New Optical Communication Capabilities Using Nanosatellites

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***Abstract*—In this paper, the benefits derived from the exploitation of nanosatellites for complex telecommunication missions are presented, along with their limitations, and laser technology is identified as a viable solution to dramatically increase the downlink and crosslink capabilities of such miniature platforms. Then, the critical technological issues concerning the integration of an optical telecom terminal on a nanosatellite platform are discussed, considering the perspective advancements in areas such as power generation, propulsion and attitude control. The incompatibility of laser terminals pointing requirements with the current and perspective nanosatellite attitude stability has been identified as the most critical issue to be addressed in order to implement optical links on nanosatellites. A possible solution is presented at the end of the discussion.**

Keywords-nanosatellite; optical link

I. INTRODUCTION

The term *nanosatellite* refers to the class of satellites weighting between 1 and 10 kg, which were initially conceived to offer students and young engineers valuable educational experiences with real flight programs; their exploitation was boosted by the introduction of the CubeSat standard in 2003. The interest showed by space agencies and academic institutions in such miniature platforms is constantly increasing because of their inherent advantages. The reduced mass, prototyping and production time of nanosatellites, as well as low launch cost as piggyback payloads allow universities, corporations and small companies to access to space easily. As of December 2012, 149 missions based on nanosatellites were flown and many others are on schedule [1], [2].

The inherent low cost of a single nanosatellite can be further reduced when mass production of standard units is applied, making these miniature platforms particularly appealing for the realization of satellite constellations suitable for earth observation, mapping or telecommunication applications. In particular, LEO telecom constellations based on nanosatellites could be attractive since they can provide global continuous coverage, overcoming the visibility limitations of large GEO platforms, and can be cost-effective even with respect to the existing LEO systems. The integration of high data rate, compact telecommunication terminals on nanosatellite platforms could pave the way to mission scenarios unexpected to this day.

In this work, three illustrative perspective scenarios have been identified and are briefly presented below.

1) *Extension of GEO satellites coverage to polar areas and urban canyons*. A LEO constellation of nanosatellites providing continuous coverage over polar regions can be used as a bridge to extend the coverage of GEO telecom satellites (see Fig. 1a), which is usually limited to the ±71° latitudinal band when a minimum elevation angle of 10° is considered. Also, the system can be used to better cover densely urbanized areas. This way, the capabilities of GEO satellites can be increased at a very low relative cost.
2) *Data relay constellation for scientific satellites in LEO*. Scientific missions in LEO produce a large amount of data, while few, short windows are available for downlink to ground stations. A constellation of miniature platforms capable of high data rate down/crosslinks providing continuous global coverage will make it possible to download data to ground stations not visible to the scientific satellites, almost in real time, as shown in Fig. 1b.
3) *Low cost constellation for situational awareness*. In case of unavailability of ground infrastructures due to natural or man-made disasters, situational awareness can be maintained exploiting a LEO nanosatellite constellation, as depicted in Fig. 1c. Crosslink capabilities could dramatically reduce the access time to any point of the Earth surface.

However, the advantages given by the exploitation of nanosatellites are counterbalanced by severe technical limitations, which make them unattractive for complex or high performance missions. Such limitations are represented by the short life (few years) and the limited on-board resources in terms of power and volume available to the payload, attitude control and telecommunications. In particular, downlink and crosslink capabilities are limited by both the on-board power and the poor attitude stabilization typical of nanosatellites, which often rely only on permanent magnet bars and hysteresis rods, preventing the exploitation of narrow-beam antennas for high data rate links. Typically, nanosatellite communication systems use the VHF or UHF frequency band, and are based on monopole or microstrip patch antennas, with wide beamwidth and data rate often bounded to a few tens of kbit/s. Sometimes the S band is

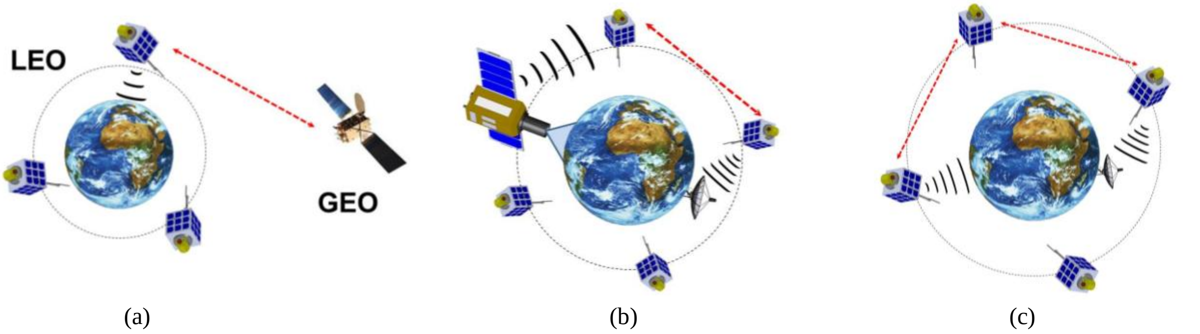

Figure 1. Illustrative new mission scenarios: (a) extension of GEO satellites coverage to polar areas and urban canyons, (b) data relay constellation for scientific satellites in LEO, (c) low cost constellation for situational awarness.

exploited for higher data rate. This is the case of the Generic Nanosatellite Bus [3], whose dual communication system uses a UHF monopole antenna receiver system for uplink at 4 kbps and an S-band transmitter patch antenna set for downlink, capable of data rates between 32 kbps to 256 kbps.

In this paper, the advantages of exploiting optical links on nanosat platforms are discussed in section II. The state of the art of the main technologies required for the realization of the aforementioned mission scenarios is summarized in section III, along with the perspective advancements in those fields. Finally, section IV presents the system that is developed by the authors to cope with the current technological limitations which these days prevent the integration of laser communication terminals onboard nanosatellites.

II. CREATING NEW COMMUNICATION CAPABILITIES USING NANOSATELLITES

In this section, the benefits derived by the exploitation of optical link devices onboard nanosatellites are discussed.

Telecom systems based on laser technology are characterized by very narrow beamwidth and high frequency carriers (hundreds of THz), which make it possible to obtain very high data rate transmissions with more compact and less power consuming devices, with respect to RF systems. In addition, optical links can provide secure channels, as they are immune to jamming and cannot be intercepted. Moreover, there are no licence regulations on the use of optical frequency bands and bandwidths, so great commercial opportunities are possible. Although it cannot be considered a standard technology yet, several optical link devices were developed and tested in the last years [4]-[6]; among them, examples of compact devices are represented by STRV-2 [7] and SOTA [8].

As an example, two RF and one laser-based communication systems for high data rate links are compared in order to determine which technical solution is more suitable for integration on nanosatellites class platforms. The carriers of the two RF systems are set to 2.5 and 20 GHz respectively, the former representing the state of the art of RF communication systems for miniature satellites and the latter representing perspective advancements in this field [9]. The selected laser wavelength is 1.55 µm. A LEO – LEO crosslink scenario is considered with an intersatellite distance of 5000 km and the link requirements are expressed in terms of desired data rate and BER, which are set to 500 Mbit/s and 1E-6 respectively. The former is set roughly 3 orders of magnitude greater than typical maximum data rates for nanosatellites. Then, in order to compare systems with equivalent performance, the RF and optical terminals design assumptions, such as antenna diameter and bandwidth, are set in order to provide the same link margin. For simplicity, the emitter and receiver terminals are supposed to be identical. After that, the link budget is assessed, leading to the estimation of the required power and system mass for all the considered solutions. As regards the optical system, the total mass and power consumption are estimated using empirical correlations between these parameters and the telescope aperture, which were derived from a literature survey on existing optical link devices. The estimates account also for the mechanical active pointing system. On the other hand, the antenna and transmitter mass, as well as the transmitter input power for the RF systems have been estimated considering the relations provided by [10]. An additional mass of at least 1 kg is added to account for the antenna steering mechanism, derived from a literature survey of analogous systems [11]-[12]. Table 1 summarizes the terminals design assumptions and presents the results given by the link budget calculation and the total mass and power consumption estimation; the total mass of the RF systems is given by the sum of the antenna, transmitter and steering mechanism masses. The pointing accuracy required by each system was also calculated according to [13] and is reported in the last line of Table 1.

The results point out that the laser-based system requires a much lower power input with respect to the RF systems and its mass is considerably lower. In fact, the total estimated masses of the RF terminals exceed the nanosat standard limits. However, the pointing accuracy needed to achieve the communication requirements is much more

TABLE I. RESULTS FROM THE LINK BUDGET FOR A RF SYSTEM AND A LASER-BASED TERMINAL PROVIDING A LINK WITH DATA RATE OF 500 MBIT/S, BER OF 10^{-6} AND SAME LINK MARGIN

DESIGN ASSUMPTIONS				
	Unit	**RF 1**	**RF 2**	**Optical**
Antenna diameter	[m]	0.3	0.3	0.02
Carrier frequency	[GHz]	2.5	20	193.5E3
Wavelength	[m]	0.120	0.015	1.55E-6
Bandwidth	[MHz]	500	500	500
Modulation	[/]	BPSK	BPSK	BPSK
RESULTS				
	Unit	**RF 1**	**RF 2**	**Optical**
Trx gain	[dB]	15.31	33.37	91.34
EIRP	[dB]	54.97	54.97	76.71
Trx power	[W]	>1000	144.62	0.035
E_b/N_0	[dB]	12.00	12.00	12.00
Link margin	[dB]	1.30	1.30	1.30
Beamwidth	[rad]	0.49	0.06	96E-6
Total mass	[kg]	>100	15	3.5
Total power	[W]	>1000	395	20
Pointing accuracy	[rad]	0.020	0.003	4E-6

stringent for the optical system, as a consequence of the very narrow beamwidth.

III. TECHNOLOGICAL GAPS

In this section the main technological issues that must be addressed to enable the exploitation of nanosatellite platforms for optical communication are briefly discussed.

A. *Miniaturized Optical Link Terminal*

The mass of existing laser-based communication terminals for space applications ranges between 5 and 160 kg, while their power consumption is within 28 and 150 W. The main drivers for sizing an optical terminal are the telescope aperture and the laser output power, which together contribute to the transmission gain. With the recent availability of compact, reliable and more powerful laser diodes the telescope dimensions can be reduced while maintaining a high transmission gain, thus enabling the realization of low-mass terminals. An optical communication system for microsatellite platforms, with preliminary mass, power consumption and data rate assessment of 5 kg, 45 W and 2.5 Gbit/s respectively, is currently under development [14]; therefore, it is expected that in the near future terminals suitable for integration on nanosatellite platforms can be realized with current technology.

B. *Power Generation*

An estimated power consumption of 20 W for the miniaturized laser terminal results from the analysis performed in section II. According to [15], so far the average available power on-board nanosatellite platforms does not exceed 10 W, even when GaAs solar cells are used. The limiting factor is essentially the small area available to solar cells, even when deployable solar arrays are exploited. A promising solution to this issue is represented by rollable solar arrays based on thin polymide foils, which are characterized by a very high specific power generation (>200 W/kg) [16], [17]. A total power consumption of 60 W can be delivered by a deployable, thin film solar array of 0.4 m^2, for a total weight of only a few hundred grams. Thus, it seems that power available on nanosatellite platforms will increase dramatically in the next years.

C. *Propulsion*

Considering a mission scenario in which a nanosatellite constellation is exploited for telecommunication, propulsion capabilities are essential for orbit maintenance and correction. In high LEO (1000 km or more), the most significant long-term semi-major axis perturbation is due to solar radiation pressure, as the Earth atmosphere density is almost negligible; for a 10 kg platform, a total ΔV of 50 m/s is estimated for orbit corrections throughout a 5 years mission. It seems that such performance can be achieved using currently available technology, as promising results were obtained in the last years exploiting pulsed plasma thrusters and field emission electric propulsion systems [18], [19].

D. *Pointing Accuracy and Stability*

As pointed out in section II, lasercom devices require very stringent pointing accuracy and stability as a consequence of their narrow beamwidth. The needed pointing accuracy is at least in the order of a ten microradians. To this date, this requirement is far beyond the capabilities of any kind of attitude control system considering both nanosatellites and larger platforms. In addition, the bus attitude stability is critical to establish an optical connection between two spacecraft. As a reference point, the ADCS of the Generic Nanosatellite Bus for the BRITE mission [20], which is scheduled to launch in 2013, will be capable of unprecedented performance for nanosatellites, with attitude accuracy and stability of <1° and 60’’ respectively, exploiting a miniature startracker for fine attitude determination and a set of nano reaction wheels. Such performance do not meet the aforementioned requirements, so it is clear that they can be achieved only with a dedicated pointing system. However, moving gimbals could generate additional disturbances the bus ADCS must deal with, which sums to the vibrations generated by large deployable solar arrays based on thin polymide films. At best, considering a nanosatellite platform provided with 3-axis attitude control and damping system, the residual vibrational environment of the bus in LEO is characterized by a few milliradians amplitude oscillations at low frequency (<5 Hz).

In summary, in the near future the capabilities of nanosatellites are expected to increase significantly as power generation and propulsion are concerned; in addition, recent advancements in laser technology will enable the realization of miniaturized optical terminals for telecommunications. However, both the state of the art of ADCS and the expected advancements in this area seem insufficient to meet the attitude stability requirements needed for a steerable laser communication terminal.

IV. CONCLUSIONS AND FUTURE WORK

The exploitation of LEO constellations based on nanosatellites for telecommunication scenarios is attractive for the benefits derived from the low mass, production time and overall cost of such miniature platforms. However, the exploitation of nanosatellites for complex missions is still prevented by their current severe resources limitations. In this paper, optical communication has been identified as a viable solution to increase significantly the communication data rate available to payloads onboard nanosatellites. The technological aspects which play a key role in the realization of new mission scenarios have been discussed considering the current state of the art of nanosatellite technologies and their perspective advancements in the near future. Considering the actual limitations of ADCS of nanosatellites, the laser terminal pointing accuracy and stability have been identified as the most critical issues which must be addressed to enable the exploitation of optical telecom terminals onboard nanosatellite platforms.

In this framework, the exploitation of a miniaturized, actively stabilized platform as an interface between the optical terminal and the host spacecraft is the chosen solution to cope with the current nanosats ACDS limitations. The active rejection of both low and high frequency vibrations from the bus to the laser terminal and viceversa not only will enable the exploitation of optical links on miniature satellites, but it will also allow to relax the requirements on both the ADCS of the host spacecraft and the pointing mechanism of the optical terminal. The authors are currently developing an integrated system composed by a miniaturized laser communication terminal and an actively controlled ultra-stable parallel platform with 3 rotational dof (shown in Fig. 2). This system is conceived to be mounted on top of a nanosatellite bus with 3-axis attitude control based on standard technologies (3 reaction wheels and 3 torquerods), but provided with sufficient power generation capabilities to sustain the optical communication terminal. The system performance will be evaluated though laboratory test using an attitude simulator testbed.

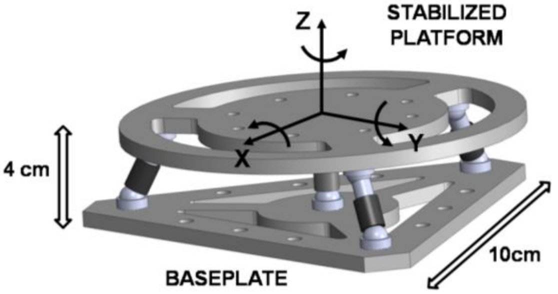

Figure 2. Preliminary configuration of the actively-stabilized platform.

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