 Perspectives of development of satellite constellations for EO and connectivity

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- Interest in LEO constellations arouse in recent years due to the increase in data rate and data volume of LEO spacecraft.

<table>
<thead>
<tr>
<th>Current VHR systems</th>
<th>Rardarsat</th>
<th>CSK</th>
<th>Sentinel 1</th>
<th>Pleiades</th>
<th>GeoEye 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payload</td>
<td>SAR</td>
<td>SAR</td>
<td>SAR</td>
<td>OPTICAL</td>
<td>OPTICAL</td>
</tr>
<tr>
<td>Payload Data Rate (Mbps)</td>
<td>400</td>
<td>600</td>
<td>1280</td>
<td>1500</td>
<td></td>
</tr>
<tr>
<td>Mass Memory Capacity (Gbit)</td>
<td>300</td>
<td>1200</td>
<td>1400</td>
<td>600</td>
<td>1000</td>
</tr>
<tr>
<td>Data Rate (Mbps)</td>
<td>2x105</td>
<td>2x155</td>
<td>2x250</td>
<td>3x155</td>
<td>740</td>
</tr>
<tr>
<td>EIRP (dBW)</td>
<td>24</td>
<td>24</td>
<td>20</td>
<td>24</td>
<td>24</td>
</tr>
</tbody>
</table>

- For instance, the Sentinel-1 Earth Observation (EO) mission launched in 2014 produces 1.3 Tb/day of data, compared to the 0.3 Tb/d of its predecessor Envisat.
• Another point of interest is the reduction of latency times for EO missions due to the ground station visibility windows.

- Medium latitude Ground Stations have 4-5 useful passes a day to communicate to SSO Satellites
- (External) Polar Stations may be used to increase number of useful passes,
- Limitations: only 10 minutes visibility over 90 minutes orbital period → High data rate

- Max Link Availability (Single polar GS)
  - Visibility
  - No Visibility
  - 10 min
  - 80 min

• EO missions can be enabled to promptly acquire images from an area of interest without the delays typical of a Ground Station direct communication.

• The infrastructure in fact can, in a “System of Systems” logic, allow instant programming and data transfer, finding the appropriate path to the EO spacecraft (via the appropriate EOSS nodes) wherever it is located around the earth.

• Programming and downlink delays are therefore removed, and the only delay remaining is due to the time needed for the EO spacecraft to move towards its acquisition target.
EOSS

LOW EARTH ORBIT COMMERCIAL SATELLITE DATA RELAY SYSTEMS

Developed in cooperation with:

Prof. Alessandro Golkar
Skolkovo Institute of Science and Technology
Introduction

- **Classic mode path**: paysat(1)-service_ground_station(5)-finaluser(6)
- **Enhanced normal mode path**: paysat(1)-EOSSsat(2)-EOSSsat(3)-EOSSground(4)-service_ground_station(5)-finaluser(6)

**Concept of Operations**

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**Classic Mode**

**EOSS Mode**

**Terrestrial Path**

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**P/L DATA**

- Telecommands
- Telemetries
An integrated approach has been developed to characterize the trade space of EOSS constellations for commercial data relay services. An overview of such approach is presented in the figure below:
> FORMULATION

By the proposed analytic process, architectures of interest are identified and characterized as a set of major decisions, providing alternatives to decision-makers for subsequent choice of which design points carry through more detailed design.

The table below shows the architectural design matrix considered for EOSS:

<table>
<thead>
<tr>
<th>Architectural decisions</th>
<th>Decision alternatives</th>
</tr>
</thead>
<tbody>
<tr>
<td>EOSS Altitude</td>
<td>700 km</td>
</tr>
<tr>
<td></td>
<td>800 km</td>
</tr>
<tr>
<td></td>
<td>900 km</td>
</tr>
<tr>
<td>Number of satellites per plane</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>14</td>
</tr>
<tr>
<td>Number of orbital planes</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>6</td>
</tr>
<tr>
<td>EOSS antenna gain</td>
<td>44 dB</td>
</tr>
<tr>
<td></td>
<td>50 dB</td>
</tr>
<tr>
<td></td>
<td>56 dB</td>
</tr>
<tr>
<td>Storage capacity per EOSS node</td>
<td>32 Gbit</td>
</tr>
<tr>
<td></td>
<td>256 Gbit</td>
</tr>
<tr>
<td></td>
<td>512 Gbit</td>
</tr>
</tbody>
</table>
The aim of the Pareto analysis is to identify, in the variation of the architectural variables (i.e. the enumeration of all the possible architectural combinations), the best trade-offs achievable between two or more different metrics of choice.

This is done by using the **Pareto non-dominance principle**:

> Given the set of all the solutions (multi-metrics values), i.e. the so-called (multi-dimensional) tradespace, an architectural configuration is optimal when it lies on the so-called Pareto-front. In fact a **Pareto-front** is the set of points (solutions) for which no solution exists which can outperform, w.r.t. each of the metrics considered, those in such set.
System architects can use this plot to choose Pareto efficient EOSS architectures at different levels of lifecycle cost. It is interesting to notice the three different regions of the Pareto front:
In the first region, small increases in cost lead to significant increases in available data volume (Region 1). This is a region of the tradespace offering low cost architectures, which however could be significantly improved by modest increases in budget available.

In the second region, increases in cost are commensurate to increases in data volume (Region 2). This region includes architectures that represent best compromises in the tradespace, in the sense of offering adequate performance for the associate total cost.

In the third region, small increases in data volume correspond to large increases in cost (Region 3). This last region offers architectures that are high performing, albeit carry a significant cost burden required to achieve that marginal increase in performance compared with best compromise solutions that are included in Region 2.

The analysis of Pareto fronts offers the opportunity to identify and compare different EOSS architectures for different assumptions on number of customers to be served and on average data rate capacity supported by the infrastructure.
Constellation intended to assist client satellites in CPU-intensive tasks
• Purpose of the study is to introduce an innovative way of supporting Low Earth Orbit satellites - in particular Earth Observation missions - by deploying a LEO infrastructure made up of high-performing computational nodes which can assist clients in their most demanding computational needs.

• In particular, this work investigates the viability of such a solution, proposing, for specific categories of missions, an approach to reduce the use of some onboard resources and to save on satellite system’s costs by offloading computationally-intensive tasks from the onboard systems, while still optimizing the exchange of data through the radio link.

• Optimization of the computational workload is performed by taking into account the minimization of radio link utilization, of power consumption, of on-board memory usage, and of wait-time for the availability of the final data that result from the overall processing.

• The proposed method relies on the application of the Pareto-downselection principle to a tradespace of architectural configurations, in order to identify optimal solutions worth being further investigated.
Categories of mission that could benefit most from the use of such infrastructure:

- Missions concerning Earth Observation, which typically deal with huge volumes of data and challenging computational needs, would be the target application that benefits most from such a processing scheme.

- Also, the application of this principle could be especially useful in satellite missions that normally perform low-demanding computational tasks and only occasionally require intensive data processing.
• Timeliness and efficiency are fundamental aspects when dealing with earth observation missions, in which critical tasks are often involved.

• In the vast majority of cases, satellite's onboard computational capabilities do not allow these operations to be performed locally and, above all, do not allow them to be completed within acceptable times.

• Nonetheless performing these tasks on board might be desirable in a number of specific situations, for example in all the cases where it would be advantageous that an autonomous decision is taken on board in order to avoid the delays intrinsic to LEO missions response times.
The following two examples will help to shed light on the convenience in taking autonomous decisions and, consequently, on the need for onboard image processing (or space segment confined image processing):

EXAMPLE #1:

The onboard evaluation of the portions of an image -acquired in the visible wavelength spectrum- that result covered by cloud formations would allow an efficient transmission to the ground facilities only of the portions of the image not affected by clouds, with consequent savings on the sides of ground access times (in particular w.r.t. narrow visibility time-windows), radiofrequency spectrum occupation, and onboard energy consumption.
EXAMPLE #2:

In a crisis management situation it could be desirable that the space segment of the mission can take autonomous decisions on programming the spacecraft for its image acquisition during the next passes over the area of interest.

For example, when a fire on the ground is detected through an image acquisition, the programming of the same or another satellite for the acquisition of a subsequent high resolution image during its next pass over the fire area would face a series of delays:

1) delay in the transfer to the ground of the first detection image,
2) delay for the time needed in order to process image for detection and for operators to identify the most suitable satellite passing over the fire area,
3) delay for the reception by such satellite of the appropriate telecommand,
4) delay for the time needed for its next useful pass over the area
5) delay consisting in the time elapsing before it reaches an available ground station for the final transmission of the high resolution image to the crisis management center.

Moreover this process could need to be iterated multiple times, multiplying this series of delays.
The table below shows the architectural design matrix considered:

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<td>700 km</td>
</tr>
<tr>
<td>Number of satellites per plane</td>
<td>8</td>
</tr>
<tr>
<td>Number of orbital planes</td>
<td>3</td>
</tr>
<tr>
<td>Number of CPUs per node</td>
<td>5</td>
</tr>
</tbody>
</table>
HYBRID POLAR/NON-POLAR NETWORKED OPTICAL CONSTELLATION FOR PROMPT EARTH IMAGERY ACQUISITION
• Increasing demand for Earth Imaging services, especially those for which timeliness and ground resolution are driving requirements, pushes the need for new paradigms in space systems and for new architectural concepts that could improve performances on both sides.

• Purpose of the study is to investigate the benefits that can derive from the integration of the capabilities of a mesh-network constellation (whose main benefits consist in providing distributed on-board data processing capabilities, shared memory capacities, and a permanent connection with the ground facilities), with those of an optical EO constellation (that allows reduced access times to the desired target w.r.t. single-satellite EO missions) and to introduce a specific methodology used to develop this hybrid concept.
**Polar Subset of Optical Satellites**

**NON-Polar** Subset of Optical Satellites

**OPTION #1**: 60 degrees inclination

**OPTION #2**: 45 degrees inclination

**OPTION #3**: 30 degrees inclination

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All Satellites in Polar Subset are permanently connected:
- each other
- with polar ground station

**Inter-Plane Satellite link**
> FORMULATION

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</tr>
</thead>
<tbody>
<tr>
<td>Altitude (km)</td>
<td>700 km</td>
</tr>
<tr>
<td>Number of POLAR satellites</td>
<td>8</td>
</tr>
<tr>
<td>Number of NON-POLAR satellites</td>
<td>1</td>
</tr>
<tr>
<td>Non-polar plane inclination</td>
<td>30°</td>
</tr>
<tr>
<td>EIRP (Watt)</td>
<td>3000 W</td>
</tr>
<tr>
<td>On-Board Memory Modules</td>
<td>1</td>
</tr>
</tbody>
</table>

- Spacecraft are equally spaced within their orbital plane of reference.
Pareto efficient architectures can be found on the highlighted front:

Image target area: 45° North

How to read labels (example)
Progressive deployment of a LEO constellation providing support services to LEO client satellites
• Scalability is a key feature in systems and networks designs whenever it is advisable to enable the system or network to handle a growing amount of workload by gradually enlarging its size and capabilities.

• Some examples of cases in which scalability has been a peculiar factor in the build-up process of an infrastructure include the expansion of coverage of cellular networks, which have naturally grown from large cities, to major transport routes and, subsequently, gradually reached areas with a lower density of population.

• In the same way transportation networks, have had in most cases a spontaneous unplanned development, progressively serving areas in which new needs had originated.
This study proposes a methodology to explore and evaluate a number of possible deployment strategies alternatives -and the associated architectural designs- for a LEO infrastructures meant to assist client satellites in communication and computational needs.

The study presents a progressive deployment strategy in which the system capacity is increased gradually.

The proposed method considers different architectural options (such as the number of orbital planes and the number of satellites per plane) and makes use of a multi-objective optimization approach.

A life-cycle simulation model has been specifically developed to provide a realistic assessment of system behavior.
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</thead>
<tbody>
<tr>
<td><strong>Altitude</strong></td>
<td>800 km</td>
</tr>
<tr>
<td>Deployment Strategy for the number of orbital planes</td>
<td>1 → 1 → 4</td>
</tr>
<tr>
<td>Deployment Strategy for the number of satellites per plane</td>
<td>4 → 4 → 12</td>
</tr>
</tbody>
</table>

**Note:** in the \([X \rightarrow Y \rightarrow z]\) sequence, **X** is the value for Phase 1 (year 0), **Y** is the value for Phase 2 (year 3), **Z** is the value for Phase 3 (year 6). **Z** represents the final value and is the same in all strategies since it is referred to a fully deployed constellation in the final intended configuration. This rule applies to both orbital planes strategy and number of satellites per plane strategy.

**EXAMPLE:** \([4 \rightarrow 8 \rightarrow 12]\) in last line, second column of the table above means:
- 4 satellites per plane deployed at year 0,
- 8 satellites per plane deployed at year 3,
- 12 satellites per plane deployed at year 6.
• The proposed methodology has been applied to an evolving scenario in which clients gradually grow from 20 to 100.

• Customers have been drawn among missions that are already operational and in-orbit.

• An example of a particular architectural configuration and deployment strategy is shown in the picture below (architectural ID [223]):
This work illustrated a systems architecture methodology to explore the tradespace of an infrastructure consisting in a constellation of LEO satellites.

Traditional approaches in the design of such infrastructures are often focused on the design of the single spacecraft rather than on the architectural vision of the whole infrastructure, underestimating the importance of the existing relation between the system architectural configuration and its functional aspects.

The choice of the platform and the payload should be the consequence of an optimization process which starts from the study of the best orbital configuration for the infrastructure nodes to provide a particular service, and not the starting point determined by reuse and recurrency criteria or by the given technological possibilities offered by a pre-existing particular industrial process.
In other words, the spacecraft design should be the result of a selection and optimization process which descends from a systemic vision, and not the driving criteria which forces some of the decisions on the overall system configuration.

The need for a more systemic vision, more focused on the architectural aspects of the infrastructure, and not mainly on the design of the platform and the payload, naturally leads to the use of optimization methods for the overall design of the infrastructure intended as a System of Systems.

We have shown with a number of different examples how the specific peculiarities of each considered application can be taken into account for the customization of the proposed general preliminary-design model.
Perspectives of development of satellite constellations for EO and connectivity

END OF PRESENTATION