SPACE LIDAR FOR EARTH AND PLANETARY MISSIONS

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1. Introduction

Fig. 1 shows the Shuttle Discovery, with LITE aboard, being launched on September 9, 1994 at 1823 EDT from the Kennedy Space Center in Florida. This momentous event led to the insertion of Shuttle into a 57°-inclined orbit and an exceedingly successful 10-day flight of the Lidar In-space Technology Experiment (LITE), which is the first Earth-orbiting atmospheric lidar. This proof-of-principle mission set the stage for the future use of Earth-orbiting lidars to study the Earth's atmosphere, oceans and surface. Its data applications have clearly shown the usefulness of this active remote sensor, and its ability to probe the troposphere with high vertical resolution taking data between clouds and through optically thin clouds down to the Earth's surface. However, LITE utilized technologies that prevented its use for long-duration; that is, flashlamp-pumped lasers, heavy optics, etc., were used which, at approximately 2000 kg and 3 kw, posed no resource issues for Shuttle. But, of course, to use this remote sensing technique for long-duration, Earth satellite or planetary missions require much more efficient lasers and lightweight technologies. Since the LITE flight, high 'wall-plug' efficient lasers, lightweight optics, and lighter and more capable electronics, have made these long-duration missions a reality.

Fig. 1. The launch of Shuttle Discovery with LITE aboard. (Courtesy NASA KSC)

LITE was followed in 1996 and 1997 with two shuttle flights of the Shuttle Laser Altimeter (SLA) in 1996 and 1997. SLA was a Hitchhiker payload which is a low-cost access to space experiment. It used two of the Get Away Special (GAS) canisters to accomplish the measurements, one with a motorized door assembly and an optical window containing the laser and a mirror and detector, and the second canister containing the control, telemetry, telecommand and power conditioning electronics. The first flight, SLA-01, was on the Shuttle Endeavour STS-72 mission launched into a 28°-inclined orbit on January 11, 1996. On day three of the mission, SLA-01 was turned-on and operated through January 19. It successfully operated for more than 83 hours, providing data on the relief of the Earth's ocean surfaces, landscapes, and cloud tops. SLA-02 was flown in August 1997 during the Shuttle Discovery STS-85 mission and incorporated a variable gain amplifier to regulate saturation. It was launched on August 7, 1997 and landed August 19, 1997. A 57°-inclined orbit allowed altimetric measurements over much more of the globe than with SLA-01. SLA-02 also produced data on the Earth's surface relief, vegetation canopy, and cloud tops.

With new technologies, and these flight experiences, why not a mission to another planet in our solar system? The first was the Mars Orbital Laser Altimeter (MOLA) launched November 7, 1996, whose primary mission was to map the surface of Mars. Although primarily a laser altimeter, one of the top ten successes was the detection of clouds and the measurement of their heights, and the identification of dynamical features in the Mars atmosphere like gravity waves. This type of mission to a planet is, as you can imagine, very difficult. MOLA, however, was exceedingly successful making approximately 640 million measurements from September 1997 to June 2001 when its oscillator stopped working.

The next space borne lidar mission was also designed primarily for altimetry. It is presently in Earth orbit and is called the Geoscience Laser Altimeter System (GLAS) aboard the Ice, Cloud and Land Elevation Satellite (ICESat)-see Fig. 2. ICESat's primary goal is to quantify ice sheet mass balance and understand how changes in the Earth's atmosphere and climate affect polar ice masses and global sea level. The GLAS instrument, unlike MOLA, does have a lidar channel for 532 nm height-resolved data and, therefore, is designed to make aerosol and cloud measurements. ICESat was launched on January 12, 2003, from Vandenburg Air Force Base, California, into a 94°-inclined, 600 km orbit. Laser 1 (of 3) was activated on February 20, 2003 and stopped working on March 29, 2003. Laser 2 was activated on February 17, 2004, with a planned 33-day data-taking period. The laser lifetime problems are apparently due to laser diode failures and are presently being investigated. Even with these shorter than expected laser lifetimes, the data are quite spectacular with measurements of dust storms, cloud heights, tree heights, and forest fire smoke in addition to altimeter measurements of the basic ice surface.

Fig. 2 shows the ICESat during fabrication in a clean room at Ball Aerospace and Technologies Corporation, Boulder, Colorado. ICESat was launched on a Boeing Corporation Delta II launch vehicle, January 2003. (Courtesy of NASA GSFC)

In May 2004, another planetary orbiting lidar is scheduled for launch. It is the Mercury Laser Altimeter (MLA), which is part of the Mercury Surface, Space Environment, Geochemistry, and Ranging (MESSENGER) mission. The mission goals include the need to make measurements of the topography of Mercury, and that is what the MLA will accomplish during its mission. The orbit is highly elliptical (200 km x 15,193 km).

These lidars, especially, LITE and GLAS, paved the way for the Cloud and Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO)—see Fig. 3-lidar mission to be launched in March 2005 from Vandenburg Air Force Base, California. LITE data, like that shown in Fig. 4, was used extensively for simulating the expected performance of CALIPSO. CALIPSO will fly on the French satellite, Proteus. The CALIPSO lidar, which is the centerpiece instrument, is called CALIOP for the Cloud-Aerosol Lidar with Orthogonal Polarization. Also boresighted with CALIOP is a wide field-of-view camera for scene registration on the daylight side of the orbit, and a French Imaging Infrared Radiometer (IIR) instrument for characterizing primarily cirrus clouds.

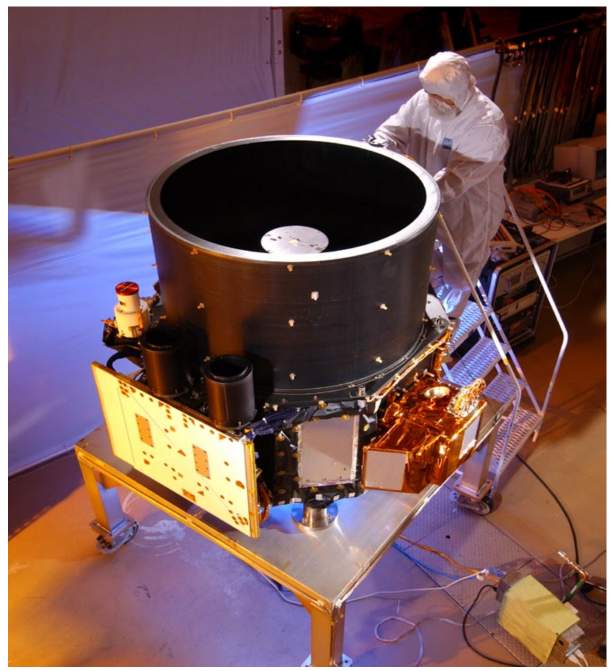

Fig. 3 shows CALIPSO during its final fabrication stages at Ball Aerospace and Technologies Corporation. (Courtesy of Ball)

CALIOP is a three-channel lidar for 1064 nm measurements, and 532 nm parallel and perpendicular, measurements. A significant addition to the CALIPSO mission is the synergy that will be created by flying in formation with a number of other satellites in a 705-km circular orbit with ascending node equatorial crossing times ranging from 1330 to 1345 local time. CALIPSO will fly in formation with AQUA, AURA, CloudSat and PARASOL (see Fig. 5). Combining data from the instruments on these spacecraft will allow a myriad of important characterizations of aerosols and clouds and their effects on radiation budget to be made.

Finally, a ground-based lidar has been approved for use aboard a Mars Lander called Phoenix, to be launched in 2007, with a Mars landing in 2008. This first-of-its-kind lidar will be a central part of a meteorological package that will measure dust above the lander, including PBL, dust devils, and through inference, winds. The lidar will be able to pan and tilt.

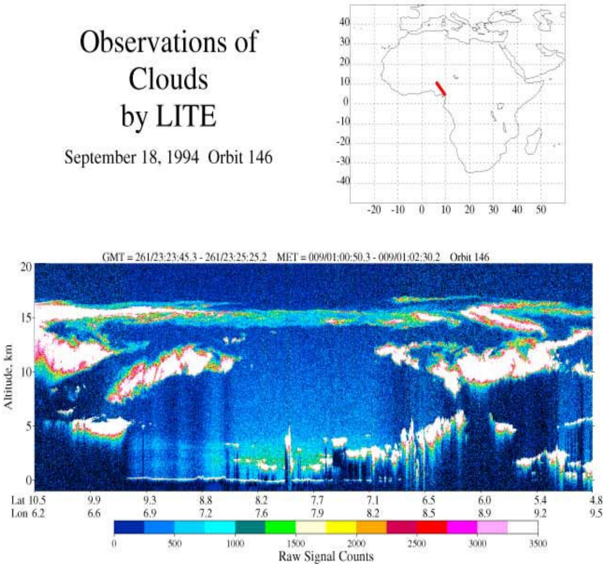

Fig. 4. An example of multiple cloud layers and cloud types in the Inter-Tropical Convergence Zone over Africa. LITE was able to penetrate a significant percentage of these clouds. Some were very optically thick preventing measurements to the surface. Multiple scattering effects allowed greater penetration but greatly complicated the measurement of the true cloud base. (Courtesy of NASA LaRC)

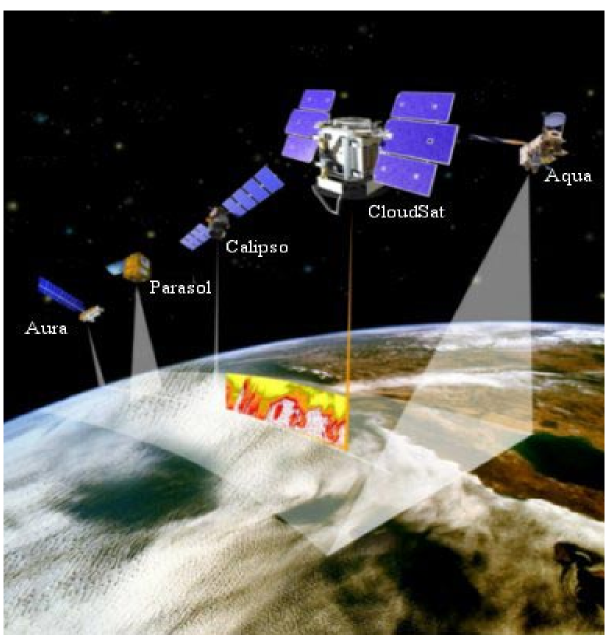

Fig. 5 shows five satellites that will fly in formation during the CALIPSO mission. This grouping is known as the EOS Aqua constellation or "A-train." The "A-train" name comes from the old jazz tune, "Take the A-Train" composed by Billy Strayhorn and made popular by Duke Ellington's band. It is an Afternoon constellation and has Aqua in the lead with Aura in the rear. (Courtesy of NASA GSFC)

2. Lidar System Details

Table 1 lists LITE, GLAS, CALIOP, MOLA, SLA and MLA instrument characteristics. The table shows that the Nd: YAG laser is being used for all these missions, both for atmospheric and altimetric measurements. This is due to its efficiency, ruggedness and long life and, of course, its usefulness for practical measurements. Because of weight and power issues, the planetary lidars have much smaller optics, output energies, and somewhat slower repetition rates. The masses and powers for the Mercury mission are, as expected, very small.

3. Future Directions

In addition to hardware/technology issues, the challenges in the near future include or ability to incorporate the data from the constellation of satellites flying in formation with CALIPSO, for example, into a more complete and understandable data set, and to use the data for various modeling studies and for a more complete understanding of various scientific studies including climate forcing. This effort, if successful, will serve as a paradigm for and, perhaps, justify future Earth-orbiting lidar missions.

These first spaceborne long duration orbital missions, as well as the MARS Phoenix mission, utilize elastic backscatter only. Many studies, however, have taken place that show the feasibility of utilizing the DIAL technique to make measurements of ozone and water vapor. The possibility of spaceborne DIAL systems flying in this first decade is technologically possible, but is problematic since neither NASA, NASDA nor ESA has chosen at this time a flight mission. The uses of elastic backscatter lidars for altimetry and atmospheric measurements will continue. MESSENGER will be followed by another mission planned to Mercury called BepiColombo funded by the European Space Agency and the Institute of Space and Astronautical Science in Japan. It will involve two orbiting spacecraft, one to map the planet and one to examine the magnetosphere. A laser altimeter will be onboard the BepiColombo for altimetric measurements of Mercury.

Another exciting development in Europe is the recent funding of the first spaceborne wind lidar. ESA has funded a facility instrument, called AEOLUS, named after 'the keeper of the winds' in Greek mythology, that is being developed for launch in October 2007.

AEOLUS will carry ALADIN (the Atmospheric Laser Doppler Lidar Instrument) that utilizes the Doppler shift in molecular backscatter associated with the wind profile. It measures in two wavelength bands on either side of the output frequency from the tripled wavelength of an Nd: YAG laser emitting at 355 nm.
As lasers become more energy efficient, provide more useable wavelengths for increased profiling capability with eye-safe operation, and increase their lifetime for useable operation, other applications will become possible. In addition to laser improvements, large deployable telescopes will allow new applications as well as enhancing the capability of existing lidars. Laser altimeters that can provide cm-height resolutions, and lasers with greater lifetimes and repetition rates, are all possible by the end of the first decade.

The above improvements will enable future applications to be implemented in the subsequent decades like studies of the carbon cycle, circulation and forecasting through global tropospheric wind measurements, DIAL for constituent measurements, and elastic backscatter for aerosol and cloud measurements. The implementation of these lidars in space will greatly enhance our understanding of the Earth and other planet's atmospheric chemistry, climate and geophysical properties. The future is indeed bright for spaceborne lidars, which are now taking their place alongside passive sensors, and fulfilling a myriad of measurement needs for the study of our solar system.

For more information about these missions, including references, see the following URLs:

LITE:
- http://www-lite.larc.nasa.gov

MOLA:
- http://ltpwww.gsfc.nasa.gov/tharsis/mola.html

GLAS:
- http://glas.gsfc.nasa.gov

ICESAT/GLAS:
- http://www.csr.utexas.edu/glas/

MESSENGER:
- http://messenger.jhuapl.edu/

CALIPSO:
- http://www-calipso.larc.nasa.gov/

PHOENIX:
- http://phoenix.lpl.Arizona.edu

AEOLUS:
- http://www.esa.int/esaLP/ESAES62VMOCaeolus_0.html

Table 1. Characteristics of satellite lidars.

	LITE	GLAS	CALIOP	MOLA	SLA	MLA
Wavelength (nm)	1064	1064-surface	1064	1064	1064	1064
	532	532-atm.	532 ‖			
	356		532⊥			
Pulse energy (mJ)	445	74-surface	110	48	40	20
	557	30-atm.				
	162					
Repetition rate (Hz)	10	40	20.16	10	10	8
Telescope diameter (m)	0.985	1.0	1.0	0.5	0.38	0.46
Vertical sampling (m)	15	0.15-surface	30-60	0.375	0.75	<1 nsec
		75-atm.				
Mass (kg)	2000	300		25.85		7.4
Power (w)	3000	330		34.2		23