of aerosols on climate and can predict the response of the system to changes in the aerosol distribution.

Although high quality observations of global coverage and of high temporal resolution are necessary to better constrain the model results and to improve the representation of important aerosol-related processes in the models, this is not sufficient. Progress in the areas of aerosol-cloud interaction (indirect effect) or aerosol-chemistry interaction is expected to come from dedicated experimental campaigns. But for these studies the systematic observations made in a network involving stations operating under a broad range of atmospheric conditions offer valuable data material. For example, recent simultaneous Raman lidar or DIAL measurements of extinction and relative humidity (from the water vapour profile) have shown that it is possible to determine hygroscopic growth of the aerosol and determine an index for the indirect effect (Wulfmeyer and Feingold, 2000; Pahlow et al., 2006b, Russo, 2007, Rogers, 2007).

2.1.2 Air quality

The importance of aerosols for air quality is exemplified by a statement made in a Communication from the Commission to the Council and the European Parliament: Thematic Strategy on air pollution, COM (2005) 446 final: "Concerning health impacts, currently in the EU there is a loss in statistical life expectancy of over 8 months due to PM in air, equivalent to 3.6 million life years lost annually." In the same document it is also stated that: "Air pollution is both a local and a trans-boundary problem caused by the emission of certain pollutants which either alone, or through chemical reaction lead to negative environmental and health impacts."

A recent US study, following up on the historical Six Cities Study (Dockery et al, 1993) has shown that a 10 μg m^{-3} increase in PM$_{2.5}$ results in a 16% increase in total mortality (cardiovascular, respiratory and lung cancer) and a 28% increase in cardiovascular mortality (Laden et al., 2006). In the US, such health studies have led to a new regulatory limit of 35 µg m^{-3} (down from 65 µg m^{-3}) of PM2.5 averaged over an 24-hour period. It is generally accepted, including at legislation level, that a major impact on local air quality is made by atmospheric transport, and it is well known that transport mainly occurs at elevated layers. The new Clean Air Interstate Rule in the US requires the assessment of interstate transport as a requirement for discrimination of the impact of distant sources on local air quality. It is thus very important to achieve adequate understanding of transport processes that are supported by observations. This is the main motivation for monitoring the vertical distribution of aerosols as far as air quality issues are concerned.

Regarding the impact of aerosols on air quality and the potential benefit from a global aerosol lidar observation network, it is obvious that the same processes that govern the global aerosol distribution also control the aerosol properties on regional to local scales. Additionally smaller scale processes have to be accounted for, and the high variability of aerosol fields requires a characterization with much higher resolution both in time and space and hence a higher density of observations. While for monitoring of the air quality at street level, i.e. where people are in direct contact with aerosols, in situ measurements are most adequate, the attribution of concentrations in receptor areas to emissions from distant sources as well as the assessment of the role of transport and transformation processes requires observations of the vertical distribution. However, one must recognize that while regulatory measures are defined only *at the surface*, this may not credibly assess what is happening aloft in the atmosphere. This is particularly true for the envisaged forecasts of air quality, where transport of primary pollutants and precursors for secondary pollutants play a major role. Key parameters to be observed for this purpose are the presence, altitude and extent of elevated aerosol layers, the height of the mixing layer, aerosol type, and mass concentration. For model evaluation as many parameters as possible are required, but only for limited time and at selected stations. For assimilation into chemical weather forecast models excellent temporal coverage, high reliability, and near real time delivery are the key properties requested. It is not yet well established which aerosol parameters are needed for successful assimilation, but it is likely that even a rather simple lidar product, namely the attenuated backscatter for a single wavelength, will be very useful.

2.1.3 Integrated approach

The use of numerical models and data from ground-based networks alone is not sufficient. For true global coverage including all relevant parameters, a system including ground-level and airborne in-situ measurements, ground-based remote sensing, and space-borne observations in combination with advanced modelling is necessary (Diner et al, 2004, and the GEOSS paradigm http://www.epa.gov/geoss/). Therefore one major purpose of GALION is the support of aerosol observations from space. Advanced lidar systems, which determine the aerosol optical properties in a quantitative way and permit the estimation of main microphysical properties, are well suited for providing ground truth for the retrieval of aerosol products from passive sensors. These retrievals typically involve assumptions about the aerosol field and/or other parameters influencing the measurements, so careful inter-comparisons with well-characterized ground-based measurements will help to improve and to assess the performance of such retrievals. Increasingly, optical depth surrogates (from sun photometry or satellite) are being used to estimate ground based particulate mass (c.f. Engel-Cox et al., 2004,2006) and it is apparent that understanding the vertical structure of the aerosol is extremely important in such correlations.

Aerosol vertical profiling from space is now a reality, the Cloud and Aerosol Lidar Pathfinder for Spaceborne Observations (CALIPSO) has completed its first year of operations on-orbit and future satellite lidar missions are in development. However, this does not make lidar network measurements obsolete, rather these are needed to complement the data acquired by satellite lidars. The properties of ground-based lidars which enhance the value of satellite observations are:

- Ground-based lidar systems can be more sensitive than satellite lidars and so can be used to confirm the sensitivity limits of the satellite instruments and characterize the atmospheric features missed by the satellite instruments.
- Ground-based instruments can determine additional parameters beyond those possible from space, e.g. independent measurements of aerosol extinction, and hence lidar ratio. Such data are necessary to validate and to help interpret space-borne measurements. Picking the example of validating aerosol optical depth (AOD) derived from lidar extinction retrievals, sun photometers give the most accurate column AOD but cannot help to diagnose the source of discrepancies with lidar AOD. Column AOD can be a useful constraint to test CALIPSO extinction retrievals, but lidar profiles are necessary to determine if errors are due to improper selection of lidar ratio, calibration errors, or other problems.
- Retrieval of microphysical aerosol properties for elevated layers is feasible only for advanced ground-based lidar, not for space-borne instruments.
- The diurnal variability of the aerosol profile can hardly be determined from space, because most atmospheric sensing satellites fly in a sun-synchronous orbit with at most two observations per day at fixed times. Mostly the repeat cycles at a given location are considerably longer. Generally this scheme provides a biased view of the aerosol profile, therefore it is necessary to use ground networks to determine the representativeness of these satellite measurements and to establish the characteristics of the diurnal cycle and other "rapid" processes.
- Ground based observations can be made under elevated cloud layers.
- Finally, CALIPSO and the satellite lidars planned to fly over the next decade have very different characteristics and will not provide a homogeneous set of aerosol measurements. For example, CALIPSO does not have any wavelengths in common with the ALADIN or ATLID instruments, as currently conceived. A ground-based lidar network providing stable, long-term measurements will be necessary to provide a benchmark against which to reference multiple satellite instruments.

2.2 Requirements

Important applications for data generated by GALION are presently foreseen in the following areas:

1. Climate research and assessment
    a. Global climatology
    b. Model evaluation
    c. Aerosol transport and tracers
    d. Impact on radiation, particularly UV, direct effect
2. Air quality
    a. Air quality assessment

    b. Air quality forecast
3. Plumes from special events
4. Support for space-borne observations
    a. Ground truth
    b. Complementary information

The characteristics of required aerosol profiling observations are clearly different for the different application areas; they may briefly be characterized as shown in Table 1.

Table 1: Measurement characteristics as required for the main application areas. Backscatter lidar (BL), Raman lidar (RL), depolarization lidar (DL), and high spectral resolution lidar (HSRL). These methods can be applied either at one or at multiple wavelengths (MBL, MRL). α= extinction, β = backscatter, δ = depolarization, S_a = lidar ratio, MPP = microphysical properties.

Application area	Parameters required	Instrument type	Operation required	Number of stations
1.a Global climatology	α, δ, (β, S_a)	RL	fixed schedule, 3/week	20?
1.b Model evaluation	α, δ, (β, S_a, MPP)	MRL	fixed schedule + diurnal cycles	
1.c Transport and tracers	β, (α, δ, MPP)	BL	fixed schedule + on alert	50
1.d Radiation	α, β, (δ)	RL	random	20
2.a Air quality assessment	α, δ, β, MPP	RL	fixed schedule	50+
2.b Air quality forecast	B	BL	quasi-continuous	??
3. Plumes from special events	β, (α, δ, MPP)	BL	on alert	50
4.a Ground truth	α, δ, β, S_a	MRL	TBD	20
4.b Complementary information	α, δ, β, S_a	MRL	fixed schedule	20

The table indicates minimum standards for the required instrument performance, in most cases the value of the observations will be significantly improved if better performance can be assured. The number of stations indicated in the table are very rough guesses only. A more detailed discussion on these numbers and the required geographical distribution of stations follows in Section 4.

Although premature at this point, GALION will set targets for component in Table 1. 0.03 km^{-1} for extinction and 0.5 Mm^{-1} sr^{-1} for backscatter have been achieved in EARLINET and the DOE ARM Programme. These targets are consistent with an estimate based on the AOD precision requirement formulated by Seinfeld et al. (2004). This requirement is based on the precision requirement for radiative forcing of aerosols, 1 W m^{-2}. To achieve that, a precision of 0.04 in AOD is estimated. If we assume that we need to achieve this for a 2 km deep aerosol layer the required precision for the extinction measurement is 0.02 km^{-1}. GALION will set such data quality objectives during the first year of operation.

Given the wide range of applications it is expected that data requests will come from different user communities. Consequently a comprehensive description of the data sources must be provided together with the data themselves, and in particular confidence limits must always be included. For most of the applications, there is no need for rapid delivery and a few month delay between measurement and availability of the results appears generally acceptable. However, more rapid turnaround appears necessary for plumes from special events, complementary information for support of space-borne observations, and in particular for air quality forecasts. In the latter case, near real time delivery is mandatory for the data to be assimilated into forecast models. It appears feasible to meet the requirements regarding data delivery for some parameters for all application areas with presently available technology. For example, near-real time delivery of attenuated backscatter is now being generated by a number of lidar groups. For assimilation systems, attenuated backscatter is likely to be the first variable ingested.

2.3 Data products

We identify and discuss here a suite of data product categories:

- Individual vertical aerosol backscatter and extinction profiles at a common time resolution.
- Multi-annual monthly aggregated profiles resembling a climatology.
- Rapid access products to be integrated in chemical forecast systems.
- Boundary layer height characterization.
- Aerosol property characterization in different layers.
- Error estimates.
- Reports on calibration and operations and metadata concerning each observation site.

Individual profile measurements and their availability are important to understand processes such as the diurnal mixing, the boundary layer evolution, the passage of weather systems and vertical inhomogeneities of the aerosol. Having individual profiles available is also important to be able to filter model output for times when observations are available for comparison. A careful comparison on the basis of daily values, instead of monthly means, avoids systematic bias due to covariation of aerosol properties and synoptic weather conditions. Preferential sampling in fair weather and thus in clear-sky conditions can be corrected.

The seasonal cycle of the vertical structure of the aerosol requires also better documentation. A climatology or multi-annual data set of spatial and temporal variability of the vertical aerosol profile on the scale of months and 1° x 1° degree horizontal resolution would be a powerful test for climate models. Lidar data need to be aggregated to characterize the different properties of the aerosol. A suggestion is to characterize aerosol for specific, well defined layers, e.g., the PBL, lower free troposphere (say up to 5 km), upper free troposphere, and stratosphere. The vertical resolution would be reasonably well described if levels near the surface would comprise about 100m near the surface, increasing up to 500m in the free troposphere. For the U.S. 3D-AQS project (Engel-Cox et al, 2007), lidar and satellite AOD data is being aggregated to correspond with the horizontal (12 x 12 km) and vertical structure of the CMAQ grid over North America.

3. METHODOLOGICAL AND TECHNOLOGICAL BASIS

3.1 Methodology

Various aerosol lidar techniques have been developed during the past about 40 years. A comprehensive description of the currently available methods is presented in Annex A. For possible operation within GALION the following types are considered most important: backscatter lidar (BL), Raman lidar (RL), depolarization lidar (DL), and high spectral resolution lidar (HSRL). These methods can be applied either at one or at multiple wavelengths (MBL, MRL).

Geometrical properties of the aerosol vertical distribution can be derived from any of these instrument types, but the performance depends on the technical implementation. Height-time displays of the range corrected signal are sufficient to provide an overview of the measurement situation in terms of the evolution of the planetary boundary layer (PBL), lofted aerosol layers, and cloud distributions (cf. Table 3), calibration is not necessarily required. These observations are particularly useful to determine the height of the convective boundary layer, which is an important parameter for model validation as well as for air quality forecasts.

Measurements of the depolarization of the backscattered signal permits to distinguish mineral dust consisting of irregularly shaped particles from urban haze or maritime aerosols where particle shape is closer to spherical. In case of clouds depolarization measurements make it easy to distinguish ice clouds from water clouds.

Accurate retrieval of extinction and backscatter profiles without making assumptions about the aerosol is only possible when measurements of two independent signals are performed. This can be either inelastic Raman scattering (RL) or elastic Rayleigh scattering (HSRL). The advantages and limitations of the corresponding methods are detailed in Annex A.

For the estimation of microphysical aerosol properties, it has been shown that measurements of both backscatter and extinction at several wavelengths are required. For particle sizes in the typical range of the accumulation mode measurements of the backscatter at, e.g., 1064nm, 532nm, and 355nm in combination with extinction measurements at 532nm and 355nm are necessary and sufficient to estimate the particle volume and surface density as well as the refractive index. The retrieval procedure is ill-posed and requires sophisticated regularization methods, so that presently the procedures are still experimental and applied for selected cases only. Schemes with higher degree of automation are under development.

An overview over the retrieval products that are available from the different lidar types, configured as stand-alone instruments as well as combined with sun-photometer, is given in Table 2. For a detailed description of the retrieval of optical and microphysical properties, the achievements, and the limitations of the available methods the reader is referred to Annex A. It is worth noting that sun-photometer operation requires that the sun is above the horizon and not obscured by clouds, so availability of the corresponding products is limited.

Table 2: Lidar-photometer setups and retrieval products. β is the volume backscatter coefficient of the particles (180° scattering coefficient), α the volume extinction coefficient, S_a **the extinction-to-backscatter ratio (lidar ratio), τ is the optical depth, Å_β, Å_α, and Å_τ are the Ångström exponents for backscatter, extinction, and optical depth, MPP the microphysical properties of the particles. 1-λ and m-λ indicate one-wavelength and multi-wavelength lidar, respectively. col and z denote tropospheric column and height, respectively. z indicates the capability to separate boundary layer and free-troposphere aerosol influences and thus local and regional from long-range-transport aerosol impacts.**

Observational configuration	Bsc. cf.	Ext cf.	Lidar ratio	Opt. depth	Ang. exp.	Microphys
1-λ standard backscatter lidar	$\beta(z)$					
1-λ standard backscatter lidar + Sun photometer	$\beta(z)$,	$\alpha(z)$ estimate	S_a(col)	$\tau(\lambda)$	Å_τ(col)	MPP(col)
m-λ standard backscatter lidar	$\beta(\lambda,z)$				$\text{Å}_\beta(z)$	
m-λ standard backscatter lidar + Sun photometer	$\beta(\lambda,z)$	$\alpha(\lambda,z)$ estimate	S_a (λ,col)	$\tau(\lambda)$	$\text{Å}_\beta(z)$, Å_τ(col)	MPP(col)
1-λ Raman lidar/HSRL	$\beta(z)$	$\alpha(z)$	S_a (z)	τ		
1-λ Raman lidar/HSRL + Sun photometer	$\beta(z)$,	$\alpha(z)$	S_a (z)	$\tau(\lambda)$	Å_τ(col)	MPP(col)
m-λ Raman lidar	$\beta(\lambda,z)$	$\alpha(\lambda,z)$	S_a (λ,z)	$\tau(\lambda)$	$\text{Å}_\beta(z)$, $\text{Å}_\alpha(z)$	MPP(z)
m-λ Raman lidar + Sun photometer	$\beta(\lambda,z)$	$\alpha(\lambda,z)$	S_a (λ,z)	$\tau(\lambda)$	$\text{Å}_\beta(z)$, $\text{Å}_\alpha(z)$, Å_τ(col)	MPP(z), MPP(col)

Which type of lidar is necessary and sufficient to obtain the most important aerosol parameters is described in Table 3, ordered according to increasing instrument and retrieval complexity. Tables 2 and 3 form the basis for the decisions to be made for the selection of instruments for the different purposes of the network operation, from a design perspective. In practicality, level of sophistication in the existing networks and instrument availability will govern the initial network configuration.

Table 3: Aerosol properties that can be derived from lidar observations. Only the simpliest lidar type that is needed to provide the product is listed. Depolarization channels (DL) are required to identify desert dust.

Parameter (product)	Basic lidar type
Range corrected signal (colour plots of aerosol and cloud distributions)	BL
Attenuated backscatter coefficient (calibrated range-corrected signal)	BL
PBL depth	BL
Aerosol backscatter coefficient	BL+SPM
Aerosol type discrimination (dust, anthropogenic)	BL+DL
Aerosol extinction coefficient (estimate), optical depth, column lidar ratio	BL+SPM
Aerosol extinction coefficient, optical depth, lidar ratio	RL or HSRL
Ångström exponent (backscatter-related)	MBL
Ångström exponent (extinction-related)	MRL
Aerosol type determination (dust, maritime, fire smoke, urban haze)	MRL+DL
Aerosol microphysical properties (volume and surface conc., refractive index)	MRL
Single scattering albedo (aerosol)	MRL

3.2 Technology

Implementation of the lidar methodologies described in Section 3.1 requires lidar instruments to collect atmospheric data. Each methodology has its specific requirements on the instrumental side. The aerosol parameters that can in principle be derived using the different instrument types are listed in Section 3.1, but the accuracy, sensitivity, and reliability of the retrieval depend on the technical implementation of the system. An overview over the basic instrumental requirements, the main issues, and the most common solutions are presented in this section.

Following the classification presented in Section 3.1 we distinguish systems which detect only elastically scattered light from both aerosols and molecules, called backscatter lidars (BL), and systems which detect the molecular scattering separately from the particle scattering. For the latter, vibrational Raman scattering from nitrogen or oxygen can be used (RL), or pure rotational Raman scattering from nitrogen and oxygen (RRL), or Rayleigh scattering in a High Spectral Resolution Lidar (HSRL). All of these instruments, BL, RL and RRL, can be operated at multiple wavelengths simultaneously (MBL, MRL), and to the BL a channel for detecting the depolarized light can be added.

Most lidars (for any application) have at least one channel that can be operated as a backscatter lidar. An aerosol backscatter lidar system typically consists of a laser transmitter and an optical receiver in parallel or collinear arrangement (Fig.1).

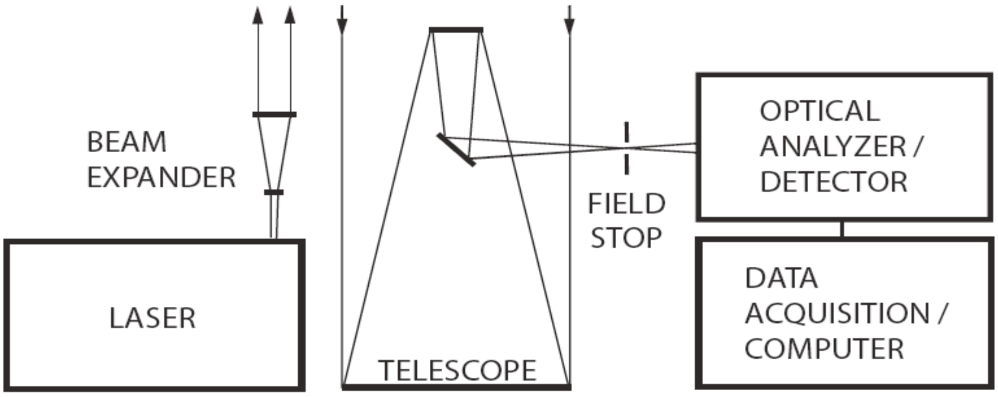

Figure 1: Block diagram of a typical lidar system in parallel configuration (adapted from Wandinger, 2005, in Chapter 1 of Weitkamp, 2005).

The laser transmits short-duration light pulses into the receiver field of view. The intensity of the light elastically backscattered by atmospheric molecules and particles is measured versus time – through the telescope receiver, collimating optics, a bandpass filter for daylight suppression – by an appropriate detector. The signal profile is recorded by an analog-to-digital converter or by a photon-counting device and subsequently stored on a computer. Lidar signals are accumulated for a selected integration period, which may range from single or a few to thousands of individual laser shots – spanning time intervals from sub-second to minutes. The elastic backscatter signal is the sum of backscatter from atmospheric molecules and backscatter from atmospheric particles, and by choice of wavelength absorption by trace gases should be avoided or at least minimized.

Main parameters defining the instrument performance are operating wavelength, laser power or pulse energy, receiver collecting area, optical throughput, out-of-band rejection ratio, as well as detector efficiency, linearity and dynamic range. Other important system properties in particular for routinely operated systems are eye-safety or appropriate risk management, and system reliability including long-term stability of adjustment.

3.2.1 Choice of wavelength

Several factors influence the choice of wavelength for an aerosol lidar. In principle, the measurements can be performed in any spectral region where the atmosphere is reasonably transparent. Because molecular scattering cross sections are proportional to λ^{-4} , Raman lidar and HSRL are practically limited to the visible and UV part of the spectrum. For aerosol particles the scattering cross section is typically proportional to λ^{-1}, for large particles the dependence is weaker, for smaller particles it may be stronger. Thus the wavelength dependence of the backscatter and extinction signals allows to estimate size distribution parameters, as explained in Section 3.1, and the choice of wavelength determines the relative contribution of particle and molecular scattering as well as the relative contributions from different particle sizes.

A common way to calibrate lidar signals is the use of atmospheric regions where Rayleigh scattering dominates, because the Rayleigh scattering cross section is readily calculated. This requires a choice of wavelength for which the Rayleigh signal is well above the detection threshold.

Laser sources are available in the whole useful spectral range from about 0.3μm to 10μm, although highly developed industrial lasers like the Nd:YAG with frequency doubling and tripling are preferred for operational systems. Efficiencies of available detectors also play a major role for the selection of wavelengths.

3.2.2 Eye-safety

Eye-safety considerations play a major role in lidar operation and have a significant impact on the choice of wavelength. In the wavelength region from 0.4μm to 1.5μm eye-safety cannot be achieved when high power lasers are used. In this spectral region either so-called micro-pulse lidars (MPL) have to be employed, or it has to be ensured through appropriate risk management that it is impossible to stare directly into the laser beam. A well-proven means to achieve this is the use of a safety radar that opens the beam shutter only when no target is in the risk area. National regulations, however, may still require observers as a control for eye safety. In the spectral regions beyond 1.5 μm and below 0.4 μm eye-safety can be achieved even for high power systems, so that one preferred wavelength for Raman lidar operation is 355nm. Lidar eye safety calculation have begun to be harmonized internationally. In the United States, the governing document is Title 21 CFR, Subchapter J (Radiological Health), Part 1040.10 of the Code of Federal Regulations and the use in the atmosphere is governed by the American National Standard for the Safe Use of Lasers, specifically ANSI Z136.1 and ANSI Z136.6(2000). In Europe, European Norm EN207 and International Electrotechnical Commission IEC-60825 (2007) discuss the maximum permissible exposure without protective eyewear. Each national investigator in GALION should address the eye safety issue in the operation of their lidar systems and discuss these with their national controlling authority for the use of lasers in the atmosphere.

3.2.3 Backscatter Lidar

The first lidars were simple backscatter units at one or more wavelengths. Called "elastic" lidars since the wavelength of light does not change during the scattering process, these units require the least technological sophistication to implement and arguably the most sophistication to turn into unambiguous scientific use. Since the basic lidar equation contains one observable (the energy returned as a function of time) and two unknowns (the backscatter coefficient of the aerosol and the two way transmission through the atmosphere which comes from the integration of the extinction with height), the system is underdetermined. Many techniques have been discussed in the literature to work around this difficulty (the slope method, Collis and Russell, 1976; the Bernoulli solution to the equation, Fernald, 1984, Klett, 1981; and column closure by the use of ancillary optical depth information, Welton et al., 2001). Nevertheless, the measurement remains only an estimate of either backscatter or extinction as long as elastic lidar-only data is available.

There is value, however, in the backscatter lidar in obtaining vertical physical measurements. In the simplest form, laser ceilometers are lidars. They measure range to a target (in this case clouds) and provide structural information on the atmosphere. Recently, sensitivity of ceilometers has been improved so that some detectability of aerosols has been demonstrated. The utility of these highly distributed sensors is attractive since they serve other purposes and are being purchased in larger numbers than aerosol lidars, but, at the time of this report, there are no published aerosol retrieval measurements which are comparable to more sophisticated lidar systems.

The easiest lidar to implement is one which has a laser which can emit significant power levels (>0.1 J per pulse) and have large receiving apertures. It is not uncommon to find lidar systems with Nd-YAG lasers and 10-30 cm aperture telescopes with photomultiplier detectors. In many cases, analog detection of the signal from the photomultipliers is simply digitized by PC cards. Such systems can be constructed for less than $100k US (perhaps much less with some technical experience). However, few commercial systems are available in this configuration. The prime reason limiting the distribution of such lidars is the difficulty in providing eye safety with such systems. Current use of these systems requires observers or in some cases, remote detection of aircraft using radars or radiodetection systems. It is not at all uniform how eye safety issues are addressed in various countries and this is a serious issue for backscatter lidars in visible wavelengths.

Systems, which operate in more eye safe regimes, have an advantage in this regard. Several companies have begun to market a small, portable 355nm backscatter lidar which is eyesafe at distances of a few hundred meters from the lidar. This system still maintains a flashlamp-pumped frequency tripled Nd-YAG laser as the source but has some novel technology in the detection scheme to allow daytime operation. Lidars have been built at 1.55 μm using OPO technology or Raman-shifted Nd-YAG transmitters (Mayor and Spuler, 2004) in order to provide completely eye-safe operation. In the future, near infrared fiber-optic based diode laser sources provide promise for relatively high power, high repetition rate operation which are being examined as lidar sources (Stephen et al, 2007).

Another class of backscatter lidar which has been widely used is the Micropulse Lidar (MPL) in which a low power, high repetition rate Nd-YLF laser is used (at 523 nm) along with photon counting detectors to provide a coaxial laser transmitter/receiver system which is eyesafe at the laser exit. MPL lidars have a disadvantage of a long transmitter/detector crossover and need careful monitoring of the thermal/optical arrangement so that this factor stays stable. Data from MPL type systems can be examined at the NASA MPLNet site (http://mplnet.gsfc.nasa.gov) and is discussed in Section 4.5.6 below.

There is a paucity of information on the comparability of such systems. GALION can play an important role in the quality assurance on such units by encouraging round-robin and multi-lidar intercomparisons to be performed. These activities would fit as a GAW Aerosol SAG role and could be encouraged through GALION. *Since these types of systems are likely to be contributed to GALION, it is important that, in the early stages, GALION sets a data objective of the precision* *of backscatter lidars in obtaining the attenuated backscatter coefficient in order to be useful for acceptance as a GALION contributing station or network.*

3.2.4 Raman Lidar and HSRL

The independent determination of backscatter and extinction is facilitated by the measurement of pure molecular backscatter, because here the backscatter coefficient can be calculated a priori with sufficient accuracy so that the extinction can be retrieved in a unique way from the molecular backscatter signal. The technologically easiest way is to use vibrational Raman scattering from nitrogen (or oxygen). Due to the high Raman shift of 2331 cm^{-1} this signal can be separated reliably from the elastic particle scattering with standard filters. For nighttime operation the filter bandwidth can be broad, for daytime operation a filter width of 0.3 nm and a laser with high pulse energy, >250mJ at 20 Hz, is required to achieve the accuracy goals. While technical implementation, in particular for nighttime operation, is quite straightforward, the disadvantage is that the scattering cross-section and hence the received signal is very low unless a high power laser and a narrow bandwidth filter is employed.

Pure rotational Raman scattering by nitrogen and oxygen offers a scattering cross section that is about a factor of 30 higher than vibrational Raman scattering. The downside is that the Raman shift is quite small, about 30 cm^{-1} only, so that separation from the elastic particle backscatter is more challenging, keeping in mind that out-of-band blocking has to be on the order of 10^{-8}. Both filter techniques and double grating polychromators have been demonstrated for this approach. In particular the combination with a Fabry-Perot comb filter can suppress daylight sufficiently to allow daytime operation. A more sophisticated setup also allows one to retrieve the temperature profile simultaneously. With this technique the price to be paid for better system efficiency is higher system complexity with corresponding sensitivity to misalignment.

A further increase in system efficiency for the signal from molecular scattering only is to separate the Rayleigh scattering from the particle scattering. The Rayleigh scattering cross section of air is more than three orders of magnitude greater than that for vibrational Raman scattering. The spectral separation is based on the Doppler broadening of the Rayleigh line, leading to an about 0.01cm^{-1} wide line surrounding the much narrower peak from particle scattering. In the HSRL technique for one channel, the centre part of the backscatter spectrum containing the particle return is suppressed with a ultra-narrowband filter, generally an iodine vapour cell, the second channel records the total signal from particle plus Rayleigh scattering. The combination of both signals allows the user to determine extinction and backscatter profiles independently. The advantage of this technique is that it suitable for daytime operation, the price to be paid for this is high system complexity and high demands on system adjustment as well as on performance control.

All three techniques have been operated successfully for aerosol profiling, at the present time no final recommendation can be given for the employment in new GALION stations. To a large extent this will depend on the expertise of the operating personnel with optical systems and to the extent of future system automation.

3.2.5 Multi-wavelength Raman Lidar

All three methods for independent determination of aerosol extinction can be used at multiple wavelengths to provide the input for the retrieval of aerosol microphysical properties. Most common is the use of vibrational Raman scattering at 355nm and 532nm, the second and third harmonics of the Nd:YAG laser. In combination with the backscatter at 1064nm from the fundamental such a system allows to estimate microphysical properties using just a single laser source. A substantial number of systems using this technique are presently operated.

A similar approach using pure rotational Raman scattering at the same wavelengths is under test, the necessary filter techniques are available.

The solution for the HSRL is not as easy as for the Raman techniques because the laser source and the high-resolution filter must be matched. Up to now no multi-wavelength approach is reported for this technique.

4. IMPLEMENTATION

4.1 General organization

4.1.1 GALION: A network of LIDAR networks

Advanced aerosol lidar systems are still relatively complex, expensive, and delicate instruments requiring substantial efforts for operation and maintenance, although substantial progress has been made towards increased reliability and automated operation. Presently it is not feasible to implement a global aerosol lidar network by installing a homogeneous set of systems at a number of stations selected for optimal coverage. Instead it is important to make use of existing systems at established stations, of the experienced operators of these systems, and of existing network structures. Therefore the operation of GALION will initially depend completely on voluntary contributions from the various existing networks (most of which, themselves, are based on voluntary cooperation) plus contributions from individual stations. The structure of GALION will reflect the principle that the contributing networks continue to pursue their original goals. Nevertheless, for GALION's success, contributing networks need to enhance GAW's observing capability and meet GAW's requirements for consistency of data across the network, insured quality, and enhanced data distribution. To improve the coverage in areas with significant aerosol load, the networks will make efforts to accept new members operating at suitable locations and provide as much support as possible. In particular cooperation with National Hydrological and Meteorological Services and installation of lidars at GAW global stations will be fostered.

4.1.2 Steering group

GALION will be headed by a Steering Group consisting of the heads or representatives of each contributing network with invitational status for significant contributing stations that are not currently in a network. Decisions to provide guidance and protocols for existing stations will be made by consensus. A speaker to represent GALION to other communities and to take care of the running business will be elected by the steering group.

4.1.3 Working groups

The real work providing the solutions for all issues should be done in the working groups which are established as necessary. Working groups are installed (and abandoned) by the steering group, but they will have much freedom to organize their work as necessary. Initially working groups on **user needs, methodology, technologies, quality assurance, and data collection and dissemination** are established. Issues concerning co-operations and capacity building will be addressed directly by the steering committee.

4.2 Scheme of operation

The observations within GALION serve different purposes requiring different operational characteristics. To establish a useful climatology it is necessary and sufficient to make regular measurements on a fixed schedule, thus avoiding a strong bias towards "blue sky" conditions. There is evidence that two measurements per week are sufficient for this purpose, so the minimum requirement for GALION is to perform measurements every Monday and Thursday. Because diurnal changes in the atmosphere require observations to be made at comparable local times, and because Raman systems are best operated at low levels of ambient light, it is suggested to perform these measurements in a time slot of a few hours around sunset. This also has the advantage that the boundary layer is typically well developed so that it is likely to observe the maximum extent of boundary layer aerosol. Local conditions may require a different time of observation, but in any case the schedule should be fixed for each station. For stations capable of making daytime measurements, two measurements on Monday (one-two hours past solar noon and the second in the evening time slot) should be taken.

The observation of special events like, e.g., aerosol plumes from wildfires, desert dust outbreaks, or volcanic eruptions make it necessary to perform observations whenever these events occur and are likely to be observable at a station. An alerting system will be established to notify the station operators of such events so that additional measurements can be initiated. Special campaigns will serve to characterize, e.g., the diurnal and weekly cycles, to provide for inter-comparisons with space-borne instruments, or to meet other special requirements.

There is an increasing demand for continuous operation with near real time delivery of data products. While this appears feasible for relatively simple systems and data products like attenuated backscatter obtained from automated backscatter lidars, it will require further development in automation of instruments and evaluation algorithms to achieve this for more complete characterization of aerosols. It is suggested that a small number of advanced systems with full aerosol characterization are operated on the minimum schedule described above, and continuous operation is attempted for a larger number of stations operating backscatter lidars.

4.3 Quality assurance

GAW Strategic Plan requests strict quality control, typically based on primary standards, methods to link station measurements to primary standard, system audits, etc. QA'ing multiple networks has never been done for lidar and that the GAW can become important in enabling quality assurance activities between networks. A quality assurance document will be required if WMO and GAW accept that GALION concept.

4.4 Data collection, archiving and dissemination

The goal is to provide the users with at least one point of contact through which data from all stations can be accessed in a consistent way. At the same time the responsibility for the data integrity and availability must remain with the stations or networks that made the observations, and duplication of work should be avoided. For these reasons it is planned to develop a web-based interface that

- Holds the metadata from all contributing stations, i.e. dates, times, and type of measurements.
- Allows searching for data matching specified criteria.
- Arranges quicklook to selected data.
- Arranges download of selected data from the original source.
- Provides tools to read and display data from different sources in a homogeneous way.
- Handles access rights consistent with predefined rules.

In this way all data remain at the original sites, either the data bases of the participating networks or at individual stations. The data remain there in their original format, the web interface provides for conversion into a common format, only that is visible to the user. Download from the original site is arranged through the interface, where control of access rights is performed. Access rights can be specified for various user groups as well as differently for different data types and data sources, to respect the individual data policies of the partner networks. The steering committee will work on the harmonisation of data policies among the partners.

The interface will be developed in a form that is portable to different platforms, so it may be installed at several sites simultaneously. e.g., the World data centre for aerosols, the world data centre climate, and the portals of the participating networks could, in principle, all hold the same interface.

While in the beginning the functionality of the interface will be restricted to the most basic requirements, it can be advanced further by making use of related developments at the partner networks.

4.5 Network development

4.5.1 Present situation and distribution of stations

GALION is built on the cooperation between existing and developing networks in different regions of the globe. This appears to be the only way to achieve useful spatial coverage right from the beginning, to bring in the required experience with lidar network operation and retrieval of aerosol parameters, to provide a solid basis for the definition and development of optimized instruments, and to establish the necessary cooperation with the communities making use of the data.

The distribution of stations as presently envisioned is shown in Figure 2, where the different colour of the dots indicate the participating networks. Details of the stations are in Table 4.

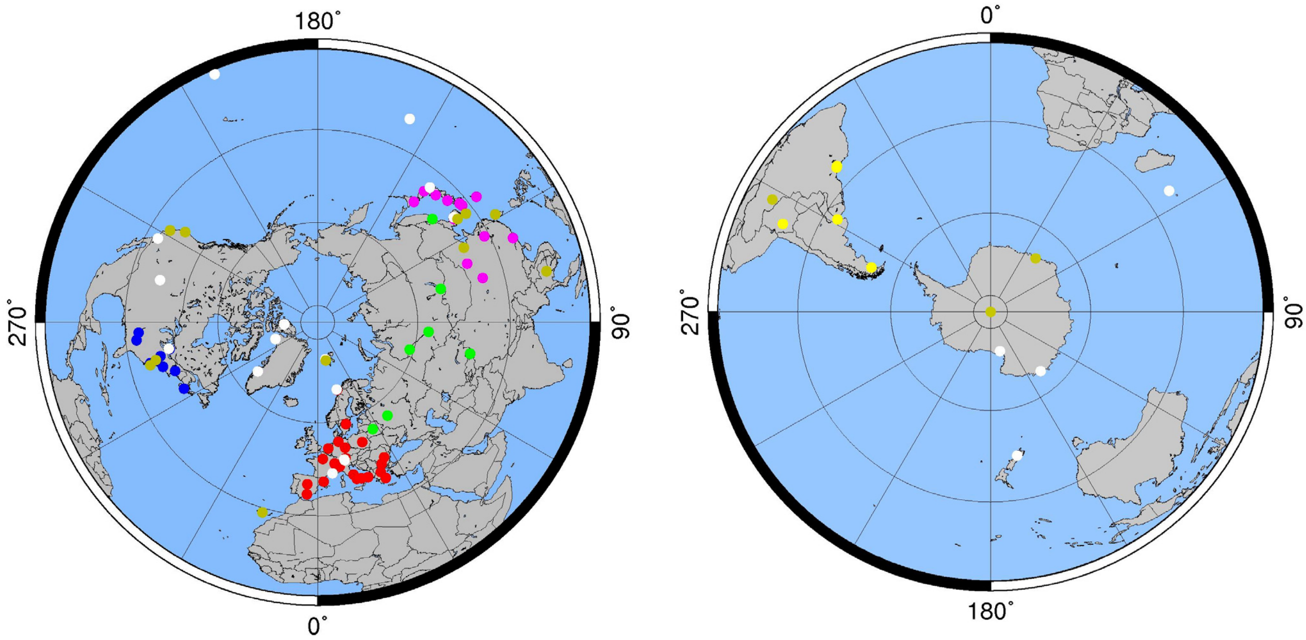

Figure 2: Distribution of stations as available through the cooperation between existing networks. The different networks are indicated by the dot colour: AD-NET violet, ALINE yellow, CISLiNet green, EARLINET red, MPLNET brown, NDACC white, REALM blue. See Table 4 for station details.

Table 4: Provides an overview of the geographical coordinates of the stations in Figure 2, the partner network, the operational status, and the type of lidar operated (or planned). While for some of the stations/networks the status is well established for others this is rather the status expected within a short time frame after GALION is established.

Station	Lat. deg N	Long. deg E	Altitude m	Status	System
AD-Net					
Tsukuba	36.05	140.12	30	O 1996	2BL+DL(+1RL)
Nagasaki	32.78	129.86	17	O 2002	2BL+DL
Fukue	32.75	128.68	50	O 2002	2BL+DL
Sapporo	43.06	141.33	30	O 2003	2BL+DL
Toyama	36.70	137.10	28	O 2004	2BL+DL
Matsue	35.21	133.01		O 2005	2BL+DL
Sendai	38.25	140.90	60	O 2005	2BL+DL
Cape Hedo	26.87	128.25	60	O 2005	2BL+DL
Niigata	37.84	138.94	1	O 2007	2BL+DL
Chiba	35.65	140.12	20	O 2007	2BL+DL
Suwon	37.14	127.04	120	O 2002	2BL+DL
Seoul	37.45	126.95	116	O 2006	2BL+DL
Phimai	15.184	102.565	212	O 2005	2BL+DL
Ulaanbaatar	47.92	106.90	1320	O 2007	2BL+DL
Sainshand	44.87	110.12	937	O 2007	2BL+DL
Zamyn uud	43.72	111.90	962	O 2007	2BL+DL
Ryori	39.033	141.833		O 2002	1RL+DL
Guangju	35.10	126.53		O (N)	(3+2)RL+DL
Taipei	25.00	121.32		O	(2+1)RL+DL
Beijing	39.97	116.37	70	O 2001	2BL+DL
Hefei	31.897	117.173	30	O 2002	2BL+DL
Shapotou	37.5	105.0	1250	O 2006	1BL+DL
Guangzhou	23.16	113.33	100	O 2006	2BL+DL
ALINE					
Rio Gallegos	-51.60	-69.32	15	O 2005	MRL
Buenos Aires	-34.60	-58.50	20	O 2001	BL, RI
Sao Jose dos Campos	-23.00	-46.00	625	O 1974	MRL
Sao Paulo	-23.30	-46.40	840	O 2001	BL
La Paz	-16.50	-68.20	3420	N 2007	BL
Arecibo	18.35	-66.75	363	O 1989	BL
Camagüey	21.24	-77.51	122	N 1991	BL
CISLiNet					
Minsk	53.917	27.383	200	O 1990	(3+1)MBL, RL, DL
Tomsk	56.48	85.05	140	O 1990	(3+2)MRL, DL
Moscow	55.45	37.37	200	O 2004	(2)BL
Surgut	61.24	73.29	80	O 2004	BL
Vladivostok	43.201	131.92	50	O 2004	(3)MBL
Teplokluchenka	42.5	78.4	2080	O 1992	(3+1)MBL, RL, DL
EARLINET					
Andoya	69.28	16.01	380	O 2006	(3+2)RL
Athens	37.96	23.78	200	O 2000	(3+2)RL
Barcelona	41.39	2.11	115	O 2000	(2+1)RL
Belsk	51.84	20.79	180	O 2002	(2)BL
Cabauw	51.97	4.93	1	O 2008	(3+2)RL
Garmisch	47.48	11.06	730	O 1998	(3)BL,HSRL
Granada	37.16	-3.61	680	O 2006	(3+1)RL, DL
Hamburg	53.57	9.97	25	O 1998	(4+2)RL
Haute Provence	43.94	5.71	683	O 2006	RL
Ispra	45.82	8.63	214	O 2006	BL
Payerne	46.82	6.93		O 2008	RL
L'Aquila	42.38	13.32	683	O 2000	RL
Linköping	58.39	15.57	80	O 2000	(2+1)RL
Lecce	40.30	18.10	30	O 2000	RL
Leipzig	51.35	12.44	90	O 1998	(3+2)RL, DL
Madrid	40.45	-3.73	669	O 2006	RL
Magurele-Bucharest	44.45	26.03	90	O 2006	(2)BL

Minsk	53.92	27.60	200	O 1986	(3+1)MRL, DL
Munich	48.15	11.57	539	O 1998	(3+2)RL, DL
Napoli	40.84	14.18	118	O 2000	(2+2)RL
Neuchatel	47.00	6.96	487	O 2000	BL, DL
Palaiseau	48.70	2.20	162	O 2000	(2)BL, DL
Potenza	40.60	15.72	760	O 2000	(3+2)RL,DL
Sofia	42.67	23.33	550	O 2002	(3)BL
Thessaloniki	40.63	22.95	60	O 2000	(2+1)MRL
MPLNET					
Abracos Hill	10º 46’ S	62º 22’ W	283	N 2002	MPL
Anmyeon-Ko	36º 32’ N	126º 19’ E	45	O 2005	MPL
Beijing	39º 45’ N	116º 58’ E	35	N 2005	MPL
COVE	36º 45’ N	75º 42’ W	10	O 2004	MPL
GSFC	36º 01’ N	76º 52’ W	50	O 2001	MPL
Gosan	33° 17' N	126° 10 E	10	O 2005	MPL
Jung-Li	24° 58 N	121° 11 E	5	O 2002	MPL
Monterey	36° 35 N	121° 51 W	52	O 2007	MPL
Ny Alesund	78° 55' N	11° 56' E	10	O 2002	MPL
Pimai	15° 11 N	102° 34 E	230	O 2006	MPL
South Pole	90° S	0° E	2840	O 1999	MPL
Syowa	69° 00' S	39° 35' E	20	O 2001	MPL
Tenerife	28° 28' N	16° 15' W	52	O 2005	MPL
Trinidad Head	41° 03' N	124° 09' W	107	O 2005	MPL
NDACC					
Eureka	80.05º N	86.42º W	n/a	n/a	O3, T, A
Ny Alesund	78.92º N	11.93º E	n/a	n/a	O3, T, A
Thule	76.53º N	68.74º W	n/a	n/a	T, A
Andoya	69.30º N	16º E	n/a	n/a	O3, T
Sondre Stomfjord	67.02º N	50.72º W	n/a	n/a	T
Hohenpeissenberg	47.80º N	11.02º E	n/a	n/a	O3, T
Garmisch	47.48º N	11.06º E	730	n/a	A, MBL, DL
Toronto	44.00º N	80ºW	n/a	n/a	O3, T, A
Haute-Provence	43.94º N	5.71ºE	n/a	n/a	O3, T, A
Boulder	40º N	105ºW	n/a	n/a	(A)
Suwon	37.20º N	127.6º E	n/a	n/a	(A)
Table Mountain	34.40º N	117.7º W	n/a	n/a	O3, T, A
Mauna Loa	36.05º N	140.13º E	n/a	n/a	O3, T, A
Christmas Island	1.88º N	157.4º W	n/a	n/a	A
La Reunion	21.80º S	55.5º E	n/a	n/a	O3, (T), A
Lauder	45.04º S	169.68º E	n/a	n/a	O3, (T), A
Rio Gallegos	51.60º S	69.31º W	n/a	n/a	O3, A
Dumont d'Urville	66.67º S	140.01º E	n/a	n/a	O3, A
McMurdo	77.85º S	166.83º E	n/a	n/a	A
REALM					
UMBC, Baltimore	39.25545	-76.7093	81	O 2001	BL, RL
Howard Univ., Beltsville, MD	39.0542	-76.8775	53	O 2006	RL
CCNY, New York	40.8192	-73.94904	98	O 2005	BL, RL
HU, Hampton, VA	37.0202	-76.3367	8	O 2007	BL, RL
MSC, Egbert, ON	44.23	-79.78	249	O 1990	BL
Dalhousie, Halifax, NS	44.63806	-63.5942	50	O 2006	BL
CART, Lamont, KS	36.617	-97.5	320	O 1998	RL

As can be seen in Table 4 there is unevenness in the metadata for the sites and this needs to be addressed in Year 1 of GALION.

The participating networks can be briefly characterized as follows:

4.5.2 Asian Dust Network, AD-Net

The Asian Dust Network (http://www-lidar.nies.go.jp/AD-Net/) is an international virtual community designed originally to track outbreaks of dust from China, Mongolia and Russia. Operating since 2001, the network consolidated operations from stations which have records back to 1997.

4.5.3 ALINE

The **A**merican **LI**dar **Ne**twork is an informal agreement among the existing lidar groups in Latin America. It includes also research teams working to host lidar instruments in the near future. The main goals of ALINE are developing the sense of community, conducting capacity building activities among young scientists and students in the region and promoting cooperation between the few existing groups (Antuña et al., 2006). A series of regular workshops every two years have been conducted beginning in 2001 (http://www.lidar.camaguey.cu/wlmla.htm). Those regular exchanges have contributed to exchanges and some preliminary cooperation among the lidar groups in the region. Special attention has been paid to the courses and lectures for students and young scientists. At the last one held in Brazil, the general agreement was reached to formalize the network. Several steps have been taken in that direction.

4.5.4 CIS-LiNet

Lidar network CIS-LiNet (Chaikovsky et al., 2006) has been established by lidar teams from Belarus, Russia and Kyrgyz Republic. Its objective is carrying out lidar observation coordinated at the territory from Minsk to Vladivostok in cooperation with EARLINET and AD-Net. During network developing lidar stations will be provided with sun radiometers and will be included in the global radiometric network AERONET. The following stations constitute CIS-LiNetL at the first stage of the network formation: - Stationary lidar stations in Minsk, Moscow, Surgut, Tomsk, Vladivostok, - Alpine stationary lidar station in Teplokiuchenka in Central Asia, Kyrgyz Republic - Seasonal lidar station on the base of a mobile lidar at the Lake Baikal - Shipboard lidar in Vladivostok All stations will carry out aerosol observations in the troposphere and stratosphere. Three stations in Minsk, Tomsk and Vladivostok implement ozone sounding in the stratosphere layer. Discrepancies of the lidar equipment, methods of data processing and software, methodology of implementation of scientific tasks are presented.

4.5.5 European Aerosol Research Lidar Network, EARLINET

EARLINET (http://www.earlinet.org) is a voluntary association of institutions with an interest in aerosol science and a long-term commitment in vertical profiling of aerosol properties with advanced laser remote sensing. It was established in 2000 as a research and technology development project of the European Commission, was continued after the end of that project on a voluntary basis, and is presently supported again by the EC as a coordination action for research infrastructure. Presently EARLINET comprises 25 stations distributed over Europe. Instrumentation is rather inhomogeneous because most lidars existed before the network was established, but most systems are now equipped with at least one Raman channel for independent determination of extinction and backscatter. The main goal is to establish a climatology for the aerosol vertical distribution, therefore regular operation at three times per week has highest priority for all stations. Special studies of, e.g., Saharan dust outbreaks across the Mediterranean, distribution of smoke from wildfires, the Mount Etna eruption, air mass modification across Europe, diurnal cycle, or CALIPSO validation required numerous additional observations which were organized as necessary through corresponding alerting schemes. Quality assurance for hardware and software was performed through direct intercomparisons, tools for routine performance checks are under test.

4.5.6 MPLNET

The only tropospheric profiling network which can claim global coverage is the NASA MPLNET (Welton et al., 2001). Designed for satellite validation, MPLNET consists of high repetition, low power, eye safe commercially available backscatter lidars.

The Micro-Pulse Lidar (MPL) was developed at NASA Goddard Space Flight Centre (GSFC) in the early 1990s (Spinhirne et al. 1995). The MPL is a compact and eye-safe lidar system capable of determining the range of aerosols and clouds by firing a short pulse of laser light (at 523 or 527 nm) and measuring the time-of-flight from pulse transmission to reception of a returned signal. The returned signal is a function of time, converted into range using the speed of light, and is proportional to the amount of light backscattered by atmospheric molecules (Rayleigh scattering), aerosols, and clouds. The evolution of the MPL from the initial Spinhirne et al. (1995) optical design to the standard design now used in MPLNET is described in detail by Campbell et al. (2002), including on-site maintenance, and calibration techniques. Post-2002 enhancements include a new data system, telescope, fiber-coupled detectors, and a new laser. These changes do not significantly alter the basic MPL optical design but increase system reliability and allow for more in-field repair options.

Data is available in near real time (same day) through the NASA MPL data site (http://mplnet.gsfc.nasa.gov).

4.5.7 Network for the Detection of Atmospheric Composition Change, NDACC

The stratosphere and upper troposphere have been monitored for at least 15 years by the NDACC (previously NDSC). NDACC is consists of more than 70 high-quality, remote-sensing research sites for observing and understanding the physical / chemical state of the stratosphere and upper troposphere and assessing the impact of stratospheric changes on the underlying troposphere and on global climate. Only a subset of the stations actually contains lidars. In this subset, the lidars are designed primarily to profile O_3 in the stratosphere and stratospheric aerosols. Because of this not all NDACC lidar data may be completely applicable to GAW purposes.

4.5.8 Regional East Aerosol Lidar Mesonet, REALM

Since 2002, a collaboration of existing lidar facilities has attempted a network operation under the name “Regional East Aerosol Lidar Mesonet” (REALM; Hoff et al., 2002). But to date only two groups and three lidars have voluntarily contributed consistent data to the network with two other groups contributing campaign style activities.

A requirement for lidar profiling in the US is in studying air quality/atmospheric transport of aerosols. The contribution from REALM was designed to contribute to this goal. Lidars which have contributed to REALM are in Baltimore MD, Princeton, NJ, New York, NY with links to ARM, MPL-Net, and Canadian data at Egbert and Halifax, CA.

4.5.9 Coverage of the main aerosol source and receptor areas

In addition to the cooperation between the existing networks cooperation will be sought with new regional lidar networks that are about to be established, e.g., in China and India. GALION will also cooperate with individual stations in regions where no network is operational.

The overview over the existing stations shows that some regions of the globe are rather well covered but large regions exist where no observations at all are available. Additionally it has to be considered that the measurement capabilities of the stations as well as their operational status are quite different.

Major source areas for natural aerosols affecting populated areas are the extended desert zones of central Asia and Africa for mineral dust, the oceans for sea salt, and Africa and South America for biomass burning.

Asian Dust: Actual coverage by lidar is irregular, with better distribution in Japan and some few lidars in China. The number of lidars should be increased in Asia.

Saharan Dust: Aerosols from the Sahara are transported according to the synoptic conditions to Europe across the Mediterranean or to America across the Atlantic. Lidars are needed in the north and east of Africa to cover both directions of transport. In Europe there is a good coverage. Both in the Central America and the northern part of the east of South America there are only lidars in Arecibo, Puerto Rico, who do not operate regularly. Lidars are needed in this region.

Amazonas Biomass Burning: The coverage of this area is very poor. There exists only one lidar in Sao Paulo, Brazil and one more prospective MPL lidar.

Industrial aerosols from North America, Europe, East Asia, India: There are few lidar networks whose sole goal is to monitor air pollution. The REALM lidar network in North America had this as a prime driver and perhaps this focus has limited the success of the network. Much of the coincident measurements in the REALM network have been driven towards detection of elevated smoke plumes and have marginally contributed to pollution detection needs. Recently, however, NASA in cooperation with NOAA and EPA has funded the contribution of REALM data to the EPA's AIRQuest database. This allows comparison of data from lidars in the US East and ground-based measurements of $PM_{2.5}$ and satellite measurements of aerosol optical depth. This project, called a Three Dimensional Air Quality System (3D-AQS; Engel-Cox et al., 2007) will benefit from GALION activities in North America.

In Asia, a number of publications have addressed urban pollution in China, Korea and Japan (Ansmann et al, 2005; Müller et al, 2006). Urban pollution often is mixed with Asian dust and the ability of lidars to use multiple wavelengths to provide discrimination between sources is increasingly important. The INDOEX (Asian Brown Cloud) experiment showed that vertical structure of haze coming from India was quite different near the continent and out over the Indian Ocean. (Ansmann et al, 2000, Müller et al, 2003).

In Europe, papers have been written about detection of large scale hazes from the Earlinet network (Ansmann et al, 2002: Wandinger et al, 2005). The ability of multiple stations to track haze masses as they move across a continent are evident.

Few papers have addressed urban or pollution issues in Africa or South America unless the sources were related to biomass burning. Given the source emissions of $PM_{2.5}$ precursors, urban pollution studies will mimic the emissions inventories for these precursors.

Finally, lidars have shown that pollution is not confined to the continent on which it is generated. Lidar measurements have seen North American pollution aerosols in Europe (Eixmann et al, 2002), Asian pollution in North America, and European outflows to Asia. From a GAW perspective, the global nature of pollution aerosols and the need for vertical detection of these aerosols well above the boundary layer is a strong motivation for the support of GALION.

4.5.10 Alignment with GAW

Building on existing networks and associated individual stations alone results in a distribution of stations which is not well matched to the existing GAW stations for surface in situ or sun photometer total column aerosol property observations. The GAW Global stations that have had tropospheric lidars are Izana, Ny Alesund, and the South Pole Station reporting MPL sites and Alert which had a system in the mid-1980's (Hoff et al, 1988, Leaitch et al, 1989). The other GAW Global stations do not have lower tropospheric lidars although the Lauder, Mauna Loa, Jungfraujoch, and Ny Alesund stations do have NDACC sites, primarily for stratospheric aerosol observations related to O_3 depletion studies. The only GAW regional stations that currently have lower tropospheric lidars installed are Egbert, Canada (also a REALM network site), two Regional GAW stations at Ryori, Japan, and Anmyeon-do, Korea (GAWSIS, 2007). All other lidar stations for vertical aerosol profiling, according to station classification criterion in the GAW Strategic Plan (GAW 2007), can be categorized as "contributing stations". All GAW stations can be found in the GAW Station Identification System (GAWSIS) on the GAW website. Since the primary goal of the network is to reach significant coverage with high-quality systems operated by experienced personnel, this appears acceptable for the initial phase. However, strong efforts should be made to get National Hydrological and Meteorological Services involved in station operation and to build high level lidar capabilities into GAW "Global stations" or "Regional stations".

4.5.11 Capacity building

As stated above, the spatial coverage that can be achieved using existing networks and associated stations alone is a good starting point for GALION but finally do not meet the requirements of GAW. Therefore, it is necessary to build up new stations in areas that are required for the network operation but where presently no or little experience with advanced lidar operation exists. To ensure proper operation adapted to the local conditions and the use of GALION data for the benefit of many countries, GALION should develop a capacity building process accounting for the real conditions in each region/network. It could combine short courses, training, workshops, and where it will be possible the development of network/regional lidar training centres.

Lecturers and trainers should be selected using both the local network/regional qualified personnel as well as personnel from other regions/networks. That selection should be coordinated by the corresponding working group.

The subjects of the courses and trainings should focus on lidar principles, operation, processing, quality control and GALION procedures. For those activities appropriated bibliographical material on the lidar subjects listed above should be provided together with the GALION official documents (methodologies, procedures etc.) Those materials (or selected ones) could be located in an online library in the future GALION site.

Capacity building actions should also be promoted in cooperation with ICLAS, CLAS and ICO.

4.6 Synergy with other GAW Measurements

4.6.1 Sun-photometer networks

In two GAW reports on guidelines and on the global aerosol optical depth network (GAW 2003; GAW 2005), the intent of GAW to include aerosol optical depth as a core parameter in GAW aerosols operations was emphasized. Subsequently, an AOD and sunphotometer working group has been formed as part of the GAW SAG for aerosols. AOD from ground based sunphotometers has been shown to be highly correlated with air mass origin and aerosol composition and AOD measurements are widely distributed around the globe. AOD measurements have the additional attribute that they can be made at high temporal resolution. In addition, satellite AOD retrievals (see 4.6.3 below) are correlated with the ground-based AOD measurements and can be used to interpolate between widely space aerosol sites.

The disadvantage of sunphotometry or AOD measurements in general is that this is a column measurement and generally gives little or no information on the location of the aerosol in the vertical. To that end, the SAG for aerosols recommended (GAW 2003) that, where possible, lidars be collocated with sunphotometer stations. Use of even the simplest lidars can determine the height structure of the aerosol, whether it is confined to the PBL or being transported aloft, whether it is in the troposphere or stratosphere, whether clouds are involved, and to some extent for sophisticated MRL systems, the type of aerosol. In addition, extinction measurements with RL, MRL, and HSRL systems can be used to provide closure on the optical depth by an extinction profile which can be integrated to give a check on AOD measurements.

Conversely, AOD measurements can be used to provide closure on the assumed column extinction to backscatter (lidar) ratio which is used in BL systems.

4.6.2 Ground-level in-situ aerosol monitoring networks

There are numerous ground level measuring networks for aerosols. In North America, there are in excess of 1800 surface sites which measure $PM_{2.5}$ and PM_{10} at hourly and daily averaging intervals. In Europe, approximately 35 sites contribute to the EMEP aerosol monitoring capability for $PM_{2.5}$ and PM_{10} (Leporini and Laj, 2006) while environmental agencies operate approximately 500 and 1500 $PM_{2.5}$ and PM_{10}, respectively. It is clear that many national agencies use surface in-situ measures of aerosol for regulatory and monitoring requirements. Lidar data do not fit neatly into these regulatory requirements and few, if any, lidars are currently being used for regulatory monitoring.

The value added by lidar (temporal frequency, vertical structure, PBL determination, etc.) is recognized now as valuable by the aerosol forecasting community but the metric for most models is mass-based rather than an optical measure such as backscatter, extinction, or AOD. Several papers (Wang et al., 2003; Engel-Cox et al., 2004, 2006) have shown that AOD can be strongly correlated with surface PM, especially if the aerosol type is singular (continental urban, for example), if the aerosol is largely confined to the boundary layer, if the aerosol column can be corrected for the hygroscopic growth of the aerosol, and the boundary layer depth is measured. In these cases, one can improve on the correlation between PM measurements at the surface and lidar or satellite AOD data (Weber et al, 2007). However, it is unlikely that lidar data will replace or be substituted for in-situ measurements of aerosols. Recognizing that, the value of GALION will be largely in determining vertical structure of aerosol distribution, aiding in source attribution and prediction of downwind impacts. Clearly, detection of smoke plumes from distant regions and their impact on local air quality is an obvious motivation for making lidar measurements in urban and regionally polluted regions.

Figure 3 shows the contributing, regional and GAW stations from GAWSIS which contain any aerosol data. Contrast this with the GALION contribution shown in Figure 2. GALION will be a significant contribution to GAW should it be adopted. Since there are so few contributing GAW stations for aerosols (in comparison to the national networks taking aerosol measurements), it should be determined if there is a nearby (i.e. <25km) aerosol station in a national network that would be appropriate to be considered a GAW contributing station, instead of trying to relocate lidar systems to contributing stations already in GAW. This may actually be a more cost effective way of tying GALION to surface networks.

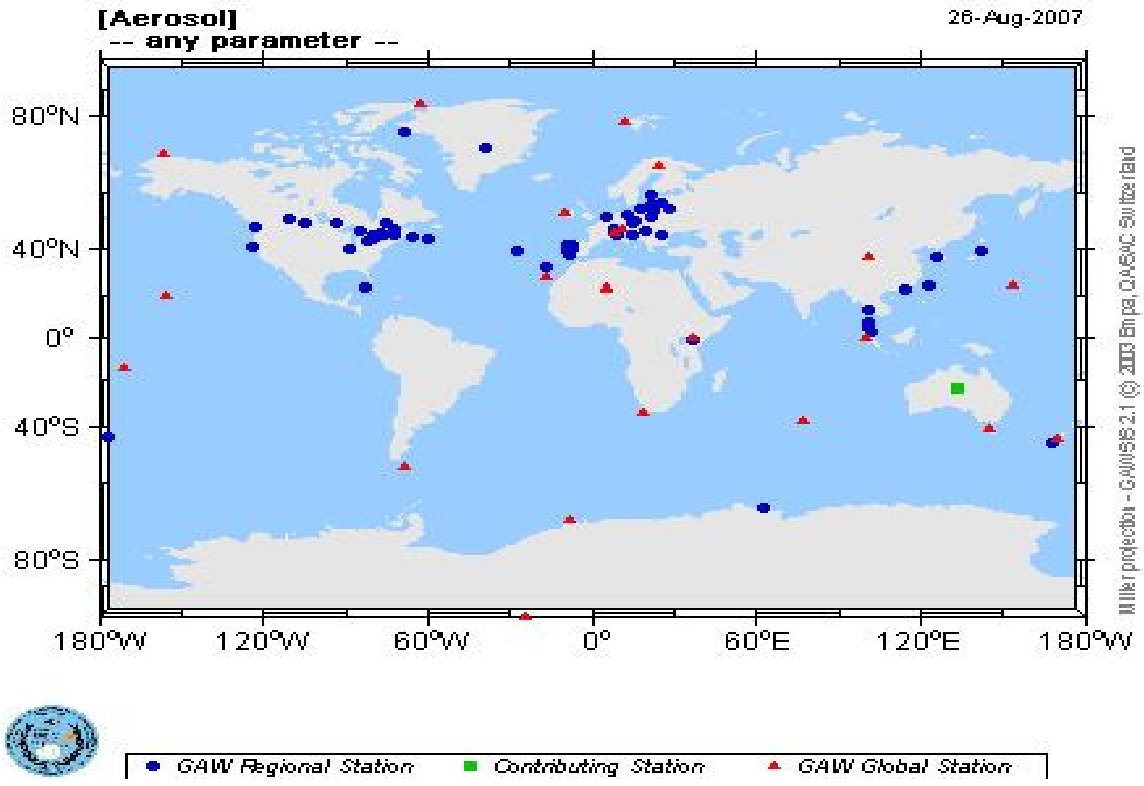

Figure 3: **GAW Global, Regional and Contributing stations for Aerosols.**

4.6.3 Satellite community (lidar and radiometry)

Two obvious areas of synergy between the satellite measurements and GALION are in validation for spaceborne lidar observations and in validation of column measurements made from satellite passive remote sensors.

In 2006, NASA launched the Clouds and Aerosol Lidar for Pathfinder Spaceborne Observations (CALIPSO) mission. Over the first year of observation, many of the stations who intend to contribute to GALION have been making targeted observations on CALIPSO overpass times. It is clear that the quality of GALION ground based measurements are crucial to the validation of the spaceborne instrument. This is especially true for aerosol types which have poorly or unknown lidar ratios which must be assumed in the CALIPSO aerosol retrieval since it is an MBL type instrument.

In future years, ESA will be launching one or more lidar systems which will also be used to map global distributions of aerosols. GALION will be well placed to provide validation for those new spaceborne lidar observations.

From the converse perspective, CALIPSO and ATLID may provide the ability to assess comparability between ground-based systems in the GALION. If calibration of the spaceborne instrument seems adequate at high quality sites, one should expect such agreement between this “orbiting transfer standard” and the ground sites. This can be a highly efficient way of monitoring GALION system performance, especially in the identification of outlier systems which may have need of some corrective action.

In a similar way, the Aerosol Optical Depth retrievals from instruments such as the Moderate Resolution Imaging Spectrometer (MODIS) on the Terra and Aqua satellites (Levy et al., 2007) or MISR (Diner et al., 2005) help synthesize a global picture between the temporally continuous daytime AOD measurements made by sunphotometers. GALION will provide the same advantage when used in a synergistic observational mode with these satellite sensors to determine the height as which aerosols reside in the atmosphere. For backscatter UV instruments such as the Ozone Monitoring Instrument on the Aura satellite, retrieval of aerosol optical depth and aerosol absorption optical depth are possible in the near UV but the retrieval is sensitive to aerosol height. Use of GALION data will be of value in constraining these retrievals (Hoff et al., 2007). Similarly, GALION data will be of use for trace gas retrievals for other OMI products since the PBL height can be determined and aerosol often serves as a passive tracer for transport.

Observations of AOD from the SEVERI instrument on the METOP geostationary platform provide high spatial and temporal resolution measurements of AOD over Africa. While GALION will have few sites in the viewing area of SEVERI, similar measurement are being made in NA with the NOAA GASP product which will shortly be extended to SA. In addition, the future GOES-R series of satellites will have multiwavelength AOD retrieval possibility and GALION clearly will be of value in validating the GOES-R satellite retrievals of AOD.

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ANNEX A

Methodology

A.1 INTRODUCTION

Various aerosol lidar techniques have been developed during the past about 40 years. Most frequently used aerosol lidars are standard backscatter lidars, Raman lidars, High Spectral Resolution Lidars (HSRL), and depolarization lidars (Kovalev and Eichinger; 2004; and book chapters by Eloranta, 2005, Ansmann and Müller, 2005, and Sassen, 2005, in Weitkamp, 2005). Data analysis schemes have been developed to retrieve vertical profiles of particle optical properties. The algorithms are well-tested and are nowadays almost routinely applied. Whereas standard backscatter lidars permit the determination of height profiles of the volume backscatter coefficient of the particles, Raman lidars and HSRL enable us to retrieve both the backscatter and the extinction coefficient profiles independently. In addition, the extinction-to-backscatter ratio is obtained which is a valuable parameter in the estimation of the aerosol type (maritime, dust, urban). In combination with Sun photometers a comprehensive set of vertically and spectrally resolved optical properties can be determined.

An overview of retrieval products for a variety of lidar-photometer configurations is given in Table A.1. The retrieval of optical and microphysical properties and the achievements and limitations of the available methods are outlined in the following paragraphs. Recommendations are given.

Table A1: Lidar-photometer setups and retrieval products. β is the volume backscatter coefficient of the particles (180° scattering coefficient, α the volume extinction coefficient, S_a the extinction-to-backscatter ratio (lidar ratio), τ is the optical depth, $Å_\beta$, $Å_\alpha$, and $Å_\tau$ are the Angstroem exponents for backscatter, extinction, and optical depth, MPP the microphysical properties of the particles. 1-λ and m-λ indicate one-wavelength and multi-wavelength lidar, respectively. col and z denote tropospheric column and height, respectively. z indicates the capability to separate boundary layer and free-troposphere aerosol influences and thus local and regional from long-range-transport aerosol impacts.

Observational configuration	Bsc. cf.	Ext cf.	Lidar ratio	Opt. depth	Ang. exp.	Microphys
1-λ standard backscatter lidar	$\beta(z)$					
1-λ standard backscatter lidar + Sun photometer	$\beta(z)$,	$\alpha(z)$ estimate	S_a (col)	$\tau(\lambda)$	$Å_\tau$(col)	MPP(col)
m-λ standard backscatter lidar	$\beta(\lambda,z)$				$Å_\beta(z)$	
m-λ standard backscatter lidar + Sun photometer	$\beta(\lambda,z)$	$\alpha(\lambda,z)$ estimate	S_a (λ,col)	$\tau(\lambda)$	$Å_\beta(z)$, $Å_\tau$(col)	MPP(col)
1-λ Raman lidar/HSRL	$\beta(z)$	$\alpha(z)$	S_a (z)	τ		
1-λ Raman lidar/HSRL + Sun photometer	$\beta(z)$,	$\alpha(z)$	S_a (z)	$\tau(\lambda)$	$Å_\tau$(col)	MPP(col)
m-λ Raman lidar	$\beta(\lambda,z)$	$\alpha(\lambda,z)$	S_a (λ,z)	$\tau(\lambda)$	$Å_\beta(z)$, $Å_\alpha(z)$	MPP(z)
m-λ Raman lidar + Sun photometer	$\beta(\lambda,z)$	$\alpha(\lambda,z)$	S_a (λ,z)	$\tau(\lambda)$	$Å_\beta(z)$, $Å_\alpha(z)$, $Å_\tau$(col)	MPP(z), MPP(col)

A.2 GEOMETRICAL PROPERTIES OF AEROSOL LAYERS

Height-time displays (colour plots) of the range-corrected signal or the attenuated backscatter coefficient (Rayleigh-calibrated range-corrected signal) are basic lidar products. They provide an overview of the measurement situation in terms the evolution of the planetary boundary layer (PBL), lofted aerosol layers, and cloud distributions (cf. Table A.2).

Any lidar can also be used to determine the thickness of the convective boundary layer (CBL). Several methods are available. The most common methods are the wavelet analysis method (Brooks, 2003), the gradient method (Menut et al., 1999), and the variance method (Lammert and Bösenberg, 2006, Martucci et al., 2007). Gradient and variance techniques date back to the 1970-1980's.

Table A.2: Aerosol properties that can be derived from lidar observations. The most simple lidar type that is needed to provide the product is listed only. The most simple lidar is the standard backscatter lidar (BL). Complex lidars are Raman lidar (RL) and HSRL. Multiwavelength lidars are indicated by MBL and MRL. SPM denotes Sun photometer. Depolarization channels (DL) are required to identify desert dust.

Parameter (product)	**Basic lidar type**
Range corrected signal (colour plots of aerosol and cloud distributions)	BL
Attenuated backscatter coefficient (calibrated range-corrected signal)	BL
PBL depth	BL
Aerosol backscatter coefficient	BL+SPM
Aerosol type discrimination (dust, anthropogenic)	BL+DL
Aerosol extinction coefficient (estimate), optical depth, column lidar ratio,	BL+SPM
Aerosol extinction coefficient, optical depth, lidar ratio	RL or HSRL
Ångström exponent (backscatter-related)	MBL
Ångström exponent (extinction-related)	MRL
Aerosol type determination (dust, maritime, fire smoke, urban haze)	MRL+DL
Aerosol microphysical properties (volume and surface conc., refractive index)	MRL
Single scattering albedo (aerosol)	MRL

A.3 RETRIEVAL OF AEROSOL OPTICAL PROPERTIES

A.3.1 Standard backscatter lidar

In the case of particle optical properties, we have to distinguish several options. The lidar of lowest complexity is the elastic-backscatter or standard backscatter lidar that measures the aerosol backscatter signal at one wavelength. This lidar allows the trustworthy retrieval of the particle backscatter coefficient (Klett, 1981, Fernald 1984, Sasano et al., 1985). A good knowledge of the incomplete overlap of the laser beam with the receiver field of view (RFOV) in the near range (usually up to 200-1000 m, sometimes up to 3-5-km height) is an important prerequisite for a proper retrieval of the particle backscatter coefficient in the lowest and most polluted part of the atmosphere.

Critical assumptions have to be made in this backscatter-coefficient retrieval. A long-lasting discussion of achievements and limitations of the technique may be found in the literature. The procedure, with all its subsequent modifications and improvements, simply suffers from the fact that two physical quantities, the particle backscatter coefficient and the particle extinction coefficient, must be determined from only one measured quantity, the elastic lidar return.

The most critical input parameter is the particle lidar ratio which is the ratio of the particle extinction coefficient to the particle backscatter coefficient. This quantity depends on the microphysical (size distribution), chemical, and morphological properties (spherical or nonspherical shape) of the particles. All of these properties, in turn, depend on relative humidity. The lidar ratio can vary strongly with height, especially when layers of marine, anthropogenic (urban, biomass burning), and desert dust particles are present above each other (Ansmann, 2006). Variations between about 20 sr and 100 sr make it practically impossible to estimate trustworthy extinction profiles. Even in the well-mixed layer the lidar ratio is not constant with height because the relative humidity increases with height and thus the lidar ratio increases with height (Ackermann, 1998). In cases with accompanying Sun photometer observations, a column lidar ratio can be estimated from the ratio of the photometer-derived optical depth to the lidar-derived column-integrated backscatter coefficient. This column lidar ratio however can only be considered as the best available guess, the true lidar ratio profile still remains unknown.

The impact of uncertainties in the assumed lidar-ratio profile on the backscatter-coefficient retrieval decreases with wavelength. Thus, the influence is lowest for large wavelengths such as 1064 nm. and highest for short wavelengths such as 355 nm.

In any case of aerosol lidar (simple backscatter lidar or more complex approaches discussed below), a calibration procedure is required. In this calibration, a so-called reference range must be chosen such that the particle backscatter coefficient in this range is negligible compared to the known molecular backscatter value. Standard-atmosphere assumptions, nearby radiosonde data of temperature and pressure, or weather prediction model outputs for the lidar site are used to compute the Rayleigh backscatter value in the reference height as well as the entire Rayleigh scattering profile along the laser beam. The Rayleigh scattering profile has to be subtracted to obtain the pure particle backscatter coefficients. Sufficiently clear air conditions as needed in the calibration are normally given in the upper troposphere for laser wavelengths < 700 nm. Calibration is critical for longer wavelengths (e.g., 1064 nm or the eyesafe wavelength of 1550 nm) because of weak Rayleigh scattering. Particle scattering is no longer negligible in the reference height.

The most important drawback of this backscatter-coefficient retrieval is however that trustworthy profiles of the particle extinction coefficient are hard to achieve. The extinction profile must be estimated from the backscatter-coefficient profile. This is done by simply multiplying the backscatter profile with the range-independent lidar ratio that was used before as input in the backscatter retrieval. As a consequence, the estimated profile of the particle extinction coefficient can be rather uncertain, especially in situations with complex layering of aerosols and thus a height-dependent lidar ratio (Ansmann, 2006). Table A.3 gives typical numbers for relative uncertainties of the backscatter and extinction coefficients obtained from standard backscatter lidar observations. A 50% relative extinction uncertainty must always be kept in mind if no information on the lidar ratio is available (e.g., when Sun photometer observations are not available to estimate the column lidar ratio, see below). Even if a climatological value for the lidar ratio of, e.g., 45 sr is used in the retrieval, the actual column lidar ratio may be close to 70 sr and introduces an underestimation of the extinction profile by 50%. The height variability of the lidar ratio may introduce additional uncertainties.

It should be mentioned that the laser wavelength (short versus long wavelength) does no longer play a role in this second step of the retrieval (extinction estimation). The quality of the estimation is controlled by the lidar ratio estimate only.

Table A.3: Typical relative errors in the retrieved particle backscatter coefficient and extinction coefficient. Retrieval input parameters (calibration, lidar ratio profile, temperature profile) are considered only. Signal noise (as a function of signal averaging and profile smoothing) and overlap correction uncertainties are not included.

Lidar type	**Backscatter error**	**Extinction error**
BL	10%	50%
BL+SPM	10%	20%
RL/HSRL	5%	10%

A.3.2 Combined lidar-photometer observations

It is therefore strongly recommended to combine standard backscatter lidar observations with Sun photometer measurements. The Sun photometer provides accurate values of the aerosol optical depth. This is an important constraint for the lidar solution. The integral of the lidar-derived extinction profile must match the photometer-derived optical depth. According to the uncertainty discussion (backscatter retrieval) above, the most appropriate laser wavelength is 532 nm. At such a wavelength in the centre of the visible spectrum, the Sun-photometer also works best. The photometer retrieval becomes increasingly difficult with decreasing wavelength, especially below 380 nm because of the sensitive impact of strong Rayleigh scattering that has to be accurately removed to separate the remaining particle optical effect. However, even if the height-independent (column) lidar ratio is available, remaining uncertainties of about 20% in the extinction coefficients must be kept in mind because of a possible variability of the lidar ratio with height. Expected errors may be considerably larger when lofted layers are present (e.g., maritime boundary layer with 25-sr lidar ratio and lofted continental layer with 50-sr lidar ratio).

The combination of MPLNET (Welton et al., 2001) consisting of low-cost, eyesafe, automated 532-nm backscatter lidars with AERONET (Holben et al., 1998), NASA's global network of more than 200 continuously running Sun photometers, is an example for a successful application of the lidar-photometer technique. Extinction profiles with 20% uncertainty are sufficient for climate impact studies.

A.3.3 Raman lidar and HSRL

For a direct and accurate determination of the particle extinction-coefficient profile with a systematic uncertainty of 10% (Table A.3), more complex lidar setups are required (Ansmann and Müller, 2005). A direct determination is possible by using a Raman lidar (Ansmann et al., 1990, 1992) or a HSRL (Shipley et al., 1983; Sroga et al., 1983; Grund and Eloranta, 1991). Critical input parameters such as a lidar ratio profile are not needed. An aerosol Raman lidar or a HSRL detects two signal profiles. In the ideal case, one channel measures the aerosol (particle+molecular) backscatter signal and the second channel a pure molecular backscatter signal. From these two signal profiles, the profiles of the extinction coefficient and the backscatter coefficient can be determined independently from each other, and thus the lidar ratio profile is obtained in addition.

The HSRL is operational at day and night and can be run automatically (see Eureka HSRL, Eloranta et al., 2006). The European Space Agency will launch the Atmospheric Dynamics Mission (ADM) and the Earth Clouds Aerosols and Radiation Explorer (EarthCARE) Missions in near future (2009-2013). Both satellite platforms will be equipped with HSRLs.

Raman lidars are less complex than HSRL and are thus widely used. Most of these Raman lidars are nighttime lidars. They work best in the absence of the strong daylight sky background. Raman signals are weak (by a factor of 500 compared to Rayleigh signals). High power Raman lidars equipped with 0.5-nm interference filters to block sunlight however allow daytime operation at least throughout the convectice boundary layer (pollution layer, Turner et al.,2001). Raman lidars are not eyesafe. This well-established technology is available in various configurations to cover the boundary layer and lower troposphere, the free troposphere up to the tropopause, or the upper troposphere and stratosphere.

More and more Raman lidars are run as automated systems. Recently the Japanese National Institute for Environmental Science (NIES) lidar network of automated small and compact lidars was upgraded with Raman channels (personnel communication, N. Sugimoto, NIES).

An important advantage of Raman lidars and HSRLs is that the profile of the backscatter coefficient is determined from a signal-ratio profile so that the overlap effect cancels out (provided the two channels are well adjusted and show the same overlap characteristics). The signal ratio is the ratio of the aerosol-channel signal to the molecular-channel signal. As a consequence, the retrieval of the backscatter coefficient is possible down to heights rather close to the surface. When using the lidar ratio at the minimum measurement height (see below) and multiplying the backscatter coefficient profile with this lidar ratio, the best available guess of the extinction profile in the lowermost troposphere is possible. Raman lidars and HSRLs provide the most accurate values of the particle optical depth that can be retrieved from lidar observations.

The overlap effect however affects the extinction profile retrieval that is based on the analysis of *one* measured signal profile, and not on a signal-ratio profile. The same problems with the overlap correction in the near range occur as in the case with the one-channel standard backscatter lidar. Our experience shows that a trustworthy overlap correction is possible from the height where the overlap is complete (e.g., 1000 m) down to a height where the overlap is close to 0.5 (about 1/3 of the full range of incomplete overlap, e.g., 350 m). Below this critical or minimum measurement height, the strong height dependence (and correspondingly strong dependence of the overlap profile from slight changes in the lidar characteristics and performance) makes it almost impossible to correct for the overlap effect properly. So, below the minimum measurement height, the extinction profile derived from Raman lidar or HSRL signal profiles are no longer trustworthy. For these heights close to the surface, the backscatter profile determined from the Raman lidar or HSRL observations must be used to estimate the extinction values close to the surface. Extensive comparisons with photometer data corroborate that this procedure is reliable.

Finally, the depolarization technique remains to be mentioned. As Table 3 indicates, any backscatter lidar can be used to discriminate desert dust from other aerosols by applying the depolarization technique. The emitted laser light is linearly polarized and the return signals are measured in two polarization channels which are parallel- and perpendicular-oriented to the laser polarization. From the linear total (particle + molecular) depolarization ratio of the scattering volume that is obtained from the ratio of the perpendicular- to the parallel-polarized signal component, the particle depolarization ratio can be calculated if the particle backscatter coefficient and the respective linear molecular depolarization ratio are known (Cairo et al, 1999, Sassen, 2005). Spherical particles as water droplets produce a particle depolarization ratio of almost zero in the case of 180° scattering. Dust particles cause a depolarization ratio of 25%-35%. Smoke, urban haze, and maritime particles show depolarization ratios of <10%. Ice particles (ice clouds) lead to depolarization ratios typically >40%-50% (at off-zenith laser beam angles). The Japanese NIES lidar network is equipped with polarization-sensitive channels so that the depolarization lidar technique can be applied to identify (lofted) Asian dust layers.

A.3.4 Retrieval of microphysical properties

Before we discuss the potential of multiwavelength lidar to provide microphysical aerosol properties by applying sophisticated inversion techniques, it should be mentioned that a two-wavelength Raman lidar (355 and 532 nm) with polarization channels already allows us to unambiguously identify the aerosol type (Mattis et al., 2003). Maritime particles show low lidar ratios at both wavelength (20-30 sr) and a low depolarization ratio. Dust, urban haze and smoke show similar lidar ratios (40-70 sr) at 532 nm. Whereas the lidar ratio is almost the same at 355 and 532 nm for urban haze and dust, it is often observed to be clearly lower at 355 nm for forest fire smoke (Müller et al., 2007). To distinguish finally urban haze from dust the depolarization ratio is needed.

During the past decade sophisticated computational procedures have been developed and successfully tested that permit the retrieval of microphysical properties of particles such as volume and surface-area concentration, effective radius, refractive index characteristics, and single-scattering albedo from multiwavelength Raman lidar observations. The parameters are derived with inversion algorithms which use the measured optical particle properties as input. In the past ten years it has been shown that the method of inversion with regularization is a practical method (Müller et al., 1999a,b, Böckmann, 2001; Veselovskii et al., 2002,2004; Böckmann et al., 2005). A minimum number of three measurement wavelengths (Veselovskii et al., 2002) as well as a combination of particle backscatter and particle extinction coefficients (Müller et al., 1999a,b; Veselovskii et al., 2002) are needed for a successful retrieval of microphysical particle properties. It has been shown that multiwavelength Raman lidars operating Nd:YAG lasers, which generate light pulses at 355, 532, and 1064 nm, are the most useful instruments. First such instruments came into operation in the mid 1990s. The success of that lidar technique in recent years triggered an increasing number of lidar groups within the EARLINET project to install such instruments. Presently, 8 multiwavelength EARLINET Raman lidars are operated. Operational instruments are furthermore found in Russia (Moscow), South Korea (Gwangju), Japan (Tokyo), and Spitsbergen.

The low number of measured optical particle properties requires introducing physical and mathematical constraints in the inversion algorithms in order to come up with sensible microphysical particle parameters. These algorithms do not attempt to accurately derive the exact shape of particle size distributions, which might not be achievable even in the near future due to the low number of measured optical information and the lack of appropriate mathematical tools. However it is possible to derive mean parameters such as the effective radius (cross-section weighted mean radius) of the particle size distribution with comparably high accuracy. The accuracy of that parameter is on the order of ±25% in the range of effective radii from around 0.1 – 1.5 μm, and on the basis of the available measurement wavelengths. At present it does not seem possible to fully retrieve particles in the so-called coarse mode of particle size distributions which is largely determined by particles from natural sources such as mineral dust. However, particles from anthropogenic activities are mainly present in the fine mode fraction which is accessible to the inversion algorithms. Other size parameters such as volume concentration and surface-area concentrations can be derived to accuracies better than ±50%, if measurement errors of the optical parameters are less than 20%, which can be achieved with Raman lidars. The complex refractive index can be derived to approximately ±0.05 in real part and ±50% in imaginary part, which allows one to derive the single scattering albedo to an accuracy as good as 0.05 under favourable measurement conditions.

There are several problems in data inversion, which have to be tackled in order to further improve the quality of the derived parameters. As mentioned before the identification of particles in the coarse mode of the particle size distribution is not possible in a satisfactory manner. An extension of the measurement wavelength range of lidar however would again complicate multiwavelength Raman lidar as well as optical data analysis. Recent studies show that taking into account multiple scattering effects might also give access to the coarse mode of particles. The combination of Raman lidar with Sun photometer offers another approach. In that respect Sun photometer operating at longer wavelengths such as is the case for AERONET instruments (measurement channel at 1640 nm) is a promising new way. Present inversion algorithms assume spherical shape of the particles. Only recently efforts have been undertaken to introduce methods that allow for a characterization of particles of non-spherical shape, such as mineral dust. However, the underlying theoretical aspects of light-scattering by irregularly shaped particles still are in a rather exploratory status. Further problems arise by the fact that the complex refractive index is wavelength-dependent. All lidar inversion algorithms however only deliver a wavelength-independent refractive index, which can be regarded as mean value for the given measurement wavelength range. Another difficulty is given by the size dependence of the refractive index. One has to keep in mind that fine mode and coarse mode particle generally possess different complex refractive indices, and that again the inversion algorithms can only derive some mean value. Last but not least, profiles of microphysical particle properties can be derived with the available algorithms, however with an extreme consumption of computer and human operator time. Thus it is desirable to extend the available algorithms toward an efficient processing of profiles of optical data, which in turn delivers profiles of microphysical particle properties. First theoretical developments toward that direction already show very promising results.

A.3.5 Synergy of lidar-photometer observations

The potential of Sun photometry to derived optical, microphysical, and radiative properties of aerosols is already well-documented (e.g., Holben et al., 1998, Eck et al., 1999, Dubovik and King, 2002, Dubovik et al., 2002, Dubovik et al., 2006). The advantage of combined lidar-photometer observations is presently discussed, e.g., by Müller et al., 2003 , Chaikovsky et al., 2004, Pahlow et al., 2006.

Let us finally collect a few arguments that underline the complementary of combined lidar-photometer observations:

- The Sun photometer provides aerosol optical properties with high spectral resolution, but without any vertical resolution. The lidar delivers information on the aerosol at one or several wavelengths only, but with high vertical resolution.

- The lidar allows us to separate the contributions to light extinction by boundary layer aerosols (local to regional influences), free-tropospheric aerosol (long-range transport), and stratospheric perturbations after strong volcanic eruptions (hemispheric scale). In this way a better characterization of the impact of different aerosols and transport ways on environmental conditions, weather and climate, and chemical processes is possible that may be mainly based on the spectrally resolved Sun photometer observations.

- The lidar provides aerosol information day and nighttime. During situations with altocumulus and cirrus cover, lidar still provides aerosol profiles below the cloud base.

- By using the lidar-derived geometrical depth of the continental haze layer and the column information on aerosol optical and microphysical properties from Sun photometry, haze-layer mean aerosol properties (column values divided by haze layer depth) can be determined. This approach works when the lidar indicates that the aerosol in the free troposphere aerosol is negligible.

- Lidar provides information on the scattering coefficient at 180°. The photometer cannot measure this quantity which is useful as a further constraint in the photometer data analysis.

- Photometers, on the other hand, measure extinction properties at many wavelengths which may be combined with the few-wavelength lidar extinction and backscatter observations to improve lidar inversion results. Recently, simple approaches of combining lidar and sun photometer data have been undertaken. A combination of optical depth measured with Sun photometer and backscatter coefficients measured with Raman lidar was used to explore the possibility of deriving important particle parameters such as effective radius and single-scattering albedo (Pahlow et al., 2006). Results from these studies are quite promising but certainly are only at the beginning of more detailed studies.

- Sun photometer can be very useful when there is a pronounced presence of particles in the coarse mode fraction of the size distribution. As outlined before inversion algorithms that use the output of standard multiwavelength lidars (operating in the wavelength range from 355-1064 nm spectral range) cannot satisfactorily retrieve mean particle sizes larger than 1.5-2 μm.

- Another example of a fruitful synthesis of lidar/sun-photometer arises from studies on mineral dust. As mentioned before the non-spherical shape of mineral dust poses extreme challenges for inversion algorithms. It has been shown in a previous study that the usefulness of particle models that assume shape characteristics in the inversion procedure in fact can be tested on the basis of such instrument combinations (Müller et al., 2003, Dubovik et al., 2006). In that context it should be mentioned once more that the Sun photometer retrieval also provides the scattering phase function of the particles. That phase function is restricted to angles less than approximately 160°, whereas the lidar can provide valuable input in terms of the scattering coefficient at 180° which is not accessible to sun photometer observations.

- As a future perspective, some more complex and rigorous lidar/sun-photometer synergy developments can be identified. For example, there are plans to develop an algorithm that simultaneously inverts both co-incident data acquired with lidar and Sun photometer. That approach could, for instance, provide a higher accuracy of the retrieved aerosol parameters in the total atmospheric column as well as their vertical variability. Such an interactive synergy approach has been already successfully realized for the simultaneous inversion of Sun-photometer and satellite radiometer observations that provides better retrievals of both aerosol and surface reflectance properties (Sinyuk et al., 2007).

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ANNEX B

Plan for the implementation of the

GAW Aerosol Lidar Observation Network: GALION

Max-Planck-Institut für Meteorologie Hamburg, Germany
(27 - 29 March 2007)

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2. Report of the Third Session of the GESAMP Working Group on the Interchange of Pollutants Between the Atmosphere and the Oceans (INTERPOLL-III), Miami, USA, 27-31 October 1980.
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126. Guidelines for Site Quality Control of UV Monitoring (lead author A.R. Webb) (WMO TD No. 884).

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159. IGOS-IGACO Report - September 2004 (WMO TD No. 1235).

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163. World Meteorological Organization Activities in Support of the Vienna Convention on Protection of the Ozone Layer (WMO TD No. 974).

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169. Chemical Data Assimilation for the Observation of the Earth's Atmosphere – ACCENT/WMO Expert Workshop in support of IGACO (edited by L.A. Barrie, J.P. Burrows, P. Monks and P. Borrell) (WMO TD No. 1360).

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