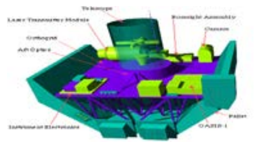
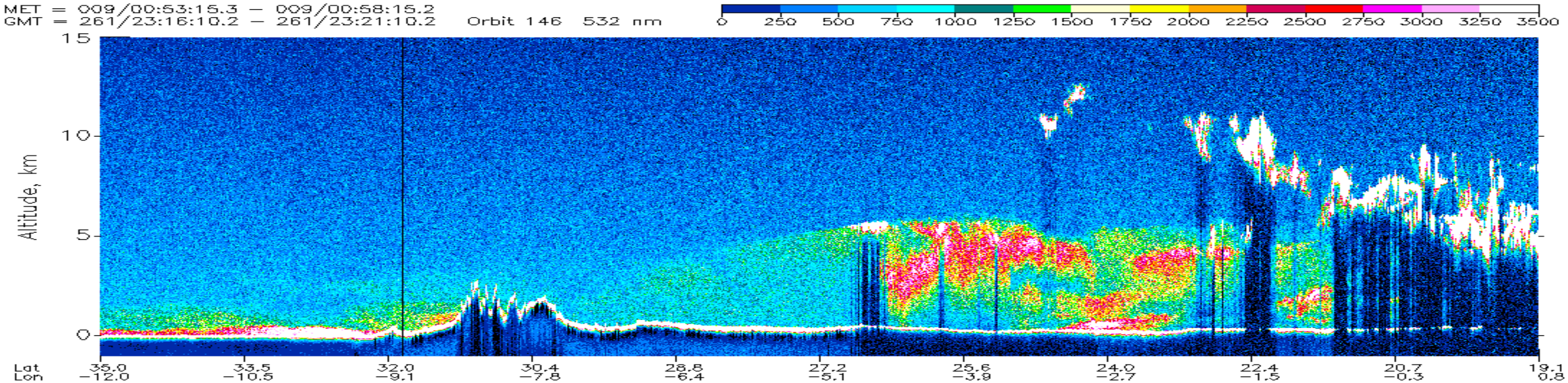


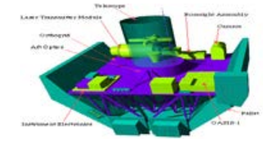
SECOND YEAR: 2604
PLANETARY REMOTE SENSING
LASERS

Prof. HARTMUT BOESCH

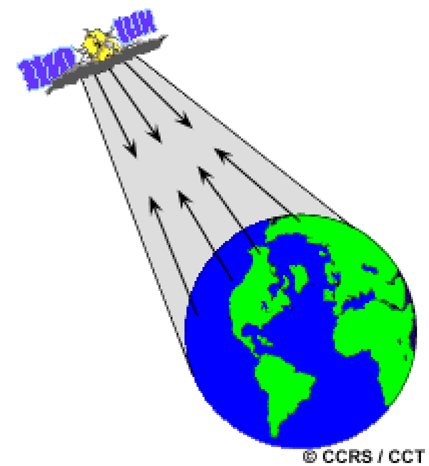
Earth Observation Science, Dept. of Physics and Astronomy, University of Leicester, U.K.



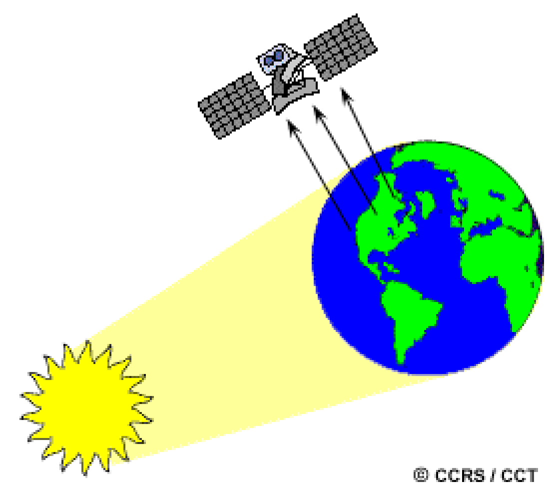
Active vs Passive Remote Sensing



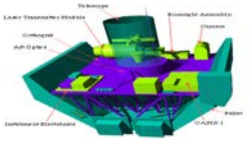
- **Active Remote Sensing: Artificial source of radiation, the reflected or scattered signal is analysed:**
  - **white light: long path DOAS (Differential Optical Absorption Spectroscopy)**
  - **Radio (and micro) waves: RADAR (RAdio Detection And Ranging)**
  - **laser light: LIDAR (LIght Detection And Ranging)**
  - **GPS**
  - **(sound: SONAR)**



- **Passive Remote Sensing: Natural sources of radiation, the attenuated, reflected, scattered, or emitted radiation is analysed:**
  - **solar light**
  - **lunar light**
  - **stellar light**
  - **thermal emission**
  - **Fluorescence (chemical)**



WHY ACTIVE REMOTE SENSING?



Active remote sensing is important because:

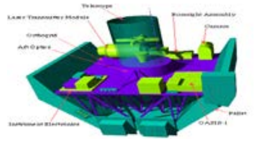
1. Signal depends on the output power of active sensor which can be controlled unlike natural sources of radiation
2. Output power is usually concentrated at specific frequencies of interest (well defined)
3. Direction of output power and hence measured input power is controllable
4. Measurement can be carried out at any time of day at any location
5. Accurate measure of time delay can lead to high temporal and hence high spatial resolution

Time is a very accurately measured variable! [thanks to atomic clocks]

The most common devices for active remote sensing are:

- Lasers
- Radars (next lecture)

LASERS IN SPACE



- All current and proposed spaceborne laser systems are lidars

  [Lidar = "Light Detection and Ranging"]

- Basic idea: Use of an active system that emits light pulses and measures intensity of backscattered light as a function of time

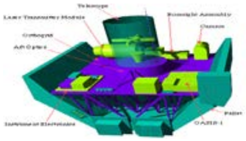
  => Time is now also a measured quantity !!!!

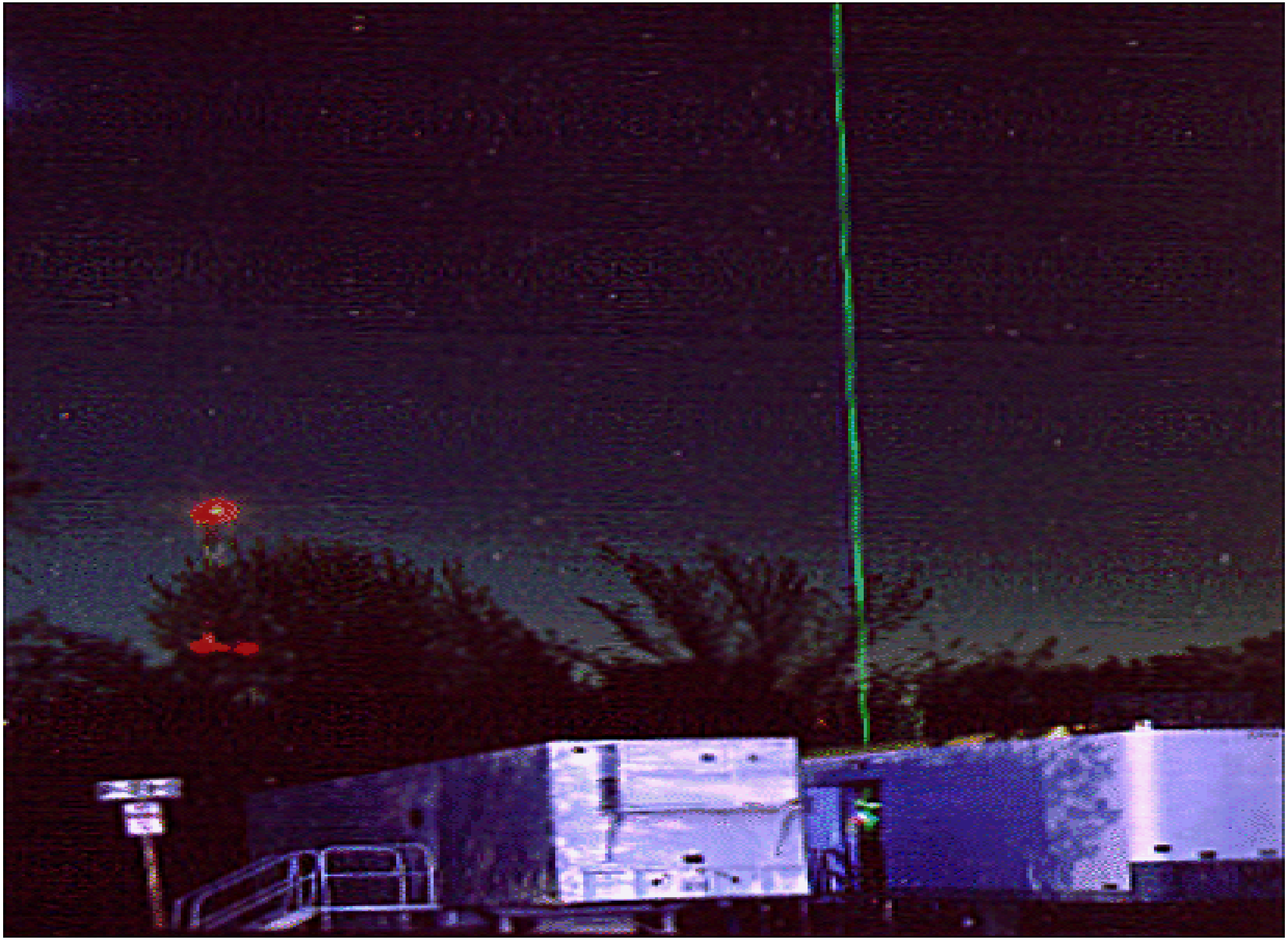
  (Lidars derive their name from the pulsed output directed towards the target (lasers themselves may be pulsed or continuous wave). The lidar detects the backscattered pulses providing time resolution and allowing range to be deduced with one instrument.)

- Instrument:
  - a strong laser with short pulses
  - a large telescope to collect the weak signal
  - transmitter (laser and output optics) and receiver (a detector) are part of same instrument.

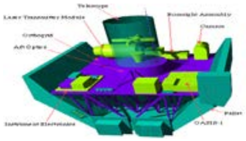
- In this lecture, we *concentrate on lidars* as the application of lasers in remote sensing.

Laser (LIDAR) IN OPERATION (GSFC)





OBSERVATION PRINCIPLE OF LIDAR IN SPACE



LIDAR

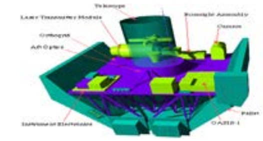
atmosphere

Light pulse emitted:
t = 0 s

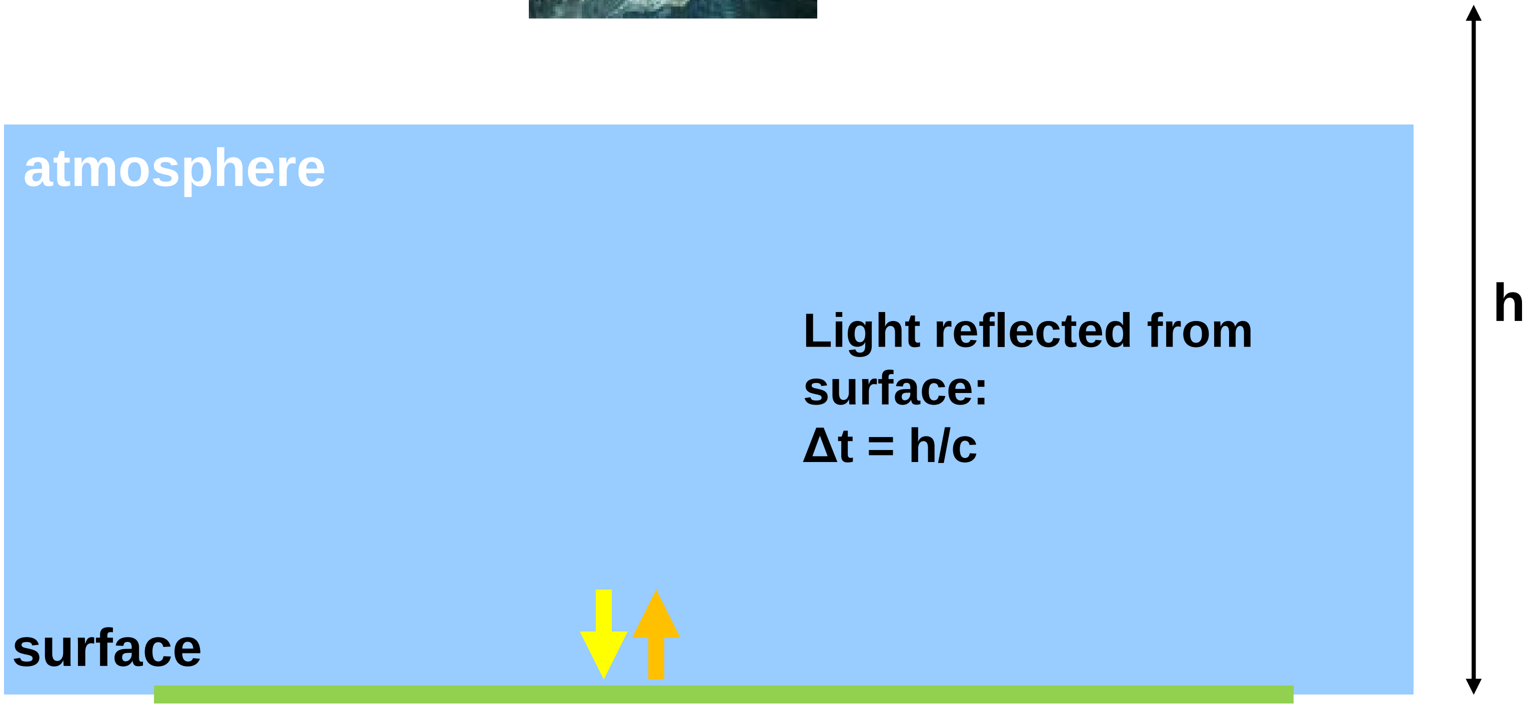
h

surface

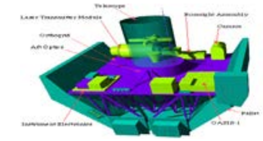
OBSERVATION PRINCIPLE OF LIDAR IN SPACE



LIDAR



OBSERVATION PRINCIPLE OF LIDAR IN SPACE



LIDAR

atmosphere

Light pulse received
at detector
$\Delta t = 2 * h/c$

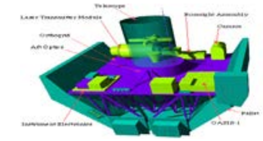
h

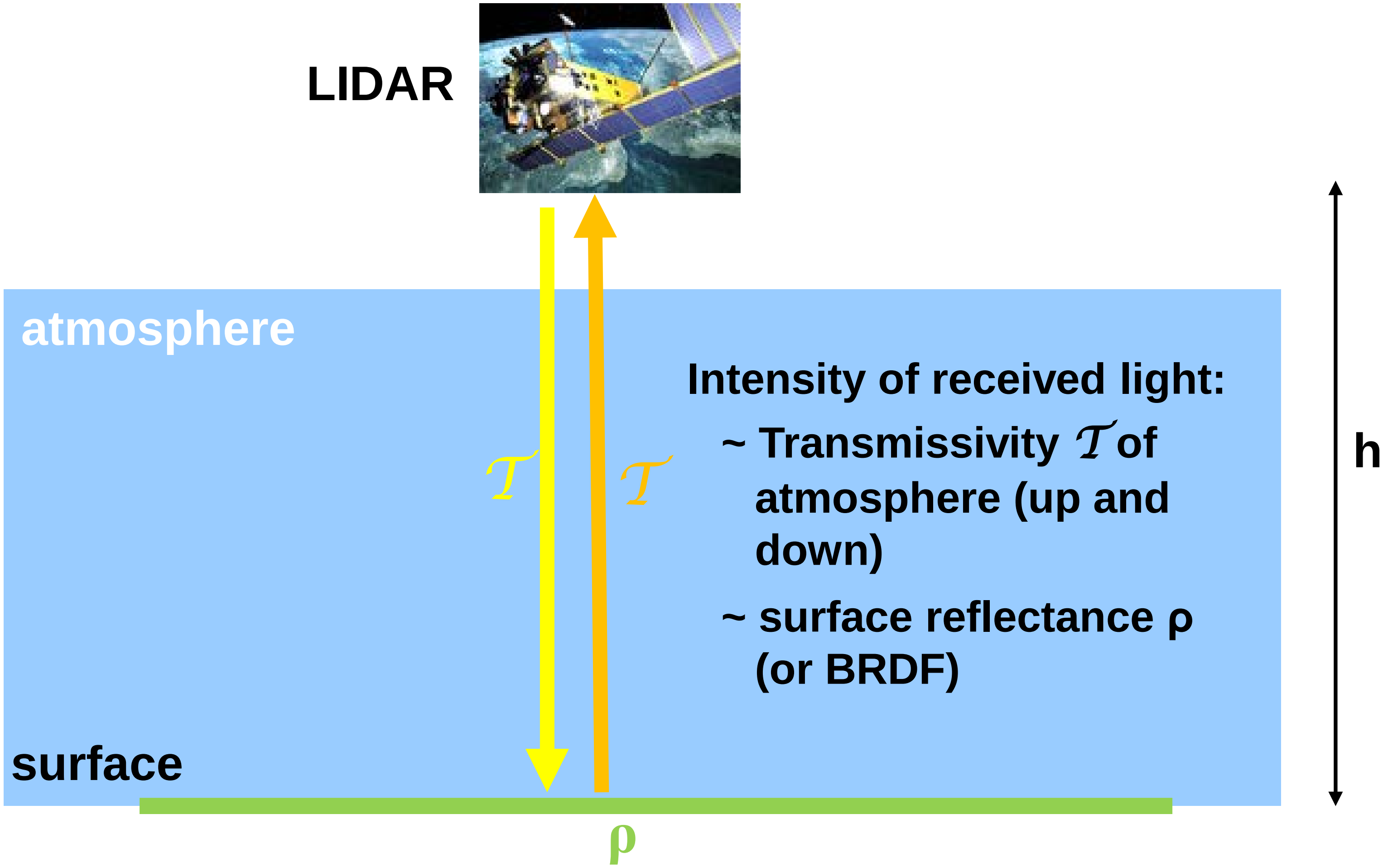
surface

Measured time lag Δt directly gives distance to surface h

Note: Speed of light (and thus refractive index) in atmosphere needs to be known

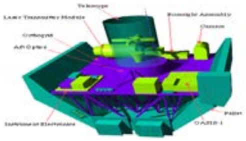
OBSERVATION PRINCIPLE OF LIDAR IN SPACE

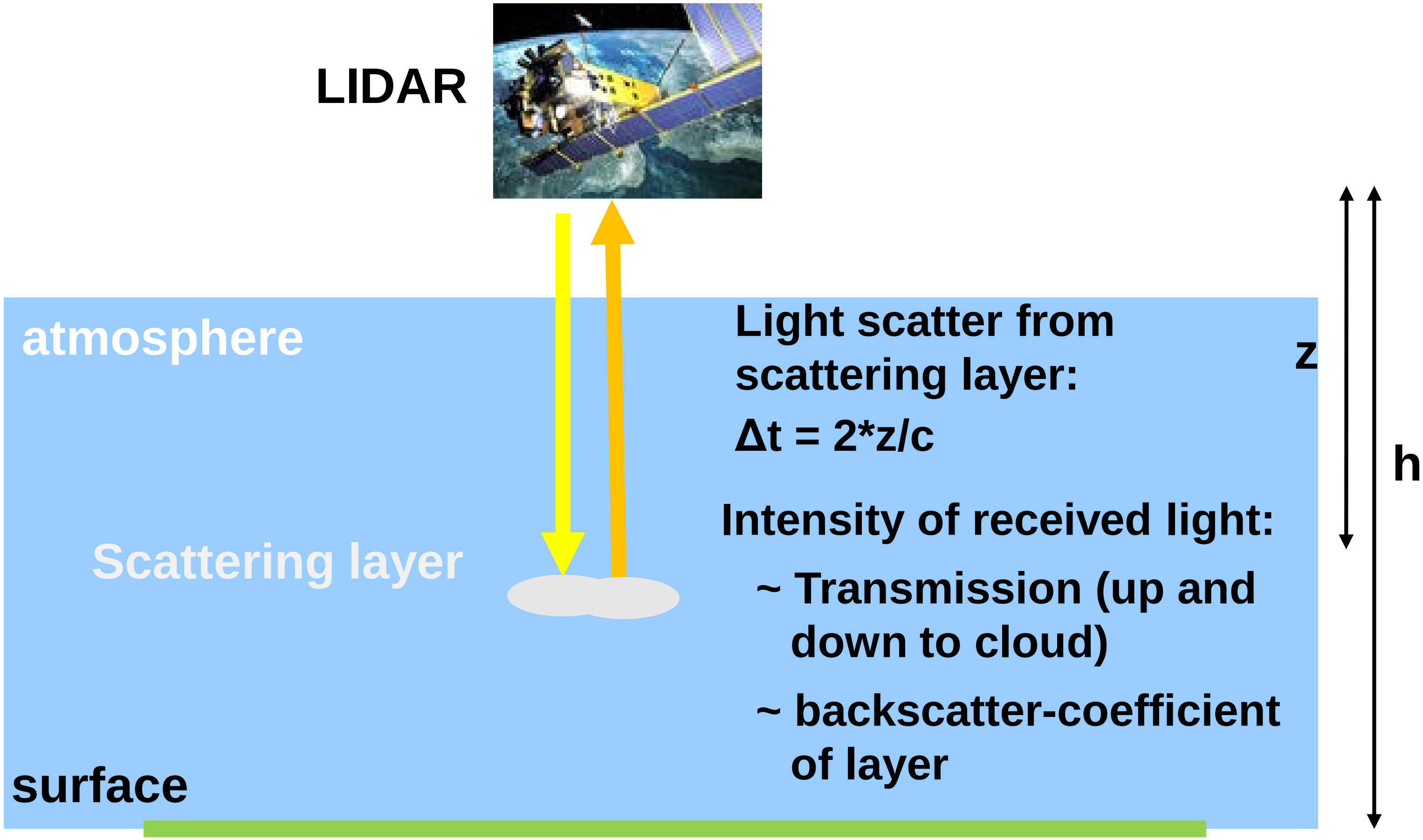




Measured signal intensity is related to surface reflectance (and atmospheric transmission)

OBSERVATION PRINCIPLE OF LIDAR IN SPACE

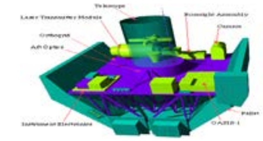


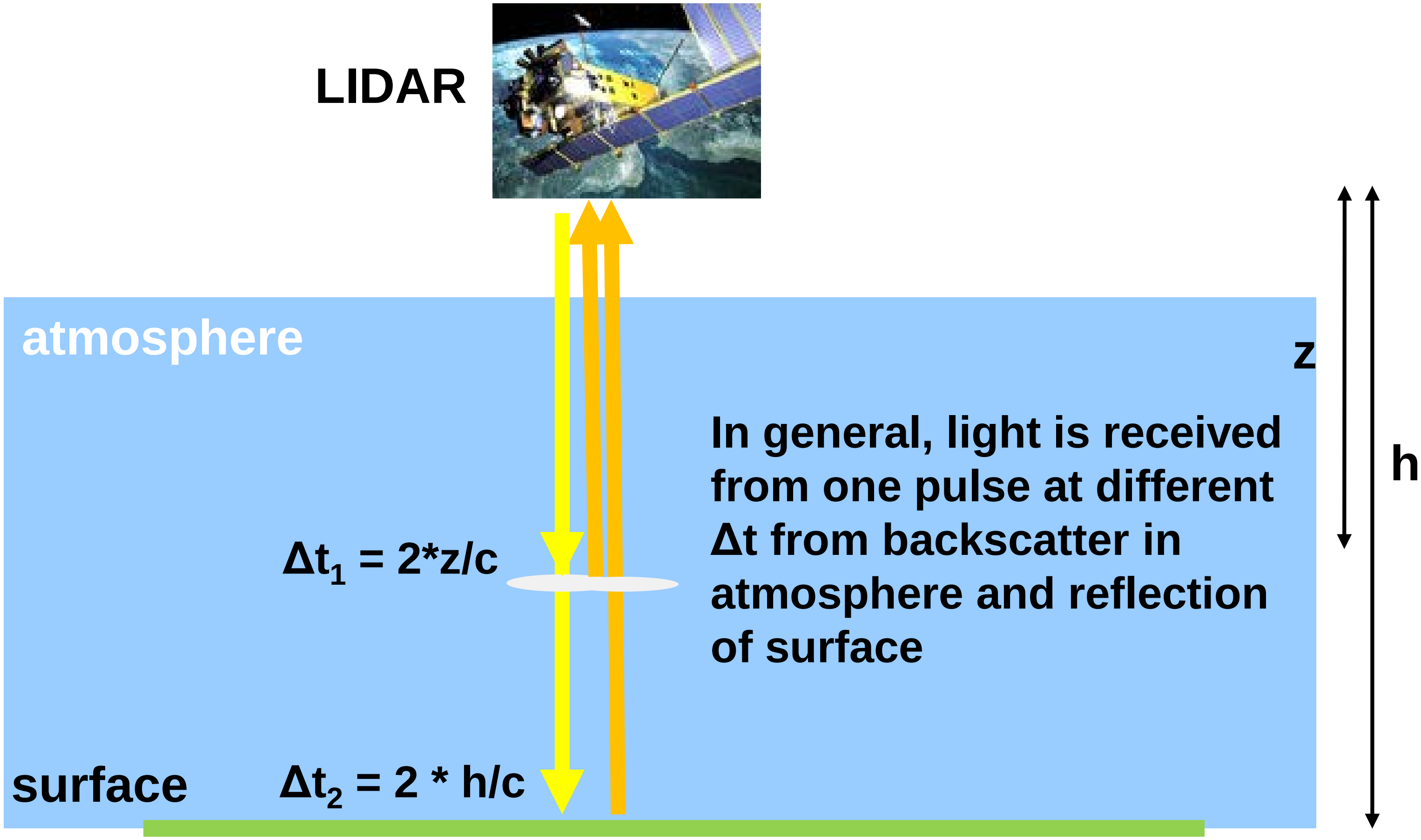


Measured time lag Δt directly gives distance z to scattering layer

Measured signal intensity is related to backscattering (and atmospheric transmission)

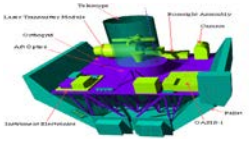
OBSERVATION PRINCIPLE OF LIDAR IN SPACE





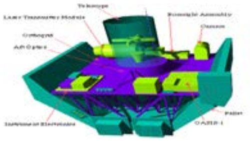
If atmosphere contains optically thick features (e.g. cloud) then no light will be received from below

LIDAR EQUATION I



- In general, interaction between light photons and particles is a scattering process or reflection at surface
- Expected photon counts are proportional to product of
  - (1) emitted laser photon number
  - (2) probability that a transmitted photon is scattered
  - (3) probability that a scattered photon is collected
  - (4) light transmission through atmosphere
  - (5) overall system efficiency
- Background photon counts and detector noise also contribute to expected photon counts

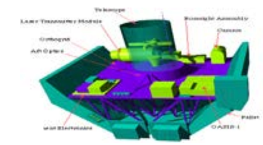
LIDAR EQUATION II



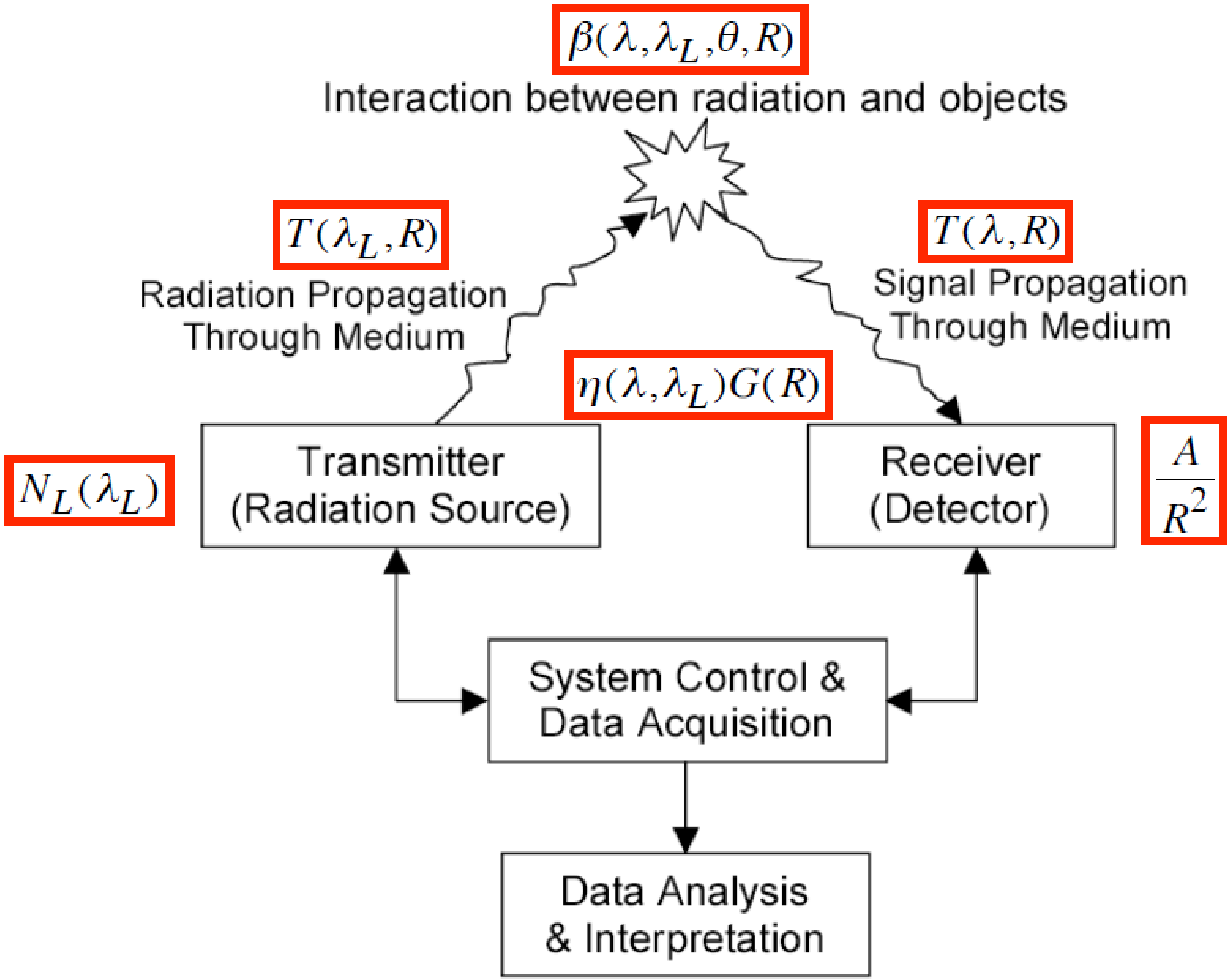
Received number of photons from altitude R at wavelength λ is given by lidar equation:

$$N_S(\lambda, R) = N_L(\lambda_L) \times \beta(\lambda, \lambda_L, \theta, R) \times \Delta R \times \frac{A}{R^2} \left(\mathcal{T}(\lambda_L, R) \mathcal{T}(\lambda, R) \right) \times \left(\eta(\lambda, \lambda_L) G(R) \right) + N_B$$

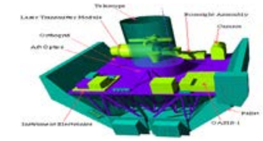
- **N_S : expected photon counts detected at λ and R**
- **1st term : emitted laser photon number**
- **2nd term : probability of a transmitted photon to be scattered by objects into unit solid angle**
- **3rd term : probability of a scatter photon to be collected by receiving telescope**
- **4th term : light transmission through medium for transmitted laser and return signal photons**
- **5th term : overall system efficiency**
- **6th term N_B : background and detector noise counts**



Physical Picture in Lidar Equation



LIDAR EQUATION II



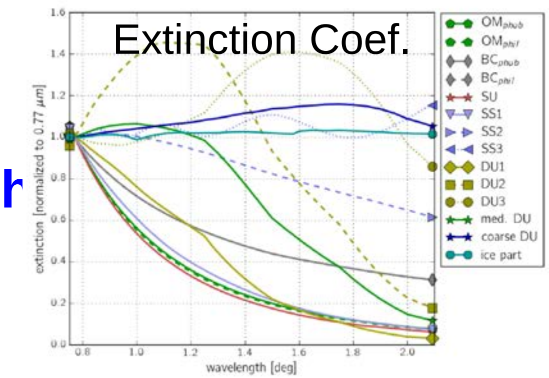
Received number of photons from altitude R at wavelength λ is given by lidar equation:

$$N_S(\lambda,R) = N_L(\lambda_L)\times\beta(\lambda,\lambda_L,\theta,R)\times\Delta R\times\frac{A}{R^2}\left(\mathcal{T}(\lambda_L,R)\mathcal{T}(\lambda,R)\right)\times\left(\eta(\lambda,\lambda_L)G(R)\right)+N_B$$

[1/sr]

Volume scattering coefficient β x scattering layer th

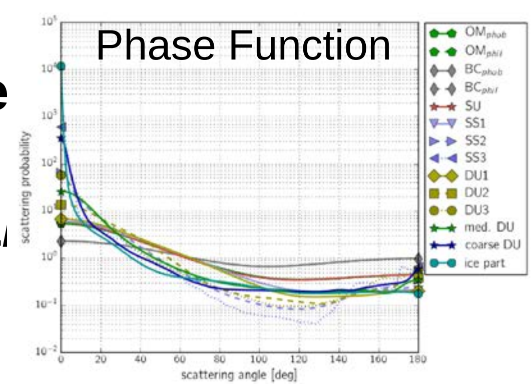
Units: [m^{-1} sr^{-1}] x [m]



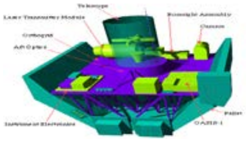
β = dσ/dΩ x n = k_s x p(cosΘ)

= scattering cross section per scattering particle angle θ x density of scattering particles

= scattering coefficient (1/m) x phase function (1/



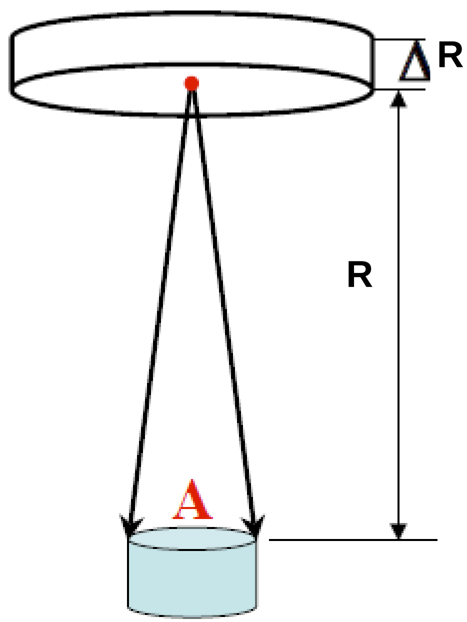
LIDAR EQUATION II



Received number of photons from altitude R at wavelength λ is given by lidar equation:

$$N_S(\lambda,R) = N_L(\lambda_L)\times\beta(\lambda,\lambda_L,\theta,R)\times\Delta R\times\frac{A}{R^2}\left(\mathcal{T}(\lambda_L,R)\mathcal{T}(\lambda,R)\right)\times\left(\eta(\lambda,\lambda_L)G(R)\right)+N_B$$

[sr]



A/R² gives solid angle of the receiving telescope

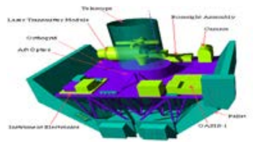
Example:

$A = \pi \times (0.5\text{m})^2$

$R = 400$ km

$A/R^2 = 5 \times 10^{-12}$ sr

LIDAR EQUATION II



Received number of photons from altitude R at wavelength λ is given by lidar equation:

$$N_S(\lambda,R) = N_L(\lambda_L)\times \beta(\lambda,\lambda_L,\theta,R)\times \Delta R \times \frac{A}{R^2}\left(\mathcal{T}(\lambda_L,R)\,\mathcal{T}(\lambda,R)\right)\times\left(\eta(\lambda,\lambda_L)G(R)\right)+N_B$$

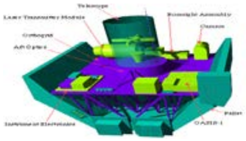
Transmissivity from laser (top of atmosphere set a R=0) to scattering point R is given by:

$$\mathcal{T} = \exp\{-\int_0^R k_{ext}(r)\,dr\}$$

Transmissivity from scattering point R to top of atmosphere is the same
Thus, total transmissivity (up and down):

$$\mathcal{T}_{tot} = \mathcal{T}\times\mathcal{T} = \exp\{-2\int_0^R k_{ext}(r)\,dr\} = \exp\{-2\int_0^R k_{abs}(r)+k_{sca}(r)\,dr\}$$

LIDAR EQUATION II



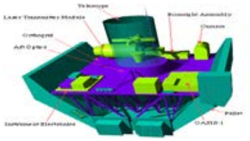
Received number of photons from altitude R at wavelength λ is given by lidar equation:

$$N_S(\lambda,R) = N_L(\lambda_L)\times\beta(\lambda,\lambda_L,\theta,R)\times\Delta R\times\frac{A}{R^2}\left(\mathcal{T}(\lambda_L,R)\mathcal{T}(\lambda,R)\right)\times\left(\eta(\lambda,\lambda_L)G(R)\right)+N_B$$

η is optical efficiency of hardware (mirrors, lenses, detector etc.)

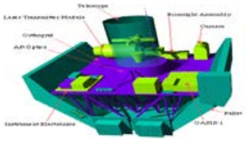
G is a factor describing the overlap of area of laser irradiation with field of view of detector

STANDARD LIDAR TECHNIQUES (SPACE)



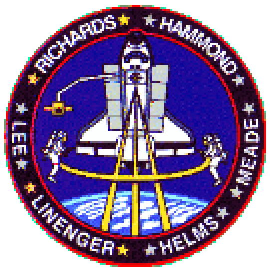
- Standard lidar techniques are based around Nd:YAG solid state laser [Nd:YAG=Neodymium: Yttrium Aluminium Garnet = “glass” type rod doped with Neodymium]
- The basic wavelength is 1064 nm. In principle, use of frequency doubling and tripling permits frequencies of 532 nm and 355 nm respectively
- Lidar systems typically use short pulses with high repetition rates
- Laser needs high frequency stability and high pulse power
- Footprints from LEO (low Earth orbit) are as small as 20 m. MOLA achieves 130 m on Mars
- Typical vertical sampling is every few hundred metres but signals may need to be averaged over 1 or 2 km

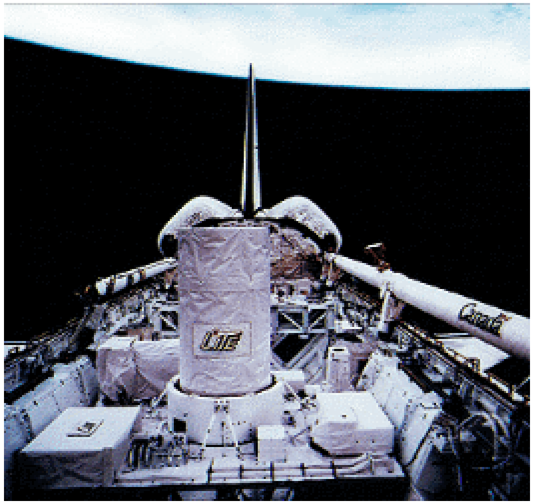
Lidar In-space Technology Experiment (LITE)



LITE- First lidar designed for atmospheric studies to fly in Earth orbit

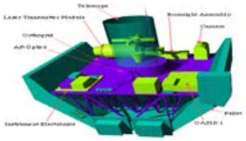
- ## Instrument:
  - flashlamp-pumped Nd:YAG laser
  - 1064 nm, 532 nm, and 355 nm
  - 1-meter diameter lightweight telescope
- ## Mission Aims:
  - test and demonstrate lidar measurements from space
  - collect measurements on
    - clouds
    - aerosols (stratospheric & tropospheric)
    - surface reflectance
- ## Operation:
  - on Discovery in September 1994 as part of STS-64 mission
  - 53 hours operation

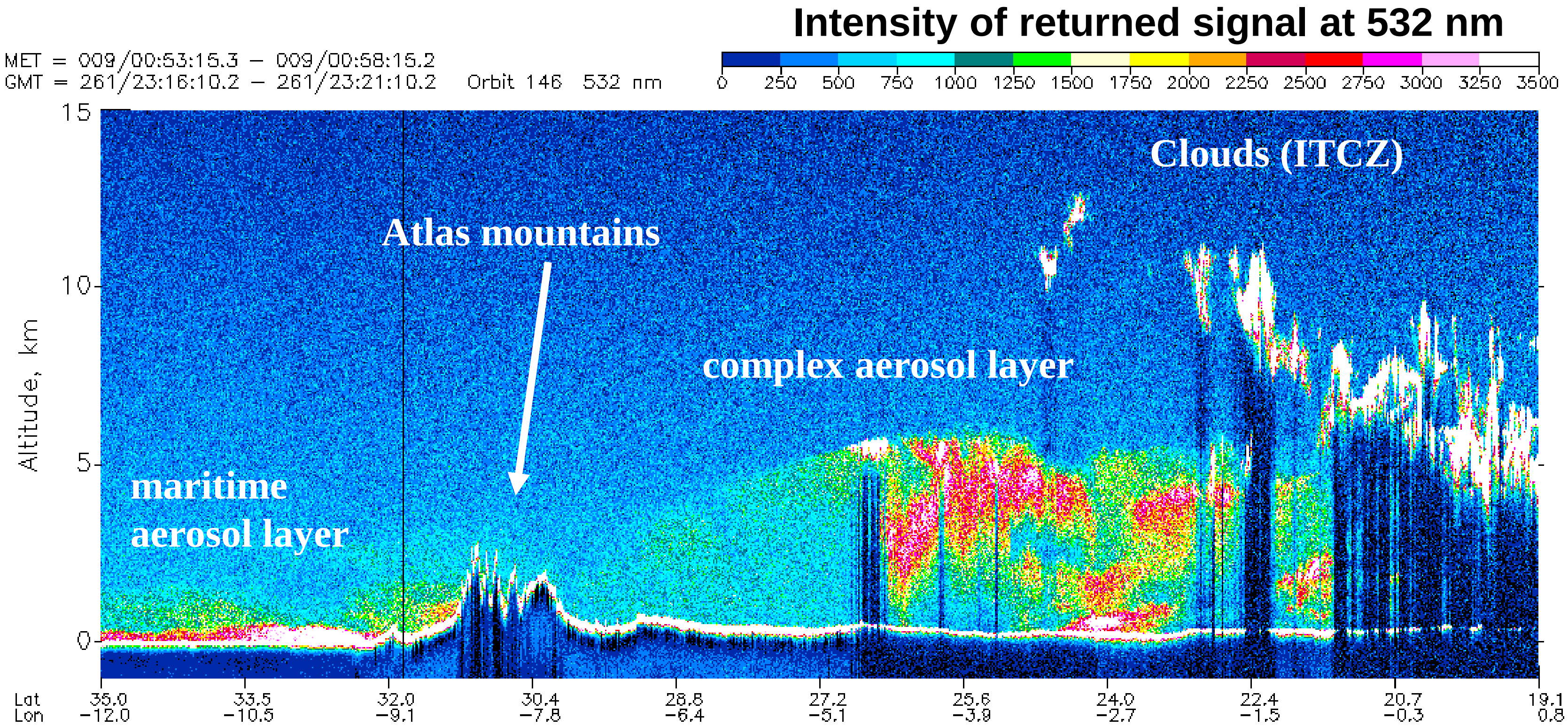




http://www-lite.larc.nasa.gov/index.html

EXAMPLE: LITE DATA OVER SAHARA

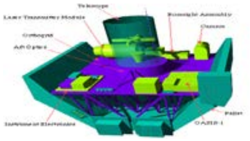




- **5 minutes of LITE data over the Sahara**
- **Low maritime aerosol layer**
- **High complex aerosol layer over Sahara**
- **Atlas Mountains separate two regimes**
- **Clouds close to the ITCZ**

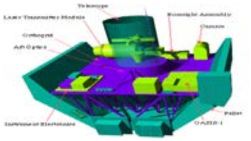
http://www-lite.larc.nasa.gov/index.html

WHICH INFORMATION CAN WE OBTAIN ?



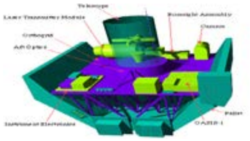
Measured Quantity	Geophysical Parameter
Time lag	
Signal intensity at λ	
Signal ratio for multiple λ	
Polarisation signal	
Signal intensity at shifted λ (Doppler effect)	

WHICH INFORMATION CAN WE OBTAIN ?



Measured Quantity	Geophysical Parameter
Time lag	Altitude information
Signal intensity at λ	Information on backscattering (or reflection) at given altitude and extinction along the light path
Signal ratio for multiple λ	Information on aerosol types or absorbers
Polarisation signal	Information on phase of scatterers
Signal intensity at shifted λ (Doppler effect)	Wind velocity, temperature

MAIN APPLICATIONS OF SPACE LIDARS I



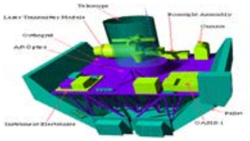
Lidars operating in space can measure:

- ***Topography and Ice sheet elevation:***
  - **Determined by finding mean return time from a received Gaussian pulse (transmitted Gaussian pulse)**
  - **Orbit cross-overs and precise repeat ground tracks are used to ensure accurate elevation changes**
- ***Densities of scattering particles (clouds and aerosols)***
  - **From inversion of backscattered signal**
  - **Observed backscatter is compared with theoretically observed backscatter (at multiple wavelengths)**
- ***Phase of the scattering particles***
  - **From measurements of returned pulse at two orthogonal polarisations**
  - **Solid particles do depolarise (incoming linearly polarized) radiation because of their shape, but liquid particles don't.**
  - **The ratio of signals at two orthogonal polarisations is called depolarisation ration:**

    High depolarisation ratio = solid particles

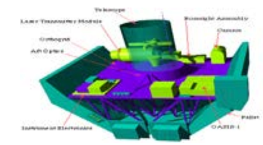
    Low depolarisation ratio = liquid particle

MAIN APPLICATIONS OF SPACE LIDARS II



- *Concentrations of atmospheric gases*
  - Deduced from absorption by atmospheric gases of both outgoing and returned radiation pulse (for wavelength with and without gaseous absorption)
- *Wind speeds*
  - determined by measuring the Doppler shift in frequency of the returned pulse.
  - The motion of the molecules will shift the frequency of the returned radiation due to the Doppler shift.
- *Temperature*
  - Can be inferred from signal if only Rayleigh scattered (Rayleigh lidar) or if in-elastic (ie. changes λ) scattering (Raman lidar) by air molecules is measured
- *Vegetation parameters e.g. canopy*
  - By investigating difference between lidar returns from canopy and lidar returns from ground [time and signal variations]

AEROSOL LIDAR I



- **Idea:**
  - **Backscattering is used to derive information on aerosol distribution and properties**
  - **Can provide unique information on vertical distribution on aerosol/clouds**

- **Lidar equation:**

$$N_S(\lambda,R)=N_L(\lambda_L)\times\beta(\lambda,\lambda_L,\theta,R)\times\Delta R\times\frac{A}{R^2}\big(\mathcal{T}(\lambda_L,R)\mathcal{T}(\lambda,R)\big)\times\big(\eta(\lambda,\lambda_L)G(R)\big)$$

- **Backscatter β and extinction α are from aerosols and molecules only:**

$$N_S(R)=N_L\times[\beta_{aer}(R)+\beta_{mol}(R)]\times\Delta R\times\frac{A}{R^2}\left(\exp\{-2\int_0^R(k_{aer}(r)+k_{mol}(r))\,dr\}\right)\times\big(\eta G(R)\big)$$

- **Molecular (Rayleigh) backscatter β and extinction k are known:**
  → for 1 wavelength: 1 equation and 2 unknowns: β_{aer} and k_{aer}

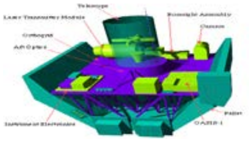
- **Assume aerosol type-specific Lidar ratio:**

$$L_{aer}(R,\lambda)=k_{aer}(R,\lambda)/\beta_{aer}(R,\lambda)$$

Result will critically depend on assumed lidar ratio, e.g. L = 20-35 for marine particles and L=70-100 for absorbing particles from biomass burning.

An advancement is Raman Lidar that allow determination of L (by separating aerosol and molecular backscattering)

AEROSOL LIDAR II



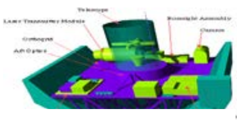
- To infer aerosol extinction more trustworthy, key is to add additional channels to provide additional information. At least, two channels of lidar profiles are needed (but note that lidar ratio is λ-dependent)

- **Multi-wavelength lidar** is to detect the common-volume aerosols using several different wavelengths that are significant apart from each other, e.g., 1064, 532, 355 nm

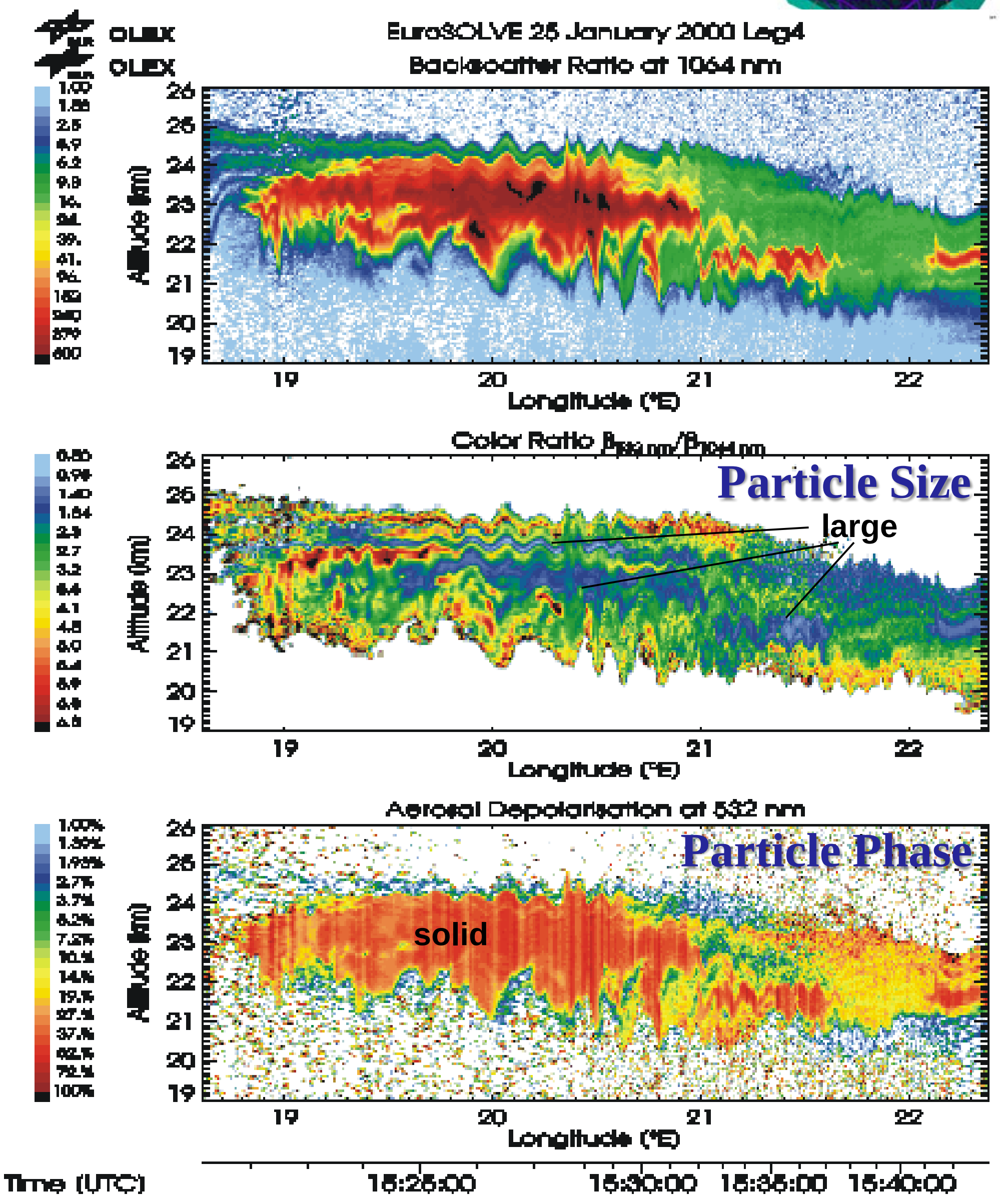
- **Colour ratio** of aerosol scattering:
  - Determination of particle size (Angstrom coefficient) and particle number density
  - Requires assumptions on particle shape and size distribution (e.g., spherical particles and lognormal distribution)

- Additional Information on Aerosol properties can be derived from **depolarisation ratio** (i.e. Are aerosols changing the degree of polarization)

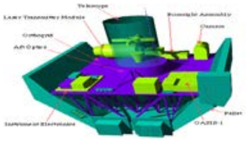
Aerosol Lidar: Example Cirrus Clouds



- OLEX lidar instrument:
  - Airborne system
  - 1064,532 and 355 nm
  - very good detection limit
  - high spatial and vertical resolution
- Detection of cirrus clouds, thin and even “subvisible“
- Particle size from colour ratio (low colour ratio = large particles)
- Particle phase from depolarisation (high depolarization = solid)



GLAS ON ICESAT – surface elevation measurements and atmosphere



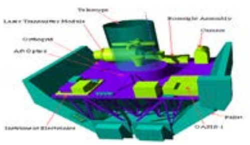
GLAS= Geoscience Laser Altimeter from Space:

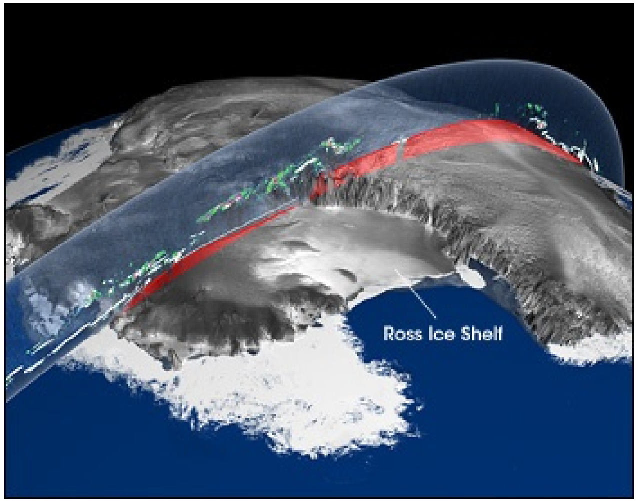
- First lidar instrument for continuous global observations of Earth
- 3 laser systems – one in operation at any time
- Wavelength = 1064 nm for surface measurements
- Wavelength= 532 nm for atmosphere influence
- Laser transmit 40 short pulses per second of 4 ns duration
- Footprint of laser is 70 m at ground, spaced at 170 m along track
- Size of instrument is set by size of receiving telescope – 1 m in diameter!
- Laser reliability problems have limited observations

ICESAT = Ice Cloud and Land Elevation Satellite

- Launched January 20, 2003
- ICESAT has accurate position by using GPS receivers, a network of ground GPS receivers and laser ranging systems
- In main operation, ICESAT would ideally repeat ground tracks to an accuracy of 35 m every 183 days.

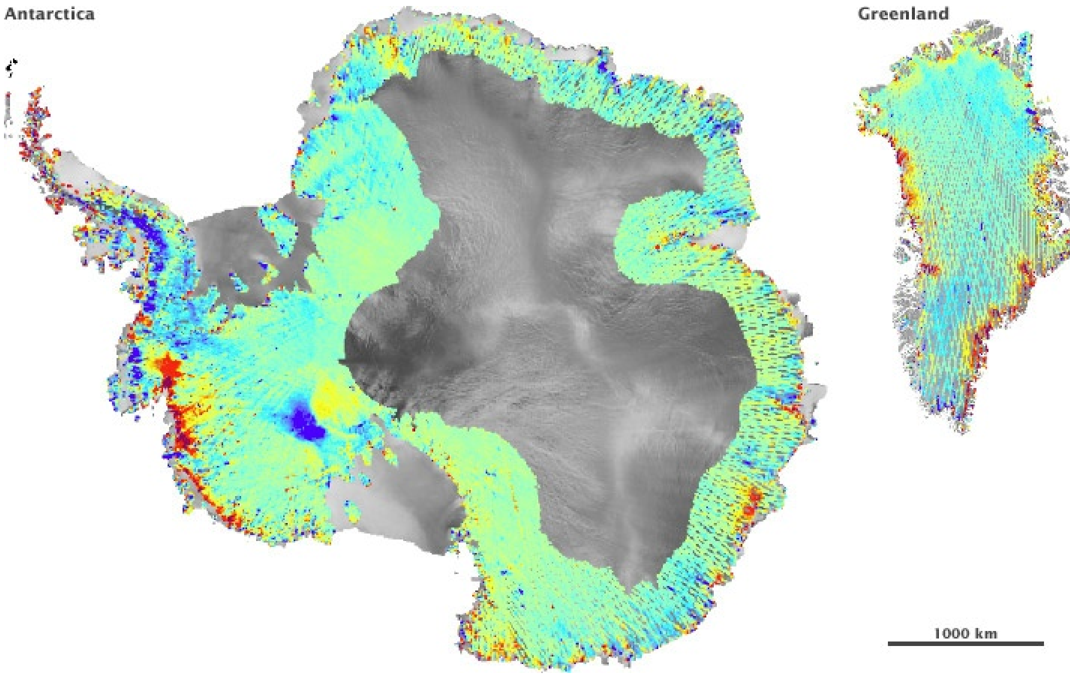
GLAS ON ICESAT – surface elevation measurements





Ice sheet elevation and cloud data from GLAS on its first day of operation, February 20, 2003.

The elevation profile (in red) is depicted relative to the Earth's standard ellipsoid, with 50x vertical exaggeration



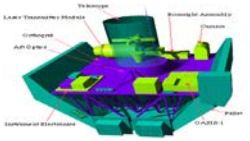
Changes to the edges of the ice sheets between 2003 and 2007 as observed by GLAS.

Red: places where glaciers thinned from lost ice over time

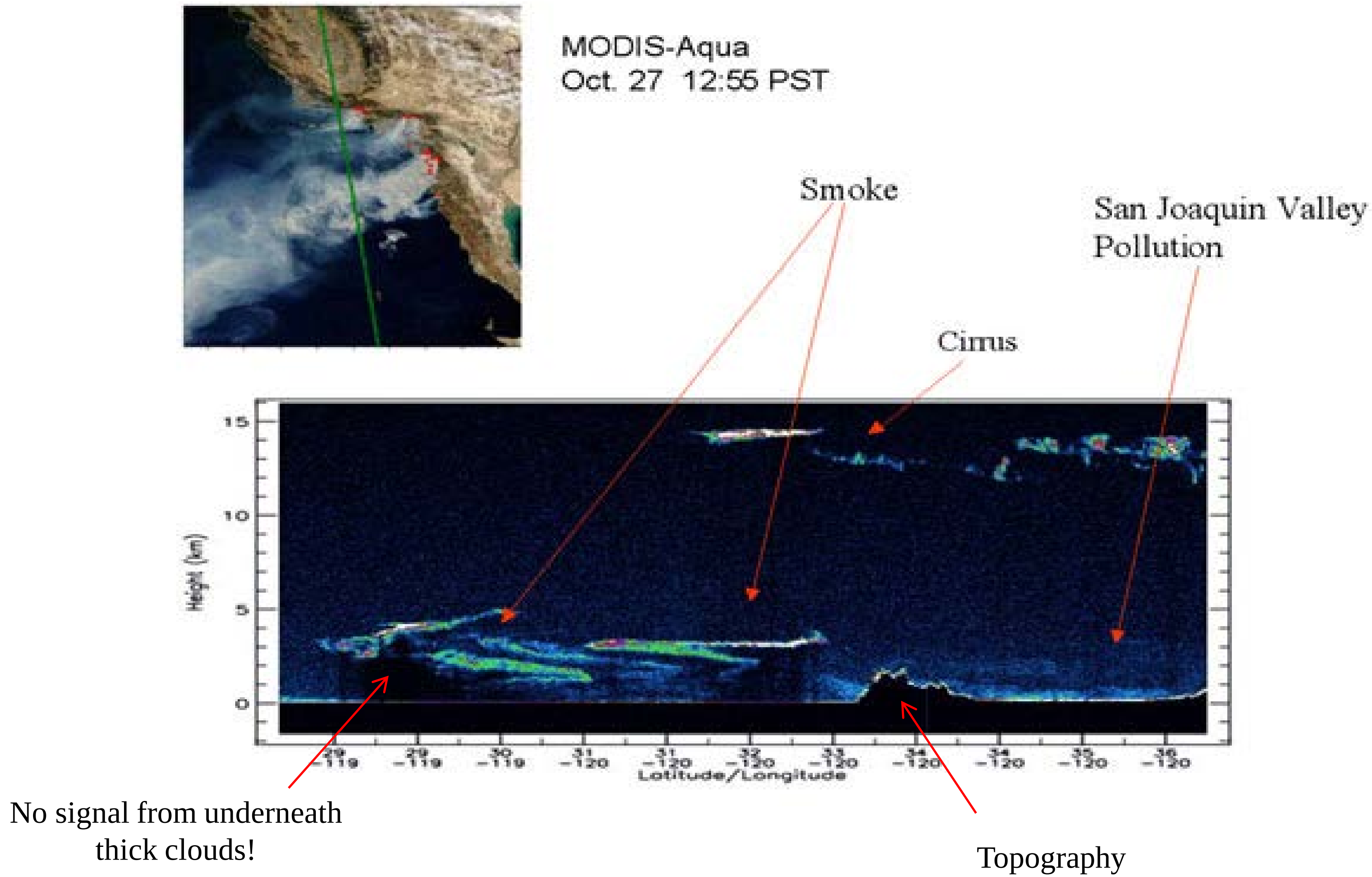
Blue: areas where glaciers or the ice sheet gained ice

Grey: not a part of the analysis

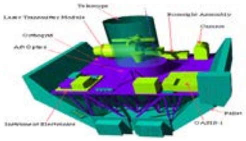
GLAS ON ICESAT – atmosphere



GLAS Observes California Fires 28-Oct-03

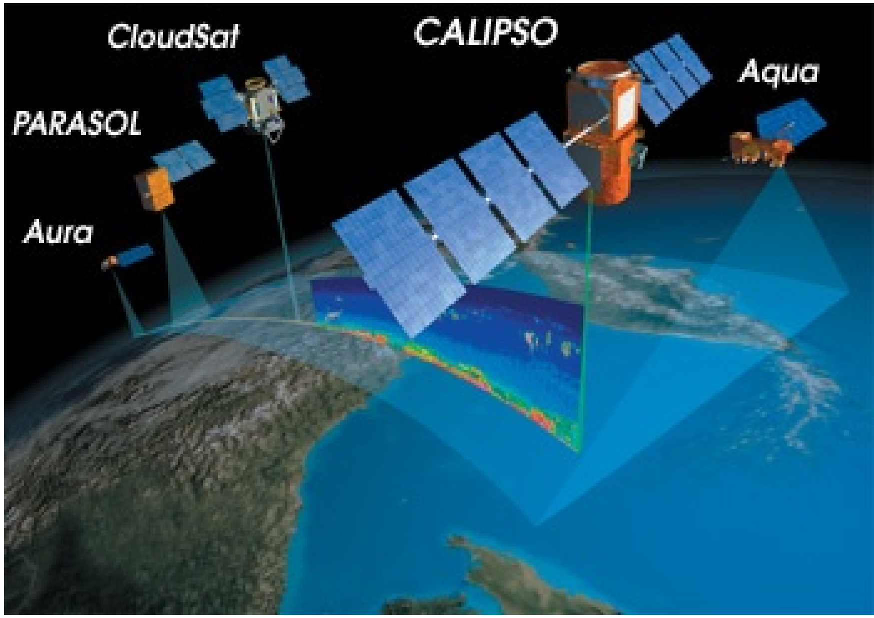


CALIPSO CLOUD/AEROSOL LIDAR

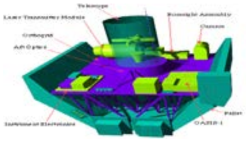


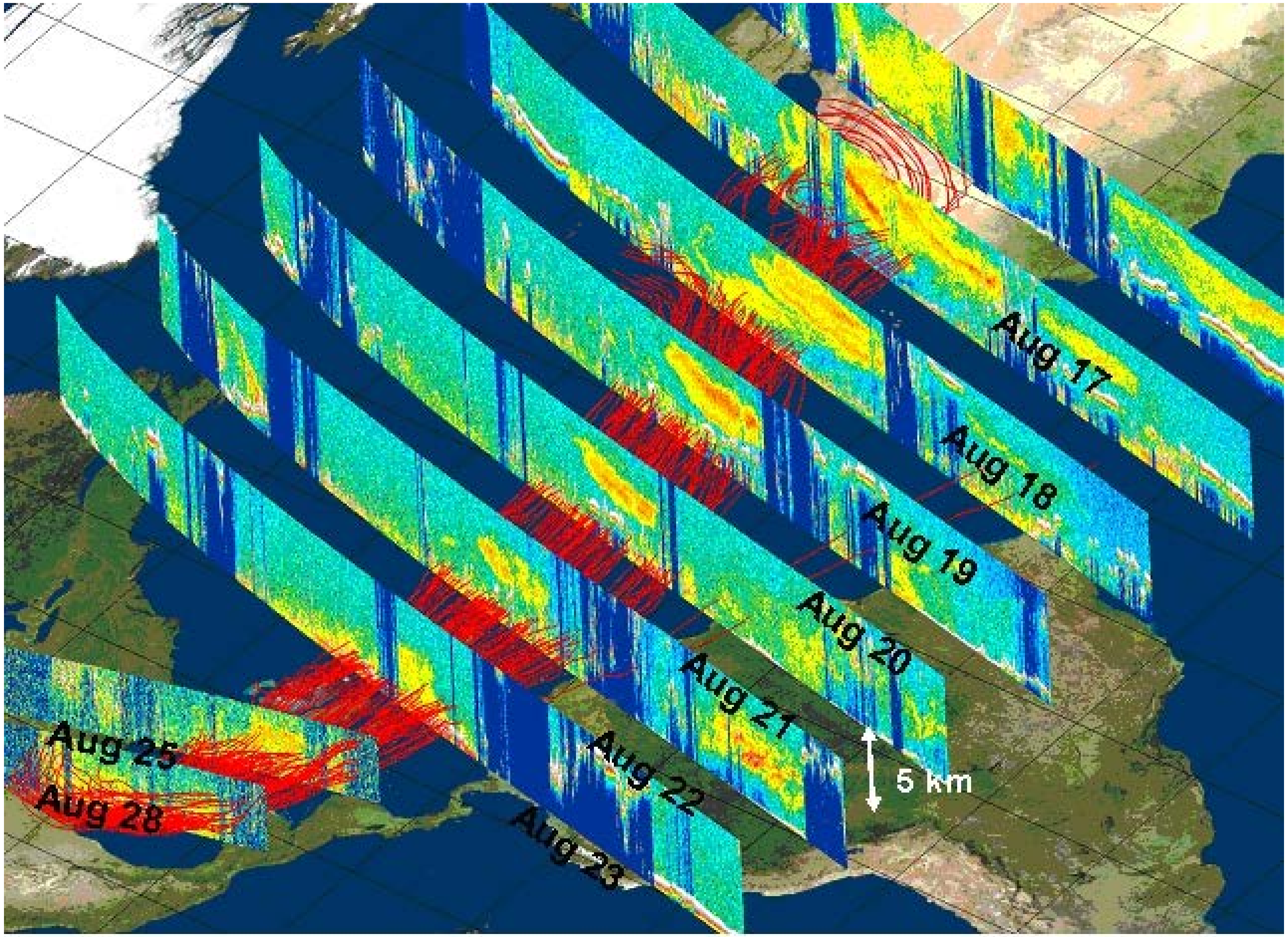
CALIPSO: Cloud-Aerosol Lidar and Infrared

- **Instrument: CALIOP: Cloud-Aerosol Lidar with Orthogonal Polarization**
- **Main objective: Aerosols and clouds**
- **Launched April 2006**
- **Part of the NASA A-train.**
- **532 nm and 1064 nm polarization-sensitive lidar**
- **Nd:YAG, diode pumped laser**
- **1.0 m diameter telescope**
- **Large range of retrieved aerosol/cloud parameters**
- **http://www-calipso.larc.nasa.gov**

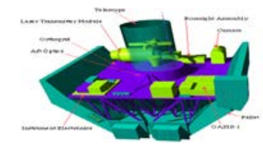


Sahara Dust Transport to America

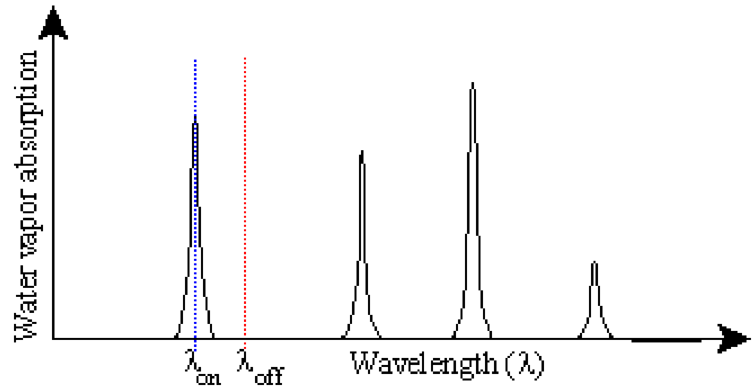




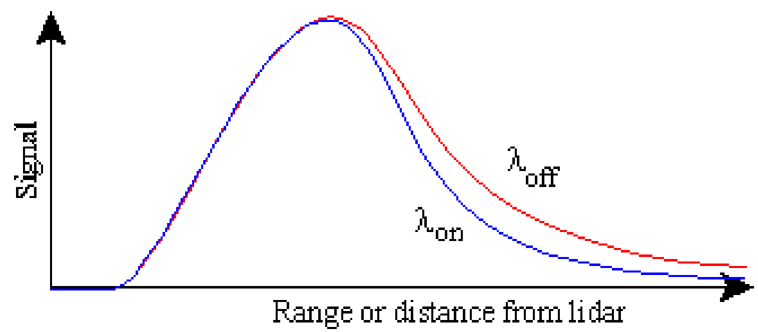
Differential Absorption Lidar (DIAL)



- Focuses on gas absorption lines to determine atmospheric concentrations of gas
- Measurements are made at wavelengths “on” and “off” absorption lines
- Concentration can be determined by “simple” ratio of signals provided that absorption cross-sections are known (DIAL equation)



(a) Water vapor absorption spectrum

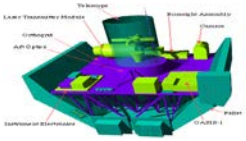


(b) Typical DIAL signals as a function of range

<u>Gas spectral regions</u>:

- Ozone: e.g. 300 nm = on
  311 nm = off
- H_2O e.g. 935.4 nm = on
  935.6nm = off

DIAL EQUATION I



- Start from the Lidar-equation for two wavelength on/off:

$$N_{S,on/off}(R) = N_{L,on/off} \times [\beta_{on/off}(R)\Delta R] \times \frac{A}{R^2}\left(\exp\{-2\int_0^R (k_{ext,on/off}(r))\, dr\} \right) \times \left(\eta G(R)\right)$$

- Forming the ratio between the received signals on and off:

$$\frac{N_{S,on}(R)}{N_{S,off}(R)} = \frac{N_{L,on}}{N_{L,off}} \times [\frac{\beta_{on}(R)\Delta R}{\beta_{off}(R)\Delta R}] \times \left(\exp\{-2\int_0^R (\Delta k_{ext}(r))\, dr\} \right)$$

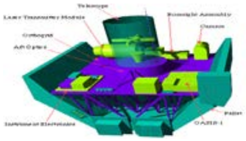
Difference in extinction coefficient between on and off

- Assume same backscatter β and emitted signal N_L for on and off:

$$\frac{N_{S,on}(R)}{N_{S,off}(R)} = \exp\{-2\int_0^R (\Delta k_{ext}(r))\, dr\}$$

(Compare Lambert Beer Law)

DIAL EQUATION II



$$\frac{N_{S,on}(R)}{N_{S,off}(R)} = \left(\exp\{-2\int_0^R (\Delta k_{ext}(r))\, dr\} \right)$$

- Take logarithm:

$$\ln\left(\frac{N_{S,on}(R)}{N_{S,off}(R)} \right) = -2\int_0^R (\Delta k_{ext}(r))\, dr \quad = -2\Delta\tau$$

Usually, only the return signal from surface is used. $\Delta\tau$ ~ total column of gas of interest

- Differentiating wrt altitude R gives

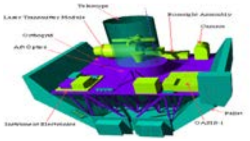
$$\boxed{\frac{d}{dR}\ln\left(\frac{N_{S,on}(R)}{N_{S,off}(R)} \right) = -2\Delta k_{ext}(R)}$$

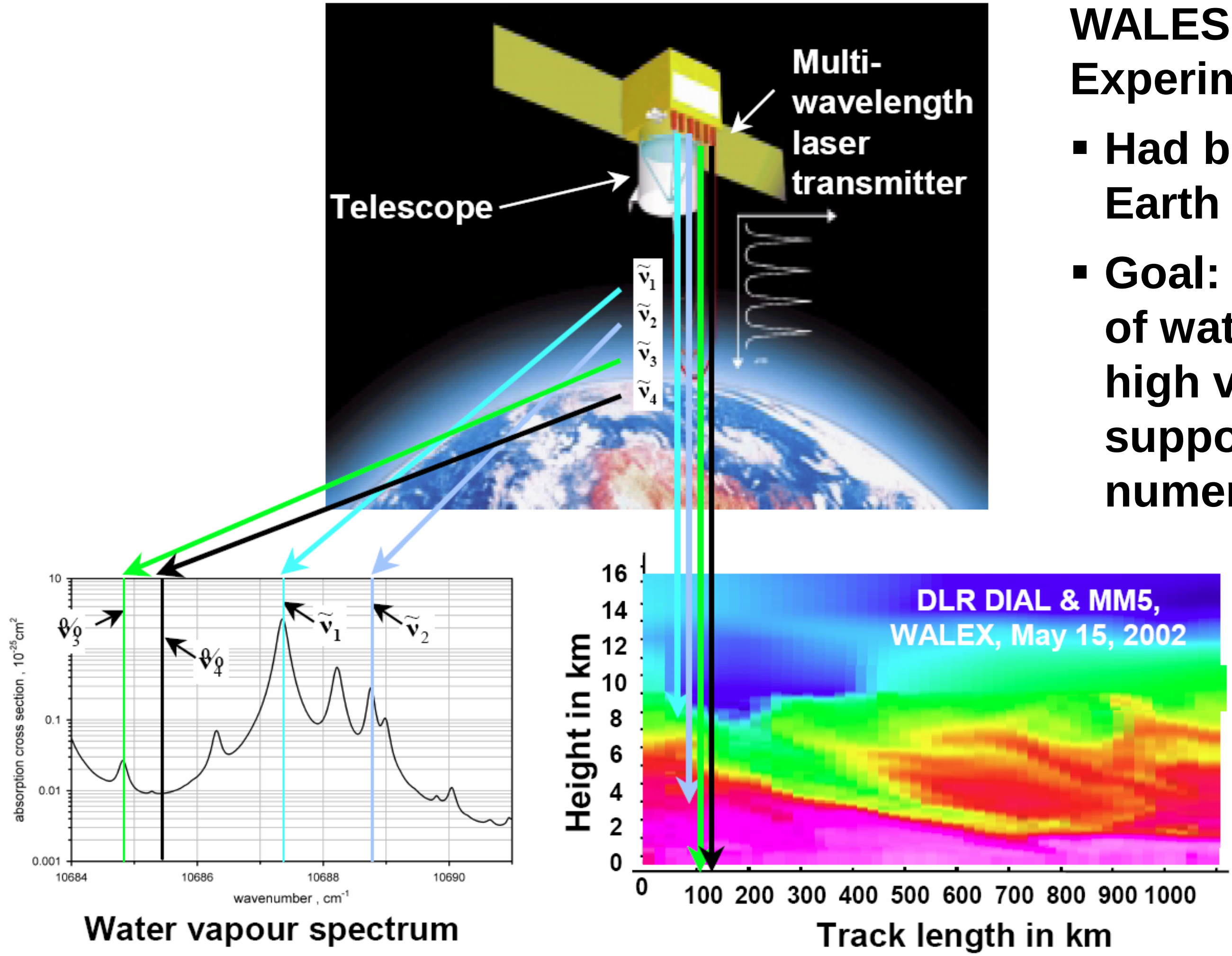
Ratio of measured signals

Differential extinction is given by differential absorption cross section $\Delta\sigma(R)$ and concentration c(r):

$\Delta k(R) = \Delta\sigma(R) * c(R)$

WALES INSTRUMENT: PROPOSED H_2O DIAL





WALES (Water vApour Lidar Experiment in Space):

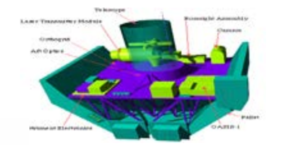
- Had been proposed to ESA Earth explorer program
- Goal: Measure accurate profiles of water vapour, globally and at high vertical resolution, to support climate research and numerical weather prediction

3 on-peak, 1 off-peak λ

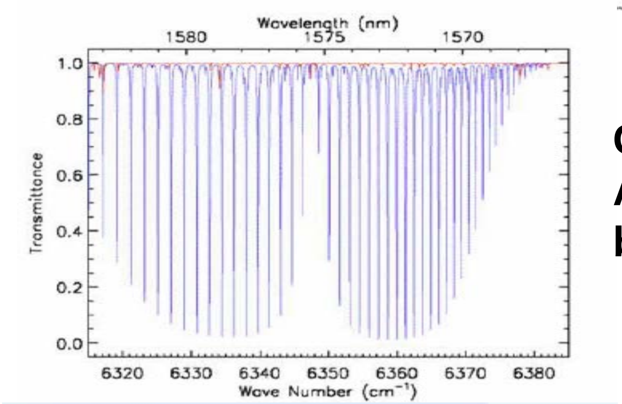
strongest line – least distance into atmosphere

weakest absorption – most distance into atmosphere

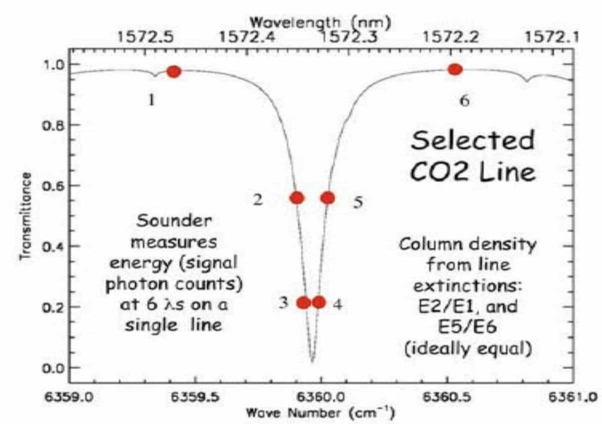
ASCENDS INSTRUMENT: PROPOSED CO_2 DIAL



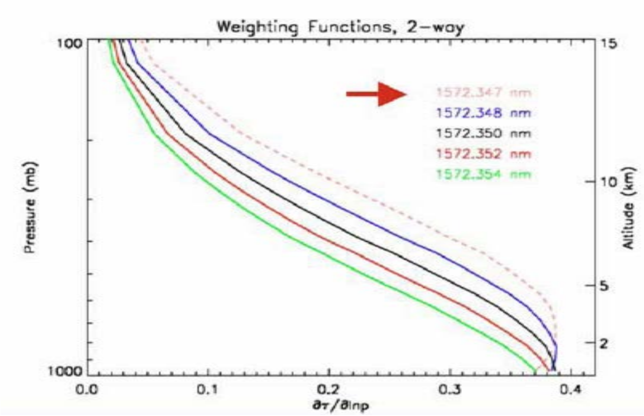
- ❑ ASCENDS is CO_2 DIAL mission proposed NASA
- ❑ GOAL: Measure atmospheric CO_2 (main greenhouse gas) to study carbon sources/sinks
- ❑ Most promising approach:
  - Multiple λ's around one absorption line at 1.57 micron:
    → vertical information
  - Pulsed DIAL:
    → Range gating eliminates cloud/aerosol scattering errors; only surface signal is used
- ❑ Main advantage over passive systems:
  - Measures day and night
  - No atmospheric effects (aerosol/clouds)



CO_2 Absorption band

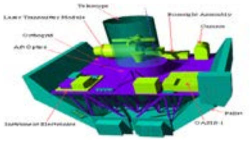


λ's of DIAL system



Vertical sensitivity

ADVANTAGES and DISADVANTAGES OF SPACE-BASED LIDARS



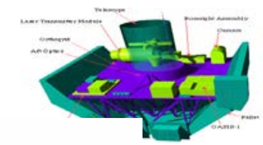
Advantage:

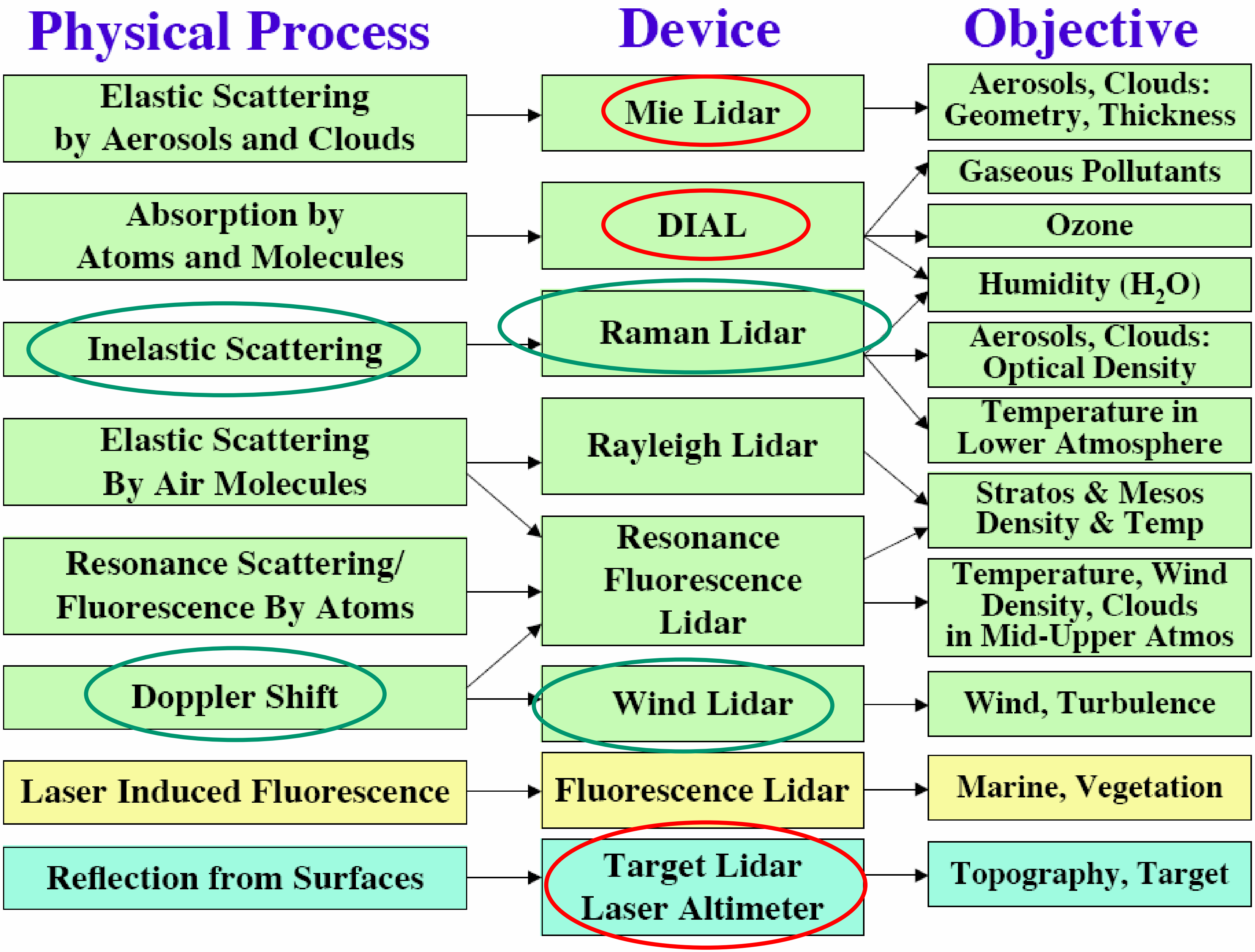
- Full control over light source
- Very good vertical resolution
- Very good spatial resolution
- Can measure all the time
- Can measure in presence of patchy clouds (small ground pixel size)
- Can easily remove atmospheric effects

Disadvantage:

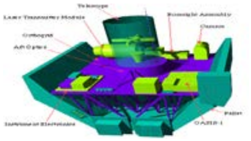
- Low coverage
- High energy consumption
- Low signal (R^{-2} dependence)
- Large telescopes required
- Challenging technology
- Cannot see through thick clouds

LIDAR: Overview





What do you need to know?



- Basic concept of lidar system
- Factors that determine observed lidar signal
- Main applications: Atmospheric and surface properties that can be measured by lidar
- Lidar laser systems and technique
- Aerosol remote sensing with lidars
- Examples: The LITE system, The MOLA on Mars Global Surveyor, GLAS on ICESAT, CALIPSO
- DIAL systems: Observation method: on/off wavelength technique and examples
- Active vs. passive system