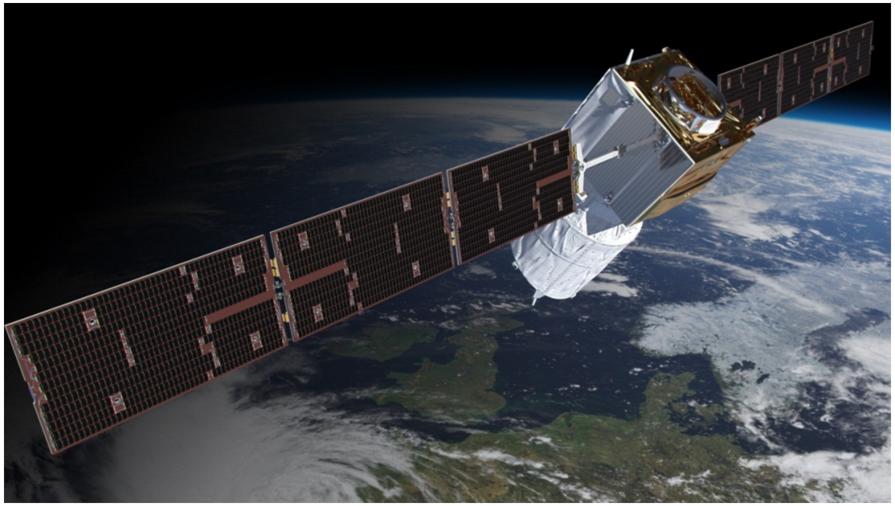
Status of the ADM-Aeolus wind lidar mission



A.G. Straume[1], A. Elfving[1], F. de Bruin[1], A. Culoma[1], T. Kanitz[1], G. Labruyere[1] , L. Mondin[1], D. Wernham[1], D. Schuettemeyer[1], F. Buscaglione[2], A. Dehn[2], S. Casadio[2], W. Lengert[2]

[1]ESA-ESTEC, The Netherlands, [2]ESA-ESRIN, Italy

http://www.esa.int/esaLP/LPadmaeolus.html

Aeolus teams

1. The Aeolus Mission Advisory Group
    - Angela Benedetti / ECMWF
    - Alain Dabas / MeteoFrance
    - Pierre Flamant / IPSL
    - Mary Forsythe / MetOffice
    - Erland Källén / ECMWF
    - Heiner Körnich / MISU
    - Harald Schyberg / met.no
    - Ad Stoffelen / KNMI
    - Oliver Reitebuch / DLR
    - Michael Vaughan / Lidar & Optics Associates
2. The Aeolus L1b, L2a and L2b algorithm development teams (DLR, ECMWF, IPSL, KNMI, MétéoFrance)
3. ESA Aeolus project and support teams (ESTEC, ESRIN, ESOC)
4. Airbus Defence and Space, and subcontractors

Outline

1. ESA's Earth Observation programme
2. Scientific motivation for ESA's Doppler wind lidar mission
3. Instrument and measurement principle
4. Mission products and their envisaged use
5. Campaigns and CAL/VAL
6. Programmatic status
7. Conclusions

ESA's Earth Observation Programme

ERS1
ERS2
Envisat

Meteosat

Earth Explorers

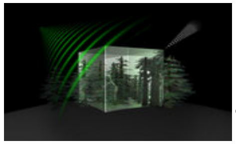
Research driven

Core Missions

GOCE
2009

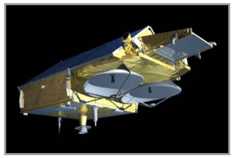
ADM-Aeolus
2015

EarthCARE
2016

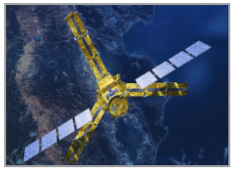


BIOMASS
2020

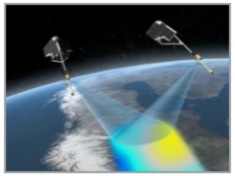
Opportunity Missions



CryoSat 2
2010



SMOS
2009



Swarm
2013

?

EE8
2022

2 candidates
CarbonSat, FLEX

Earth Watch

Service driven

Operational Meteorology

- MSG
- MTG
- Metop
- Metop SG

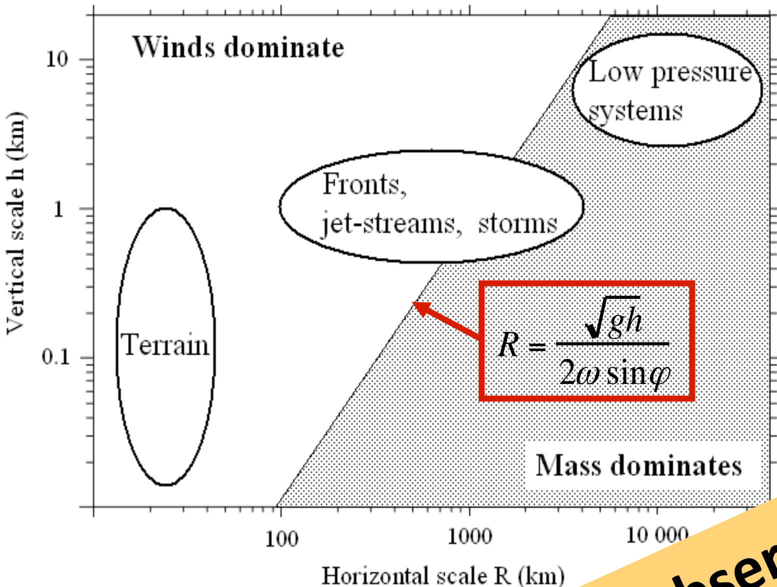
COPERNICUS

- Sentinel 1
- Sentinel 2
- Sentinel 3
- Sentinel 4
- Sentinel 5/5p

www.esa.int/livingplanet

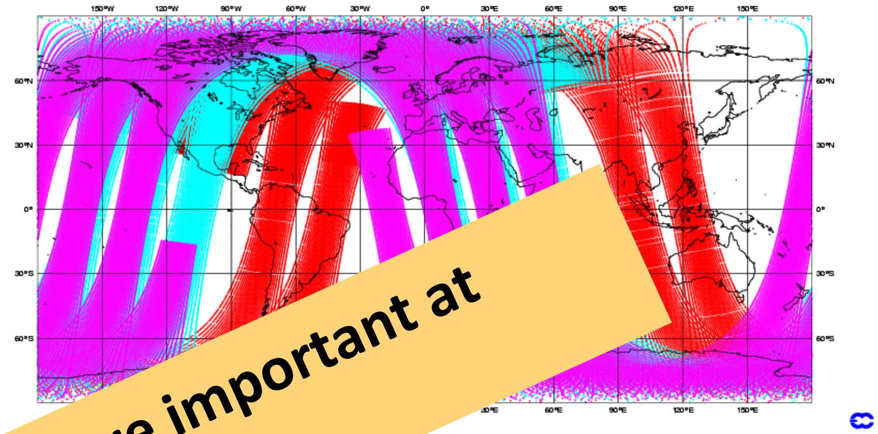
The importance of direct wind observations

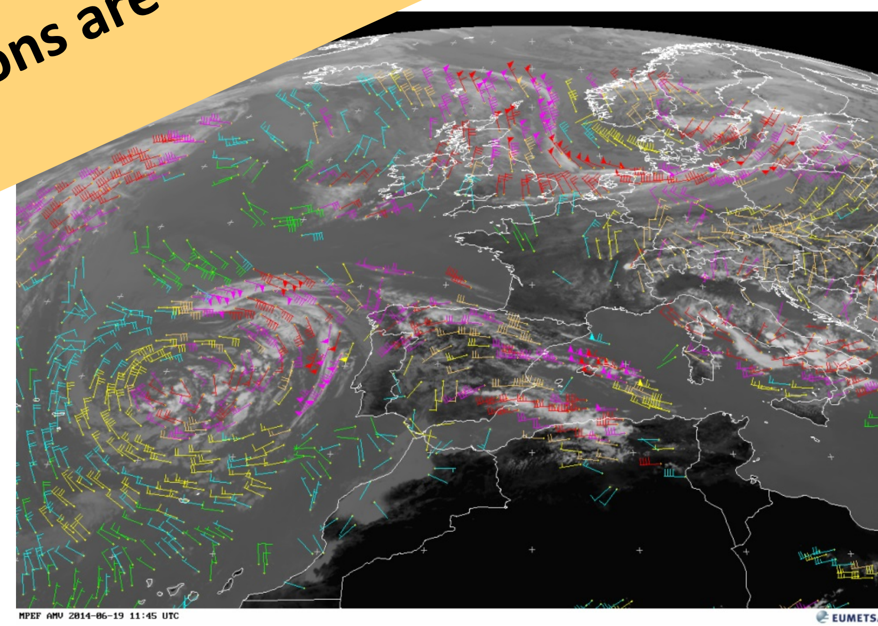
ROSSBY RADIUS OF DEFORMATION



g: gravitational acceleration, h: a…
velocity of Earth's rotation …

Global temperature soundings





Direct wind observations are important at smaller scales

Aeolus objectives

What are the scientific requirements?

Improve our understanding and predictability of

1. Atmospheric dynamics and global atmospheric transport
2. Global cycling of energy, water, aerosols, chemicals

How are they achieved?

Improved atmospheric analysis fields through use of Aeolus winds, in particular:

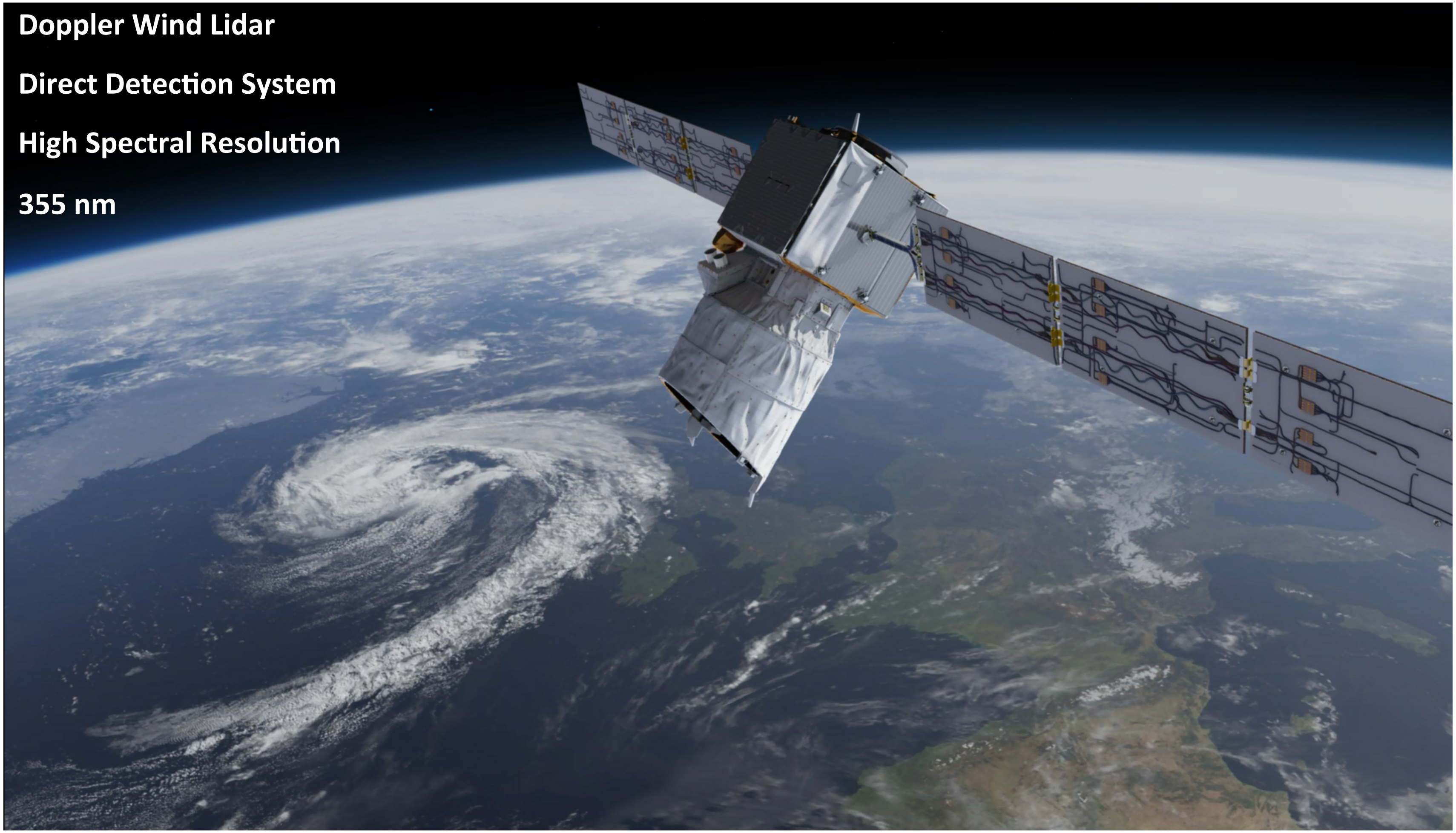
1. Tropics: Wind fields governs dynamics
2. Mid-latitudes: Intense storm developments and mesoscale circulation

What are the benefits?

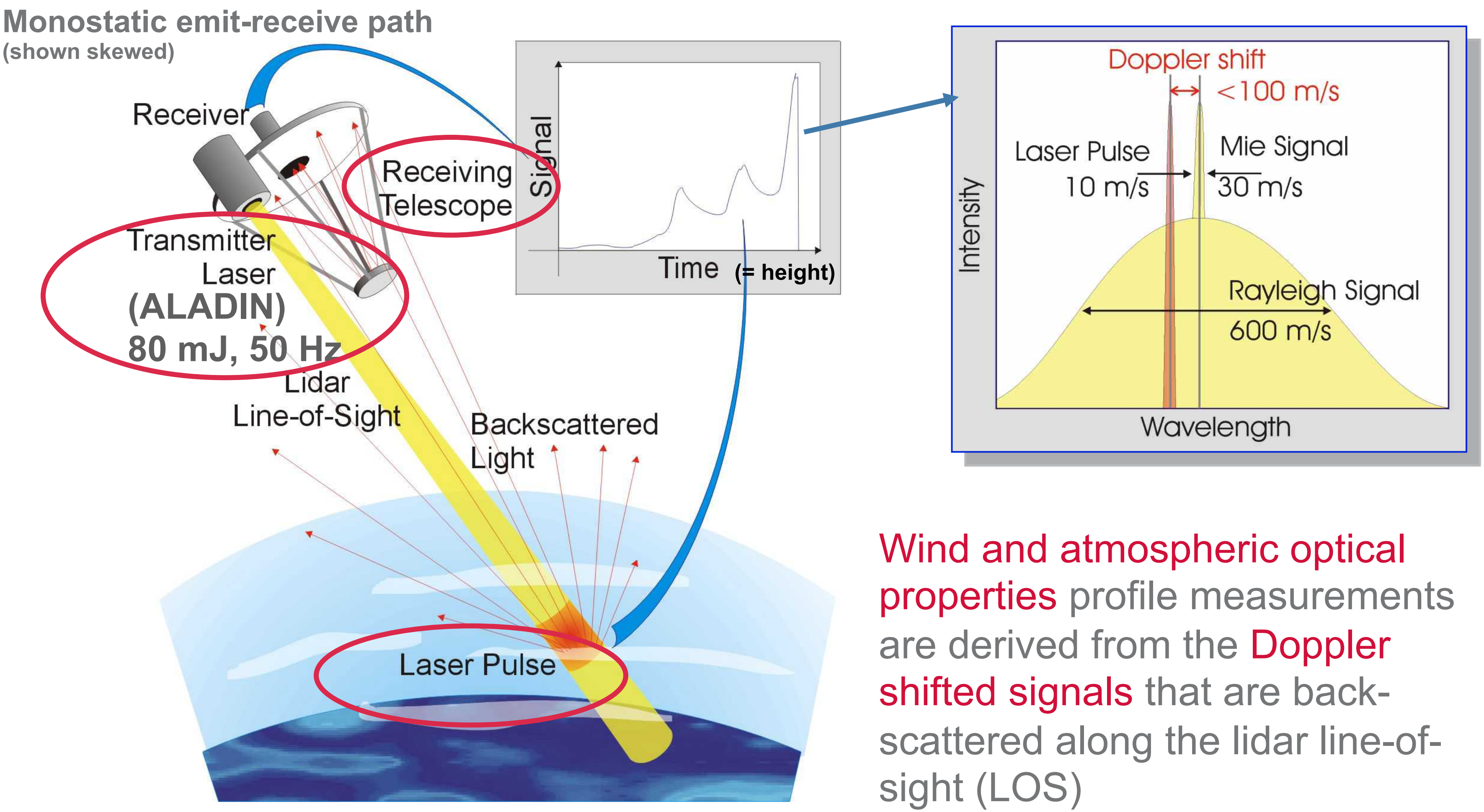
1. Better initial conditions for weather forecasting
2. Improved parameterisation and modelling of atmospheric processes in climate and forecast models

Demonstrate the capabilities of space-based Doppler Wind LIDARs (DWLs) for global wind profiling and its potential for operational use

Aeolus Mission



Aeolus measurement concept

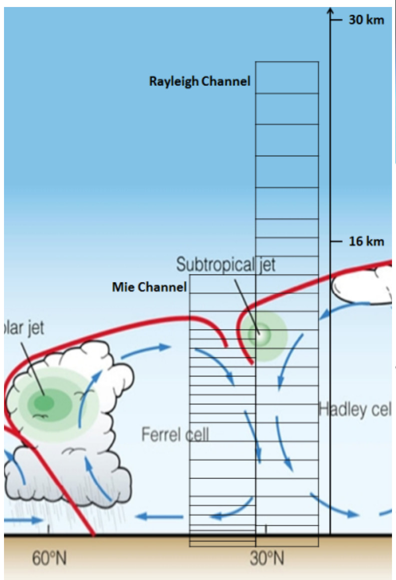


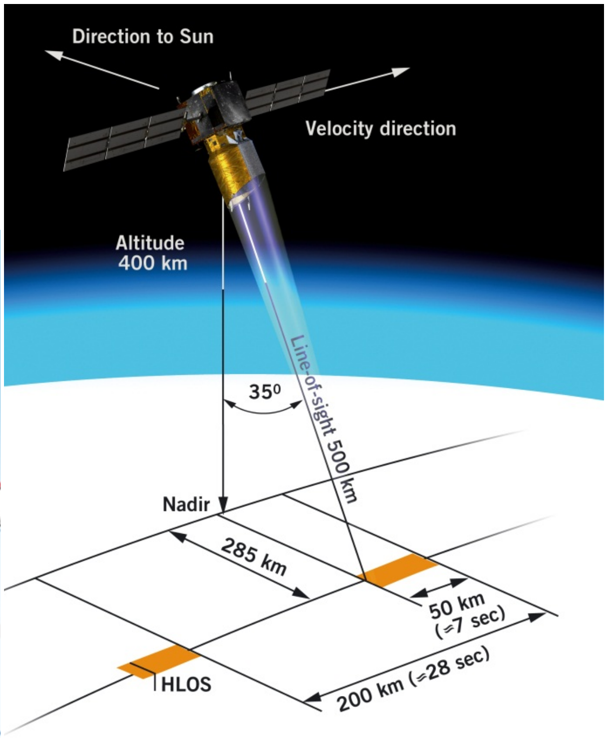
Wind and atmospheric optical properties profile measurements are derived from the Doppler shifted signals that are back-scattered along the lidar line-of-sight (LOS)

Measurement baseline

Old measurement baseline

Example of ADM-Aeolus vertical sampling





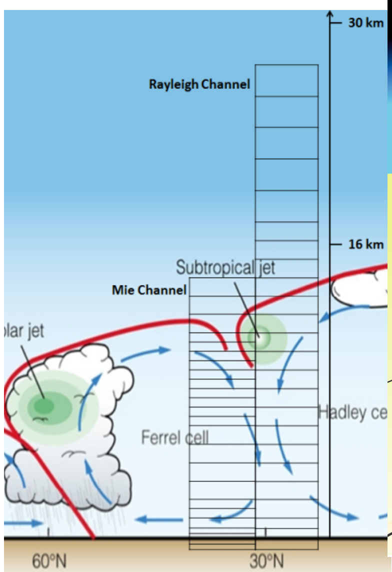
1. High Spectral Resolution: Separate molecular and a particle backscatter receivers
2. UV (355 nm , circularly polarized)
3. Cross-linear polarized light detected in polarizing scenes
4. Ground calibration (nadir and off-nadir)
5. Adjustable vertical sampling of atmospheric layers

   Δz: 0.25–2 km

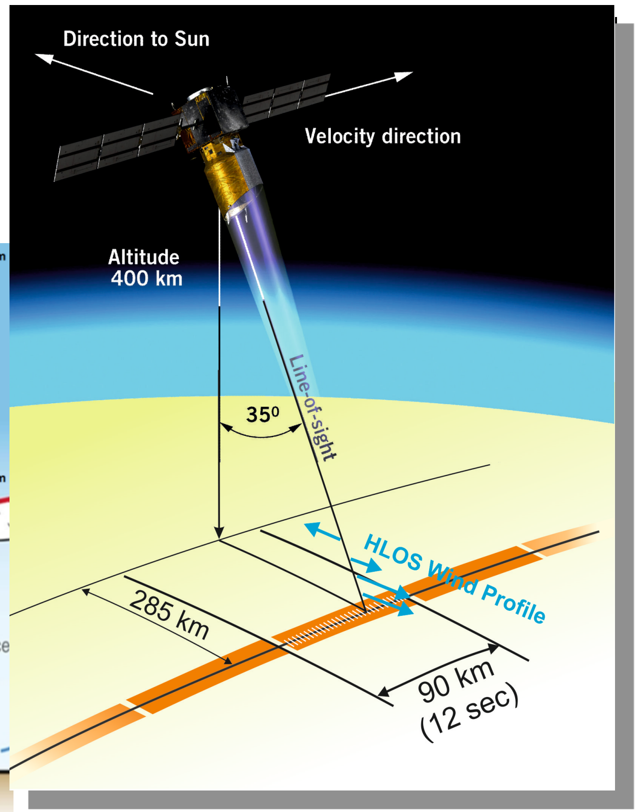
   z: 0-30 km

Measurement baseline

Example of ADM-Aeolus vertical sampling



New measurement baseline



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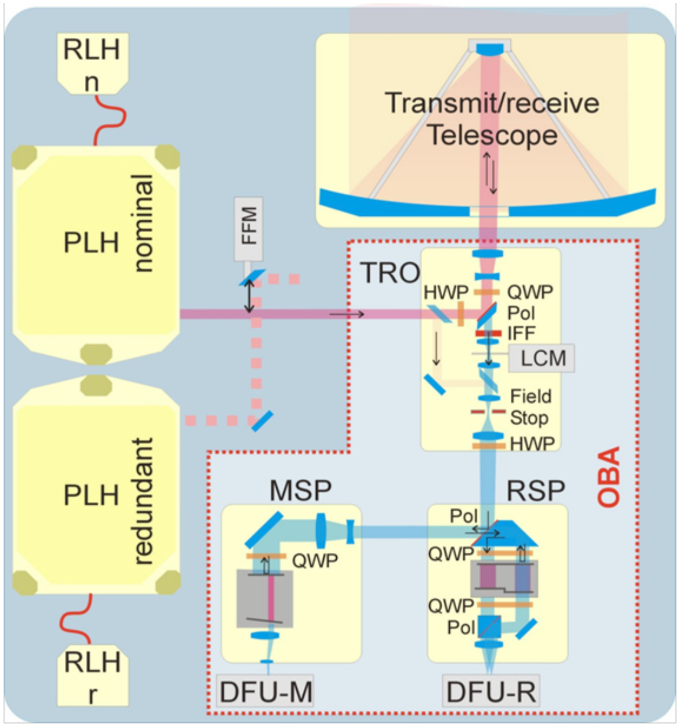
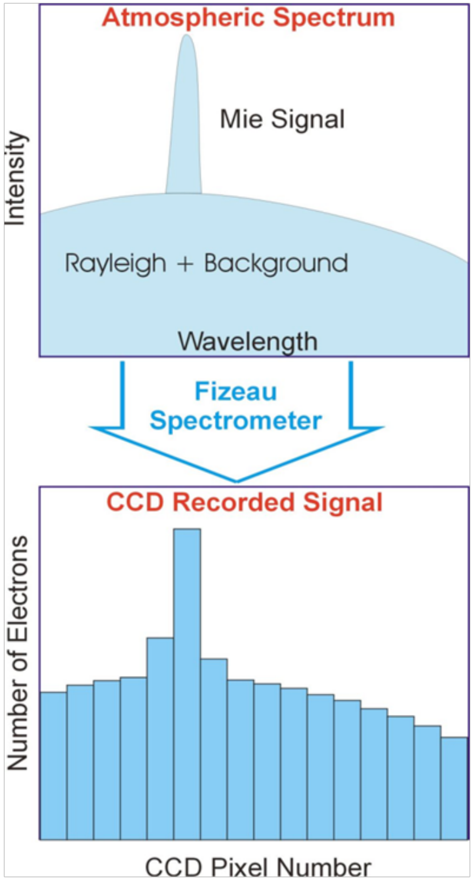
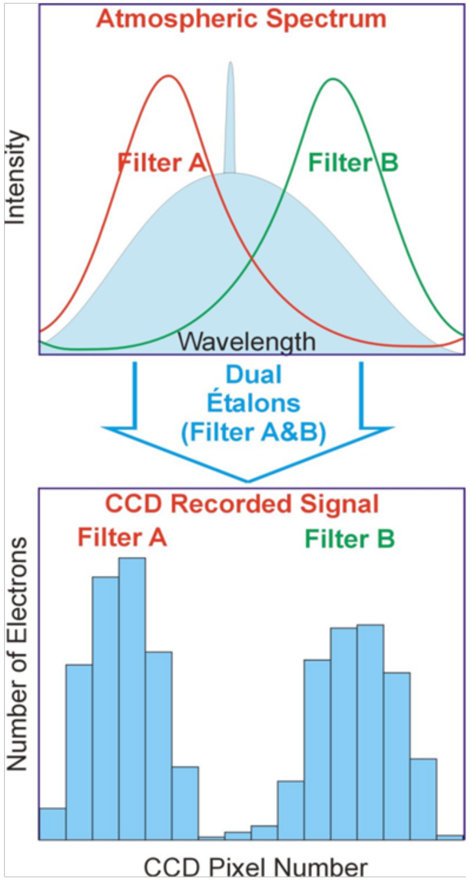
Aladin design



Optical architecture of ALADIN.
PLH: Power Laser Head, RLH: Reference Laser Head, FFM: Flip-Flop Mirror, LCM: Laser Chopper Mechanism, TRO: Transmit/Receive Optics, RSP: Rayleigh Spectrometer, DFU: Detection Front-end Unit, QWP: Quarter-Wave Plate, HWP: Half-Wave Plate, Pol: Polariser, IFF: Interference Filter.

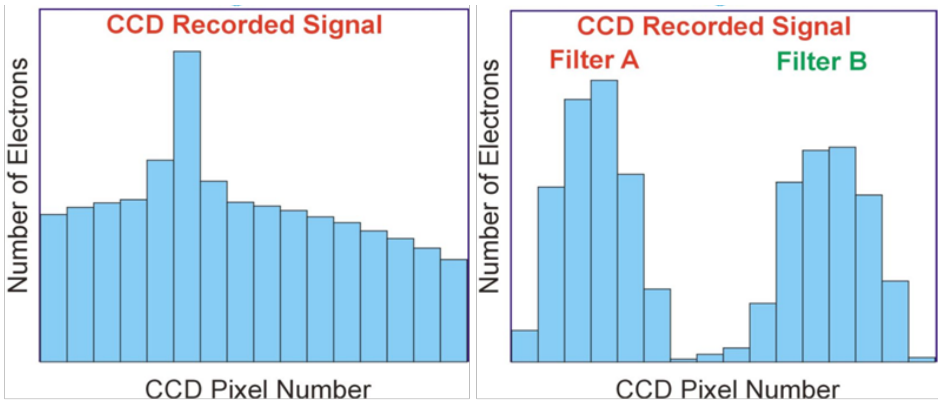


Mie receiver: fringe imaging Fizeau spectrometer



Rayleigh receiver: double edge Fabry-Pérot etalon

Aeolus wind speed determination

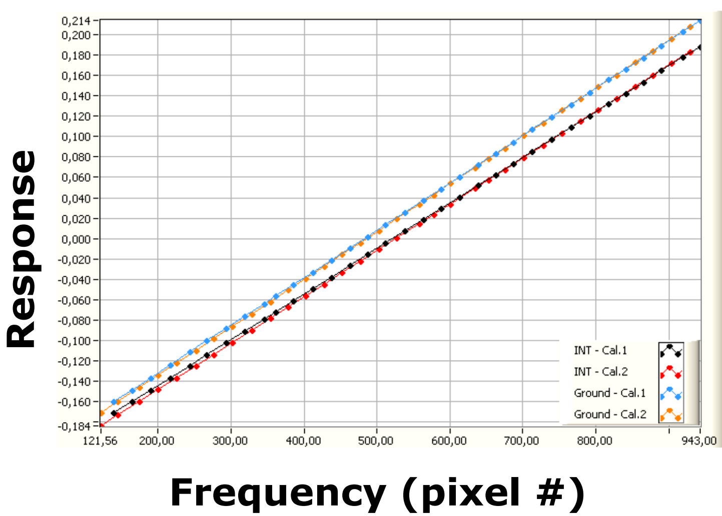


Mie receiver: fringe imaging Fizeau spectrometer

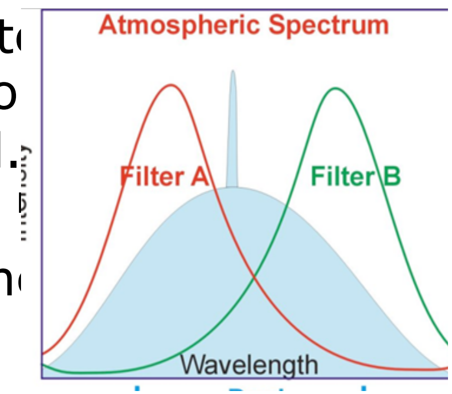
Rayleigh receiver: double edge Fabry-Pérot etalon

$$R = \frac{N_A - N_B}{N_A + N_B} \rightarrow \text{inversion} \rightarrow v_r$$

R: Rayleigh response

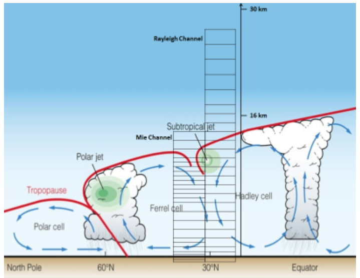


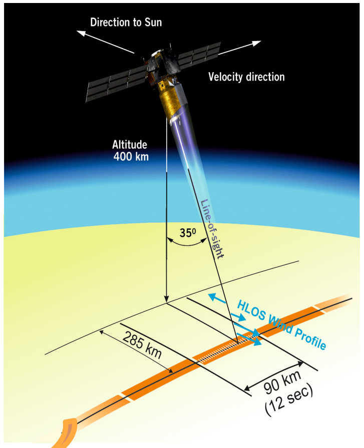
- Important to accurat the instrument respo accurate wind speed.
    - Dedicated calibration
- Use NWP T and p wh Dopplershift
- Challenge to determine wind altitude representativeness within a layer in cases with strong wind shear



Aeolus atmospheric products

1. **Primary (L2b) product:**
   a. Horizontally projected LOS (HLOS) wind profiles
      – Approximately zonal at dawn/dusk (6 am/pm)
      – 3 km-averaged measurements and ~85 km observation averages – scene classified
      – From surface to ~30 km in 24 vertical layers
      – Random errors: 1-2(PBL), 2(Trop), 3-5(Strat) m/s
      – Bias requirements: 0.5 m/s





2. **Spin-off (L2a) products:**
   a. Optical properties profiles
      – β, σ, OD, scattering ratio
      – Cloud/aerosol cover/stratification

in)

5 km observation

Powerful space-borne lidar with separate molecular and particle backscatter detection

Near Real Time delivery of L1b data + L2b processor serves
*** numerical weather prediction (NWP)**
*** potential for aerosol assimilation in forecast and climate models**

Dusk/dawn orbit

Courtesy N. Žagar

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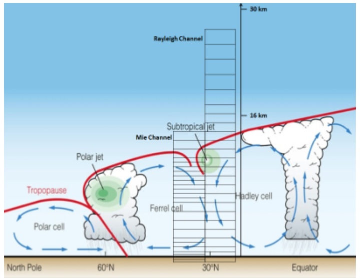

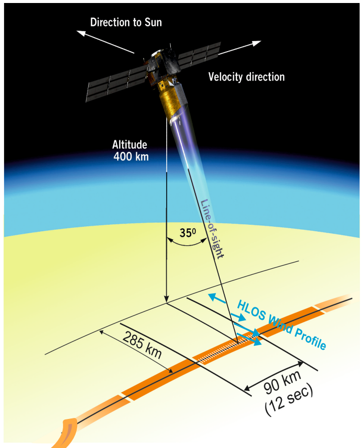

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Courtesy N. Žagar

Dusk/dawn orbit

L2A processor
(P. Flamant, A. Dabas, V. Levert, P. Martinet)

- Aims at reterieving the optical properties of the aerosols detected by the lidar: backscatter coefficient, extinction coefficient, backscatter to extinction ratio

- ALADIN = first lidar in space able to discriminate particle from molecular backscatter

In principle, backscatter and extinction coefficients can be determined independently, there is no need for a priori values of the backscatter to extinction ratio

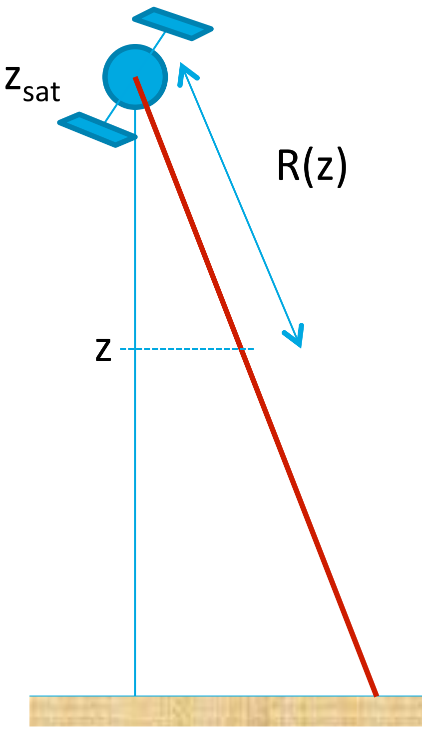
This opens the way to qualitative estimations of the type of aerosols, despite the lack of wavelength-dependent and polarization dependent information

The lidar equation

1. Strength (in Watts) of a lidar signal as a function of the altitude z:

$$S(z) = K\frac{\beta(z)T^2(z)}{R^2(z)} \quad \text{with} \quad T^2(z) = \exp\left(-2\int_z^{z_{sat}} \alpha(x)dR(x)\right)$$

   a. K is a calibration constant.
   b. R(z) is the range from the lidar to the altitude z.
   c. $\beta(z)$ is the backscatter coefficient (in m^{-1}) of the atmosphere. It measures the capacity of the atmosphere to "reflect" the *circularly polarized* laser light.
   d. $T^2(z)$ (no unit, less than 1, decreasing function of range) is the transmission factor (measures photon loss).
   e. α (in m^{-1}) is the extinction coefficient of the atmosphere.



The strength of the signal received by the lidar is a function of two optical, altitude dependant, parameters of the atmosphere, the backscatter $\beta(z)$ and extinction coefficients $\alpha(z)$ of the atmosphere.
Backscatter depend on scene polarization

Aeolus - HSRL

For each observation, ADM provides to signals, one Rayleigh, one Mie, related to the optical parameters of the atmosphere via the equations:

$$S_{Ray}(z) = K_{Ray}\left[C_1\beta_{mol}(z) + C_2\beta_{aer}(z)\right]\frac{T^2_{mol}(z)T^2_{aer}(z)}{R^2(z)}$$

$$S_{Mie}(z) = K_{Mie}\left[C_3\beta_{mol}(z) + C_4\beta_{aer}(z)\right]\frac{T^2_{mol}(z)T^2_{aer}(z)}{R^2(z)}$$

where C_1, C_2, C_3, C_4, K_{ray} and K_{mie} are characterized calibration constants.

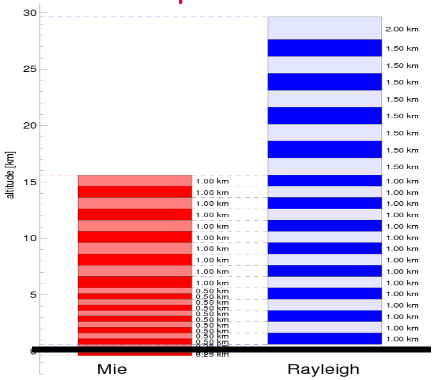
In principle, it is possible to determine $\alpha_{aer}(z)$ and $\beta_{aer}(z)$ from the equations above.

In practise, difficulties are encountered due to:

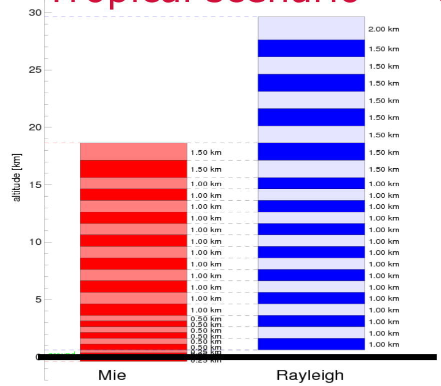
- The lidar cannot distinguish absorption and scattering when detecting extinction
- Large thickness of the height bin (vertical inhomogeneities give ambiguous results when solving the lidar equation)
- Dependence on a priori T and p information
- Only way to discriminate aerosol versus cloud particles: use β/α (non-trivial) or co-located cloud observations (not available at present)

Variation of Aeolus sampling along the orbit

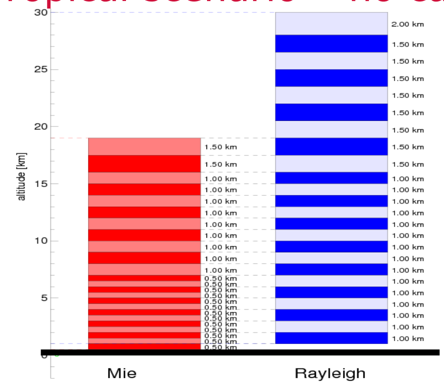
Extra-tropical scenario



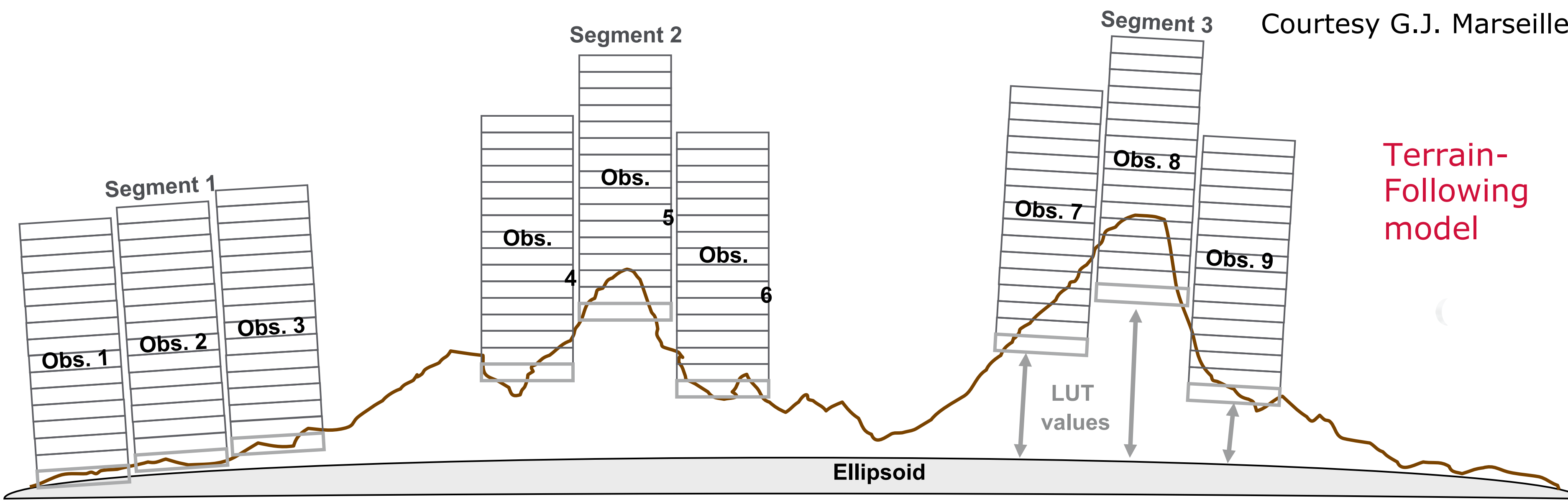
Tropical scenario



Tropical scenario – no calibration



Courtesy G.J. Marseille



Terrain-Following model

Co-location of Mie and Rayleigh channel sampling within an observation is essential

Science related activities in support of the mission

1. ***Phase 0***
   - investigating data impact on NWP and atmospheric modelling
2. ***Phase A***
   - elaborating on system and data processing requirements (performance and end-to-end simulation tools), user requirements (impact studies), ground-based validation campaigns

-> Lead to the scientific and technical mission concept which was evaluated and recommended at the Granada UCM in 1999

3. ***Phase B***
   - OSSE impact experiment, data assimilation, wind and cloud/aerosol statistics, signal processing, random and systematic errors and quality control

-> Leading to the 2001 Mission Requirements Document (MRD) and SRD

4. ***Phase C/D***
   - Wind and spin-off product processing, campaigns, **product optimisation**, **further impact verification following baseline changes**

Mission Baseline changes resulting from hardware qualification

1. Change from Burst Mode (BM) to Continuous Mode (CM) operation in 2010 to ensure the necessary stable laser operation

2. Relaxation of the planned laser output power operati… of the mission from 110 to 80 mJ in 2012

3. ADM-Aeolus MAG:
   a. Is the mis… i.e. will the mission still … modelling and NWP impact?
   … data processing?

4. **Tw… scientific Impact Study activities** were launched to prov…de a consolidated answer using different tools and methods:
   a. KNMI, met.no, MISU/SMHI: Theoretical and Ensemble Data Assimilation impact experiment using simulated observations
   b. ECMWF: Impact of real observations adapted to the ADM-Aeolus sampling / properties in an Observing System Experiment (OSE)

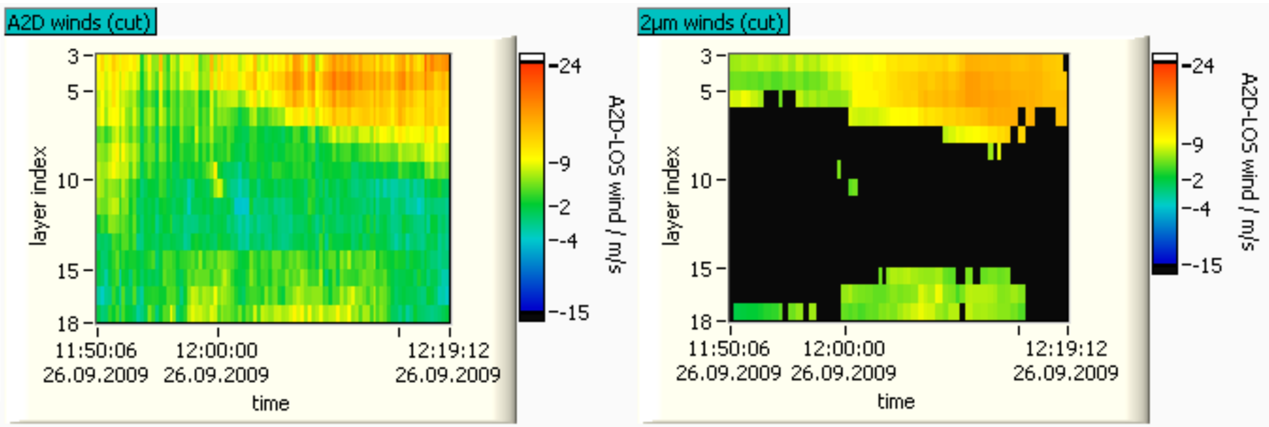
Results will be shown in presentations by M. Rennie and A. Stoffelen

Aeolus campaigns

1. **Objective:**
   a. Validation of the predicted instrument radiometric and wind measurement performance using the Aladin Airborne Demonstrator (A2D)
   b. Establishing a dataset of atmospheric measurements obtained with an Aeolus type Lidar to improve algorithm development

2. **2006 – 2009 A2D Campaigns:**
   a. Two ground-based (2006, 2007) and three airborne (2007, 2008 and 2009)
   b. So far, on the order of 100 recommendations for the Aeolus mission (instrument and algorithm development and testing)
   c. First atmospheric measurements worldwide with a Fizeau and Double Fabry-Perot UV lidar system

Preliminary comparisons of A2D and DLR 2µm wind lidar measurements on-board the Falcon, near Greenland, 2009. Courtesy: U. Marksteiner, DLR



Aeolus CAL/VAL AO delta-call 2014

Aeolus CAL/VAL AO call, 2007:

1. Draft Phase E1 (and E) CAL/VAL plan and requirements established
2. Call open to experts/scientists worldwide
3. 16 (joint) proposals received and reviewed
4. 15 proposals were selected but now uncertain/no longer valid due to launch delays

⇒ **DELTA AO CAL/VAL CALL NEEDED**

Aeolus AO delta-call Objectives:

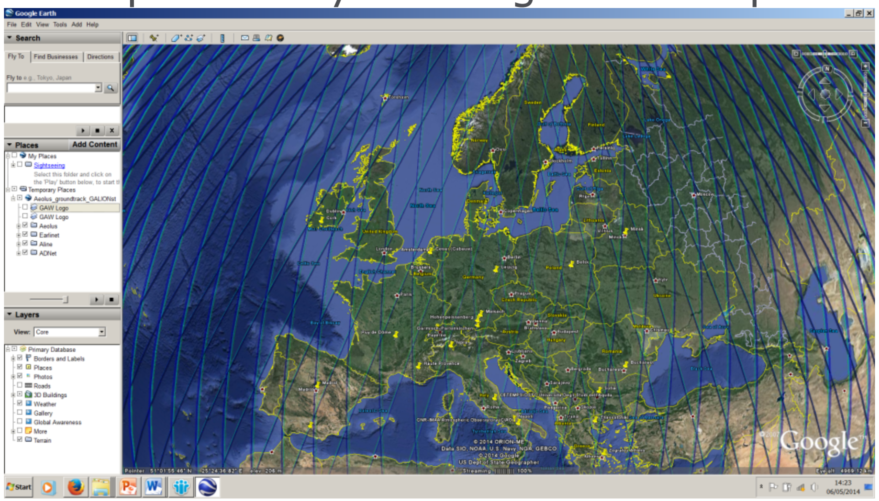
1. Allow for confirmation/update of current proposals
2. Attract new proposals

CAL/VAL Schedule:

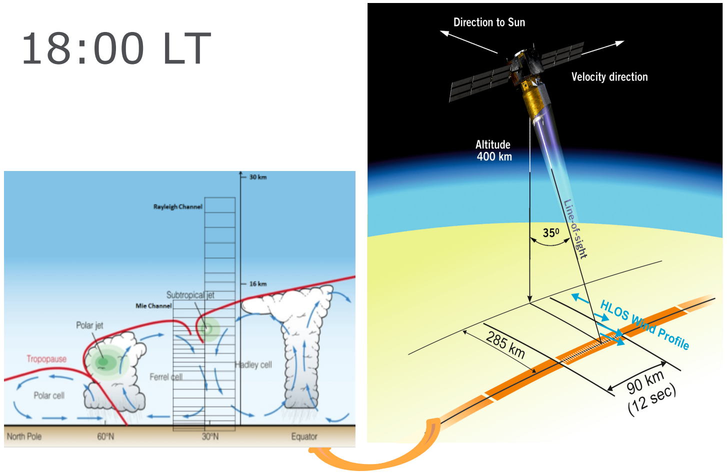
1. Delta-call release: 1 May 2014, **http://earth.esa.int/aos/AeolusCalVal**
2. Phase E1 preparatory CAL/VAL Workshop end 2014 / early 2015:
   a. Refinement of CAL/VAL plan and compile implementation plan
   b. Campaigns planning and coordination amongst AO proposals and external campaigns
3. Launch (End 2015)
4. Phase E1 CAL/VAL Workshop/meeting (date TBC)
5. Phase E CAL/VAL monitoring and Workshops (coordinated by Mission Manager)

Aeolus sampling and CAL/VAL requirements

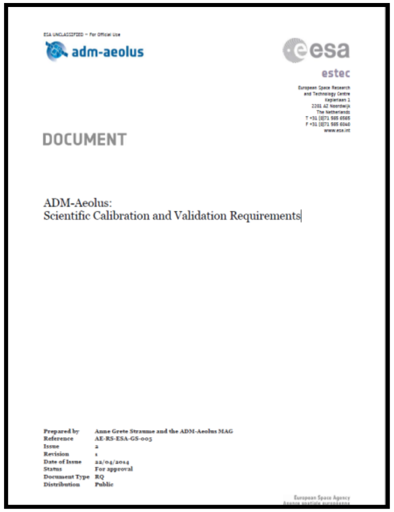
1. Reference orbit: Equat. cros. time ascend node: 18:00 LT
2. Repeat cycle: 7 days
3. Track spacing in 1 week: ~300 km at mid lat
4. Example weekly coverage - one repeat cycle:



T. Kanitz



5. **ADM-Aeolus: Scientific Cal. and Val. Requirements**
   a. Detail Aeolus specifics concerning its wind and aerosol products and areas for special CAL/VAL attention:
   b. Available at **http://earth.esa.int/aos/AeolusCalVal**



adm-aeolus

esa

estec

DOCUMENT

ADM-Aeolus:
Scientific Calibration and Validation Requirements

Why support our "BYO" CAL/VAL?

1. Early access to data (commissioning phase, first 3 months)

2. Access to data quality information, facilitating a good understanding of product quality and product use

3. Forum of exchange in learning how to work with the data from processing to visualization

4. Access to CAL/VAL data and results from other validation groups from ground-based to airborne and model assimilation experiments

5. Access to national funding sources and early preparation of your centre to assimilate Aeolus data

Aeolus Project status

1. The platform was completed in 2009, has been regularly health checked and delta-tested, and is being prepared for satellite integration early 2015
   - In-situ Cleaning System is being implemented
   - Satellite tests with VEGA to determine shock levels showed compliance
   - Satellite characterization w.r.t. microvibrations by the reaction wheels: very low disturbance accelerations were measured at the laser position thanks to wheel dampers;
2. The transmitter laser is the most challenging for the qualification
   - The 1st flight laser transmitter operated for 5 weeks (August->September 2013) in vacuum: 150Mshots at 100-110 mJ output energy with ~7MHz frequency stability!
   - Transmitter successfully passed full environmental qualification in autumn 2013
   - Transmitter delivered to Airbus Defence & Space (Toulouse) for Aladin instrument integration and performance tests
   - 2nd and 3rd flight laser transmitters undergoing acceptance testing
3. Aladin instrument delivery early 2015
4. Flight Acceptance Review: November 2015

Conclusions

1. The Aeolus wind lidar mission will deliver wind (suitable for data assimilation) and atmospheric optical properties products (could become suitable for NWP assimilation after R&D)
2. Aeolus L1b wind profiles (not corrected for temperature and pressure effects and no scene classification) will be delivered NRT together with a stand-alone processor
3. Impact studies has shown that recent measurement baseline updates will still allow for significant mission impact
4. CAL/VAL AO delta-call release: 1 May 2014, deadline 15 July
5. The Aeolus off-line L2a optical properties products will be made available to users off-line (now every 12 hours) but could in the future become available every 4 hours or more often
6. Aeolus laser qualification has recently been successfully completed, instrument integration and testing has started
7. Launch: End 2015

An artist's view of Aeolus in-flight

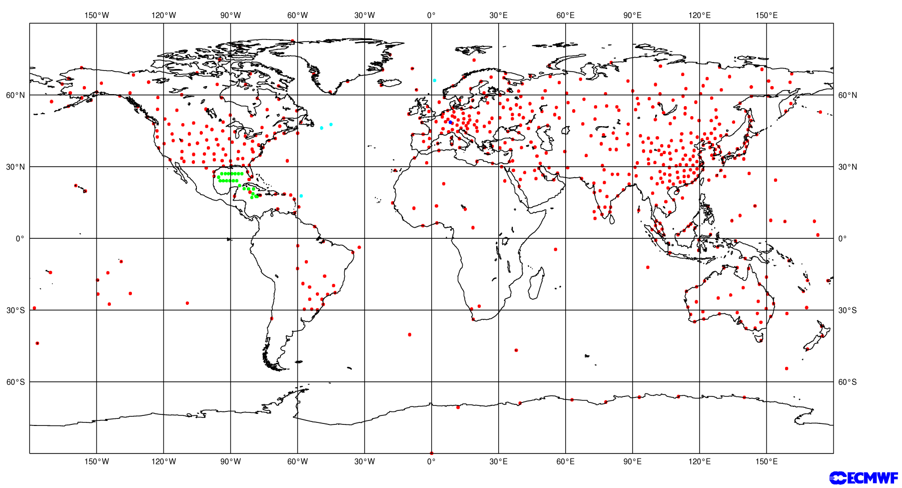
http://www.esa.int/esaLP/LPadmaeolus.html

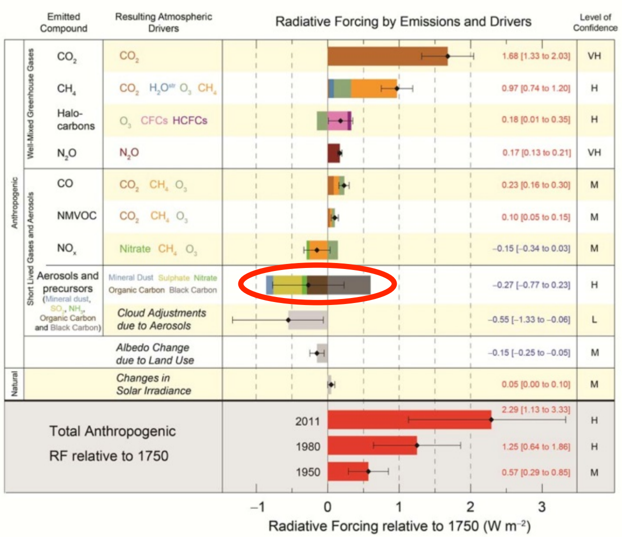
Spare slides

Areas of concern to weather forecasting and climate modelling

1. Lack of homogeneous global coverage of direct wind profile measurements in the current Global Observing System (GOS)
2. Large uncertainties in the estimated contribution of aerosols and clouds to the global radiative forcing

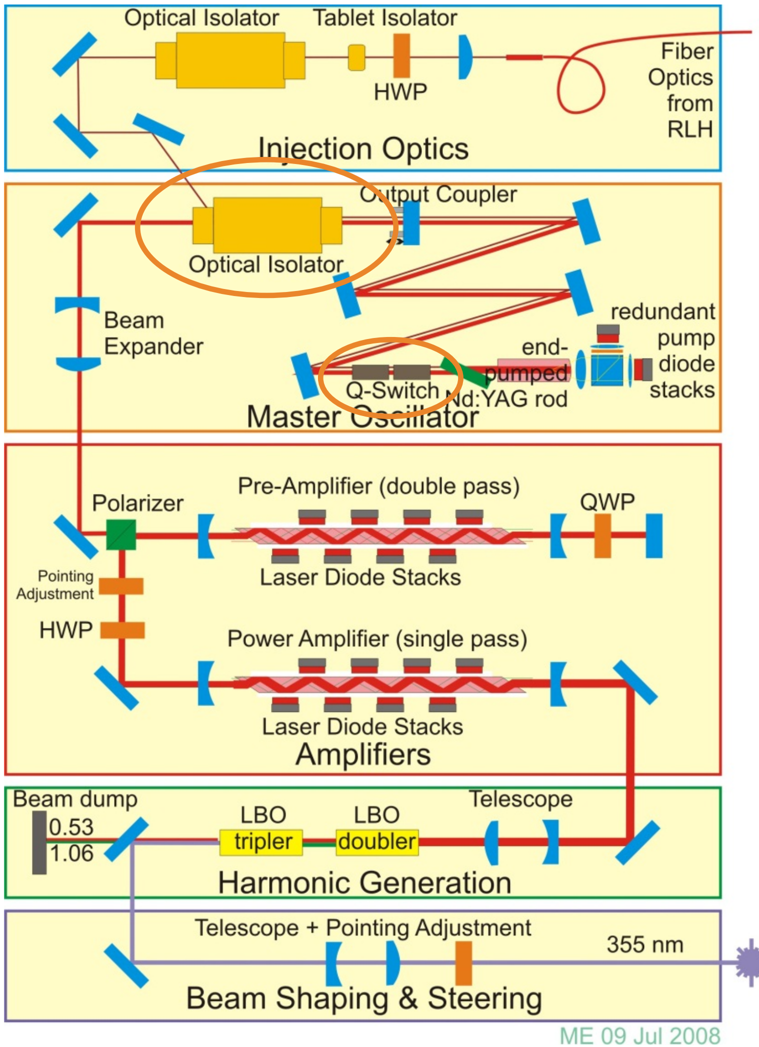
Radiosonde network





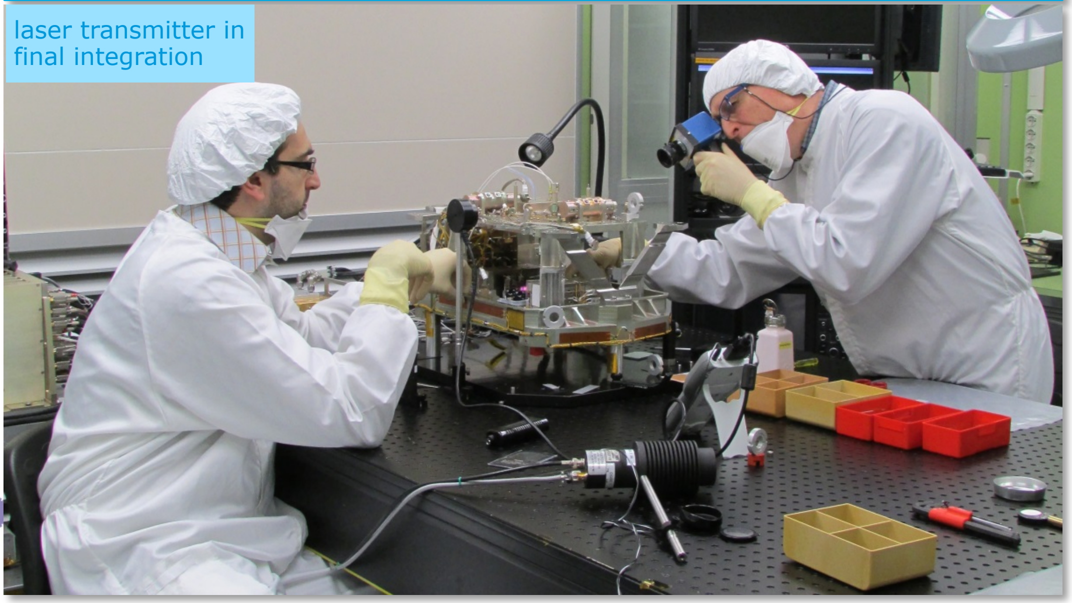
Aeolus mainly addresses the first and provides spin-off products in support of the latter

Aeolus: ALADIN Laser Transmitter



- The Master Oscillator is a stable resonator with an end-pumped rod. A crystal q-switch is used. Pulses of about 5 mJ energy at 1.06 um are generated.
- Two diode pumped slab amplifiers generate about 350 mJ at 50 Hz pulse repetition frequency.
- These IR pulses are frequency tripled to the UV (355 nm) in two harmonic generator crystals with ~35% efficiency.
- UV optics to shape and steer the output beam for compatibility with ALADIN transmit optics.

laser transmitter in final integration



AUX_CAL

- Calibration coefficients defined by

$$S_{Ray}(z)=K_{Ray}\left[C_1\,\beta_{mol}(z)+C_2\,\beta_{part}(z)\right]T_{mol}^2(z)\,T_{part}^2(z)/R^2(z)$$

$$S_{Mie}(z)=K_{Mie}\left[C_4\,\beta_{mol}(z)+C_3\,\beta_{part}(z)\right]T_{mol}^2(z)\,T_{part}^2(z)/R^2(z)$$

where

- K_{Ray}, K_{Mie}, C_1, C_2, C_3 and C_4 are calibration constants,
- β_{mol} and β_{part} are the molecular and particle backscatter,
- $R(z)$ is the range from the satellite to the point at altitude z on the line-of-sight,
- T_{mol} and T_{part} the molecular and particle transmission factors

$$T_{mol,part}(z)=\exp\left(-\int_{z}^{z_{sat}}\alpha(z)\,dR(z)\right)$$

N.B.: $S_{Ray}(z)$ is the sum of the number of photons counted in channels A and B of the Rayleigh reciever (« useful » signals).

AUX_CAL

- If the calibration constant are known, the molecular and particle contributions to the signals can be separated:

$$\underbrace{\frac{C_1}{C_1 C_3 - C_2 C_4} \frac{R^2(z) S_{Mie}(z)}{K_{Mie}} - \frac{C_4}{C_1 C_3 - C_2 C_4} \frac{R^2(z) S_{Ray}(z)}{K_{Ray}}}_{=X_{part}(z)} = \beta_{part}(z) T_{mol}^2(z) T_{part}^2(z)$$

$$\underbrace{-\frac{C_2}{C_1 C_3 - C_2 C_4} \frac{R^2(z) S_{Mie}(z)}{K_{Mie}} + \frac{C_2}{C_1 C_3 - C_2 C_4} \frac{R^2(z) S_{Ray}(z)}{K_{Ray}}}_{=X_{mol}(z)} = \beta_{mol}(z) T_{mol}^2(z) T_{part}^2(z)$$

- From which it follows that

$$\beta_{part}(z)/\beta_{mol}(z) = X_{part}(z)/X_{mol}(z)$$

(Basis of the L2A processor)

AUX_CAL

- Coefficients C_1 to C_4 are computed from $T_A^{CSR}(f)$, $T_B^{CSR}(f)$ and $T_{FIZ}(f)$ (transmission of the Fiseau determined from an ISR)

$$C_1(\nu,P,T) \propto \int I_{RB}(f-\nu,P,T)\left(T_A^{CSR}(f)+T_B^{CSR}(f)\right)df$$

$$C_4(\nu,P,T) \propto \int I_{RB}(f-\nu,P,T)\,T_{Fiz}(f)\,df$$

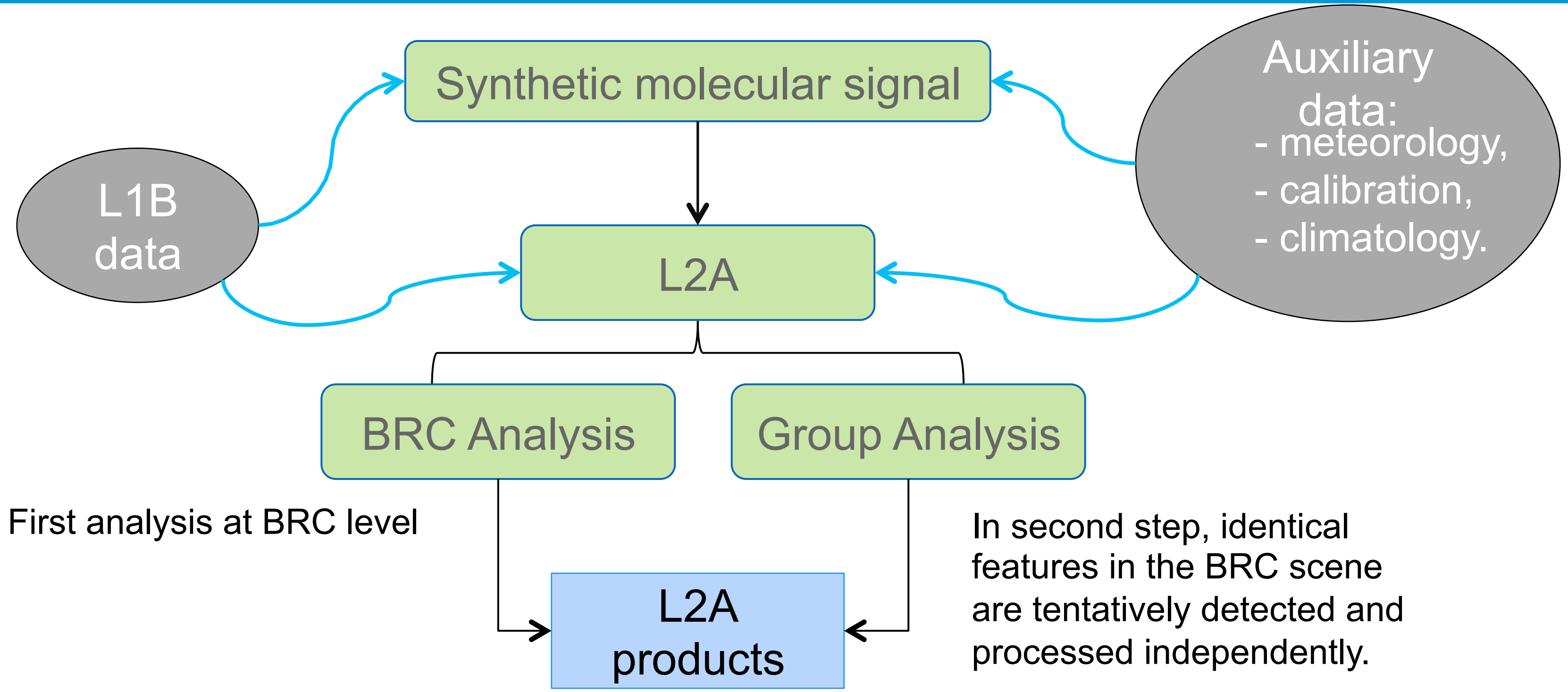
$$C_2(\nu) \propto T_A^{CSR}(\nu)+T_B^{CSR}(\nu) \qquad C_3(\nu) \propto T_{Fiz}(\nu)$$

- And K_{Ray} and K_{Mie} are estimated in a way similar to the generation of the AUX_CSR: useful signals of an IRC are predicted and compared to the real ones, and K_{Ray} and K_{Mie} are determined so that both match.

Scientific Cal/Val Requirements

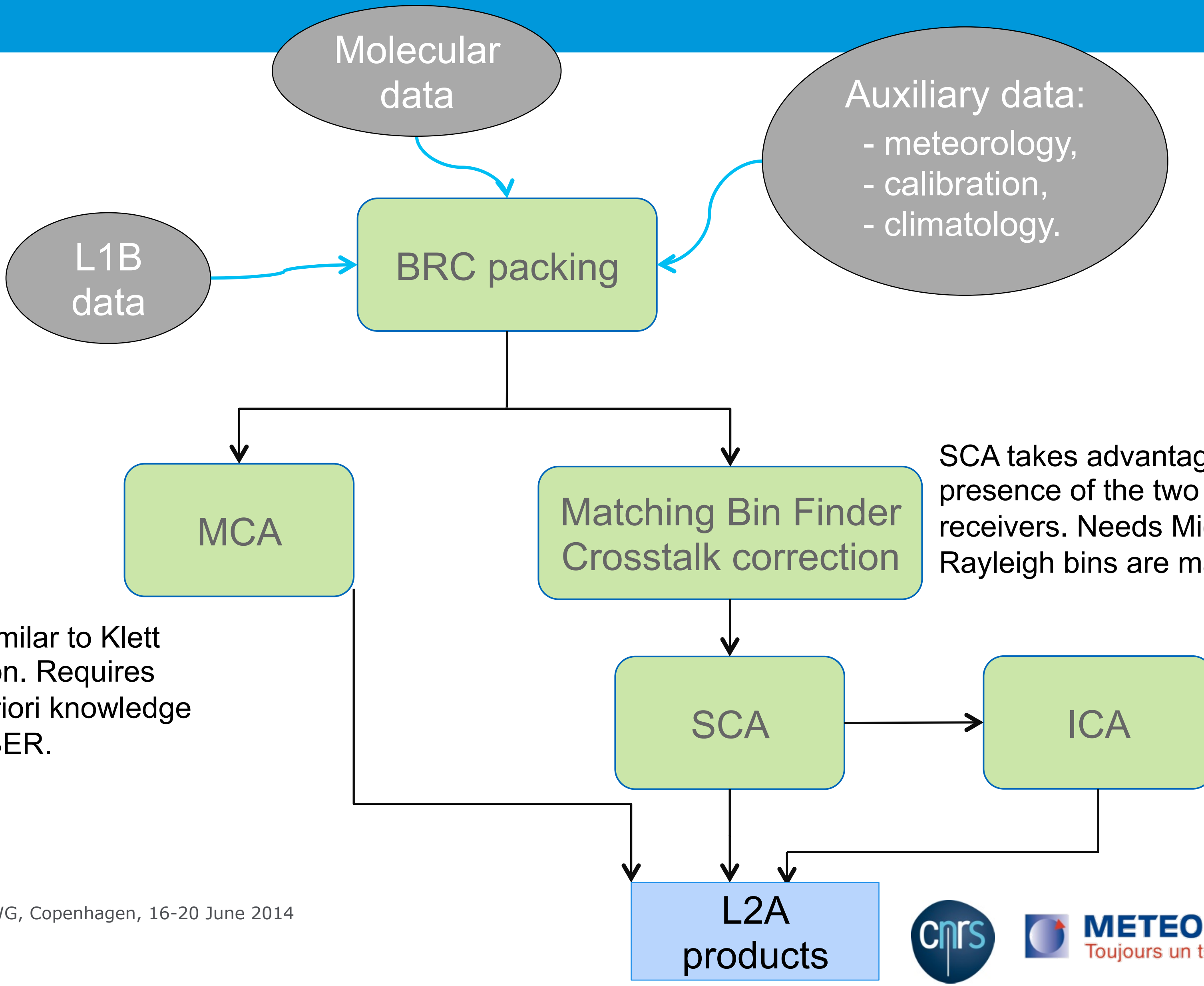
1. Understanding of the products and product properties
2. Consult product requirements (Mission Requirements Document)
3. Areas of special attention:
   a. Atmospheric sampling by the space-borne and validation instrumentation
      - Horizontal (scene dependent)
      - Vertical (scene and commanding dependent)
      - Variable along the orbit
   b. Space-borne and validation product quality as function of
      - measurement and retrieval technique
      - atmospheric scene (clear and cloudy products, use of apriori)
   c. Complimentarity of different validation techniques
      - Validation over different spatial and temporal scales
      - Different information content
   d. Co-location criteria
   e. …

L2A: Overarching view



Synthetic molecular signals = prediction of the Mie and Rayleigh signals the lidar should detect is there were no aerosols in the atmosphere (pure molecular signals). The signature of the aerosols is determined by comparing the signals actually detected by the lidar to these synthetic signals.

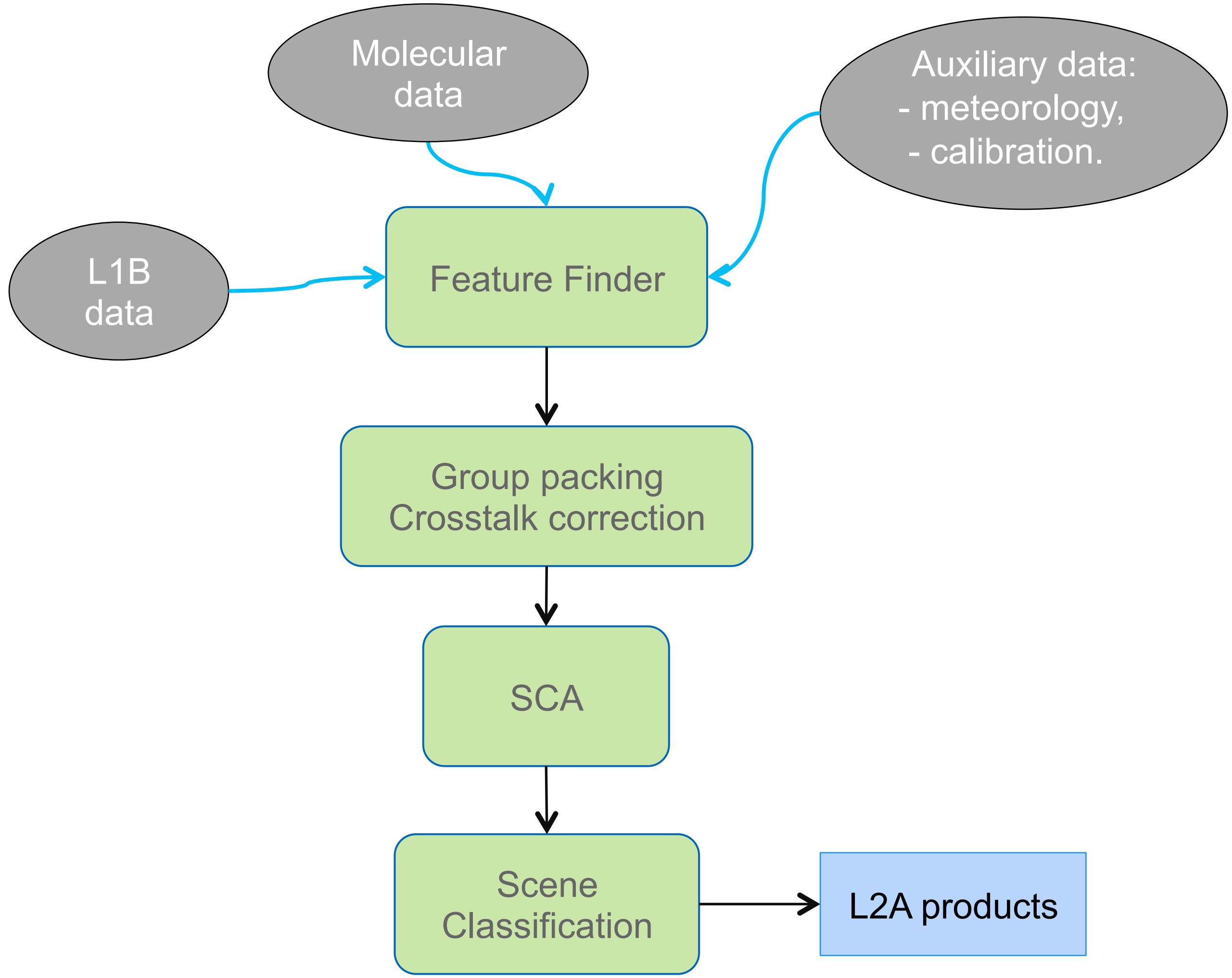
L2A: Observation analysis



SCA takes advantage of the presence of the two receivers. Needs Mie and Rayleigh bins are matching.

MCA similar to Klett inversion. Requires the a priori knowledge of the BER.

L2A: Group analysis



Feature Finder's rationale

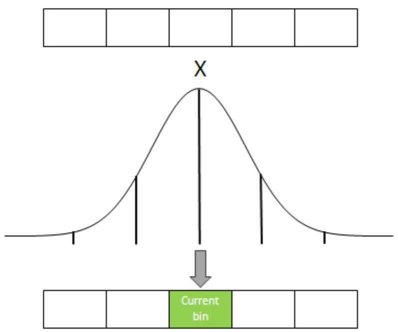
Based on the **particle backscatter coefficient of the group**

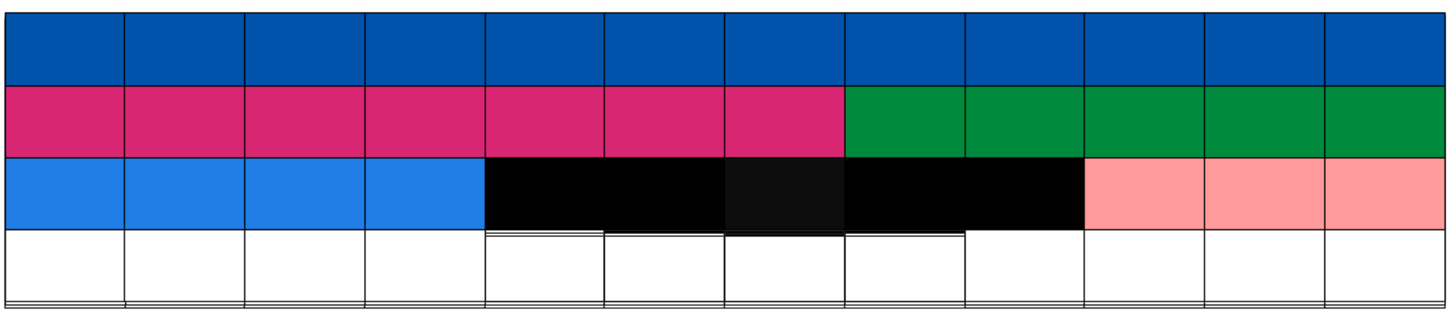
1. Horizontal Gaussian filter

2. Peak detection: group seeds

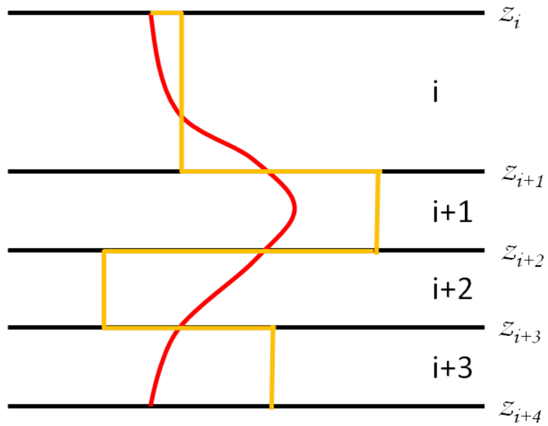
3. Parallel sprouting: aggregation of neighbour bins
   ⇨ Criteria based on the group's $\sigma_{\beta_p}(\mu_{\beta_p})$

4. Eviction of dubious groups (high relative error on β_p)





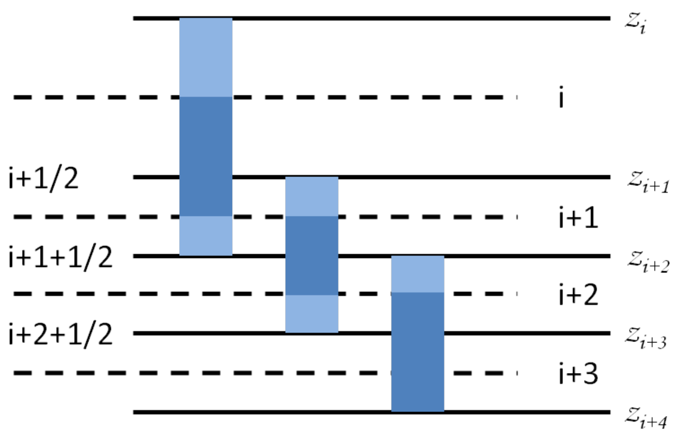
SCA on groups



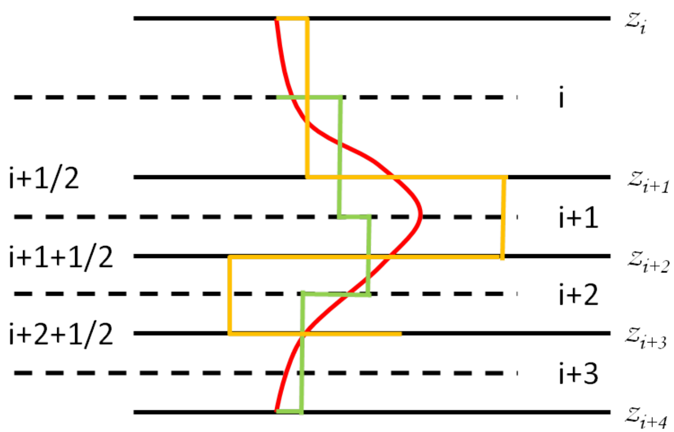
2-bin periodic oscillations on α_p

Need for averaging

Averaging with neighbours:



Creation of intermediate bins



1-bin-wide resolution kept in the sphere of influence of the averages

Scene classification

Cloud-aerosol discrimination for each group, including averages centred on its upper and lower boundary:

- A 16-classes flag:
  - -2 BERs : $\approx 0.05\ sr^{-1}$ => Water cloud
  - -1 SR : > 2.5 => Water cloud
  - -NWP's RH : > 94% => Water cloud

- Consolidated by a 12-classes flag:
  - -NWP's CLWC & CIWC : 4 domains (only vapour, liquid, mixed-phase, ice),
  - -NWP's temperature , 2 boundaries 233.15 K and 273.15 K : 3 domains.

L2A Conclusion

- The L2A processor is now complete.
- Fine tuning of settings still necessary, but the possible output products are there.
- Full use of the possibilities offered by the High-Spectral-Resolution of the lidar requires matching Mie and Rayleigh bins (→ constraint on the mission).
- From now on, major refinements will come from real observations.