Principios ópticos y tecnológicos de los sistemas LiDAR

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Webinar UARG sobre proyectos en cursos, avances y desafios, 20 de Agosto 2021

Index Presentation

Remote sensing

- **Remote sensing** is defined as the technique of obtaining information about objects through the analysis of data collected by instruments that are not in physical contact with the objects of investigation.

http://jan.ucc.nau.edu/~geog-p/geog/RemoteSensing/

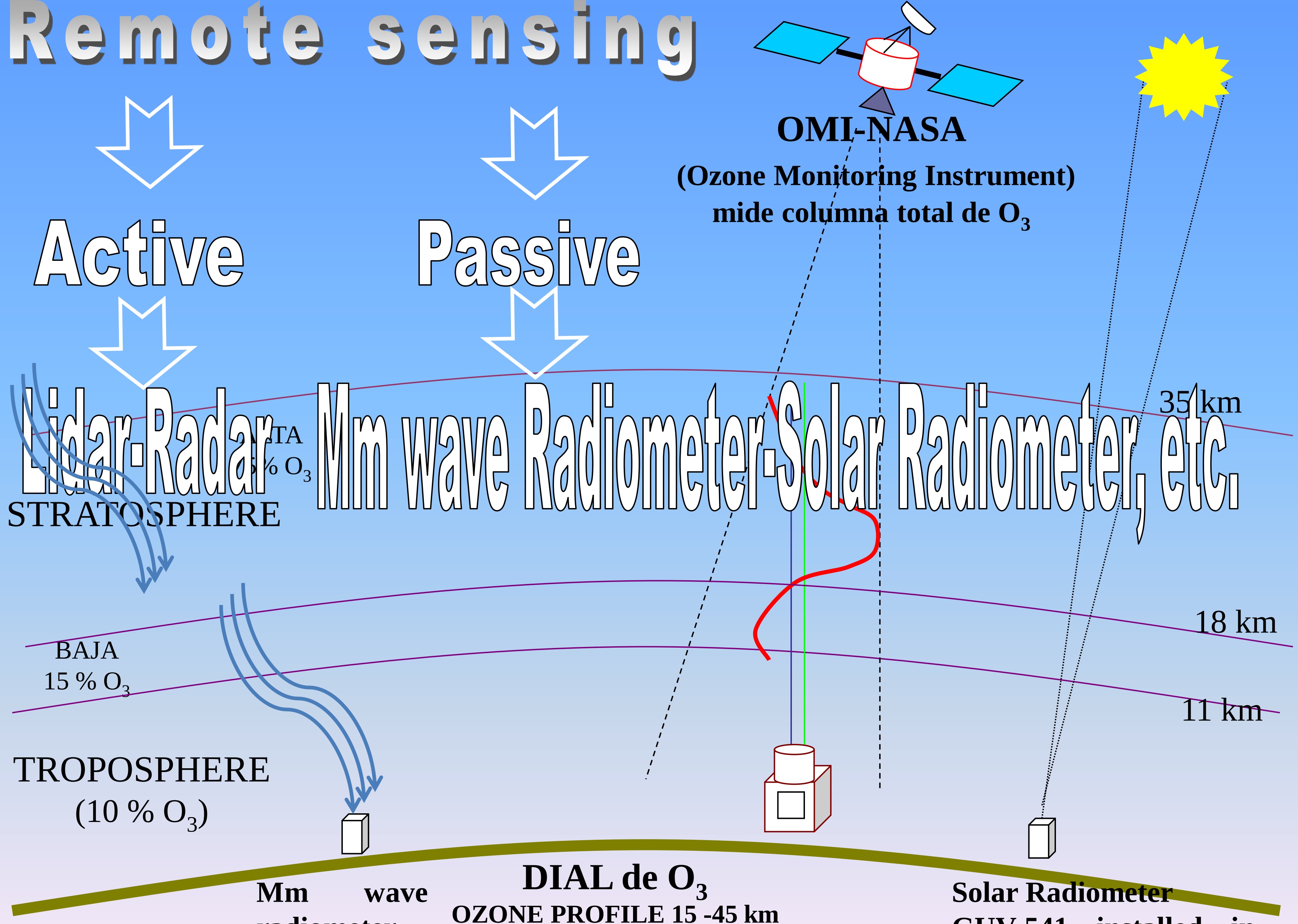
Remote sensing

Active

Lidar-Radar

Passive

Mm wave Radiometer-Solar Radiometer, etc.



OMI-NASA

(Ozone Monitoring Instrument)

mide columna total de O_3

Mm wave radiometer 40-80 km

DIAL de O_3

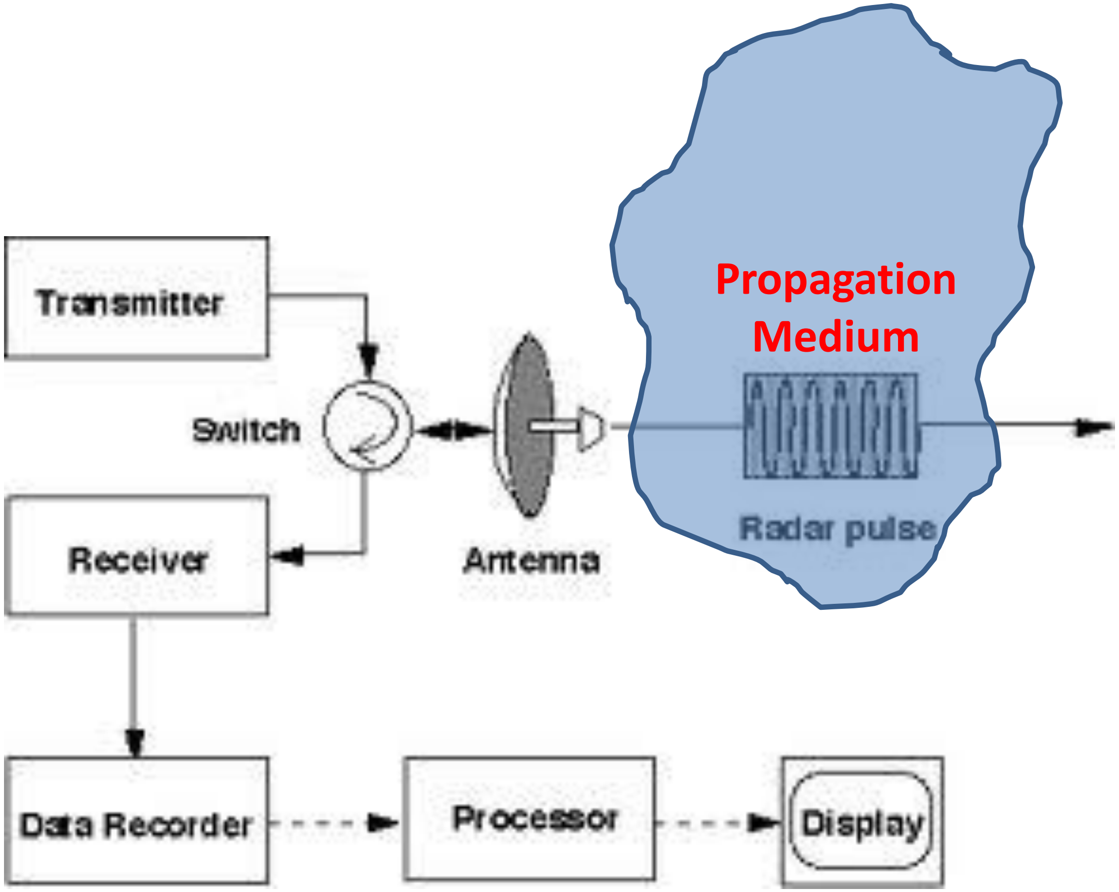
OZONE PROFILE 15 -45 km

Solar Radiometer GUV-541 installed in Río Gallegos since 2005

Principle of Active Remote Sensing

RADAR

RAdio Detection And Ranging



Introduction to LIDAR technique

LIDAR: LIght Detection And Ranging

LIDAR History

The introduction of the lidar principle dates back to pre-laser times.

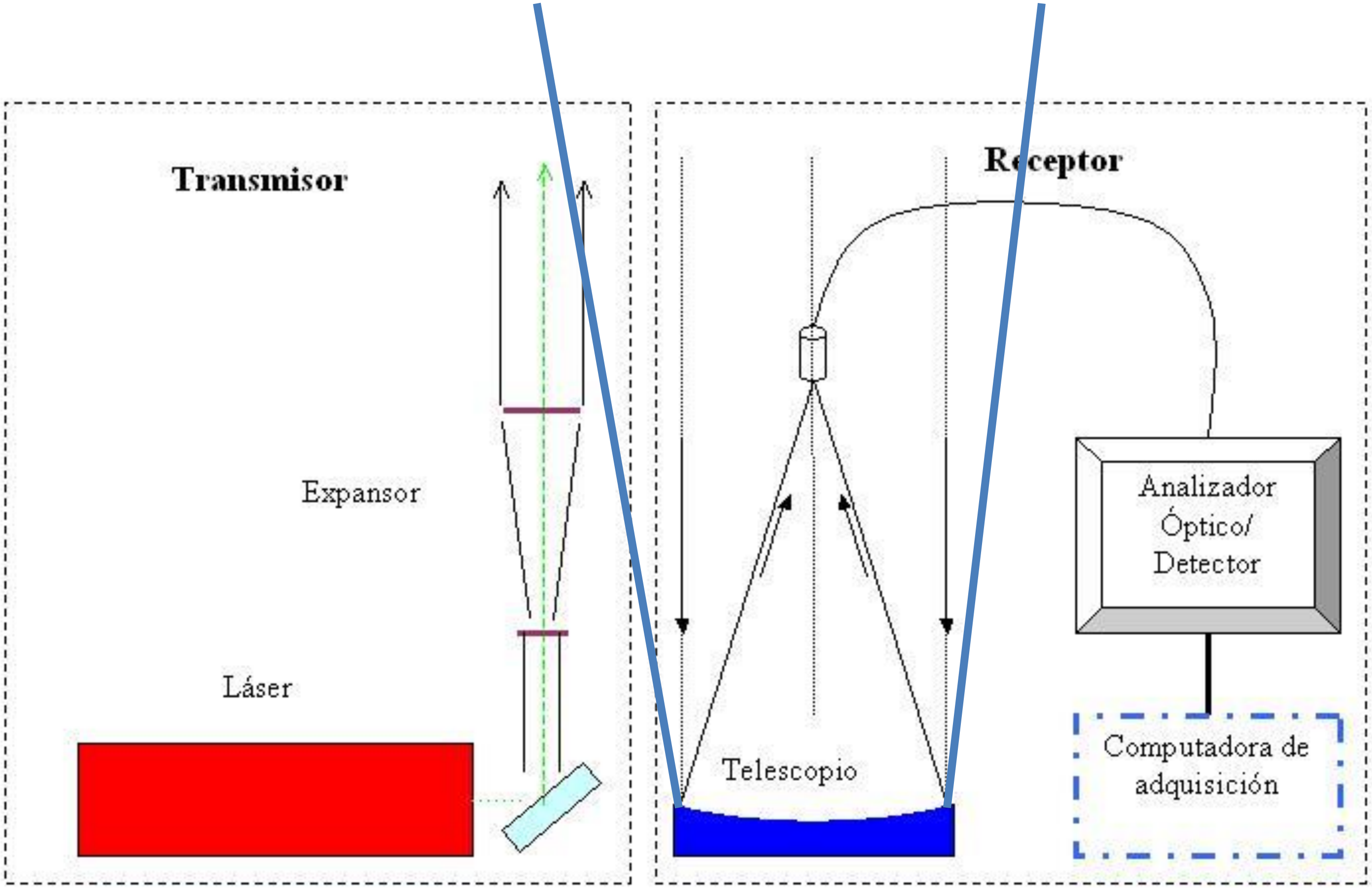
In the 1930s first attempts were made to measure air density profiles.
E.H. Synge: Phil. Mag. 9, 1014 (1930)

In 1938, pulses of light were used for the first time to measure cloud base heights.
R. Bureau: La Mitdorologie 3,292 (1946)

LiDAR acronym was introduced in 1953.
W.E.K. Middleton, A.F. Spilhaus: *Meteorologicnl Iizstrunzents* (University of Toronto Press, Toronto 1953)

Ref: LIDAR Range-Resolved Optical Remote Sensing of the Atmosphere, Claus Weitkamp, Springer Series

Basic Diagram of a LIDAR



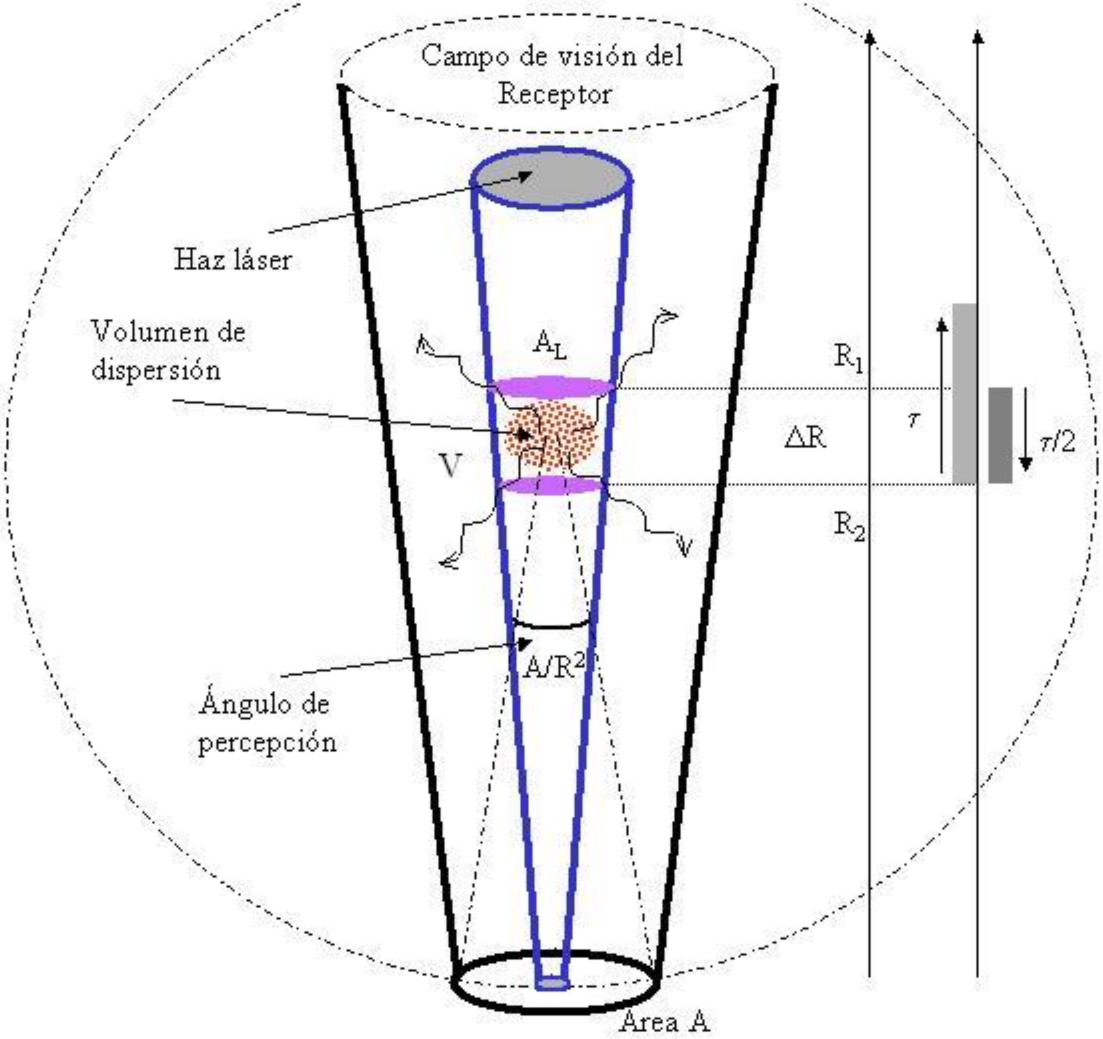
LIDAR Equation(1)
Elastic Lidar

(1) $$P(R) = KG(R)\beta(R)T(R)$$

(2) $$K = P_0 \frac{c\tau}{2} A\eta$$

(3) $$\Delta R = R_1 - R_2 = \frac{c\tau}{2}$$

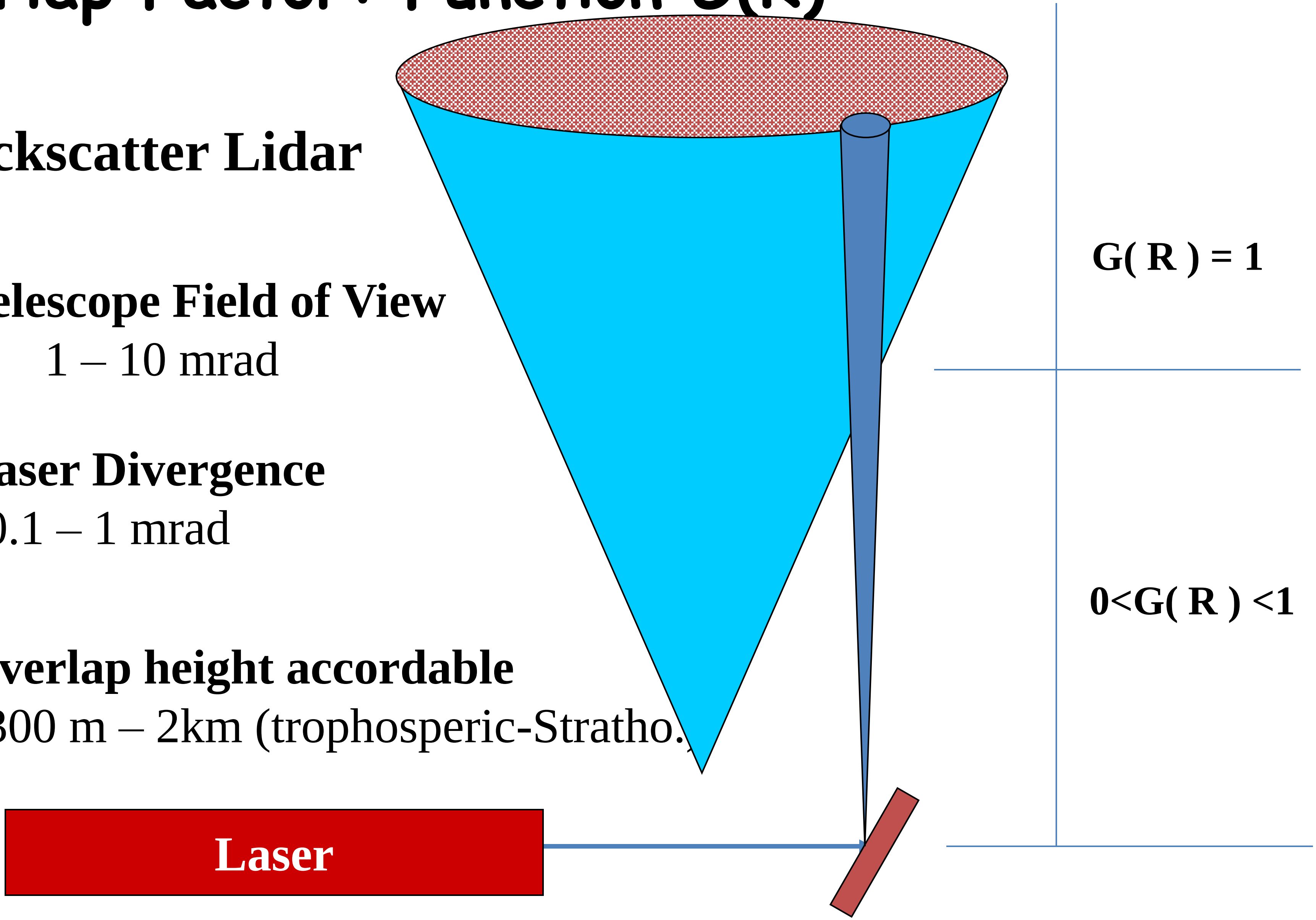
(4) $$G(R) = \frac{O(R)}{R^2}$$



Overlap Factor: Function G(R)

Backscatter Lidar

- **Telescope Field of View**
  1 – 10 mrad
- **Laser Divergence**
  0.1 – 1 mrad
- ✓ **Overlap height accordable**
  300 m – 2km (trophosperic-Stratho.)



G(R) = 1

0<G(R) <1

Laser

LIDAR Equation(2)

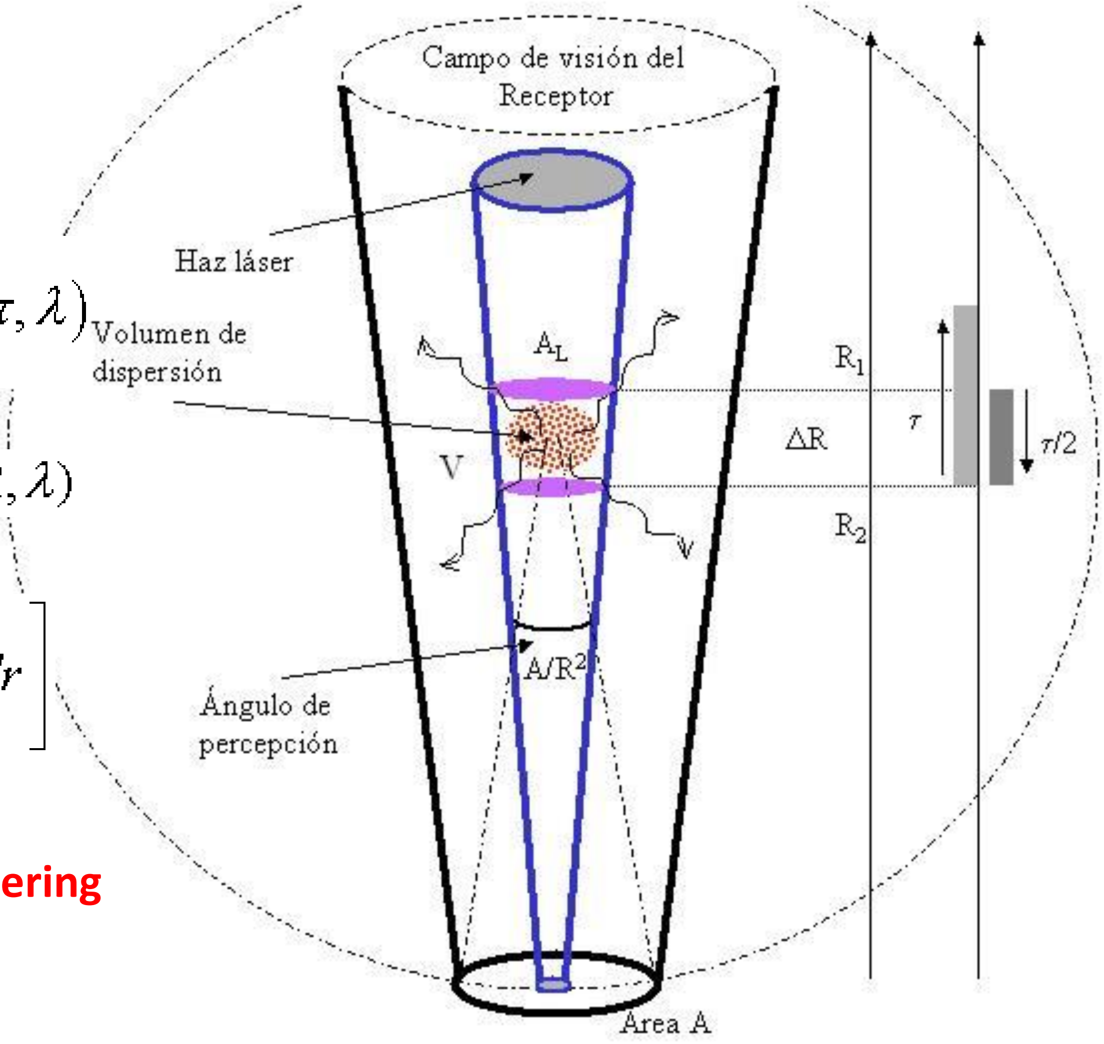
(1) $$P(R) = KG(R)\beta(R)T(R)$$

(5) $$\beta(R,\lambda) = \sum_j n_j(R)\frac{d\sigma_{j,sca}}{d\Omega}(\pi,\lambda)$$

(6) $$\beta(R,\lambda) = \beta_{mol}(R,\lambda) + \beta_{aer}(R,\lambda)$$

(7) $$T(R,\lambda) = \exp\left[-2\int_0^R \alpha(r,\lambda)\,dr\right]$$

Total Backscattering



LIDAR Equation(3)

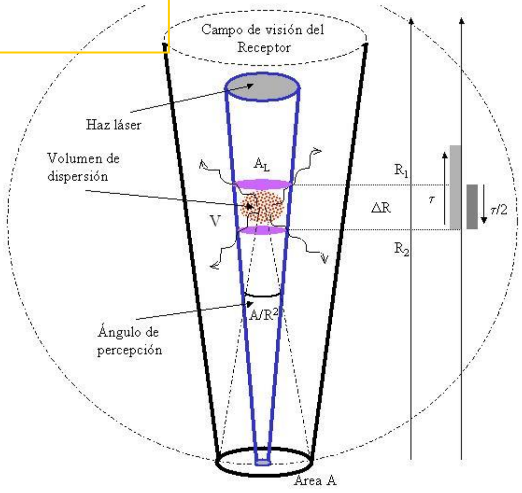
$$P(R) = KG(R)\beta(R)T(R) \qquad (1)$$

Replacing in Eq (1) the other Eqs. (2), (4), (5) Y (7), then:

$$P(R,\lambda) = P_0 \frac{c\tau}{2} A\eta \frac{O(R)}{R^2} \beta(R,\lambda) \exp\left[-2\int_0^R \alpha(r,\lambda)dr\right] \qquad (8)$$

Depends of a Wavelength and Range

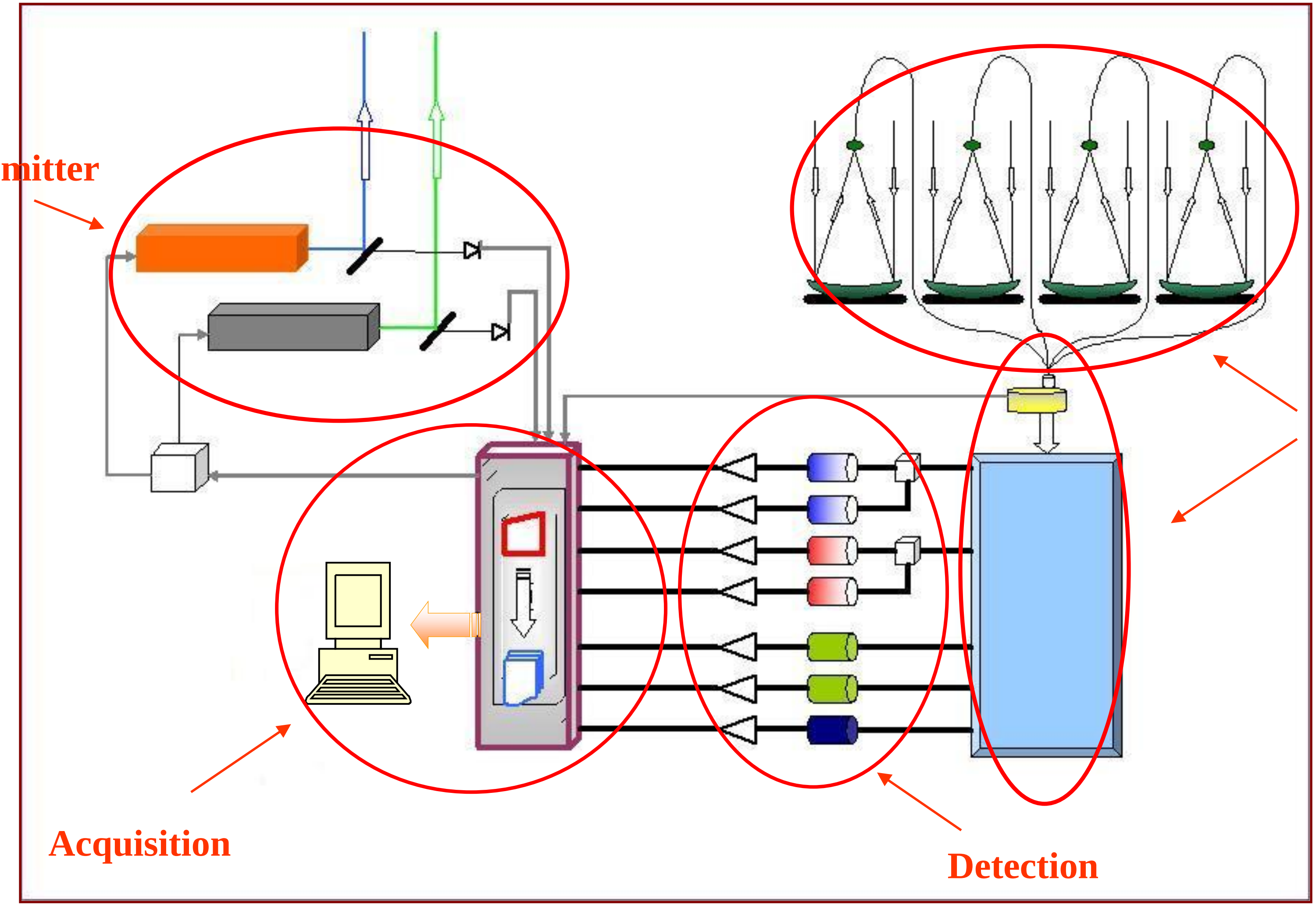
where P(R) is the power received from range R,
P0 is the average transmitted power during the laser pulse,
η is the receiver efficiency,
A is the receiver area,
R is the range to the scattering volume,
c is the speed of light,
t is the laser pulse duration,
and ß and a are the atmospheric backscatter coefficient
and atmospheric extinction coefficient at range R



DIAL Motivation

- DIAL systems in both the ultraviolet (UV) and infrared (IR) spectral regions were developed and fielded for ozone and industrial emissions including SO2, NO2, NH3 , HCl, CO etc.
- The DIAL technique uses the idea of differential-absorption measurement.
- Two light pulses of different wavelengths are launched along the same path into the atmosphere, and two corresponding backscattered profiles are simultaneously measured.
- The DIAL wavelengths are selected so that the light at the one wavelength, λon, is strongly absorbed by the absorbing species under investigation, whereas the light at the second wavelength, λoff, is absorbed not at all or at least much less

Description DIAL System

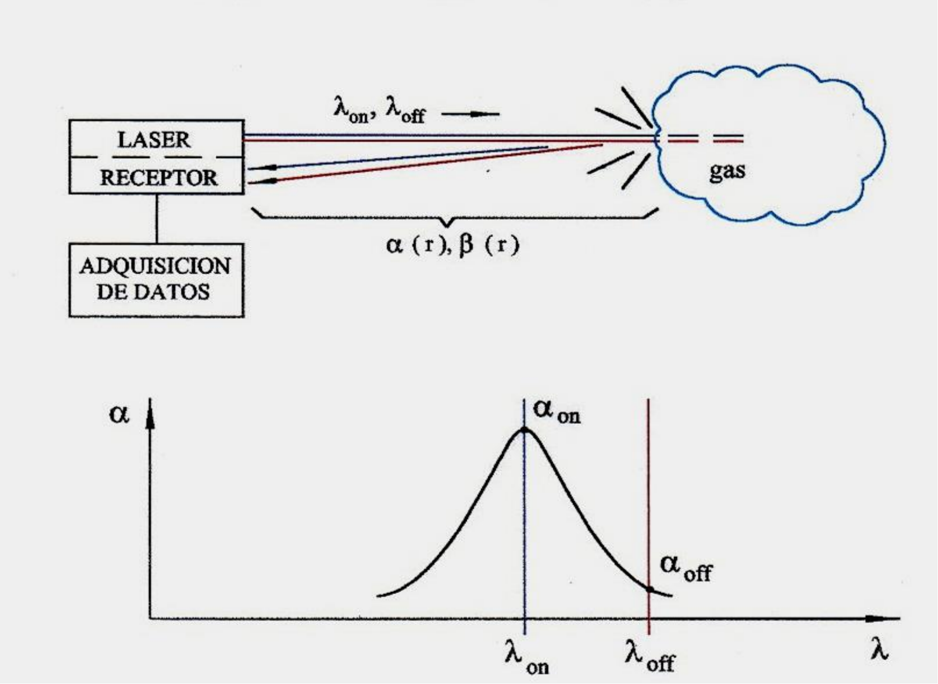


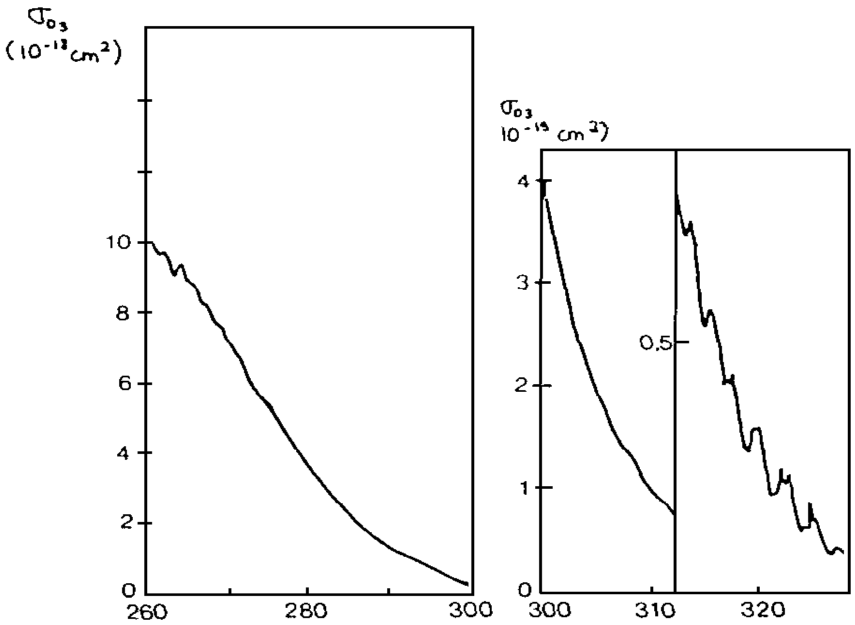
Differential Absorption Lidar

Wavelength Pair Selection

$\lambda_{on:}$ partial wavelenght absorption by the gas under study

$\lambda_{off:}$ reference wavelenght





(Inn y Tanaka, 1953).

La elección de la longitud de onda de referencia (λ_{off}) se determina por la condición De que la diferencia de la sección eficaz entre $\lambda_{off}\lambda_{on} > 100$

$\Delta\lambda$ > 37 nm in the UV Region

DIAL equation (1)

Lidar Equation

$$P(R,\lambda) = P_0 \frac{c\tau}{2} A\eta \frac{O(R)}{R^2} \beta(R,\lambda) \exp\left[-2\int_0^R \alpha(r,\lambda)\,dr\right]$$

Transmission

$$T(R,\lambda) = \exp\left[-2\int_0^R \alpha(r,\lambda)\,dr\right]$$

Extinction

$$\alpha(R,\lambda) = \alpha_{mol,sca} + \alpha_{mol,abs} + \alpha_{aer,sca} + \alpha_{aer,abs}$$

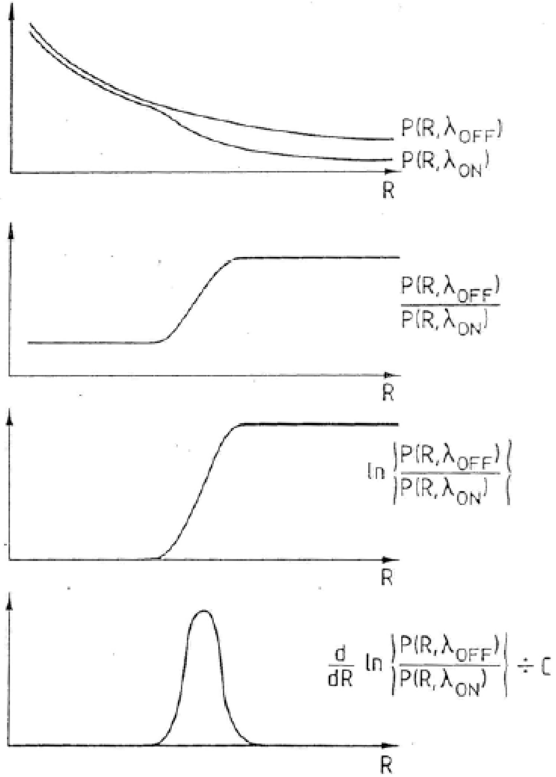
Molecular and Particle Scattering
(Rayleigh – Mie Scatt.)

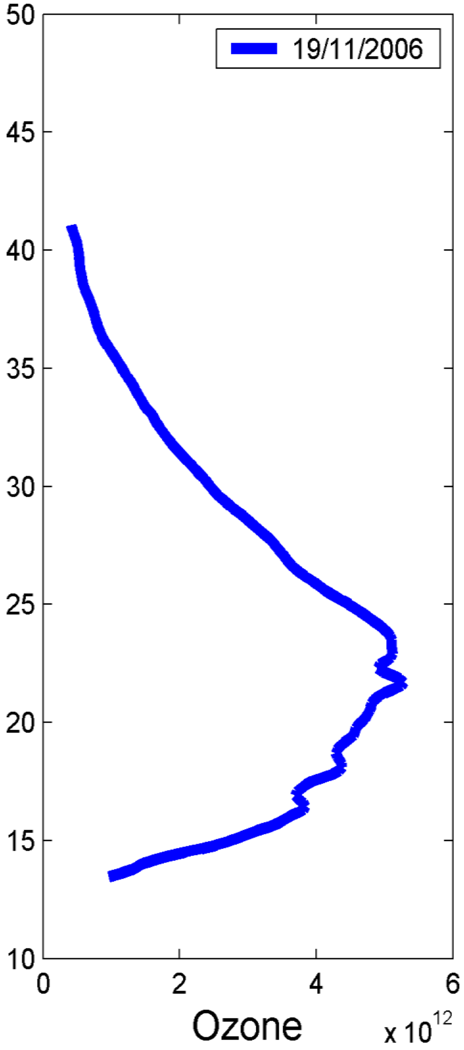
Molecular and particle Absorption

DIAL equation (1)

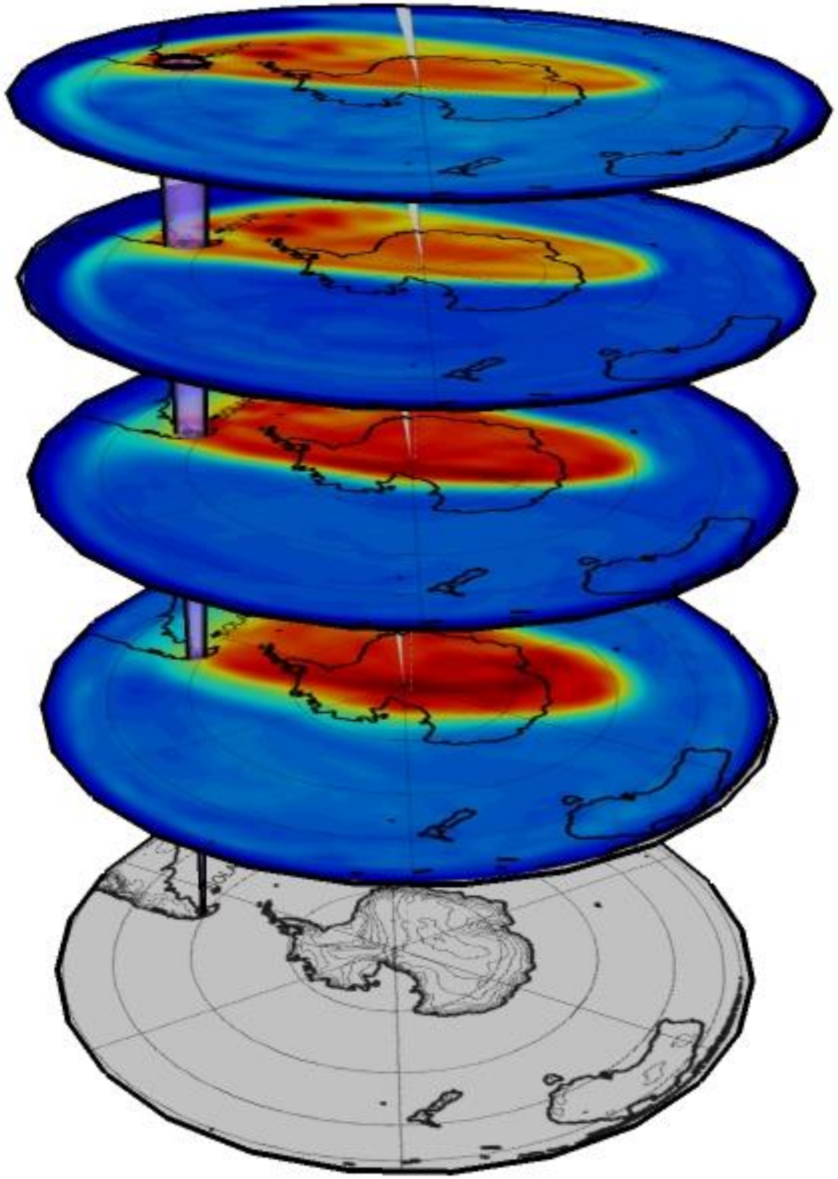
Signals: Generally in the detection each Pon and Poff signals are separated in High and Low Channels due the dinamical range of the lidar signal.

$$N(R)=\frac{1}{2\Delta\sigma}\frac{d}{dR}\ln\left(\frac{P(\lambda_{off},R)}{P(\lambda_{on},R)}\right)-\frac{1}{2\Delta\sigma}\frac{d}{dR}\ln\left[\frac{\beta\big(\lambda_{o}}{\beta\big(\lambda_{o}}\right.$$





DIAL Measurement

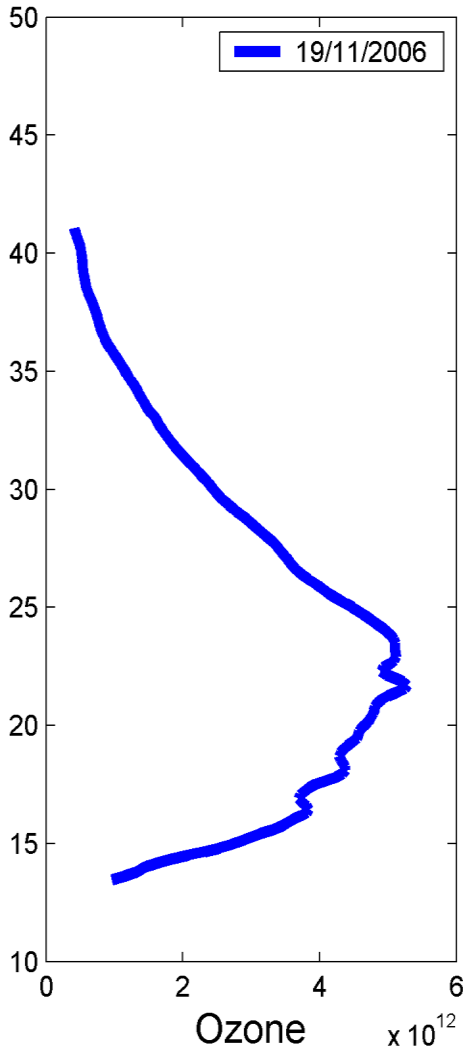


45 km

35 km

25 km

15 km



DIAL equation (1)

Simplified case: Extinction due only to absorbing gas

$$\Delta\alpha = N\,\Delta\sigma$$

where N is the molecule number density of the trace gas and

$$\Delta\sigma = \sigma(\lambda_{\mathrm{on}}) - \sigma(\lambda_{\mathrm{off}})$$

where σ is the molecular absorption cross section.

$$N = \frac{1}{2\Delta\sigma}\left[\frac{\mathrm{d}}{\mathrm{d}R}\ln\left(\frac{P_{\mathrm{on}}}{P_{\mathrm{off}}}\right)\right].$$

With the assumption that
Backscattering absorption
At two wavelength are
identical

DIAL equation is **self-calibrating measurement techniques**!!!!!
No instrumental constants appear in final equation

Lidar Retrieval for O_3 Measurements

DIfferential **A**bsorption **L**idar: **DIAL**

Statistical Error:

$$\varepsilon_s(z) \propto \left(A\,\Delta Z_f^{\,3}\,P_o\,T_a\right)^{-1/2}$$

A	telescope area
ΔZ_f	final vertical resolution
P_o	emitted laser power
T_a	duration of the measurement

Corrective o complementary term:

$$\delta n_{O_3}(z) = \frac{1}{\Delta\sigma_{O_3}(z)} \cdot \left[\underbrace{\frac{1}{2}\cdot\frac{d}{dz}\ln\frac{\beta(\lambda_{on},z)}{\beta(\lambda_{off},z)}} - \Delta\alpha_{Ray}\underset{\downarrow}{(z)} - \Delta\alpha_{Mie}\underset{\downarrow}{(z)} - \underbrace{\sum_e \Delta\sigma_e(z)\cdot n_e(z)} \right]$$

differential Rayleigh & Mie extinction coefficients

$\boxed{\beta = \beta_{Ray} + \beta_{Mie}}$

differential atmospheric scattering (Rayleigh & Mie)

$\boxed{\alpha(\lambda_{on},z) - \alpha(\lambda_{off},z)}$

differential extinction by other atmospheric constituents

O_3 Concentration Algorithm

Time-average lidar signals

Reading of LIDAR signals ($N_{\lambda i}$, i=6)

Background signal correction ($Nbg_{\lambda i}$, i=6)

OK?

non

yes

Signal desaturation & Slopes Calculations

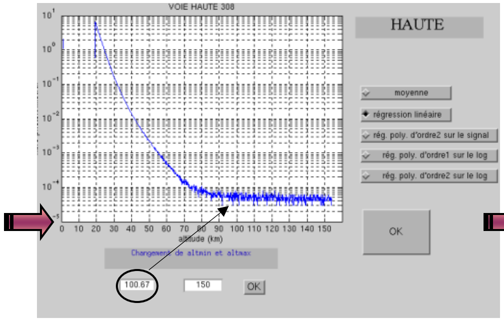
Low & High Rayleigh Slopes combination

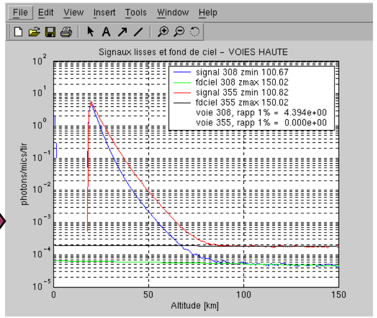
Ozone Absorption Cross Section (σ_λ =f(T) with $T_{radiosonde+cira}$)

O_3 Correction term Calculation (O_3 - cor_Ray)

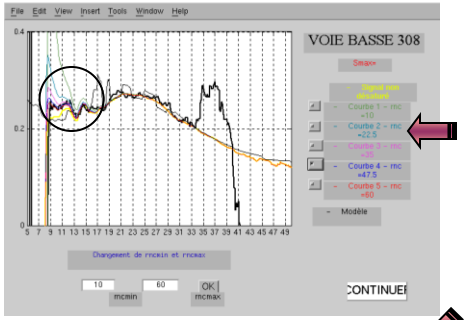
Combination of Raman & composite ozone profile

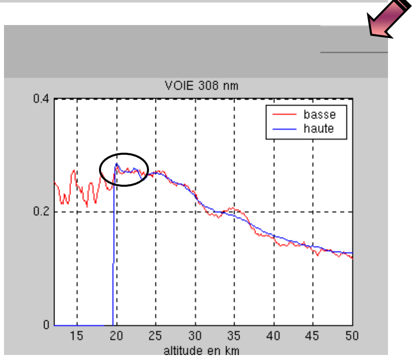
Ozone signal Filtering (binomial filter)





signal 308 zmin 100.67
fdciel 308 zmax 150.02
signal 355 zmin 100.82
fdciel 355 zmax 150.02
voie 308, rapp 1% = 4.394e+00
voie 355, rapp 1% = 0.000e+00





Calculation of Ln(($N_{\lambda i}$ - $Nbg_{\lambda i}$)z^2)

Vertical Resolution (number of points)

Slopes Calculation (2nd order linear regression)

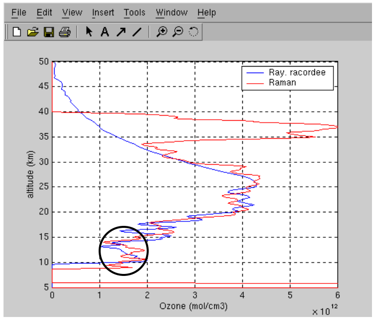
Desaturation : Pulse pile-up correction (Poisson's statistics)

⇩

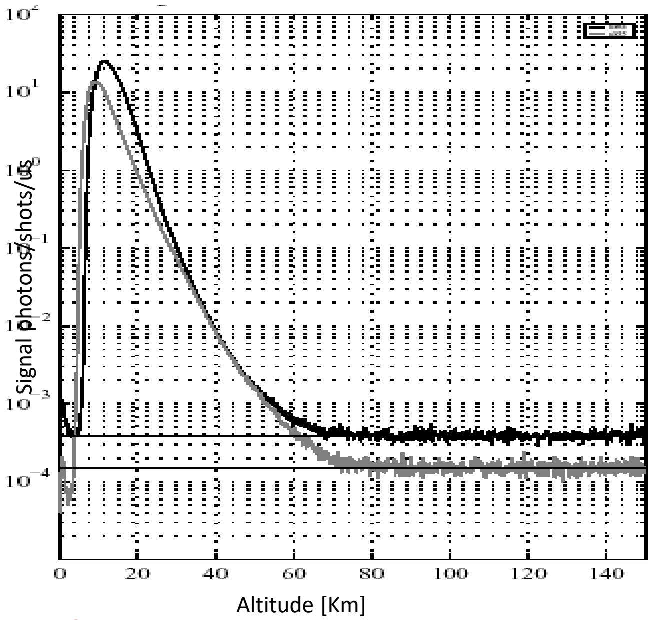
Comparison : Ray low - model Ray f(Raman signal)

Ray high - Ray low

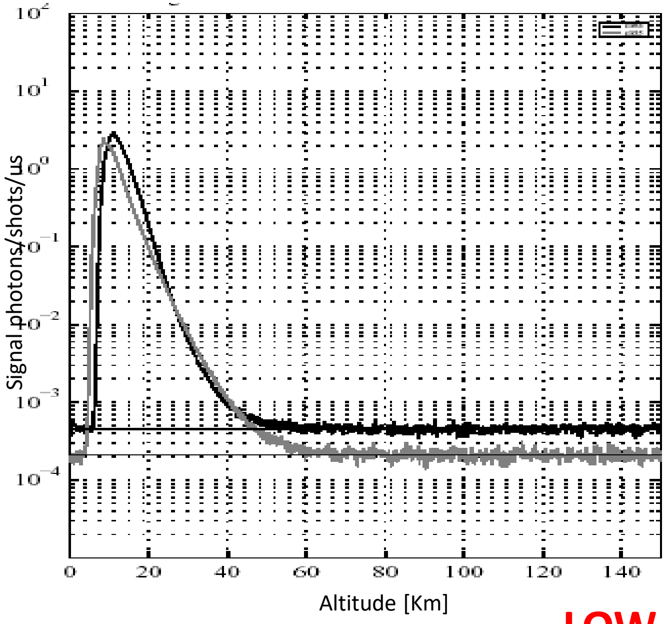
T, p, O_3



O_3 profiles, error, T, p



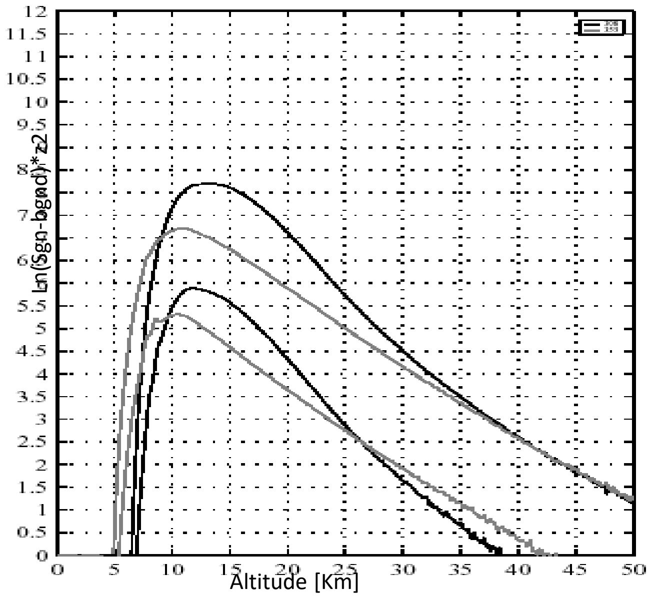
Signals high and background



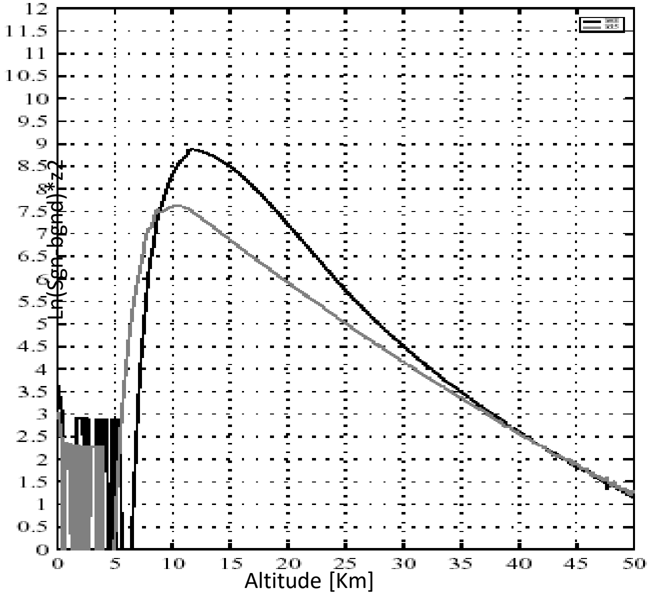
Signals low and background

HIGH Channels

LOW Channels

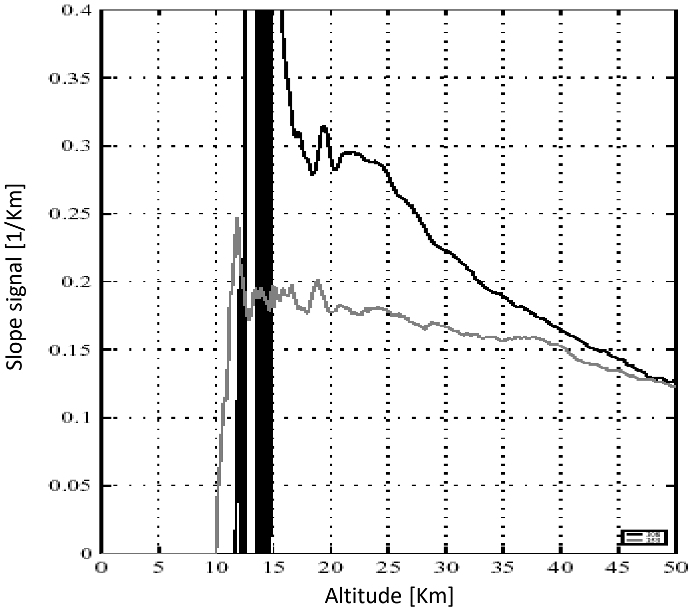


Rayleigh channel high and low

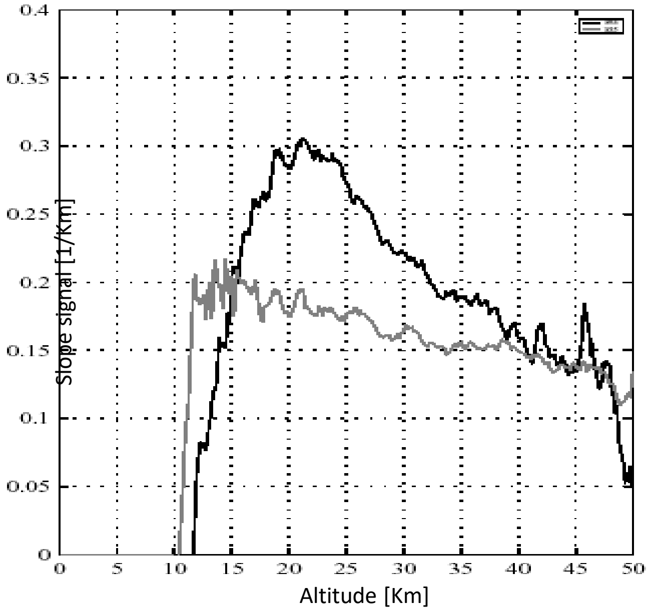


Rayleigh channel high and low

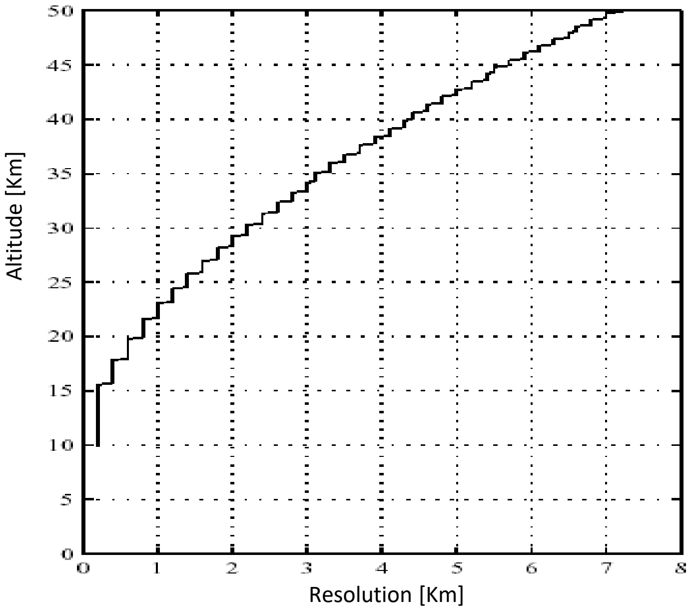
Rayleigh channel high



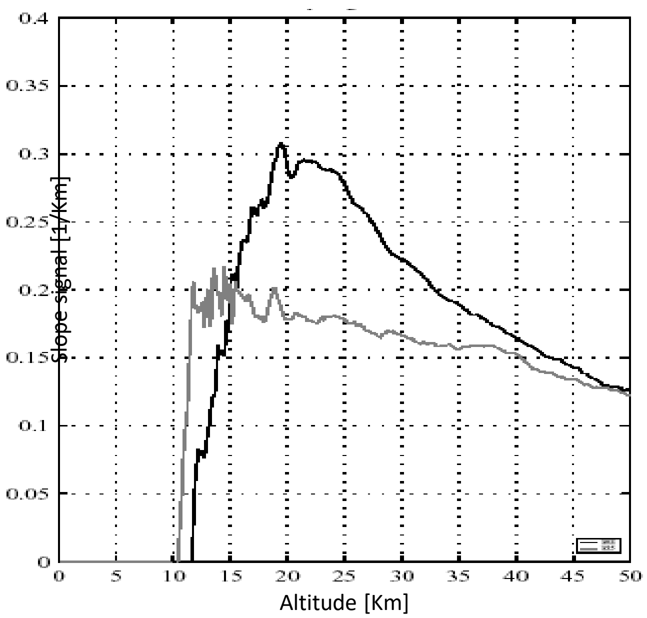
Rayleigh channel low

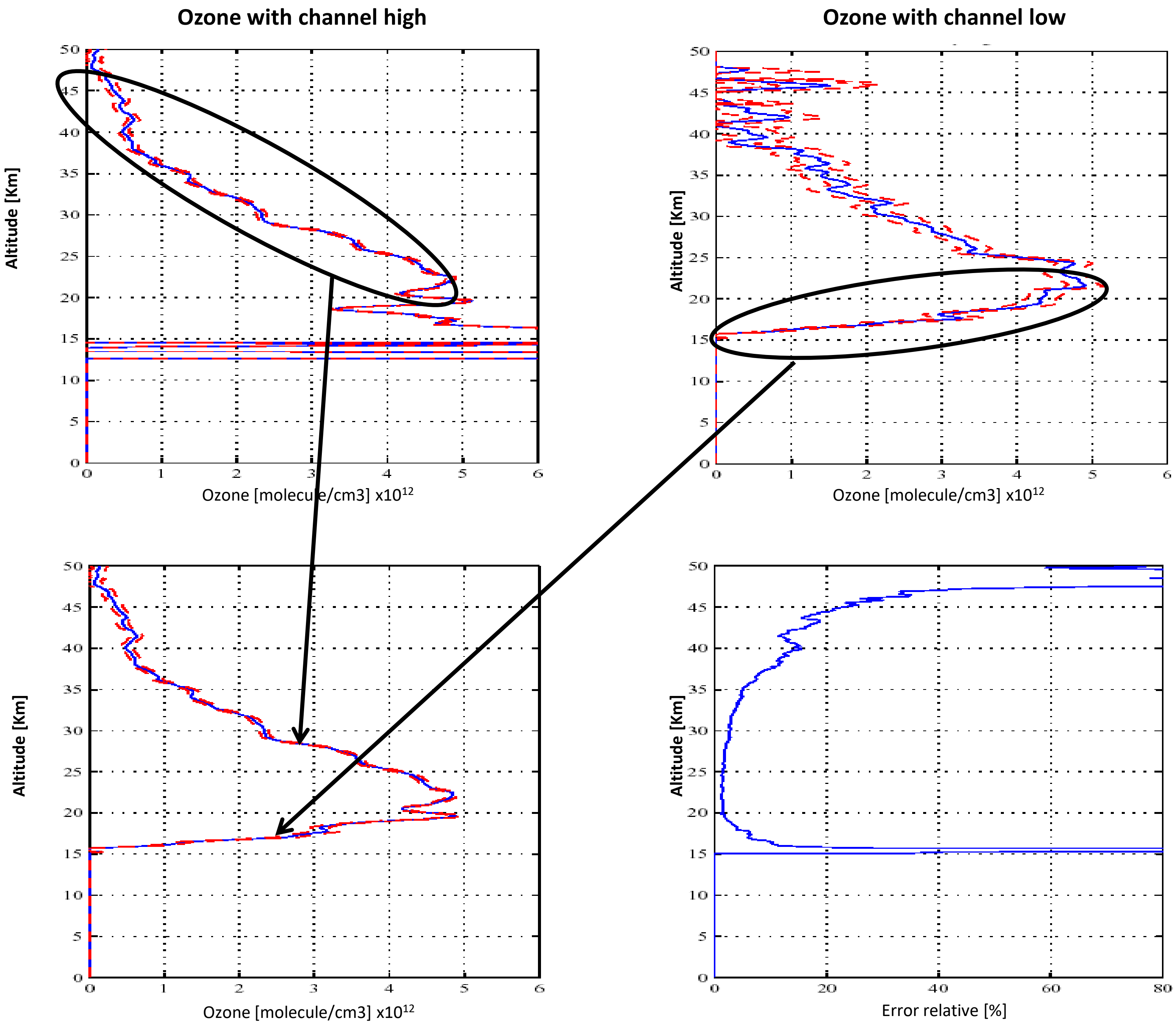


Resolution



Rayleigh channel

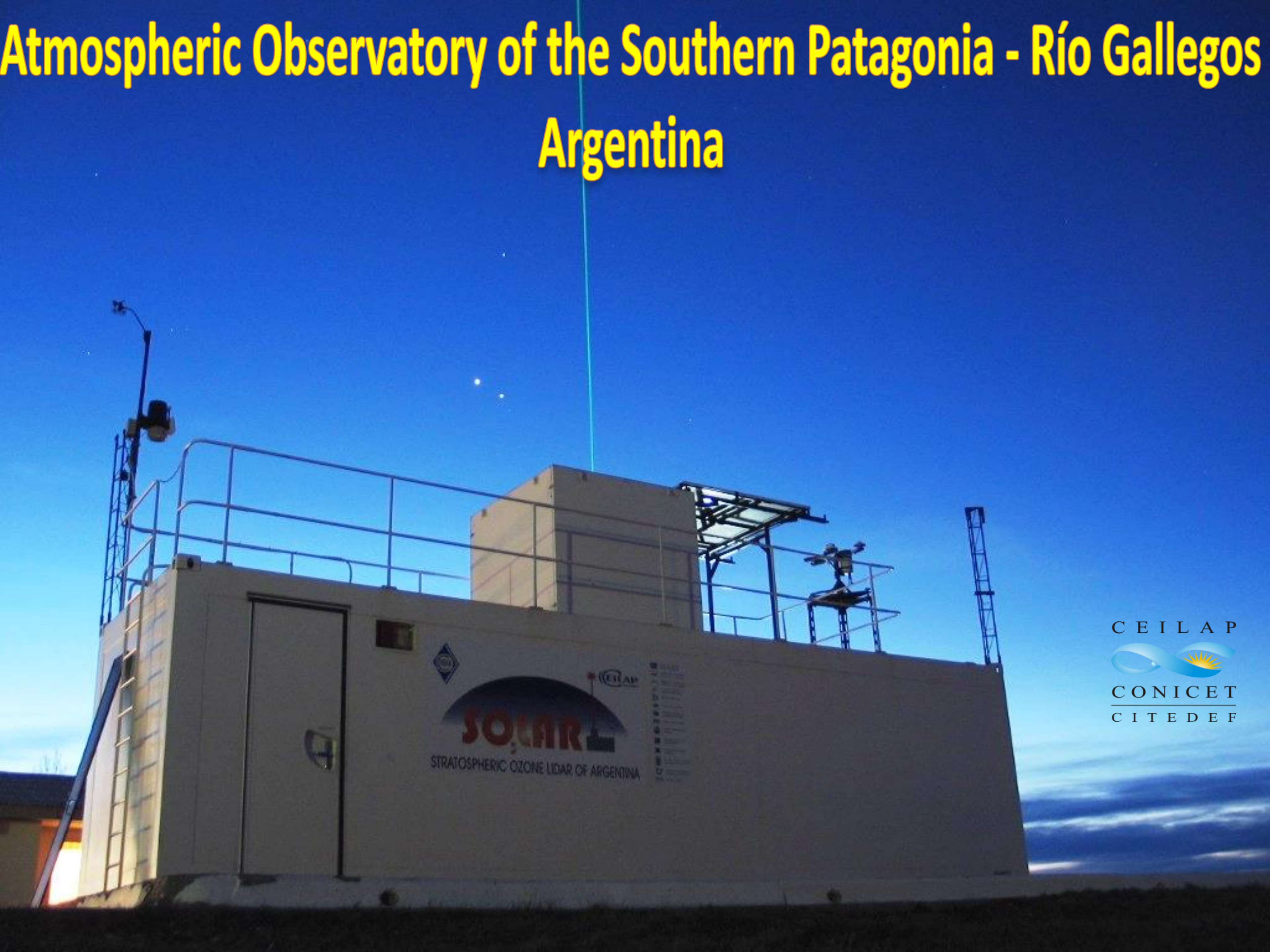




Ozone with channel high

Ozone with channel low

Atmospheric Observatory of the Southern Patagonia - Río Gallegos Argentina



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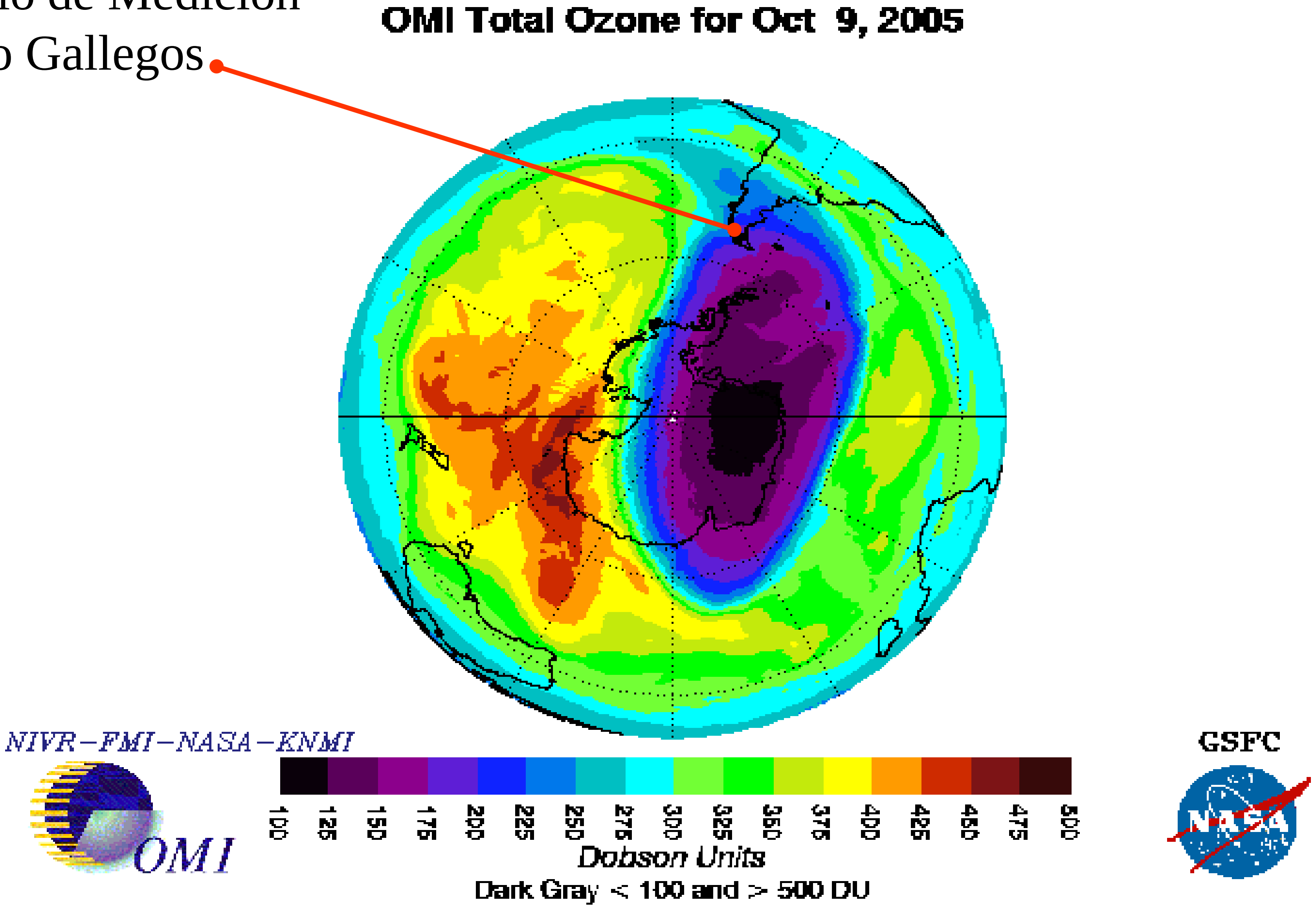
- Sitio de Medición Río Gallegos



Objectives

- Study the Ozone Layer at South of Argentina
- To Study the Vortex Overpass to Continental Part of Argentina
- To Measure UV Radiation at Ground Surface
- To Characterize the Atmosphere by additional measurements of:
  - ✓ Backscatter Measurements of aerosols
  - ✓ Water Vapor Mixing Ratios
  - ✓ Ground Surface Radiometric Measurements

Atmospheric Observatory of Southern Patagonia

Province of Santa Cruz, Argentine Patagonia.

Lat: 51º 36’ S, Lon: 69º 19’ W.

Military Air Force Base, Río Gallegos - Fuerza Aérea Argentina

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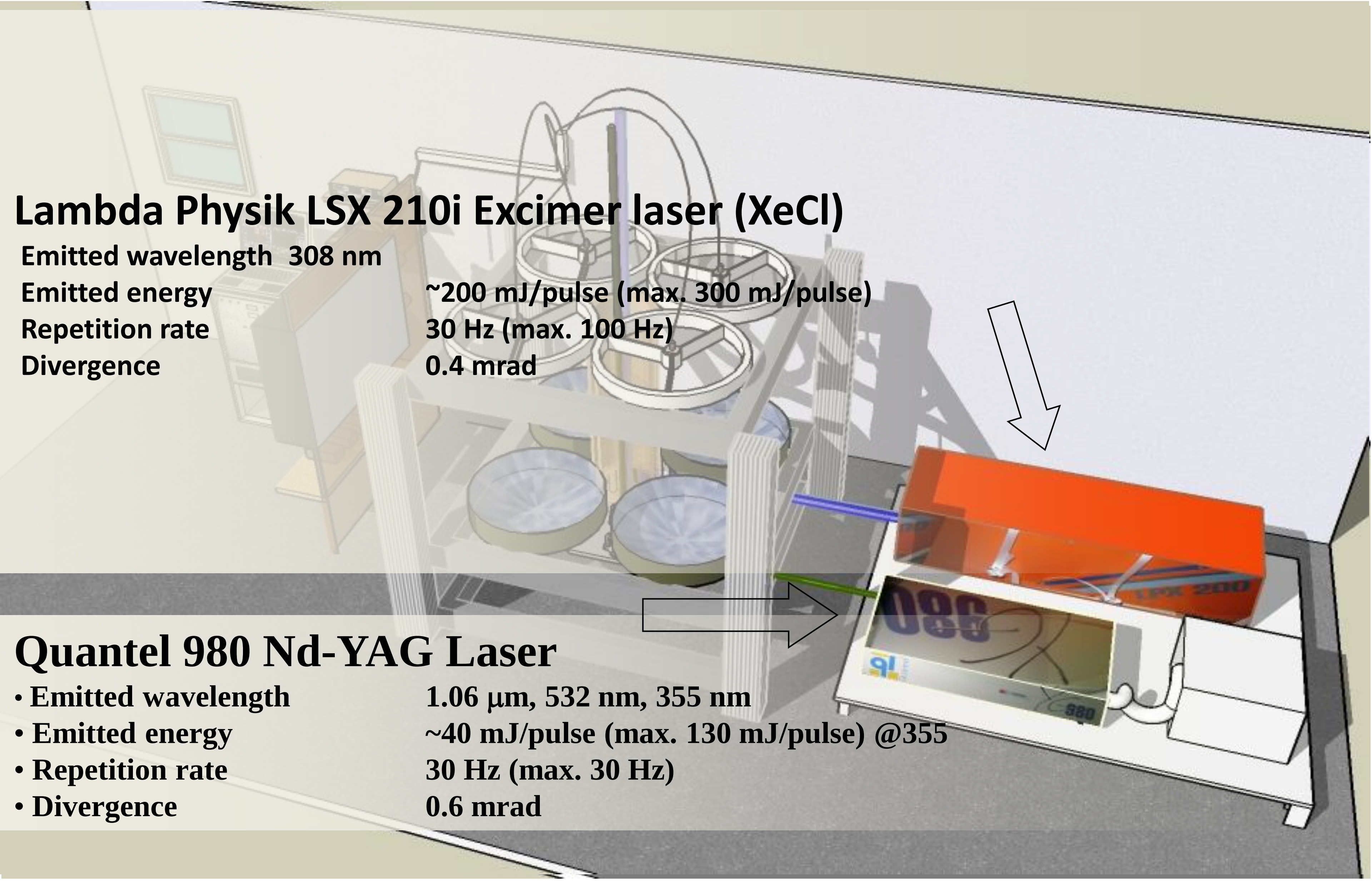
Observatorio Atmosférico de la Patagonia Austral

Lat: 51º 36’ S
Lon: 69º 19’ W
Elev:15 m s.n.m

DIAL SYSTEM Transmitter



Lambda Physik LSX 210i Excimer laser (XeCl)

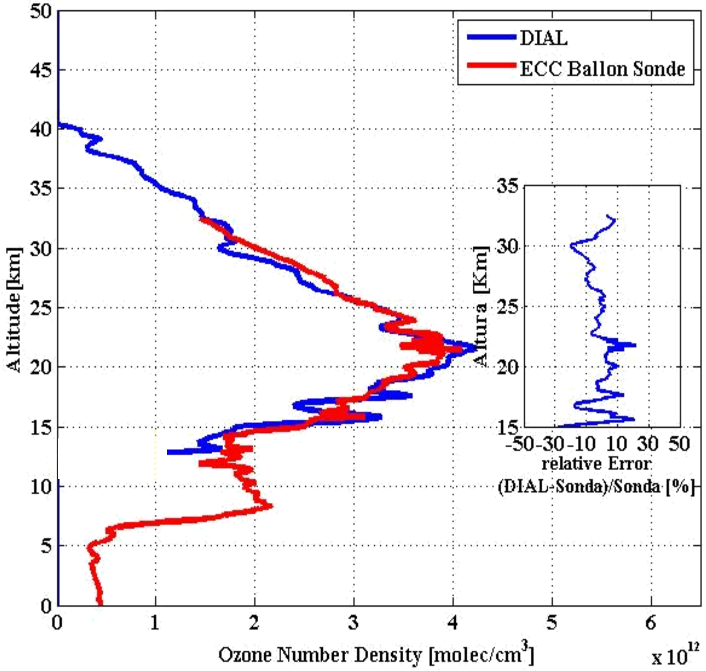
Emitted wavelength	**308 nm**
Emitted energy	**~200 mJ/pulse (max. 300 mJ/pulse)**
Repetition rate	**30 Hz (max. 100 Hz)**
Divergence	**0.4 mrad**

Quantel 980 Nd-YAG Laser

• **Emitted wavelength**	**1.06 μm, 532 nm, 355 nm**
• **Emitted energy**	**~40 mJ/pulse (max. 130 mJ/pulse) @355**
• **Repetition rate**	**30 Hz (max. 30 Hz)**
• **Divergence**	**0.6 mrad**

Intercomparison Campaign Río Gallegos 2010 and 2011

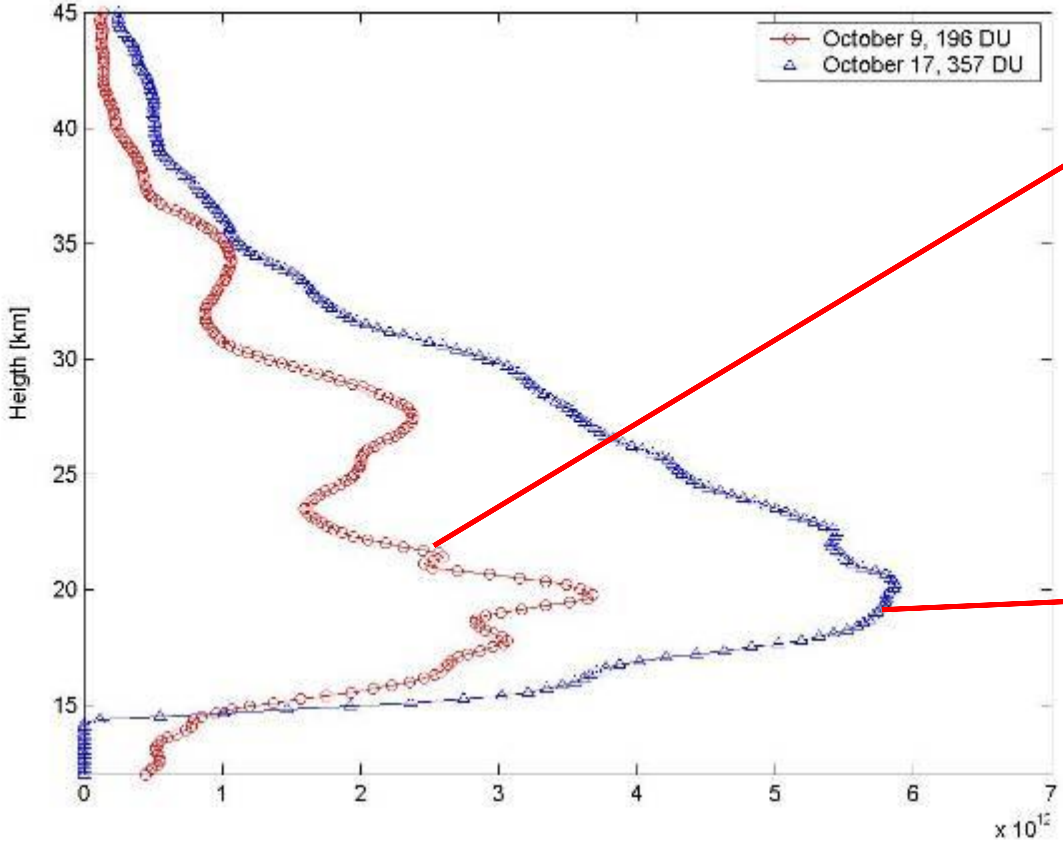
Argentina – Chile collaboration
3 sondes launched in
Río Gallegos site, collocated with
DIAL during first week of March

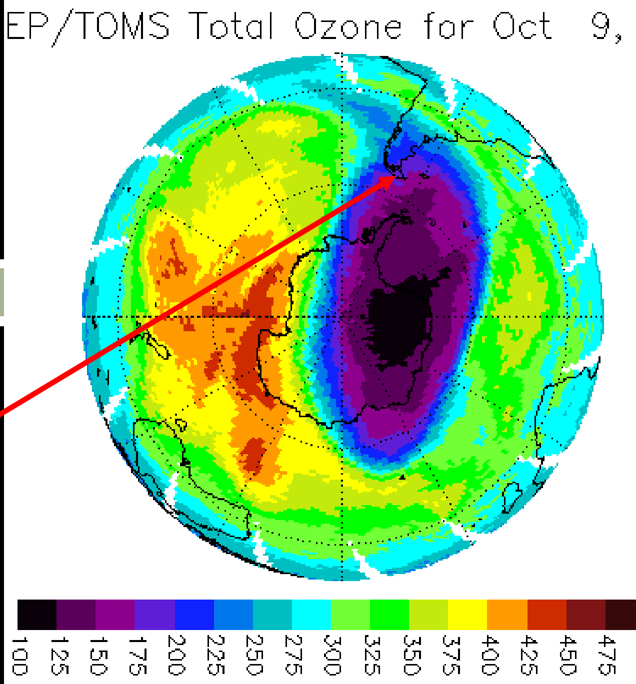


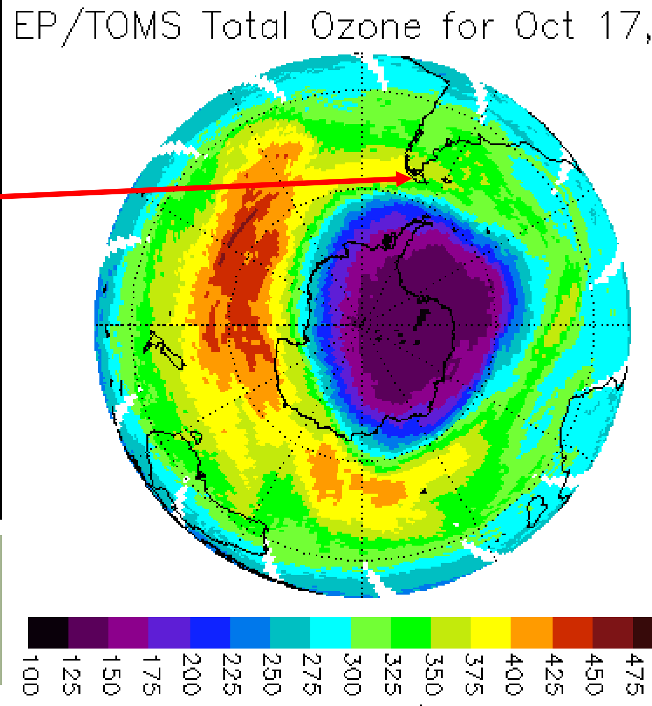
Extreme Depletion Event

Rio Gallegos.

October 9 2005







Monitoring of Ozone Reduction
SOLAR Campaign 2005

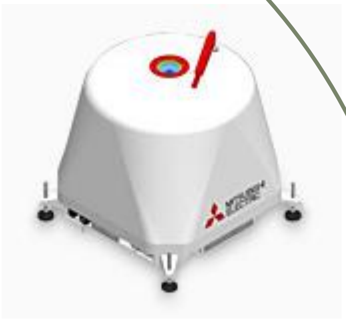
Detección coherente

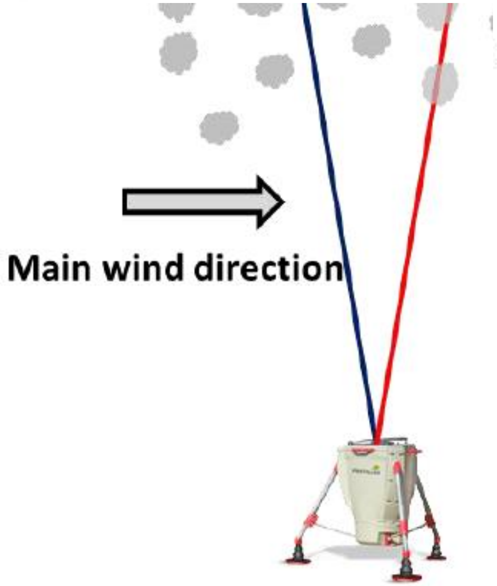
Detección directa

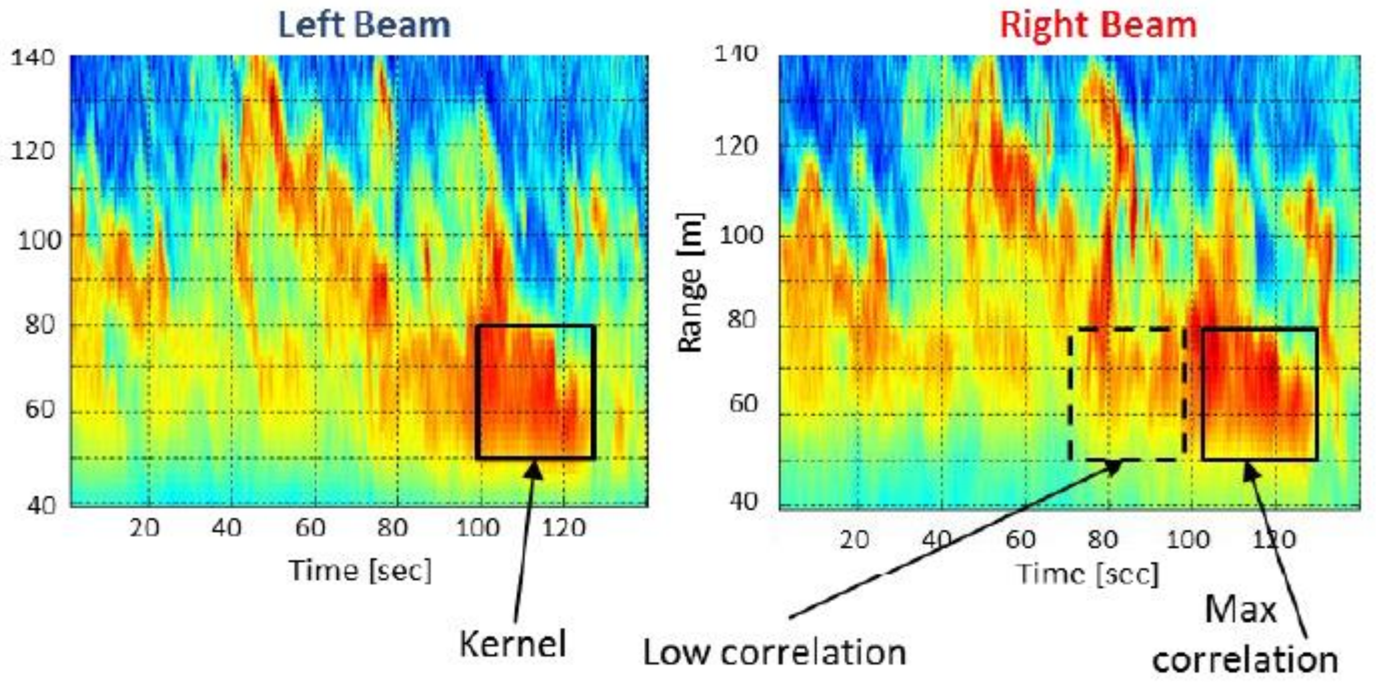
1/4

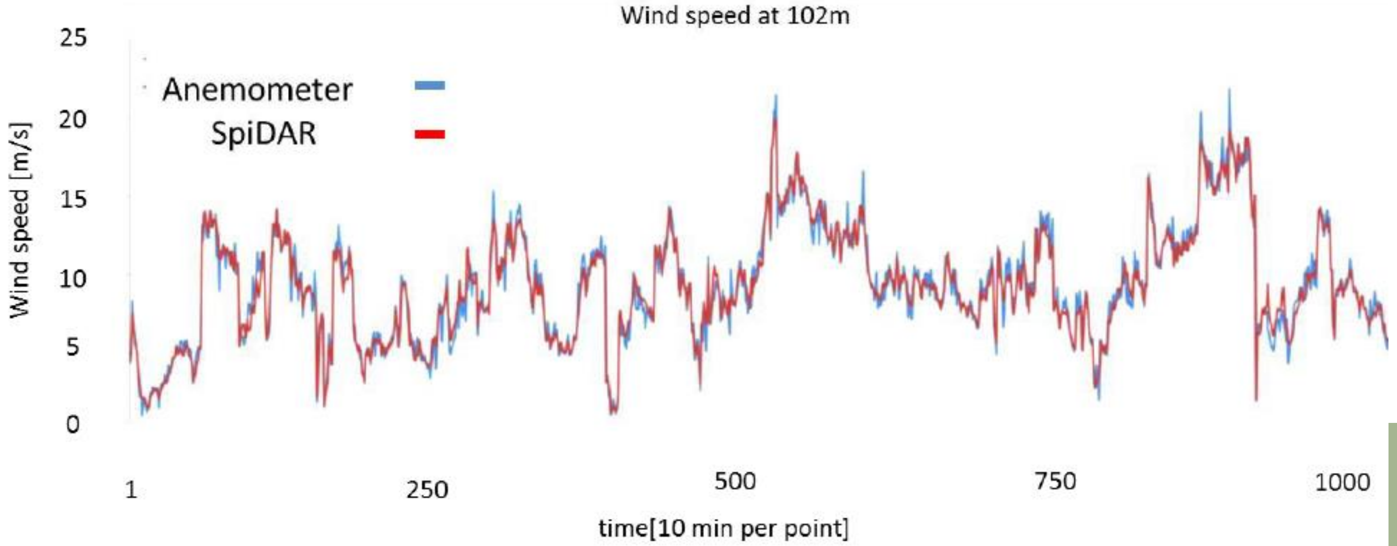

ZephIR 300M

- 3 years warranty offshore
- patented lidar for floating platforms
- DNV GL Stage 3 for fixed platforms
- unrivalled experience offshore

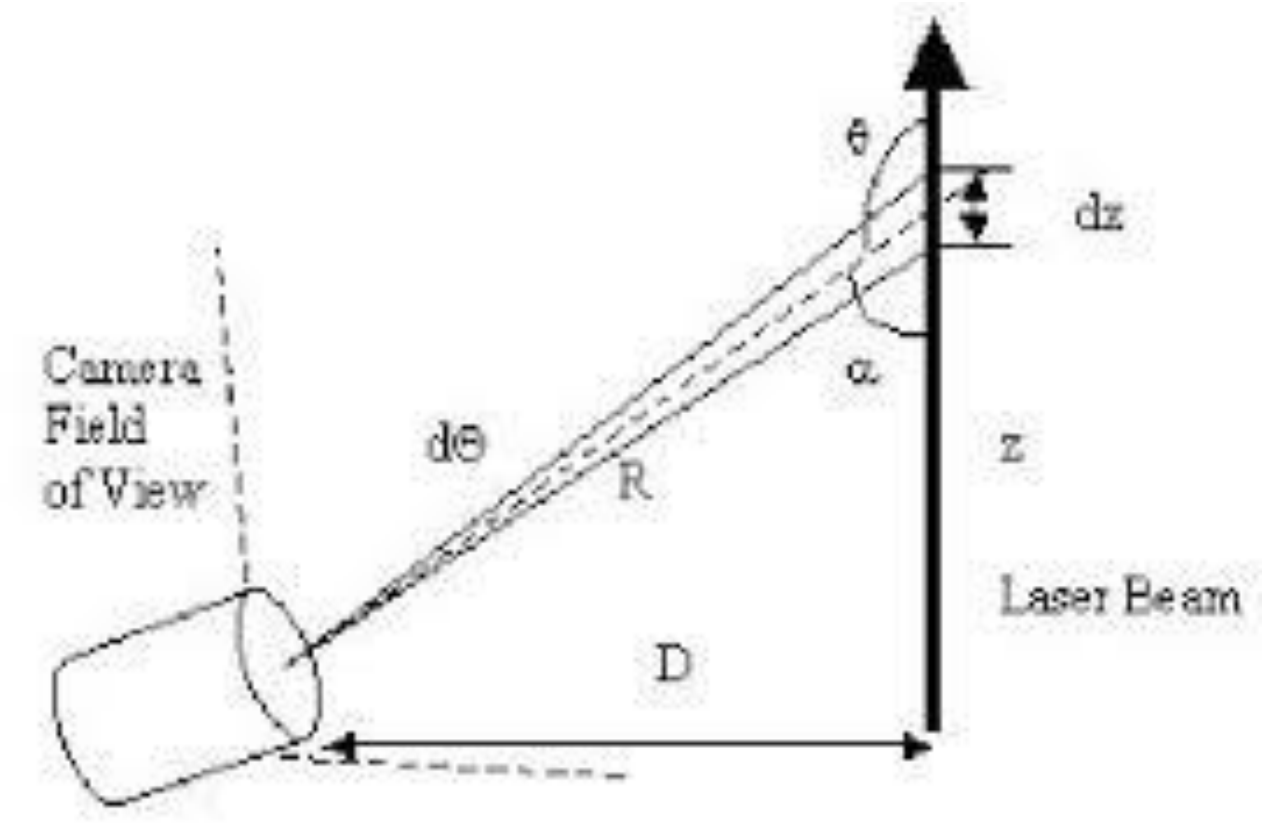



Main wind direction


Left Beam
Right Beam
Range [m]
140
120
100
80
60
40
20
40
60
80
100
120
Time [sec]
Kernel
Low correlation
Max correlation


Wind speed at 102m
Anemometer
SpiDAR
Wind speed [m/s]
25
20
15
10
5
0
1
250
500
750
1000
time[10 min per point]

Camera Imaging Lidar



Muchas gracias por su atención

A simple Introduction:

Obtention Temperature Profile in Stratosphere (line 355 nm)

$$P(r) = M_0\eta\frac{A}{r^2}\frac{c}{2}\beta(r)\exp\left(-2\int_0^r \alpha(r')dr'\right) \quad (1)$$

Mo is the number of photons transmitted
A is the receiver collecting area
η is the eficiency of the receiver
c is the speed of light

Above the stratospheric aerosol layer according to Equation (1) the return signal is proportional to the atmospheric density

$$n_R(r) \propto P(r)r^2$$

Range Corrected

If the density at some reference altitude is known eg from a radiosonde or a model atmosphere the lidar can be used to measure absolute density

The ideal gas law:

$$p = n_R k_B T \quad (2)$$

Assuming hydrostatic equilibrium the pressure change with altitude is given by the weight of the air column between two altitude levels

$$\frac{dp}{dr} = -n_R(r)Mg(r) \quad (3)$$

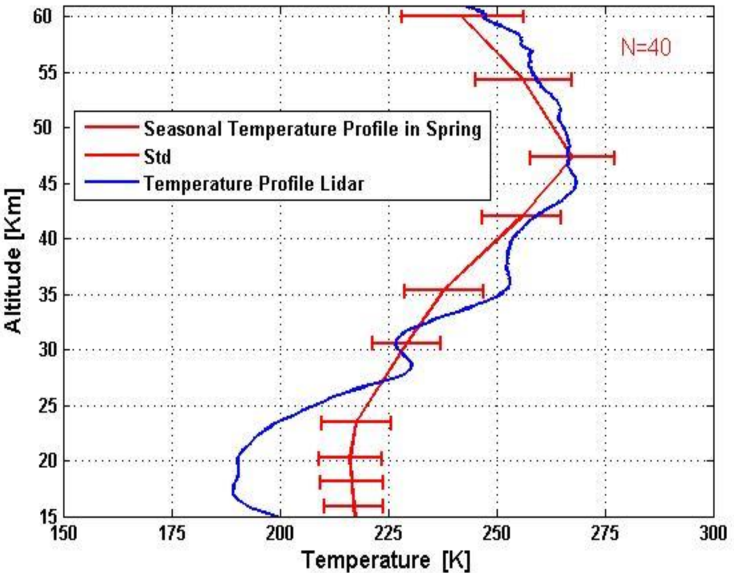
Integration of the hydrostatic equation (3) and use of the ideal gas law (2) give: :

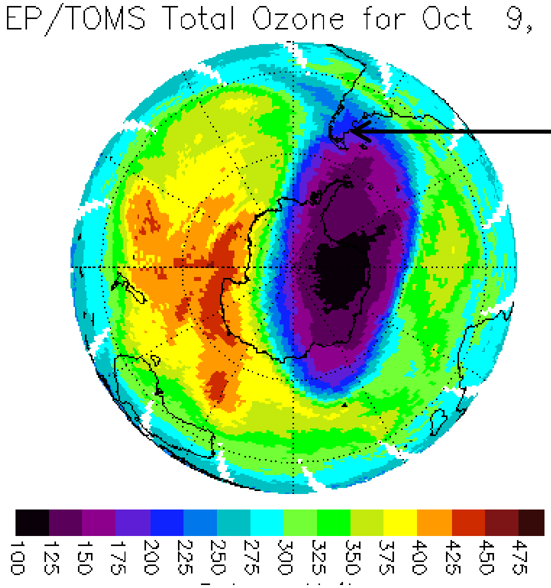
$$n_R(r)k_B T(r) = n_R(r_o)k_B T(r_o) - \int_r^{r_o} n_R(r')Mg(r')dr'$$

$$\boxed{T(r) = T(r_o)\frac{r_o^2 P(r_o)}{r^2 P(r)} + \frac{M}{k_B}\frac{\int_{r_o}^{r} r'^2 P(r')g(r')dr'}{r^2 P(r)}}$$

Dynamic of the Polar Vortex

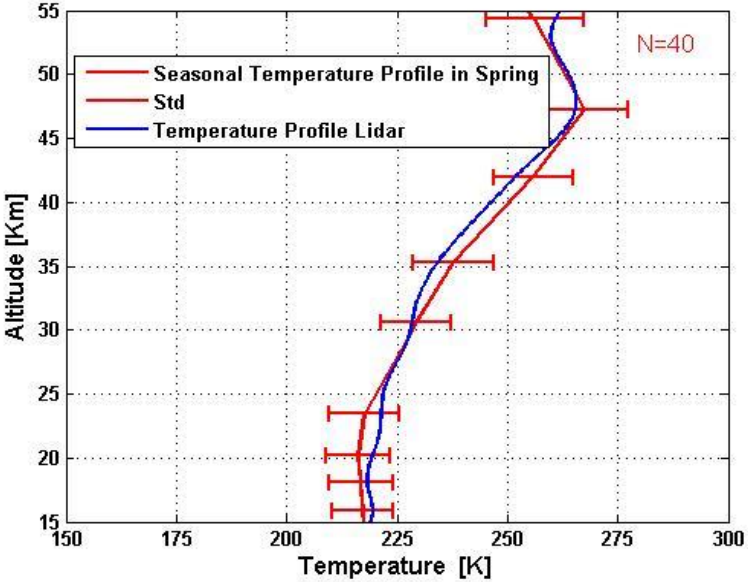
October 9, 2005

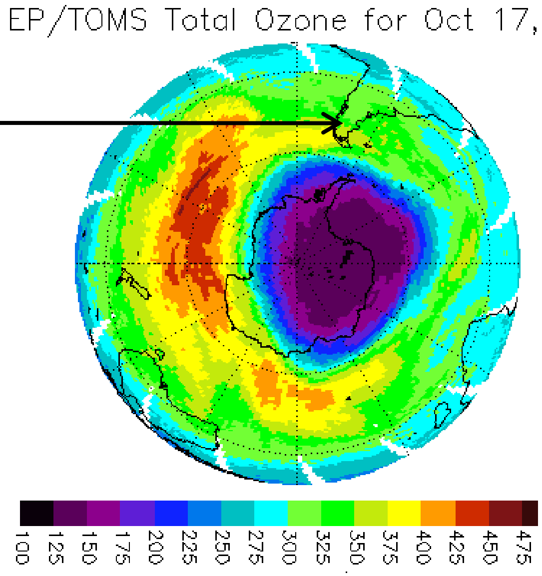




8 days

October 17, 2005





Measurement precision

History

Principle

NDACC

Mid-lat & Tropics

Polar studies

Trends Validation

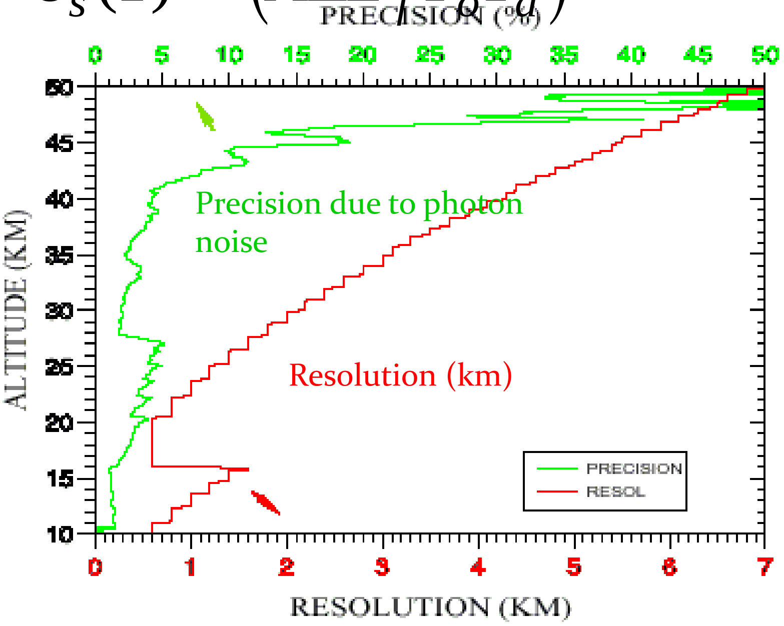
Perspective

Statistical error (photon noise)

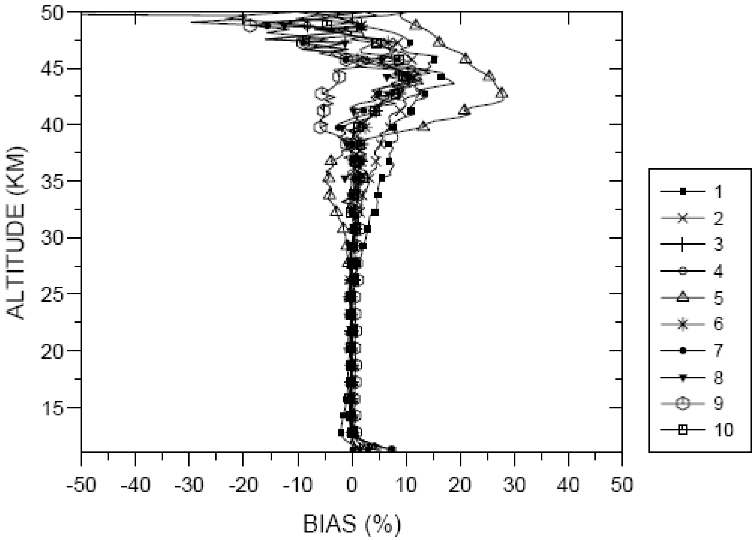
coefficients of derivative filter

$$\varepsilon_s(z) = \frac{1}{2n_{O_3}(z)\Delta\sigma_{O_3}\Delta Z}\left[\sqrt{\sum_{i,j}\frac{c_j^2 P_{i,j}}{N_i(P_{i,j}-P_{bg\,i})^2}}\right]$$

$$\varepsilon_s(z) \propto \left(A\Delta Z_f^3 P_o T_a\right)^{-1/2}$$



Bias of DIAL derivative filters



Godin et al., App. Opt., 1999

Accuracy of DIAL ozone profiles

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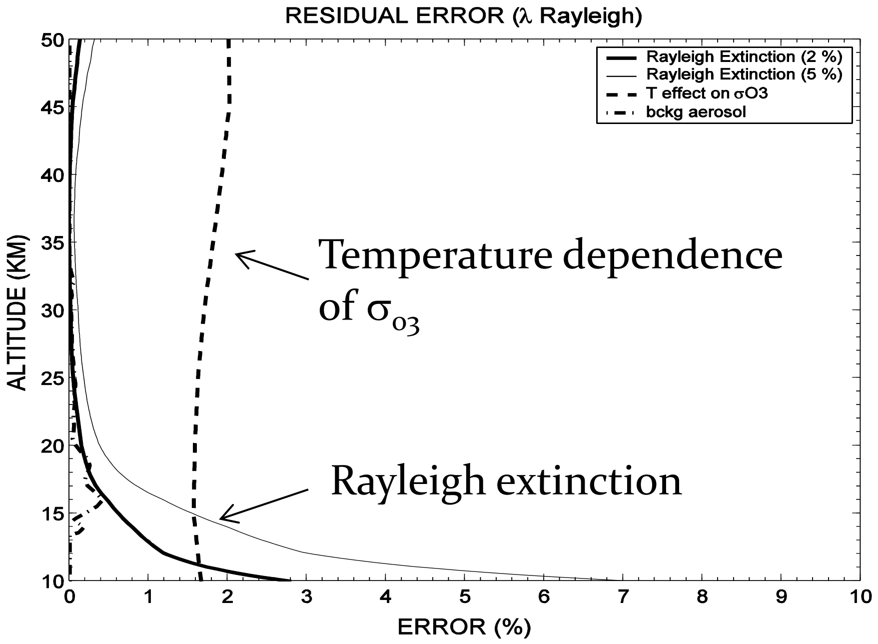
Residual error after correction of δno3 **not including the photon noise**



Temperature dependence of σ_{o3}

Rayleigh extinction

- Atmospheric number density 5% error
- 1.5 % precision in ozone cross-section, Temperature : error of 5 K

Above ~15-20km, residual error dominated by error on σo3(λ,z)

e.g. Godin-Beekmann et al., JEM, 2003

For most molecular species such as H2O, SO2,NO2, and NOthe wavelength separation between the **ON** and **OFF** wavelengths can be smaller than 1 cm-^{1}. If this is the case, the differences in the **scattering properties** of the atmosphere and **the differential extinction** due to aerosol and interfering gases **can be neglec**ted and the gas number density is given simply by:

$$N(R) = \frac{1}{2\Delta\sigma}\frac{d}{dR}\ln\left(\frac{P(\lambda_{off},R)}{P(\lambda_{on},R)}\right)$$

For the particular species mentioned above **great care should be taken to avoid systematic errors or random deviations** due to large laser linewidth or wavelength instability of the lidar transmitter.

This problem is not essential for species like ozone or chlorine that has broad absorption features.

The determination of gas concentration profiles with DIAL must include the following operations (Browell, 1985):

(1) Measurement of the elastic lidar signals at the on and off wavelengths.
An additional lidar signal measurement may also be made at a reference wavelength, lref, that allows determination of the backscattering and extinction corrections.

(2) Calculation of the first raw estimate of the absorbing gas concentration profile *N(R)* .This makes it possible to estimate the data quality and the achieved measurement range.

(3) Calculation of the particulate extinction coefficient profile at the reference wavelength and determination of the backscatter and extinction corrections for the ozone concentration.

(4) Calculation of the final absorbing gas concentration profile by using the backscatter and extinction corrections. Note that the backscatter and extinction corrections can be made either after taking the derivative oft he signal ratio logarithm or before this operation. One can avoid additional numerical differentiation when determining the backscatter correction
term, making the corrections before the ozone concentration is extracted (Kovalev and McElroy, 1994; Kovalev et al., 1996).

Interference with volcanic aerosol

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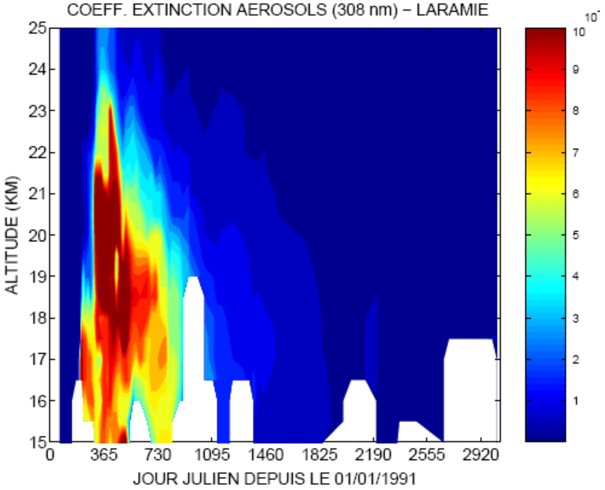
Use of N_2 Raman wavelengths

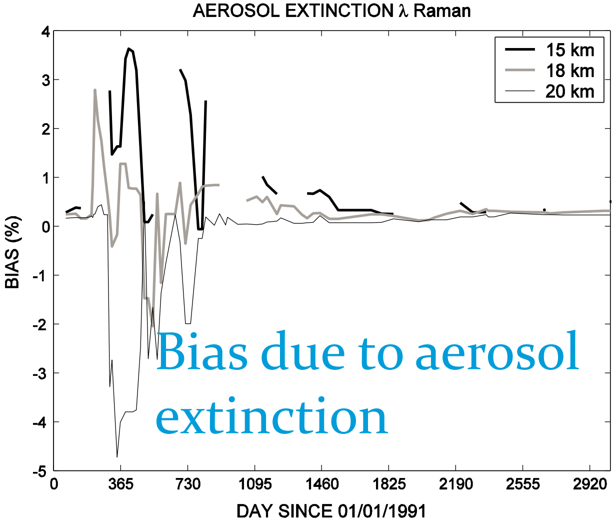
$$n_{O_3}(z) = -\frac{1}{2\cdot\Delta\sigma_{O_3}(z)}\frac{d}{dz}Ln\left(\frac{S(\lambda^R_{on},z)-S_b(\lambda^R_{on},z)}{S(\lambda^R_{off},z)-S_b(\lambda^R_{off},z)}\right)+\delta n_{O_3}(z)$$

$$\sigma_{O_3}(\lambda_{on},z)-\sigma_{O_3}(\lambda_{off},z)+\sigma_{O_3}(\lambda^R_{on},z)-\sigma_{O_3}(\lambda^R_{off},z)$$

McGee et al., GRL, 1993

Bias due to Pinatubo volcanic aerosol (using opical counter data from Deshler et al. GRL, 1993)





Bias due to aerosol extinction

DIAL equation (1)

In practice, lidar signals are **not** recorded or analyzed as continuous functions, but rather as values in **discrete range bins.**

$$N = \frac{1}{2\Delta\sigma}\left[\frac{\mathrm{d}}{\mathrm{d}R}\ln\left(\frac{P_{\mathrm{on}}}{P_{\mathrm{off}}}\right)\right]. \Rightarrow N = \frac{1}{2\Delta\sigma\,\Delta R}\ln\left(\frac{P_{\mathrm{off}}(R+\Delta R)}{P_{\mathrm{off}}(R)}\,\frac{P_{\mathrm{on}}(R)}{P_{\mathrm{on}}(R+\Delta R)}\right)$$

A real lidar system will have some limit with which it can resolve the term in parentheses

lidar's *limit of detection N$_{LD}$* *for the gas of interest.*

R.T.H. Collis, P.B. Russell: Lidar Measurement of Particles and Gases by Elastic Backscattering and Differential Absorption. In *Laser Monitoring of the Atmosphere, E.D. Hinkley, ed. (Springer-Verlag, NewYork 1976), p. 102*

Error propagation

Assuming for simplicity that the error in the off signal can be ignored in comparison with that in the on signal, one can obtain a simple formula for the relative error of the chemical species concentration.

$$\delta n' = \frac{1}{2\Delta\tau_{A,\mathrm{dif}}}\sqrt{\left[\frac{\Delta P_{\mathrm{on}}(r)}{P_{\mathrm{on}}(r)}\right]^2 + \left[\frac{\Delta P_{\mathrm{on}}(r+\Delta r)}{P_{\mathrm{on}}(r+\Delta r)}\right]^2 \pm [\mathrm{COV}(P_r, P_{r+\Delta r})]^2}$$

$$\Delta\tau_{A,dif} = \tau_{A,on} - \tau_{A,off} = N(R)\Delta\sigma\Delta R$$

where $\Delta\tau_{A,dif}$ is the differential optical depth, that is, the difference between the optical depths $\tau_{A,on}$ and $\tau_{A,of}$f over the range

When ΔR *is small, the quantities Pon(R) and Pon(R +* Δ*R) may be highly correlated;* therefore, the covariance term of the signals, COV(P_R, P_R+Δ*R) Is included*

the range element Δ*R in DIAL measurements must be long enough to* provide acceptable accuracy in the retrieved chemical species concentration. Thus the local differential absorption optical depth is the *most important fac*tor *that influences accuracy of the measured data*.

First lidar measurements of ozone

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- First lidar measurements of ozone vertical distribution using dye lasers

  Mégie G., J.Y Allain, M.L. Chanin, J.E. Blamont

  Nature **270**, 329 - 331 (1977) | doi:10.1038/270329a0.

- Optimisation of lidar ozone measurements

  Minimisation of statistical error following Shotland, J Appl Meteor 13 (1974), for water vapor measurements

  Pelon J. and G. Mégie, Nature, 1982

- First measurements with an excimer laser

  Possibility to reach the high stratosphere

  Werner J, K. W. Rothe and H. Walter: Appl. Phys. B, 1983

Outlook and Conclusions

- Any lidar technique is dependent on the availability of suitable lasers, but for DIAL, the requirements are especially inflexible because the required laser characteristics are determined by the spectra of the molecules to be measured.
- The biggest problem has historically been to develop reliable lasers with outputs at appropriate wavelengths. (Tunable laser sources, especially OPOs)
- Remote monitoring of localized pollution sources such as plumes was demonstrated very early in the history of DIAL
- DIAL systems for ozone and industrial pollution will no doubt continue to gain acceptance as costs become lower,

Como desarrollar aun mas estas ideas

- Recurrir a financiamiento local, internacional (ventajas/desventajas).
- Facililidad en gestion de compras en el exterior.
- Generar redes y grupos de trabajo.