Vertical profiles of atmospheric aerosol

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II Lectures on Atmospheric Mineral Dust

Barcelona,
6th of November, 2012

Outlook

- Lidar (laser radar) principles
- Types of aerosol lidar
- Aerosol lidar networks
- Space-borne systems
- Access to aerosol lidar data
- Summary

RSLAB

- Question: why remote sensing of aerosols ≈ optical methods? (e.g. sun-photometer, lidar)
- Answer: Strong interaction at optical wavelengths between electromagnetic radiation and suspended particles

RSLAB

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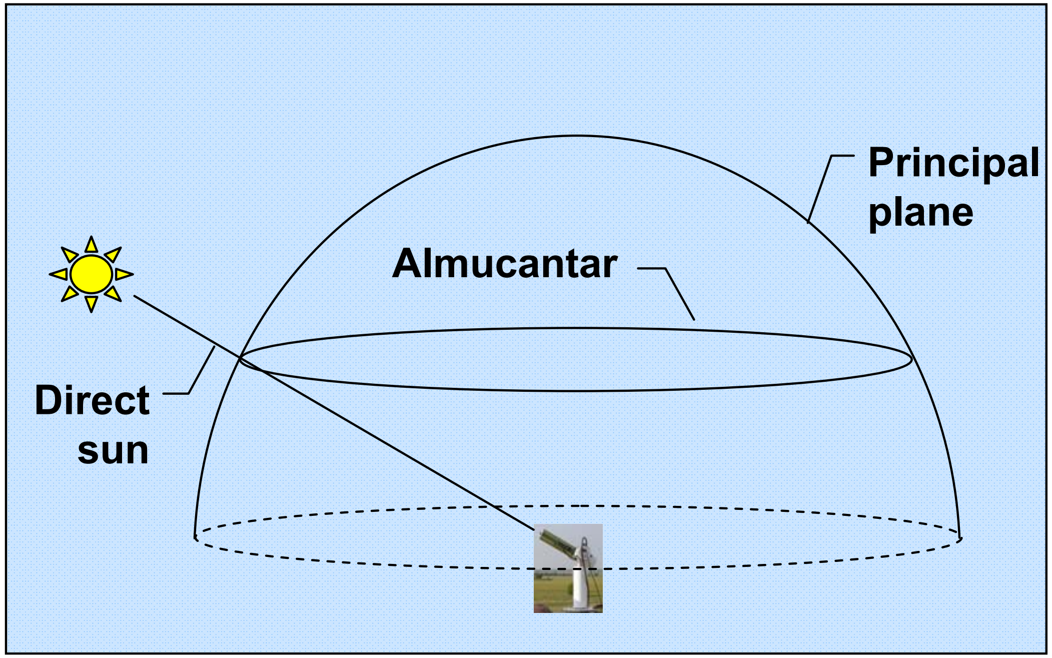
- Ans optical wav nagnetic radi cles

RSLAB

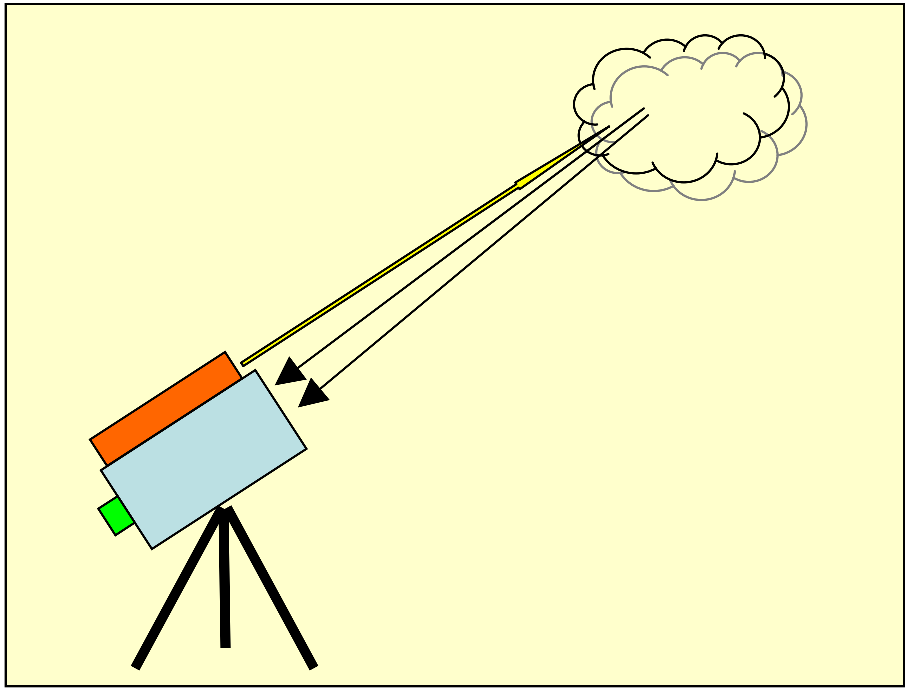
- Question: why remote sensing of aerosols ≈ optical methods? (e.g. sun-photometer, lidar)
- Answer: Strong interaction at optical wavelengths between electromagnetic radiation and suspended particles
- Light scattering by aerosol is used to obtain information on aerosol optical and microphysical properties

Ground-based aerosol remote sensing
Passive (≈ sun photometer) vs Active (≈ →≡ lidar)

Passive



Active



Ground-based aerosol remote sensing
Passive (≈ sun photometer) vs Active (≈ → ≡ lidar)

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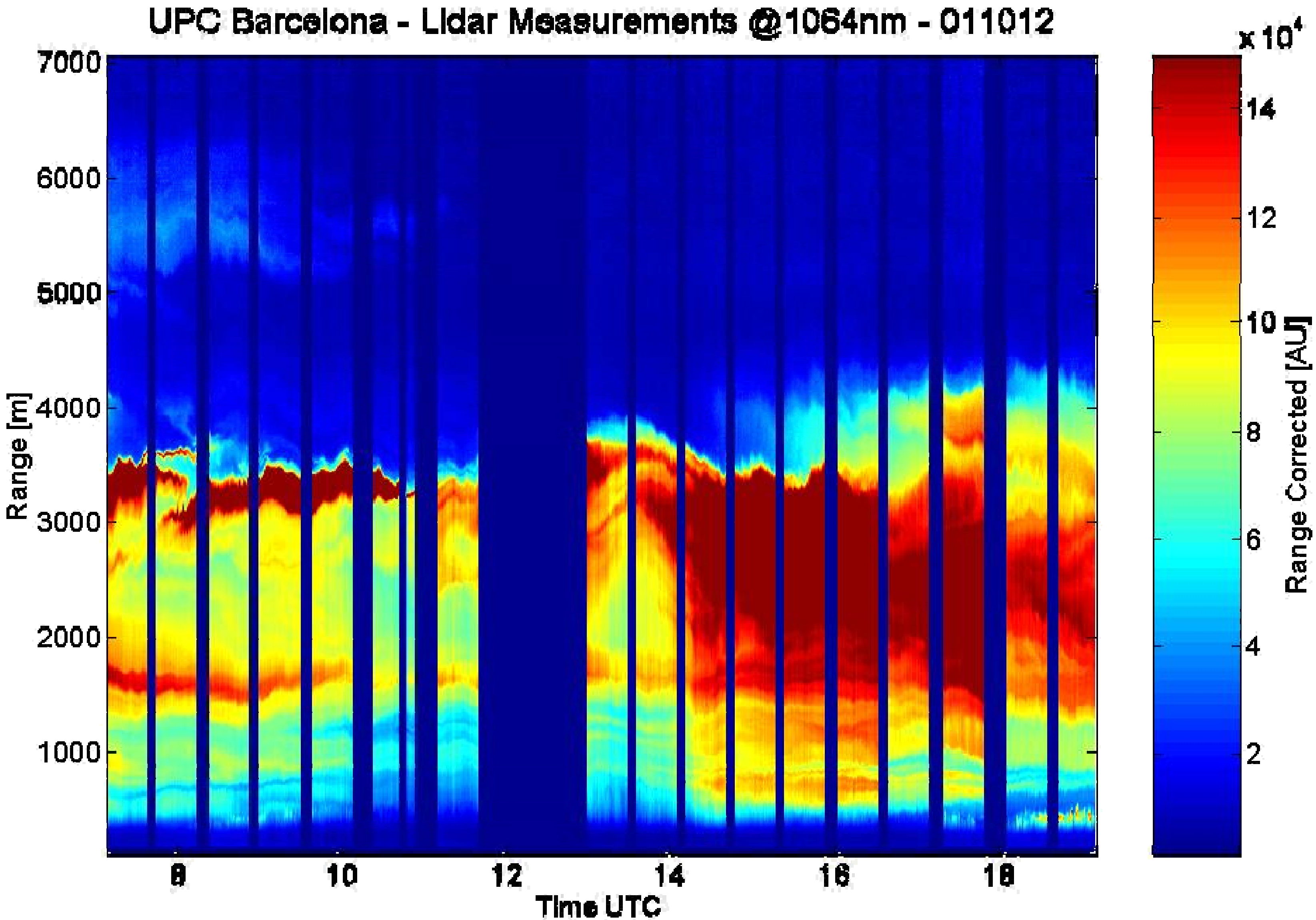
Passive	Active
• Depends on sun (or stars) → cannot operate in night-time (except if it uses star light) nor under cloudy conditions	• Has its own interrogator source (laser) → night- and day-time operation, without and with clouds
• Many wavelengths (solar spectrum bands) → relatively easy to retrieve aersol microphysical properties	• Few wavelengths → difficult retrieval of microphysical properties
• Column-integrated properties	• Range resolution

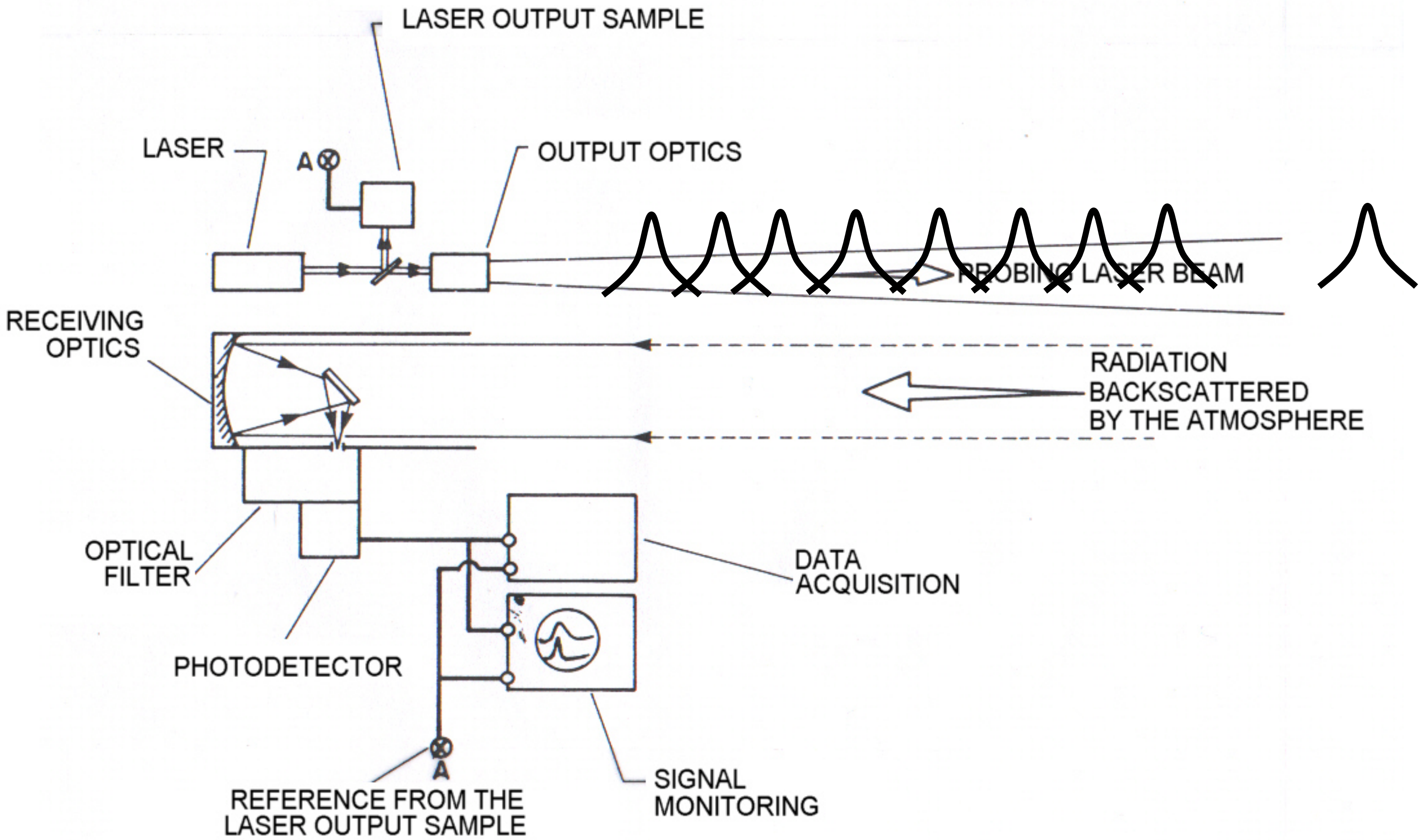
ipal

RSLAB

Range resolution



Basic lidar (laser radar) setup



Adapted from R. M. Measures: "Laser Remote Sensing. Fundamentals and applications". John Wiley & Sons, 1984

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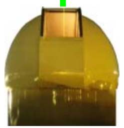
Aerosol lidar

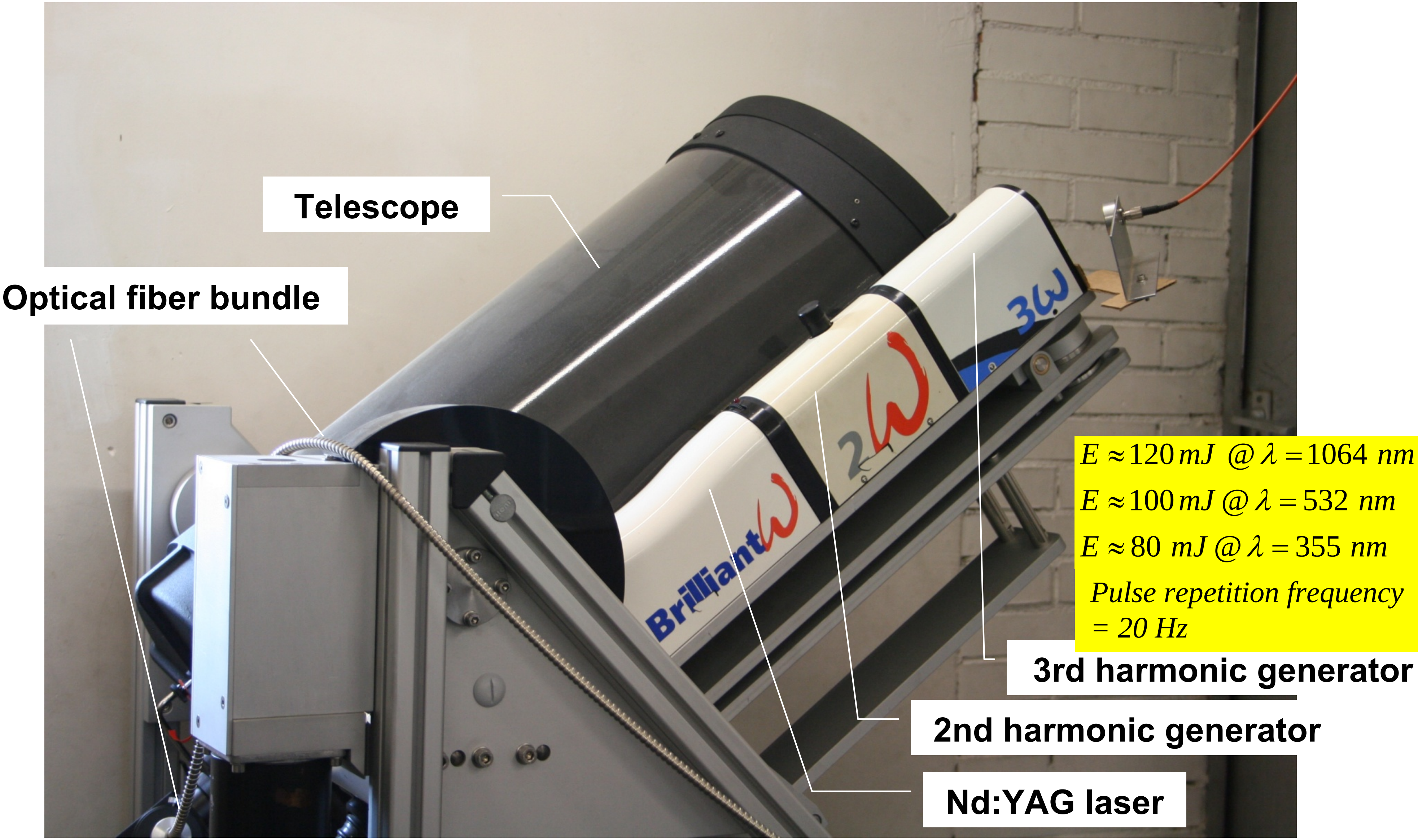
- **Physical principle:**
  - Elastic scattering, both Mie (particles of size in the range of the wavelength→i.e. aerosols) and Rayleigh (particles of size << wavelength → molecules)
  - Raman-shifted scattering by N_2 or O_2 ← advanced systems

- **Primary product:**
  - Range-resolved aerosol optical coefficients (extinction, backscatter)

- **Lasers:**
  - Ruby (λ = 694.3 nm, 347.2 nm)
  - Excimer (λ ~350 nm)
  - <u>Nd:YAG</u> (λ = 1064 nm, 532 nm, 355 nm)



Example of aerosol lidar



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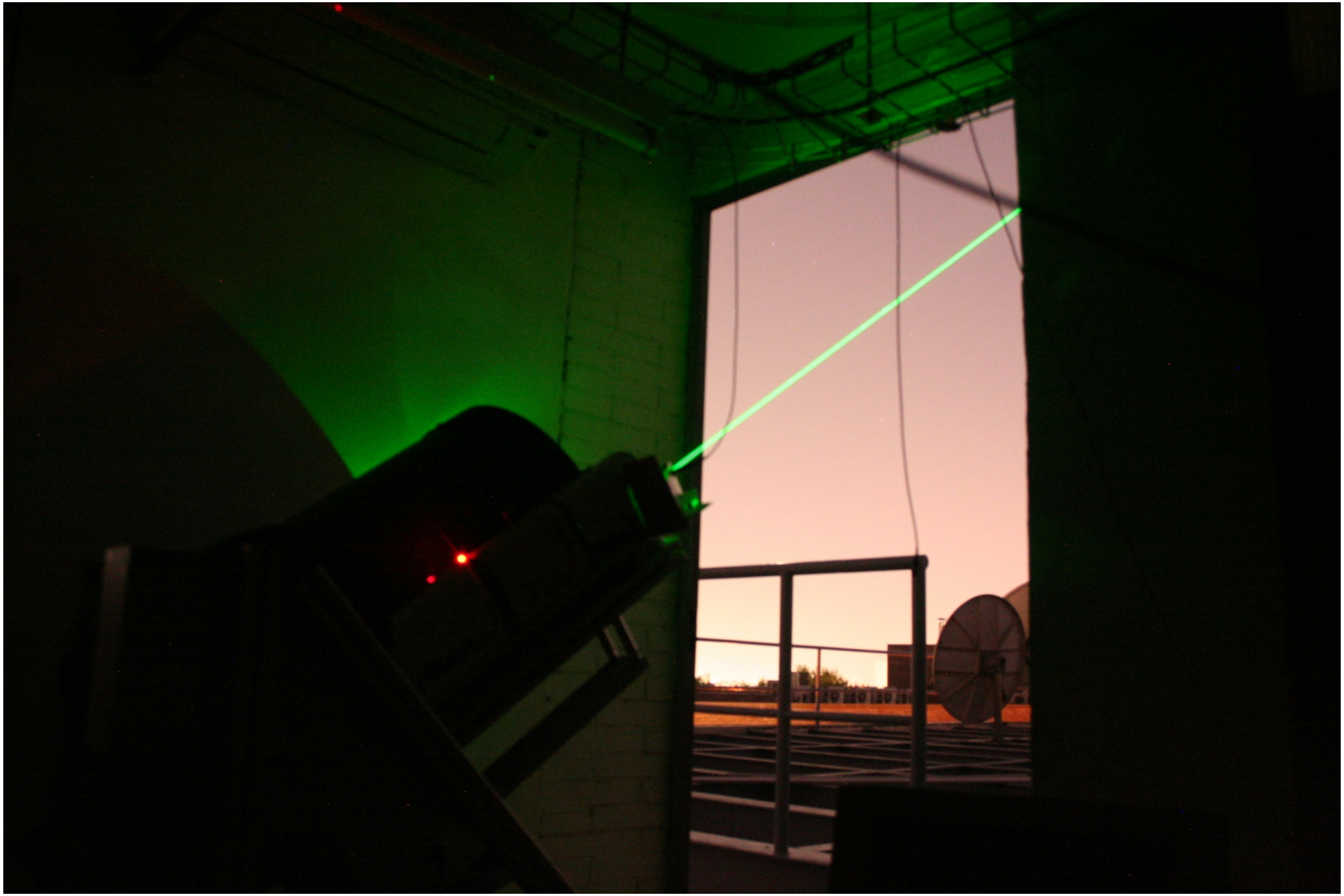
In operation...



In operation a few days ago

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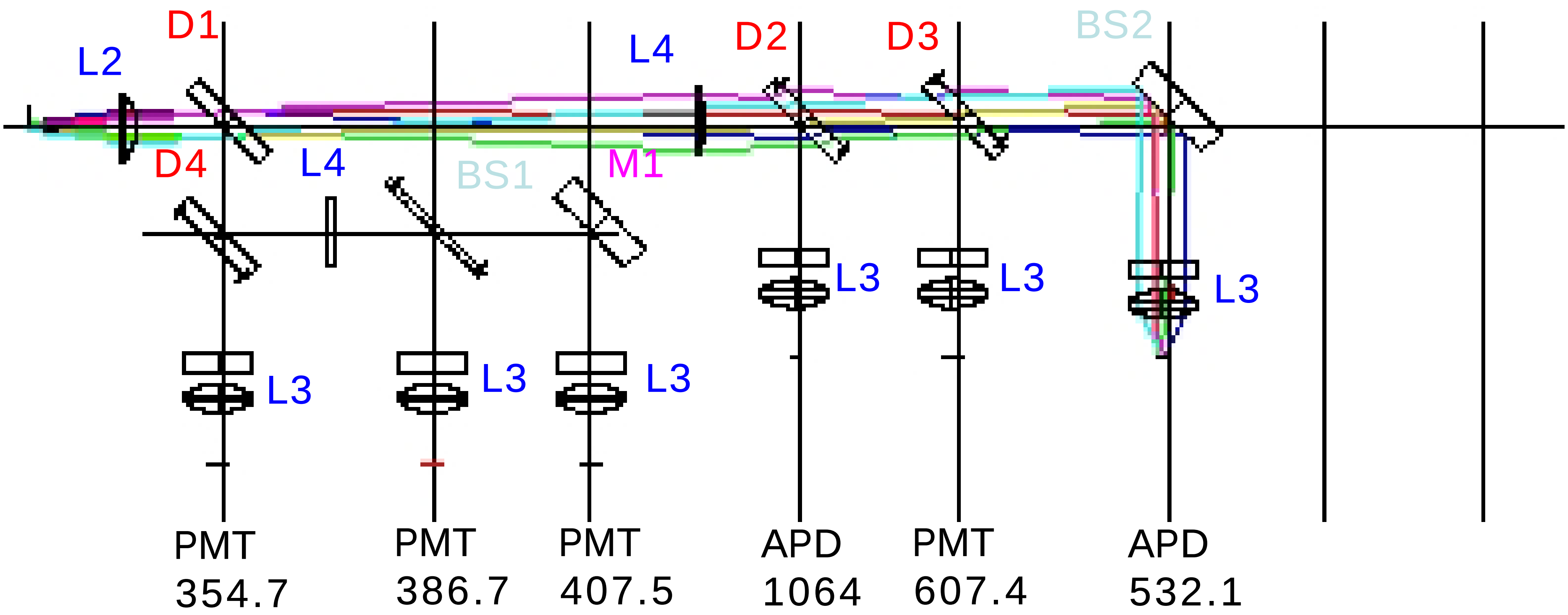
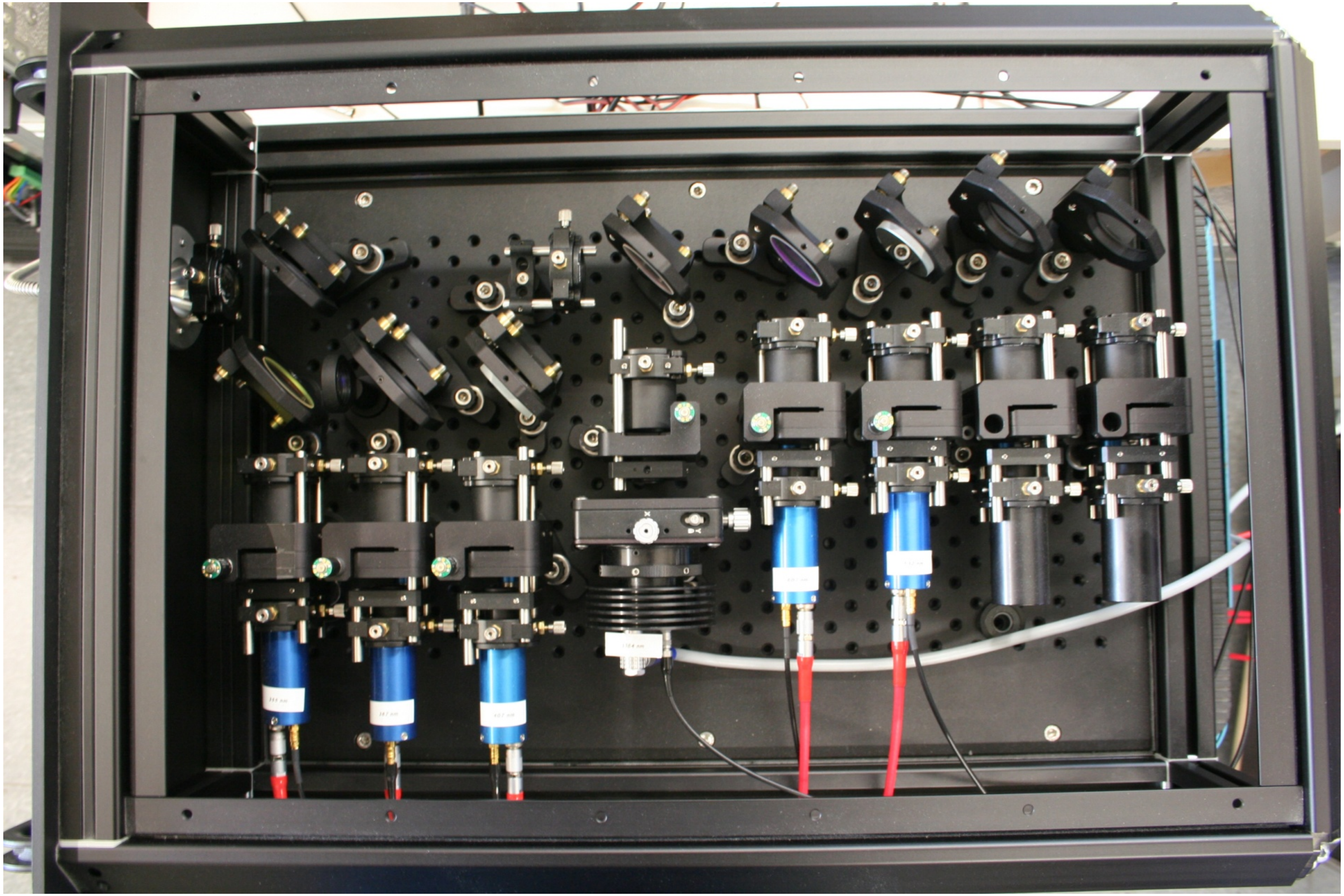
Receiving system...



... materialized



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The complete system...

Lidar equation

$$P(R) = \frac{C\,O(R)}{R^2}\beta(R)\exp\left(-2\int_0^R \alpha(x)\,dx\right)$$

C : Instrument constant

O(R) : overlap factor — takes into account signal suppression at short ranges due to the optical arrangement

R: Range

β(R) : backscatter coefficient

α(R) : extinction coefficient

Range-corrected signal — The lowest-level lidar product: quantitative information about layer height, but not on optical coefficients

$$X(R) = K P(R) R^2 = K C\,O(R)\beta(R)\exp\left(-2\int_0^R \alpha(x)\,dx\right)$$

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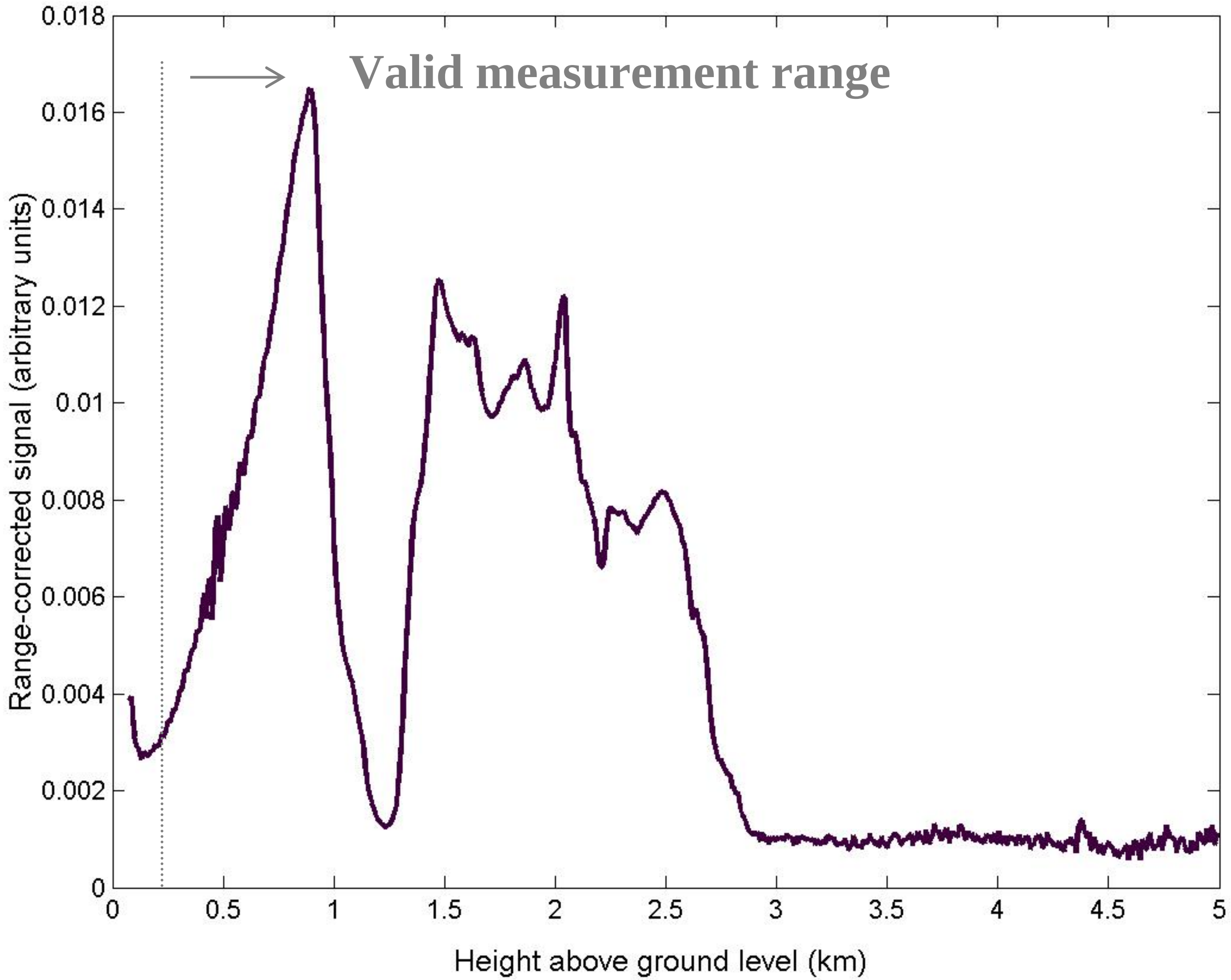
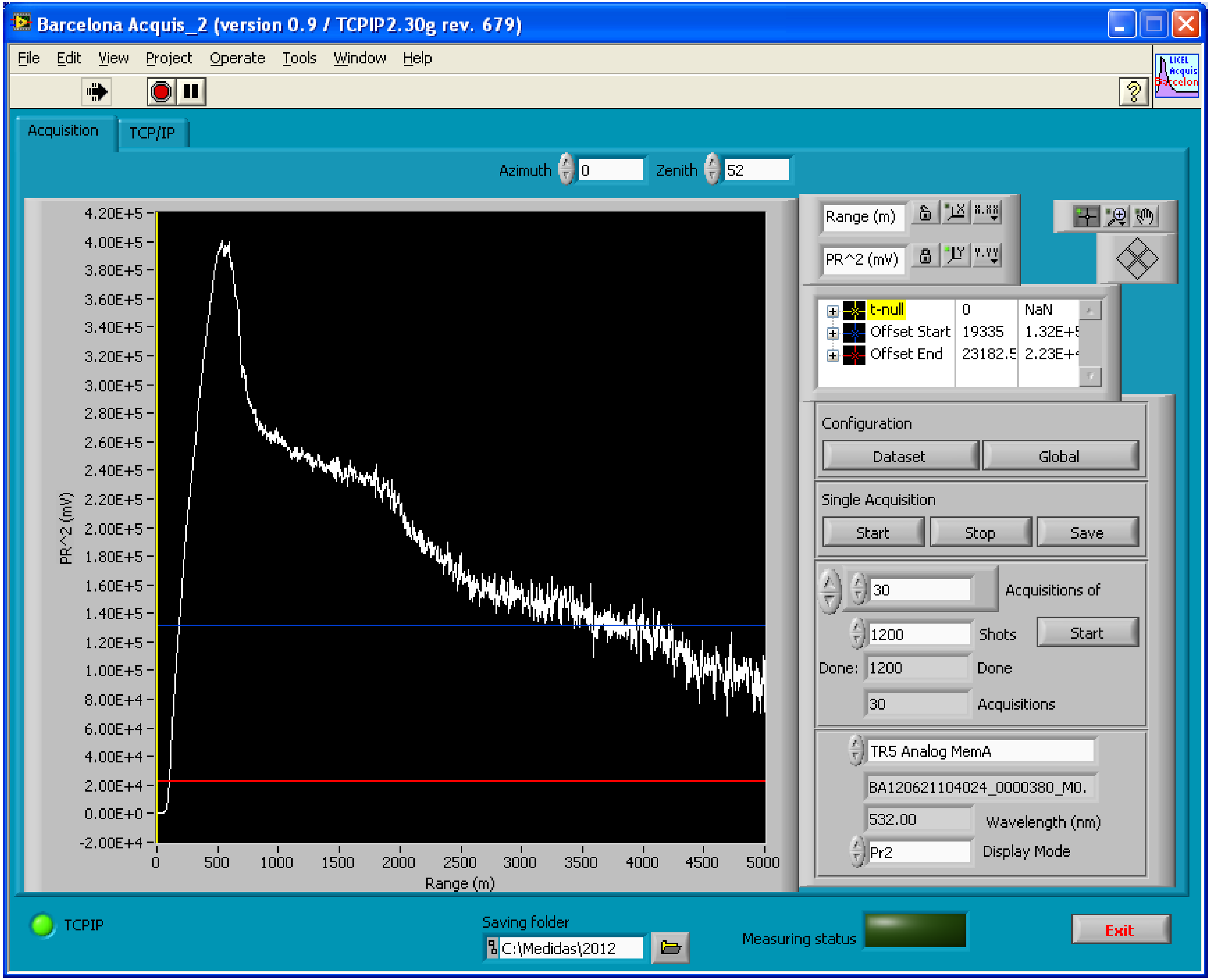
Range-corrected signal




Barcelona Acquis_2 (version 0.9 / TCPIP2.30g rev. 679)
File Edit View Project Operate Tools Window Help
Acquisition
TCP/IP
Azimuth 0
Zenith 52
PR^2 (mV)
Range (m)
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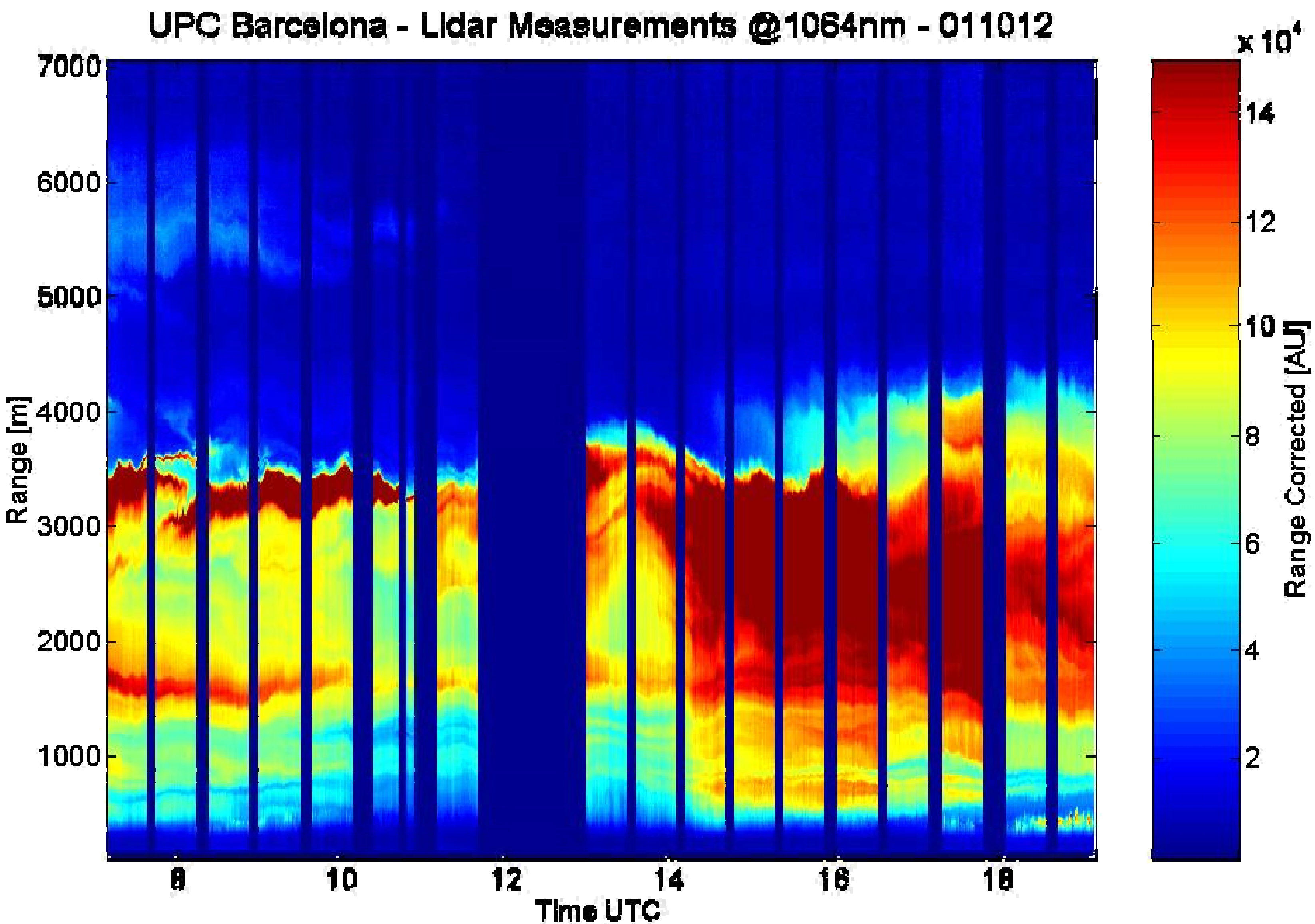
Offset Start 19335
Offset End 23182.5
Configuration
Dataset
Global
Single Acquisition
Start
Stop
Save
30 Acquisitions of
1200 Shots
Start
Done: 1200 Done
30 Acquisitions
TR5 Analog MemA
BA120621104024_0000380_M0.
532.00 Wavelength (nm)
Pr2 Display Mode
TCPIP
Saving folder
C:\Medidas\2012
Measuring status
Exit

Range-corrected signal



Ceilometers: simple lidars initially designed to measure cloud-base range, but also used to measure aerosol returns at short ranges

Retrieval of the optical coefficients

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$\beta(R)=\beta_m(R)+\beta_a(R)$, $\alpha(R)=\alpha_m(R)+\alpha_a(R)$

$\beta_m(R)$: molecular (Rayleigh) backscatter

$\alpha_m(R)$: molecular (Rayleigh) extinction

$\beta_a(R)$: aerosol backscatter

$\alpha_a(R)$: aerosol extinction

Simplest systems (backscatter lidars)

- Only one transmitted wavelength
- Only one received wavelength from elastic backscatter
- To retrieve the optical coefficients an assumption has to be made concerning the relationship between $\alpha_a(R)$ and $\beta_a(R)$:

$$S_a(R) = \alpha_a(R)/\beta_a(R)$$

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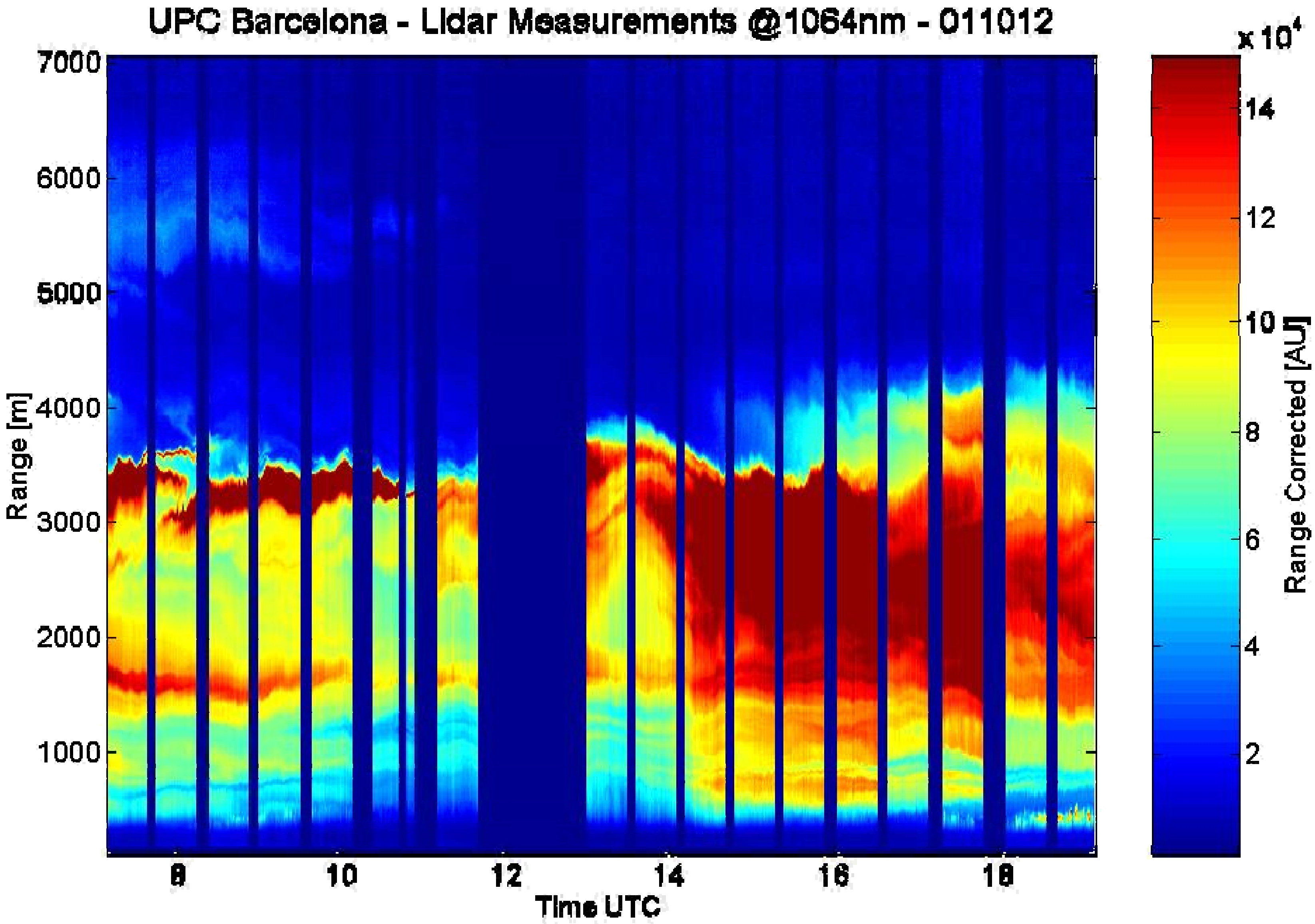
Klett-Fernald retrieval method

$$\beta_a(R)=\frac{\beta(R_m)X(R)\exp\left(-2\int_R^{R_m}\left(\frac{8\pi}{3}-S_a(x)\right)\beta_m(x)dx\right)}{X(R_m)+2\beta(R_m)\int_R^{R_m}S_a(x)X(x)\exp\left(-2\int_x^{R_m}\left(\frac{8\pi}{3}-S_a(x')\right)\beta_m(x')dx'\right)dx}-\beta_m(R)$$

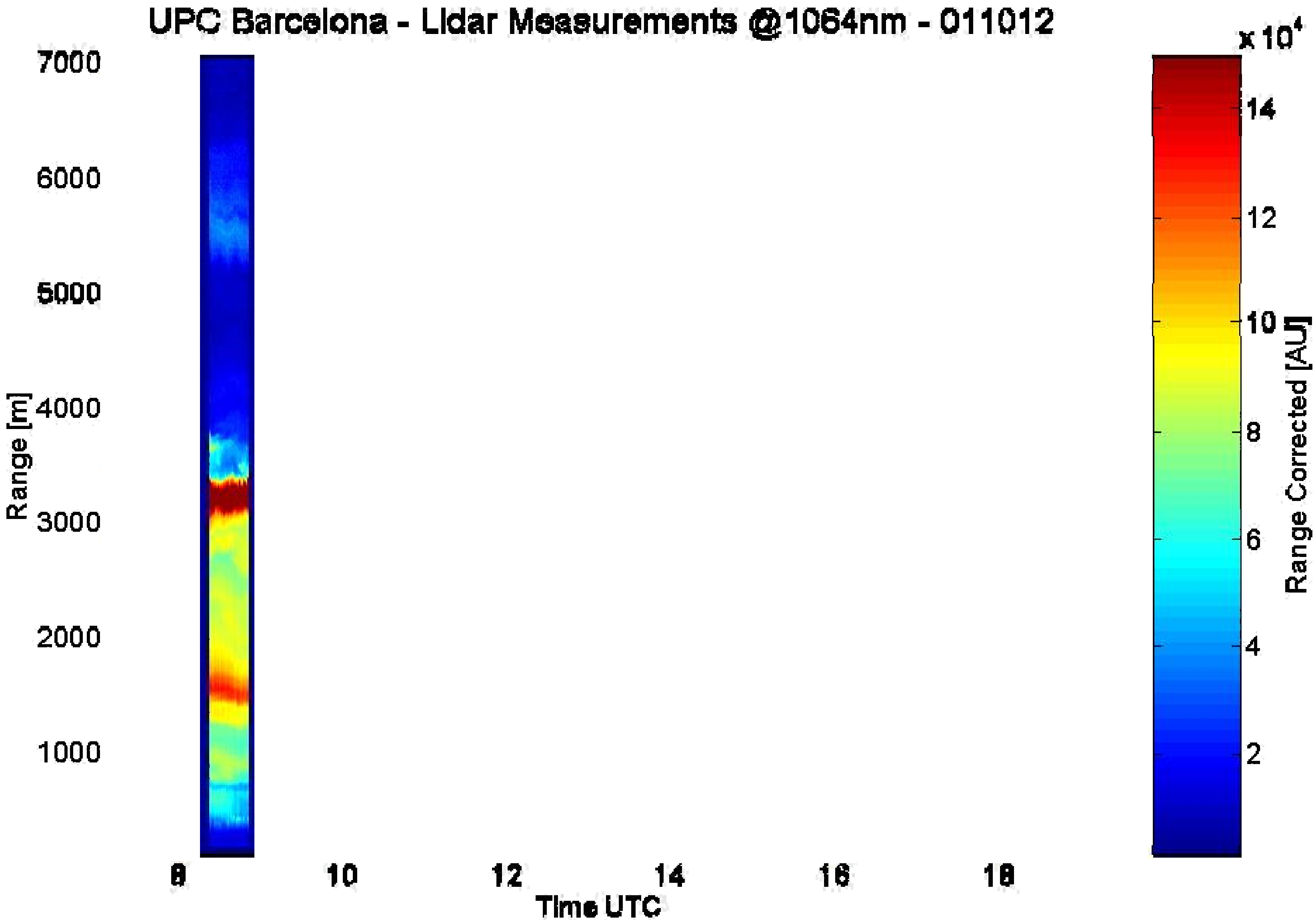
R_m: range at which β is known → usually range high enough to be free of aerosols, for which β is purely molecular (therefore known)

$$\alpha_a(R)=S_a(R)\beta_a(R)$$

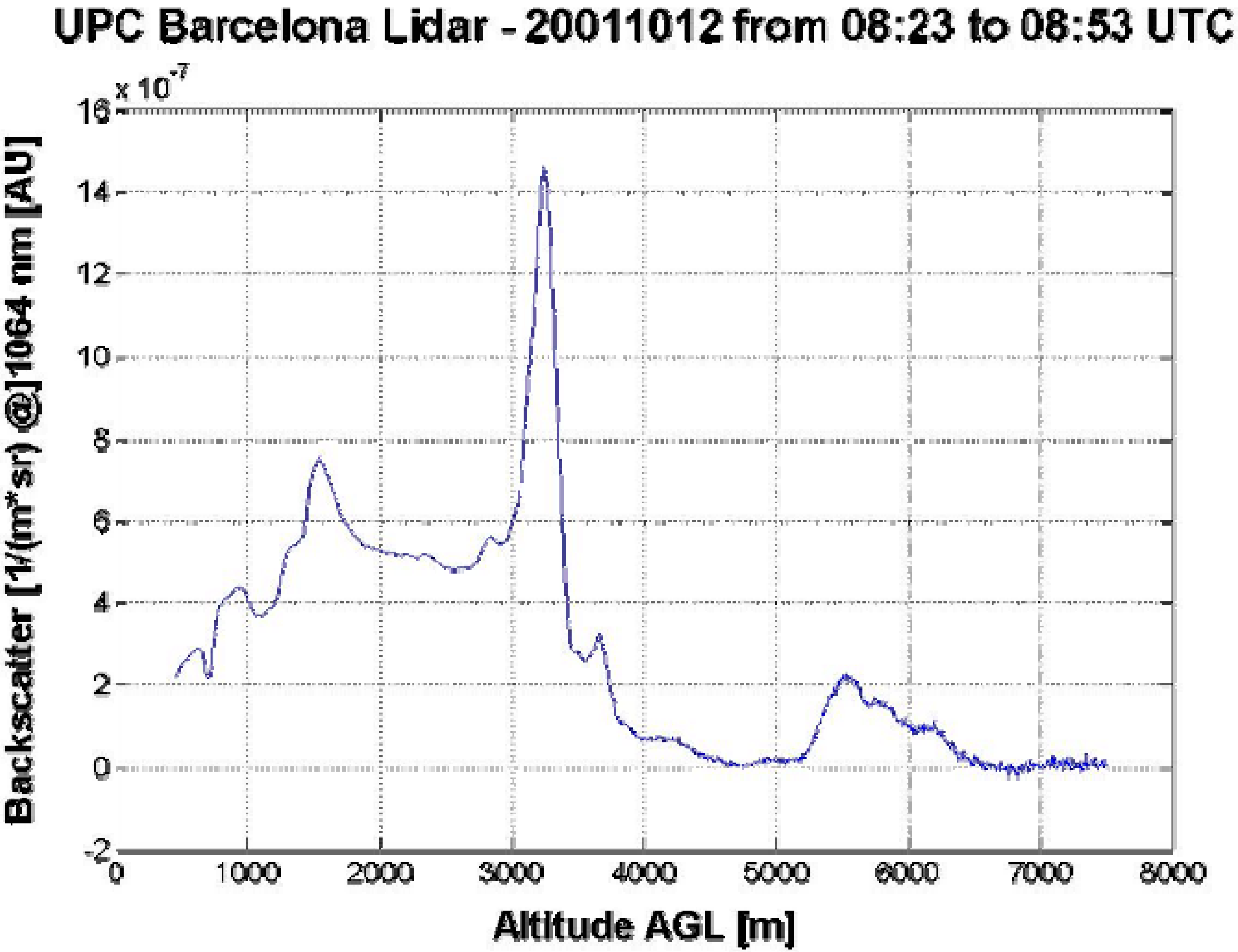
Range-corrected signal



Range-corrected signal



Range resolution



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Klett-Fernald solution: "refinement" if aerosol optical depth of a close-by sunphotometer is available

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An constant "average" (throughout the column) S_a is assumed

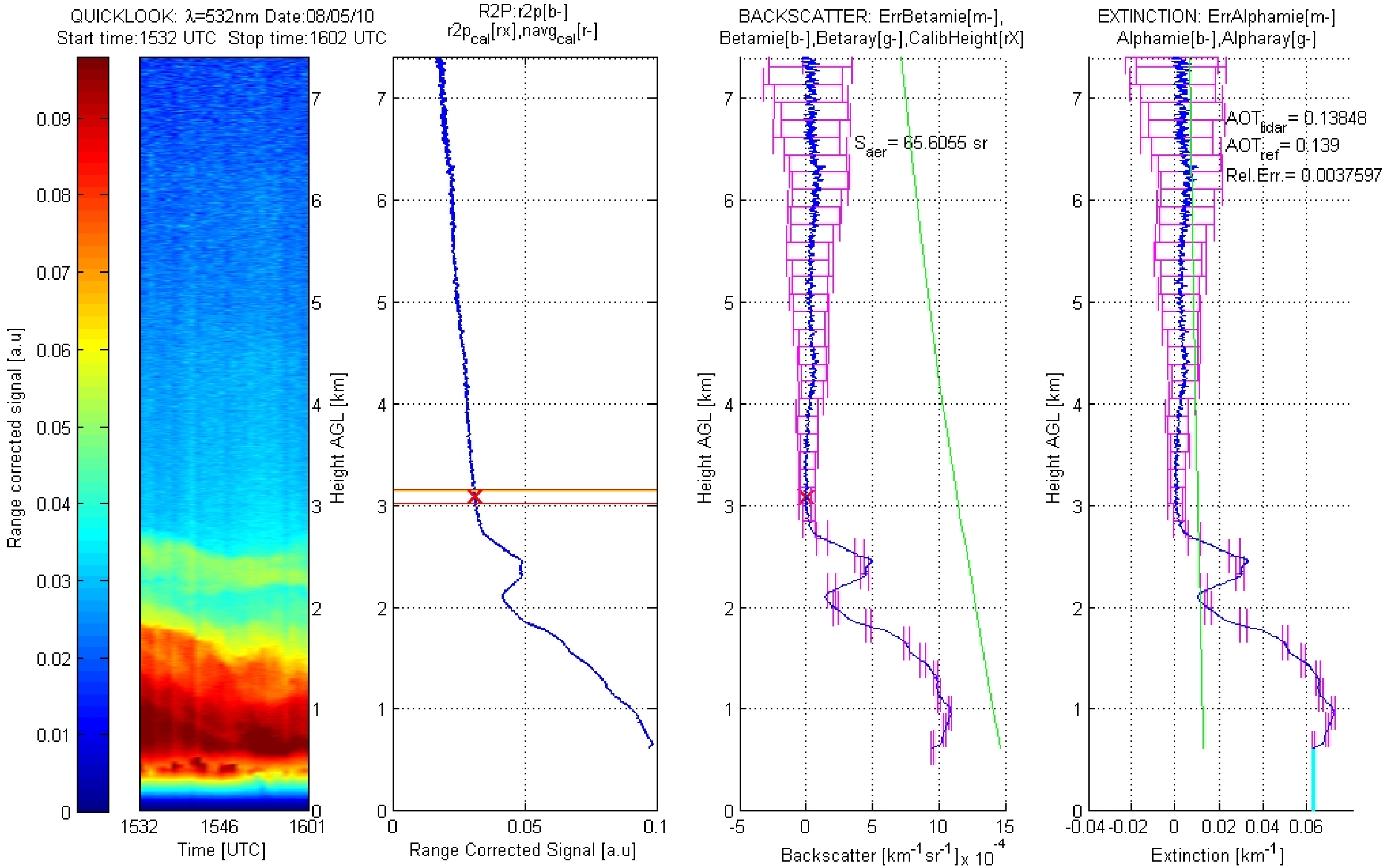
$$\beta_a(R) = \frac{\beta(R_m) X(R) \exp\left(-2\int_R^{R_m}\left(\frac{8\pi}{3} - S_a\right)\beta_m(x)\,dx\right)}{X(R_m) + 2\beta(R_m)\int_R^{R_m} S_a X(x) \exp\left(-2\int_x^{R_m}\left(\frac{8\pi}{3} - S_a\right)\beta_m(x')\,dx'\right)dx} - \beta_m(R)$$

$$\alpha_a(R) = S_a \beta_a(R)$$

S_a is iteratively adjusted until

$$\int_0^{R_m} \alpha_a(R)\,dR \approx AOD_{SP}$$

Example of Klett-Fernald method constrained by sunphotometer AOD measurement



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More elaborated systems (elastic-Raman lidars)

- One transmitted wavelength
- Two received wavelengths:
  - Elastic (aerosol + molecules)
  - Raman-shifted wavelength from an abundant (e.g. N_2) atmospheric constituent
- The Raman-shifted wavelength acts as a "marker" signal
- No assumption about relationship between $\alpha_a(R)$ and $\beta_a(R)$ is needed
- Independent retrieval of $\alpha_a(R)$ and $\beta_a(R)$

RAMAN SCATTERING

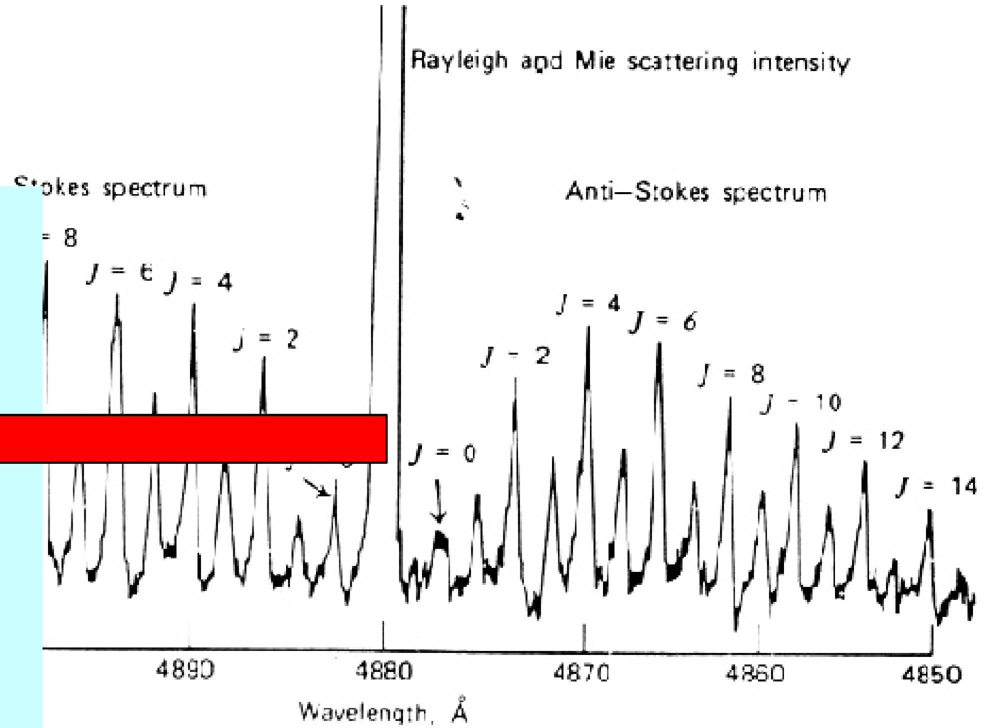
RSLAB

Lines of Q,O, S branches of Raman vibrational-rotational spectrum ~2330 cm⁻¹

551 nm under excitation @ 488 nm

607 nm under excitation @ 532 nm

387 nm under excitation @ 355 nm

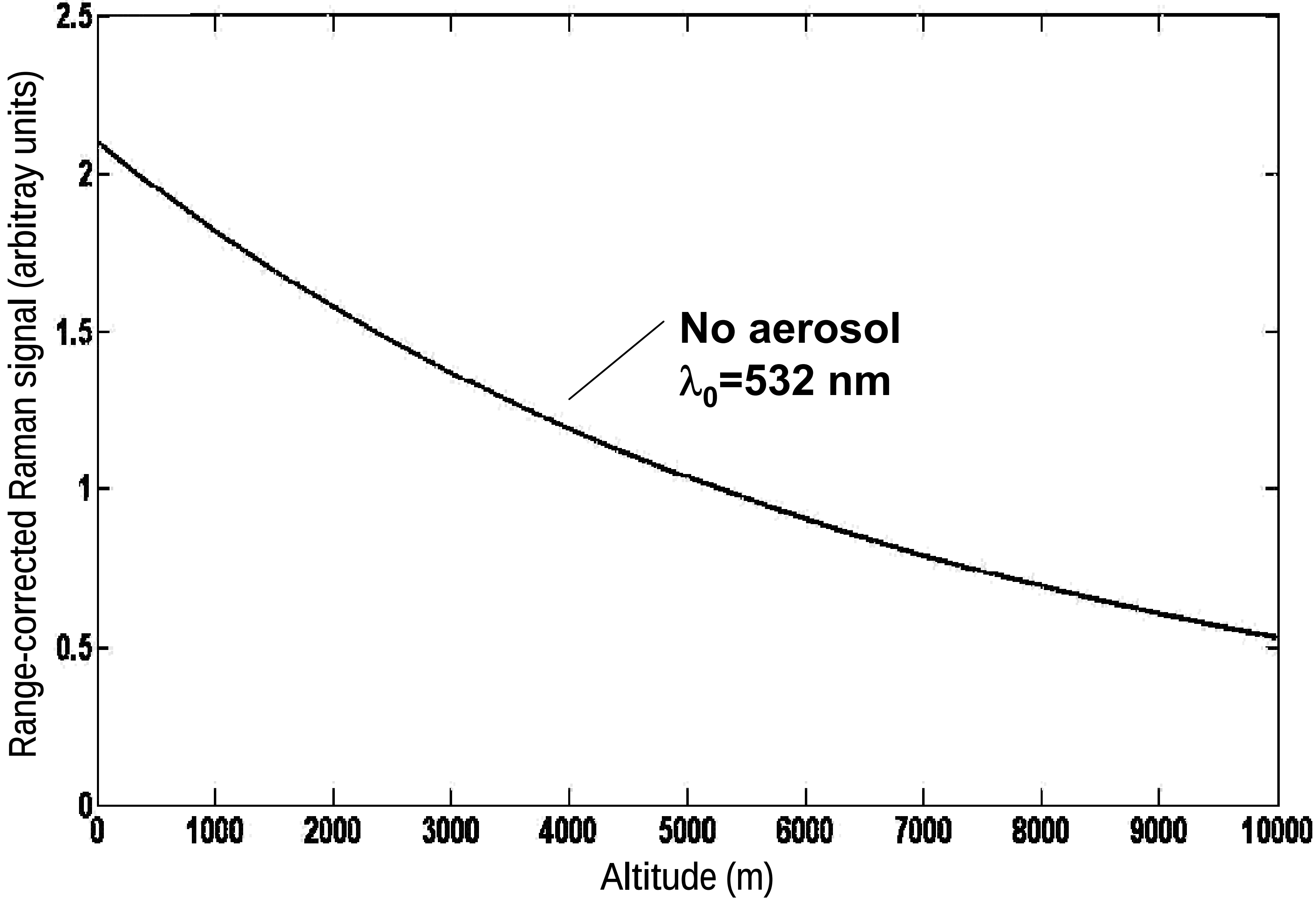


...tally measured pure rotational Raman spectrum of nitrogen. Laser excita-
...nm (Salzman, 1974).

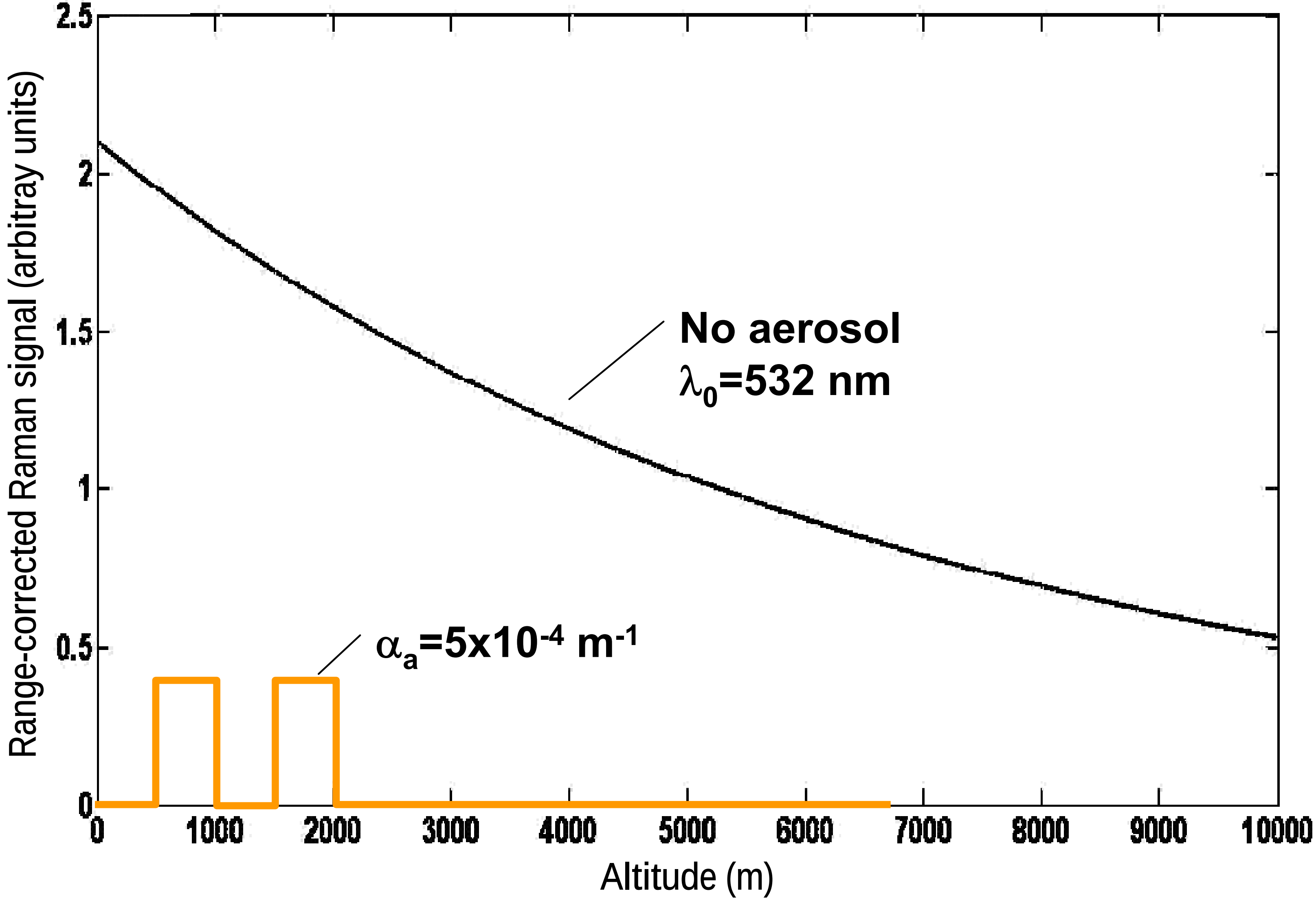
2nd and 3rd harmonics of Nd:YAG laser fundamental frequency (1064 nm wavelength)

Combination of elastic backscatter + N_2 Raman backscatter

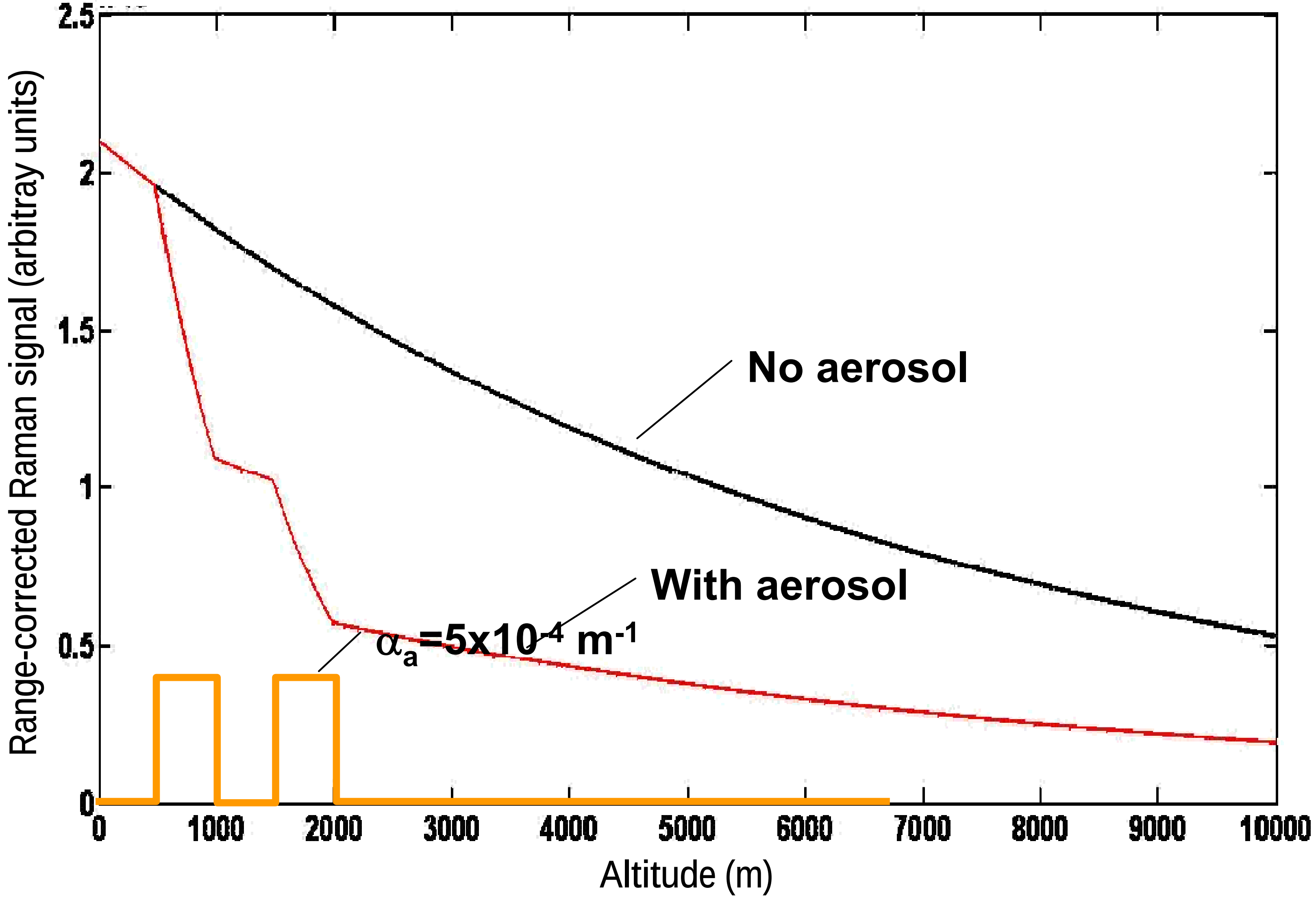
RSLAB



Combination of elastic backscatter + N_2 Raman backscatter



Combination of elastic backscatter + N_2 Raman backscatter



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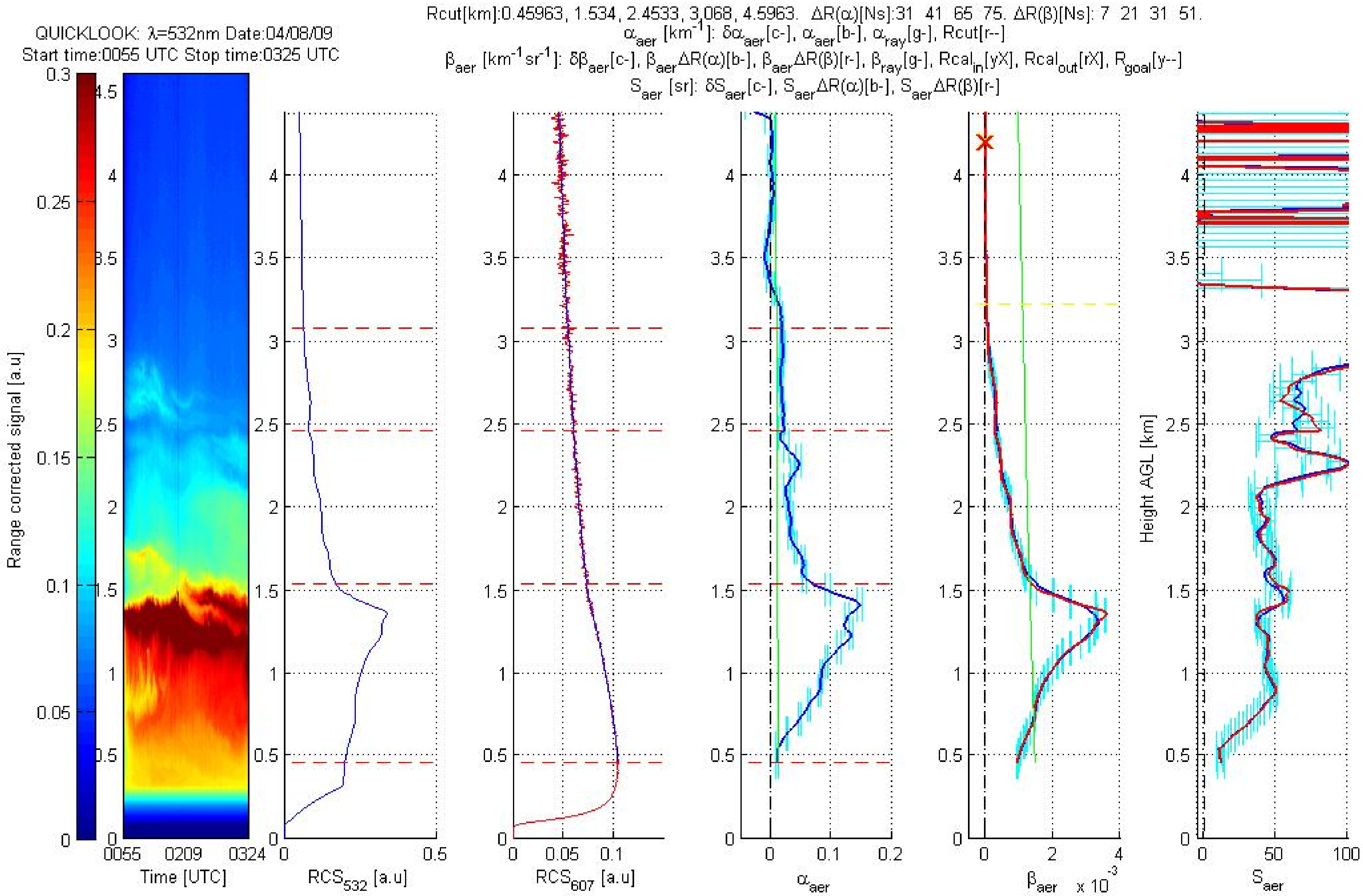
Elastic-Raman retrieval method

$$\alpha_{a\lambda_0}(R) = -\frac{\dfrac{\dfrac{d}{dR}\left[\dfrac{R^2 P_{\lambda_{Ra}}(R)}{N_{N_2}(R)}\right]}{\dfrac{R^2 P_{\lambda_{Ra}}(R)}{N_{N_2}(R)}} + \alpha_{m\lambda_0}(R) + \alpha_{m\lambda_{Ra}}(R)}{1 + \left(\dfrac{\lambda_0}{\lambda_{Ra}}\right)^k}$$

$$\beta_{a\lambda_0}(R) =$$

$$\beta(R_m)\frac{P_{\lambda_0}(R)P_{\lambda_{Ra}}(R_m)}{P_{\lambda_0}(R_m)P_{\lambda_{Ra}}(R)}\frac{N_{N_2}(R)}{N_{N_2}(R_m)}\frac{\exp\left(-\int_R^{R_m}\left[\alpha_{a\lambda_0}(x)+\alpha_{m\lambda_0}(x)\right]dx\right)}{\exp\left(-\int_R^{R_m}\left[\alpha_{a\lambda_{Ra}}(x)+\alpha_{m\lambda_{Ra}}(x)\right]dx\right)} - \beta_{m\lambda_0}(R)$$

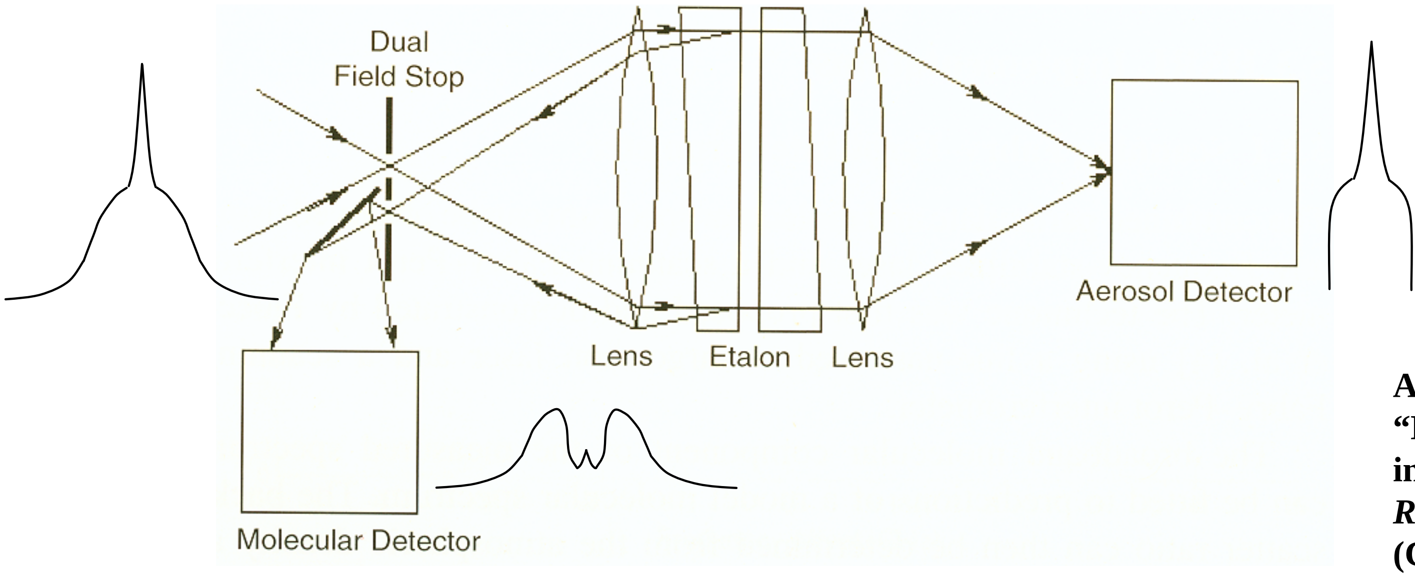
Elastic + Raman combination



- Backscatter Raman very faint → difficult to operate Raman channels in day time because of noise induced by background radiation.
- Alternative: high-spectral resolution lidar (more complex than Raman, but more sensitive)

HIGH SPECTRAL RESOLUTION LIDAR (HSRL)

Principle similar to Raman, but using Doppler-widened elastic molecular return



Adapted from E. E. Eloranta, "High Spectral Resolution Lidar", in *Lidar. Range-Resolved Optical Remote Sensing of the Atmosphere* (C. Weitkamp, ed.), Springer, 2005

$$P(R)R^2 = C\beta_m(R)e^{-2\int_0^R\left[\alpha_a(x)+\alpha_m(x)\right]dx}$$

Another step further: multiwavelength lidars

- The retrieval of extinction and backscatter coefficients at several wavelengths allows the retrieval of aerosol particle microphysical properties:
  - effective radius
  - volume concentration
  - complex refractive index

- It has been shown **“that under certain constraints a minimum data set of three backscatter coefficients and two extinction coefficients is sufficient for a successful inversion”** (C.Böckmann et al. JOSA A, **22**, 3, Mar. 2005, pp. 518-528)

→ **EARLINET standard**

EARLINET standard

- Nd:YAG laser with 2nd and 3rd harmonic generators → 3 transmitted wavelengths: 1064 nm (IR), 532 nm (VIS), 355 nm (UV)

- Receiving channels:
  - Elastic backscatter: 1064 nm, 532 nm, 355 nm
  - Raman N_2 channels: 607 nm, 387 nm
  - Advisable: depolarization channels

Barcelona EARLINET lidar station

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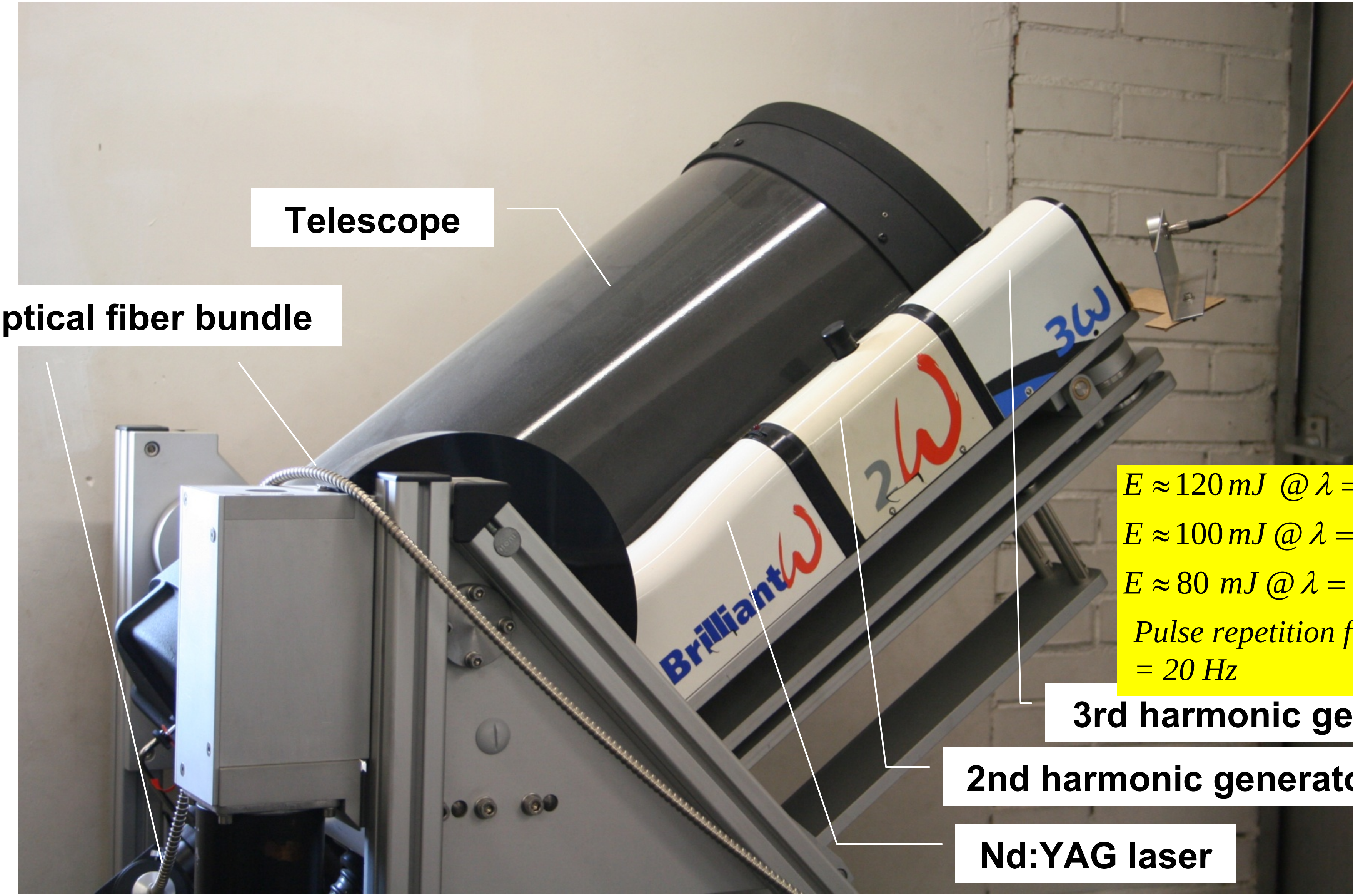

$E \approx 120\, mJ\ @\ \lambda = 1064\ nm$

$E \approx 100\, mJ\ @\ \lambda = 532\ nm$

$E \approx 80\ mJ\ @\ \lambda = 355\ nm$

Pulse repetition frequency = 20 Hz

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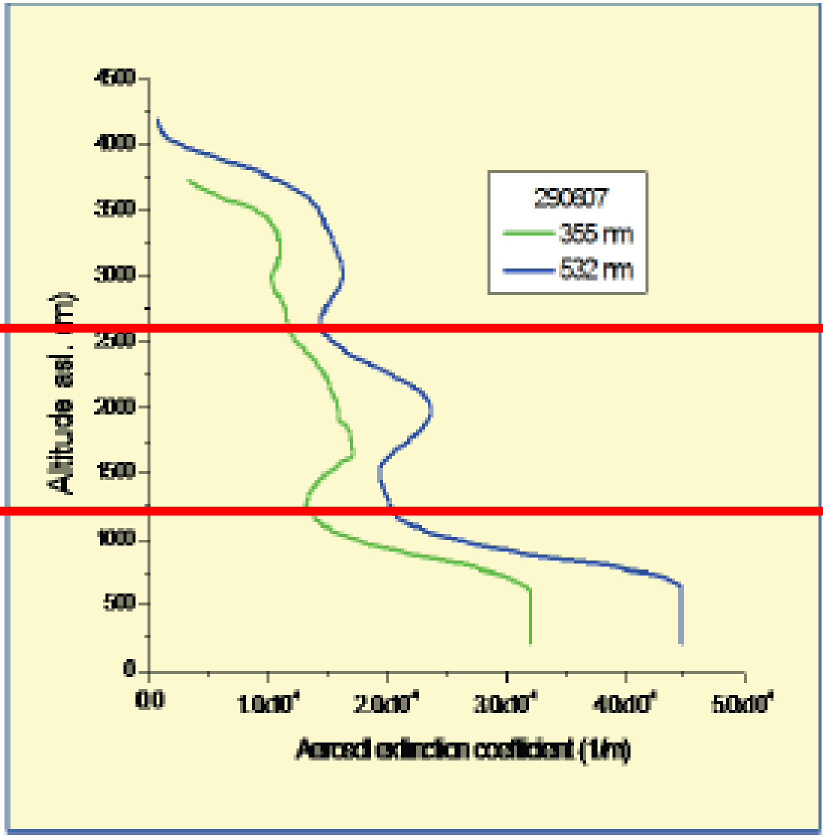
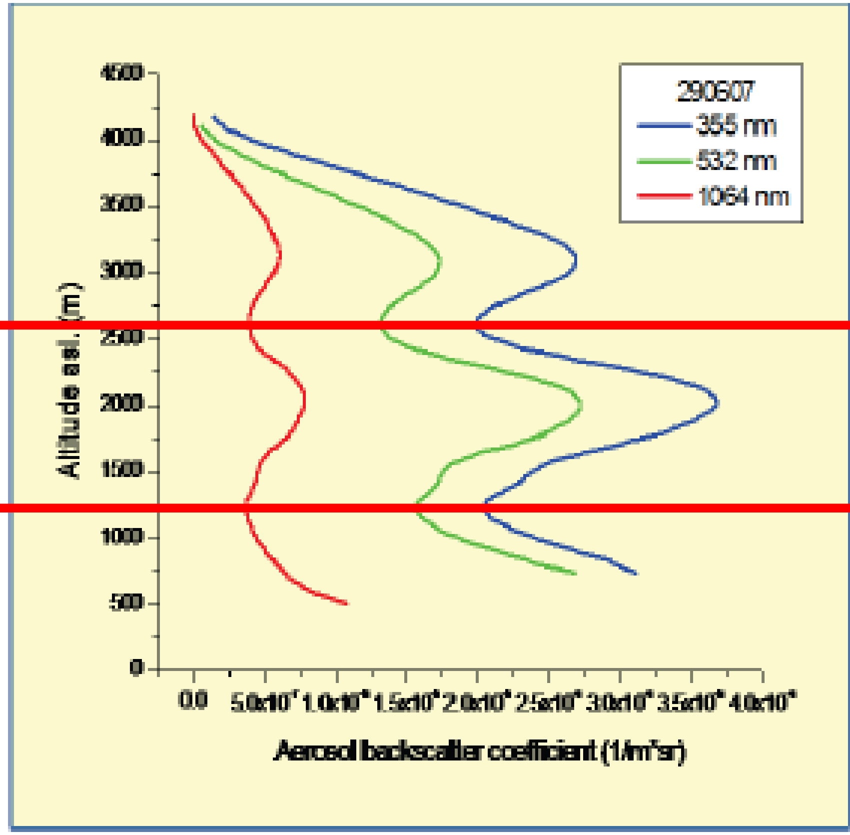
Another example

Input data (wildfire smoke plume in Athens, 29 June 2007)





From Böckmann et al. Proc. IGARSS 2008, pp. II-422 – II-425

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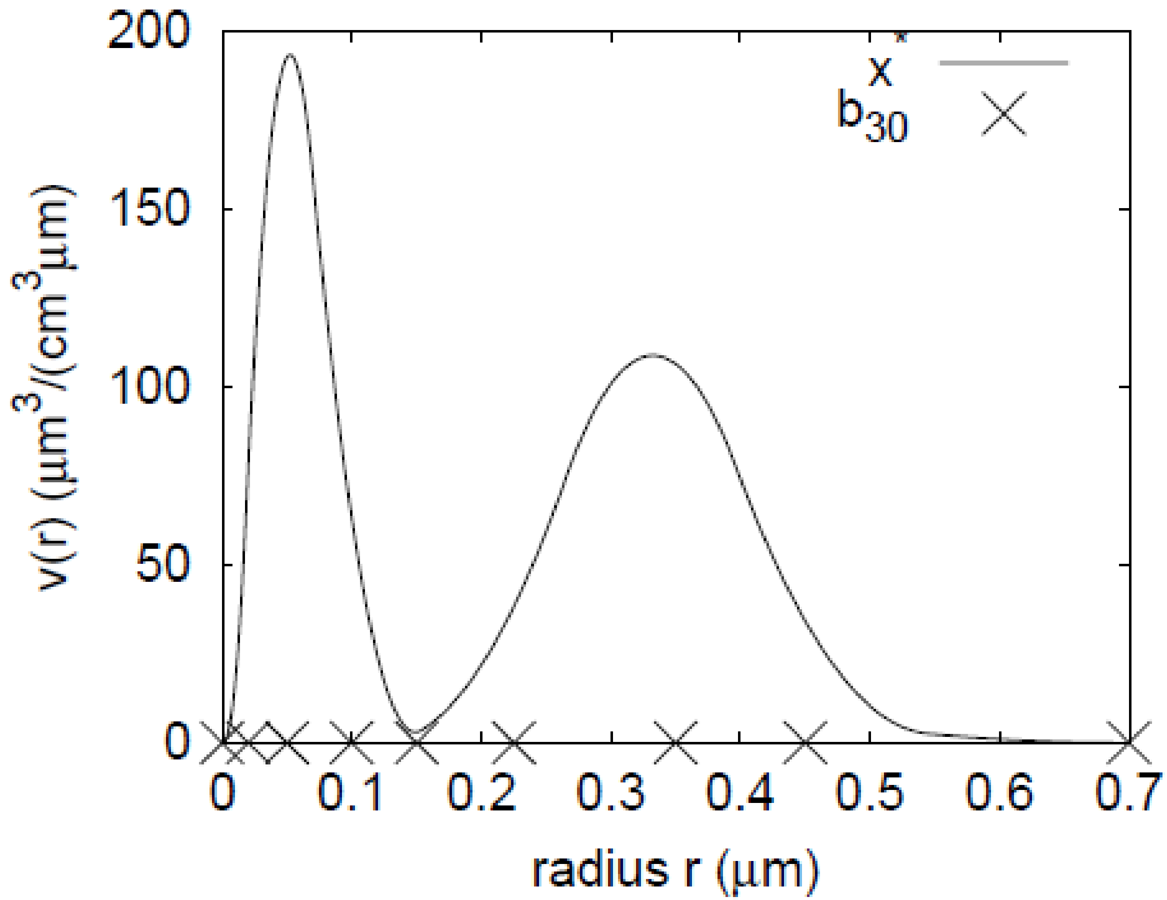
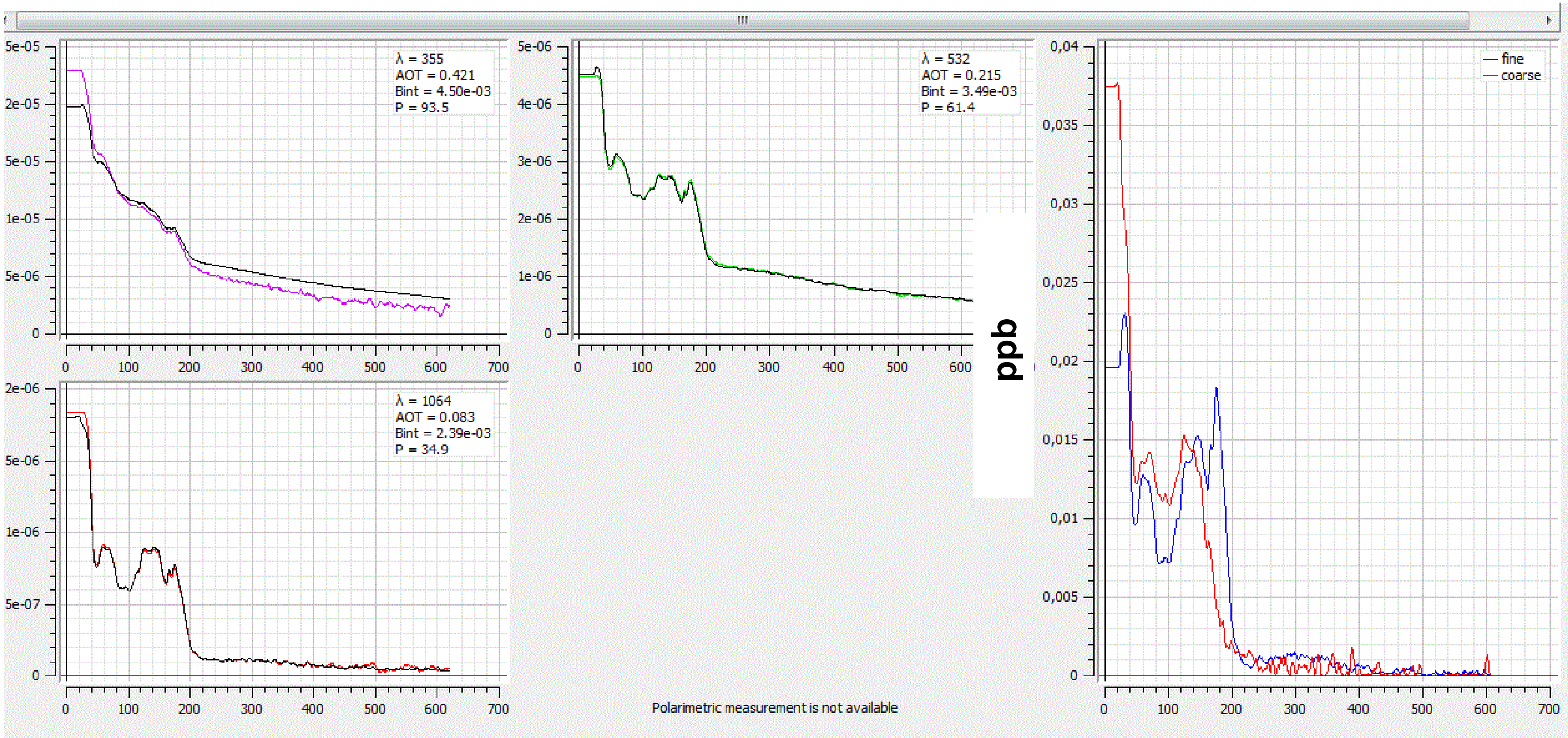
Results: volume distribution of particles, mean refractive index m = 1.37 + 0.006i



From Osterloh et al., Open Atmos. Sci. J., 5, pp. 61-73, 2011

Multiwavelength lidar + sunphotometer

In day time, with no Raman channels available, synergies with sunphotometer allow volume profiles of fine and coarse mode volume concentrations



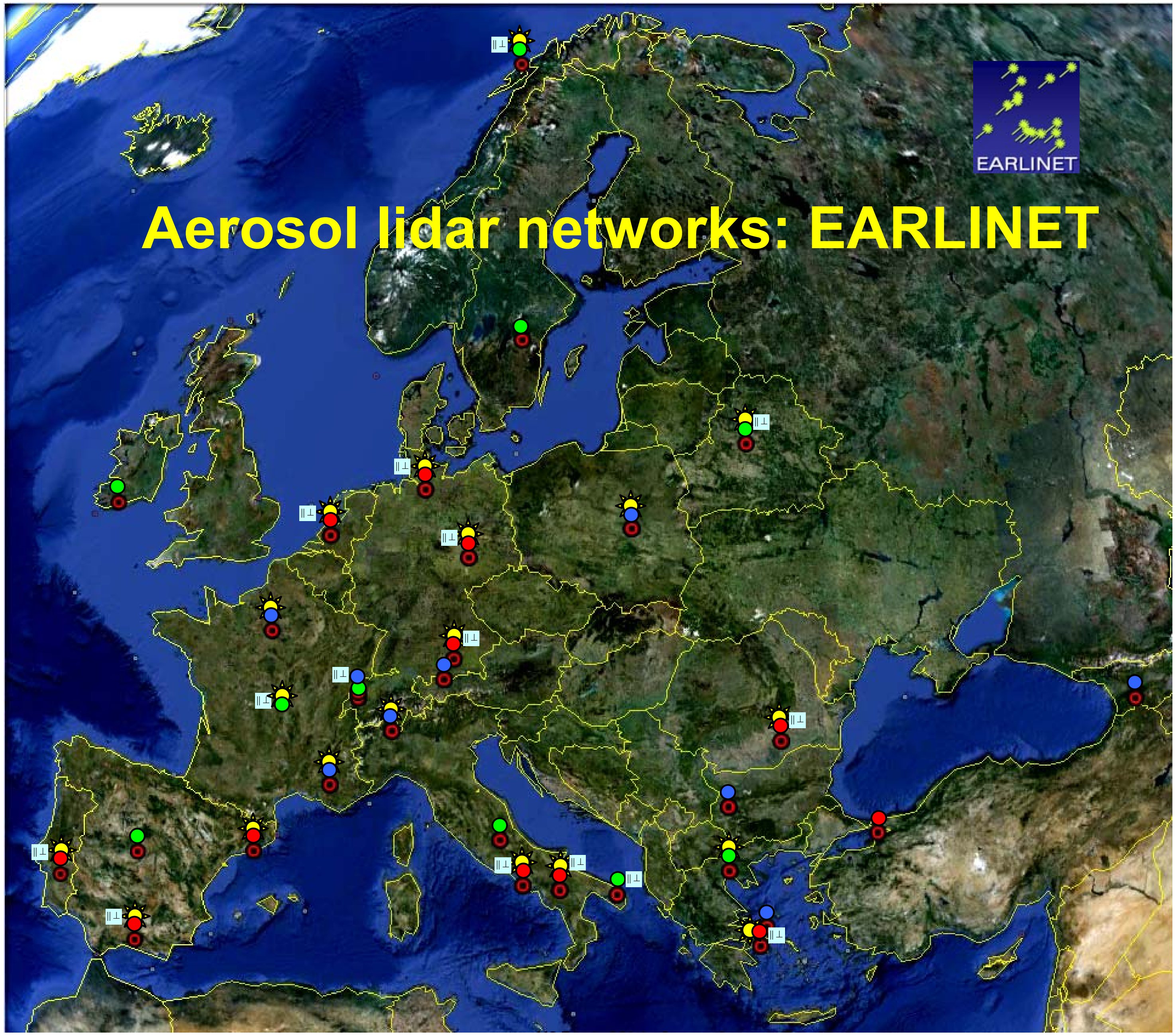
x 15 m

Results of LIRIC software (A. Chaikovsky's, Inst. of Physics, Nat. Acad. Sc. of Belarus) on UPC lidar measurements

RSLAB

30 lidar stations operating in a coordinated way: → 4D picture of aerosol distribution at continental scale → aerosol climatology at continental scale

- 3+2 (+...) stations (aerosol typing, microphysics): 13
- Raman lidars (extinction profiling): 9
- Backscatter lidar: 9
- Depolarization channel (aerosol typing): 15
- Collocated sun-photometer: 19



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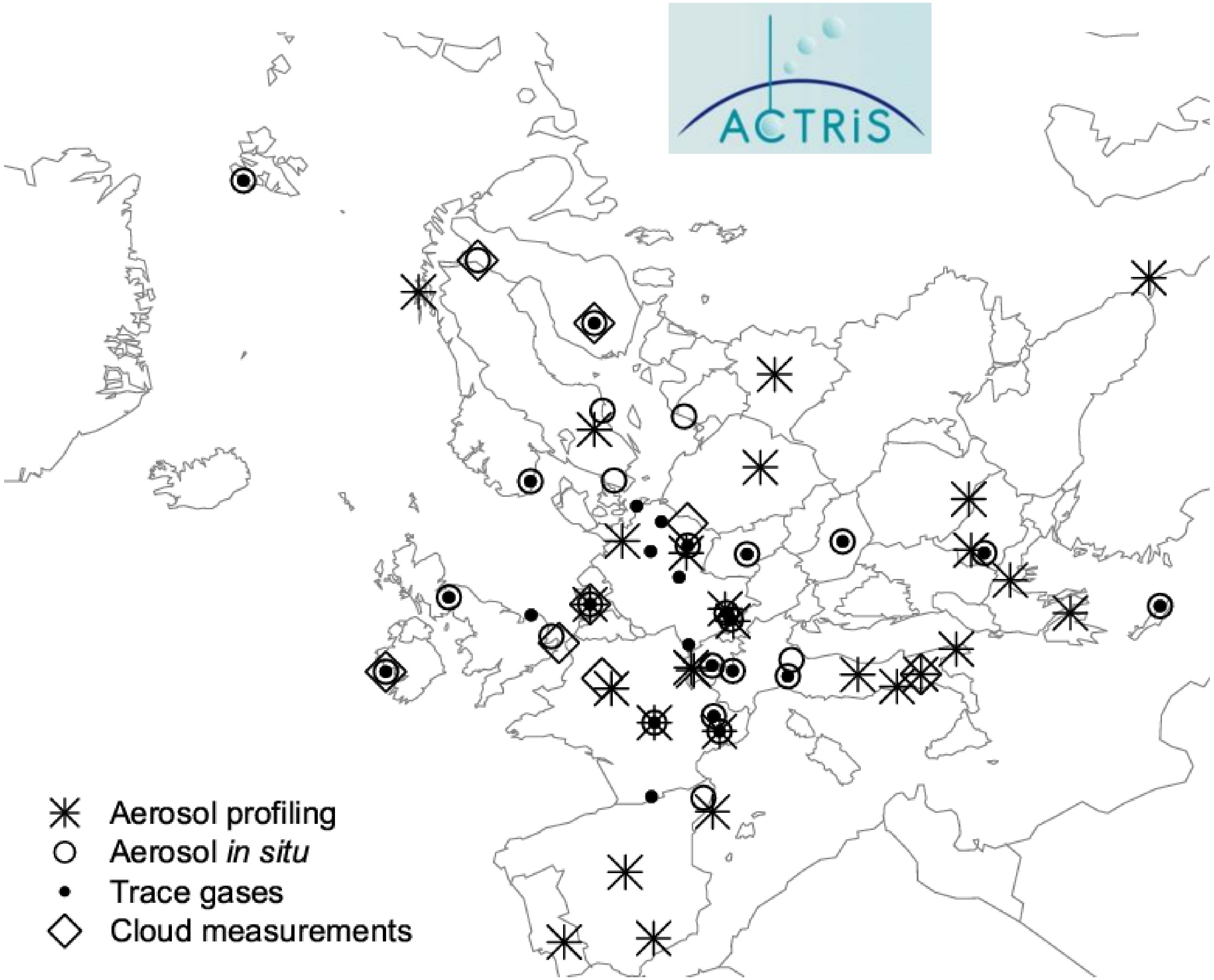
ACTRIS infrastructure



BEYOND EARLINET

- GALION: WMO's Global Atmosphere Watch Aerosol Lidar Network
- Federates existing lidar networks
- EARLINET is striving to set up the standards for measurement methodology, and hardware and software quality assurance

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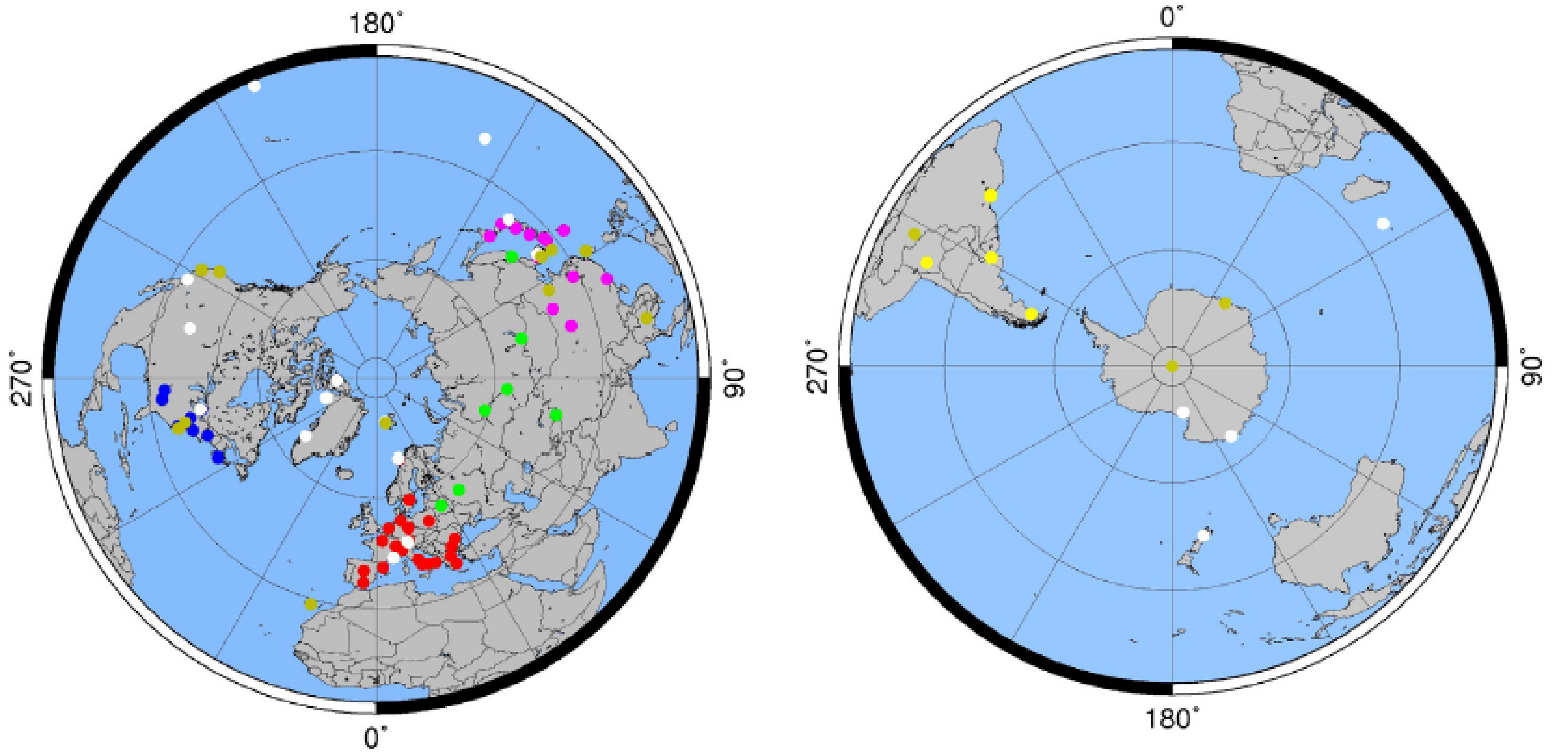
GALION



● ALINE ● AD-NET ● CISLiNet ● EARLINET ● MPLNET ● NDACC

● REALM/CREST - CORALNet (Canada) not shown

EARLINET SUPPORT FOR SPACE-BORNE LIDARS

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- **Calibration – validation activities for**
  - **CALIPSO (current)**
  - **ADM-Aeolus (future)**
  - **EarthCARE (future)**

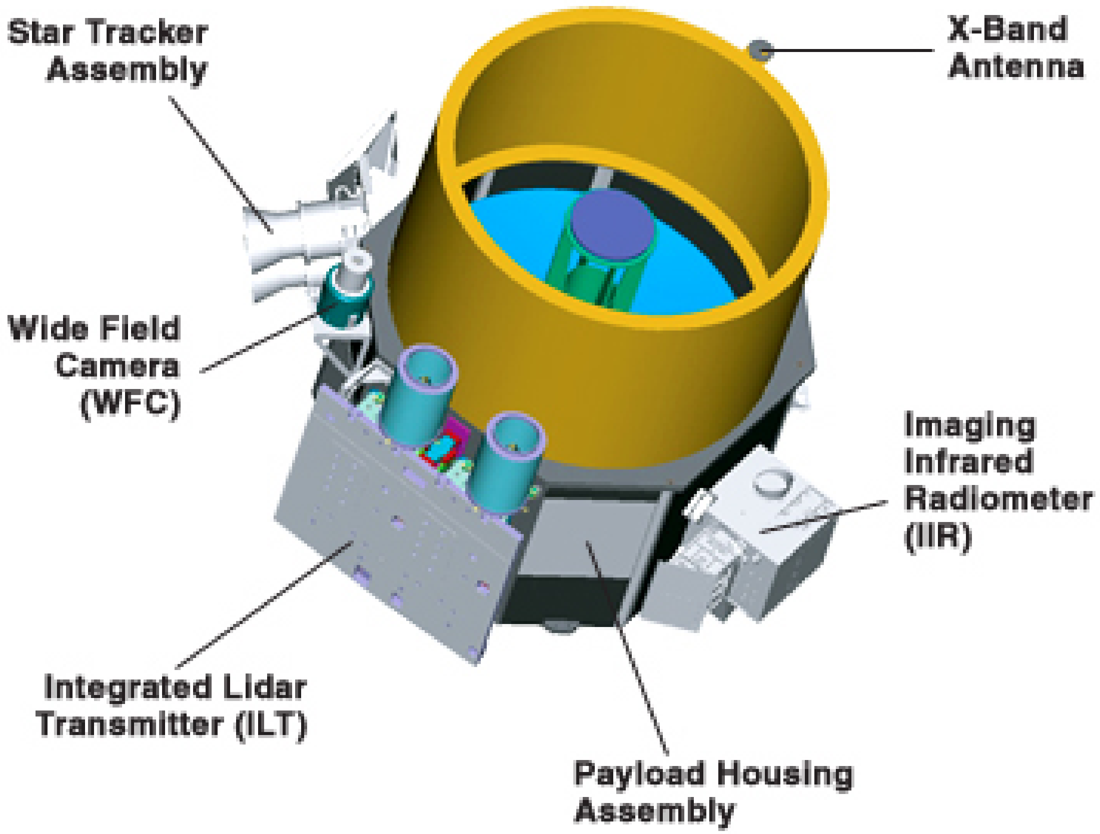
Lidar from space: CALIOP instrument on board CALIPSO satellite (NASA-CNES)

(since april 2006)

http://www-calipso.larc.nasa.gov/about/payload.php

CALIOP on board CALIPSO (NASA-CNES)

(since april 2006)



Characteristics

	CALIOP
laser:	Nd: YAG, diode-pumped, Q-switched, frequency doubled
wavelengths:	532 nm, 1064 nm
pulse energy:	110 mJoule/channel
repetition rate:	20.25 Hz
receiver telescope:	1.0 m diameter
polarization:	532 nm
footprint/FOV:	100 m/ 130 µrad
vertical resolution:	30-60 m
horizontal resolution:	333 m
linear dynamic range:	22 bits
data rate:	316 kbps

http://www-calipso.larc.nasa.gov/about/payload.php

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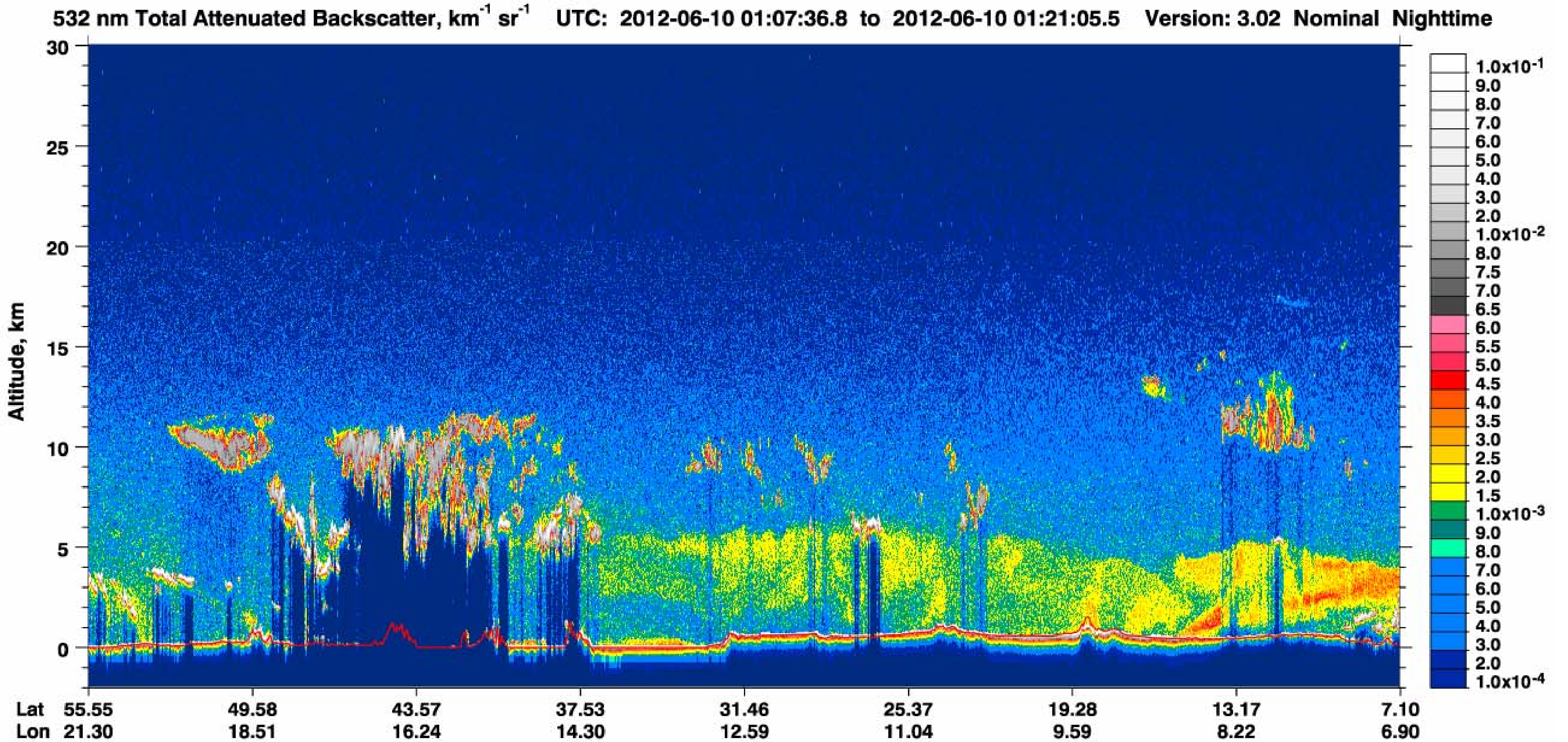
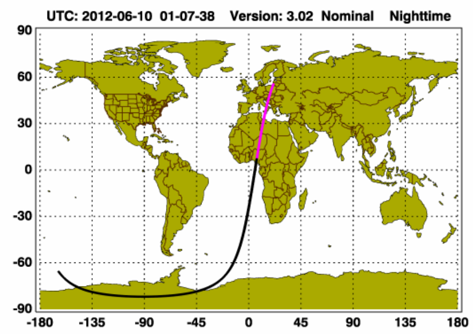
Lidar from space: CALIPSO



http://www-calipso.larc.nasa.gov/products/lidar/



Access to ACTRIS-EARLINET data

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II Lectures on Atmospheric Mineral Dust –
Barcelona, 6th of November, 2012

http://www.actris.net

Access to ACTRIS-EARLINET data

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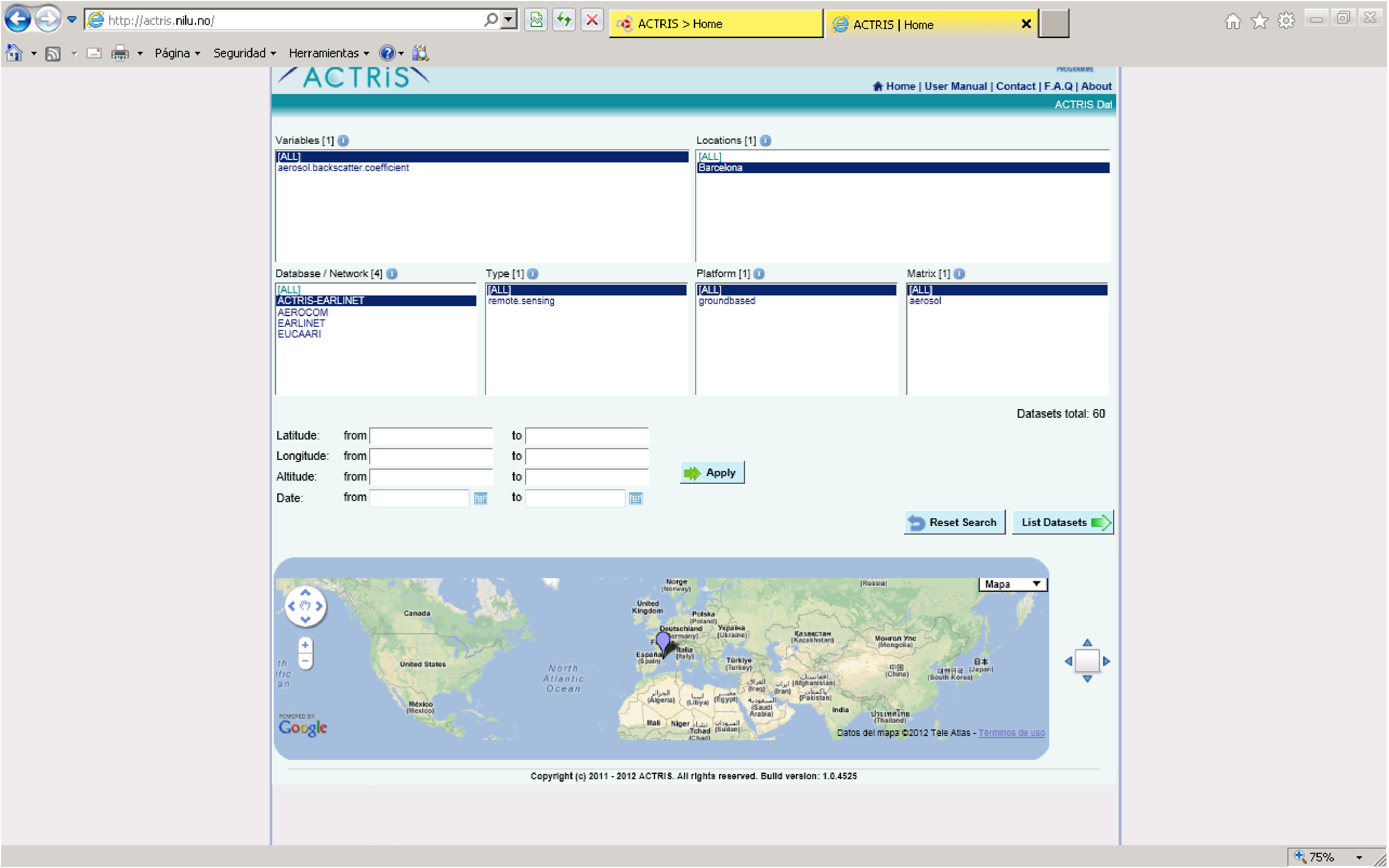
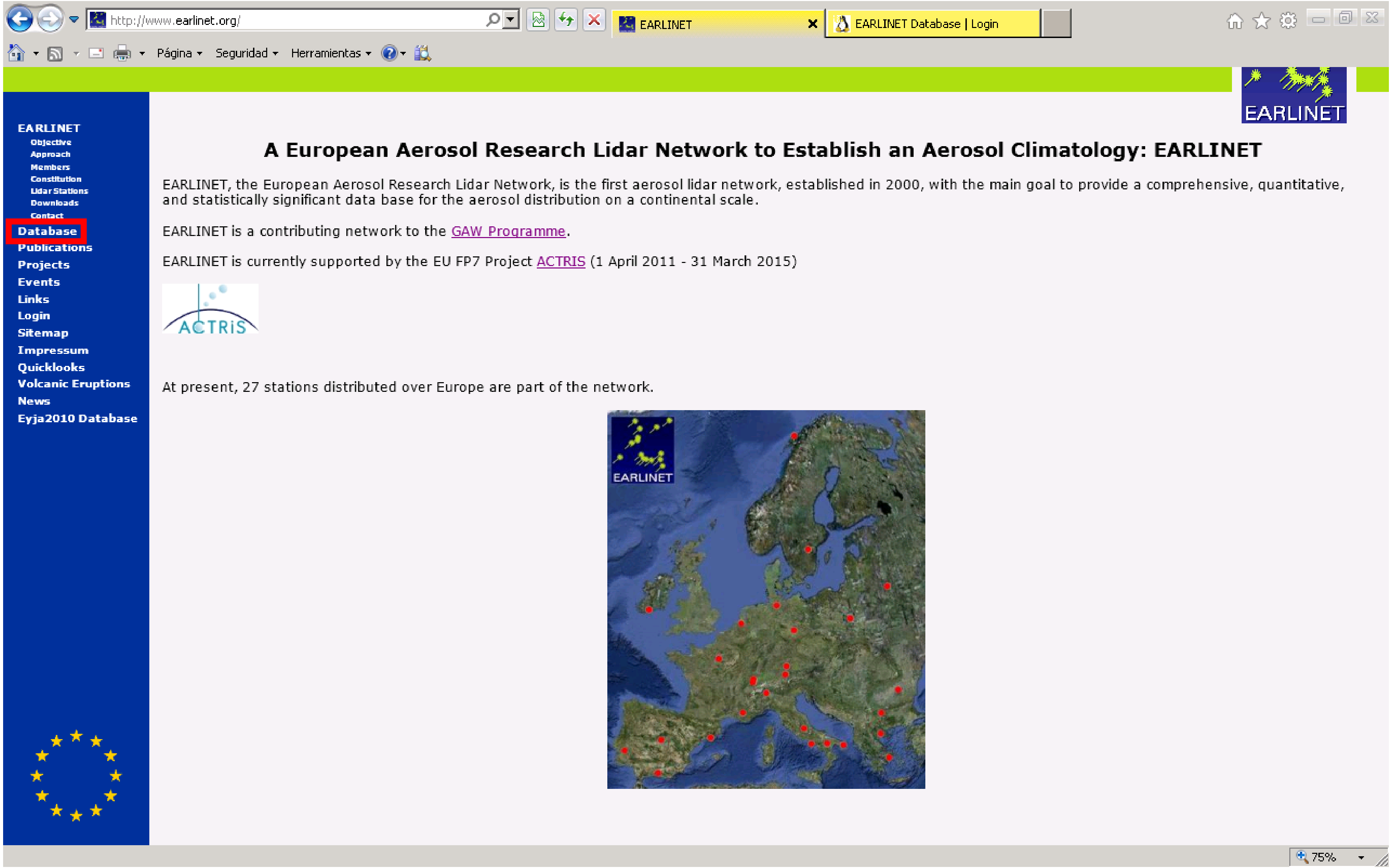


Access to EARLINET database



RSLAB

http://www.earlinet.org

RSLAB

Access to EARLINET database

Logout | logged in as adc

EARLINET

- EARLINET Home
- Fileformat Docs
- Introduction
- Search
- Results
- Feedback

Dataset Search

Date minimum:	2010-04-01 (YYYY-MM-DD)	+	×
Date maximum:	2010-05-31 (YYYY-MM-DD)	+	×
Daytime hours between:	and (HH:MM)		×
Season between:	and (MM-DD)		×
Station:	ba	+	×
Categories:		+	×
Emission wavelength:		+	×
File type:		+	×
Public data only:	☐		

68 matching datasets

Search

100%

Access to EARLINET database

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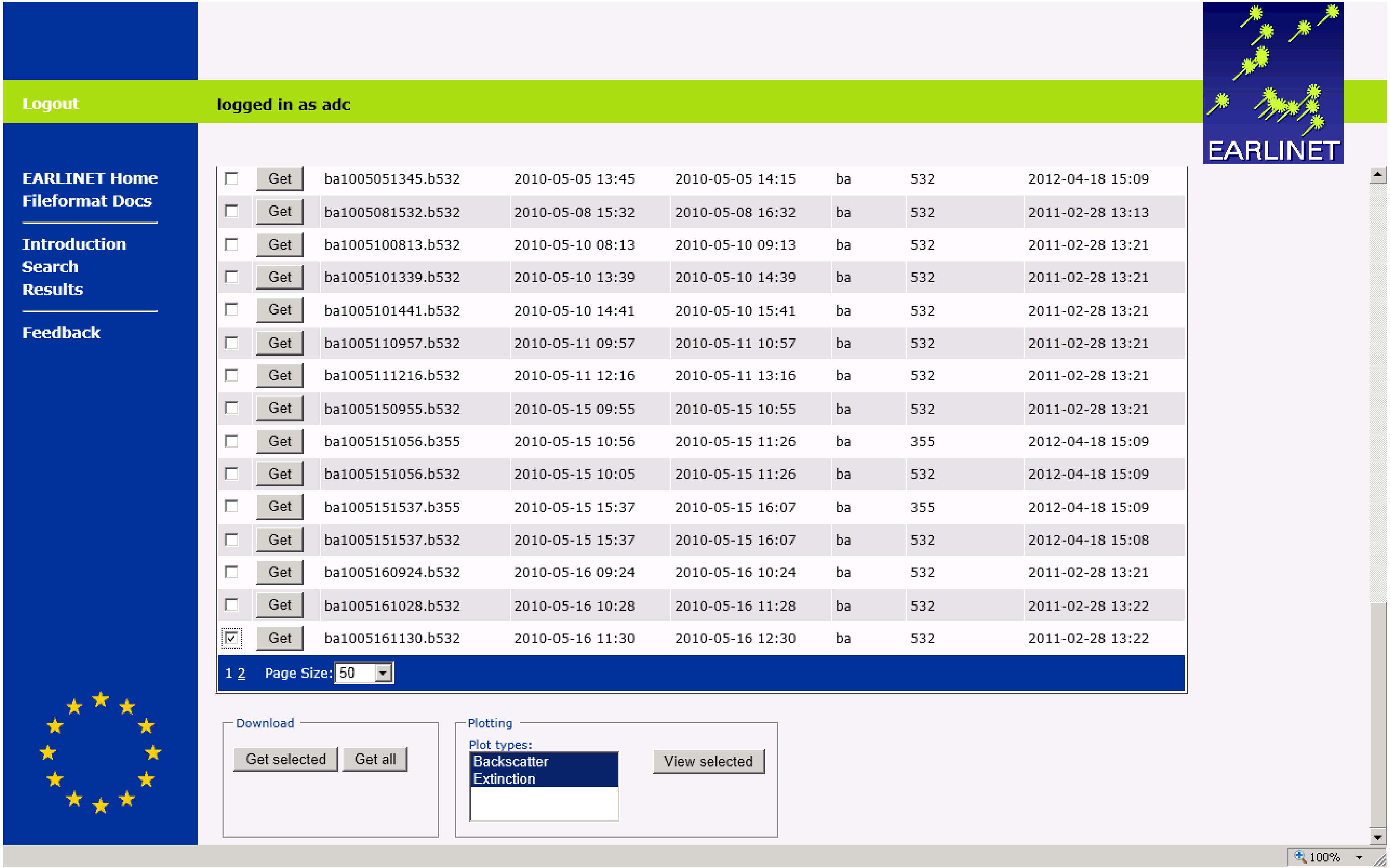

☐	Get	ba1005051345.b532	2010-05-05 13:45	2010-05-05 14:15	ba	532	2012-04-18 15:09
☐	Get	ba1005081532.b532	2010-05-08 15:32	2010-05-08 16:32	ba	532	2011-02-28 13:13
☐	Get	ba1005100813.b532	2010-05-10 08:13	2010-05-10 09:13	ba	532	2011-02-28 13:21
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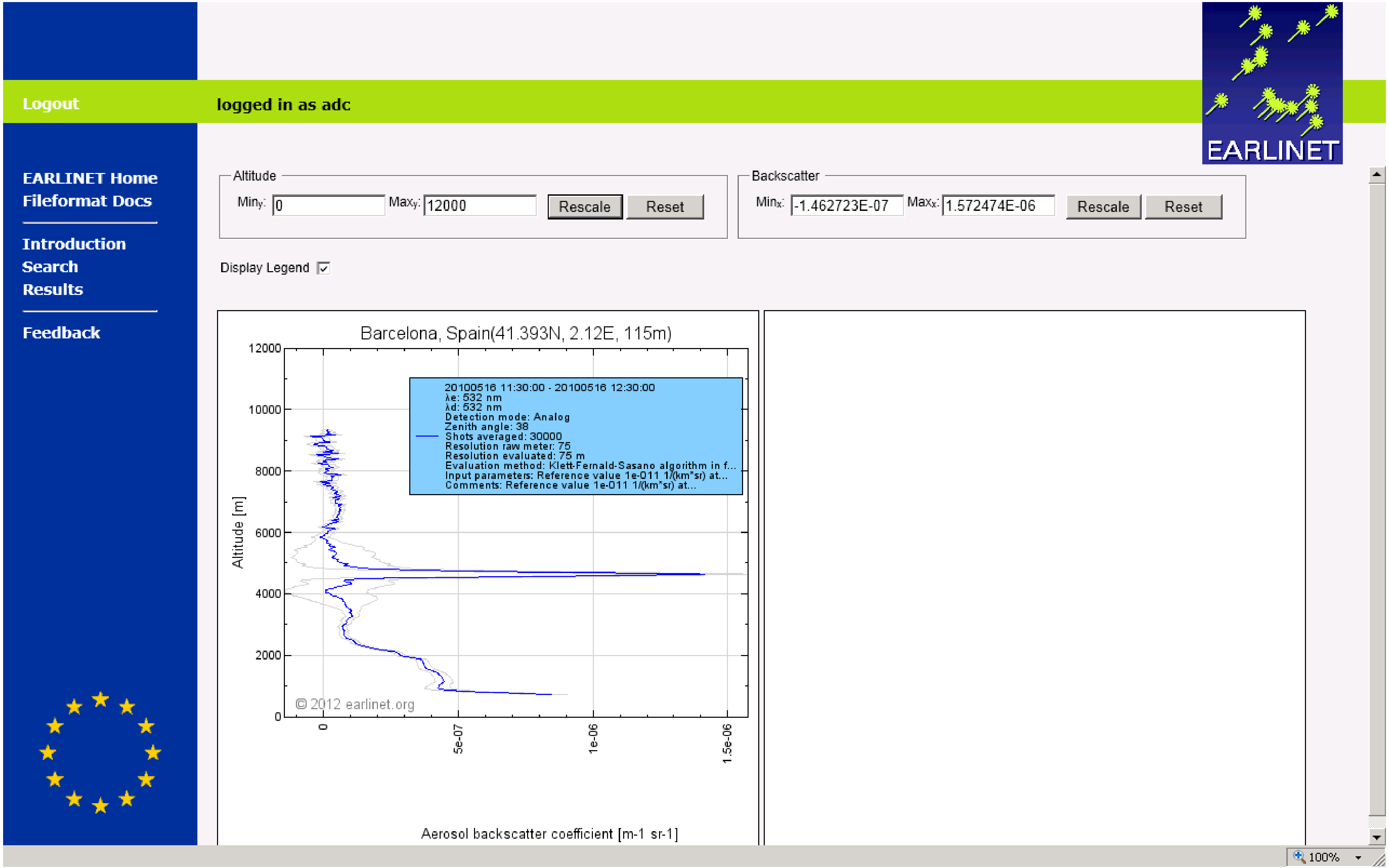
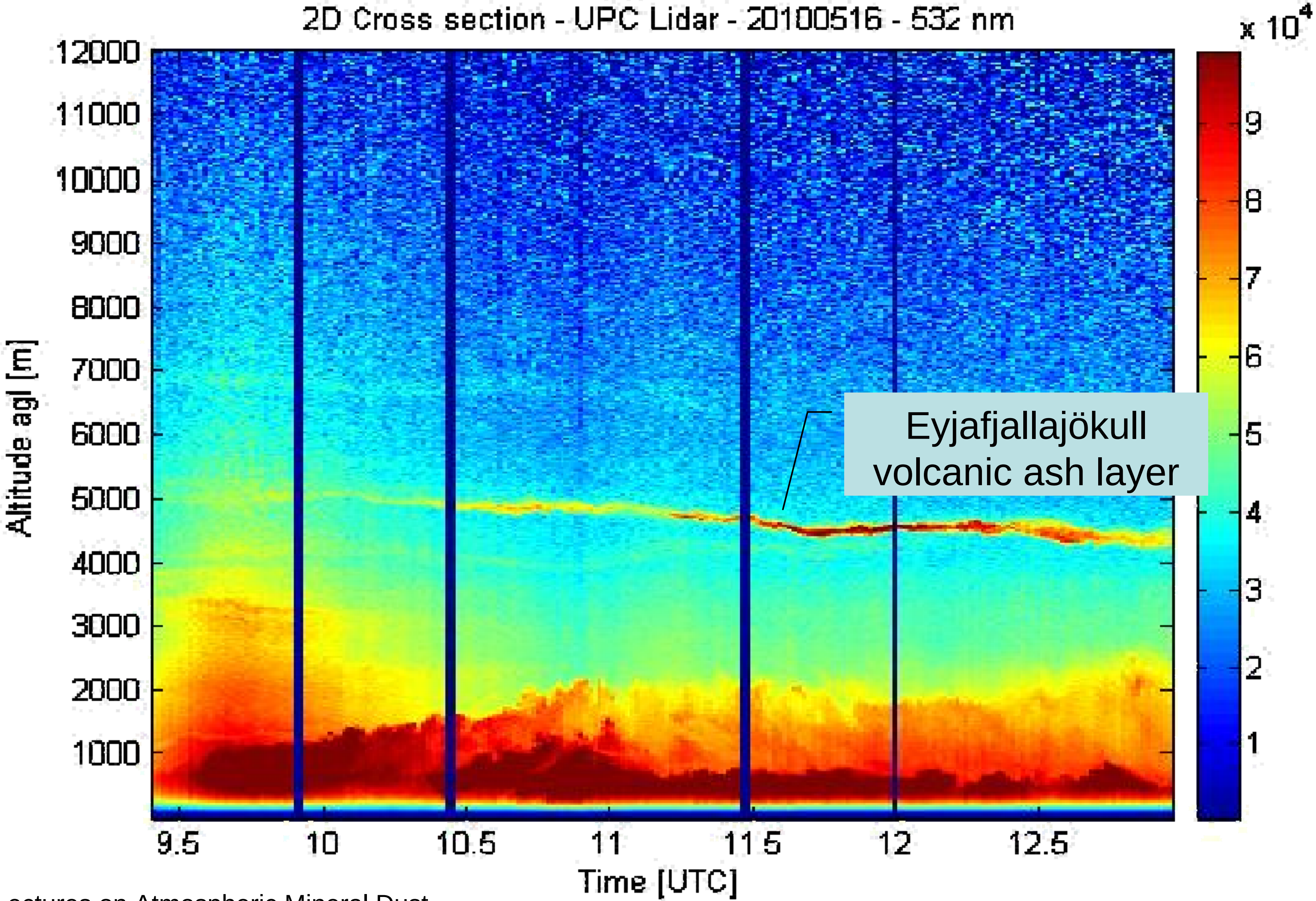


Contribution to air-traffic safety assessment



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Summary

- Lidar: powerful tool for the measurement of vertical profiles of dust → contribution to climate, meteorological and air-quality modelling + …→ possibility of operational networks

- Wide range of systems: from simple single-wavelength backscatter instruments to multiwavelength systems combining elastic and N_2 Raman channels, or using high-spectral resolution techniques → from information on layering to microphysical properties of aerosol

- Synergies with sun-photometers

- Coordinated ground-based networks → continental to global coverage

- Satellite-borne systems for global coverage

- Cooperation between ground-based networks and satellite instruments

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