ICAROHS - INTER-COMPARISON OF AEROSOL RETRIEVALS AND OBSERVATIONAL REQUIREMENTS FOR MULTI-WAVELENGTH HSRL SYSTEMS

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ABSTRACT

The ESA-STSE study ICAROHS exploits the potential improvements and benefits of novel multi-wavelength High Spectral Resolution Lidar (HSRL) technology combined with innovative retrieval methods for future satellite missions. Single-wavelength HSRL data from several field studies form the data base for developing improved scientific algorithms for retrievals of aerosol optical properties and of tools for future multi-wavelength spaceborne HSRL instrument assessments. These quality-controlled observational data feed into the existing EarthCARE simulator (ECSIM), which serves as the platform for algorithm development and verification. Light scattering by non-spherical particles is implemented into ECSIM as scattering libraries based on T-matrix calculations. Recommendations for future multi-wavelength HSRL missions are formulated on the basis of a combined retrieval of aerosol properties from the entire available lidar and in-situ data. This retrieval study forms the benchmark for aerosol properties accessible by respective HSRL missions and defines the technical limits for required accuracy and resolution of the lidar input data to the novel algorithms.

1. INTRODUCTION

Aerosols play a key role in the Earth radiation budget through direct radiative effects (extinction and reflection of solar and IR radiation) and indirect effects (impact on cloud formation and life time). In the atmospheric boundary layer they are a key component affecting air quality. The bulk part of aerosols remains in the planetary boundary layer and influences local and regional air quality close to the source regions. Some source processes like desert dust mobilisation, forest fire and grassland burning, however, lead to lifted aerosol layers which are transported over large distances in the free troposphere well above the boundary layer. Particularly with respect to the long-range transport of aerosols, to air quality impacts, and to climate effects, the observation of aerosols on a global scale requires strong improvements compared to the current status.

To large extent, uncertainties in climate prediction are related to uncertainties in the contribution of aerosols to climate change [*1*]. With the exception of light-absorbing aerosol species like black carbon and mineral dust, aerosol particles and clouds have an overall cooling effect on climate as indicated by the negative radiative forcing values associated top aerosol effects in the latest IPCC report on Climate Change [*1*].

The U.S. Climate Change Science Program report [*2*] gives an extended overview of the present status of atmospheric aerosol research, of the gaps in our knowledge, provides a list with the most important open questions as well as recommendations concerning the next steps to be done. The authors of the report state that the way forward requires more certain estimates of aerosol radiative forcing, which in turn requires better observations and improved models, and a synergistic approach that combines satellite monitoring, dedicated field campaigns, long-term network activities, laboratory work, and modelling (local to global scale).

In recent years, a strategy for the global mapping of the aerosol properties relevant for climate impact studies [*3*] has been developed. This approach is based on the aerosol radiation efficiency E given in Watts per square meter per unit aerosol optical depth. The property E depends on the intensive aerosol properties single-scattering albedo ω_0 (SSA: the ratio of scattering to extinction) and the hemispheric backscatter fraction β_{up} (the fraction of light which is scattered back into space), and on the surface reflectivity R_s [*4-6*]

$$E \propto \omega_0 \, \beta_{up} \times [(1 - R_s)^2 - 2 R_s \beta_{up}^{-1} (\omega_0^{-1} - 1)] \qquad (1)$$

Hence, the global mapping of the following key parameters governing the direct climate forcing of aerosol particles is required:

- aerosol optical depth δ,
- hemispheric backscatter fraction β_{up},
- single-scattering albedo ω_0.

For isolating the anthropogenic contribution to the radiation efficiency, the fine mode fraction with particle diameters < 2.5 µm is interpreted as the anthropogenic fraction of the aerosol radiative effect [3].

The modification of the outgoing shortwave flux at top of atmosphere ΔF_{up} defines the direct climate forcing of anthropogenic aerosols. This quantity can be expressed as

$$\Delta F_{up} = \delta \times E \quad (2)$$

ΔF_{up} is linked to the temperature change ΔT via the climate sensitivity parameter λ

$$\Delta T = \lambda \, \Delta F_{up}. \quad (3)$$

Based on this concept, the list of important aerosol parameters include the aerosol optical depth, particle mass concentration, size, composition, structure, and mixing state, which are mediated both by source type and subsequent atmospheric processing and determine how particles interact with radiant energy via scattering and absorption, and how they influence the energy balance of the earth-ocean-atmosphere system.

In contrast to the direct effect of aerosol particles on climate, the indirect effects via the influence of particles on cloud formation, properties, life cycle, and heterogeneous ice formation and the related changes in radiative transfer and precipitation is much more complex and the estimation of the indirect effects of aerosol particle on climate is thus rather uncertain because many aspects are poorly or even not understood.

According to the CCSP report [2], outstanding issues for future research on aerosol-climate interactions are:

- measuring aerosol absorption and single scattering albedo with better than 0.03 accuracy as a function of height;
- estimating the aerosol direct radiative forcing over land;
- distinguishing anthropogenic from natural aerosols as a function of height;
- profiling the vertical distributions of aerosols.
- characterizing the diurnal cycle of aerosol direct radiative forcing;
- studying aerosol-cloud interactions and indirect radiative forcing;
- quantifying long-term trends of aerosols at regional scales;
- linking aerosol long-term trends with changes of surface solar radiation.

The separation of anthropogenic from natural aerosols is essential for assessing the human impact on climate. In this context it is worth mentioning what the GALION initiative (GAW Aerosol Lidar Observation Network) (http://lidar.dkrz.de/galion/galion_whitepaper_draft080610.pdf) recommends for ground-based lidar networks: Lidar measurements should include the identification of aerosol layers in the troposphere and stratosphere, vertical profiles of optical properties with known and specific precision (backscatter and extinction coefficients at selected wavelengths, lidar ratio, Angström exponents, aerosol type, e.g., dust, maritime, fire smoke, urban haze, and microphysical properties as volume and surface concentrations, size distribution parameters, refractive index).

So far data from multi-wavelength Raman lidar systems have been used for characterizing aerosol microphysical parameters [7, 8]. However, the aerosol Raman lidar technique is not appropriate for spaceborne applications because the backscattered Raman lidar signals are too weak. Comparably long signal integration times of 5-30 minutes are needed. Thus (3β +2α) aerosol lidar in space must be based on the High Spectral Resolution Lidar (HSRL) technology. ADM-Aeolus [9] and EarthCARE [10] will embark the first ever space-borne HSRL, however, with a single wavelength only. The development of a space-borne multi-wavelength HSRL would be the next revolutionary step in space-borne lidar history.

2. STUDY OBJECTIVES AND STRUCTURE

The ICAROHS study exploits the potential improvements and benefits of novel multi-wavelength high spectral resolution lidar technology combined with innovative retrieval methods for future satellite missions.

The main goals of ICAROHS are:

[1] Delivery of quality-controlled and validated retrieval algorithms for primary geophysical products as backscatter and extinction profiles, lidar ratio profile, aerosol classification.
[2] Validated aerosol microphysical products inversion from spaceborne multi-λ HSRL, as effective radius, refractive index, aerosol layer structure and height.
[3] Recommendations for future single and multi-λ HSRL instruments which meet the accuracy requirements of current aerosol-climate interaction modeling.

Recommendations for future multi-wavelength HSRL missions are formulated on the basis of a combined retrieval of aerosol properties from the entire available lidar and in-situ data. This retrieval study forms the benchmark for aerosol properties accessible by respective HSRL missions and defines the technical limits for required accuracy and resolution of the lidar input data to the novel algorithms.

The selected study approach relies on the following key tools and methods to be used:

- #1 **Airborne single-λ HSRL** data for various aerosol types from field studies.
- #2 **Airborne aerosol in-situ** data aligned with single-λ HSRL data.
- #3 **Ground-based multi-λ Raman lidar** data aligned with airborne HSRL and in-situ data from field studies.
- #4 **Scattering libraries** for implementation into ECSIM for non-spherical particles (dust) based on the T-matrix method supplemented by geometric optics.
- #5 **ECSIM** as the key platform for development, testing and implementation of new algorithms.
- #6 **Inversion of aerosol properties** from HSRL, multi-λ backscatter lidar and aerosol in-situ data for testing uncertainties and defining requirements for future multi-λ HSRL instruments.

Current single-wavelength HSRL data from several field studies are used as data base for the development of improved scientific algorithms for retrievals of aerosol optical properties and of tools for future multi-wavelength space-borne HSRL instrumentation assessments. These quality-controlled data sets feed into the existing ECSIM which is used as a platform for further algorithm testing and improvement.

The study will use observational data from airborne (aerosol in-situ, single-λ HSRL) and ground-based (multi-wavelength Raman lidar) observations from field studies coordinated by members of the consortium:

LACE	Central European continental aerosol; forest fire smoke plumes in the free troposphere;
EUCAARI	Central European continental aerosol; clean polar air masses;
SAMUM-1	desert dust from NW Sahara; polluted and aged desert dust; marine aerosol;
SAMUM-2	desert dust from the Sahel; Central Africa biomass burning aerosol.

The long-term target instrument is a spaceborne multi-wavelength HSRL in (3β +2α) configuration. The study investigates various potential configurations based on the EarthCARE simulator. The ATLID instrument serves as a reference instrument for the instrument configurations investigated in ICAROHS [11]. In summary, the selected approach is considered to provide a detailed assessment of requirements and expected benefits for any multi-λ HSRL systems for global aerosol observation. The strength of the approach is the fact that all algorithms can be tested against real data from airborne HSRL, ground-based multi-λ lidar and extensive aerosol in-situ data sets.

3. HIGH SPECTRAL RESOLUTION LIDAR

The only current observational techniques for separating aerosol signals from molecular backscatter signals are the High Spectral Resolution Lidar (HSRL) and Raman lidar approaches. The power of atmospheric backscatter detected by a lidar instrument from range r is proportional to

$$P(r,\lambda) \propto \frac{1}{r^2}\,\beta(r,\lambda)\exp\left[-2\int_0^r \alpha(R,\lambda)\,dR\right] \qquad (4)$$

β(r, λ) is the volume backscatter coefficient, and α (r, λ) is the volume extinction coefficient. The integral of the extinction coefficient over range r is termed optical thickness; the exponential term is denoted optical transmission.

With conventional backscatter lidar instruments climatically relevant aerosol properties like aerosol extinction can only be derived by inverting the lidar signal under the assumption of an a-priori known lidar ratio S(r) = α(r) / β(r), i.e., extinction / backscatter, which generally is a highly variable quantity. Uncertainties in the lidar ratio will consequently cause large errors in the retrieved optical properties [12].

A high spectral resolution lidar (HSRL) can provide direct and independent observations of the backscatter from molecules and aerosols. In contrast to a Raman lidar, the HSRL detects the Rayleigh-Brillouin scattering which is several orders of magnitude more intense. To separate the Rayleigh-Brillouin scattering from the Mie scattering of aerosols, a HSRL takes advantage of the different spectral broadening of light, backscattered by molecules and aerosols, respectively. At atmospheric temperatures close to 300 K the Doppler-broadening of the molecular backscatter spectrum amounts to 2.6 GHz for green light with a wavelength of 532 nm. The Doppler-broadening is due to the fast thermal motion of the molecules. In contrast, aerosol backscatter is hardly broadened due to the relatively slow wind-driven motion of heavy aerosol particles, so that it can be characterized by the laser frequency distribution. Principally a HSRL separates the returned atmospheric lidar signals into two channels.

One of which is equipped with an extremely narrow band optical filter which strongly suppresses the aerosol backscatter while transmitting the molecular backscatter. Thus, only molecular backscatter is measured. The signals are compared to a reference signal calculated from atmospheric temperature and pressure profiles. Aerosol extinction coefficients are calculated by comparing the measured molecular signal, which is attenuated by aerosol extinction, to the calculated unattenuated molecular signal. Thus, no assumption about the lidar ratio is needed. The narrow band optical filter can be realized by interferometers like Fabry-Perot etalons and atomic or molecular vapour filters, respectively. Both filter methods show specific advantages and shortcomings. The choice of a specific technology depends on several design criteria like the available laser technology, the measurement platform (ground-based, airborne or spaceborne) or system requirements. At DLR, Germany, an airborne HSRL was developed based on an iodine vapour absorption filter and a high power, frequency doubled Nd:YAG laser [13]. A similar airborne instrument exists at NASA[14]. The detailed description of HSRL method is beyond the scope of this paper. Interested readers may refer to these references.

The aerosol properties relevant for the aerosol climate impact can potentially be accessed by multi-λ HSRL products as listed in Table 1.

Table 1: Lidar products from multi-wavelength HSRL and related aerosol properties

Aerosol Property	Lidar Product
aerosol opt. thickness $\delta(\lambda)$	extinction coefficient
aerosol effective diameter or radius, resp., d_{eff}, r_{eff}	extinction-related Ångström exponent
aerosol absorptivity single-scattering albedo ω_0	spectral backscatter and extinction coefficients
hemispheric backscatter fraction $\beta_{up}(\lambda)$.	spectral backscatter and extinction, depolarization
aerosol type microphysical properties	lidar ratio, depolarization ratio, backscatter-related and extinction-related Ångström exponents

4. INSTRUMENT REQUIREMENTS

Current aerosol profile data are far from being adequate for quantifying the aerosol radiative forcing and atmospheric response to the forcing. The data have limited spatial and temporal coverage, even for current spaceborne lidar measurements. Current space-borne lidar measurements are also not sensitive to aerosol absorption. For achieving an accuracy of 1 W/m^{-2} in radiative forcing estimation, the required accuracy of measured AOD should be 0.01 - 0.02 at 500 nm, and the single scattering albedo (SSA) should be constrained to 0.02 over land. Threshold values for backscatter coefficients are 0.0005 $km^{-1} sr^{-1}$, corresponding to 0.02 km^{-1} for extinction coefficients [12]. Any climate-research driven future multi-wavelength lidar mission should be capable of providing measurements which enable the estimation of aerosol parameters listed in Table 2.

Table 2: High-level aerosol parameters necessary for evaluating the climate impact of anthropogenic aerosols based on a TOA impact on the order of 1 W/m^2 [12, 15].

Property	Detection threshold[1]	Accuracy range[2]	Horizontal Resolution
aerosol optical depth (500 nm)	0.01 – 0.02	10%	100km
single-scattering albedo	0.02	5%	100km
effective diameter [3]	200 nm	20%	100km
Hemispheric backscatter fraction $\beta_{up}(\lambda)$.	N/A	10%	100km

Apart from the optical depth the parameters listed in Table 2 cannot be measured directly by lidar. Instead, they must be derived from a suitable set of multi-wavelength aerosol backscatter and extinction measurements. It is conceivable that a data set consisting of backscatter coefficients at 355, 532, and 1064 nm and extinction coefficients at 355 and 532 nm measured with a multi-wavelength $(3\beta + 2\alpha)$ aerosol lidar allows the retrieval of microphysical properties and of the refractive index characteristics (absorption, scattering, SSA) from the measured spectrally resolved optical properties with the accuracies compiled in

[1] Detectability is defined as the value measurable with not more than 100% RMS error.

[2] Accuracy range associated with typical aerosol loadings (which may be many times higher than the detectability threshold).

[3]This value is to a large part determined by the minimum measurement wavelength that is used for the space-borne lidar (355 nm) and the specific properties of the investigated particle size distributions. To a lesser part the signal-to-noise ratio of the lidar signals influence the detection threshold. Any quantification of the comments made here require simulation studies.

Table 2. Extinction and backscatter coefficients must be known with an uncertainty (standard deviation) on the order of 10% to allow a successful inversion of the optical data into the microphysical properties and other important aerosol parameters [7, 8]. An additional depolarization channel provides a clear indication of the presence of desert dust, the most important natural, continental aerosol component, and of ash in forest fire smoke and aerosol intrusions in the stratospheric layer.

5. ECSIM SCENE CREATION AND EVALUATION

In order to help developing retrieval algorithms and in order to investigate various instrumental trade-off issues, it was deemed necessary to simulate the EarthCARE mission in the framework of ICAROHS. This lead to the intensive usage of the EarthCARE simulator, which is capable of performing 'end to end' simulations of any, or a combination, of the EarthCARE instruments. ECSIM consists of a modular general framework populated by various models. The models within ECSIM are grouped according to the following scheme:

1. Scene creation models (3D atmospheric scene definition)
2. Orbit models (orbit and attitude of the platform as it overflies the scene)
3. Forward models (calculate the signal that arrives to the telescope/antenna of the instrument(s) in question)
4. Instrument models (calculate the instrument response to the signals calculated by the Forward models)
5. Retrieval models (invert the instrument signals to recover relevant geophysical information)

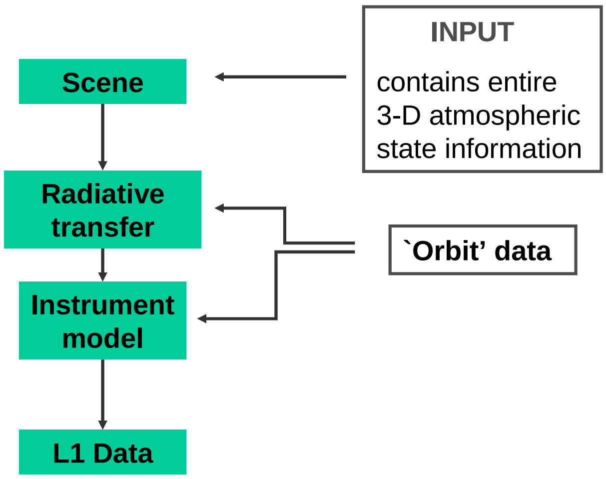

Figure 1. Schematic of the ECSIM modular structure.

Figure 1 shows a schematic of the ECSIM modules. Validating retrieval algorithms require the creation of atmospheric scenes ranging in complexity from very simple to 'realistic' scenes generated from measurements or model output data sets.

To satisfy this need for creation of input scenes on demand by the end user, a scene creator application was constructed; see Figure 2. Within ICAROHS there was the need for realistic scenes based on HSRL measurements from the DLR aircraft for the testing and validation of multi-λ HSRL retrieval algorithms from space.

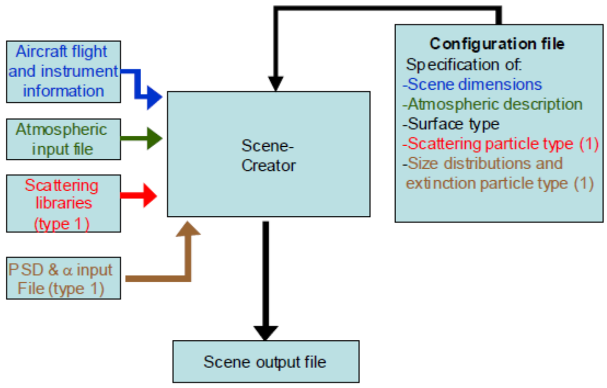

Figure 2. Flow diagram of the ECSIM scene creation [ICAROHS Algorithm Theoretical Basis Document].

Figure 3 shows one example of an ECSIM scene evaluation based on observational data from SAMUM-1 when desert dust layers were probed over Morocco near to the border of the Saharan desert. Details of the measurements are given in [16, 17]. The bottom panel shows the excellent agreement between measured and simulated data. Furthermore dust-spheroids libraries have been adopted and yield in realistic depolarization values; first set of scenes for different aerosol types are validated against measurements; realistic aerosol scenes are used for further validation of retrieval algorithms and instrument sensitivity studies.

6. AEROSOL TYPE CLASSIFICATION

The present efforts in climate modeling are far from being sufficient for providing realistic numbers on the influence of anthropogenic aerosols on the state of the atmosphere [*1*]. To improve this unsatisfactory situation, future spaceborne aerosol lidar missions must allow an accurate characterization of the aerosol in terms of aerosol type, vertical layering, light extinction and absorption properties, and microphysical properties

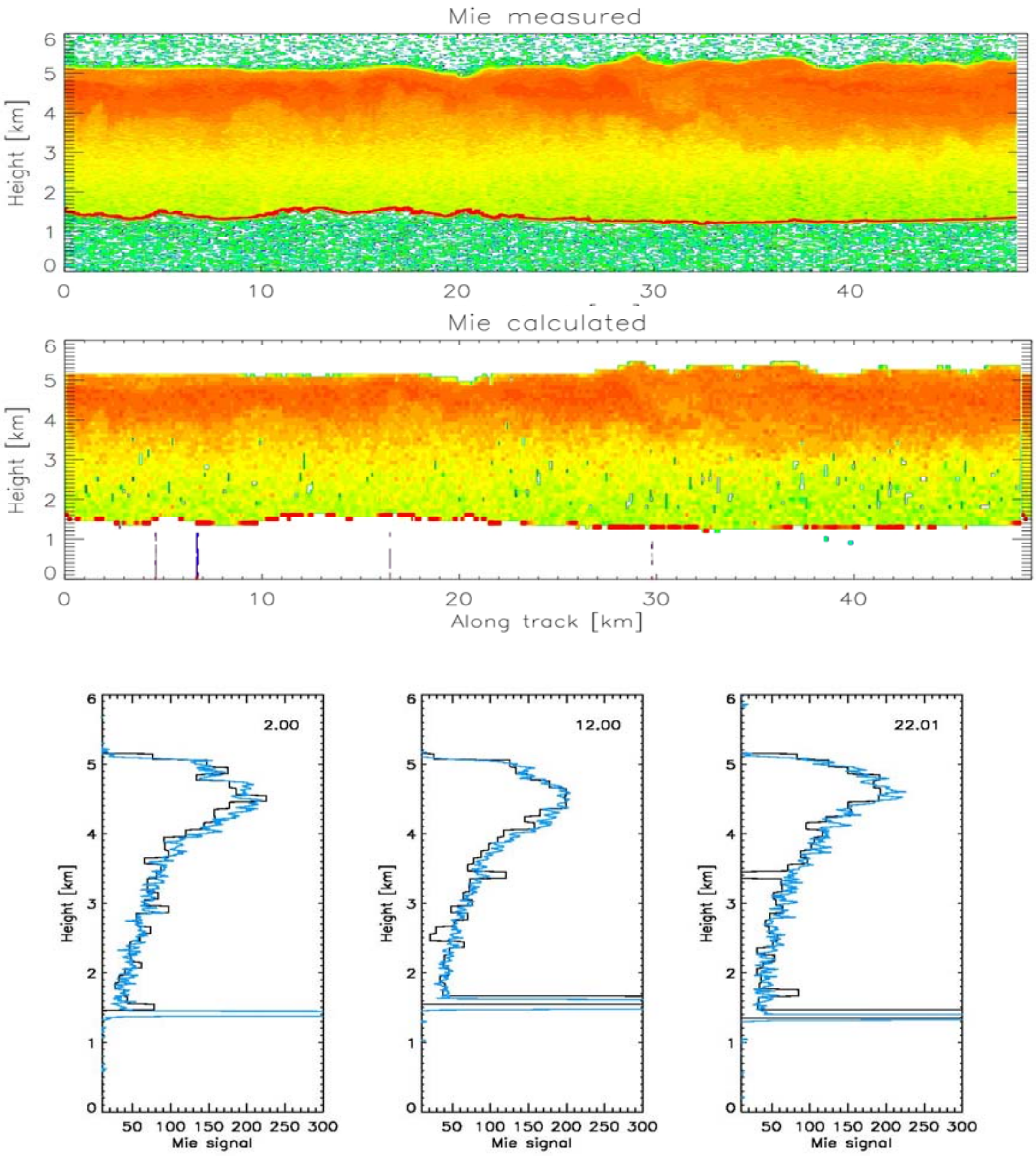

Figure 3. Evaluation of ECSIM based on SAMUM-1 field data of a well-mixed Saharan dust layer over Ouarzazate, Morocco, on 19 May 2006; top panel: dust structure measured by airborne HSRL; mid panel: dust structure simulated by ECSIM; bottom panel; comparison of measured (blue) and calculated Mie signals at three along-track distances of 2 km, 12 km, and 22 km.

including a proper monitoring of the long-range transport of anthropogenic particles like haze or smoke, natural aerosols like volcanic ash, mineral dust, marine particles, and especially mixtures of the mentioned aerosol types on a regional to hemispheric scale.

In this section we describe how different aerosol types can be classified by means of an empirical approach using previous lidar measurements. The approach is based on a combined single-wavelength HSRL and multi-wavelength Raman lidar analysis of aerosol observations during various field measurements.

During three recent field campaigns aerosol properties have been measured by the DLR airborne HSRL and an extensive set of aerosol in-situ probing instruments. The comprehensive data sets obtained throughout these field experiments contain information about some of the most

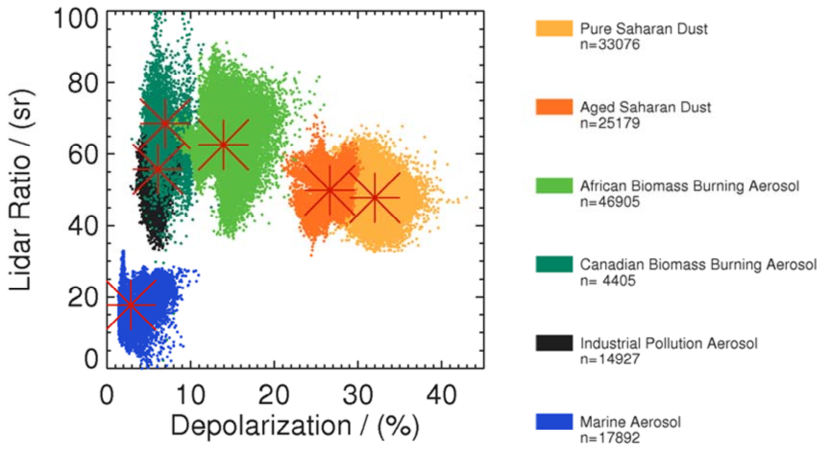

Figure 4. Depolarization and lidar ratios of various aerosol types measured by airborne HSRL [12].

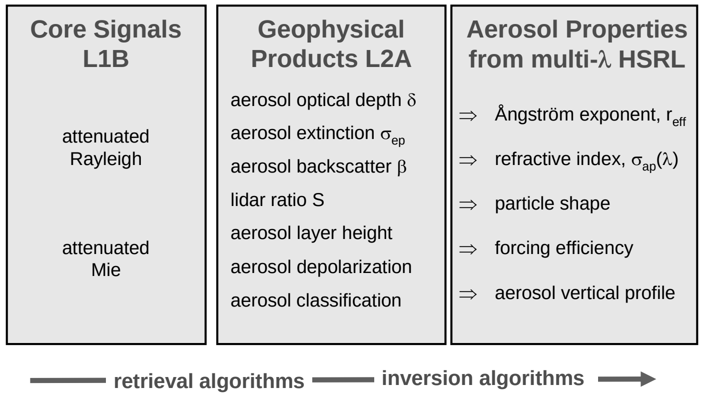

Figure 5. Logical chain of ICAROHS retrieval of geophysical products followed by aerosol properties inversion.

prominent atmospheric aerosol types: mineral dust aerosol, sea salt aerosol, biomass burning aerosol, continental background aerosol, and urban pollution aerosol. Based on the HSRL measurements two aerosol-specific quantities are derived: the lidar-ratio and the depolarization-ratio. The analyses of both quantities reveal that characteristic values can be attributed to the different aerosol types. Figure 4 shows HSRL measurements of the aerosol depolarization ratio and the lidar ratio as dots and their averages as red crosses. The measurements are associated with the source regions of the assigned aerosol types by means of backward trajectory analyses. The different aerosol types were observed mainly close to their origin. As can be seen the properties of the shown aerosol types cluster in different regions and can be separated very well, allowing the replacement of aerosol masks by the more precise aerosol type classification. It is worth noting that the selection of aerosol types is not complete and that mixtures of several aerosol types might show optical properties in between those of the rather pure ones.

7. KEY DELIVERABLES

More accurate characterization capabilities and the derivation of aerosol microphysical properties are expected from multi-wavelength HSRL instruments combined with powerful data inversion techniques [8, 18, 19]. A first operator-controlled version of such an inversion algorithm was successfully tested [20]. This inversion algorithm is based on a strong interaction of the data-operator with the inversion software package, and for that reason a comparable high accuracy can be achieved. Improvements of the microphysical data products may be achieved in the context of future algorithm developments. Novel inversion methodologies are under development [21], but require extensive simulation studies. The accuracies of the microphysical data products will also depend on the requested vertical and horizontal resolutions. In general a reduced resolution (vertical and horizontal) is expected to increase the accuracy as the errors of the optical input data will also be reduced.

Summarising, key requirements for operational aerosol properties inversion algorithms are

- automated and unsupervised operation;
- <1 sec per complete set of $3\beta+2\alpha$;
- retrieval of absorption profiles and single-scattering albedo;
- first-order estimate of phase function for particle classification: dust/marine versus urban haze;
- combination with passive remote sensors which might operate in combination with $3\beta + 2\alpha$ lidar.

Combining ECSIM capabilities and powerful inversion algorithms ICAROHS will deliver the complete chain from core signal processing to the inversion of aerosol properties from multi-λ HSRL as shown in Figure 5. In detail, ICAROHS deliverables are:

- Theoretical basis for HSRL for spaceborne applications as ATBD [20].
- Database of reference scenes for ECSIM both in binary format and as Technical Note [12].
- Database of scattering phase functions of non-spherical particles for ECSIM both in binary format and as Technical Note [22].
- Validated retrieval algorithms for geophysical products including HSRL-λ = 355, 532 nm.
- Validated inversion algorithms for aerosol properties from multi-λ HSRL data ($3\beta+2\alpha$).
- Recommendations for future multi-λ HSRL missions.

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