FEDERATED SYSTEMS OF PICO-SATELLITES
FOR
FUTURE SPACE-BASED SERVICE INFRASTRUCTURES

Raycho Raychev, Alexander Kolev
Endurosat, Sophia, Bulgaria
E-mail: raycho@endurosat.com

Marco Lisi
ESA-ESTEC, Noordwijk, The Netherlands
E-mail: marco.lisi@esa.int

I. INTRODUCTION

Both satellite manufacturers and satellite operators are presently facing the challenge of emerging trends, going
in the direction of more open, flexible, responsive and cost-effective space missions.

There is an increasing demand in the space community for systems more sustainable, cost effective, robust and
reliable. As a matter of fact, the general approach to space is moving from single satellite missions, mainly
focused on technology and on the achievement of “ad hoc” objectives, to systems or systems of systems,
actually realizing space-based infrastructures, focused on the delivery of capabilities and services.

In synthesis, we are witnessing the advent of what the Director General of ESA, Prof. Woerner, has defined as
the “Space 4.0” era, in which space has become a day-to-day business and in which interaction with society,
the commercialization of space, new roles for industry and new cooperative relations with public institutions play
important roles.

To achieve the goal of an effective service-oriented, space-based infrastructure a radical (mostly conceptual)
paradigm shift is needed: from a technology/mission focused approach to a service approach.

We need in other words to start from the end, asking ourselves the following questions:
- What capabilities do the users need?
- How can we make an effective use of existing resources, on ground and on orbit?
- How can we plan for future more flexible and interoperable space infrastructures?

As far as the space segment is concerned, in order to achieve the goal of a truly interoperable, service-oriented
space infrastructure, potential benefits are expected from the introduction of micro, nano and pico-satellites
(Cubesats) in swarm or federated/fractionated system configurations.

The paper explores the potentialities of pico-satellites in “Space 4.0”, with particular focus on their applications
in infrastructures supporting the ESA promoted “Moon Village” international project.

II. HISTORICAL EVOLUTION FROM SINGLE-SATELLITE SYSTEMS TO DISTRIBUTED AND
FEDERATED SATELLITE SYSTEMS
From an historical viewpoint, satellite systems developed first as single-satellite, single-mission systems. Typical examples of this type of systems were, and still are, the geostationary satellites for telecommunications. Single-satellite systems then evolved becoming multi-mission (e.g.: trunk communications, mobile communications and television broadcasting), growing in size, mass, power capability and complexity. Constellations of satellites in Low Earth Orbit (LEO) also developed early, mainly for Earth observation and surveillance purposes. The first satellite systems achieving their mission objectives through the concurrent use of all satellites in a constellation were the NAVSTAR GPS (in the late 70’s, early 80’s) and, in the 90’s, the two LEO constellations for personal mobile communications, Globalstar and Iridium. In the Iridium satellite system, inter-satellite links (ISL’s) started also playing a determinant role. Navigation and telecommunications constellation systems opened the way to the concept of distributed satellite systems, that is, systems where a constellation of small to medium sized satellites replace larger spacecraft, also realizing mission objectives otherwise unachievable with monolithic, single satellite approaches [1].

A general trend, being developing in the last twenty years, is towards the emergence “network-centric” satellite systems or “systems of systems”, that is large and complex systems able to convey data seamlessly throughout a number of different possible media and to deliver useful information after a data fusion process. In this “network-centric” scenario, satellites play a key role as ideal means to observe, gather and transmit information. In Europe, good examples of such large and complex satellite systems are the European Copernicus Earth observation and surveillance system and the Galileo global navigation satellite system, both aiming in perspective to being interoperable with similar world-wide systems and to merge eventually in “systems of systems” in their respective field of applications [2].

A more recent and novel approach, also posing challenging requirements in terms of interoperability and concurrency, is that of “federated satellite systems” (FSS’s) [3]. The FSS paradigm is based on satellites belonging to different missions, which are offering on a peer-to-peer basis some of their capabilities (e.g.: sensors, feeder link throughput, on-board memory, etc.). The obvious assumption is that such satellites must be able to exchange information through inter-satellite links, coping with heterogeneous waveforms, protocols and standards.

III. RECONFIGURABILITY, FLEXIBILITY AND RESPONSIVENESS IN SPACE APPLICATIONS

The need for reconfigurable payloads arose in order to catch the evolving requirements of a very unpredictable market over a satellite lifetime. But the evolution of the mission requirements is not the only reason for aiming at flexibility: another very serious problem is that of technological obsolescence, made ever more evident by the advent of digital communications.

One evident characteristic of digital communications is the continuous evolution of air interfaces (i.e. encompassing from physical layer to higher OSI layers’ protocols and formats). What on ground can be at worst the cause of an expensive upgrading of the software and possibly of the physical components of a network, in satellite systems, unless based on transparent payloads, can translate in a much cruder reality: obsolescence. Satellites are nowadays designed and built with a fifteen years on-orbit expected lifetime. As a matter of fact, fifteen years correspond to several generations of software and hardware evolution. Let us think of our PC, its peripherals and its software: nothing that we used fifteen years ago could today be easily operated and even data files could be difficult to retrieve if stored on no longer utilized physical supports. The answer to the obsolescence problem could then be twofold: (relatively) simple payloads or flexible payloads.

The need for flexibility, however, originates from many other circumstances, also characterizing the satellite communications market. Satellite operators are today more concerned about capital investment, flexibility and reliability rather than about technological advancement. The concerns of space insurance companies about the reliability of newly designed components and fancy technologies further enforce this trend. In-orbit flexibility is required to adapt to evolving business conditions, as seen before, or to crisis situations; reconfigurable payloads would also allow the elimination of dedicated in-orbit spare satellites. Customer needs are oriented toward higher EIRP’s, broader bandwidths, reconfigurable coverage areas, higher reliability, and flexibility to adapt to evolving digital standards. The challenge is achieving improved payload flexibility and performance without dramatically increasing complexity and cost. On the other hand, satellite manufacturers expect substantial benefits from the adoption of modular, “general-purpose” payloads, mainly in terms of development schedule and non-recurring cost reduction.

The original concepts of reconfigurability and flexibility have been evolving and merging into a more general one: that of responsiveness. Responsiveness in satellite communications payloads can be defined as the ability
to react to various forms of uncertainty, ranging from geopolitical operational requirements to technological obsolescence to technical failures.

The responsiveness requirement could lead to a revolution in the design of satellite payloads. Rather than focusing, as it happened so far, on technical requirements, developing highly customized (and costly) solutions, architectures encompassing built-in reconfigurability and flexibility features could be adopted.

Another possible and potentially effective answer to the responsiveness requirement can be that of swarm or federated constellations of small or very small satellites, sharing some key resources (e.g. primary power, onboard mass memory, down and up-link communication capabilities).

IV. SWARMS AND CONSTELLATIONS OF FEDERATED PICO-SATELLITES (CUBESATS)

CubeSats paved the way for a new approach of exploiting LEO orbit. The restriction of finite minimalistic dimensions for the satellite bus (as small as 1 or 1.5 cubic liter), drove new wave of innovation to space engineering. Using off-the-shelf components and non-space-graded elements, made the CubeSat significantly more affordable and easier to build than the bigger spacecraft systems. Yet, the small dimensions limit the science, technologic and business applications of a single CubeSat in comparison with a small sat system. This let to multi-CubeSat missions where the single functionality of a bigger satellite is distributed between several CubeSats, compensating performance by numbers. [5]

In order to leverage the advantage of a swarm and/or constellations of CubeSat configuration in LEO there are strict requirements and technical challenges that must be considered. LEO spaceflights are limited by orbital decay, by power and by coverage. Most CubeSat spacecraft do not carry their own propulsion subsystem and this limits further their mission duration and flexibility. In concrete cases different missions are flying in similar orbits and create a risk of collisions and interference. Each spacecraft bus has to carry complex systems onboard (EPS, OBC, communication modules, battery pack sufficient for powering the entire spacecraft, payload, including all different connectors, antennas for transmission to the ground station) and normally has no capability of communicating directly with other satellites. The CubeSat size limitations complicate the utilization of payload space and limit its capabilities for high performance in orbit.

This is the reason for launching multiple CubeSats with a single mission in order to optimize their performance. Constellation or swarm of spacecraft (especially CubeSats) provides an opportunity to design single infrastructure combining all spacecraft capabilities in the process, each with unique characteristics and each complementing the overall functionality of the entire infrastructure.

Currently all CubeSat constellations are composed of single design spacecraft. This means that they all have the same hardware and software onboard and they do not function as a federated satellite system, optimizing the overall performance of the entire infrastructure [6].

The same is valid for bigger spacecraft in LEO. Most satellite missions today are designed as standalone systems, lacking any awareness of other spacecraft flying/passing relatively near-by in orbit. Designing and establishing a network of interconnected satellites, covering diverse orbits, could in principle significantly increase their combined performance as a federated space infrastructure.

In a space scenario where responsiveness is needed, e.g. that of a detected potential disaster event, the satellite will not have to wait for a predefined pass over a ground station in order to send the data back to Earth. It can retransmit it immediately, using the closest satellites available at a certain time. This will be only possible if most satellites have interconnecting capability and defined protocols for inter-satellite communications according to agreed standards and regulations.

V. A REMOTE SENSING CUBESAT FEDERATED MISSION

A Remote Sensing mission based on a constellation of federated CubeSats was considered. The constellation will be composed of three completely different CubeSats, complementing each other’s capabilities by been constantly interconnected.

One of the CubeSats (“Flying Camera 1”) will carry vital electronics for Remote Sensing (camera in IR or near-IR) plus the control subsystem dedicated to guiding the camera toward a selected area on the ground and a WiFi client.

The second CubeSat (“Flying camera 2”) will carry vital electronics for Remote Sensing (camera in visible spectrum) plus control subsystem dedicated to guiding the camera toward a selected area on the ground and a WiFi client.
The third CubeSat will function as a “Flying server” with a WiFi router and transmission system capable to receive data from the other two “Flying-camera” spacecraft, process it and send it through a high-speed communications link to a ground station (or to a GEO satellite for re-transmission). This mission scenario is in fact a complete space-based federated infrastructure. The idea is that of optimizing communications techniques and protocols and then scale-up the approach to larger satellites.

VI. COMMUNICATIONS AND NAVIGATION INFRASTRUCTURES FOR THE “MOON VILLAGE”

The exploration of Moon and Mars with human and robotic missions and their colonization, through the establishment of permanent bases, will require planetary communications and navigation infrastructures.

All architectural approaches considered so far by NASA and ESA can be divided into two main categories:
- comprehensive, well-structured and forward looking (but costly) architectures, based on constellations of orbiters and relay satellites;
- “ad hoc”, flexible, expandable architectures, based on a fusion of all available resources and on COTS technologies.

As far as positioning and navigation are concerned, the first obvious question is: can we use GNSS (GPS) beyond Earth Orbit and on the Moon?

Detailed analyses show that GNSS (GPS) signals are effective up to the Earth-Moon 1st Lagrange Point (L1), that is 322,000 km from Earth and approximately 4/5 the distance to the Moon. As a matter of fact, GPS signals can be tracked to the surface of the Moon, but they are usable only with the adoption of advanced GPS receiver technology (fig. 1).

![Diagram of GPS signals reaching the Moon](image)

The AEGIS NASA study on Moon and Mars communications and navigation constellations was aiming at the following objectives:
- to provide a flexible communications and navigation infrastructure supporting human and robotic missions to the Moon and Mars;
- to provide navigational support to mission elements with a minimum 100 m resolution;
- to provide communication between mission elements and mission operations with availability of 95%;
- to use existing technology to reduce cost;
- to be based on small, highly manufacturable satellites reducing cost and engineering time.

The AEGIS lunar constellation design was eventually based on two Relays in high polar orbit at 10,000 km, spaced at 180°, and on a total of 18 Orbiters, equally distributed (six per plane) over three orbital planes at 4,800 km, spaced evenly at 60°. This configuration can be shown to offer a complete lunar coverage with four satellites in view (fig. 2).
The results of the ESA study about “Weak GNSS Signals Navigation on the Moon” (by the Portuguese company Deimos) would also suggest (fig. 3) a Moon-GNSS architecture based on:

- EGNSS: Earth GNSS constellations (GPS/Galileo);
- MGNSS: GNSS satellite orbiting around the Moon;
- MSB: Moon Surface Beacon.

VII. FEDERATED SPACE SYSTEMS OF CUBESATS FOR MOON EXPLORATION

CubeSat systems can be used for space exploration missions. Moon exploration and utilization is a major milestone for the European space program (“Moon Village” project) and federated constellation can provide necessary support for the infrastructure on the surface.

Federated CubeSat systems in Moon’s orbit will enable diverse applications. Programs for Moon observation using CubeSats such as Lunah-Map are already planned [8] but most missions are designed not to have inter-satellite connection capabilities.

The CubeSat platform provides opportunity for establishing a redundant federated system in Moon’s orbit. CubeSats can be launched as a constellation, providing navigation, communication and observation capabilities for all lunar surface infrastructure and vehicles. Using mainly COTS elements and benefiting from the miniaturization of atomic clocks, a CubeSat Lunar Positioning System (LPS) can be established. A hybrid federated system of multiple CubeSats and two polar small satellites (“Master satellites”) will enable an efficient navigation service on the Moon as well as constant communications with the Earth. The CubeSats will have the capability to communicate with each other using standardized protocols, providing opportunity for every lunar orbital mission to utilize the existing infrastructure for communications between spacecraft in Moon’s orbit and for communications with Earth.

The lunar CubeSats will be used for direct downlink/uplink of data to and from the lunar surface, as well as for re-transmission/relay of data to/from the Master satellites. These latter will have the capability to communicate directly with Earth.

Establishing standards for inter-sat communication in lunar orbit and designing federated satellite system for lunar exploration and utilization will create opportunity for permanent human settlement on the Moon’s surface. It will also create redundancy in exploration mission design and operations.

VIII. CONCLUSION
Constellations of federated pico-satellites (CubeSats) can be an affordable and effective solution to many mission scenarios. Moreover, such constellations can be the test bench for experimenting design and operational solutions, to be then scaled-up into more ambitious and capable satellite systems. The use of constellations of federated CubeSats is also considered promising in establishing affordable and sustainable infrastructures to support planetary explorations (e.g. the Moon Village). The final paper will address all topics with more details, also presenting the results of the main design trade-off’s performed.

REFERENCES