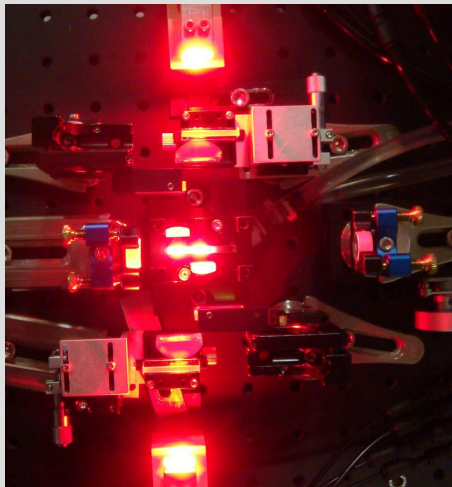
Imperial College London

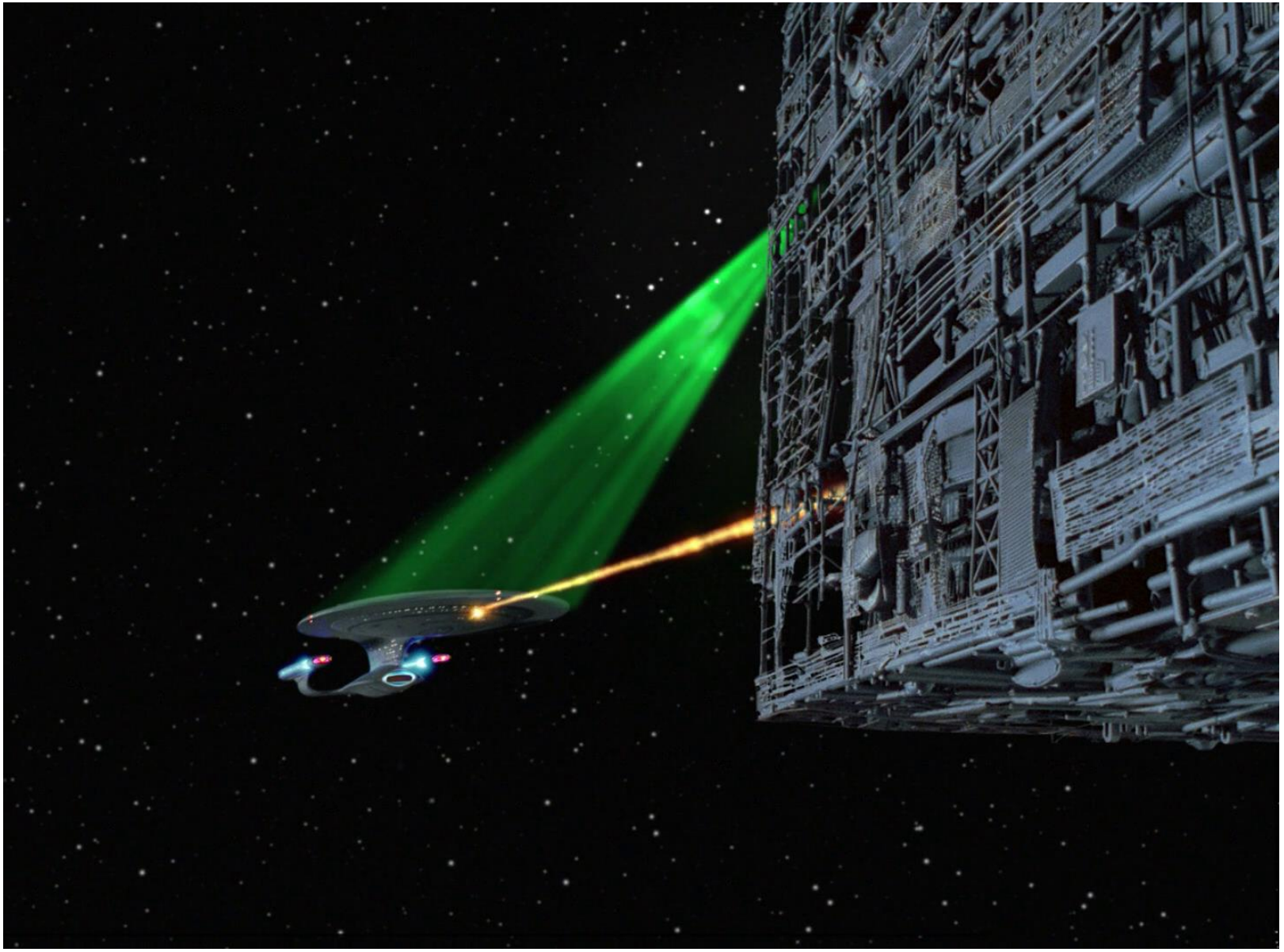
Siegman International School on Lasers
August 2017, CIO Mexico

Space Lasers 1

Professor Mike Damzen
Imperial College London, UK



Space Lasers?



Outline of Presentations

- *Space Lasers 1 – Applications & Laser Requirements*
- *Space Lasers 2 – Development of Tunable Alexandrite Lasers for Remote Sensing (+ other)*
- *A Commercial Laser Story – Midaz Lasers Ltd*

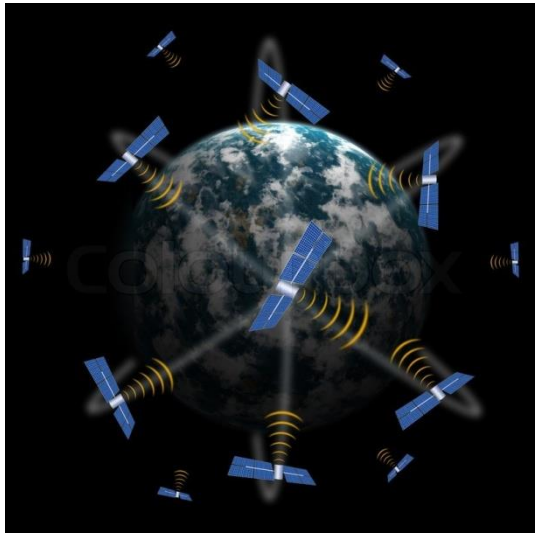
Outline of Space Lasers 1

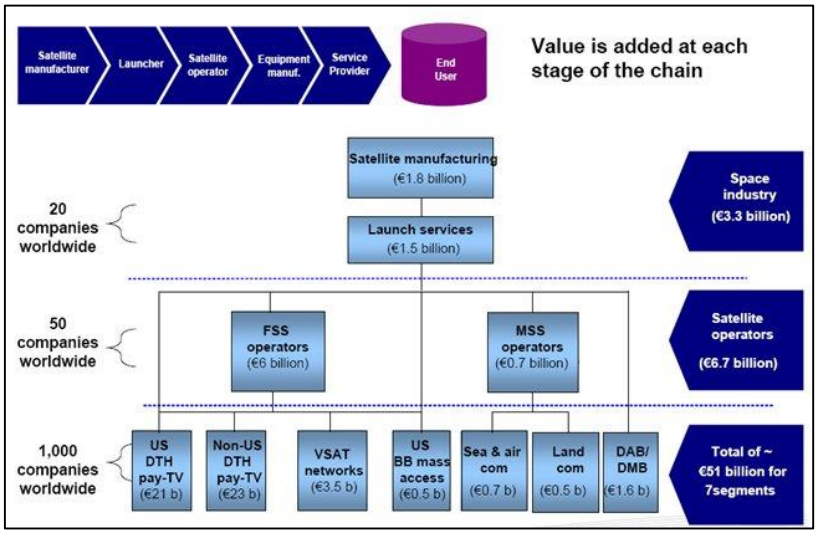
- *Laser Applications in Space Domain*
- *Lasers for Remote Sensing (Lidar)*
- *Laser Specification for Applications*
- *Engineering Challenges for Space Environment*

Space Application Sectors

Space Science

Earth Observation

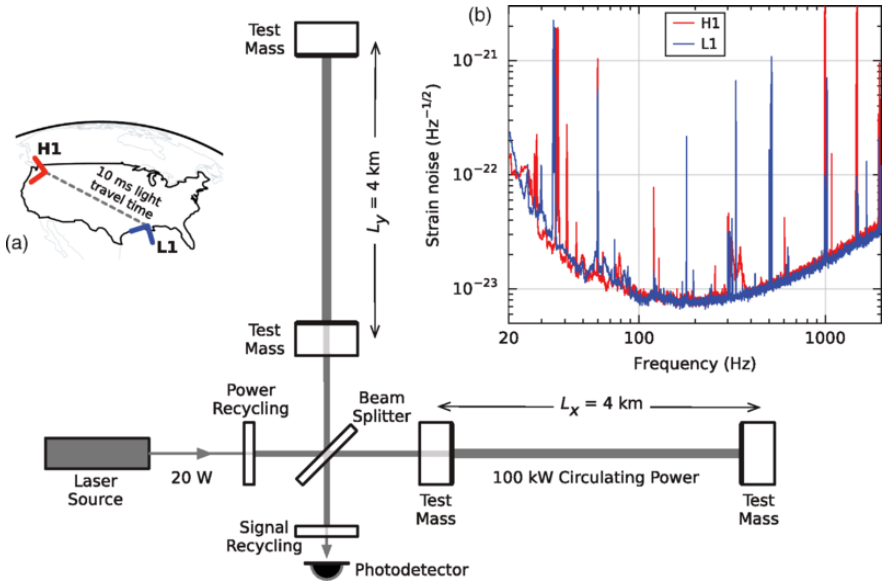


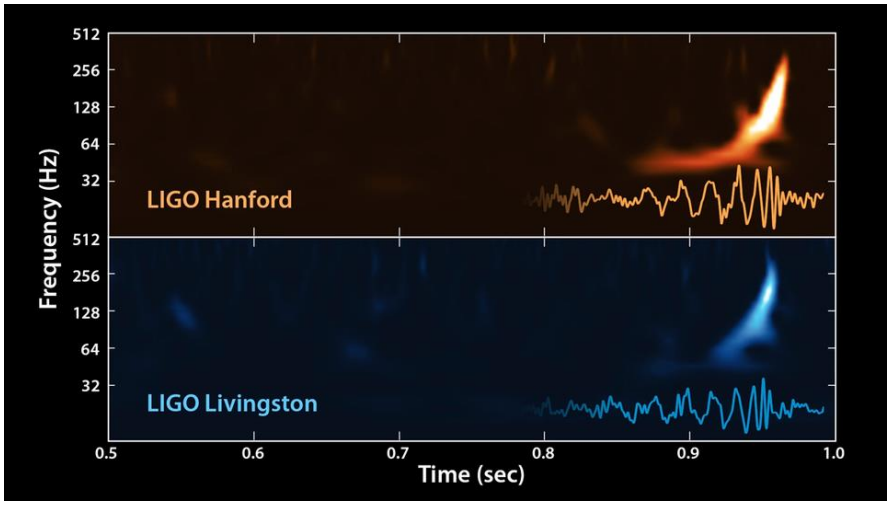


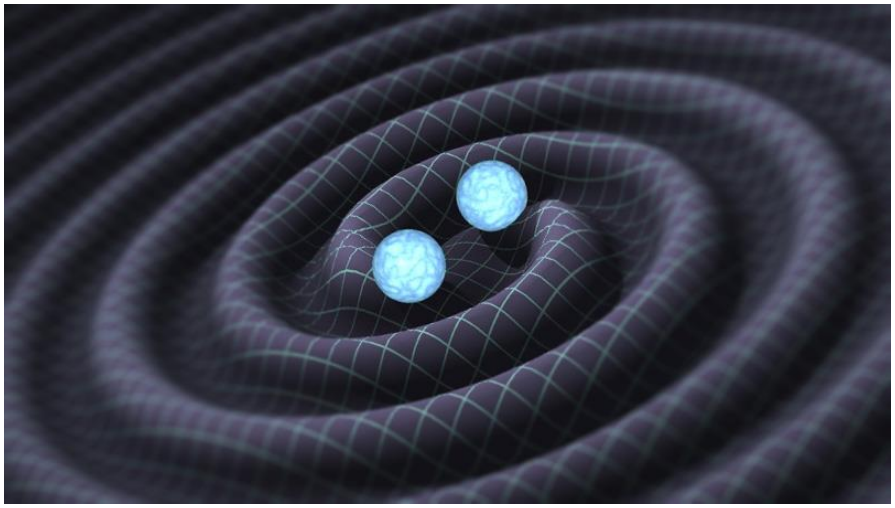
Satellite Telecom

"Downstream" data-services

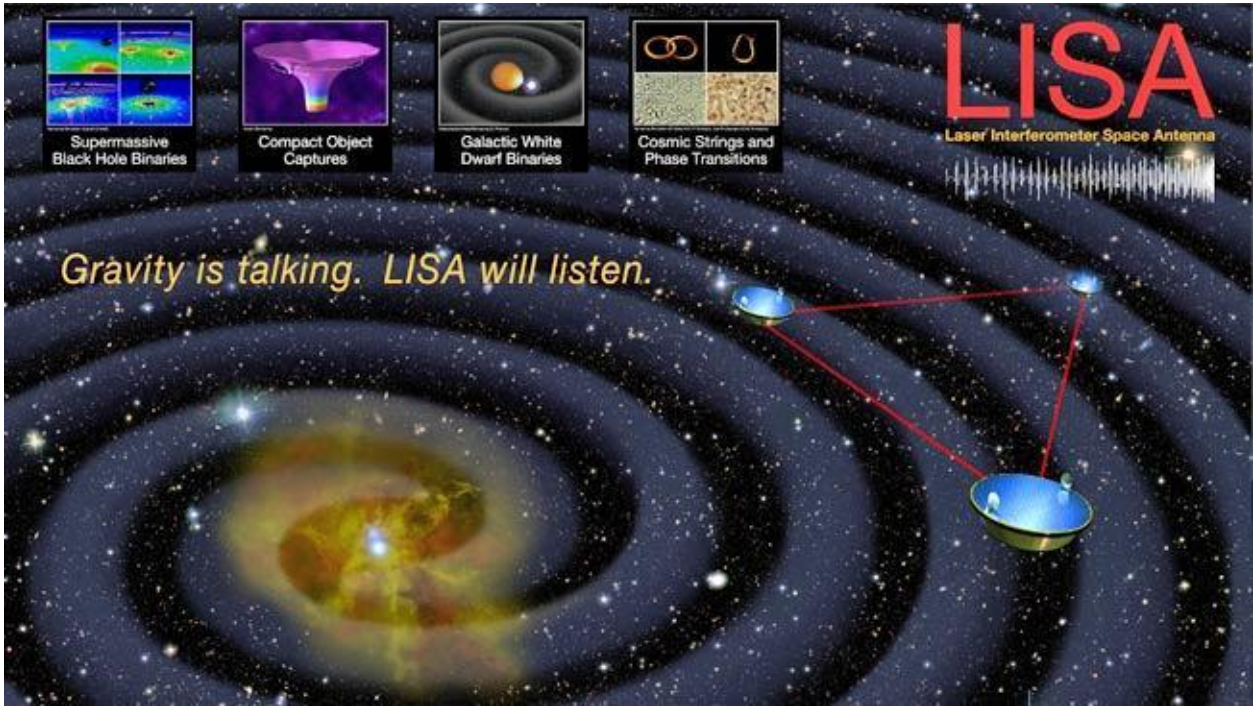
Gravitational Interferometers



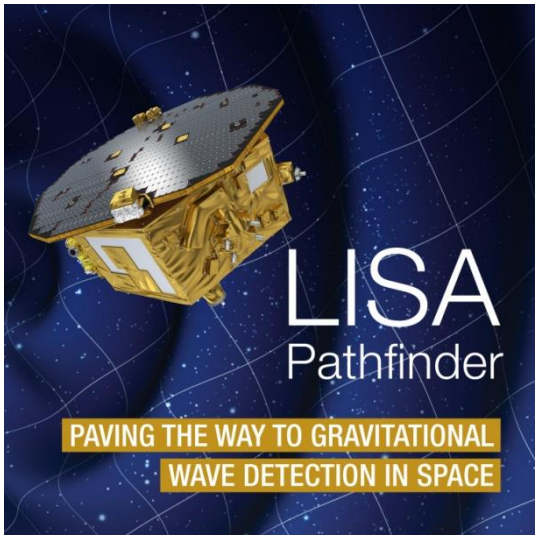


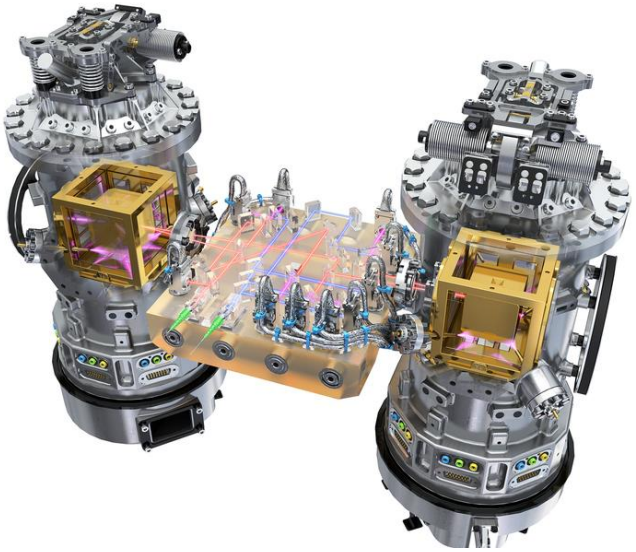


Gravitational Interferometers in Space

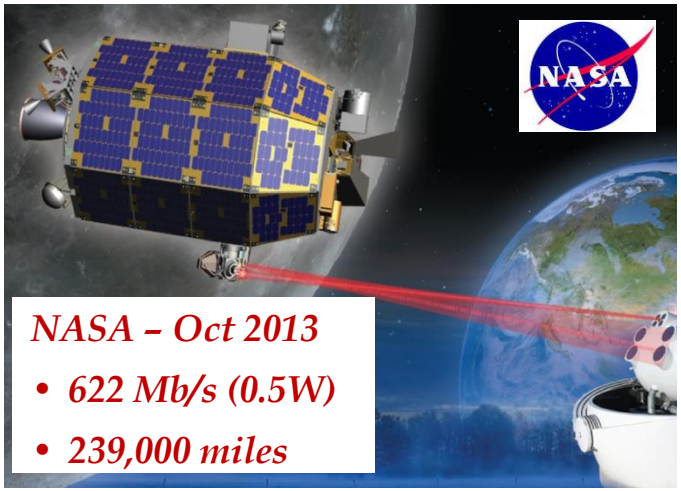


Arm length:
L = 5M km



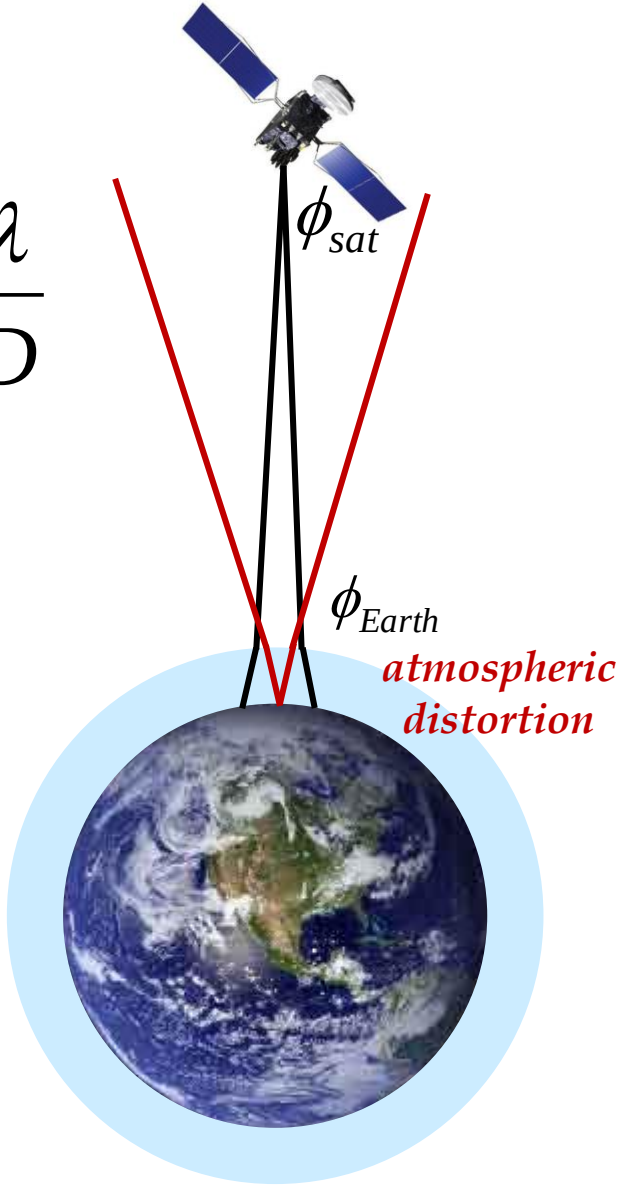


Laser Communications in Space



Satellite to Earth

$$\phi = \frac{\lambda}{D}$$



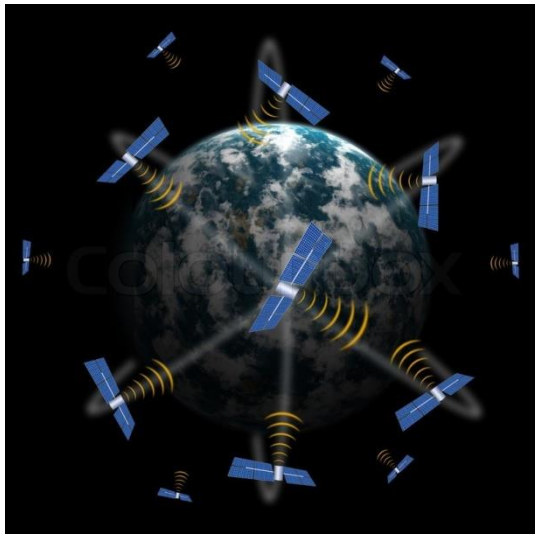
- *High data rates (optical vs RF)*
- *Low optical power requirement*
- *Secure (point-to-point)*

$$\phi_{Earth} > \phi_{sat}$$

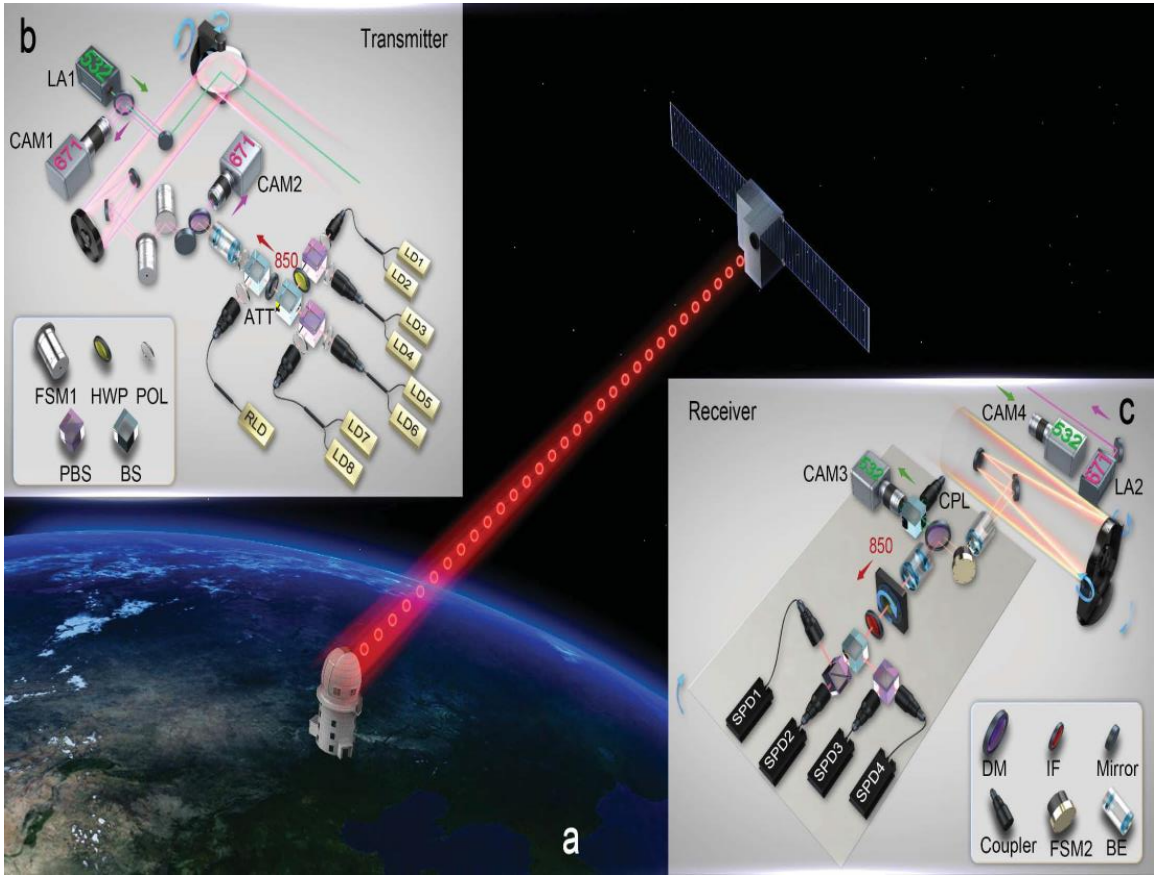
$$P_{Earth} > P_{sat}$$

The "shower curtain" effect

Optical Internet of Space



The Internet of Space
Free-space satellite-based laser communication links



Quantum Key Distribution over 1200 km –using entangled photons from Chinese satellite (2017)

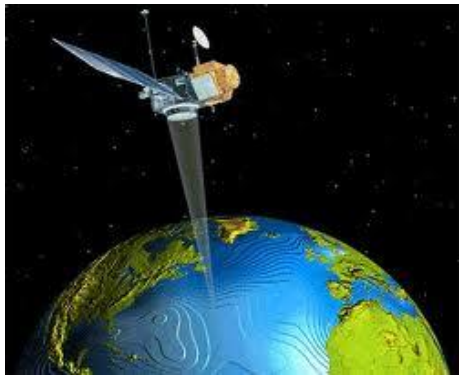
Space Lasers for Remote Sensing

- lasers can reach out to great distances and acquire valuable scientific data!

What is Remote Sensing?

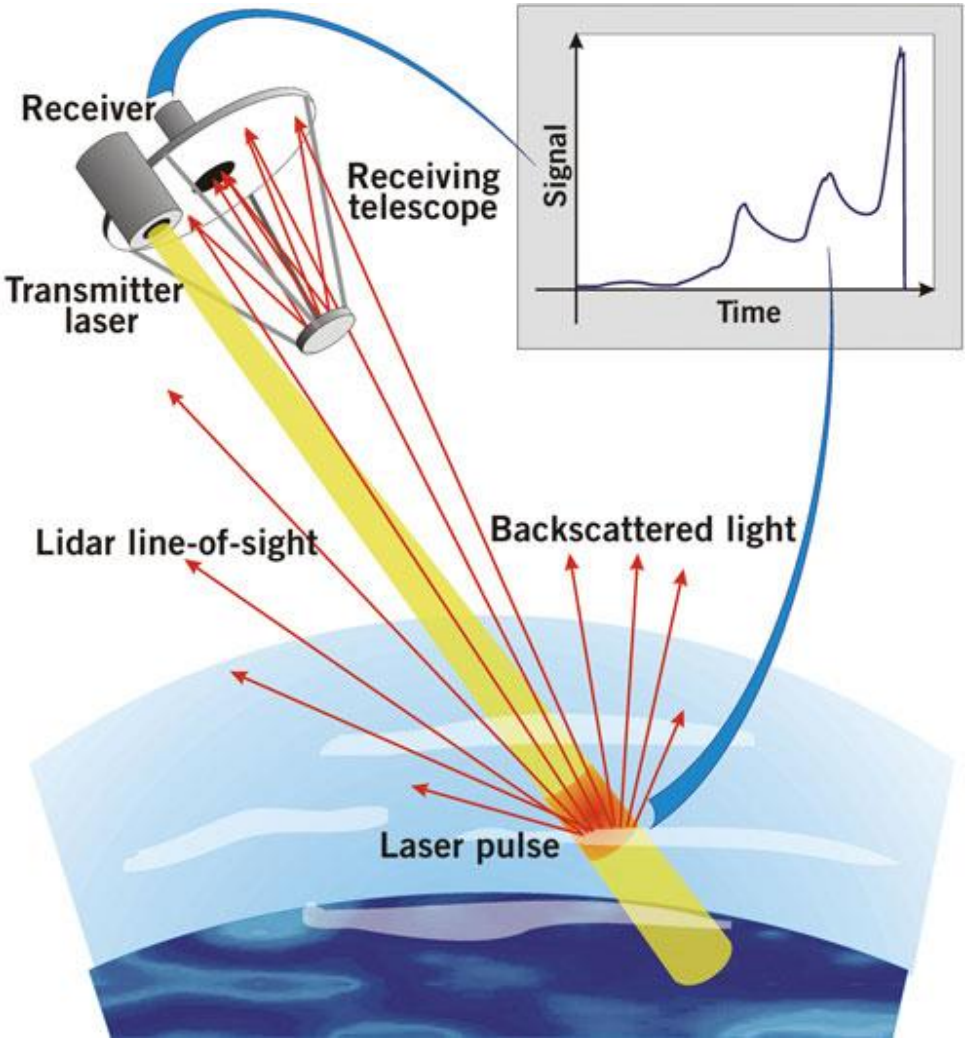
The acquisition of information about an area, object or phenomenon without the need for direct physical contact

- **Passive techniques** – e.g. objects lit by sunlight
- **Active techniques** – radiation (e.g. laser) is actively emitted from instrument to act as a probe
  - **Li**ght **D**etection **A**nd **R**anging (LIDAR)
  - Laser Altimetry
  - LIBS
  - SAR (Radar)



LIDAR Technique

LIDAR Instrument = Transmitter (Laser pulses) + Receiver (with detection equipment)



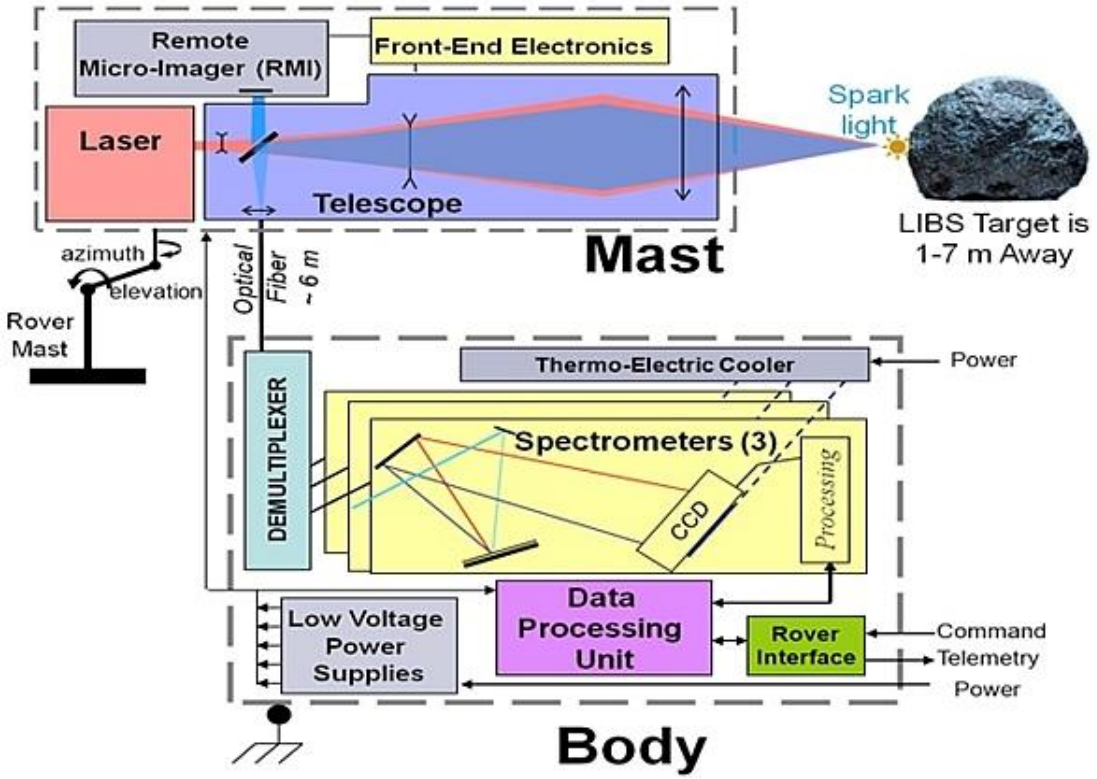
Mars “Curiosity” Rover

Quite short-range remote sensing: 1 – 7 m

The Mars Science Laboratory mission’s “Curiosity” rover carries the tunable laser spectrometer (TLS), which will investigate isotope ratios in carbon, hydrogen, and oxygen to assess present-day habitability and whether Mars ever supported life.

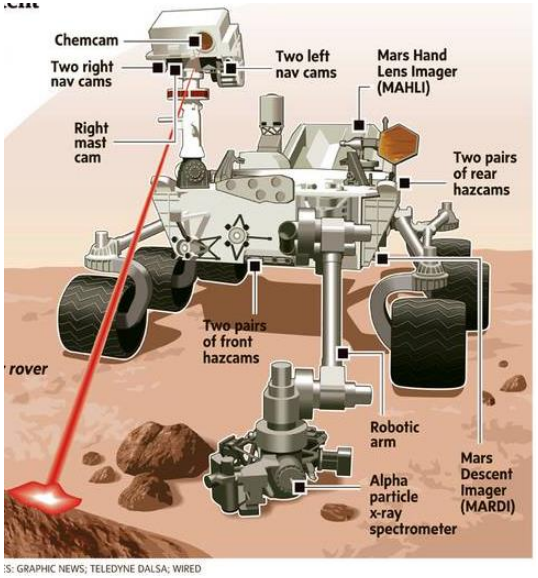
But on Mars!!

LIBS (Laser-Induced Breakdown Spectroscopy)



Laser Pulse ablates small amount of material, as hot plasma that emits light.

Spectrometer identifies material by its spectral lines.



Q-switched Nd:KGW laser (1067nm)

- ***10mJ / 5ns pulse (2MW)***
- ***Focused to >1 GW/cm^2 at target***

Satellite-based Remote Sensing

Quite long-range remote sensing: >400 km!

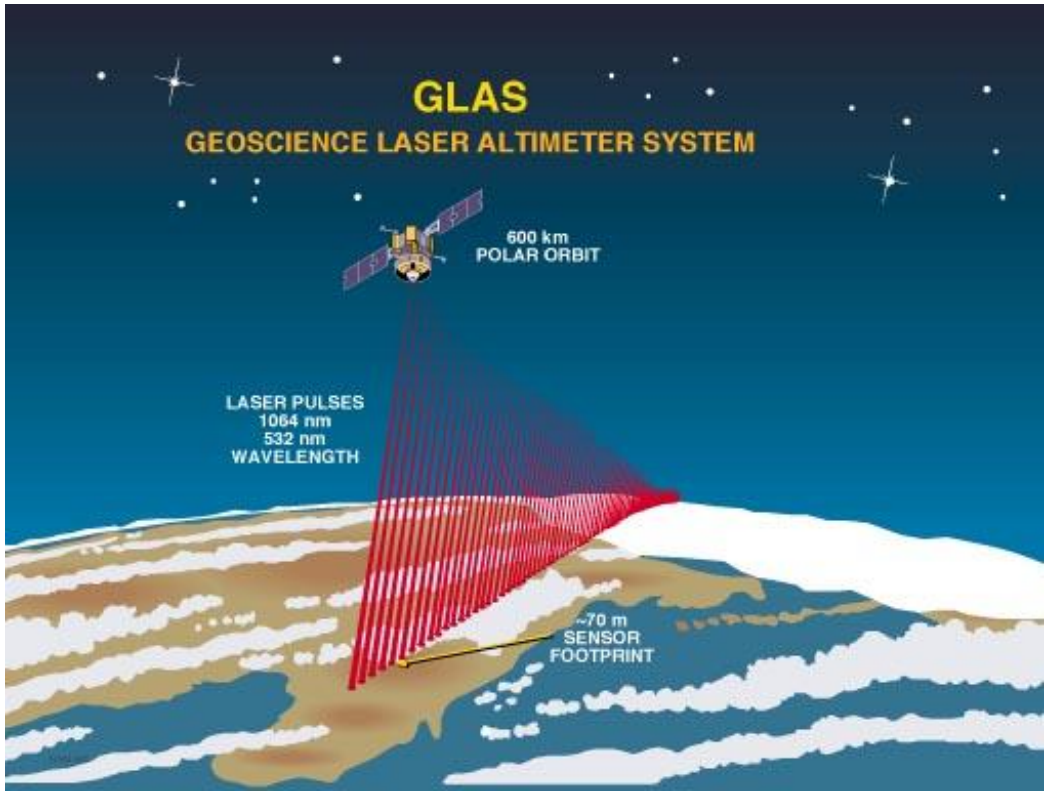
- **Satellite-based Earth Observation** is a powerful global mapping tool for
  - ✓ surface mapping (altimetry)
  - ✓ weather monitoring and prediction;
  - ✓ environmental research (atmospheric modelling, climate change science);
  - ✓ environmental monitoring (e.g. pollution);
  - ✓ monitoring and management of natural resources (e.g. vegetation);
  - ✓ disaster mitigation

Some Issues to address:

- Ice cap melting,
- Vegetation; agriculture
- Weather
- Aerosols/clouds ; radiation balance,
- O_3 Ultraviolet shield and smog, human health
- CO_2, CH_4 Greenhouse gases, global warming
- O_2 Atmospheric temperature measurement,

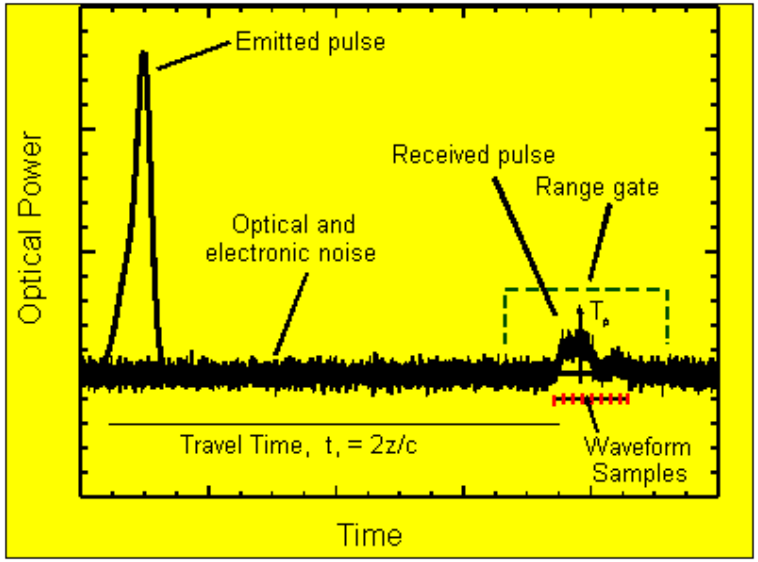
Laser Altimetry

Time-of-Flight (TOF) provides a precise measurement of range



Use GPS for satellite reference

$$t = 2z/c$$



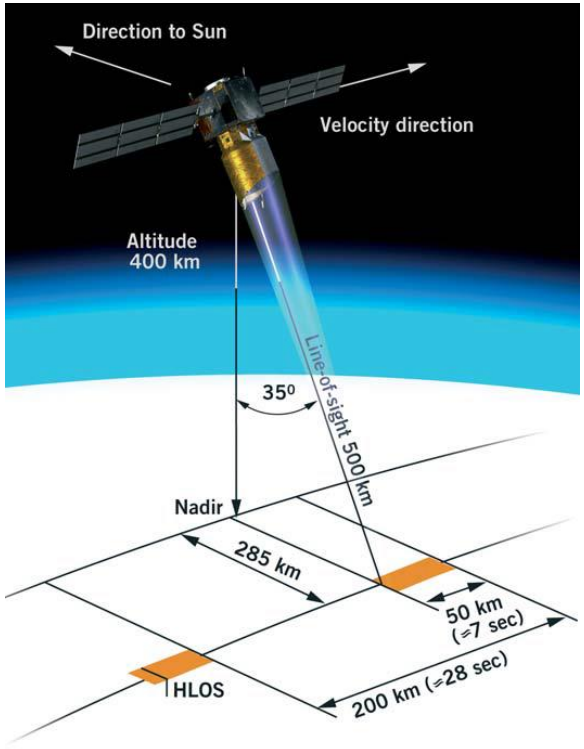
1ns = 15 cm

Laser Resolution

Beam Size (Foot-print) at target determines lateral spatial resolution

$$\theta = \frac{\lambda}{\pi w_0}$$

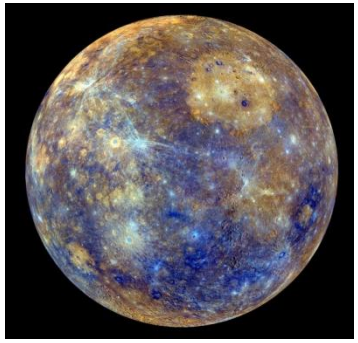
Beam size	Divergence (θ)	Size Increase @ 400 km
1 mm	1 mrad	400 m
1 cm	0.1 mrad	40 m
1 m	1 μrad	~ 0.4 m



NASA Laser Altimeters - MLA, MOLA, LOLA

- Mission Objectives: Time-of-flight mapping of surface topography.

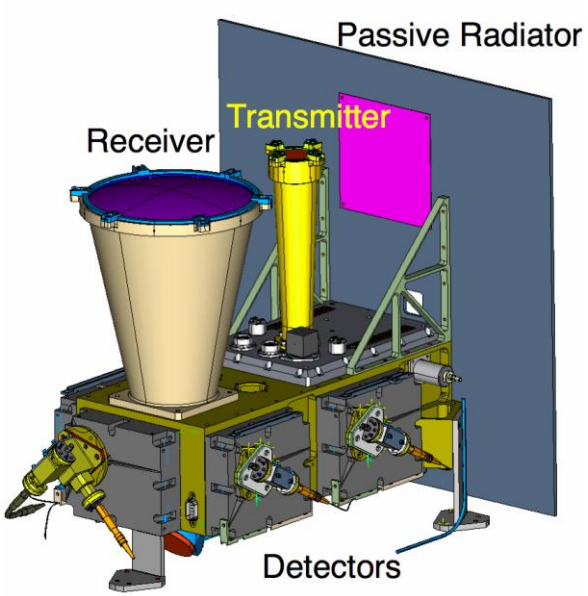
MLA
Mercury Laser Altimeter
• Diode pumped, passively Q-switched
Cr:Nd:YAG laser @ 1064nm, 20mJ, 6ns, 8Hz
• Mission scheduled to end in March 2012

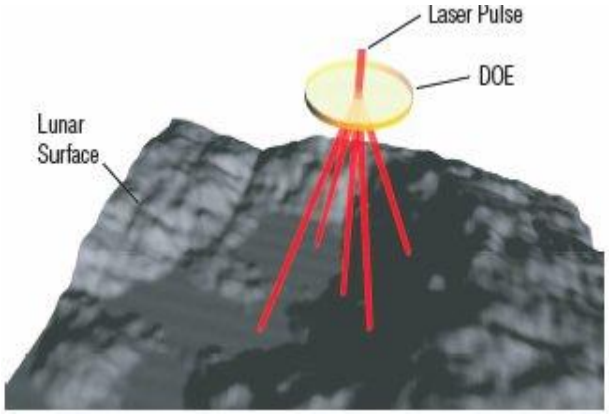


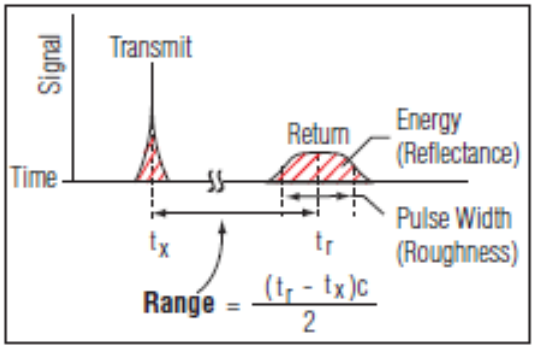
MOLA
Mars Orbiter Laser Altimeter
• Diode pumped, actively Q-switched
Cr:Nd:YAG laser @ 1064nm, 48mJ, 10Hz
• Collected altimetry data1996 - 2001

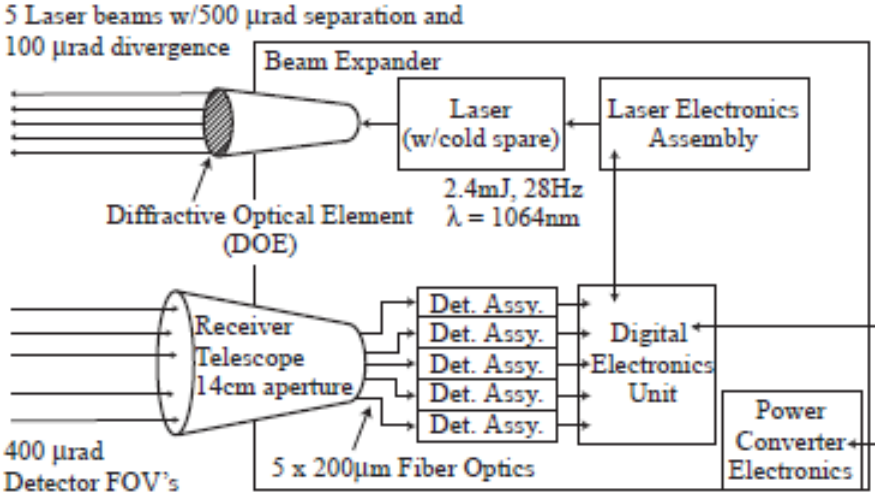
LOLA
Lunar Orbiter Laser Altimeter
• Diode pumped, passively Q-switched
Cr:Nd:YAG @ 1064nm, 2.7mJ, 6ns, 28Hz

Laser Altimeter - LOLA



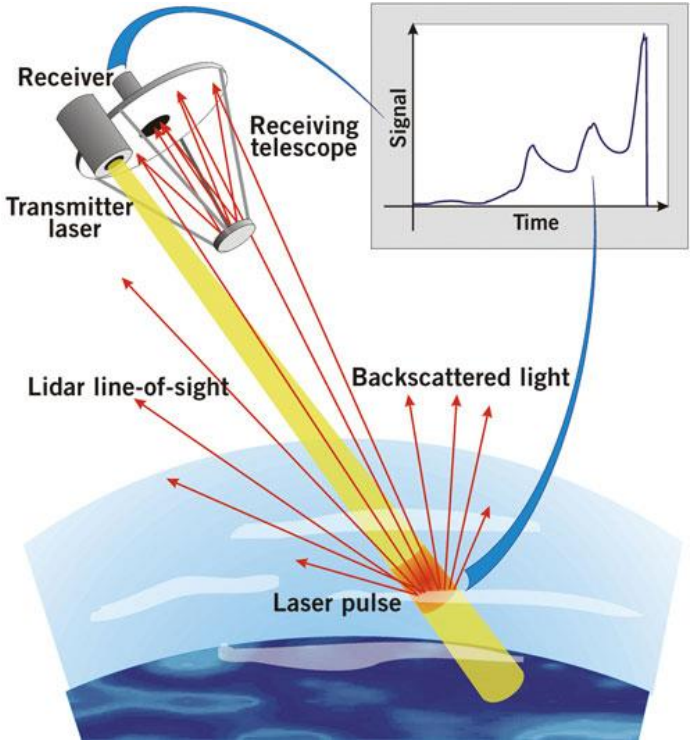


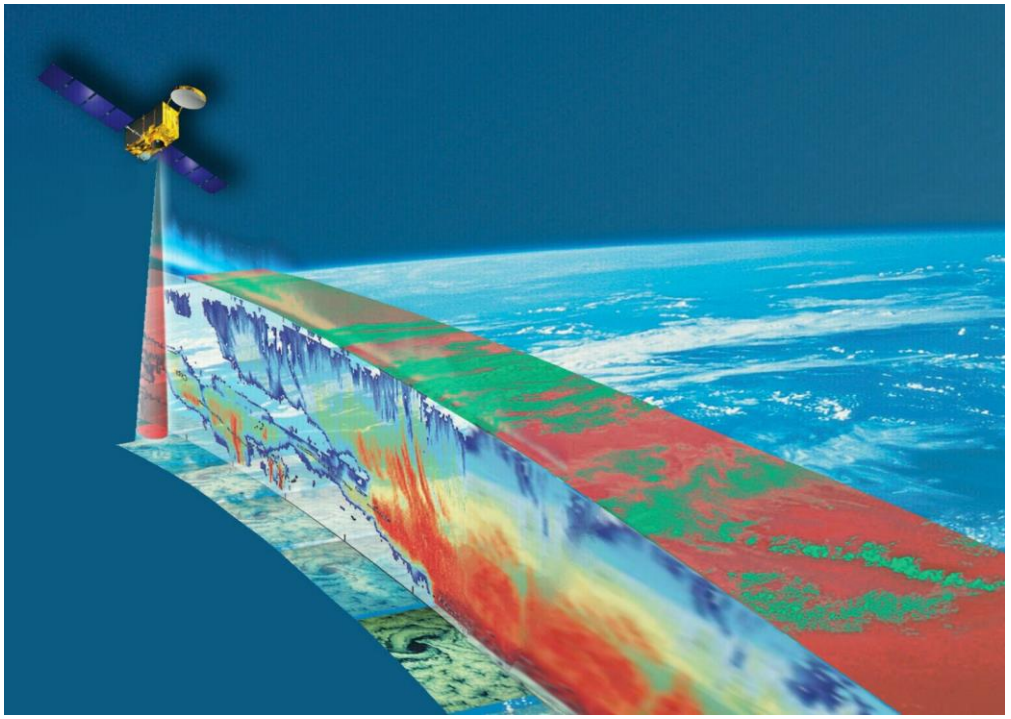




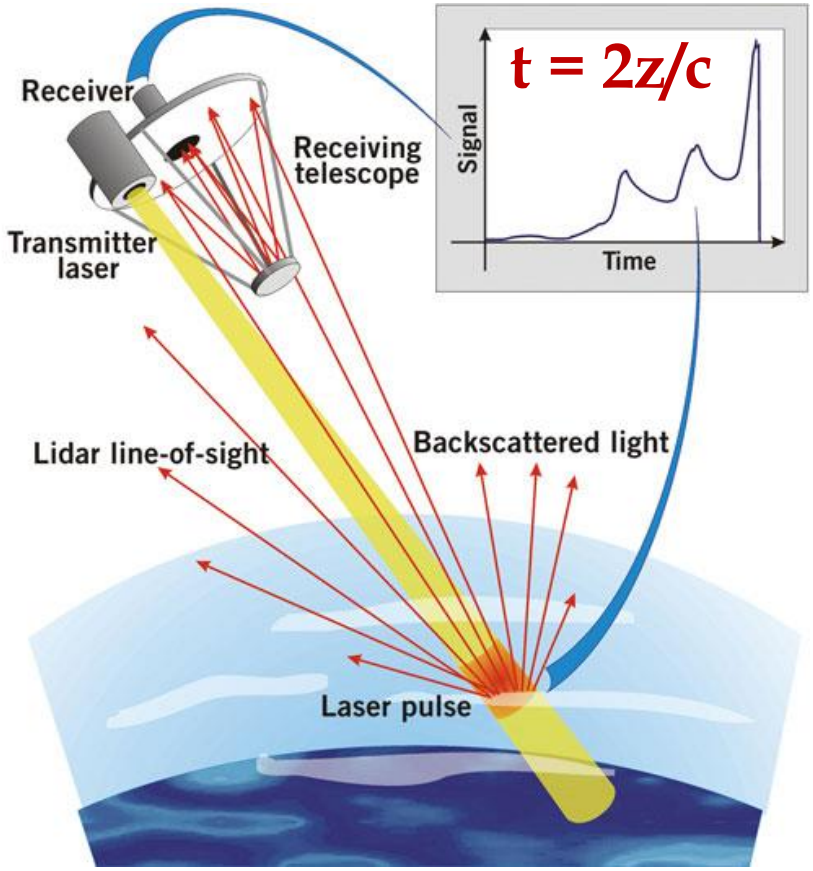
Space Lidar for Earth Observation

- **Atmospheric vertical (3-D) profiles of wind / clouds / aerosols...**
  - global coverage (on satellite platform)
  - ranging information
  - day/night operation



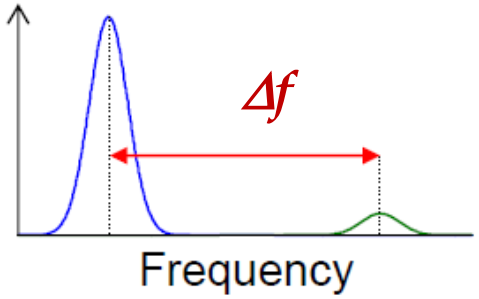


Laser-Based Lidar principles



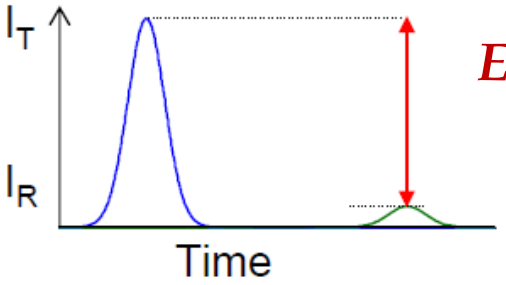
Light Detection And Ranging (LIDAR)

Doppler wind lidar



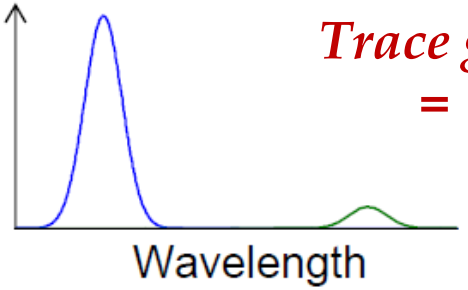
$V=\lambda/2*\Delta f$

Backscatter lidar: cloud/aerosol profiles



$Extinction=I_R/I_T$

Differential absorption lidar (DIAL)



Trace gas concentration $= \log (I_{\lambda,on}/I_{\lambda,off})$

The Lidar Equation

ELASTIC LIDAR EQUATION (SINGLE SCATTERING)

$$P(\lambda, z) = P_L \frac{A_0}{z^2} \frac{c\tau_L}{2} \xi(\lambda, z) \beta(\lambda, z) e^{-2 \int_0^z \omega(\lambda, \varsigma) d\varsigma}$$

z: altitude

λ: wavelength

P_L: laser power $\frac{A_0}{z^2}$ acceptance angle $\frac{c\tau_L}{2}$ vertical resolution ξ: efficiency

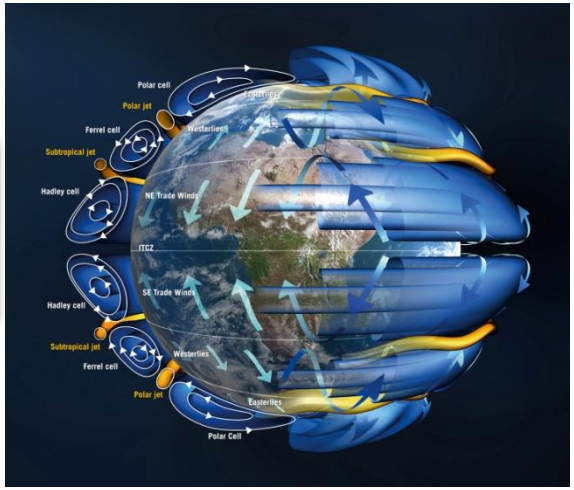
Small signal return from atmosphere requires

high pulse energy lasers

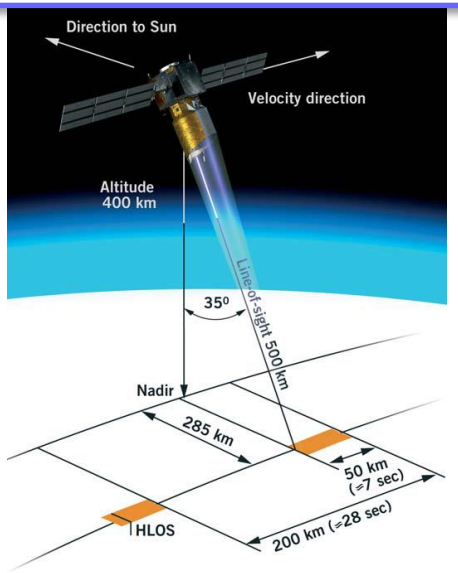
Satellite-based LIDAR Missions (ESA)

ADM AEOLUS Mission: –

acquire global **WIND** profiles for CLIMATE & WEATHER MAPPING

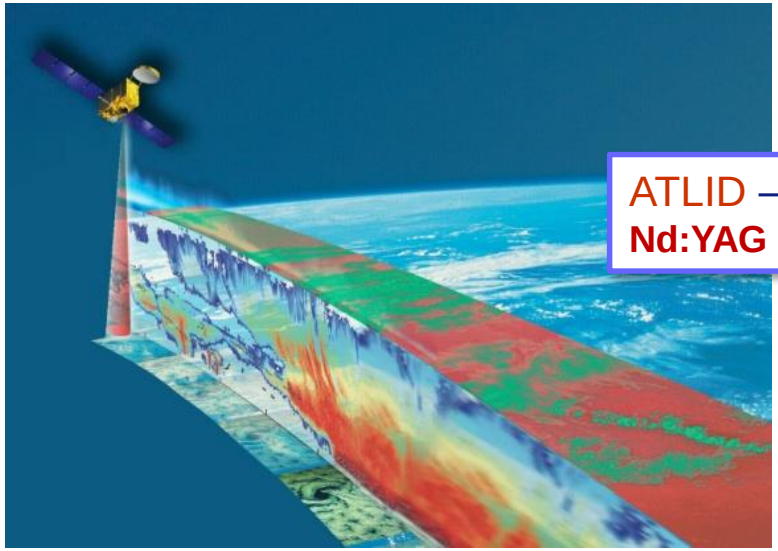


ALADIN - Doppler Wind Lidar
Nd:YAG 3ω (UV - 355nm)



EARTHCARE Mission: –

acquire vertical profiles of **CLOUDS & AEROSOLS**

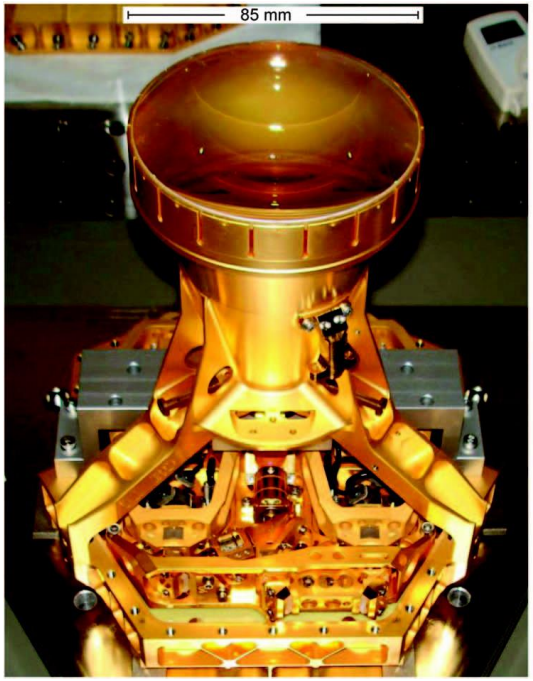


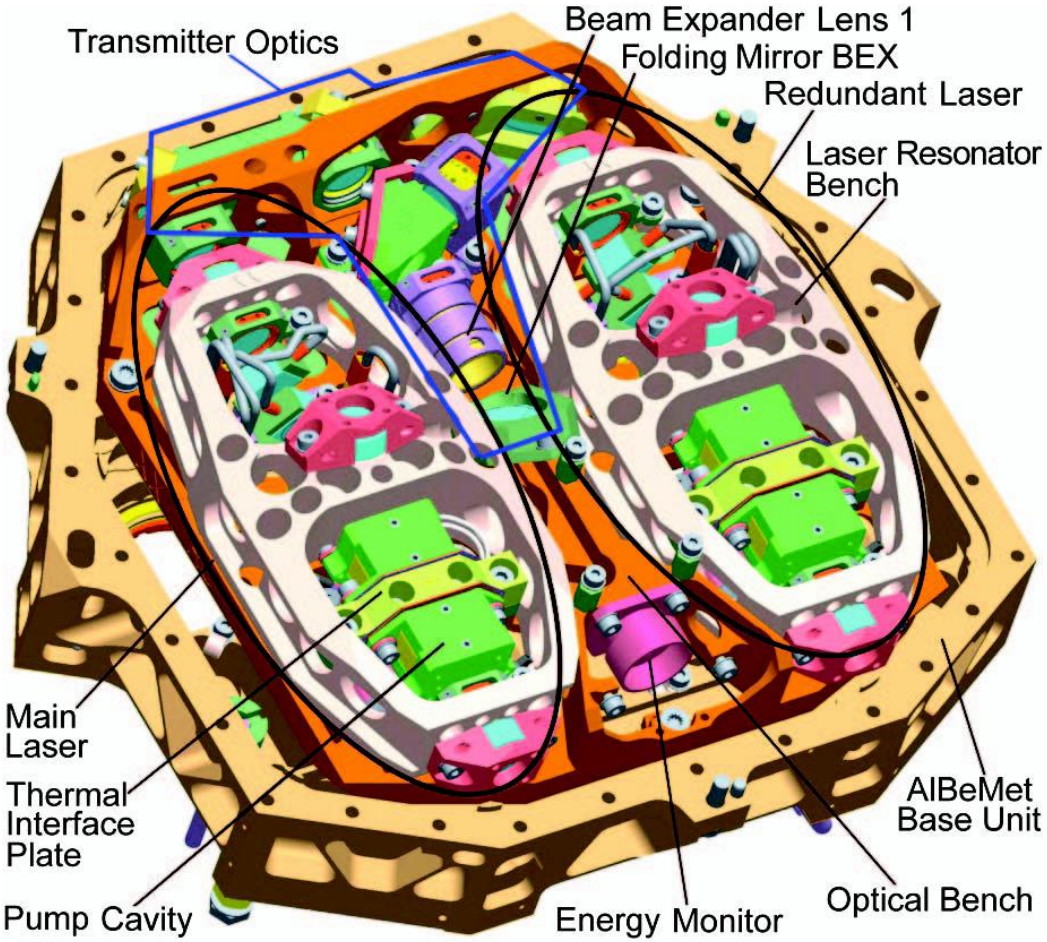
ATLID – Backscatter Lidar
Nd:YAG 3ω (UV - 355nm)

Space Laser Technology - Altimeter

BEPI COLOMBO Laser Altimeter
ESA : Mercury Planetary Orbiter (2018)

Q-switched Nd:YAG laser
@ 1064nm,
50mJ, 5ns, 1-10 Hz

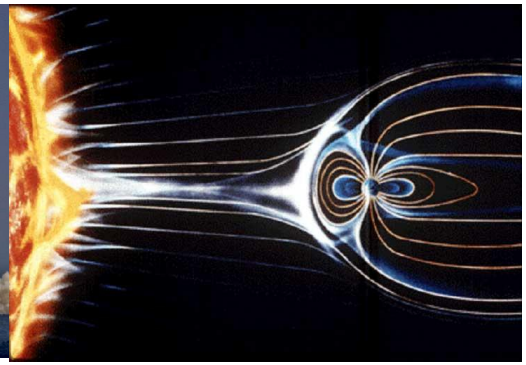




Laser (LIDAR) Instrument - Space Qualification is Hard

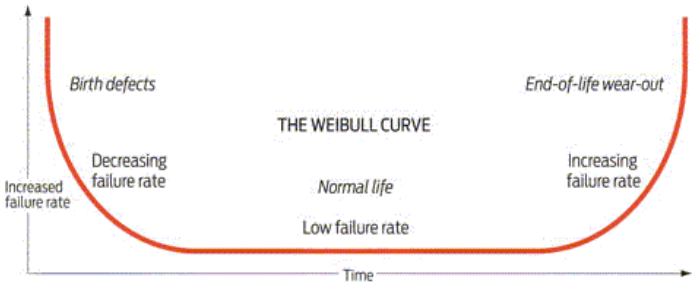
Laser Specification
- High pulse energy / pulse rate
- Ultra-narrow/stable frequency
- High Efficiency

Structural Tests
- Vibrations
- Acceleration (~40 g)
- Thermal cycling
- Leak tests



Radiation Tests
- 100 kRad (gamma & proton)

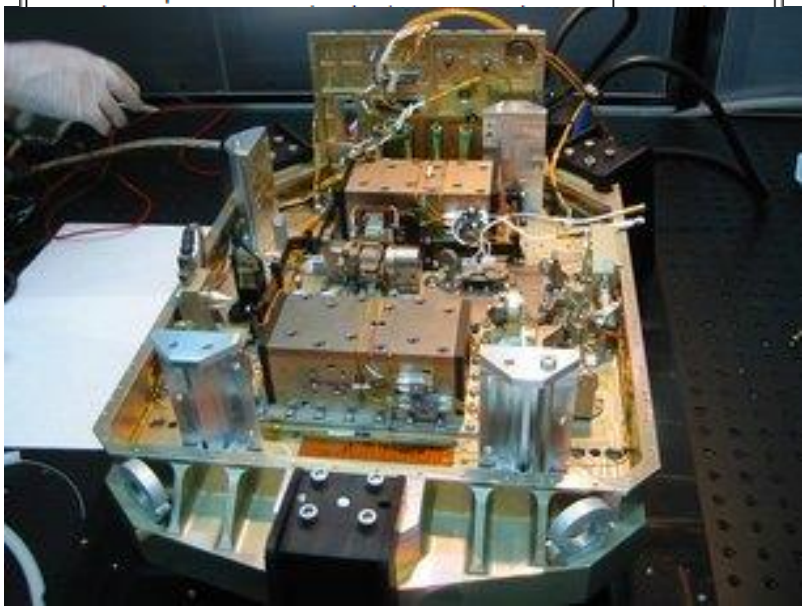
Rigorous Lifetime Tests
- Whole system & sub-components
- Electrical tests
- Laser-induced damage tests

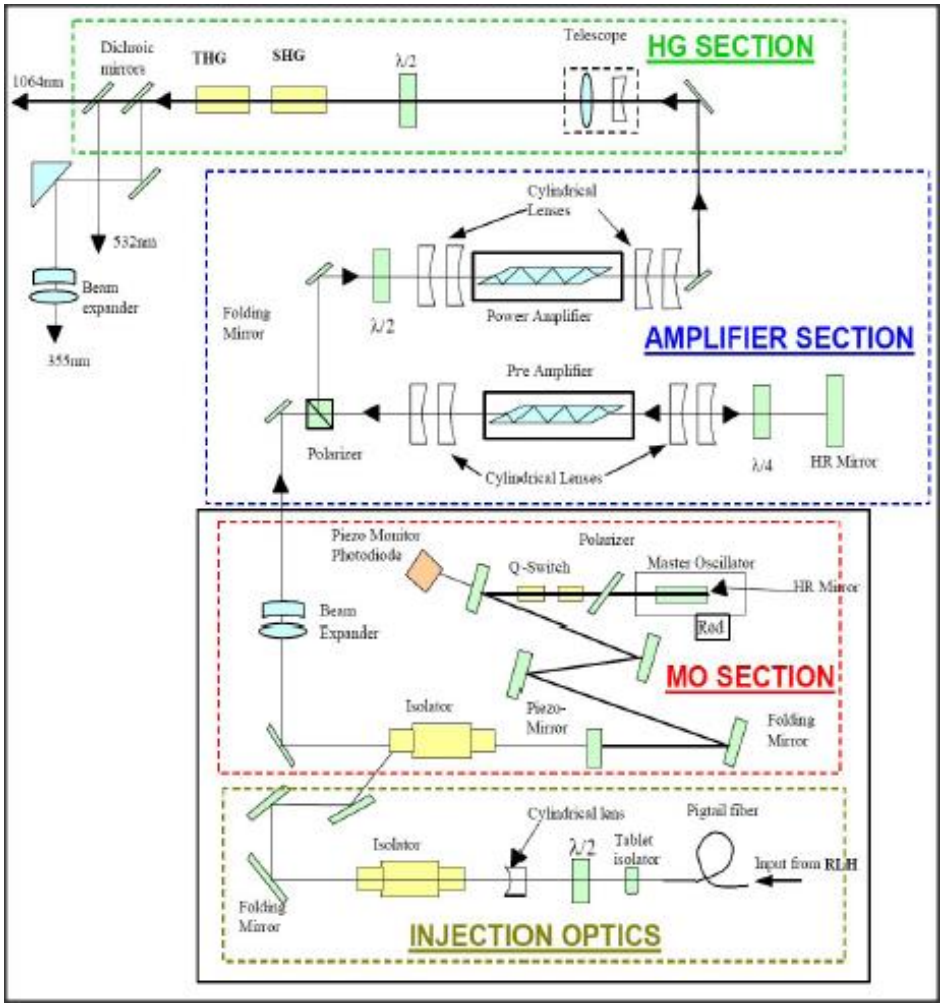


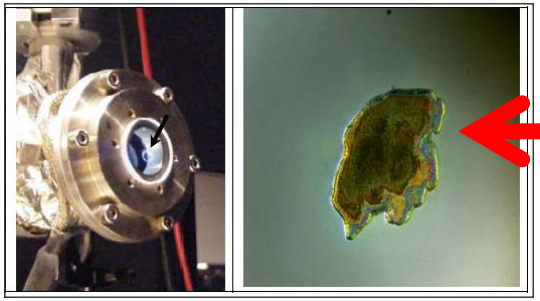
Space Laser Technology - LIDAR

ALADIN - Doppler Wind Lidar Instrument
Nd:YAG 3ω (UV - 355nm)

Transmitter (Nd:YAG)	
Wavelength	355 nm
Pulse energy	120 mJ
Repetition rate	100 Hz
Line width	30 MHz
Duty cycle	42 %
Transmit-receive Telescope	
Telescope diameter	1.5 m





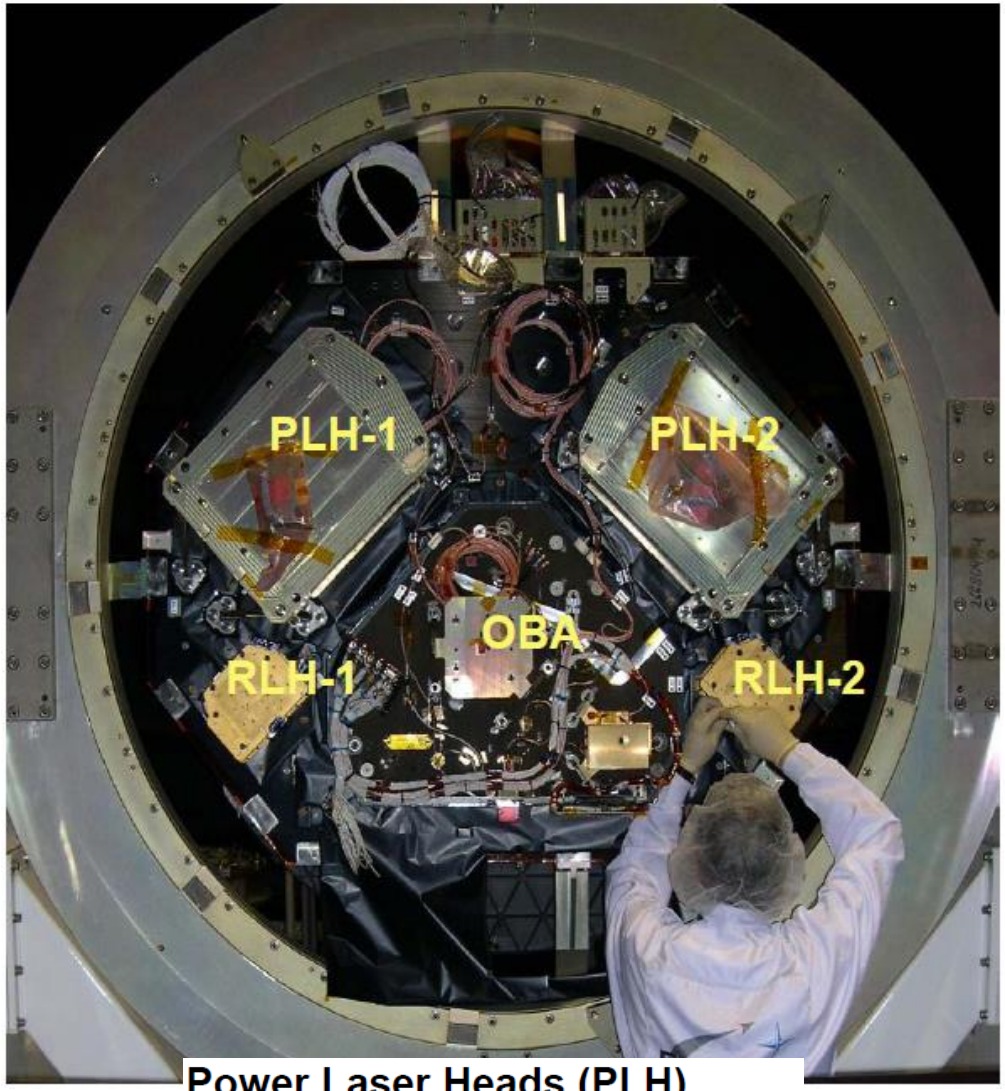


UV optical coating damage

Low Wall-plug efficiency ~ 2%

[Alves et al. ,ESA, ICSO, 2010]

Space Laser Technology - LIDAR



Power Laser Heads (PLH)

Reference Laser Heads (RLH)

Optical Bench Assembly (OBA)

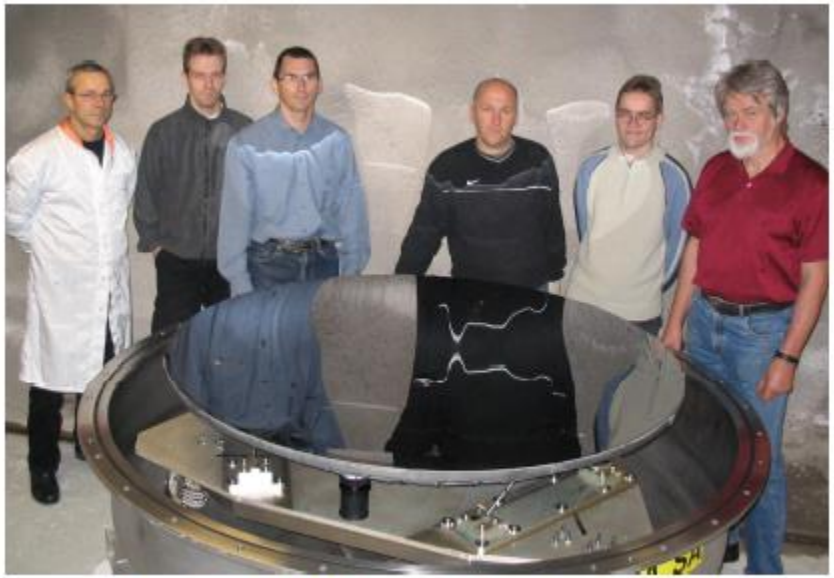


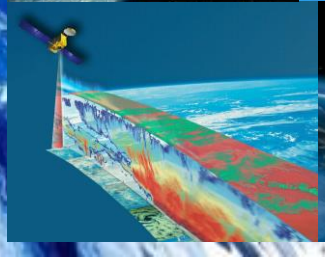
Fig. 6. Polished Aladin M1 mirror in its transportation box before shipping

SiC mirror

Demanding space requirements for laser

has meant Nd:YAG is nearly only space-deployed laser

Altimetry: **(1064nm)** *Surface mapping of Earth, Mercury (MLA, BELA), Mars (MOLA), Moon (LOLA)*

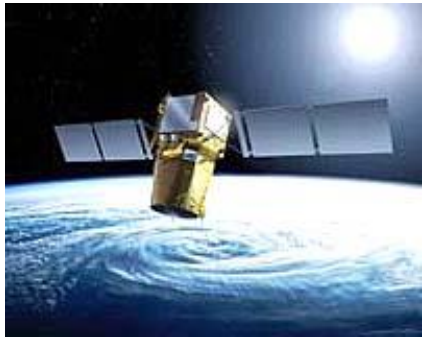


Lidar: *GLAS (1064/532nm); CALIOP (1064/532nm); ATLID (355nm); ALADIN (355nm)*

The Need for New Space Laser Technology

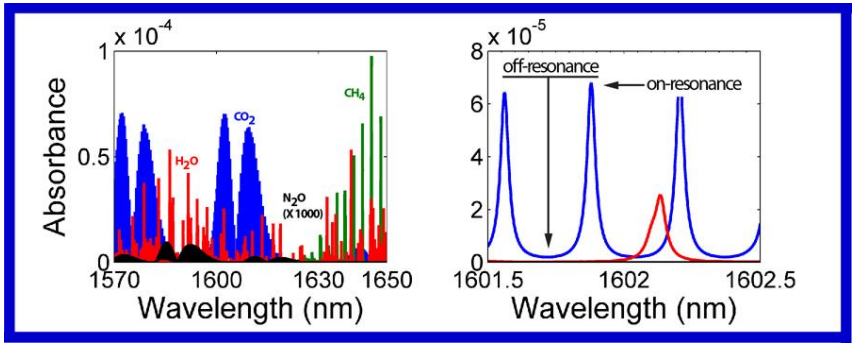
Higher efficiency

- **Reduced on-board power requirement**
- **Reduced heat dissipation issues**



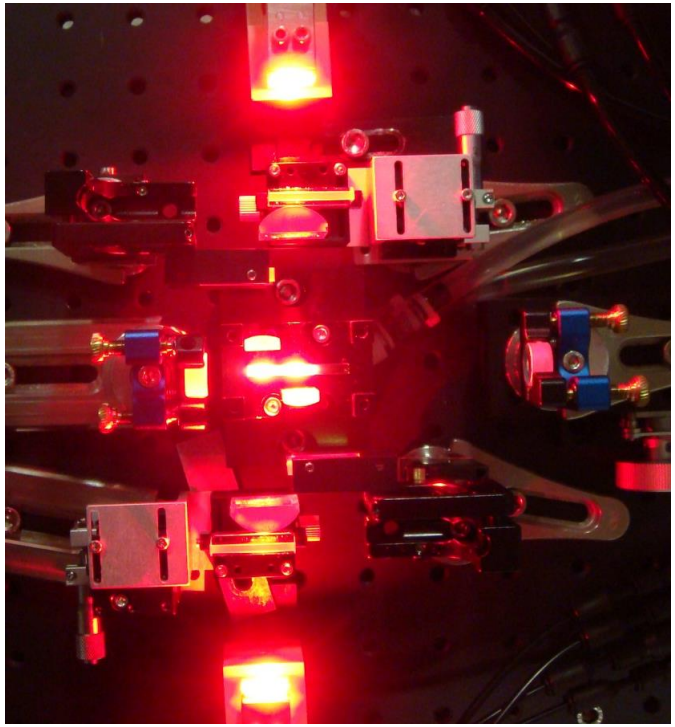
Versatile tunable wavelength

- **Superior information gathering capability (Resonantly detect atmospheric species)**
- **Better spectral match to application (e.g. ~ 800nm for vegetation altimetry)**



Imperial College led-programme supported by ESA

.....to enable new / better space-borne Remote Sensing



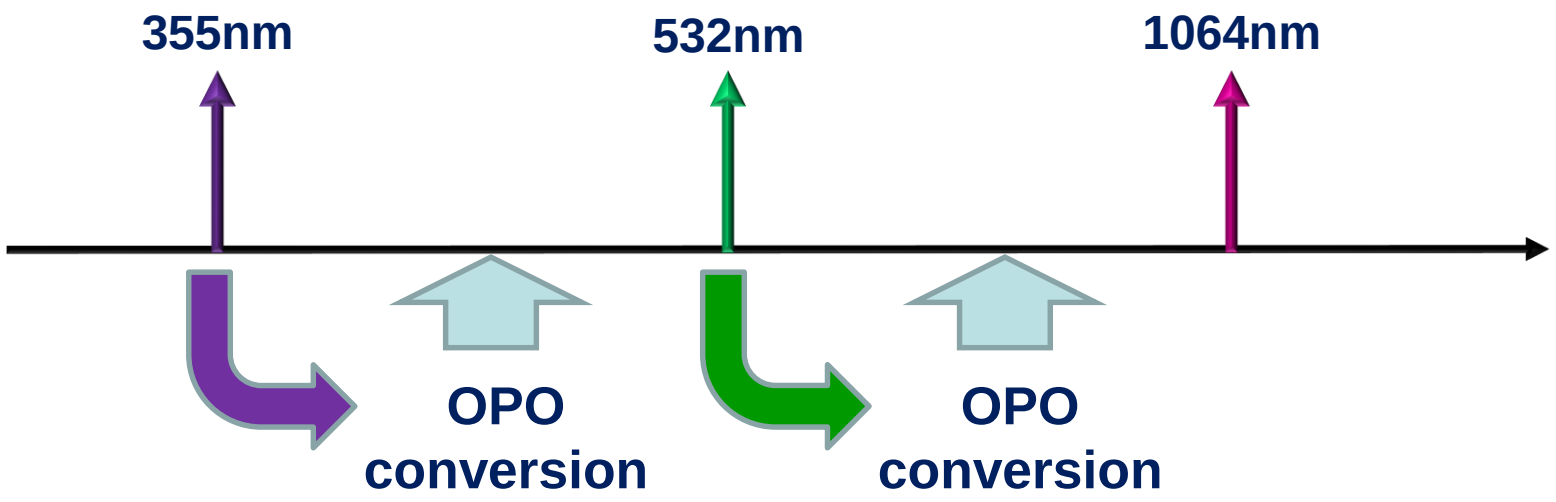
Imperial College London

esa

Nd:YAG laser and its harmonics has limitations.....

In particular.....

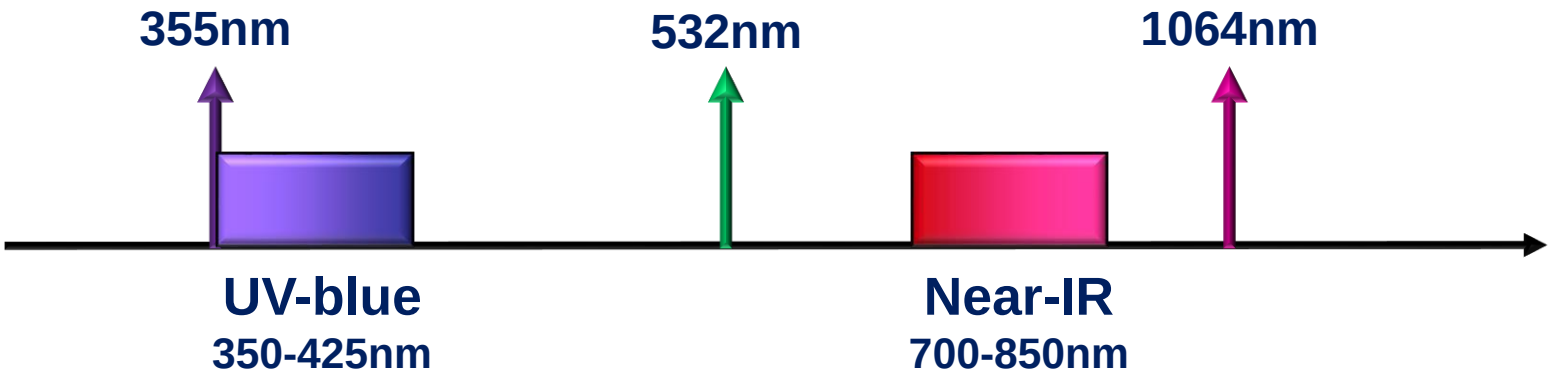
- *no wavelength tunability*
- *entirely missing regions of the spectrum*
- *limited efficiency & high heat dissipation*



OPO nonlinear optical conversion can be used to fill gaps – but
significant further loss of efficiency
& significant added reliability issues!

Alexandrite is a tunable solid-state laser

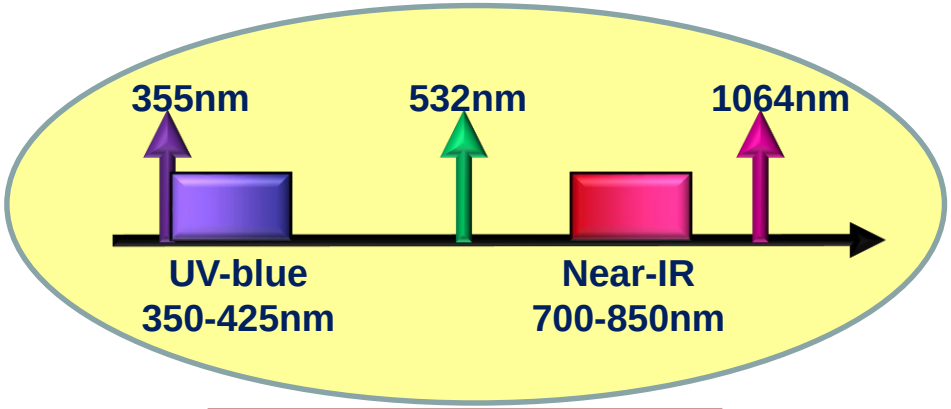
Alexandrite has broad lasing band ~700-850nm



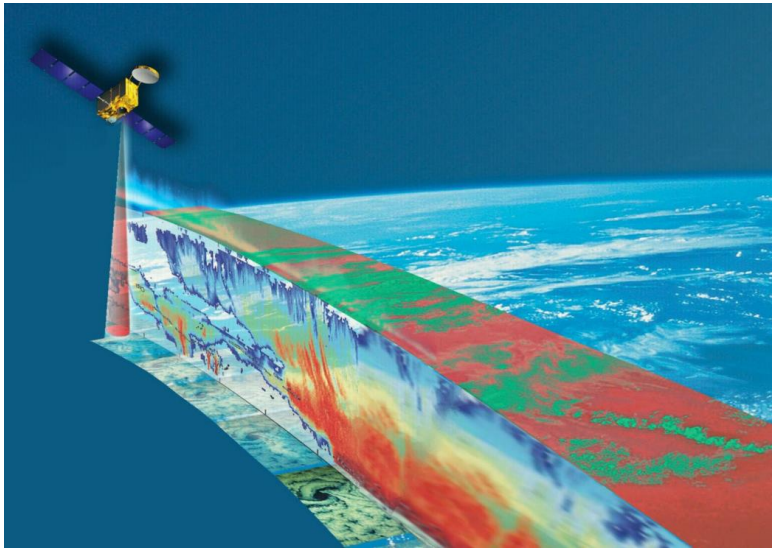
- *accesses new wavebands in near-IR and UV/blue (with SHG)*
- *offers continuous wavelength tunability*
- *excellent laser properties favourable to high pulsed power operation*

Fixed wavelength(s) → **Choose your wavelength(s)!**

Flexible wavelength enables new/better LIDAR Sensing



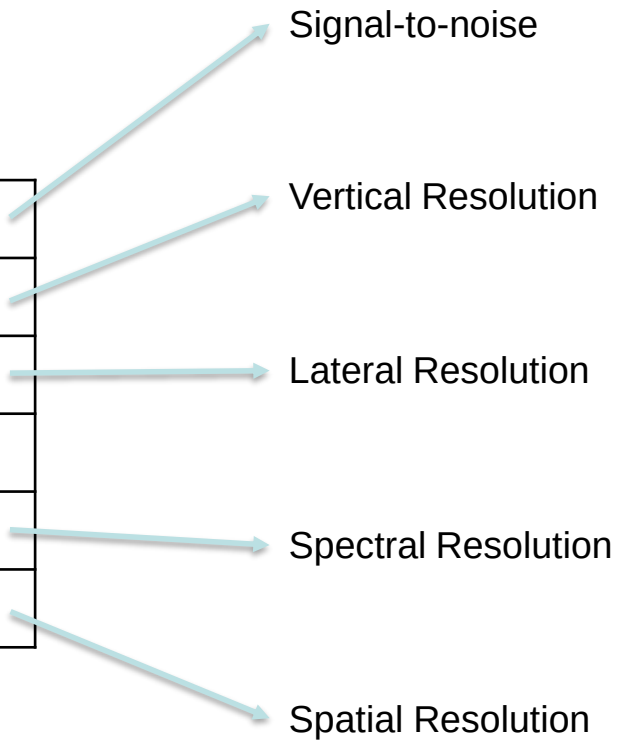
Molecular Resonant:
BS Lidar & DIAL



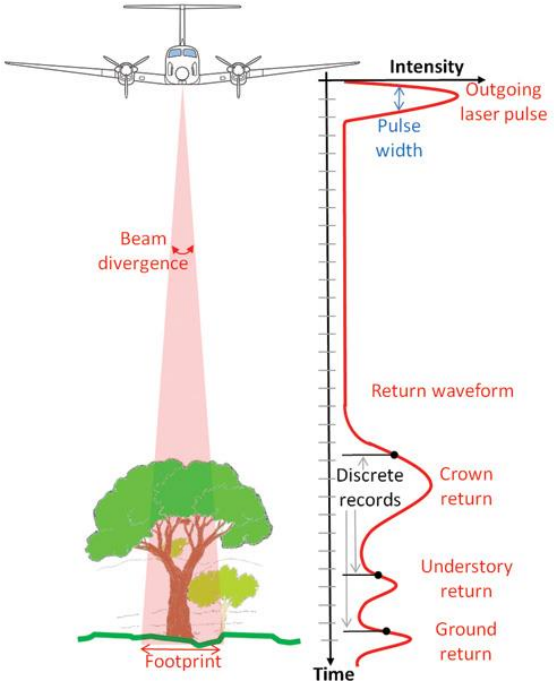
H_2O @ 730nm / 820nm
O_2 @ 761 nm
K @ 770nm
Fe @ 248nm

Atmospheric LIDAR Specification

Pulse Energy	**100mJ**
Pulse Duration	< 100ns
Pulse Repetition Rate	100Hz
Central Wavelength Band	720 – 820nm
Spectral Width	**< 0.0001nm (50MHz)**
Spatial Beam Quality	$M^2 < 1.5$

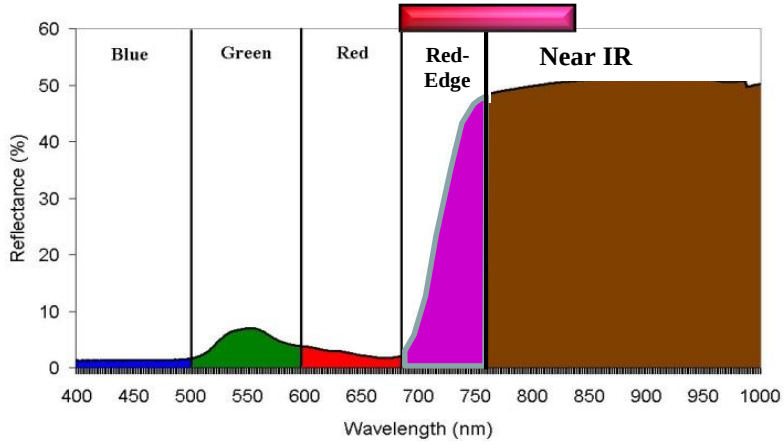


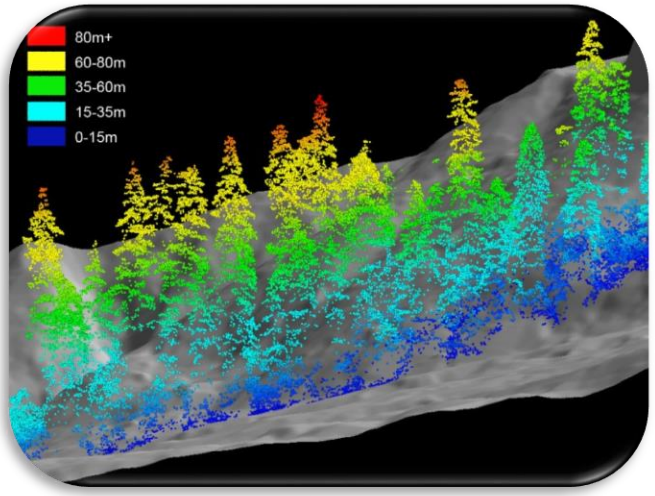
Alexandrite for Vegetation Lidar



"...see the woods and the trees!"

Alexandrite operates across the red-edge band of vegetation





Red-edge change is a sensitive indicator of health/stress in vegetation.

Vegetation LIDAR Specification

Pulse Energy	0.1mJ (single-photon counting detection)
Pulse Duration	**< 3ns**
Pulse Repetition Rate	10 kHz
Central Wavelength Band	720 – 820nm
Spectral Width	-
Spatial Beam Quality	$M^2 < 1.5$

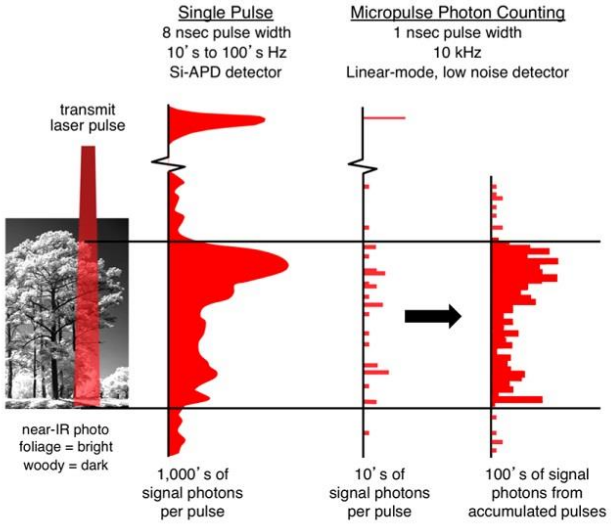
Signal-to-noise

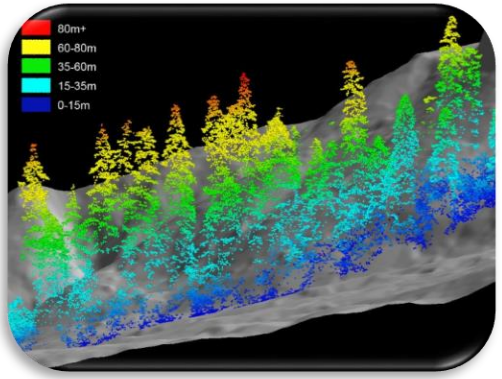
Vertical Resolution

Lateral Resolution

Spectral Resolution

Spatial Resolution





Status of Alexandrite?

Tunable (λ)
~700-850nm

High Power (P)
~100W

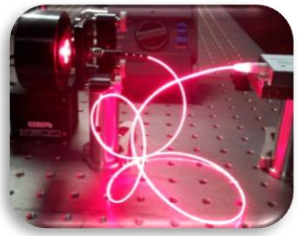
High Energy (E)
>1J

Lamp-Pumped

Cosmetic medical market

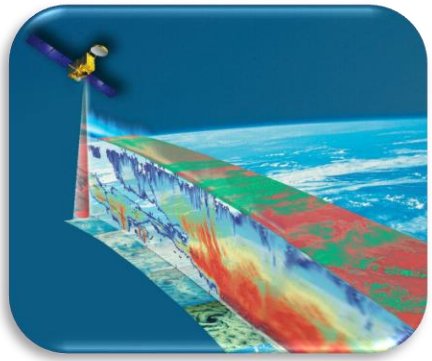
(Red) Diode-Pumping of Alexandrite is Possible!

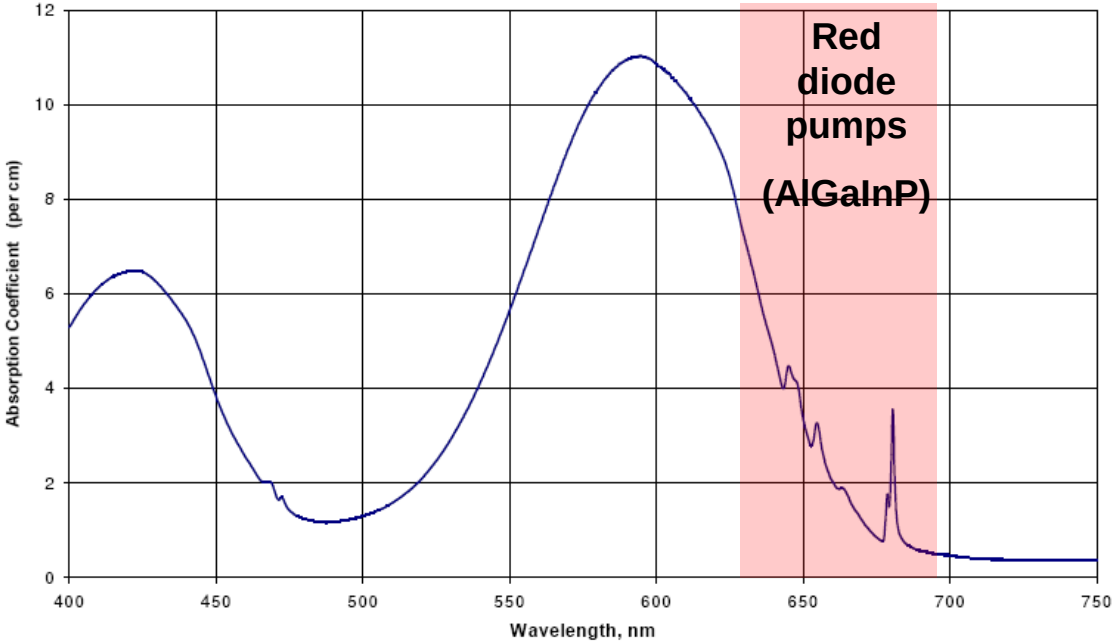
Diode-Pumped



High efficiency
compact
long lifetime

Space Compliant

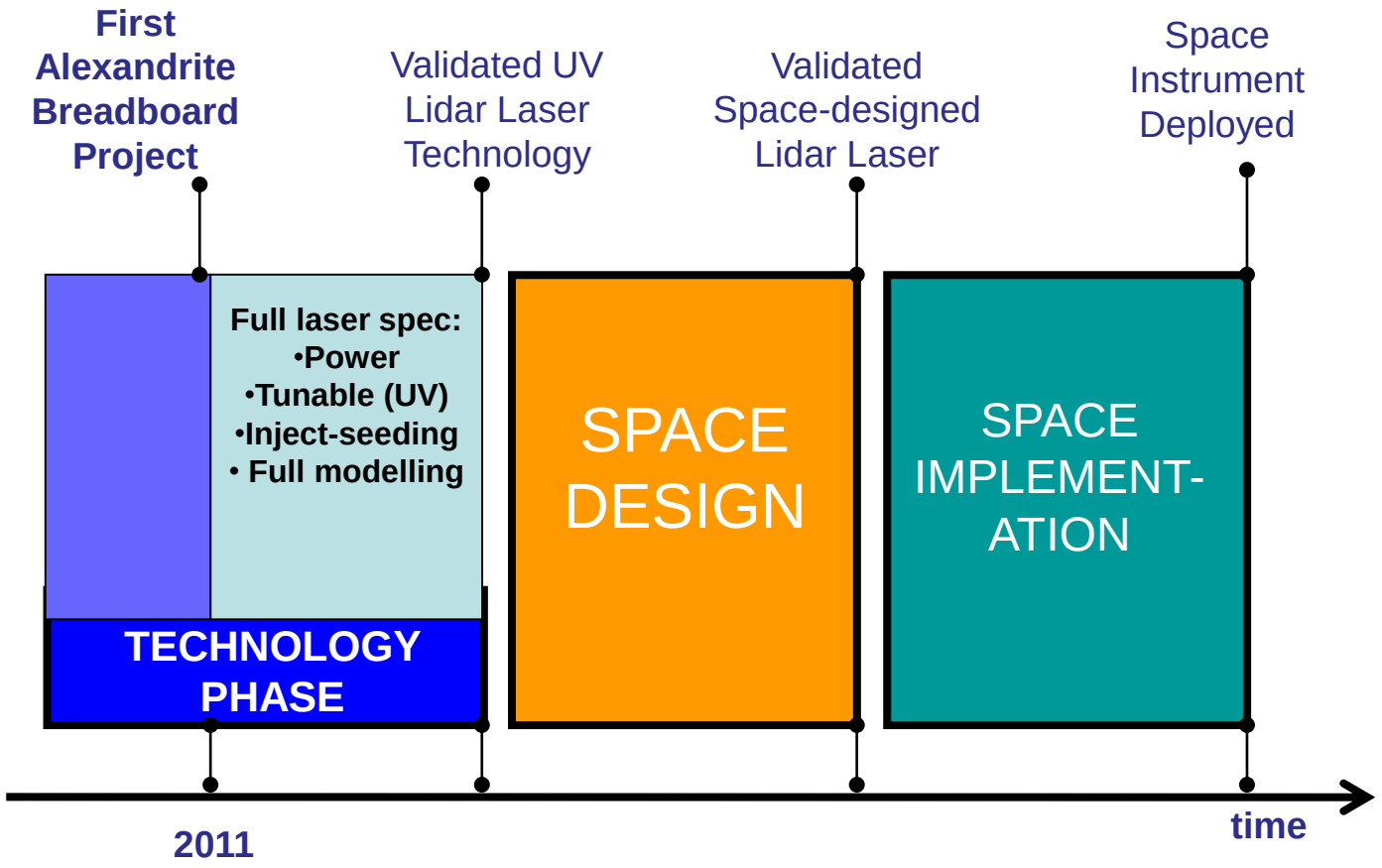




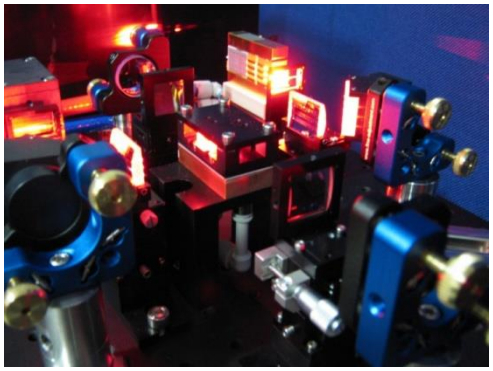
x10 increase in efficiency!

Alexandrite and Space Qualification

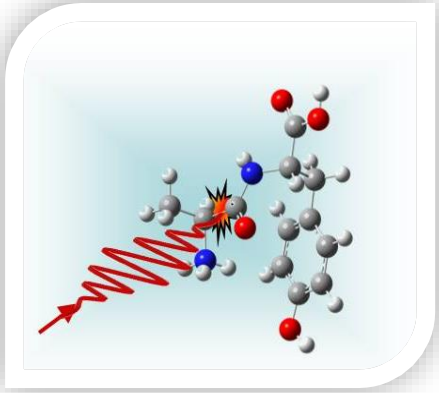
A very long road....



And beyond?



REMOTE SENSING



NEW SCIENCE

OTHER APPLICATIONS