| ISSN: 2395-7852 | www.ijarasem.com | Impact Factor: 4.271 |Bimonthly, Peer Reviewed & Referred Journal|

| Volume 5, Issue 3, May 2018 |

USES OF OPTICAL LASER IN SPACE DYNAMIC

DR. SANTOSH KUMAR SAXENA

DEPT. OF PHYSICS, SNKP GOVT. COLLEGE, NEEM KA THANA, RAJASTHAN, INDIA

ABSTRACT

NASA has developed a new laser beam pointing technology for use in space optical communications. With further development, possible applications include communications from the Earth to spacecraft in Earth orbit and in deep space, such as at the moon and Mars. A possible application is to the Artemis Program for CubeSats in low-Lunar Orbit (LLO). Current architectures use dynamical systems, (i.e., moving parts, e.g., fast-steering mirrors (FSM), and/or gimbals,) to turn the laser to point to the ground terminal and possibly use vibration isolation platforms (VIP). This patented technology from NASA Ames uses a combined lens system and a vertical-cavity surface-emitting laser (VCSEL)/Photodetector Array. This static system has the potential to replace the current dynamic systems and VIP, dependent on studies for the particular application. Laser beam pointing is very challenging for low-Earth Orbit (LEO), including science missions. Computer simulations using this design have been made for an application to a CubeSat in LEO.

Keywords- optical, laser, space, dynamic, earth, beam

INTRODUCTION

This invention provides a new method for optical data transmissions from satellites using laser arrays for laser beam pointing. The system is simple, static, compact, and provides accurate pointing, acquisition, and tracking (PAT). It combines a lens system and a vertical-cavity surface-emitting laser VCSEL)/Photodetector Array, both mature technologies, in a novel way for PAT. It can improve the PAT system's size, weight, and power (SWaP) in comparison to current systems. Preliminary analysis indicates that this system is applicable to transmissions between satellites in low-Earth orbit (LEO) and ground terminals. Computer simulations using this design have been made for the application of this innovation to a CubeSat in LEO. The computer simulations included modeling the laser source and diffraction effects due to wave optics. The pointing used a diffraction limited lens system and a VCSEL array. These capabilities make it possible to model laser beam propagation over long space communication distances. Laser beam pointing is very challenging for LEO, including science missions. Current architectures use dynamical systems, (i.e., moving parts, e.g., fast-steering mirrors (FSM), and/or gimbals) to turn the laser to point to the ground terminal, and some use vibration isolation platforms as well. This static system has the potential to replace the current dynamic systems and vibration isolation platforms, dependent on studies for the particular application. For these electro-optical systems, reaction times to pointing changes and vibrations are on the nanosecond time scale, much faster than those for mechanical systems. For LEO terminals, slew rates are not a concern with this new system.[1,2,3]

With declining costs of space launches due to advances in launch vehicles reusability, the number of satellites in Earth orbit is likely to increase significantly over the coming years as space becomes more easily accessible and more widely exploited for commercial applications. As the density of satellites in orbit increases, the risk of collisions increases along with it. It is all but inevitable that more collisions will occur in the future, necessitating the development of effective, feasible and scalable debris remediation to ensure the long-term safety of the space environment in Earth orbit.

Satellite collisions (such as the Iridium-Kosmos collision of 2009), or the testing and eventual use of anti-satellite weapons - which have seen relatively frequent testing in recent years - result in the production of large numbers of debris fragments. Over moderate timescales, these spread into shells due to precession of the nodes (Pardini and Anselmo, 2011). Due to extremely low atmospheric density, debris orbits decay very slowly, with many fragments of the aforementioned Iridium-Kosmos collision still persisting in orbit some 13 years later. In the extreme, these debris shells have the potential to render their orbital altitude bands completely unusable for satellites, and also highly dangerous for launch vehicles to traverse until the shell naturally deorbits. For higher orbits, this is particularly concerning as the atmospheric drag is even weaker, and fragments take even longer to deorbit due to natural processes.

In the event of such a high-altitude collision, active removal would likely be necessary to clean up the orbital region due to the longer lifetime. However, the large number of fragments produced means that any proposed mitigation strategy which involves rendezvous, capture, and deorbiting would be impractical due to the huge propellant expenditure required for hundreds or thousands of orbit-matching maneuvers. Such strategies are better suited for the removal of larger, uncontrolled objects such as defunct satellites or spent upper stages. Very few strategies have been proposed which have the capability scale to large numbers of fragments, which is necessary to clean up the result of a collision if prevention is impossible.[4,5,6]

Lasers enable the ability to transfer small amounts of momentum to an object at a distance, provided sufficiently powerful optics are available to track the fragment and allow accurate laser pointing, all without any need for orbit-matching maneuvers. Photon pressure has been proposed in multiple mission concepts as a means to apply a small perturbation to fragment orbits, potentially reducing the collision risk with another space object. One such example is LightForce (Yang et al., 2016), which employs multiple ground-based continuous-wave (CW) lasers which illuminate the target fragment over multiple overhead passes, compounding the along-track displacement. Mason et al. (2011) proposed another photon pressure-based concept for collision avoidance using a laser on the ground, and showed that collision risk could be substantially reduced using such an approach. Such ground-based strategies require that the fragments are large or bright enough to track optically from Earth's surface at distances above approximately 500 km. Additionally, these ground-based strategies have typically relied on multiple engagements with individual fragments to increase the displacement, which of course requires knowledge of the objects' orbits to re-engage at a later time.[7,8,9]

Space-based platforms are able to circumvent some of the limitations of ground-based systems. Their advantages originate primarily from the lack of atmospheric attenuation, shorter distance to target (resulting in less beam divergence and higher fluence), particularly for those higher orbits in which the lifetime is long, and the possibility of for better alignment between the negative velocity vector and the applied Δv vector. Ground-based platforms suffer from a tradeoff between better beam alignment with the retrograde direction, and atmospheric depth traversed causing greater attenuation: when the fragment is near the horizon the beam is best-aligned, but also traverses the most atmosphere and longest distance, causing a far lower surface fluence. Additionally, ground-based platforms which require precise focussing must deal with complications due to atmospheric turbulence. However, since the size, weight and power restrictions are far more generous for ground-based systems, these disadvantages may be offset by simply constructing more powerful lasers. Vasile et al. (2010) proposed and modelled the use of both surface ablation and photon pressure from solar concentrators with a space-based platform which follows the targeted piece of debris. This work showed the capability of such a system to lower debris orbits from 800 km to 200 km in a few hundred days of operation, from where natural decay would fully remove the fragments.

Surface ablation is an alternative mechanism to photon pressure whereby an object's orbit may be influenced by a laser. Of the debris remediation strategies using ablation, L'ADROIT (Phipps, 2014) is one of the most well-developed space-based concepts, employing a single large satellite in an elliptical polar orbit between 560–960 km. L'ADROIT is in some respects similar to the concept proposed in this paper, utilising an opportunistic interaction strategy with passing fragments rather than targeting specific fragments whose orbits are known a priori. This paper builds on the L'ADROIT concept in several ways. Firstly, the altitude range targeted by L'ADROIT, as will be discussed in this paper, already has a relatively short natural lifetime for small fragments, making the potential return on investment limited - this paper instead targets higher orbits with a longer natural lifetime. Secondly, the analysis simplified the effects imparted Δv misalignment with the negative velocity vector, which this paper attempts to model in more detail.[10,11,12]

This paper will present an analysis of the use of photon pressure and ablation from one or more space-based platforms, first for debris removal and then for collision avoidance. The key contributions of this paper which distinguish this work from previously mentioned space-based concepts like L'ADROIT (Phipps, 2014) and the work of Pieters and Noomen (2014) are the following. Firstly, a high-fidelity model of photon pressure and ablation was used to characterise the impulse transferred in a given interaction, rather than relying on simplifying assumptions. Secondly the proposed mission utilises a constellation of satellites rather than a single station. Thirdly, rather than following the debris and illuminating it continually as was proposed by Vasile et al. (2010), this concept uses short, opportunistic interactions with passing fragments. Finally, photon pressure was investigated as a means of debris remediation, from the aforementioned space-based platform.

This paper is an extension of previously published work by the authors (Walker and Vasile, 2015, Walker et al., 2015), in which this concept was initially introduced. This work builds on these papers in several ways - firstly by including analysis on the off-axis component of transferred momentum and its implications for beam tracking, secondly by extending the analysis of the collision avoidance scenario to include the expected encounter rate between a single object and satellites in a 10-satellite constellation. Finally, it adds new analyses on the effects of extreme laser fluence on the attitude motion of illuminated fragments to determine if objects tend towards an orientation that reduces the net momentum transfer.

We first present an overview of the mission concept, and some initial analyses on orbital lifetime to justify a choice of altitude at which to focus the concept. Then, a process for generating orbital elements of a debris shell is described in

Section 3, and the process of orbital propagation, encounter identification and downselection of candidate encounter events is described in Section 4. Section 5 describes the high-fidelity models of momentum transfer via photon pressure and ablation, and Section 6 presents the results of the full 10-year mission simulation for both cases. Following this, Section 7 discusses and simulates an adaptation of the concept to the goal of collision avoidance in the case of photon pressure, and finally Sections 8 Effect of laser illumination on debris attitude, 9 Lateral movement of fragments during ablative interaction analyze the effects of the laser interaction on debris attitude and lateral movement with respect to the beam axis.[13,14,15]

Mission concept

The proposed concept is as follows. The targeted population of debris is those fragments in the sub 10 cm size range - those which are both numerous and often too small to be accurately tracked from Earth. A small constellation of satellites is inserted into a shell around the Earth such that the constellation has access to all longitudes. The target altitude would be chosen such that the satellites reside close to an altitude band which is particularly debris-dense. To mitigate the obvious collision risk of operating satellites in proximity to large numbers of debris, an orbit slightly higher than the peak of debris density may be chosen. Also, as will be discussed, this concept relies on optical tracking of fragments by on-board optics, and it is thus conceivable that an orbital catalogue of the debris shell may be built up over time, allowing for collisions to be anticipated and avoided.

Each satellite carries two primary instruments: a camera for acquisition and tracking of debris fragments, and a high-power laser, which is used to impart momentum to passing fragments. The scenarios of both CW and pulsed-mode lasers, using photon pressure and ablation respectively, is simulated.

Due to the high power consumption of the laser system combined with an expected low overall duty cycle, the laser is to be powered by a battery bank onboard the spacecraft, with sufficient capacity to power typical interaction events, and sufficiently-sized solar arrays to fully recharge in the typical duration between consecutive encounters. This battery bank and solar array could also serve to power low-thrust electric propulsion for orbit maintenance or adjustments, prolonging the lifespan of such satellites and enabling transfer to different orbits as needed.

The camera continually scans the sky in a cone behind the spacecraft, searching for fragments inside its field of view (FOV). When a fragment is identified, the laser is steered onto the target fragment to initiate an interaction, and tracks its movement across the sky. The aperture diameter of the lasers used in this concept is 20 centimetres to reduce the mass of the steering related components and overall optical system. No prior knowledge of the fragments' orbits is assumed as the premise of the concept is to be able to interact with small, untrackable fragments. Thus, fragments are acquired and interacted with opportunistically, as they pass through the camera's FOV.[16,17,18]

An additional use of the camera which is not studied here is to reconstruct the orbits of the debris fragments that are encountered. Since this concept is aimed at smaller, untracked fragments, this data alone provides valuable information relating to collision risk and avoidance and could enable better cataloguing and collision prediction with small fragments.

Beyond the power system, no detailed attempt to estimate the size and mass of the individual spacecraft is made, however it is expected that these would be of the small-sat class, between 100 and 300 kilograms each. To launch a constellation of one hundred 300 kg satellites, two Falcon 9 launches would be required (SpaceX, 2015), costing $100 million with reused boosters. This assumes onboard electric thrusters are used to transfer from the delivery orbit to the operational orbit.

Since the net velocity change from photon pressure based interaction is expected to be small, an initial study was performed to assess the lifetime impact of small impulsive Δv applications at varying altitudes to better target a given altitude band. Since lower fragments naturally deorbit more quickly, it is expected that more meaningful lifetime reductions could be achieved for higher orbits. However, as the orbit gets higher, the spatial density of debris and the subsequent interaction rate would lower for a roughly uniform shell. Thus this class of mitigation strategy should be targeted at orbits that are high enough to have relatively long lifetimes, while not being so high that the interaction rate becomes very low.

Orbits are propagated in this paper using a tool developed at the University of Strathclyde called CALYPSO (Di Carlo et al., 2015). CALYPSO propagates orbits semi-analytically, taking into account perturbations including atmospheric drag, third body and J2-J4 perturbations. However, for the sake of computational efficiency, orbit propagations in this paper are performed with drag as the only perturbation. This is a limitation of this study as the combined effect of zonal harmonics and light pressure would change the revisit time and also the eccentricity of the orbits of the fragments. For modelling atmospheric drag, the volume, size and area-to-mass ratio (AMR) from a 3D model of a 2 cm aluminium hex nut are used to represent debris fragments. The AMR of this 3D model is 0.3391. This coincides approximately with the peak of the distribution of the catalogued debris from the Iridium-Cosmos collision (Wang, 2010) and thus is a reasonable representation of a typical fragment produced in such a collision. The same 3D model is also used when simulating the laser momentum coupling.

Circular orbits of varying altitudes, inclined at 45 degrees were propagated until reentry. An initial impulsive Δv was applied in the negative velocity direction ranging from zero to 50 ms^{-1}.

The effects on the time-to-reentry . It can be seen that, for higher orbits, a given Δv application results in a larger absolute lifetime reduction, as expected. For lower orbits, the reduction becomes less meaningful - for example for 700 km altitude, the expected lifetime is already under 10 years, so smaller Δv interventions may only reduce a fragment's life by a few months at best. For a 1200 km orbit, a smaller Δv has a more significant impact, with only 10 ms^{-1} reducing lifespan by over 10 years[19,20,21]

DISCUSSION

The combination of coherent light, such as that of a laser, and the stringent requirements to implement new technologies in space allows for several applications in optical communication, illumination, target designation, and active remote sensing to demonstrate unprecedented results compared to previously used technologies. Moreover, the scientific advances of laser emitting technologies allow for the implementation of new devices and applications. In the past, only giants, such as the National Aeronautics and Space Administration (NASA), the Soviet Union (now Russia), the European Space Agency (ESA) and, more recently, the Japan Aerospace Exploration Agency (JAXA), China, and India, had the capacity to launch technology into space. Israel has now also entered the race, as have private companies, such as SpaceX, Virgin, Blue Origin, and SpaceIL. The recent boom of micro and nanosatellites, with volumes as small as one litre and weights below 1.5 kilograms [1], has enabled new actors to launch new devices into space [2] for Earth observation, communication, Internet of Things (IoT), and geolocation, among others [3]. Due to the market demands and new active players, the number of devices deployed in space is rising significantly. For example, the UK alone plans on launching 2000 small satellites by 2030 [4]. Thanks to the intrinsic advantages of photonic applications (bandwidth, mass, power consumption, and immunity to electromagnetic interference), many of the new deployments in space will include many new laser devices [5]. In this publication, we will review the principal laser-based photonic applications for space, focusing on their technological aspects.

Laser Devices

The first successful use of a laser for a space experiment was registered on 9 May 1962, as part of the Laser Lunar Ranging experiment [6]. Since the laser device was located on the Earth's surface, it did not need to fulfill additional specifications required for space flights, such as mechanical stability, thermal shocks, and radiation resistance.[22,23,24]

The story of laser operation in space started in 1971, when the Apollo 15 carried what would be the first laser outside Earth, a flash-lamp-pumped Q-switched Ruby laser built by the RCA Corporation and used for the Laser Altimeter experiment [7]. The first diode-pumped solid-state laser (DPSSL) to be sent into space was delivered in 1992 and launched as part of the Mars Orbiter Laser Altimeter (MOLA) in 1996; the laser used an Nd:YAG crystal as the active medium [8]. In November 2001, the use of semiconductor laser technology in space was reported for a direct laser application rather than pumping, when the world's first laser-based optical data link connected the Artemis satellite from the ESA with the Centre National d'Études Spatiales (CNES) Earth observation satellite SPOT 4 [9], using GaAlAs laser diodes emitting at 0.8 μm. It is also worth highlighting the first laser pulse emitted on a planet surface other than the Earth on 19 August 2012, by the laser integrated in the ChemCam device installed on the Curiosity Mars rover, which used an Nd:KGW crystal DPSSL [10].

The constraints associated with laser operation in space are different from those in terrestrial applications. Thus, the lasers suitable for space applications need to present specifications, such as long lifetime, high efficiency, low susceptibility to optical misalignment and contamination, and unattended operation, among others. The best laser has to be selected depending on the requirements of the application and environment. Wavelength, repetition rate, peak power, pulse length, flexibility, maintainability, manufacturing cost, and operating cost are important parameters to take into account, but the environment is also essential, depending on whether the laser will be in the low atmosphere, in deep space, near the sun, or on another planet.

The following subsections will address the most commonly used types of lasers suitable for space deployment, together with some of their specifications, applications, and examples of real-life deployments.

Semiconductor Lasers

Semiconductor lasers have been studied and used for years in space applications. Some of their main advantages include operation under direct current injection, which provides high electrical to optical power conversion efficiency, but also long lifetime and high output power. Although their divergence, beam quality, and intensity noise are not suitable for all applications, they are also the preferred pump element for solid-state lasers (SSLs) and fibre lasers since their wavelength can be slightly tuned to achieve optimum absorption of the laser media, making them the cornerstone for laser technologies used in space applications. Many materials are being used, such as GaAs, InGaAs, InP, and InGaAsP. The two most common types of semiconductor laser are the edge-emitting laser (EEL) and the vertical-cavity surface emitting laser (VCSEL).[25,26,27]

Edge-Emitting Laser (EEL)

EELs are the most common semiconductor laser devices. Thanks to their diode junction structure, these devices can transform electrical energy into light. Apart from SSL pumping, they are mostly suited to applications, such as information relay (inter and intra satellite), matter light interaction (spectroscopy and pyrotechnics), planetary exploration and monitoring, metrology, and sensors [11]. Some direct applications for which they are being used include, for instance, the autofocus system of the ChemCam laser [12] or the rendezvous sensor for the docking of the European Automatic Transfer Vehicle to the International Space Station (ISS) [13]. EEL have already been deployed in satellites, in deep space, and also on the Martian surface.

Vertical-Cavity Surface-Emitting Laser (VCSEL)

The VCSEL differs from the EEL in its manufacturing process but, more characteristically, in its beam emission. The output laser beam of a VCSEL is emitted perpendicular to the top surface. Due to the differences in the manufacturing and packaging processes, the devices have to be independently qualified for the missions. Moreover, VCSELs require less electrical power due to their low threshold. Already in early studies, VCSELs were identified as good candidates for space applications. Carson [14] , reported that, although several factors must be taken into account to optimise VCSEL lasers for space applications, they display better radiation resistance than their EEL counterparts. LaForge et al. [15], described in detail the possibility to use VCSELs as space multi-processors, as well as the issues they may exhibit when exposed to radiations. The publication focused on the implementation of devices for satellite missions in different orbits. Moreover, Ellmeier et al. [16], demonstrated the functionality of VCSELs in harsh environmental conditions, such as low vacuum. The aim of this last work was to demonstrate that these devices could be used in space missions, such as JUpiter ICy Moon Explorer (JUICE) 2014, where the devices must be operative for about 17 years and support severe amounts of radiation. Similarly, Chaudron et al. [17], presented in their study of 1550 nm VCSEL devices the effects of temperature on different parameters of the optical device performances, such as optical output power, threshold current, and relative noise intensity.

Solid State Laser (SSL)

In this review, most of the SSLs that we will discuss are pumped by semiconductor diode lasers (DPSSL). SSL present several advantages over semiconductor laser, such as beam quality and the possibility to allow for extra versatility by reaching wavelengths and/or output powers which are not easily achieved by semiconductor lasers.[28,29,30] In addition, short pulses can be emitted, for instance, through Q-switching, which are commonly used in range-finding applications. The space applications in which DPSSL lasers are used include Light Detection and Ranging (LIDAR) and spectrometer devices. An example of the former application would be the GEDI (Global Ecosystems Dynamics Investigation Lidar) instrument, developed for NASA's Earth Venture Instrument (EVI) space program, which uses a version of the High Output Maximum Efficiency Resonator (HOMER) laser, an Nd:YAG crystal side-pumped by seven, 4-bar G-package laser diode arrays [18]. An example of the latter application would be the ESA/ROSCOSMOS ExoMars 2015 mission to Mars, that includes a Raman Laser Spectrometer (RLS) instrument whose excitation source is an intracavity frequency-doubled DPSSL emitting at 532 nm, pumped by a CW (continuous-wave) Q-mount diode emitting at 808 nm [19].

RESULTS

Fiber Lasers

The development of fiber optics technology for telecommunications have resulted in new devices, including novel optical sources, which have also been beneficial for space applications. Some of the most interesting aspects for space applications include standard benefits, such as high power, cost, beam quality, and efficiency, but also more space-relevant improvements, such as unattended operation, compactness, low susceptibility to optical misalignment and contamination, thanks to their monolithic structure, low sensitivity to environment changes, and high reliability. Space-qualified pump and seed laser sources are also available for this technology. NASA has already demonstrated its relevance for remote sensing and laser altimeters, but other applications include LIDAR, metrology, telecommunications, and automated planetary rovers [20].

In 2009, the first fiber laser was launched into space within the Fiber Sensor Demonstrator for ESA's Proba-2 satellite. One of the aims of this mission was to demonstrate the reliability of a full fiber-optic sensor network in space The device included a fiber laser that could sweep the wavelength range from 1520 to 1560 nm. The systematic monitoring of the demonstrator showed that seven years after the launch, the system was still working as expected [21].

Other Types of Laser Sources

Other types of lasers have been studied for space applications, such as gas, dye, and chemical lasers, but they present more difficulties to be adapted to space environments [11]. Common drawbacks include short lifetime and poor radiation resistance [22]. In particular, excimer lasers have lifetimes of less than 100 h due to the degradation of the gas charge, and ion lasers' lifetime is less than 1000 h. Dye lasers are not robust and suffer from a low efficiency, and chemical lasers, such as hydrogen fluoride (HF) lasers, have short lifetimes limited by the fuel charge [23]. Variations of the lasers described in the current section might become relevant for space applications in the future, such as Quantum Dot semiconductor lasers, disc lasers, or photonic crystal fiber lasers. Lasers pumped by other means are also being studied; for instance, a solar-pumped laser was demonstrated in 1966 [24] and such devices have been considered since by both NASA [25] and ESA [26], as they would be extremely relevant in the space environment, although the deployment is not yet realistic due to the low maturity level of such devices.[31,32,33]

Lasers in Space

Science

Although recent applications have been focused towards industrial usage of space technologies, several under way deployments are still catering to scientific purposes, aiming at increasing the knowledge regarding the history of the universe and the discovery of traces of potential life. In the following section, we will be addressing scientific objectives, before discussing more pragmatic matters, such as industrial application of space technologies.

Remote Sensing (LIDAR)

Earth Observation

The observer effect is a well-known physics phenomenon that states that observation of an experiment can alter some of its parameters, so remote, non-interfering characterization techniques can provide better objective information. In the same way, observing the Earth from space can provide better perspective, additional information, and a more global vision to study our planet. New services and information channels can be developed to solve challenges, such as deforestation, climate change effects, and pollution, as well as enable more sustainable processes for precision agriculture, fleet management optimisation, tree-harvesting, construction, and even mining, which can help humans live in better harmony with the planet. Thanks to recent improvement in satellites and the development of micro- and nano-satellites, it is now easier than ever to send experimental devices to orbit the Earth. Many examples of laser photonic devices and missions that have successfully studied our planet evolution from space have been reported, although the most common example is the space-based LIDAR, which sends laser pulses to the target surface and analyzes the reflected signal

The early laser LAser GEOdynamic Satellite (LAGEOS) NASA mission was launched in 1976. It was the first satellite dedicated exclusively to high-precision laser ranging, a passive experiment with ground emitter/receiver laser devices that could improve the current knowledge of our planet's shape, and paved the way for the next satellite missions [28]. The mission had resemblances with the first 1962 Lunar Laser Ranging experiments, in terms of shooting at an object with a ground laser beam and waiting for the response signal. The results obtained using the orbiting mirror helped to prepare for future medium orbit satellite missions. It was followed in 1992 by the LAGEOS-2, which was designed by the Italian Space Agency, based on the original LAGEOS design.[34,35,36]

NASA launched the LIDAR In-space Technology Experiment (LITE) mission on the Discovery Space Shuttle in September 1994 to validate key LIDAR technologies for spaceborne applications. LITE operated with a two-lasers system providing redundancy in case one laser failed, emitting at three wavelengths (1064 nm fundamental, 532 nm second harmonic, and 355 nm third harmonic) from an Nd:Cr:YAG laser crystal pumped by two flash lamps [29].

The BALKAN instruments were launched by Russia in 1995 and were also based on flash lamp pumped Nd:Cr:YAG crystals, frequency doubled in order to use the 532 nm wavelength [30].

In 1996 and 1997, the Shuttle Laser Altimeter experiment produced laser altimetry and surface LIDAR data as results of the test flights for transition of the technology to low Earth orbit [31]. The lasers on both flights were copies of the MOLA laser and, as such, were based on a passively switched Nd:Cr:YAG crystal producing 10 pulses per second with energies of 40 mJ and width of 10 ns at 1064 nm [30].

The ESA Envisat 2002 mission studied ocean and atmospheric chemical and physical composition, Earth topography, and the ice sheets, among other [32]. The mission could acquire data of about 4.6 Mbps that was later communicated through an X-band direct link to the ground [33]. The Envisat European mission is considered the predecessor of the Sentinel missions that are currently being deployed.[37,38,39]

The Geoscience Laser Altimeter System (GLAS) Laser Transmitter, launched in 2003, was an Earth observation LIDAR whose main objective was the study of the Earth ice sheet mass. The device contained the first passively Q-switched, master oscillator power amplifier (MOPA) that worked in space, representing a one order of magnitude power improvement over the MOLA laser system [34]. The device designed with three redundant laser units produced a laser output of 75 mJ at 1064 nm with a repetition rate of 40 Hz, pulse width smaller than 6 ns, and they emitted just under 2 billion shots before the mission was completed in 2011 [35]. This output was used for altimetry. The lasers also simultaneously emitted at 532 nm pulses with 30 mJ energy, used for cloud and aerosol lidar [36].

In 2006, NASA launched the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) instrument inside the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) mission, jointly with the French National Centre for Space Studies (CNES). The objective was to provide new insight into the role that clouds and atmospheric aerosols, such as airborne particles, play in regulating the Earth's weather, climate, and air quality [37]. CALIOP used two redundant Q-switched Nd:YAG lasers, and used three receiver channels, one at 1064 nm and two at 532 nm, measuring orthogonally polarised components of the backscattered signal. A pulse energy of 110 mJ per channel was used, at a 20 Hz repetition rate [38,79,80,81].

The ESA Sentinel missions started in 2014 with the launch of Sentinel-1A and will continue delivering monitoring satellites for at least another half a decade. The satellites battery includes different optical devices from mission control devices to Earth monitoring, through communication devices that study tectonic plates, the oceans, and emissions of gases, among others [39].

The Cloud-Aerosol Transport System (CATS) mission, which was launched in 2015, was installed on the ISS and used a two-laser LIDAR system, each of the lasers operating at three wavelengths (1064, 532, and 355 nm), to provide vertical profiles of atmospheric aerosols and clouds [40]. A ring oscillator design was selected and the pulse widths were, respectively, 8.2 ns and 5.3 ns at 1064 nm, with a pulse energy of 3 mJ [41].

The ESA Aeolus mission, originally planned to be launched in 2008 and mainly aimed at studying global wind profiles, will help improve significantly the weather forecasts. The mission, finally launched in 2017, uses a 355 nm UV pulse laser emission, resulting from frequency-tripling of a diode-pumped Nd:YAG crystal in a lithium triborate (LBO) crystal, to study the atmosphere composition and evolution [42].

In 2017, NASA also launched the ICESat-2 mission that includes an Advanced Topographic Laser Altimeter System (ATLAS) mostly used to study the ice-sheet topography. The ATLAS included two lasers and a MOPA able to deliver a pulsed beam frequency doubled to 532 nm through second harmonic generation, with a 1 ns full width at half maximum (FWHM) pulse width and 10 kHz repetition rate, split into six beams to create a pattern for better resolution of the application [43].

Water, mineral, and underground natural resources detection are studied in the GRACE-FO NASA mission launched in 2017 [44]. Laser ranging interferometry (LRI) is used to continuously measure the distance between the two satellites flying together. The acceleration and deceleration of the two separate bodies will provide information on gravitational changes, helping to understand the underground surface composition [45].

The Global Ecosystem Dynamics Investigation (GEDI), launched in December 2017, also participates in the Earth Observation effort by providing high resolution laser ranging of Earth's forests and topography from the ISS. The device employs three laser transmitters emitting at 1064 nm at a 242 pulses per second repetition rate [46].

Other Solar System Targets

Similar devices to those described in the previous section have been successfully sent to study other bodies in our solar system. We highlight here some of these devices that have been sent to the Moon, Mars, and Mercury, among other targets.[40,41,42]

The first topographic mapping of the Moon from orbit was performed by Apollo 15 in 1970, which was then extended by the Apollo 16 and Apollo 17 missions. The lasers were flash-lamp pumped based and mechanically Q-switched with a ruby laser emitting at 694.23 nm with a pulse energy of 200 nJ and a pulse width of 10 ns [35]. In 1994, the Clementine mission was launched, which mapped the surface of the Moon over a period of more than two months. It carried on board a compact, lightweight, diode-pumped Nd:Cr:YAG laser, emitting pulses of 180 mJ energy and 10 ns width at 1064 nm. The Q-switching was performed by a Lithium Niobate[76,77,78] ($LiNbO_3$) crystal-based Pockels cell [47]. SELENE, also known as Kaguya, was a Japanese mission launched in 2007 that orbited the Moon for more than one and a half years and surveyed it with LIDAR technology using an Nd:YAG laser with 100 mJ output power at 1064 nm, a pulse width of 15 ns and a repetition rate of 1 Hz. The Q-switch was also performed actively by a $LiNbO_3$-based Pockels cell [48]. China also created a lunar exploration program called Chang'E. The first mission was launched in 2007 and the lunar surface was mapped between November 2007 and July 2008. The laser specifications were similar to those of previous missions, with an output wavelength of 1064 nm emitted from a diode-pumped Nd:YAG crystal actively Q-switched with a potassium dideuterium phosphate (KD*P) crystal. The energy emitted was 150 mJ per pulse and a pulse width of less than 7 ns at repetition rate of 1 Hz [49]. A similar laser was used for the Chang'E-2 mission launched in 2010, but with a repetition rate of 5 Hz. The resolution of the measurements was increased to achieve a 5 m vertical accuracy [50]. In 2008, India launched its first lunar probe called Chandrayaan, equiped with the Lunar Laser Ranging Instrument (LLRI) that mapped the surface topography using a Q-switched Nd:YAG laser at 1064 nm with a pulse energy of 100 mJ and a pulse width of 15 ns. The active Q-switching was also performed by an $LiNbO_3$ crystal [30]. The NASA Lunar Orbiter Laser Altimeter (LOLA) was also launched in 2008, one of its objective being the validation of technologies for following missions to the Moon. It uses a DPSSL with an Nd:Cr:YAG slab with passive Q-switch and a cross-Porro resonator configuration working at 1064 nm, 28 Hz repetition rate and about 3 mJ at 5 ns for the both mounted redundant lasers [51,52].

The NASA DPSSL for MOLA was launched in 1996 with the objective of studying the Martian topography. The mission used a diode-pumped, Nd:Cr:YAG zigzag slab, cross-Porro, electro-optically Q-switched laser transmitter. The laser design parameters were 40 mJ energy with pulse width of 10 ns and repetition rate of 10 Hz, although the experimental data was closer to 45 mJ with pulses of 8 ns width [53]. In 2008, the PHOENIX lander, equipped with a LIDAR system, reached Mars. The dual wavelength Nd:YAG laser it carried was capable of delivering pulses with energies of 30 mJ at 1064 nm and 40 mJ at 532 nm after frequency-doubling in a KTP crystal with a pulse width of 15 ns at a repetition rate of 100 Hz provided by a saturable observer. The apparatus was used to study the Martian atmospheric dust, clouds, and precipitations, such as ice, fog, and snow [54].[73,74,75]

The Mercury Laser Altimeter (MLA) on board of the NASA mission MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) launched in 2004 is a passive Q-switched LIDAR laser operating with 5 ns and 20 mJ laser pulses at a 8 Hz rate used to gather topographic information of the planet. In this case, the configuration used a similar zigzag slab design, although in other aspects, its design had a direct linage from the GLAS laser passively Q-switched DPSSL [52,55]. The BepiColombo mission, launched in 2017 and set to build on the achievements of the MESSENGER mission, incorporates a space-qualified miniaturized laser operating at 1064 nm and a repetition rate of up to 10 Hz, based on a Q-switched Nd:YAG rod oscillator pumped by two semiconductor diode lasers [56].

A 1064 nm Nd:Cr:YAG laser rod pumped by a gallium arsenide laser diode array was used as one of the principal components for the Near-Earth Asteroid Rendezvous (NEAR) laser ranging investigation launched in 1996 by the NASA, which observed the asteroid 433 Eros between 2000 and 2001. A laser pulse width of 12 ns was achieved at 1064 nm using an Nd:YAG laser crystal, with an energy per pulse of 15 mJ [57]. [70,71,72]In 2003, Hayabusa 1 was launched by JAXA to study the Itokawa asteroid. The LIDAR system was used in rendezvous and approach phases of the mission, but also provided important surface information of the asteroid itself. The spacecraft was equipped with a laser altimeter system based on a diode-pumped, [43,44,45]Q-switched, single-mode Nd:Cr:YAG emitting 8 mJ energy pulses at 1064 nm, with pulse widths of 14 ns and a repetition rate of 1 Hz through the use of Lithium Niobate Pockels cell [58]. The laser for the following Hayabusa 2 mission was developed based on the lasers for Selene and Hayabusa 1, but the output pulse energy was increased to 15 mJ and the pulse width reduced to 7 ns [59]. Hayabusa 2 was launched in 2014 and rendezvoused in 2017 with the asteroid Ryugu. NASA's Origins Spectral Interpretation Resource Identification Security–Regolith Explorer (OSIRIS-REx) mission was launched in 2016 to study the asteroid Bennu. It was equipped with the also called OSIRIS-REx Laser Altimeter system which is currently performing LIDAR measurements to provide high resolution topographical information of the asteroid. Two different Nd:YAG lasers operate at 1064 nm: a low-energy source operating at 10 kHz with a 10 μJ per pulse that can be used for rapid time-of-flight imaging down to 225 m and a higher-energy source emitting 1 mJ pulses at 100 Hz repetition rate to scan the asteroid at distances between 7.5 km and 1 km from the surface [60]. The OSIRIS-REx mission also plans to bring small samples from Bennu back to Earth. Finally, NASA's JUICE mission, which will be launched in 2014 to study the icy moons of Jupiter (Ganymede, Callisto, and Europa), will also use two cold-redundant, transversely-pumped, actively Q-switched Nd:YAG rod laser emitting 17 mJ pulses at a repetition rate of 30 to 50 Hz with a pulse width of 5.5 ns and a wavelength of 1064 nm [61]. The design of the whole LIDAR system is based on the designs of the Kaguya and Hayabusa missions, as well as that of the BepiColombo Laser altimeter.

The examples above illustrate how a demonstrated and qualified laser configuration can be replicated with small updates to adapt the device to the specific requirements of following space missions in order to guarantee their success.[46,47,48]

Spectroscopy

Spectroscopy is a very common analytic technique that can be used to probe the composition of an object. Thanks to the electromagnetic radiation emitted from a body, the resulting spectrum can be analyzed to infer the physical properties of that object, such as chemical composition, mass, and temperature. This emission signal can be amplified by exciting the target with the energy of a source. Both passive and active spectroscopy are useful in a wide range of scientific and industrial applications, but also in space applications where they have allowed, for instance, to confirm the expansion of the universe [62]. Many different types of excitation sources can be used for active spectroscopy, such as light bulbs, flash lamps, ion, electron, or X-ray beams, although a number of spectrometers rely directly on Solar light, such as the devices used in the Chandrayaan missions. Spectroscopy is also commonly used to study astronomical bodies and samples in laboratories. Here, we will concentrate on the space application of spectroscopy techniques that rely on lasers, such as Raman Spectroscopy and Laser Induced Breakdown Spectroscopy (LIBS).

In 2011, NASA sent the Curiosity Rover to Mars, which contained the ChemCam instrument that could analyze targeted samples composition up to 7 m away. The ChemCam LIBS instrument, one of the firsts of its kind launched in space, used a 1067 nm laser pulses of ≥10 MW/mm2 generated by an Nd:KGW crystal to create laser-induced breakdown, to later analyze the generated plasma thanks to the also incorporated spectrometer device [63]. The future NASA 2015 mission to Mars intends to use improved devices, [67,68,69]allowing moreover to search and analyze organic compounds. To do so, the SuperCam instrument, apart from being able to perform LIBS analysis, counts also with Raman spectroscopy capabilities. To allow for both analyses, the laser device is designed with an Nd:YAG crystal instead of an Nd:KGW as its predecessor was [64]. The mission intends also to perform proximity Raman spectroscopy using a 248.6 nm beam emitted from a Neon-Copper Transverse Excited Hollow Cathode laser. The latter device will be installed in the robotic arm instrument called Scanning Habitable Environments with Raman & Luminescence for Organics[49,50,51] & Chemicals (SHERLOC) [65,66,67]. Similarly, the 2015 ESA mission will carry the Rosalind Franklin rover, which includes the Mars Organic Molecule Analyser (MOMA) and the Raman Laser Spectrometer (RLS) instruments [68]. Both instruments, independently designed and manufactured, are based on different laser approaches. The MOMA uses a 266 nm laser with a tunable beam between 35 and 250 MW/cm^2 generated from a frequency quadrupled beam from an Nd:Cr:YAG crystal [69,70], while the RLS instrument incorporates a DPSSL designed with an Nd:YAG crystal emitting an output beam frequency doubled to 532 nm [71]. The rover internal laboratories and lasers will analyze samples that will have been previously extracted from the Martian underground thanks to a mechanical drill incorporated on the rover.

Similar laser spectrometer devices will also be deployed in-situ, as, for example, on the Pragyan rover on the Chandrayaan-2 mission to the Moon. The mission is planned to be launched in September 2016 and will carry a LIBS device with an Yb:Er:Phosphate glass laser operating at a wavelength of 1534 nm, with pulse energies between 2 and 3 mJ and a pulse duration of 7 ns [72]. Other techniques, such as tuneable laser spectroscopy (TLS), have been used at the ISS and also incorporated in Mars missions for atmospheric composition analysis [73].

With the astonishing results obtained by the Curiosity mission and the great possibility of being able to analyze the composition of planets and space bodies in-situ, the interest of developing new laser spectrometer devices for future missions has arisen, such as the Standoff ultracompact micro-Raman sensor developed by Nuril Abedin et al. [74], for future planetary surface explorations.[52,53,54]

Quantum Scientific Technologies

Scientific experiments addressing quantum physics challenges have also been launched into space. Atomic clocks and atom interferometers, which can be used for various space applications, are some of the devices that have been tested. Atomic clocks based on laser-cooled atoms are widely used as primary frequency standards and are a key component of the Global Navigation Satellite System (GNSS). Atom interferometers are used in applications described in the article of Schuldt et al. [75], such as measurements of the Earth's gravitational field, gravitational wave detection, navigation, and tests of the weak equivalence principle.[64,65,66] In the same paper, authors reported an atom interferometer device built with a laser system based on a hybrid approach using fiber-based telecommunication components and high-power laser diode technologies, designed in the framework of the space mission Space-Time Explorer and QUantum Equivalence Principle Space Test (STE-QUEST). The purpose of this mission is to perform quantum experiments to test the Einstein Equivalence Principle to a high precision level, as well as search for new fundamental constituents and interactions in the Universe [76]. Similar technologies were demonstrated in the Quantus project, and in rocket mission experiments, such as MAIUS and Kalexus. The first cold atom experiment in space was reported in 2017 with the Matter-Wave Interferometry in the Microgravity (Maius 1) [55,56,57]mission [77], although it only lasted six minutes. The laser module was based on a MOPA configuration where the oscillator was built of a 1 mm long double quantum well, AlGaAs based ridge-waveguide distributed feedback diode laser emitting at 766.7 nm with a linewidth of approximately 1 MHz [78], and where a self-seeded tapered amplifier (TA) was used to generate an output power of more than 1 W [79]. The output power emitted through the back facet of the Distributed FeedBack (DFB) diode laser was monitored with a photo diode. Nevertheless, there has been some controversy on which experiment was performed first, since China started a mission called Cold Atom Clock Experiment in Space (CACES) in 2011 that resulted in launching an atomic clock in space in 2016, but the results were only reported one year later. In this case, the system used two input distributed Bragg reflector diode laser beams for laser cooling of rubidium [80].

The Cold Atom Lab experiment, launched to the ISS in May 2017, was designed and built at NASA's Jet Propulsion Laboratory (JPL). It uses a very complex design based on commercial laser equipment and has successfully produced Bose-Einstein Condensates (BEC) of Rubidium atoms in orbit for the first time. Thanks to the microgravity conditions of the ISS, the BEC produced are colder and more stable, which should allow to observe new quantum phenomena and test fundamental laws of physics which could be applied in quantum detectors, optical clocks, and gravity monitoring. The light source consists in external cavity diodes, where a reference laser is used for each species: one at 766.701 nm, the other at 780.240 nm. The laser cooling system uses stabilized New Focus Vortex Plus diode lasers and New Focus TA-7600 tapered amplifiers [58,59,60]

CONCLUSION

Further atomic clock missions in space will include ESA's Atomic Clock Ensemble in Space (ACES), which has been tested and integrated on the payload and will be ready for launch to the Space Station by 2015. The objective is to place atomic clocks in orbit and compare their performance to ground clock systems, as well as perform fundamental scientific experiments, such as gravitational red-shift and light anisotropy measurements, amongst others [82]. The cesium atomic clock system called PHARAO (Projet d'Horloge Atomique Par Refroidissement d'Atomes en Orbite), to be deployed within the ACES mission, has been developed by the CNES (Figure 3). The laser source is a commercial JDS 5421 master diode laser, based on the extended cavity laser diode (ECLD) concept and emitting 30 mW at 852 nm with a linewidth of 100 kHz and a single mode tunability of 1 GHz, that seeds two slave laser diodes for output powers of 100 mW [61,62,63]

REFERENCES

1. CubeSats: Tiny, Versatile Spacecraft Explained. Available online: https://www.space.com/29320-cubesats-spacecraft-tech-explained-infographic.html (accessed on 4 June 2016).
2. CubeSats: Tiny Payloads, Huge Benefits for Space Research. Available online: https://www.space.com/34324-cubesats.html (accessed on 4 June 2016).
3. A Basic Guide to Nanosatellites. Available online: https://alen.space/basic-guide-nanosatellites/ (accessed on 4 June 2016).
4. Britain Competes for the Launch of an Estimated 2000 Satellites by 2030. Available online: https://www.gov.uk/government/news/britain-competes-for-the-launch-of-an-estimated-2000-satellites-by-2030 (accessed on 4 June 2016).
5. Karafolas, N.; Armengol, J.M.P.; Mckenzie, I. Introducing photonics in spacecraft engineering: ESA's strategic approach. In Proceedings of the 2009 IEEE Aerospace Conference, Big Sky, MT, USA, 7–14 March 2009. [Google Scholar]
6. Smullin, L.D.; Fiocco, G. Optical echoes from the moon. Nature 1962, 194, 1267. [Google Scholar] [CrossRef]
7. Yu, A.W.; Li, S.X.; Shaw, G.B.; Seas, A.; Stephen, M.A.; Troupaki, E.; Vasilyev, A.; Ramos-Izquierdo, L.; Lukemier, A.; Mamakos, W.; et al. Overview of Space Qualified Solid-State Lasers Development at NASA Goddard Space Flight Center. In Proceedings of the SPIE LASE: Lasers and Applications in Science and Engineering, San Jose, CA, USA, 13 February 2009; Volume 7193. [Google Scholar]
8. Zuber, M.T.; Smith, D.E.; Solomon, S.C.; Muhleman, D.O.; Head, J.W.; Garvin, J.B.; Abshire, J.B.; Bufton, J.L. The Mars Observer Laser Altimeter Investigation. J. Geophys. Res. 1992, 97, 7781–7797. [Google Scholar] [CrossRef]

9. A World First: Data Transmission between European Satellites Using Laser Light. Available online: https://www.esa.int/Our_Activities/Telecommunications_Integrated_Applications/A_world_first_Data_transmission_between_European_satellites_using_laser_light (accessed on 4 June 2016).
10. War of the Worlds: Curiosity Fires First Laser Shot on Mars. Available online: https://newatlas.com/curiosity-laser-firing/23761/ (accessed on 4 June 2016).
11. Mondin, L. Laser Diodes in Space: Needs Expression. CNES Laser Diodes in Space Workshop. 2006. Available online: https://escies.org/download/webDocumentFile?id=2208 (accessed on 5 July 2016).
12. Cousin, A.; Maurice, S.; Parot, Y.; Michel, Y.; Le Roch, N.; Dalmau, J.; Pares, L.; Perez, R.; Cros, A.; Wiens, R. ChemCam (MSL) Autofocus Capabilities. In Proceedings of the 40th Lunar and Planetary Science Conference, Woodlands, TX, USA, 23–27 March 2009; p. 1684. [Google Scholar]
13. Minec-Dube, S. Evaluation and Space Qualification of laser diodes for ATV-videometer and PHARAO projects. Workshop Laser Diodes in Space. 2006. Available online: https://escies.org/webdocument/showArticle?id=683&groupid=6 (accessed on 5 July 2016).
14. Carson, R.F.; Taylor, E.W.; Paxton, A.H.; Schone, H.; Choquette, K.D.; Hou, H.Q.; Warren, M.E.; Lear, K.L. Surface-emitting laser technology and its application to the space radiation environment. In Proceedings of the SPIE OPTO, San Diego, CA, USA, 29 July 1997; p. 10288. [Google Scholar]
15. LaForge, L.E.; Moreland, J.R.; Bryan, R.G.; Fadali, M.S. Vertical Cavity Surface Emitting Lasers for Spaceflight Multi-Processors. In Proceedings of the IEEE Aerospace Conference, Big Sky, MT, USA, 4–11 March 2006; Volume 1355. [Google Scholar]
16. Ellmeier, M.; Hagen, C.; Piris, J.; Lammegger, R.; Jernej, I.; Woschank, M.; Magnes, W.; Murphy, E.; Pollinger, A.; Erd, C.; et al. Accelerated endurance test of single-mode vertical-cavity surface-emitting lasers under vacuum used for a scalar space magnetometer. Appl. Phys. B 2017, 124, 18. [Google Scholar] [CrossRef][Green Version]
17. Chaudron, S.; Gernigon, V.; Rissons, A. Vertical-cavity surface-emitting laser characterizations for space applications. In Proceedings of the SPIE OPTO, San Francisco, CA, USA, 4 March 2015; Volume 9381. [Google Scholar]
18. Coyle, D.B.; Stysley, P.R. The High Output Maximum Efficiency Resonator (HOMER) Developed for Long Life, Space-Based Altimetry. In Proceedings of the IEEE Aerospace Conference, Big Sky, MT, USA, 4–11 March 2006. [Google Scholar]
19. Ribes-Pleguezuelo, P.; Moral, A.; Basset, M.G.; Rodriguez, P.; Rodriguez, G.; Laudisio, M.; Galan, M.; Hornaff, M.; Beckert, E.; Eberhardt, R.; et al. Assembly process comparison for a miniaturized laser used for the Exomars European Space Agency mission. Opt. Eng. 2016, 55, 116107. [Google Scholar] [CrossRef]
20. Coyle, D.B. Applications of Fiber Amplifiers for Space: Laser Altimetry and Mapping. The First ESA-NASA Working Meeting on Optoelectronics: Fiber Optic System Technologies in Space. 2005. Available online: https://escies.org/download/webDocumentFile?id=1609 (accessed on 8 July 2016).
21. Haddad, E.; Kruselecky, R.V.; Mena, M.; Tagziria, K.; Ricci, F.; McKenzie, I.; Karafolas, N.; Hannoteau, F. Optical Fiber sensors system on Proba-2 after 7 years. In Proceedings of the ICSO 2016 International Conference on Space Optics, Biarritz, France, 18–21 October 2016. [Google Scholar]
22. Rogers, M.E. Lasers in Space–Technological Options for Enhancing US Military Capabilities; Occasional Paper No.2; Center for Strategy and Technology, Air War College: Montgomery, AL, USA, 1997. [Google Scholar]
23. Lingvay, L.S.; Bowman, A.P.; Wallace, A.S. Laser Payloads on Small Satellites; White Paper; Space Applications Corp: Arlington, VA, USA, 1990. [Google Scholar]
24. Young, C.G. A sun-pumped cw one-watt laser. Appl. Opt. 1966, 5, 993–997. [Google Scholar] [CrossRef] [PubMed]
25. Eubanks, P.; Marzocca, P.; Payziyev, S.; Radley, C. Solar Pumped Lasers to Directly Convert Sunlight to Laser Radiation; White Paper: Information Program NNH15ZOA001L; Leeward Space Foundation: Americus, GA, USA, 2015. [Google Scholar]
26. Wittrock, U. Perspective of Solar pumping of Solid State Lasers for ESA missions. Contract Number 400106760. 2013. Available online: https://nebula.esa.int/content/perspective-solar-pumping-solid-state-lasers-esa-missions (accessed on 8 July 2016).
27. Adsys Controls, Inc. Laser Application for Space Navigation. Available online: https://www.nasa.gov/sites/default/files/atoms/files/05_adsys_controls_laser_application_for_space_navigation.pdf (accessed on 27 March 2016).
28. NASA- LAser GEOdynamic Satellite (LAGEOS). Available online: https://lageos.cddis.eosdis.nasa.gov/ (accessed on 8 March 2016).
29. Lidar In-Space Technology Experiment. Available online: https://www-lite.larc.nasa.gov/ (accessed on 18 June 2016).
30. Chen, W. Spaceborne Laser Technology for Lidar Remote Sensing. Light: A Bridge between Earth and Space: Winter College on Optics. 2015. Available

online: http://indico.ictp.it/event/a14287/session/6/contribution/21/material/slides/0.pdf (accessed on 8 June 2016).

31. Bufton, J.L.; Harding, D.J.; Garvin, J.B. Shuttle Laser Altimeter Mission Results and Pathfinder Accomplishments. NASA, 1999. Available online: https://pdfs.semanticscholar.org/5618/67f6271d662da728e60031a8567c3cce4947.pdf?_ga=2.81158608.696812552.1560850487-1171316160.1557831070 (accessed on 30 July 2016).
32. ESA- Rain Forest Observation. Available online: https://www.esa.int/Our_Activities/Observing_the_Earth/Earth_from_Space_Rainforest_river (accessed on 8 March 2016).
33. The Envisat Satellite and Its Integration. Available online: https://www.esa.int/esapub/bulletin/bullet106/bul106_2.pdf (accessed on 2 April 2016).
34. Afzal, S.R.; Yu, A.W.; Dallas, J.L.; Melak, A.; Lukemire, A.T.; Ramos-Izquierdo, L.; Mamakos, W. The Geoscience Laser Altimeter System (GLAS) Laser Transmitter. IEEE J. Sel. Top. Quantum Electron. 2007, 13, 511–536. [Google Scholar] [CrossRef][Green Version]
35. Patil, D.S. Semiconductor Laser Diode: Technology and Applications; InTech: Rijeka, Croatia, 2012; p. 223. ISBN 978-953-51-0549-7. [Google Scholar]
36. Sun, X.; Abshire, J.B.; Krainak, M.A.; Spinhime, J.D.; Palm, S.S.; Lancaster, R.S.; Allan, G.R. Cloud and aerosol lidar channel design and performance of the Geoscience Laser Altimeter System on the ICESat mission. In Proceedings of the Conference on Lasers and Electro-Optics (CLEO), San Francisco, CA, USA, 16–21 May 2004. [Google Scholar]
37. The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO). Available online: https://www-calipso.larc.nasa.gov/ (accessed on 18 June 2016).
38. CALIPSO PAYLOAD. Available online: https://www-calipso.larc.nasa.gov/about/payload.php (accessed on 18 June 2016).
39. ESA- Sentinel-1. Available online: https://www.esa.int/Our_Activities/Observing_the_Earth/Copernicus/Sentinel-1/Satellites_shed_new_light_on_earthquakes (accessed on 8 March 2016).
40. Storm, M.; Stevenson, G.; Hovis, F.; Gavert, W.; Dang, X.; Darab, A.; Chuang, T.; Burns, P. LIDAR and LASER technology for NASA's Cloud-Aerosol Transport System (CATS) payload on the International Space Station (JEM-EF). ILRC 27 2016, 119, 04002. [Google Scholar] [CrossRef]
41. Hovis, F. Recent Progress on Lasers for Space-Based Wind, Aerosol, and Altimetry Lidar Systems. LWG Meeting. 2014. Available online: http://cires1.colorado.edu/events/lidarworkshop/LWG/May14/presentations/Fibertek%20LWG%20Boulder%201514v4.pdf (accessed on 8 July 2016).
42. ESA-Aelus. Available online: https://www.esa.int/Our_Activities/Observing_the_Earth/Aeolus/Aeolus_laser_shines_light_on_wind (accessed on 12 March 2016).
43. NASA- ICESat-2. Available online: https://directory.eoportal.org/web/eoportal/satellite-missions/i/icesat-2 (accessed on 2 April 2016).
44. NASA- EUMETSAT. Available online: https://gracefo.jpl.nasa.gov/mission/overview/ (accessed on 8 April 2016).
45. NASA- Lasers in Space: Earth Mission Tests New Technology. Available online: https://www.nasa.gov/feature/jpl/lasers-in-space-earth-mission-tests-new-technology (accessed on 7 April 2016).
46. ISS Utilization: GEDI (Global Ecosystems Dynamics Investigation Lidar). Available online: https://directory.eoportal.org/web/eoportal/satellite-missions/content/-/article/iss-gedi (accessed on 20 June 2016).
47. Shannon, M.J. The Clementine Satellite. In ET and TR; 1994. Available online: https://str.llnl.gov/etr/pdfs/06_94.1.pdf (accessed on 4 July 2016).
48. SELENE. Available online: https://earth.esa.int/web/eoportal/satellite-missions/s/selene (accessed on 19 June 2016).
49. Chang'e - 1 (Lunar-1 Mission of China). Available online: https://directory.eoportal.org/web/eoportal/satellite-missions/c-missions/chang-e-1 (accessed on 19 June 2016).
50. China to launch Chan'E 2 on Friday, October 1. Available online: http://www.planetary.org/blogs/emily-lakdawalla/2010/2684.html (accessed on 20 June 2016).
51. Smith, D.E.; Zueber, M.T.; Jackson, G.B.; Cavanauch, J.F.; Neumann, G.A.; Riris, H.; Sun, X.; Zellar, R.S.; Coltharp, C.; Connelly, J.; et al. The Lunar Orbiter Laser Altimeter Investigation on the Lunar Reconnaissance Orbiter Mission. Space Sci. Rev. 2010, 150, 209–241. [Google Scholar] [CrossRef]

52. Troupaki, E.; Stephen, M.A.; Vasilyev, A.A.; Yu, A. Laser Diode Pump Technology for Space Applications, Semiconductor Laser Diode Technology and Applications; Patil, D.S., Ed.; InTech: London, UK, 2012; pp. 219–240. ISBN 978-953-51-0549-7. [Google Scholar]
53. Afzal, R.S. Mars Observer Laser Altimeter: Laser transmitter. Appl. Opt. 1994, 33, 3184–3188. [Google Scholar] [CrossRef]
54. Whiteway, J.; Daly, M.; Carswell, A.; Duck, T.; Dickinson, C.; Komguem, L.; Cook, C. Lidar on the Phoenix mission to Mars. J. Geophys. Res. Planets 2008, 113, E3. [Google Scholar] [CrossRef]
55. Cavanaugh, J.F.; Smith, J.C.; Sun, X.; Bartels, A.E.; Ramos-Izquierdo, L.; Krebs, J.D.; McGarry, J.F.; Trunzo, R.; Novo-Gradac, A.M.; Britt, J.L.; et al. The Mercury Laser Altimeter Instrument for the MESSENGER Mission. Space Sci. Rev. 2007, 131, 451–479. [Google Scholar] [CrossRef][Green Version]
56. Kallenbach, R.; Murphy, E.; Gramkow, B.; Rech, M.; Weidlich, K.; Leikert, T.; Henkelmann, R.; Trefzger, B.; Metz, B.; Michaelis, H.; et al. Space-qualified laser system for the BepiColombo Laser Altimeter. Appl. Opt. 2013, 52, 8732–8746. [Google Scholar] [CrossRef] [PubMed][Green Version]
57. Zuber, M.T.; Smith, D.E.; Cheng, A.F.; Cole, T.D. The NEAR laser ranging investigation. J. Geophys. Res. 1997, 102, 23761–23773. [Google Scholar] [CrossRef]
58. Mizuno, T.; Tsuno, K.; Okumura, E.; Nakayama, M. Evaluation of LIDAR System in Rendezvous and Touchdown Sequence of HAYABUSA mission. Trans. Japan Soc. Aero. Space Sci. 2010, 53, 47–53. [Google Scholar] [CrossRef]
59. Namiki, N.; Mizuno, T.; Senshu, H.; Yamada, R.; Noda, H.; Shizugami, M.; Hirata, N.; Ikeda, H.; Abe, S.; Matsumoto, K.; et al. Performance of Hayabusa-2 Lidar in acceptance and verification tests. In Proceedings of the 46th Lunar and Planetary Science Conference, The Woodlands, TX, USA, 16–20 March 2015; p. 1798. [Google Scholar]
60. Neumann, G.A.; Barker, M.K.; Mazarico, E.; Barnouin, O.S.; Daly, M.G.; Lauretta, D.S. OSIRIS-REx Laser altimeter 1064-nm reflectance investigation at Bennu. In Proceedings of the 49th Lunar and Planetary Science Conference, The Woodlands, TX, USA, 19–23 March 2017; p. 1676. [Google Scholar]
61. Hussmann, H.; Lingenauber, K.; Kallenbach, R.; Oberst, J.; Enya, K.; Kobayashi, M.; Namiki, N.; Kimura, J.; Thomas, N.; Lara, L.; et al. The Ganymede Laser Altimeter (GALA). Epsc Abstr. 2014, 9, EPSC2014-347. [Google Scholar]
62. Edwin Hubble and the Expanding Universe. Available online: https://www.atnf.csiro.au/outreach/education/senior/cosmicengine/hubble.html (accessed on 21 June 2016).
63. Ciminelli, C.; Del'Olio, F.; Armensie, M.N. Photonic Sensors and Instruments. In Photoncis in Space, Advanced Photonic Devices and Systems; World Scientific: London, UK, 2016; pp. 180–185. ISBN 9789814725101. [Google Scholar]
64. Wiens, R.C.; Sylvestre, R.C.; Perez, F.R. The SuperCAM remote sensing instrument suite for the Mars 2015 rover mission: A preview. Spectroscopy 2017, 32, 50–55. [Google Scholar]
65. Beegle, L.; Bhartia, R.; White, M.; DeFlores, L.; Abbey, W.; Wu, Y.H.; Cameron, B.; Moore, J.; Fries, M.; Burton, A.; et al. Sherlock: Scanning habitable environments with Raman and luminescence for organics and chemicals. In Proceedings of the IEEE Aerospace Conference, Big Sky, MT, USA, 7–14 March 2015; pp. 1–11. [Google Scholar]
66. Solanki, R.; Fairbank, W.M.; Collins, G.J. Multiwatt Operation of Cu II and Ag II Cathode Lasers. IEEE J. Quantum Electron. 1980, QE-16, 1292–1294. [Google Scholar] [CrossRef]
67. Photonsystems-Space Qualified Deep UV. Available online: https://photonsystems.com/space-qualified/ (accessed on 28 February 2016).
68. Vago, J.L.; Westall, F.; Coates, A.J.; Jaumann, R.; Korablev, O.; Ciarletti, V.; Mitrifanov, I.; Josset, J.L.; DeSanctis, M.C.; Bibring, J.P.; et al. Habitability on Early Mars and the Search for Biosignatures with the ExoMars Rover. Astrobiology 2017, 17. [Google Scholar] [CrossRef]
69. Goesmann, F.; Brinckerhoff, W.B.; Raulin, F.; Goetz, W.; Danell, R.M.; Getty, S.A.; Siljestrom, S.; Missbach, H.; Steininger, H.; Arevalo, R.D.; et al. The Mars Organic Molecule Analyzer (MOMA) Instrument: Characterization of Organic Material in martian Sediments. Astrobiology 2017, 17, 655–685. [Google Scholar] [CrossRef]
70. Kolleck, C.; Buttner, A.; Ernst, M.; Hulsenbusch, T.; Lang, T.; Marwah, R.; Mebben, S.; Priehs, M.; Kracht, D.K.; Neumann, J. Development of a pulsed UV laser system for laser-desorption mass spectrometry on Mars. In Proceedings of the International Conference on Space Optics (ICSO), Rhodes Island, Greece, 20 November 2010; Volume 10. [Google Scholar]
71. Ribes-Pleguezuelo, P.; Guilhot, D.; Gilaberte Basset, M.; Beckert, E.; Eberhardt, R.; Tünnermann, A. Insights of the Qualified ExoMars Laser and Mechanical Considerations of Its Assembly Process. Instruments 2016, 3, 25. [Google Scholar] [CrossRef]

72. Laxmiprasad, A.S.; Sridhar Raja, V.L.N.; Goswami, A.; Menon, S.; Rao, M.V.H.; Lohar, K.A. Laser Induced Breakdown Spectrometer (LIBS) for Chandrayaan-2 Rover. Planex 2011, 1, 16–18. [Google Scholar]
73. Webster, C.R.; Christensen, L.E.; Flesch, J.G.; Forouhar, S.; Briggs, R.; Keymeulen, D.; Blacksberg, J.; Mahaffy, P.R. Tunable Laser Spectrometers for Space Science. In Proceedings of the International Workshop on Instrumentation for Planetary Missions (IPM-2014), Greenbelt, Maryland, 4–7 November 2014. [Google Scholar]
74. Nurul Abedin, M.; Bradley, A.T.; Misra, A.K.; Bai, Y.; Hines, G.D.; Sharma, S.K. Standoff ultracompact micro-Raman sensor for planetary surface explorations. Appl. Opt. 2017, 57, 62–68. [Google Scholar] [CrossRef] [PubMed]
75. Schuldt, T.; Schuber, C.; Krutzik, M.; Bote, L.G.; Gaaloul, N.; Hartwig, J.; Ahlers, H.; Herr, W.; Posso-Trujillo, K.; Rudolph, J.; et al. Design of a dual species atom interferometer for space. Experimental Astronomy 2015, 39, 167–206. [Google Scholar] [CrossRef]
76. ESA STE-QUEST. Available online: http://sci.esa.int/ste-quest/ (accessed on 28 March 2016).
77. Schkolnik, V.; Hellmig, O.; Wenzlawski, A.; Grosse, J.; Kohfeldt, A.; Doringshoff, K.; Wicht, A.; Windpassinger, P.; Sengstock, K.; Braxmaier, C.; et al. A compact and robust diode laser system for atom interferometry on a sounding rocket. Appl. Phys. B 2016, 122, 217. [Google Scholar] [CrossRef]
78. Luvsandamdin, E.; Kurbis, C.; Schiemangk, M.; Sahm, A.; Wicht, A.; Peters, A.; Erbert, G.; Trankle, G. Micro-integrated extended cavity diode lasers for precision potassium spectroscopy in space. Opt. Express 2014, 22, 7790–7798. [Google Scholar] [CrossRef] [PubMed]
79. Gilowski, M.; Schubert, C.; Zaiser, M.; Herr, W.; Wubbena, T.; Wendrich, T.; Muller, T.; Rasel, E.M.; Ertmer, W. Narrow bandwidth interference filter stabilized diode laser systems for the manipulation of neutral atoms. Opt. Commun. 2007, 280, 443–447. [Google Scholar] [CrossRef]
80. Liu, L.; Lu, D.S.; Chen, W.B.; Li, T.; Qu, Q.Z.; Wang, B.; Li, L.; Ren, W.; Dong, Z.R.; Zhao, J.B.; et al. In-orbit operation of an atomic clock based on laser-cooled 87Rb atoms. Nat. Commun. 2017, 9, 2760. [Google Scholar] [CrossRef] [PubMed]
81. Elliott, E.R.; Krutzik, M.C.; Williams, J.R.; Thompson, R.J.; Aveline, D.C. NASA's Cold Atom Lab (CAL): System development and ground test status. NPJ Microgravity 2017, 4, 16. [Google Scholar] [CrossRef]