Some Aspects of Lidar Design & Sizing

ASTRIUM SATELLITES
Earth Observation, Navigation & Science
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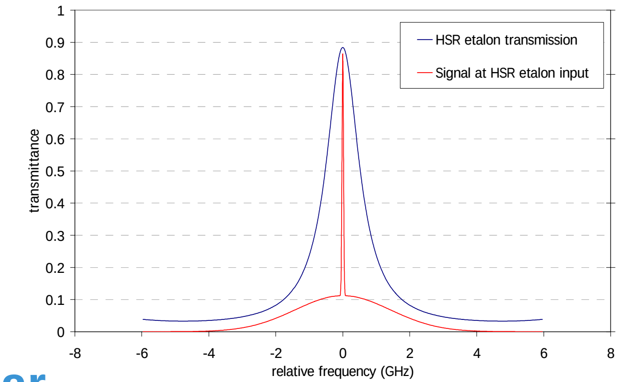
CEOI Training Workshop

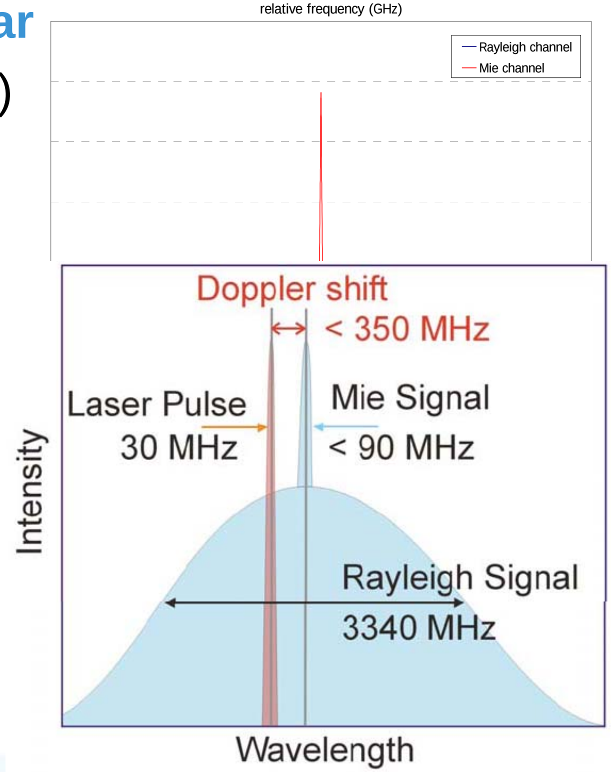
London, 15th March 2010

All the space you need

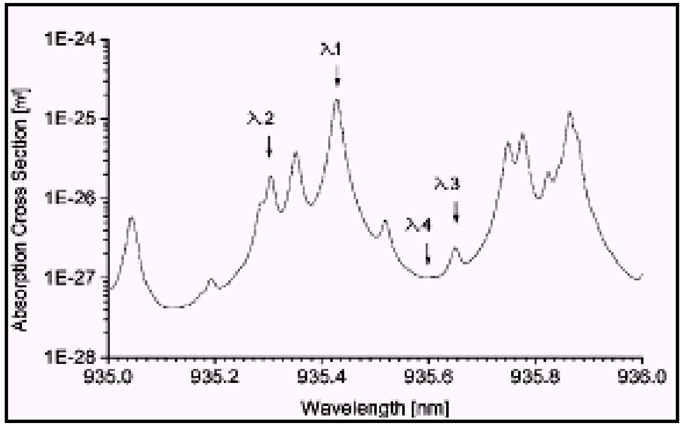
A wide range of lidars… (1/2)

- **Simplest: laser altimeter**
  - Usually a function more than a lidar concept
- **Simplest for atmospheric science: backscatter lidar**
  - One case: High Spectral Resolution Lidar (HSRL)
    - ATLID, but also ALADIN!
    - An extremely narrow filter (gas cell or Fabry-Perot etalon) separates molecular and aerosol backscatter → Rayleigh & Mie channels
  - Vertical profiles of aerosols and thin clouds
- **Wind Doppler Lidar**
  - Aeolus: direct (incoherent) method
  - NASA considering coherent method for wind & ocean/river surface currents

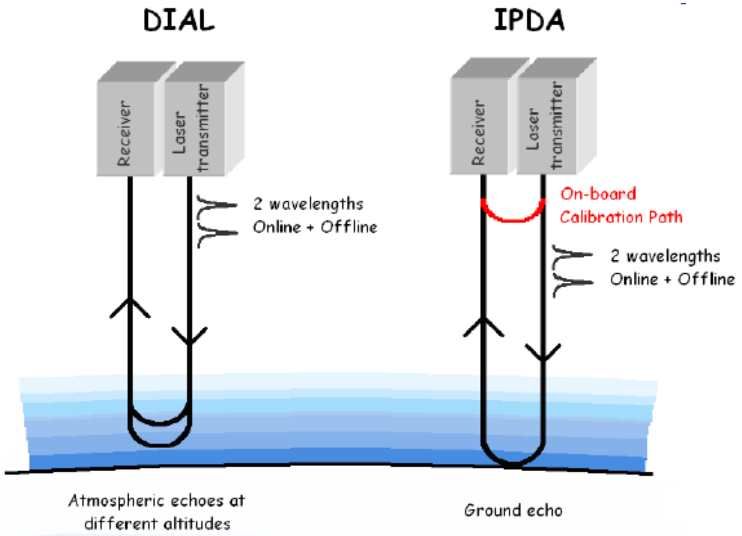




A wide range of lidars… (2/2)

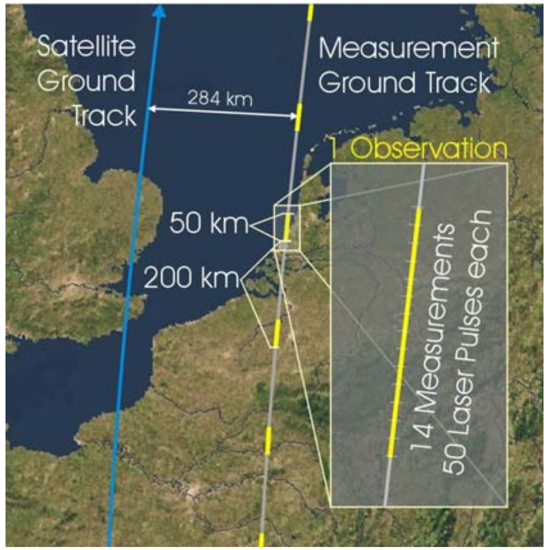


- **Differential Absorption Lidar (DIAL)**
  - 2 spectrally-close laser beams: one on-line (absorption), one off-line
  - WALES: water vapour profiles (2 pairs)
- **Integrated Path Differential Absorption (IPDA) Lidar**
  - Same as DIAL but returns a total column
    - Also needs a calibration path
  - A-SCOPE (up to Phase 0) for CO_2
- **Raman, fluorescence, etc…**

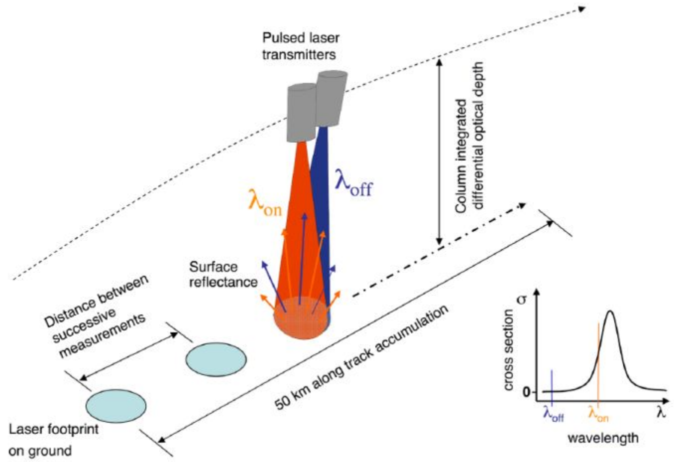


When to use a Lidar?

- **They benefit from the general laser properties:**
  - High power density, monochromaticity, short-duration, highly collimated beam
  - Lidar are independent of solar illumination, can see between clouds
- **But[1]…**
  - Only one ground sample at a time, many days before a revisit
    - Temporal resolution is low
      → only resolve slow events
  - Next ground sample tens of metres away
    - Spatial resolution is low
      → only resolve large scale phenomena



ADM-Aeolus



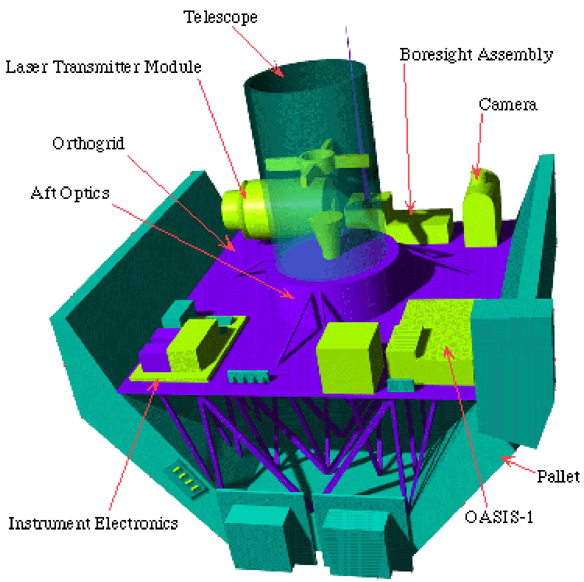
A-SCOPE

[1]Bakalski, I., *Space Lidars: design and operational constraints*, CEOI Enabling Technologies for Lidar Missions Challenge Workshop, 21 Sept. 2009.

A brief history of spaceborne Lidars Manned missions

- **Demonstrators:**
  - NASA, Sept. 1994: Lidar In-space Technology Experiment (LITE) on Space Shuttle
    - 355/532/1064 nm, 486 mJ (@1064 nm), 10 Hz
  - Russia, May 1995: Balkan-1 on MIR
  - CNES, Apr. 1996: ALISSA on MIR
  - NASA: Shuttle Laser Altimeter (Jan. 1996 & Aug. 1997)

Name	Wavelength (nm)	Beam Energy (mJ)	Aperture diameter (m)	PRF (Hz)
LITE	355 532 1064	196 460 486	0.956	10
Balkan-1	532	150		0.18
ALISSA	532	40		8



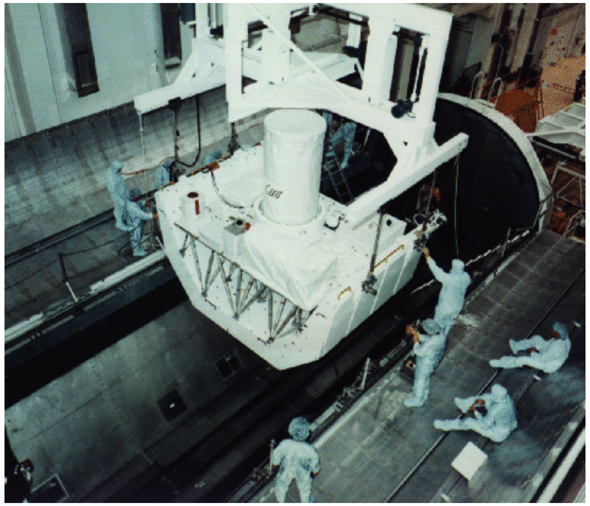
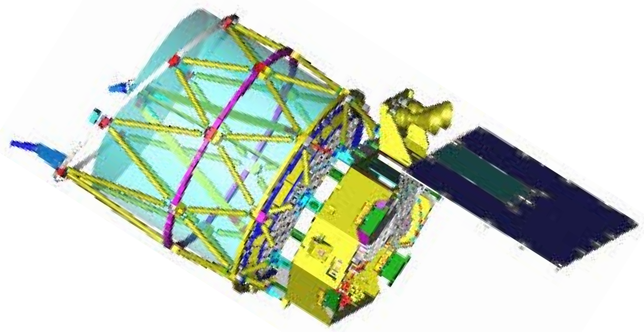


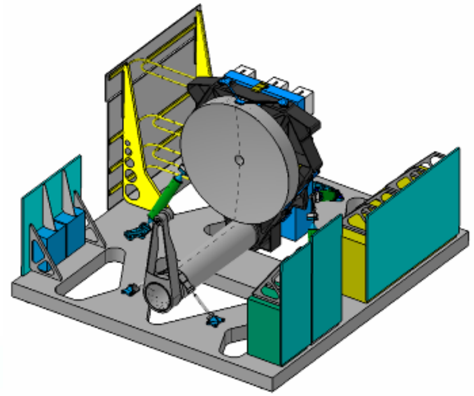
Photo credits: NASA

A brief history of spaceborne Lidars
Unmanned missions

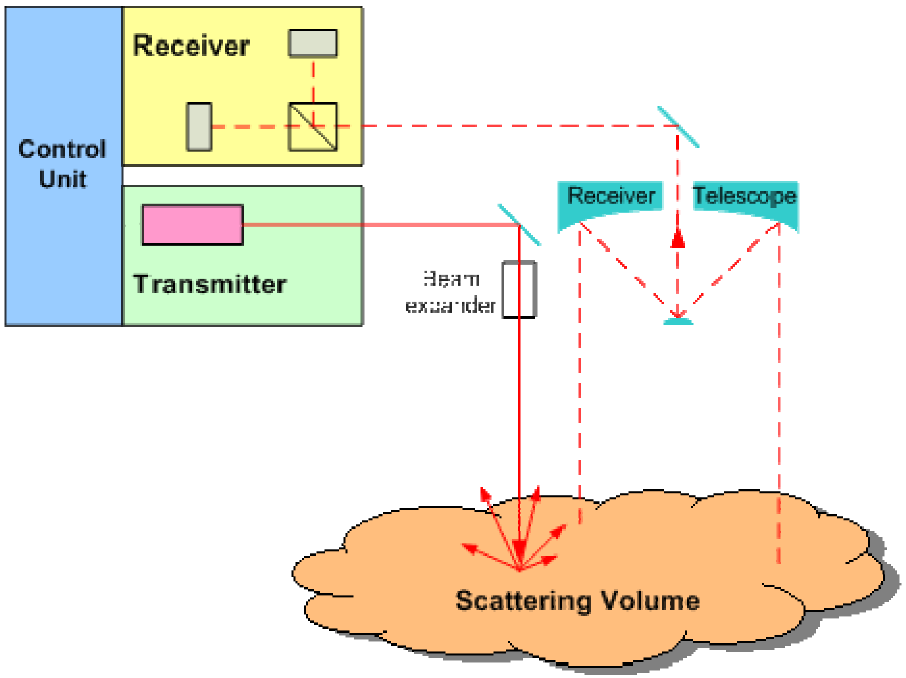
Mission	ICESAT		CALIPSO		VCL	Aeolus	EarthCARE
Instrument	GLAS		CALIOP		MBLA	ALADIN	ATLID
Launch date	Jan. 2003		Apr. 2006		*cancelled*	2011	2012
Altitude	600 km		705 km		400 km	408 km	450 km
Lidar technique	Backscatter & altimetry		Backscatter		Altimetry	Doppler	Backscatter
Mission objectives	cloud & atmospheric properties ice & land elevation		aerosol & cloud backscatter and extinction profiles		Tree canopy height; ground topography	global wind profile	Cloud & aerosols profiles
Laser type	Nd:YAG		Nd:YAG		Nd:YAG	Nd:YAG	Nd:YAG
Wavelengths	532 nm	1064 nm	532 nm	1064 nm	1064 nm	355 nm	355 nm
Laser beam energy	36 mJ	73 mJ	110 mJ	110 mJ	10 mJ	150 mJ	19 mJ
PRF	40 Hz		20 Hz		242 Hz	100 Hz	100 Hz
Pulse length	6 ns		20 ns		5 ns	15 ns	<20 ns
Laser beam divergence	110 urad		100 urad		?	< 400 urad	8 urad
Aperture diameter	1 m		1 m		0.9 m	1.5 m	0.6 m
Rx FoV (microrad)	160	475	130		300	15	25
Mass	300 kg		156 kg		133 kg	464 kg	231 kg
Power	330 W		124 W		220 W	840 W	370 W
Dimensions	1100 (W) x 1100 (L) x 1750 (H)		1000 (W) x 1490 (L) x 1310 (W)		?	1600 (dia.) x 2200 (H) approx.	1600 (L) x 1480 (W) x 933 (H)
Data Rate	450 kbps		332 kbps		?	11 kbps	822 kbps

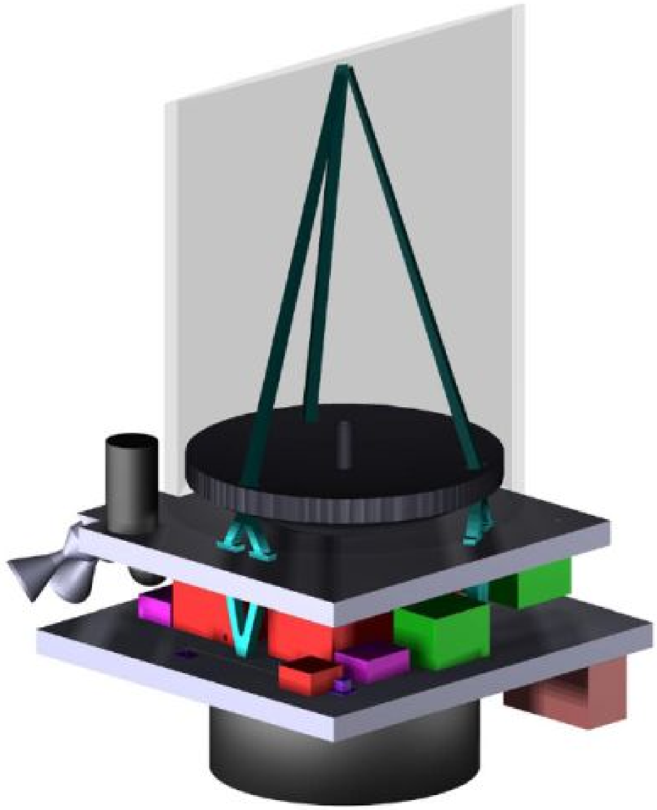
GLAS (credits: NASA)





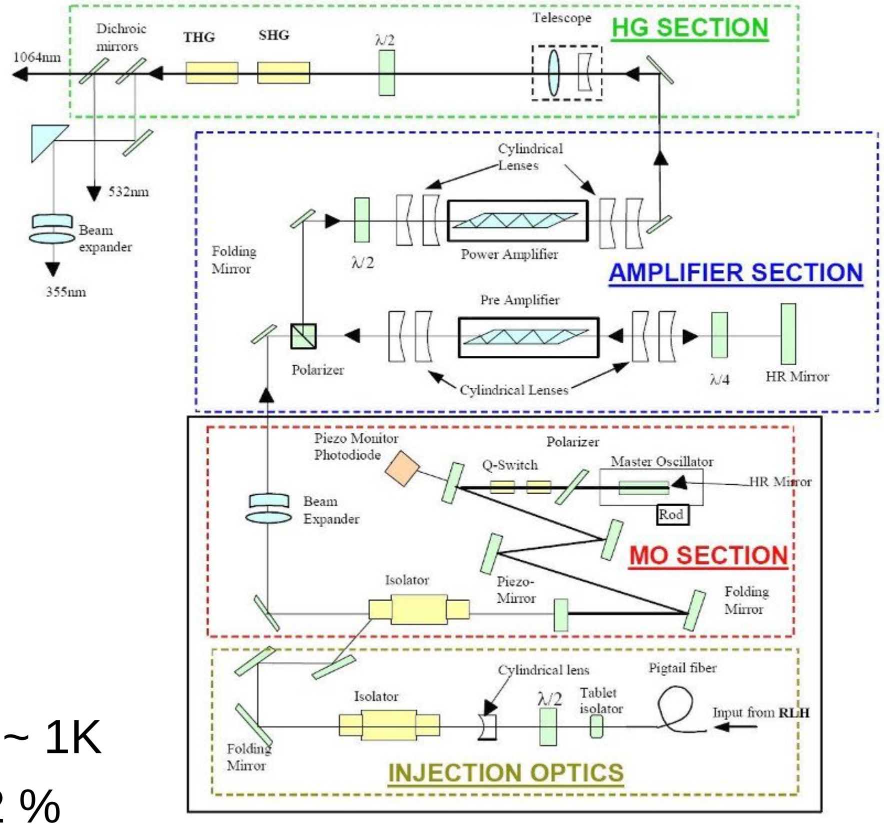
Basic Elements of a Lidar





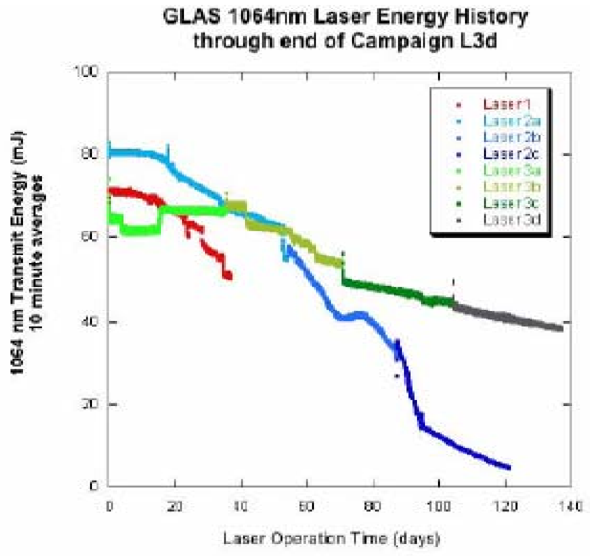
Transmitter

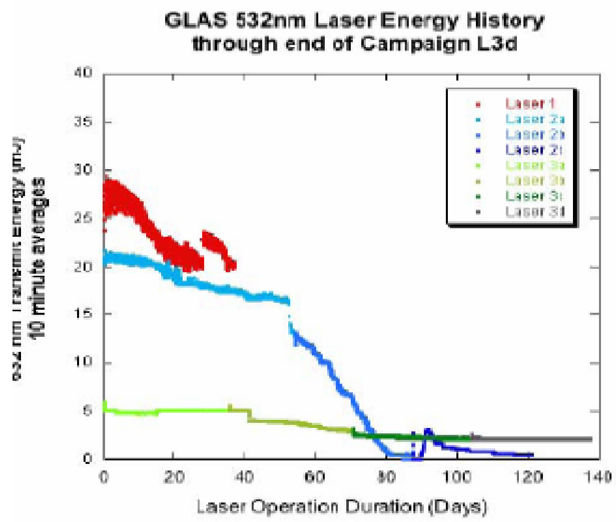
- **One possibility: Master Oscillator / Power Amplifier (MOPA)**
  - Multiple lasers working in tandem
  - Particularly well suited when a high energy pulse of high beam quality is required (ALADIN, ATLID)
- **Laser source: Nd:YAG (1064 nm)**
  - Frequency doubled/tripled
  - Optical Parametric Oscillator
- **Some key issues:**
  - Laser required temperature stability ~ 1K
  - Wall-plug efficiency typically 0.5 to 2 %
    - The rest is converted to heat which must be removed! Not trivial in space!



Problems experienced by GLAS

- **Laser 1: catastrophic failure of laser diode array (37 days)**
  - Actions:
    - Reduce duty-cycle (100 → 27%)
    - Reduce operating temperature of laser
- **Laser 2: Degradation of beam energy quicker than expected → laser-induced damage**
  - Actions:
    - Lower operational temperature
    - Lower beam energy (in particular at 532 nm)
- **Laser 3 failed**
  - Reverted to Laser 2, which in turn failed

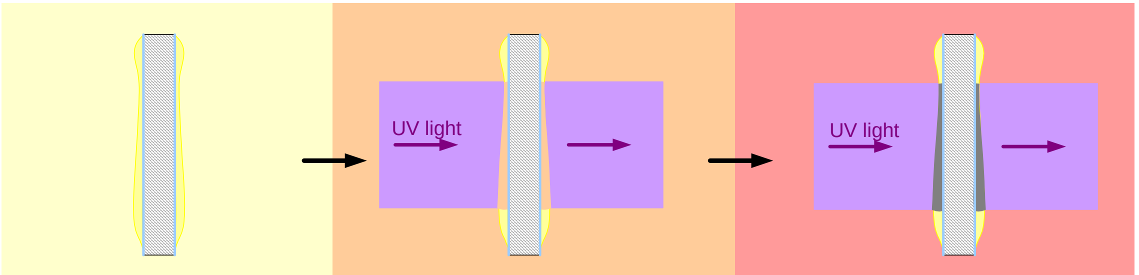




Afzal et al., Photonics West 2006, SPIE 6100

ALADIN Technical Challenges

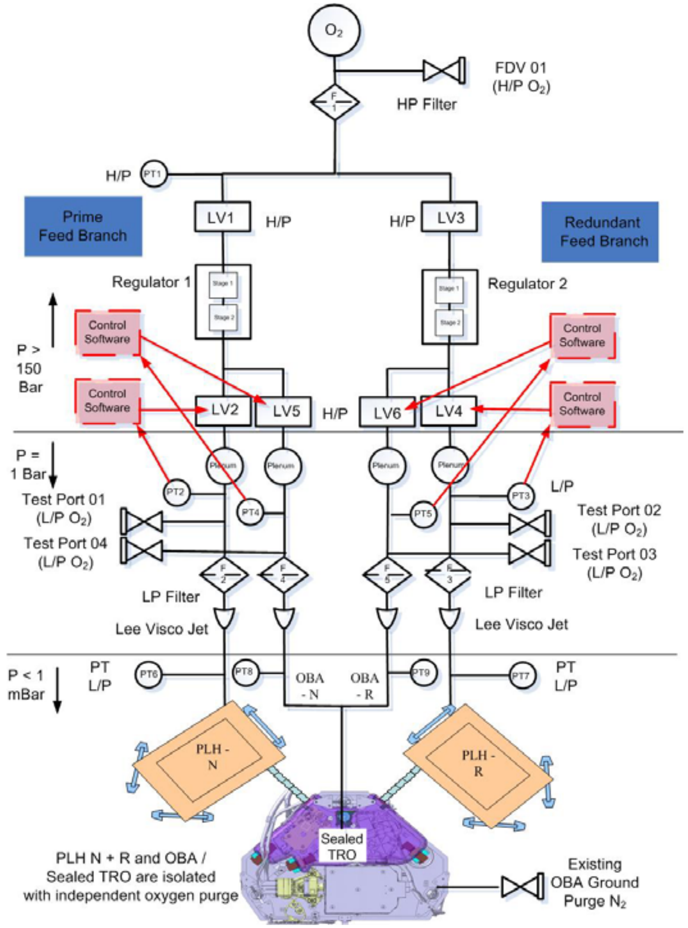
- **Space qualification of diode arrays**
  - Testing, screening procedures, LDA cooling
- **Laser Induced Damage**
  - 3 possible sources of
    - Power density exceeds the damage threshold of optical elements coatings in vacuum
    - Optical fatigue over the mission duration
    - Effects of optics contamination in vacuum
  - Solution: Slightly pressurised TRO & PLH



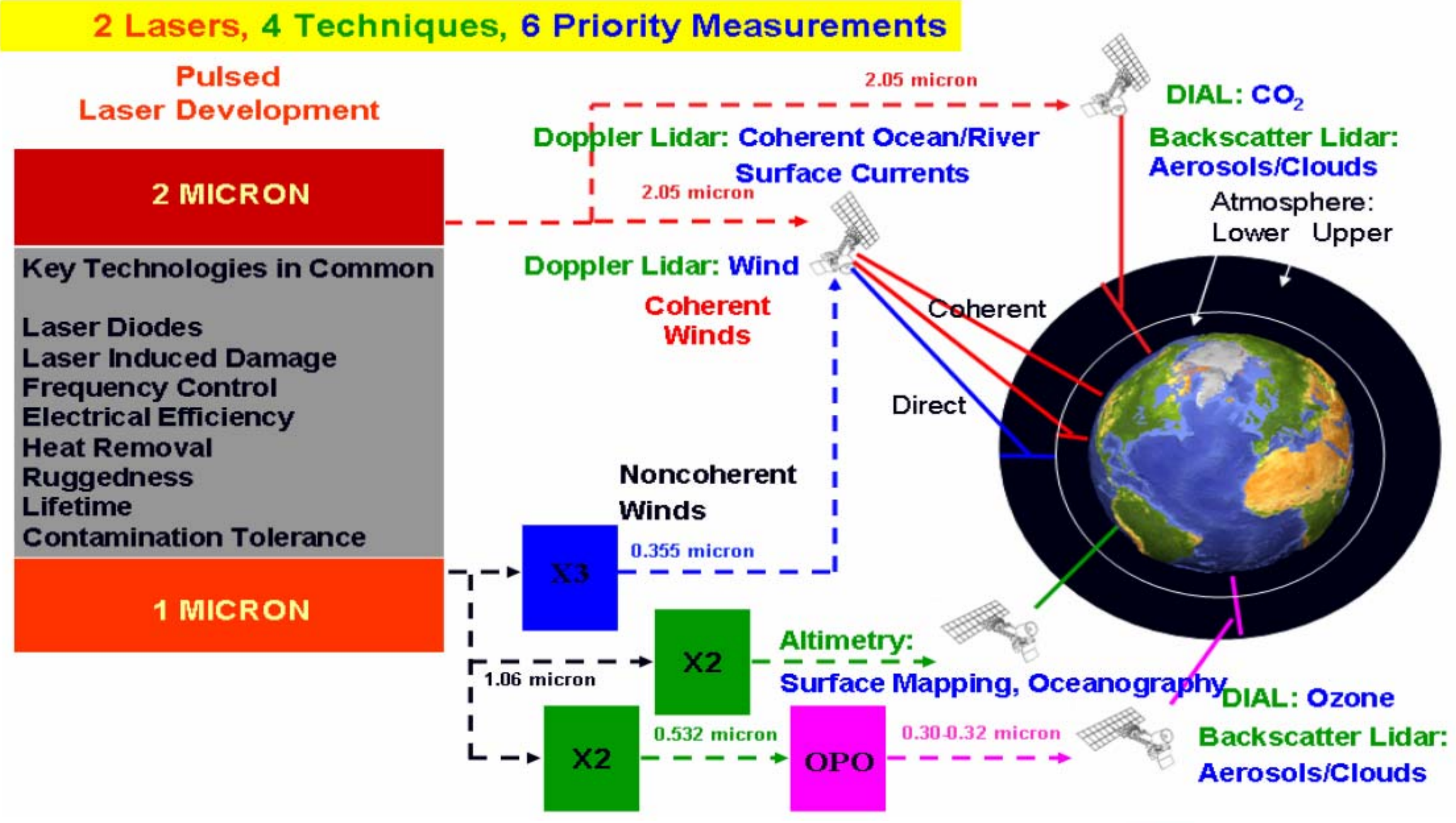
Step 1 : standard monolayer contamination. The laser is not involved

Step 2 : under UV illumination, molecules are « plated » and chemically transformed and become absorbant

Step 3 : under UV illumination, the absorbing layer is heated up to the pyrolysis threshold and becomes dark

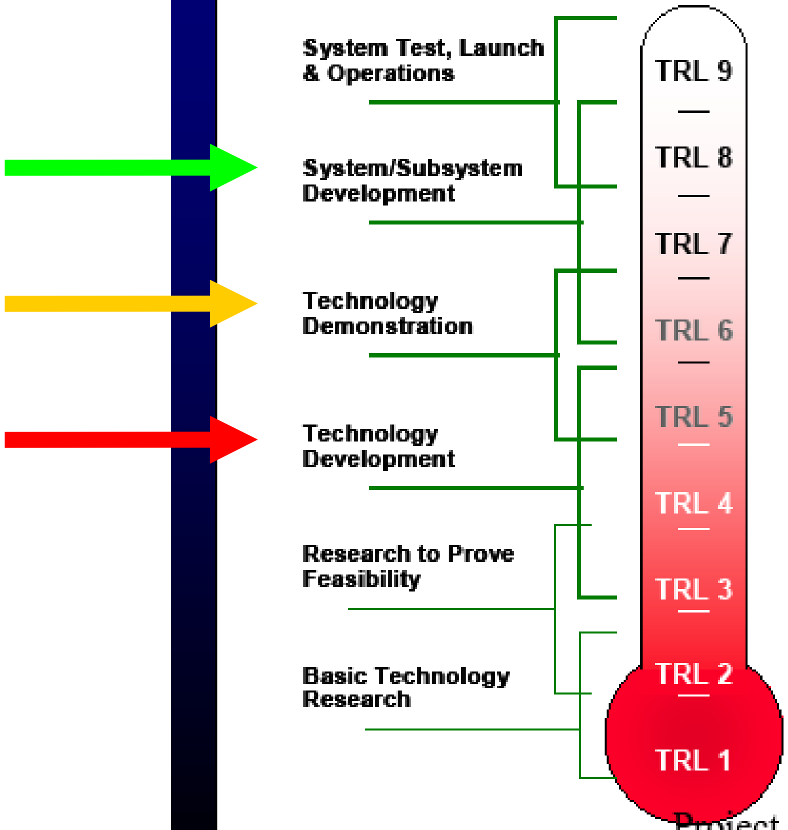


Current Lidar Challenges and Technology Developments at NASA



Singh, U.P., W.S. Heaps, G.J. Komar, AIAA 2005-6773.

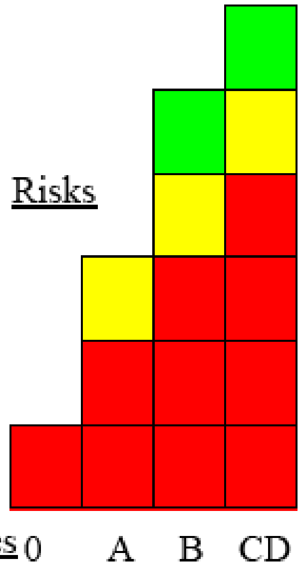
TRL - philosphy



Technology is with access to space one of the enabling activities of ESA

The requirements on technology are increasing, performance, reliability, etc so as to make impact on science and provide services

Failure to have technology at the right readiness level at each project phase is a major sources of risks for schedule delays and cost overruns



Technology development shall be sufficiently and timely supported

esa SCIENCE

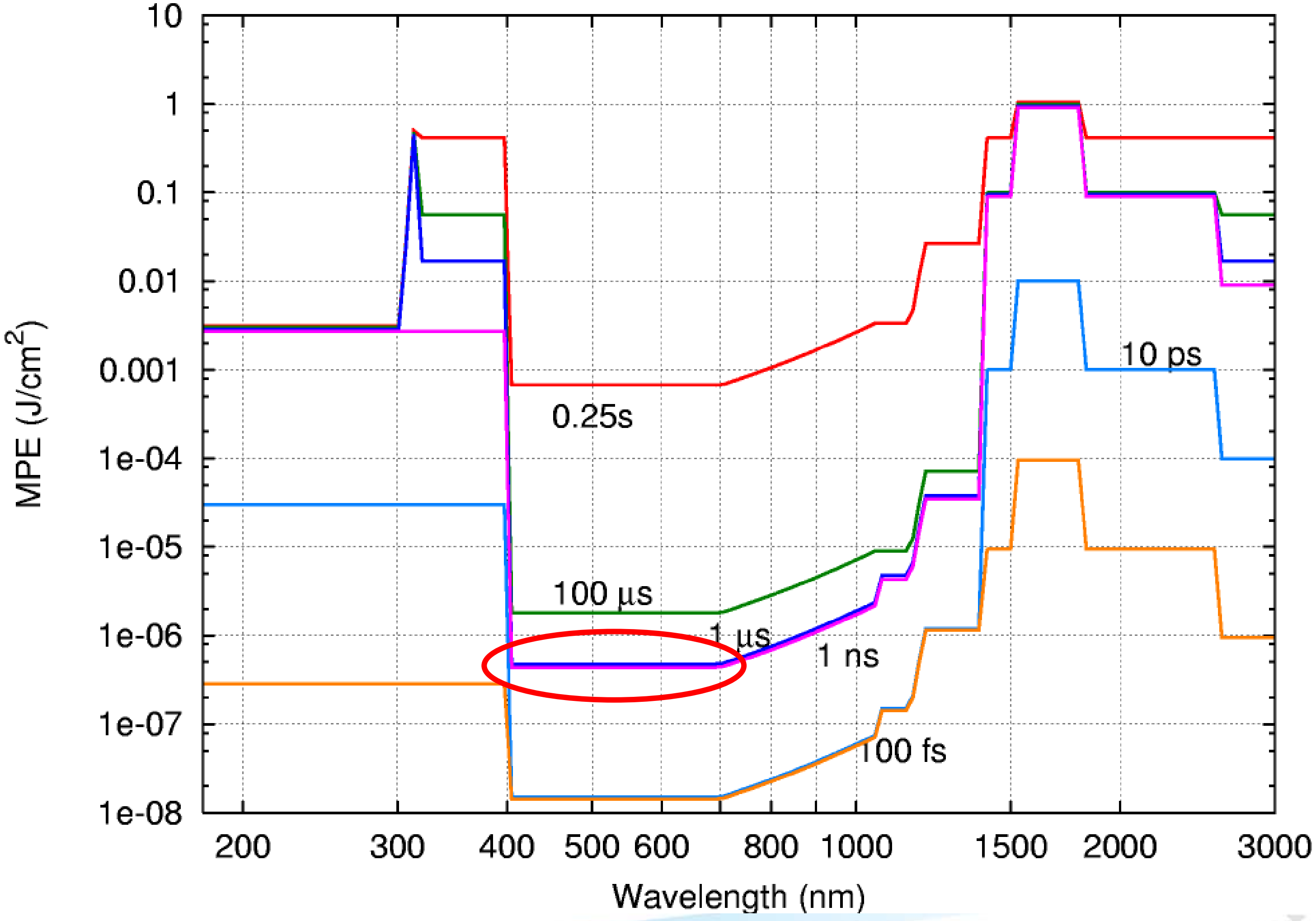
Designing & Sizing a Lidar – Key drivers & considerations

- **TRL!**
- **Figure of merit for lidar sizing, based on the performance for a specific case:**

$$\frac{D^2}{R^2} P_{TX} = cst \quad \Rightarrow \quad \frac{D^2}{R^2}\left(E_{beam} \cdot PRF\right) = cst$$

  - You cannot scale a ground-based or even airborne lidar for spaceborne applications
  - You need a suitable first reference
- **Consider eye-safety too**
  - Including an observer with a telescope (say, 80-mm)
- **Off-nadir pointing**
  - Avoid specular reflection

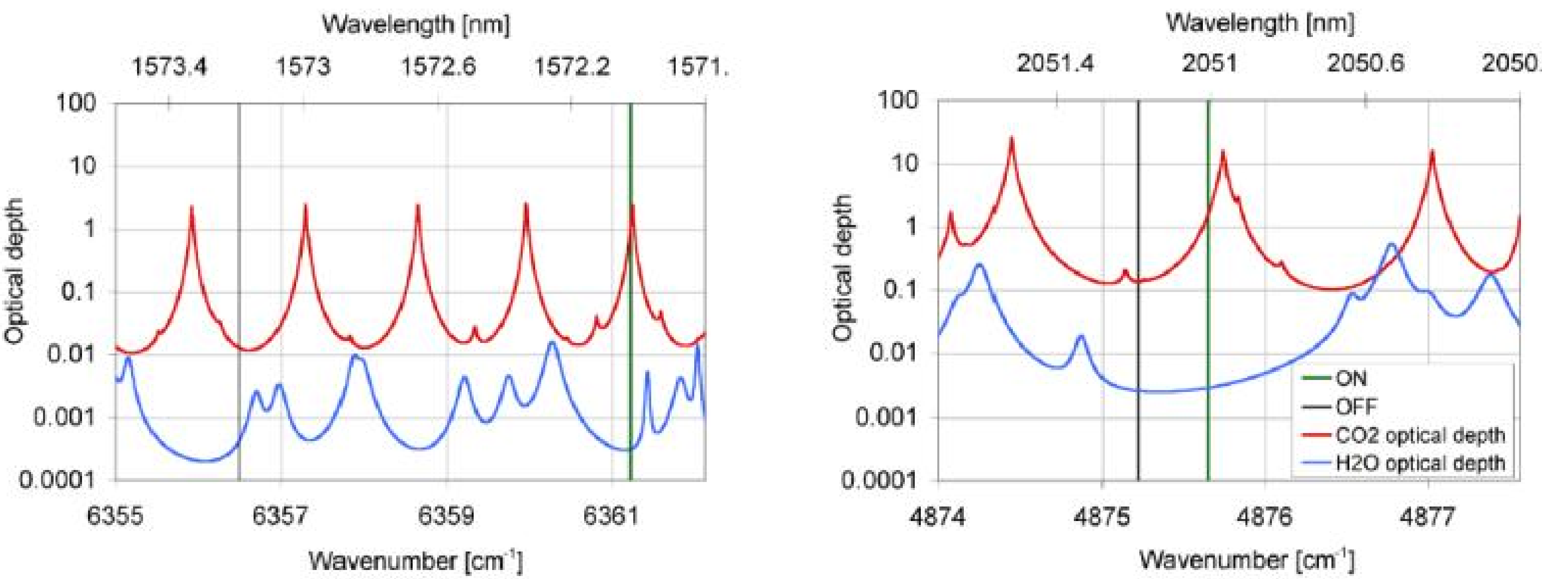
Eye-Safety



http://en.wikipedia.org/wiki/File:IEC60825_MPE_J_nm.png

Some high-level trade-offs

- **Operation wavelength(s)**
  - Often depends on the subject under investigation, e.g. A-SCOPE
    - B1 has more stringent requirements but B2 detector has a very low TRL



[ESA]

Figure 6.2: One-way CO_2 and H_2O optical depths around 1.57 µm (left) and 2.05 µm (right). Selected on/off- lines are 6361.2246/6356.50 cm^{-1} and 4875.6487/4875.22 cm^{-1}..

Practical Case – A-SCOPE

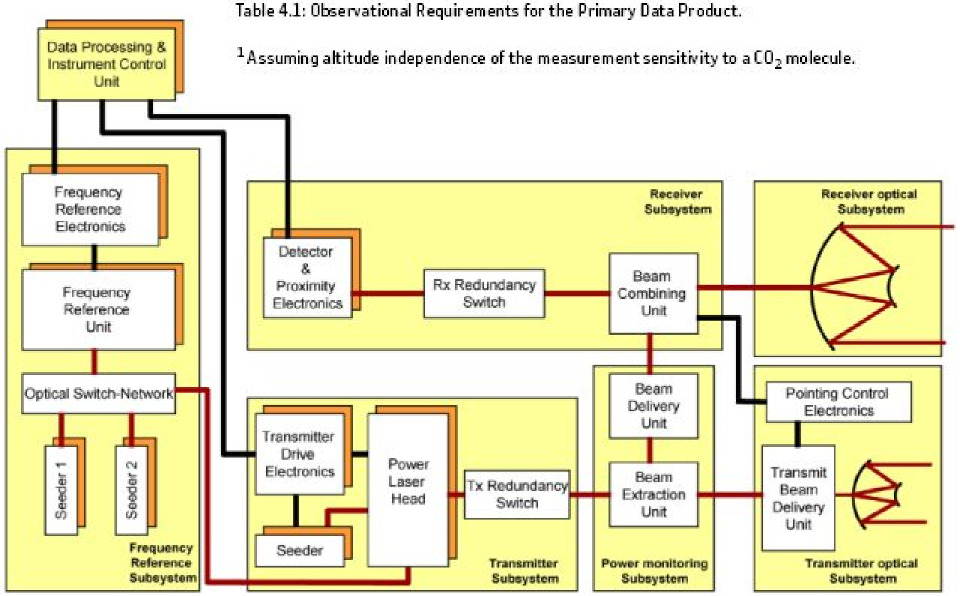
[ESA]

Parameter	Target	Threshold
Geophysical data product	XCO_2	
Random error[1]	0.5 ppm	1.5 ppm
Systematic error	0.05 ppm	0.15 ppm
Coverage	Global	Global
Horizontal resolution: Observation Individual measurement	 50 km < 100 m	 50 km < 100 m
Vertical resolution	Total column	Total column
Local overpass time	6 am/6 pm	6 am/6 pm
Absolute accuracy of scattering surface elevation	3 m	10 m
Timeliness	1 month	1 month

Table 4.1: Observational Requirements for the Primary Data Product.

[1] Assuming altitude independence of the measurement sensitivity to a CO_2 molecule.

- **Total column of CO_2**
- **Spreadsheet model is highly simplified and very specific to A-SCOPE B2 channel**
  - It only considers the Relative Error
    - Sufficient to get an idea of the lidar size
  - It ignores other important issues
    - Systematic errors are extremely important to consider when looking into the details of the instrument

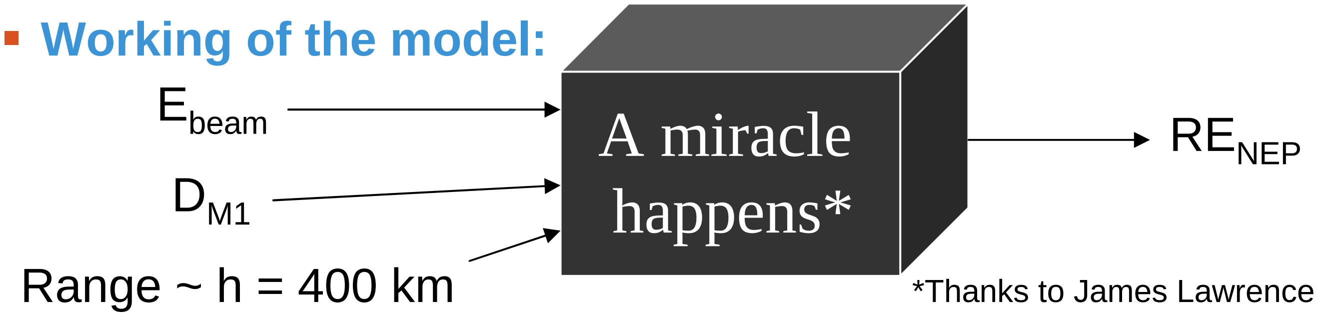


Step 1 – DAOD Random Errors and Instrument Sizing

- **The Lidar must be sized to meet the DAOD Random Errors**
  - For 2.05 µm:

$$RE_{NEP} \propto \frac{1}{DAOD} \frac{1}{\sqrt{N}} \frac{NEP\sqrt{\Delta t}}{S} \qquad DAOD = \frac{1}{2}\ln\left(\frac{P_{on}}{P_{off}}\right)$$

- **Working of the model:**



*Thanks to James Lawrence at the University of Leicester

Input variables				
Laser beam energy	E(beam)	**10**	mJ	<-- *drop-down menu*
Primary mirror aperture diameter	D(M1)	**0.5**	m	<-- *drop-down menu*

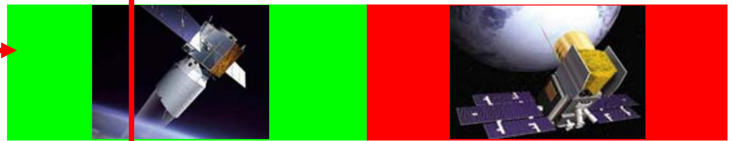
DAOD Random Error			Target / Threshold
Desert	4.38E-03	-	1.5 / 4.5 E-3
Ocean	2.63E-02	-	
Snow	3.74E-02	-	
Vegetation	2.81E-02	-	

Step 2 – Scale the Lidar

- **Possibility to play with altitude / aperture diameter / beam energy**

Parameter scaling control box				
What parameter do you want to keep constant?	**altitude**			*<-- drop-down menu*
What parameter do you want to vary?	**altitude**	**ERROR**		*<-- drop-down menu*
Enter new value here:	**0**		km	*<-- enter manually*

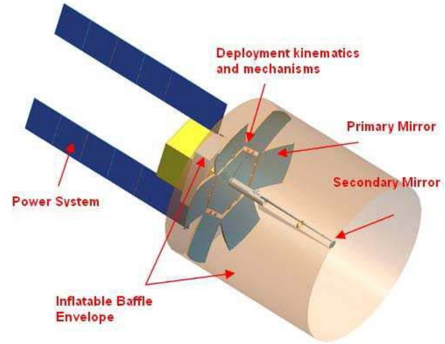
Lidar configuration
Aeolus-like
Telescope accommodation:
OK



New Parameters				
Altitude	h	400.00	km	*These parameters would result in (approximately) the same Random Error*
Aperture Diameter	D(M1)	#VALUE!	m	
Beam energy	E(beam)	#VALUE!	mJ	

- **The Lidar configuration does not affect the performance of the lidar, but the mission (telescope size when in LV fairing, atmospheric drag)**
- **Example of some considerations when playing with altitude / aperture diameter / beam energy…**

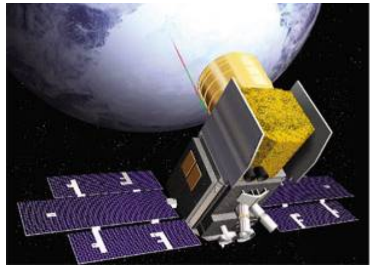
Aperture diameter, D



Mazzinghi et al. (2006), ESA SP-621

Receiver Aperture Diameter → Large / Small

<table>
<tr><th></th><th>Large</th><th>Small</th></tr>
<tr><td>Primary mirror segments</td><td>Single element?
Multiple elements, deployable?</td><td>Single element?</td></tr>
<tr><td>Rx telescope size</td><td colspan="2">How compact can the Rx telescope be (fast focal ratio)?</td></tr>
<tr><td>Spacecraft accommodation / satellite configuration</td><td>Aeolus-like?</td><td>ICEsat/EarthCARE-like?</td></tr>
<tr><td>Drag & perturbation forces</td><td colspan="2">Cross-section area → propulsion system and amount of propellant
CoP away from CoM → torques → AOCS actuators requirements</td></tr>
<tr><td>Launch vehicle accommodation / class</td><td colspan="2">Launch vehicle fairing size, payload mass
COST: 1 Soyuz = 3 Vega</td></tr>
<tr><td>Mirror Material</td><td colspan="2">high specific stiffness E/ρ?
Low thermal distortion ratio: low CTE, α / high thermal conductivity λ?
Cost?</td></tr>
</table>

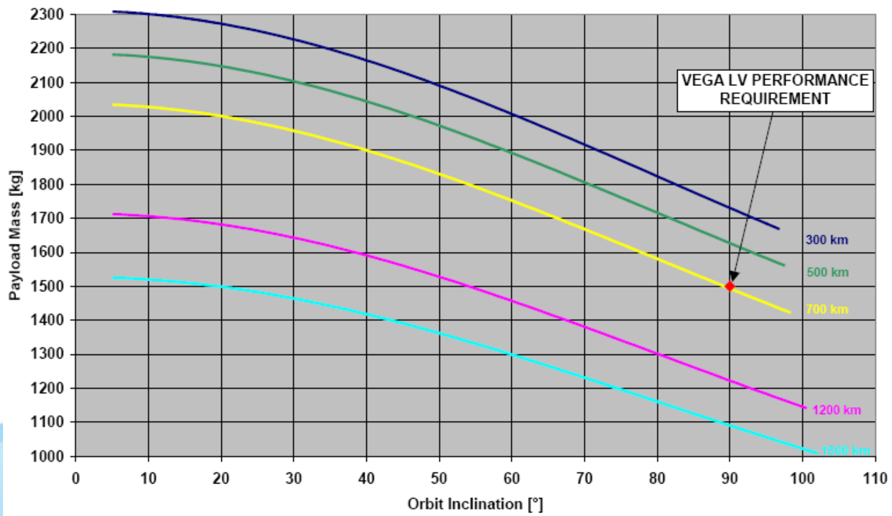

NASA


ESA

Range, R

Altitude

	High	Low
Drag force (& torque)	Low atmospheric density	High atmospheric density
	Delta-V & propellant budget, AOCS actuators	
Launch vehicle accommodation / class	Launch vehicle performance (mass delivered at a given altitude) COST: 1 Soyuz = 3 Vega	
Pointing requirements	Geo-location: the lower, the easier (But is it challenging in the first place?)	
Eclipse duration	Size of the thermal control system (heater power) Size of the solar arrays	
Repeat ground track	Selectable altitudes (if applicable)?	



Arianespace (2006)

Vega User's Manual

Beam Energy × PRF

	(Energy x PRF) High	(Energy x PRF) Low
Power consumption, Power dissipation	Large	Lower
Tx stage heat dissipation	Tend towards large radiators, can be difficult to accommodate	

Step 3 – Check Results

- **Mass, power and volume budgets**
- **A section called "consequences" shows the impact of the options you have chosen on the radiator size and at mission level**
  - Some colour-coding feedback to help you but it does not represent a strict statement

- **Your turn!**

Exercise Objectives

- **Come up with 2-3 design options achieving different degree of performance**
  - You will be asked to summarise your selected options
  - For the selected options, trade-off between RE performance and instrument characteristics
- **Reminder**
  - Step 1
  - Step 2

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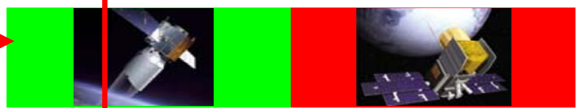

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