BAMS Article

Wind Profile Satellite Observation Requirements and Capabilities

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ABSTRACT: The *Aeolus* mission objectives are to improve numerical weather prediction (NWP) and enhance the understanding and modeling of atmospheric dynamics on global and regional scale. Given the first successes of *Aeolus* in NWP, it is time to look forward to future vertical wind profiling capability to fulfill the rolling requirements in operational meteorology. Requirements for wind profiles and information on vertical wind shear are constantly evolving. The need for high-quality wind and profile information to capture and initialize small-amplitude, fast-evolving, and mesoscale dynamical structures increases, as the resolution of global NWP improved well into the 3D turbulence regime on horizontal scales smaller than 500 km. In addition, advanced requirements to describe the transport and dispersion of atmospheric constituents and better depict the circulation on climate scales are well recognized. Direct wind profile observations over the oceans, tropics, and Southern Hemisphere are not provided by the current global observing system. Looking to the future, most other wind observation techniques rely on cloud or regions of water vapor and are necessarily restricted in coverage. Therefore, after its full demonstration, an operational *Aeolus*-like follow-on mission obtaining globally distributed wind profiles in clear air by exploiting molecular scattering remains unique.

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It is very clear that improved deterministic analyses and prediction of atmospheric turbulence, convection and dynamics go hand in hand with a better analysis of the initial atmospheric state (Bauer et al. 2015; Dee et al. 2011). Hence, to determine and follow the full dynamic atmospheric state in great detail, an effective and refined composite global observing system is needed, particularly including wind observations on the 3D turbulent scales below 500 km (Stoffelen et al. 2005). While satellite observations initially added negligible skill to the operational forecasts in last century, around the turn of the century this changed (Simmons and Hollingsworth 2002) and today satellite observations contribute to most of the forecast error reduction (English et al. 2013). The question today is whether this skill can be effectively maintained and further improved in the coming decades.

The important operational role of satellite observing systems is well documented in the World Meteorological Organization (WMO) Rolling Requirements Review (RRR) and in the Observing Systems Capability Analysis and Review tool (OSCAR).[1] Nevertheless, there are still major limitations and challenges in our ability to model key atmospheric dynamical processes.

More wind observations at all levels in the troposphere and stratosphere would help to better depict atmospheric tropical circulation and prediction (Žagar et al. 2005). Moreover, vertical and horizontal wind shear structure in the equatorial region is poorly modeled, where more observations would be helpful for a better sampling of the tropical dynamics and circulation (Houchi et al. 2010; Lin et al. 2016). Outside the tropics, the slow atmospheric evolution manifold is captured by radiance measurements that prescribe the atmospheric mass field, but do not depict the large-scale circulation in full detail (Belmonte Rivas and Stoffelen 2019). On the turbulent scales below about 500 km, on the other hand, wind and wind shear measurements are key to initialize the mesoscale flow (de Haan and Stoffelen 2012; Marseille and Stoffelen 2017) and these measurements are currently lacking. In addition, a recent WMO workshop on the impact of various observing systems on numerical weather prediction (NWP) recommended enhanced profiling capability in the Arctic (Sato and Riishojgaard 2016).

The increasing demand for well-resolved wind information is particularly acute over the oceans, tropics, and Southern Hemisphere, which are currently void of wind profiles. Atmospheric motion vectors (AMVs) fill this gap partially, as they may be obtained at high temporal resolution and at several heights. However, height assignment and vertical sampling will remain a limiting issue for this type of wind observations. Wind scatterometers and

[1] WMO OSCAR, www.wmo-sat.info/oscar/.

microwave radiometers provide information on ocean surface winds in a growing virtual constellation [Committee on Earth Observation Satellites (CEOS)],[2] but do not provide information on vertical shear nor do they provide any upper air information. Further, research missions are studied with satellite Doppler cloud radars or tandem (stereo) multiangle imagers to provide vector winds near clouds. Since clouds constitute only about 30% of the tropospheric volume and represent a dynamically and optically heterogeneous environment, the development of these techniques to fulfill the global demand for accurate 3D wind information can only be partial. Finally, research in obtaining winds from tandem IASI profiles, e.g., by employing optical flow techniques, may not meet the requirement to obtain high-resolution wind and shear data. Particularly in conditions of strong flow with linear features and in areas where the atmosphere is dry, small-scale wind variability cannot be detected. Tracking of ozone may be an alternative in the dry stratosphere, but again small-scale wind features and shear are not well represented by the ozone variability. On the other hand, an *Aeolus*-like follow-on mission, obtaining wind profiles in clear air by exploiting molecular scattering appears worthwhile[3] (Stoffelen et al. 2006). Nevertheless, several scientific and technological aspects of such a mission need further consideration as outlined in this manuscript.

[2] ceos.org/ourwork/virtual-constellations/, CEOS virtual constellations.

[3] www.ecmwf.int/en/about/media-centre/news/2019/tests-show-positive-impact-new-aeolus-wind-data-forecasts

Wind observation requirements

Application requirements. The WMO in collaboration with other relevant organizations provides specifications of evolving observation requirements in different operational meteorological application areas and corresponding guidance in support of the continuing development of the WMO Integrated Global Observing System (WIGOS) (WMO 2017). Since applications and observing capabilities evolve, the requirements review is continually evolving (rolling); see appendix A for details.

The required vertical resolution for weather and climate applications is about 1 km in the troposphere and 2 km in the stratosphere, where the typical horizontal wind vector accuracy requirement is 2 m s^{-1} at a required 1–6-hourly coverage. These requirements are not met today over the oceans, tropics, and most of the Southern Hemisphere (Table 1).

Scientific requirements. Several sources for scientific requirements exist and without being exhaustive, we address the ESA Living Planet Programme (LPP), the World Climate Research Programme (WCRP) Grand Challenges, scientific requirements related to Copernicus Climate Change and Atmosphere Monitoring Services and scientific issues in atmospheric dynamics.

ESA Living Planet Programme. ESA's LPP document (ESA 2015) addresses scientific challenges which all have a wind-related or dynamical component.

The main acknowledged gap is currently a lack of accuracy of the models to describe the full complexity of the interactions of climate with dynamics, clouds, chemistry, and aerosols. Synergetic measurements of physical processes in the atmosphere are particularly needed, i.e., 3D turbulence, convection and associated transports of momentum, heat, and constituents, through cloud, entrainment, and precipitation processes. The ESA LPP reiterates the need for better quantification of the physical processes determining the life cycle of aerosols and their interaction with clouds. To better understand these physical processes, simultaneous profile measurements of wind, humidity, temperature, cloud, aerosol, and precipitation would be required with a very high temporal resolution.

In tropical regions, the appropriate satellite information (on winds) is lacking to achieve the same level of 1–5-day forecast performance as obtained in midlatitudes. This discrepancy

Table 1. Existing satellites and sensors for observation of the tropospheric dynamics.

Sensor type	Satellites or sensors	Variable	Location	Limitation(s)
DWL	*Aeolus*	Wind vector* profile	Troposphere, stratosphere	Single track
Scatterometer	ASCAT, ScatSat, HY-2°, *CFOSAT*, …	Wind vector	Surface	Single level, only ocean
Image tracking	MSG, MODIS, …	Wind vector	Troposphere	Vertical resolution, only tracers
Microwave imaging	SSM/I(S), MIS, AMSR, …	Wind speed	Surface	No direction, single level, only ocean
Multiangle imager	MISR, GEO, …	Wind vector, cloud, aerosol	Troposphere	Only tracers, few vertical levels
Infrared, microwave sounder	IASI, AIRS, ATOVS, …	Temperature, humidity, wind	Troposphere	Vertical resolution, clouds, ice surfaces
GNSS-R/altimeter	GNSS/radar	Wind speed over ocean	Surface	No direction, single level, only ocean, single track

* In case, e.g., a perpendicular fore or aft view is provided in addition to cross-track observations.

arises because of a fundamental difference in the dynamical behavior of the atmosphere in the tropics and at midlatitudes, i.e., the absence of geostrophic balance near the equator. In cloudy regions, such as the inter-tropical convergence zone, the observational coverage of wind and humidity profiles needs to be improved, in particular, to better depict this part of the global water cycle and its influence on the energy balance. Tropical heating is associated with an overwhelming presence of convectively driven deep mesoscale circulations with fast-changing convergence and divergence areas throughout the troposphere (cf. CNES 1988).

Forcings induce feedbacks due to dynamical, physical, and chemical processes. The most important feedbacks involve winds, humidity, and clouds, also affecting changes in the atmospheric composition. Extreme weather events involve complex and inadequately understood processes within the atmosphere, including interactions of the dynamical wind and pressure fields with radiation, clouds, and convection.

In terms of addressing the above challenges and gaps the following deficits are outstanding:

- The vertical stratification of the atmosphere and wind shear are important for vertical mixing and transports of mass, momentum, and energy, thus driving turbulence and convective processes. However, current satellite measurements often lack the vertical resolution to characterize these phenomena. Moreover, mesoscales in the atmosphere evolve much faster than the large scales.
- Convective scales are only a few tens of minutes and a few hundred meters in horizontal scale, thus posing further requirements for temporal and horizontal resolution.
- When going to mesoscales (<500 km), wind rather than temperature and pressure determine the evolution of the atmosphere in a regime of 3D turbulent flow. Wind measurements are thus of prime importance here. In these cases wind convergences/divergences in addition to humidity structures may trigger convection, leading to clouds and precipitation. Humidity information is thus also essential to describe atmospheric evolution.
- Wind, cloud, precipitation, and aerosol information is important to characterize cloud processes, such as entrainment, heating/cooling, and transport, which in turn affect larger-scale dynamics and radiation balance.
- For satellite product validation more advanced/resolved measurements are needed, e.g., lidar, radar and multiangle imagers. Better validation can be performed when these instruments collocate with the operational sounders and imagers.

These interconnected deficits in the present observing systems are addressed, and priorities for overcoming these deficits are defined in Table 2.

WCRP Grand Challenges. The WCRP recognizes a so-called Grand Challenge on clouds, circulation, and climate sensitivity. It addresses the coupling between clouds and circulation, and their influence on Earth's radiation budget, in the present climate and in response to global warming. The WCRP recognizes that limited understanding of clouds is the major source of uncertainty in climate sensitivity, but also contributes substantially to persistent biases in GCMs, as discussed by Bony et al. (2015).

Copernicus Climate Change and Atmosphere Monitoring Services. The ECMWF Copernicus Climate Change (C3S) and Atmosphere Monitoring Services (CAMS) provide in the reanalysis (ERA5) hourly estimates of a large number of atmospheric, land, and oceanic climate variables. The data cover Earth on a 30-km grid and resolve the atmosphere using 137 levels from the surface up to a height of 80 km. The ERA5 architecture is based on a frozen version of the ECMWF's Integrated Forecasting System (IFS) and it inherits from it the type of biases shown in Fig. 1. Since many climate assessments are based on reanalyses datasets, a wealth of observations is crucial for the accuracy and the validity of such assessments. In particular, satellite wind observations are needed to constrain the upper level flow in poorly observed regions. At the same time, a more accurate representation of transport would also benefit CAMS products. For example, dust aerosol production is entirely dependent on surface winds over source regions (i.e., deserts) which are currently completely unobserved. The convective transport of pollutants from the surface into the free troposphere, where chemical lifetimes are often longer and the transport process is much faster, makes that issue a global one. Transport of volcanic ash following major eruptions has also global impact. Ozone is also transported down from the stratosphere, but precise estimates are still lacking due to uncertainty about the upper troposphere–lower stratosphere (UTLS) transport. Accurate wind fields are required to understand where the polluted air masses are coming from. Changes in circulation connected to climate variability will greatly affect the future pollution scenarios and determine mitigation actions.

Atmospheric dynamics. Schäfler et al. (2018) describe the North Atlantic Waveguide and Downstream impact Experiment (NAWDEX), focusing on large-scale waveguide dynamics in

Table 2. Recommendations for further improvement of satellite observation systems to meet scientific needs.

Topic	Observational needs
Dynamics, transport	Spatially resolved, particularly vertically, and high-accuracy measurements of wind and humidity measured in concert with existing instruments for synergy (both LEO and GEO)
	Particularly UTLS
Physical processes	3D turbulence on scales <500 km
	Vertical mixing of air; in particular, wind shear profiles
	3D or 4D measurements of convective, cloud, radiative and precipitation processes involving wind, humidity, cloud parameters, aerosol, and precipitation forms
	Improved observation techniques and algorithms to measure and retrieve these physical properties
	Compare physical properties/processes with weather or circulation models
	Generation, propagation, and dissipation of gravity waves on all scales
Satellite product validation	Spatially resolved, particularly vertically, and high-accuracy measurements of wind, humidity, aerosol, and cloud process properties measured in concert with existing instruments for validation, e.g., (Doppler) lidar, radar, multiangle imagers

relation to wind shear and moist (diabatic) processes, in turn affecting the dynamics of the flow and which must be understood and represented more accurately in models in order to further improve forecast quality. Others describe further improvements by providing a spatially and temporally more detailed description of the atmosphere in the 3D turbulence regime, e.g., Stoffelen et al. (2005) and Baker et al. (2014). We describe the characteristics of this regime in order to understand the detailed requirements.

Spatially resolved, accurate, and frequent observations of convective processes and mesoscale dynamics are much needed, particularly in the tropics. Figure 1 shows the uncertainty in tropical circulation due to lack of observations and poor modeling. For example, projected climate changes in tropical cyclone characteristics are uncertain and inherently tied to changes in large-scale teleconnection patterns such as ENSO, associated changes in sea surface temperature and deep convection. These uncertainties are caused by poor observation of the tropical circulation and processes and also affect stratosphere and high-latitude weather (Polvani et al. 2017). Satellite observations are needed to obtain the required spatial, particularly vertical, and temporal coverage of the atmosphere in order to capture tropical dynamical weather regimes.

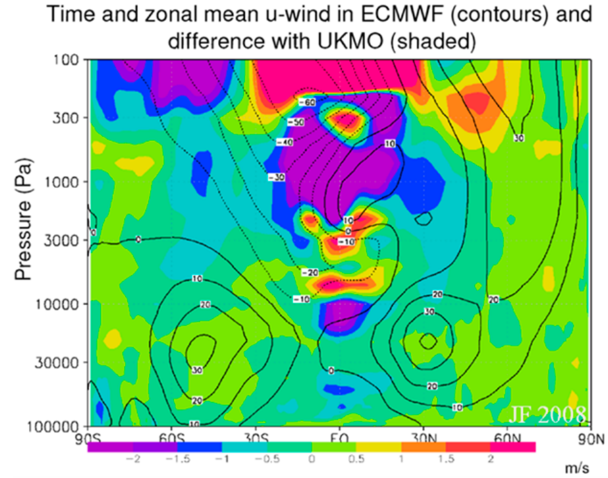

Fig. 1. Zonally mean westerly ECMWF wind component (contours) and difference with Met Office (shaded) for January and February 2008 showing large upper-air analysis differences near the ITCZ (Marseille et al. 2013).

Thus, large observation gaps exist in high-resolution vertical profiles of wind and humidity. As a result, many global circulation models do not well describe mesoscale, convective and turbulence processes. Figure 2 depicts the measured wind effects at the surface in areas of widespread convection. Figure 3 shows an example of the lack of turbulence in state-of-the-art global atmospheric models, which exists both at the surface and in the upper air. Global atmospheric weather (NWP) and climate models do not dynamically resolve 3D atmospheric turbulence and convection, while these are important for the distribution of heat and atmospheric constituents.

As depicted in Fig. 3, wavenumber spectra reveal the presence of 3D turbulence through an elevated tail of the small-scale wave amplitudes ($k^{-5/3}$ tail at high wavenumbers k). Upscale developments, e.g., through moist convection, create uncertainties in weather prediction capability (King et al. 2015) and our observing system should be able to capture these small-scale developments for improved NWP initialization. However, the amount of wind variability on scales smaller than 100 km amounts generally to only about 1 $m^2 s^{-2}$ and if we require to effectively capture these signals, the measurement uncertainty should be below 1 m s^{-1} too, which is challenging indeed.

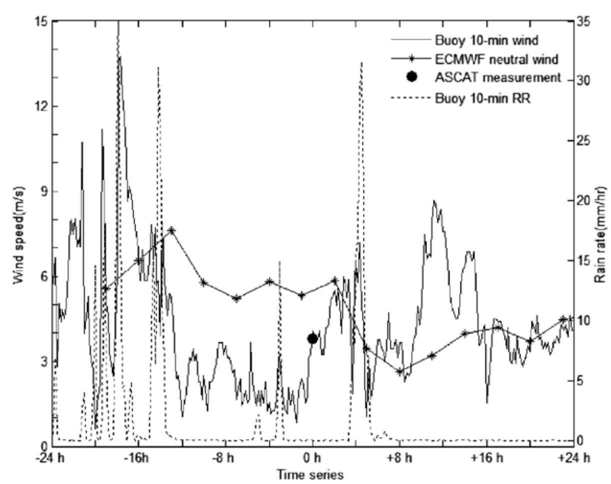

Fig. 2. Time series of buoy winds and rain, and ECMWF wind forecasts for the period of ±24 h of the ASCAT satellite overpass (see legend). The black circle represents the ASCAT-retrieved wind speed. The time series corresponds to buoy 52003 (8°S, 165°E) and is centered on 2200 UTC 10 Aug 2007 (Portabella et al. 2012). copyright IEEE.

Besides being small in amplitude, the atmospheric dynamics for large wavenumbers is fast, which is another important challenge. For example,

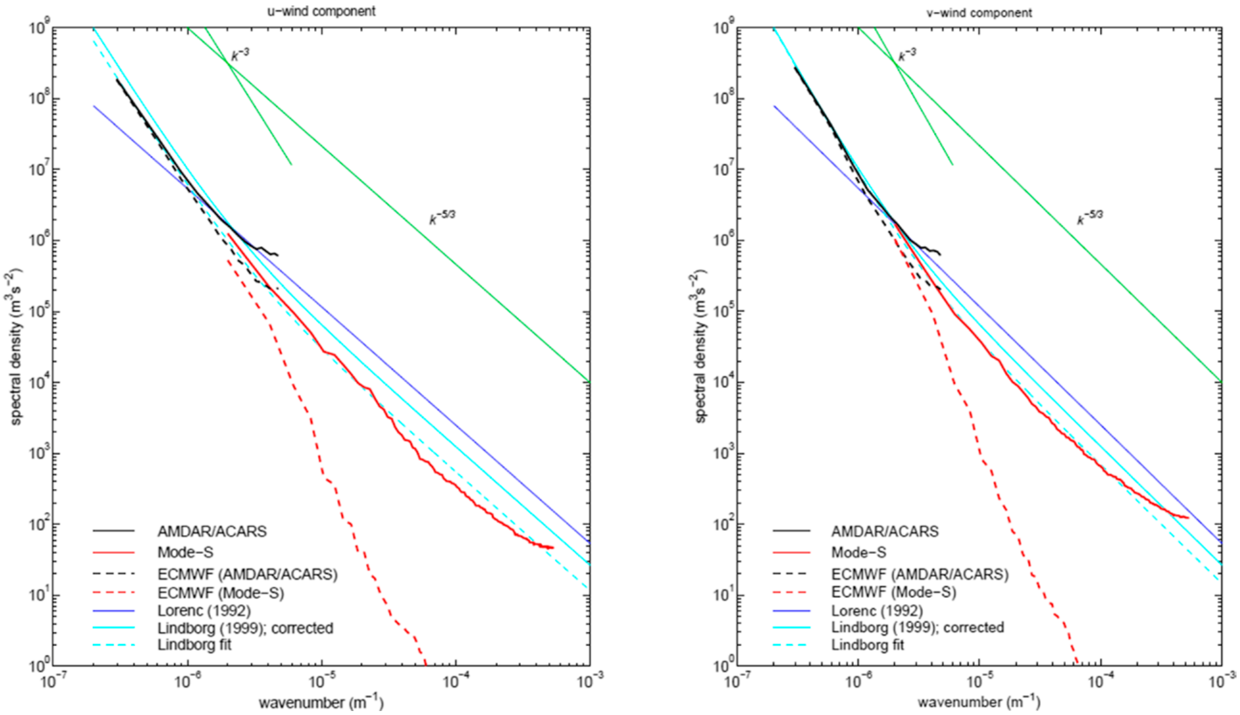

Fig. 3. Wavenumber spectra of collocated ECMWF model and observed aircraft winds; (left) east–west component (*u*) and (right) south–north component (υ). The straight lines represent wavenumber (*k*) spectra proposed in literature following a $k^{-5/3}$ power law (Marseille et al. 2013).

Stoffelen et al. (2014) find that providing OceanSat Scatterometer (OSCAT) winds only 2.5 h after providing local ASCAT winds leads generally to independent improvement of the forecast skill, in line with the objective of the CEOS virtual scatterometer wind constellation, being built to improve the frequency of observation (Sato and Riishojgaard 2016).

Concerning vertical resolution, Houchi et al. (2010) found that the average vertical shear of the horizontal wind amounts to about 4 m s^{-1} per 1-km height. It may be clear that height sampling knowledge and wind accuracy are intimately linked and that poor height assignment or height averaging leads to inaccurate or inadequate winds for depicting 3D turbulence. Houchi et al. (2010) also found, on the basis of full vertical resolution radiosonde measurements, that the climatological shear profiles in the tropics are poor too. Since vertical shear plays a key role in exchange processes, one may expect that the representation of 3D turbulence and convective processes and associated exchanges is rather poor in atmospheric circulation models.

A last and obvious requirement for small-scale detection is the requirement for spatially dense observations. In summary, multiple challenges are facing us to further improve the detail of analyses of atmospheric dynamics.

Wind profile capabilities

Current systems. The conventional radiosonde network is, although very sparse, key in providing vertically resolved atmospheric winds. Moreover, land areas profit from profilers and ascent and descent wind profiles from civil aircraft (de Haan and Stoffelen 2012) and, where it rains over land, from radar Doppler measurements. In addition, satellite wind information is being provided. (see Table 3).

Winds are derived from tracking clouds and areas of water vapor in sequences of satellite images. These are known as AMVs and have the advantage of excellent horizontal and temporal coverage, but the vertical sampling and representation is rather poor. Due to advanced quality control (QC) methodologies, AMVs have beneficial impact in NWP. Height assignment

Table 3. All instruments for measuring horizontal winds, their relevance, maturity, and operational limitations (from WMO OSCAR: www.wmo-sat.info/oscar/).

Instruments	Relevance of measurement	Processing maturity	Operational limitations
ALADIN	Primary	Methodology to consolidate	Nonscanning, radial viewing, cloud
GIIRS IRS HIS	Primary	Methodology to consolidate	From humidity profile and tracers
HRDI TIDI WINDII	High	Methodology being tuned	Mesosphere and lower thermosphere
ABI AHI FCI AGRI AMI MSU-GSM	High	Consolidated methodology	Tracers needed
MSU-GS SEVERI MSU-GS/A ISR	High	Consolidated methodology	Tracers needed
IMAGER (*GOES 8–11*) IMAGER (*INSAT-3D*) IMAGER (MTSAT) JAMI MI IMAGER (*GOES 12–15*) S-VISSR (*FY-2C*/*D*/*E*)	Medium	Consolidated methodology	Tracers needed

can be problematic, due to transparent, multilevel, and broken clouds (Nieman et al. 1993; Sherwood et al. 2004). Poor height assignment generally leads to inaccurate winds due to the high vertical shear (on average 4 m s^{-1} km^{-1}. Moreover, when retrieving cloud winds on smaller scales, the inherent cloud and air dynamics, associated with cloud growth, cloud dissipation, and mixing, limit our capability to track representative winds in dynamical conditions on the scale of minutes (see Fig. 4). Validation and calibration of AMV height assignment algorithms as such remain a challenge. Additional sensor capability, such as that provided by Doppler wind lidar (DWL), may prove useful in this respect (Salonen and Bormann 2016; Folger and Weissmann 2014; Lean and Bohrmann 2019).

Operational meteorological satellites also measure ocean surface vector wind information by microwave sensing of the ocean surface by scatterometers and radiometers. Scatterometers are radars that view the ocean under several incidence and azimuth angles and measure the microwave return from the ocean roughness on the centimeter scale (e.g., Figa-Saldaña et al. 2017). Although these instruments well depict mesoscale weather features at the ocean surface (King et al. 2017), they lack upper air wind information, while this is governed by a similar 3D turbulence regime (see, e.g., Fig. 3).

Prospective capabilities. Key satellite missions relevant to atmospheric wind profiling either probe molecules in clear air, aerosol and cloud particles, or humidity structures at frequencies varying from the ultraviolet (UV) to the microwave regime.

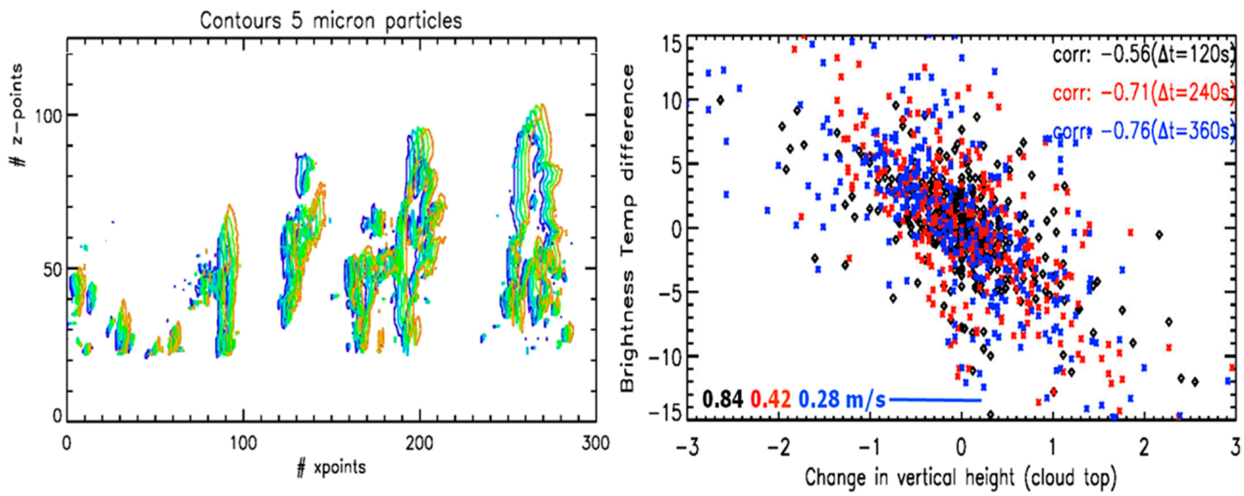

Fig. 4. Cloud-resolving model simulation at a horizontal grid of 200 m over 2–6 min. (left) Section in height and zonal (*u*) direction of the cloud boundaries as defined by the presence of 5-μm particles contoured at *t* = 0, 2, 4, 6, and 8 min. (right) Brightness temperature and height changes of simulated pixels with clouds over 2, 4, and 6 min; numbers in the bottom-left corner specify the unit vertical motion (m s^{-1}) for each time interval. Besides advection by the uniform large-scale wind (*u* = 3.3 m s^{-1}), cloud transformation is evident on the minute scale. Credits: Gerd-Jan van Zadelhoff, KNMI.

Instruments that view the ocean and measure its emission or return include Global Navigation Satellite System- Reflectometry (GNSS-R) (Clarizia et al. 2009), but also L-, C-, X- and Ku-band scatterometers and radiometers that sense winds, waves and ocean currents from the ocean roughness. These instruments provide essential information on mesoscale weather features and air-sea interaction processes, but do not offer a solution to obtain upper-air information, which challenge is addressed below.

***Aeolus* Doppler wind lidar profiles.** The ESA *Aeolus* mission features the first high-spectral-resolution Doppler lidar in space for wind measurement. Launched in August 2018, *Aeolus* acquires profiles of the wind on a global scale, particularly filling observation gaps over the oceans, poles, tropics, and Southern Hemisphere. ESA's *Aeolus* wind mission is well on its way to demonstrate the beneficial impact in NWP[3] of measuring global wind profiles from space, using laser technology.

While this novel mission is providing much-needed data to improve the quality of weather forecasts, it also contributes to long-term climate research. The *Aeolus* satellite carries just one large instrument, a DWL, called Atmospheric Laser Doppler Instrument (ALADIN), that is probing the lowermost 30 km of the atmosphere. *Aeolus* is now furthermore providing important information on the vertical structure of aerosol and clouds (cf. Flamant et al. 2008). Figure 5 shows that in particular the molecular channel is effective in providing wind observations, with almost full coverage above 12 km height, 70% in the upper troposphere and about 50% at the boundary layer top along the laser track (see also Stoffelen et al. 2005). In addition, the cloud and particle returns provide complementary wind, cloud, and aerosol information. The molecular returns provide the much-needed wind coverage in clear air, particularly in the UTLS (see Fig. 5).

The ESA *Aeolus* mission aims to extend radiosonde quality and coverage to the oceans, tropics, and Southern Hemisphere, thereby demonstrating beneficial impact of this extended vertically resolved wind profile network (Stoffelen et al. 2006; Marseille et al. 2008a; Žagar et al. 2008; Horányi et al. 2015; Megner et al. 2015).

Following the realization of the planned *Aeolus* demonstration in space,[3] an *Aeolus* follow-on is currently being planned. An *Aeolus* follow-on would benefit from increased vertical and horizontal resolution and thereby improved wind, aerosol, and cloud profiling. Moreover,

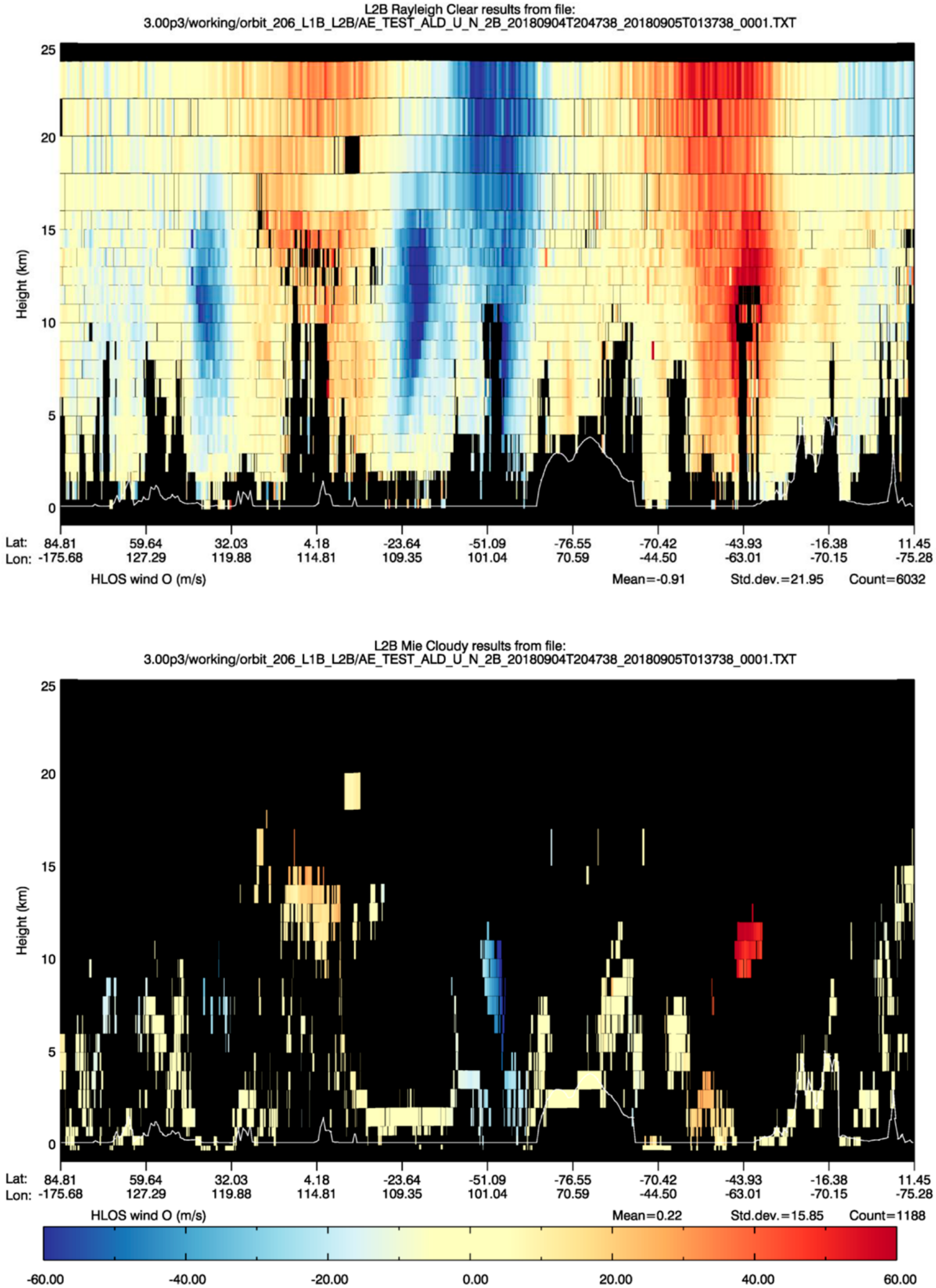

Fig. 5. Along-track and height section of almost an orbit of measured, but uncalibrated, Aeolus horizontally projected line-of-sight wind component profiles, covering (top) the molecular (Rayleigh) detection channel in clear air and (bottom) the particle (Mie) detection channel in clouds and aerosol.

besides the current across-track measurements, along-track (backward) or fore and aft measurements could be considered, thus providing information on both horizontal wind components in clear air. In particular, to fulfill the temporal requirements for wind profile observations to track mesoscale dynamic weather evolution, several orbits should be implemented in a set constellation (Marseille et al. 2008b), similar to the objectives of the international CEOS virtual constellation for ocean vector winds.

Hyperspectral IR instruments. Wind information may be obtained indirectly by geostationary and polar satellite radiances for both infrared and microwave wavelengths in a 4D-Var data assimilation context (Peubey and McNally 2009; Geer et al. 2014). To do so, the tight requirements as discussed above on precision, accuracy, spatial and temporal sampling, and coverage need to be met, but now for radiance information. In addition, as radiances must be tracked in the NWP model domain, a capability of the data assimilation system to capture and represent fast and small scales must exist, which however is presently limited, see Fig. 3. Recently a study was undertaken at ECMWF looking at the impact of hyperspectral sounder data on wind analyses using a reduced observation baseline as the control. The moisture sensitive channels were shown to have most impact on the wind fields and of a comparable magnitude to the AMVs assimilated at ECMWF (Salonen and McNally 2017), which is very encouraging. Although abundant, just like for AMVs, these radiances do not provide a direct measure of the wind vector. In fact, motion is inferred from changes in the mass field or from tracking horizontal radiance gradients in the 4D-Var data assimilation window. For the latter, one may obtain the wind component along the gradient, but not the wind component normal to the gradient. Unfortunately, dynamical changes to the air mass that affect the radiance field are not entirely caused by advection, but also by transformation due to convergence, divergence, subsidence, convection, and gravity waves, for example, associated with cloud dynamics. As mentioned above, the mesoscale features in the dynamics are currently not well presented in NWP models and are thus the most difficult to track in 4D-Var. Finally, similar to AMVs, given the large and poorly represented shear in the atmosphere (Houchi et al. 2010), local height assignment errors of radiances may give rather large correlated error covariances in the observation data. Indeed, as for AMVs, *Aeolus* is very useful for assessing these radiance errors in observations and models by providing high-quality height-resolved wind information in the data assimilation system. Without doubt, given their complementarity, the simultaneous provision of humidity information from hyperspectral instruments and wind information from a DWL would present a leap forward in NWP.

Cloud radar. As may be inferred from Fig. 5, cloud measurements may play a partial role to fulfill the need for wind profiles. Figure 4 further suggests that clouds are very heterogeneous and fast and manifest dynamics associated with cloud growth and cloud dissipation.

With Wind Velocity Radar Nephoscope (WIVERN), a new satellite concept to provide global in-cloud winds, precipitation and cloud properties, Illingworth et al. (2018) propose and present a cloud radar exploiting Doppler capability with a rotating beam in a polar orbit. It would demonstrate the capability to obtain in-cloud winds, facing the aspects of cloud heterogeneity and fast-evolving 3D convection. Given the relatively large wind variability and NWP model errors near clouds (Lin et al. 2016), these cloud observations would also be very useful for NWP.

Geometric cloud winds. Complementary to cloud radar, in an ESA satellite convoy study, Stoffelen et al. (2014) proposed a tandem thermal multispectral imager, that would be able to sense clouds simultaneously from different directions, enabling geometric cloud wind height and motion estimation from parallax observations. Fisher et al. (2016) demonstrated that such stereo retrieval is indeed able to improve the accuracy of retrieved cloud-top height when compared to collocated *Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations* (*CALIPSO*) data. Recently, the Flow by IR tandem (FLIRt) mission proposal was submitted to ESA (Muller et al. 2017), with the objective to retrieve updraft speeds, wind fields, thermal buoyancy, and rates of mixing with ambient air as well as the impact of aerosols on cloud convective processes. Improved cloud-top heights (CTHs) will synergistically aid in the height assignment of AMVs and in their QC. The high density of the wind fields alongside the addition of the vertical updraft speed in the mid- to upper troposphere would have great utility for severe weather forecasting, particularly in the midlatitudes and tropics, but also for polar lows. By combining several simultaneous and near-simultaneous views at each location and at a high horizontal sampling of 200 m, similar vertical accuracy of the cloud-top heights can be achieved and hence wind accuracies of better than 1 m s^{-1} appear achievable for geometric cloud winds. High horizontal resolution goes at the expense of spatial coverage, though, and this is why trade-offs in costs and benefits need to be further demonstrated. On the other side, note that any contrast in the atmosphere that is visible on satellite images may be exploited in such tandem satellite configuration, hence potentially useful for precise height and motion observations away from clouds too, e.g., by geometrically imaging humidity structures. The impact in NWP data assimilation of these high-quality wind observations is expected to be very beneficial.

Way forward toward an operational wind profiling mission

Aeolus is demonstrating the technology of obtaining molecular winds in most of the atmosphere and its beneficial impact in NWP. In addition, cloud and aerosol winds will be demonstrated, some in areas where molecular winds are absent. A UV DWL has then proven to be a good candidate for an operational wind profiling mission and expertise has been build up in Europe to extend the technology into the future.

Operational* Aeolus *follow-on. Given its unique capabilities and after demonstration of its benefit, an *Aeolus*-like operational follow-on mission, obtaining wind profiles in clear air by exploiting molecular scattering appears worthwhile. In addition, such capability may well include height-resolved observations on cloud and aerosol. However, several technological and scientific aspects of such a mission need further consideration.

First, *Aeolus* is a demonstration mission and even though NWP benefit is being demonstrated, its time and space coverage is rather limited. NWP data assimilation practice suggests that wind profiles may be effectively provided at 100-km density and every 3 h, but which implies several DWLs fly in a constellation, similar to, for example, the CEOS ocean surface vector wind scatterometer constellations. Such constellations may be achieved through international collaboration, which could already be imagined in the design phase.

To obtain molecular winds, the *Aeolus* UV wavelength is favorable since the underlying incoherent Rayleigh scattering decreases with the fourth power of the wavelength. Therefore, although other wavelengths may be considered, meeting the wind accuracy requirements in clean air will be very challenging for longer wavelengths. As for *Aeolus*, in areas with aerosol and cloud, Mie scattering may be exploited to obtain winds.

The *Aeolus* mission has been designed 20 years ago and today many aspects of its design should be tailored to the objectives of an operational mission in the 2030–40 time frame. Improved quality wind profiles and optical profiles are targeted, which, as outlined in appendix B, can be achieved by improved accuracy and enhanced vertical and horizontal resolution.

Obtaining vertically resolved profiles of optical properties from aerosol and clouds (backscatter, extinction, and depolarization) with laser technology is an ancillary requirement that may be served by a DWL in space. High interest exists in obtaining aerosol and cloud characteristics and it is thus of interest to evaluate possible capabilities that are synergetic with wind profiling.

While the above considerations may already be elaborated before the *Aeolus* mission data have been evaluated, we will also need to consider lessons learned from *Aeolus* data, e.g., on calibration–validation and data processing that will undoubtedly further alter the detailed design of an operational *Aeolus* follow-on mission.

Conclusions

The ESA *Aeolus* mission included the launch of the first DWL to space in August 2018, following a well-expressed need for wind profile observations to initialize numerical weather prediction (NWP) models. Given the success of the *Aeolus* mission, it is high time to look forward to future vertical wind profiling capability to fulfill the rolling requirements in operational meteorology.

Requirements for wind profiles and information on vertical wind shear have evolved since *Aeolus* inception, while the need for wind information to capture and initialize small-amplitude, fast-evolving and mesoscale dynamical structures increases as the resolution of global NWP improved well into the 3D turbulence regime on horizontal scales smaller than 500 km.

The increasing demand for vertically well-resolved and accurate wind profile information to cover areas over the oceans, tropics and Southern Hemisphere is well addressed by *Aeolus*. Other observation techniques, some still in development, will at most partially fulfill the global demand for 3D wind information. Therefore, after demonstration of its feasibility, an *Aeolus*-like follow-on mission, obtaining operational wind profiles in clear air by exploiting molecular scattering, is well motivated. Given such a resource-demanding level of ambition, international collaboration working toward a joint international constellation must be an effective way forward. This requires a well-coordinated joint action by several international space agencies. It is currently being demonstrated that *Aeolus* winds make a significant difference to weather[3] and climate prediction quality, thus laying the foundation for a follow-on operational mission.

As outlined in this manuscript, several technological and scientific aspects of such mission need further consideration in preparation of an operational *Aeolus* follow-on. For example, high interest exists in obtaining aerosol and cloud characteristics (backscatter, extinction, and depolarization) and it is thus of interest to evaluate possible capabilities that are synergetic with vertical wind profiling. Moreover, progress in laser technology, possibly resulting in a factor-of-2.5-higher electro-optical efficiency and thus a higher number of laser shots at higher energy seem feasible. In addition, given the progress in solid state physics, detectors with improved resolution and efficiency are available, leading, inter alia, to improved vertical resolution of the optical profiles of both Rayleigh and Mie scattering and, consequently, improved wind profiles and improved optical profiles.

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Appendix A: Wind profile gap analysis

A building block of the WMO RRR is the OSCAR tool. For each of the application areas OSCAR defines quantitative user-defined requirements for the observation of physical variables. It covers observation requirements of both satellite and surface-based measurement capabilities. It also provides expert analyses of space-based capabilities and detailed information on all Earth observation satellites and instruments. Therefore, it facilitates the WMO RRR process, comparing "what is required" with "what is, or will be available," in order to identify gaps and support the planning of integrated global observing systems. An objective is to automatically generate first-level analyses of compliance between the quantitative requirements and the actual capabilities (space or surface based) to support an overall gap analysis and future vision (WMO 2009).

OSCAR links user requirements in the different meteorological applications to instrument capabilities for all instruments and satellites in diverse categories. For example, in rating the different instruments, OSCAR describes how the distinct instruments, by design, have the potential to contribute to capability identified in the WMO vision of global observing systems, assuming nominal operation of space and ground segments. Performance levels are associated to a numbered color code, which for horizontal winds are rated as primary (1) for a DWL like *Aeolus*, very high (2) for water vapor–tracking imagers, high (3) for cloud-tracking imagers on geostationary satellites (GEO) and generally fair (4) or marginal (5) for polar low-Earth-orbiting (LEO) imagers. These qualifications are related to vertical and horizontal coverage, and demonstrated geophysical errors associated with tracking targets and height assignment for the imagers. OSCAR thus offers the capability to match requirements and capabilities for a set of application areas to produce a gap analysis between requirements and capabilities, paving the way to a vision of how to develop the global observing system.

The OSCAR tool recognizes capability gaps in variables, e.g., lacking measurement techniques of the vertical wind component, in missions, e.g., when continuity of instruments is not guaranteed along the timeline of a variable, and in characteristics, for example, when vertical resolution is lacking. Such gaps are implicitly linked to the lack of knowledge in atmospheric processes, though not explicitly. As capabilities improve, requirements evolve and tend to cover more detailed dynamical processes.

Appendix B: Lessons learned from *Aeolus* and Doppler wind lidar technology development

The *Aeolus* mission has been designed 20 years ago; the hard-won experience that has now been gained during the lengthy development and commissioning provides many important guidelines for the future. These include realistic, attainable objectives for an operational mission in the 2030 time frame for the four primary components of the lidar: telescope and optical arrangement, optical spectrometers, and detector element.

In brief, the *Aeolus*[B1] lidar incorporates a frequency-tripled yttrium–aluminum–garnet (YAG) laser operating at 355 nm, giving nominally up to 120-mJ, 20-ns pulses at a continuous 50-Hz rate. Scattered light from the atmosphere is collected in a 1.5-m-diameter telescope of stiffened honeycomb structure, and passed to the two optical spectrometers—a dual channel pair of Fabry Perot interferometers for the broadband molecular Rayleigh scattering and a Fizeau interferometer for the narrow-band aerosol Mie scattering. The intermediate optics incorporates many beam splitters, polarizing elements and mirrors etc., and recycles the light between the various spectroscopic elements. The light filtered at the spectrometers is passed to a charge-coupled device (CCD) detector which incorporates a 16 × 16 pixel array with rapid charge transfer. The required Doppler shifts in the scattered light from the atmosphere are measured by direct assessment of fringe position in the Mie aerosol spectrometer, and indirectly by ratioing the intensities of the interference fringes in the dual channel Rayleigh molecular spectrometer.

[B1] ESA *Aeolus* mission, www.esa.int/Our_Activities/Observing_the_Earth/Aeolus.

The ALADIN Airborne Demonstrator (A2D) is based at Deutsches Zentrum für Luft- und Raumfahrt (DLR), Oberpfaffenhofen, and has contributed a vast wealth of data and information for *Aeolus* (Lux et al. 2018a,b; Reitebuch et al. 2009, 2017). In fact, it is fair to say that the present progress and understanding of *Aeolus* would not have been possible without the knowledge and hands-on experience contributed by the A2D.

The laser itself presents formidable problems of optical, thermal, and mechanical design. Robust solution of these problems is essential to achieve good, reliable long-term laser frequency stability and laser beam quality for efficient third harmonic generation to the UV. Ancillary problems of laser operation include laser induced contamination (LIC) and laser induced damage (LID). An enormous amount of work has been done in contending with these problems, including the development of better resolved inspection methods, careful selection of components to minimize outgassing, use of hard nonporous optical films and a controlled oxygen environment. For selection of future operational laser sources, this extensive body of knowledge and experience will be immensely valuable. In particular, progress in laser technology, mainly resulting in higher electro-optical efficiency (a factor of 2 is demonstrated, a factor of 2.5 seems feasible).

As noted, for efficient use of optical signal, quite complex systems of recycling the light between the spectrometers have been developed and provide a useful gain in transmission. Spectral analysis of the resultant fringes and accurate measurement of Doppler shift require good knowledge of the actual fringe shapes and of any departures from the ideal. Very extensive investigations of these topics have been conducted for both the Fabry Perot and Fizeau spectrometers, including questions of the uniformity of illumination, angular alignment, and effective aperturing. Various anomalies of fringe shape have been analyzed and attributed to recycling and multiple reflections in the Fabry Perot instrument, and in the Fizeau to nonuniform illumination and local surface imperfections in the plates.

In the current CCD detector, the effective quantum efficiency is in the region of 85%, so any further improvement would have marginal impact. In frequency space, the CCD detector channel width is close to the width (full width, half height) of the spectrometer fringes. It has generally been considered that about three detector channels per fringe width provide an optimum choice for fringe analysis and measurement; advances in detector technology should certainly provide this in the future. Moreover, given the progress in solid state physics, detectors with improved vertical resolution of the optical profiles of both Rayleigh and Mie scattering seem feasible.

For an operational system and design of a follow-on mission, many fine judgements will be required between creating direct copies of a successful *Aeolus* and those siren voices calling for an almost total redesign based on latest technology. At this stage, it is premature to make any specific points, but it is perhaps worth recalling the following truisms:

- The laser is the starting point of any lidar design and provides its essential beating heart. Direct detection lidar at least offers flexibility as to how the laser power may be distributed; integration of few large pulses or many small pulses is in principle the same (in sharp contrast to coherent detection lidar). Nevertheless, there are lessons to be learned: first, the provision of an adequate number of monitoring points throughout the system for examination of performance. Second, the need for laser performance margins to be built into the planning. Third, the vital necessity of a "reference/baseline" system based on the functional analysis to which all experimental data and findings can be referred.
- Optical diagrams are deceptively simple in principle, but often fiendishly difficult to achieve in practice. Successful alignment, control, monitoring, and analysis with actual hardware composed of mirrors, lenses, filters, optical mounts, base plates, monitoring points, etc., can be exceptionally time consuming and arduous with many setbacks. Any apparent gains in, for example, transmission or optical efficiency need very careful and critical analysis in terms of additional optical complexity. Conceivably, the introduction of integrated optical modules in the future may offer robust simple solutions.
- For *Aeolus*, the two multiple-beam interferometers, Fabry Perot and Fizeau, were selected on the analysis of over 20 years ago. This included theoretical considerations of signal efficiency and near quantum limit performance, and practical considerations of thermal and mechanical stability. For the foreseeable future, many of these issues will probably

remain unchanged from a strictly spectroscopic viewpoint. However, the prospects for other types of interferometer—notably, two-beam devices akin to the Mach Zehnder and Michelson instruments will be worth further examination. Ultimately, all such instruments have quantum-limited, Cramer Rao, sensitivity and the question will be how well can any given device approach this performance limit in a practical realistic manner.

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