IS SPACE READY FOR THE QUANTUM LEAP?

QUANTUM @ THALES ALENIA SPACE

TOMMASO CATUOGNO
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PART 1:
THALES ALENIA SPACE & THE SPACE SECTOR
THALES ALENA SPACE – COMPANY OVERVIEW

/// Thales Alenia Space delivers cost-effective solutions for telecommunications, navigation, Earth observation, environmental management, exploration, science and orbital infrastructures.

THALES (67%)
LEONARDO (33%)

8,000 EMPLOYEES
2,15 BN € SALES
Thales Alenia Space teams up with Telespazio to offer a unique combination of expertise covering the entire value chain

System & Services
FROM EARTH TO DEEP SPACE…
/// Competencies

- Satellite assembly integration testing
- Space systems design
- Earth observation radar
- Navigation
- Telecoms Defence Satellites
- Antennas
- Equipment

4000 sqm

clean rooms
DONI MISSION

DESIGN, MANUFACTURE AND SUPPLY END-TO-END SYSTEM FOR

SATELLITE OBSERVATION & NAVIGATION SOLUTIONS

FROM EQUIPMENT TO END-TO-END SYSTEM

COSMO-SkyMed
Copernicus
Galileo
EOS20
DONI Product Lines

Radar & EO MW systems and constellation

EO Radar
4 products covering almost all EO applications, from very high resolution (HP-R, HE-R) to high revisit acquisition scenarios (constellation HE-R, HR-R).

PDHT
State of art Payload Data Handling & Transmission solutions to enable high data volume/rate provision.

Microsatellites & Constellations
- Micro constellation solutions
- NiMBUS / PLATINO multi-mission platform, to be used also for HR-R.

DONI Space Segments
- PRISMA platform product family solutions & optical satellites

Ground Systems & E2E Solutions
Ground solutions encompassing product concept to enforce “bundle” concepts capabilities and small sat constellations management. Using Big data and deep learning technologies, with cybersecurity solutions.

Navigation systems, payloads, satellites & Aerocom

Navigation Users Solutions
- Spaceborne and Ground navigation Solutions for specific user contexts (Space, SoL railway solutions, synchronets, navigation assisted solutions, Space & ground receivers)

Navigation & Aerocom Systems Solutions
The Galileo Space Segment will comprise a constellation of a total of 30 Medium Earth Orbit (MEO) satellites, in a so-called Walker 24/3/1 constellation. The Galileo satellite constellation has been optimized to the following nominal constellation specifications:

- Circular orbits (satellite altitude of 23 222 km)
- Orbital inclination of 56°
- Three equally spaced orbital planes
- Eight operational satellites, equally spaced in each plane
- Constellation geometry repetition period of 10 sideral days (corresponding to 17 orbital revolutions)

**IOV Phase**

**4 satellites In-Orbit**

- **Mass at Launch**: 700kg
- **Power Consumption**: 1420W
- **Dimensions**: 2.7 x 1.6 x 14.5 m
- **Orbit Injection**: Direct into MEO orbit
- **Attitude Profile**: Yaw Steered

**FOC Phase**

**24 satellites In-Orbit**

- **Mass at Launch**: 733kg
- **Power Consumption**: 1900 W
- **Dimensions**: 2.5 x 1.1 x 14.7 m
- **Orbit Injection**: Direct into MEO orbit
- **Attitude Profile**: Yaw Steered
NAVIGATION SATELLITES – GALILEO SECOND GENERATION

/// On-board Galileo 2\textsuperscript{nd} Generation to boost performance and cybersecurity for the constellation

- Inter-satellite links
- Digitally configurable Antennas
- Full electric propulsion systems
- First satellites in orbit by 2024
NAVIGATION SATELLITES – LUNAR NAVIGATION

Thales Alenia Space Has Been Selected By The European Space Agency To Study Specific Technical Aspects For A Future Lunar Radio Navigation System

- Real-time On-Board Navigation
- Earth Sciences
- Launch Vehicle Range Ops
- Attitude Determination
- Time Synchronization

R&D – Autonomous Orbit Determination With Crater Matching
SPACE TO OBSERVE & PROTECT

CHIME
CIMR
CRISTAL
ROSE-L
CO2M
LSTM

SENTINEL -1
SENTINEL-2
SENTINEL-3
SENTINEL-4
SENTINEL-5
SENTINEL-6

LAND MONITORING
EMERGENCY MANAGEMENT
MARINE MONITORING
ATMOSPHERE MONITORING
CLIMATE CHANGE
SECURITY
THE ITALIAN CHAMPION IN EO (1/2): COSMO-SKYMED

The **COSMO-SkyMed** (Constellation of small Satellites for the Mediterranean basin Observation) Series consists of two generations of Synthetic Aperture Radar (SAR) satellites with the overall objective of providing frequent all-weather Earth observation, which can be applied to defence and civil needs.

- 4 satellites High resolution, X-Band,
- > 2 x 650 km on ground access capability
- Global Earth access (including polar caps) with all weather / night-daylight sensing capability
- **Conceived for dual use**: performance, accessibility, operational capability and security.
THE ITALIAN CHAMPION IN EO (2/2): COSMO-SKYMED & COSMO SG

COSMO-SkyMed Second Generation (CSG) consists of two enhanced SAR satellites. It provides Polarimetric SAR.

/// 2 satellites, Last launch on Jan 2022.
Focus ON

/// Artificial Intelligence
/// Quantum Technologies
/// Cyber Security
/// Virtual Reality, Augmented R., Mixed R.
/// GNSS-Reflectometry
/// Digital Twin
OUR INTERESTS IN HPC APPLICATIONS

/// Ground Applications
/// Payload Data processing (oil spill detection, Vessel Detection, …)
/// Mission Planning Optimization & Acquisition Scheduling
/// Mission Analysis Optimization and Complex Orbital/Trajectory Simulation
/// Critical Failure Prediction
/// …

/// On-board applications
/// Sub-system Failure detection and reaction
/// Processing of SAR Raw data (on-board focusing)
/// Cognitive radar (automatic detection of targets)
/// Data compression
/// Automated collision avoidance
/// Security (anti-jamming, chiphering, …)
/// Formation flying satellites
/// Precise spacecraft attitude determination
THE PROBLEM OF ON-BOARD COMPUTING

On-board payload data processing encompasses the data acquisition, transfer, storage, data compression or reduction and transmission to ground of instrument and sensor data. Quite often the amount of raw data generated by modern instruments is in excess of what can be transmitted to ground.

The issue for the space industry is that it is not possible to reuse in a straightforward way the hardware platforms of terrestrial applications, given the specific constraints of satellite data systems especially in terms of radiation.

Ground Segment

- The Training stage defines the weights of each connection:
  - Massive dataset
  - High computational efforts

Space Segment

- The Inference stage uses only NN architecture with weights:
  - Real time analysis
  - Low computational efforts

Strong Interest of TAS in testing novel computing paradigms to:
- Increase Computational efficiency
- Reduce Power Consumption

Interest in photonic and quantum computing platforms
TREND ON DISTRIBUTED COMPUTING ON-BOARD SATELLITE

- Multisensor Satellites
- ISS offloading of big data calculations
- Link to OGS
- Link to GS
PART 2:
QUANTUM TECHNOLOGIES FOR SPACE
DONI’S INTEREST IN QUANTUM TECHNOLOGIES

Empower Computing

Goal:
Enable New previously impossible applications enabled by Quantum Computing exploiting quantum systems’ properties (superposition, entanglement)

Enable New Sensing

Goal:
Exploiting quantum systems to measure a physical quantity (classical or quantum)
- Increase Sensitivity, resolution and quality of the measurements
- Overcome classical Measurement limits

High Performance/Secure Communications

Goal:
Exploiting quantum systems to develop new ways for encoding and transmitting information over long distances
- Upgrade existing critical communication infrastructures to prevent quantum attacks
- Exploit Distribution of Entangled state to implement protocol for new features

- Identify advantages and drawbacks compared to classical solutions
- Space application sustainability (costs, operational and environmental)
- Identify expected time frame for use in IoD / Commercial missions
- Define a technology roadmap for space missions
- Develop, at short term, solid demonstrator to show capability and space use feasibility

Common Objectives for all topics of interest
DONI APPLICATIONS OF QUANTUM TECH

TASI is putting in place a long term research and development programme on quantum technologies applied to space. In this frame, Domain Observation and Navigation Italy (DONI) sees potential Technologies in the three branches of QT:

/// QUANTUM SENSING
- Explore Performance, limitations and applicability for Quantum Navigation systems based on Quantum Accelerometer, Gyroscopes, Gravimeters, proposing novel schemes and implementing prototypes where possible
- Quantum Illuminations techniques analysis, including FSO feasibility and performance analysis with Channel Impairments simulations and device prototyping
- RF Signal Generation and Manipulation via Integrated photonic circuits

/// QUANTUM COMPUTING
- Quantum computation architecture and processing models case studies targeting on-board satellite QC. (LOQC, Boson Sampling, Superconductive,...)
- Identify and Engineer Quantum Algorithms assuming NISQ computational capability, impacting the Satellite Communication/Navigation/Observation

/// QUANTUM COMMUNICATION & TIME METROLOGY
- Quantum protocols adaptation for secure Time-Frequency satellite transfer
- End-to-end QKD protocols, architecture and components vulnerability analysis taking also into account trusted nodes
- Quantum & Photonic Clocks benchmarking and study
## DONI APPLICATIONS OF QUANTUM TECH

<table>
<thead>
<tr>
<th>MACRO-AREA</th>
<th>SPECIFIC AREA</th>
<th>DESCRIPTION</th>
<th>TIME PERIOD</th>
<th>TARGET USE CASES</th>
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</thead>
</table>
| QUANTUM COMMUNICATION & TIME METROLOGY | Unconditionally Secure Information Transfer            | Exploring new solutions enabled by hybrid QKD systems (fiber and free space) together with the concept of &Trusted nodes               | Near term (< 5 y.) | • Galileo Time Generation, Encryption and Transfer  
• Satellite autonomous enahancement due to highly stable clocks (Lunar environments or beyond)  
• Scientific EO payload (e.g. gravitational wave detection) |
|                             | New systems for time/frequency generation and distribution | Photonic quantum Clocks for ground and space segment                                                                                  | Middle term (5÷10 y.) | • Enabling on-board Satellite computing with resilience to cosmic rays and van allen belt.  
• Integrated, efficient (space and energy consumption) computing platform |
|                             |                                                         | QKD based optical Time Transfer in FSO                                                                                                       | Middle term (5÷10 y.) | • Constellations for Distributed computing in space  
• New platforms for efficient ground and on-board computing  
• Solving complex optimization problem like mission planning |
| QUANTUM COMPUTING           | Enabling HPC both in space and on ground exploiting hybrid Quantum/Classical computing to speed up space related complex tasks. | Testing and benchmarking photonic processors as hardware accelerator both onboard and at ground                                          | Near term (< 5 y.) | • New generation quantum payload to enhance sensing capabilities for navigation, EO and SSA.  
(Augmented Orbit Determination systems, Magnetic/gravimetric field Mappings)  
• Augmenting capabilities of EO imaging systems with quantum physics (Entangle-Enahanced SAR, LIDAR) |
| QUANTUM SENSING             | Quantum Sensing devices                                 | Study, characterization and Space qualification of quantum platforms for sensing (superconductors, diamond vacancies, cold atom interferometers, photons) | Near term (< 5 y.) | • New generation quantum payload to enhance sensing capabilities for navigation, EO and SSA.  
(Augmented Orbit Determination systems, Magnetic/gravimetric field Mappings)  
• Augmenting capabilities of EO imaging systems with quantum physics (Entangle-Enahanced SAR, LIDAR) |
|                             | Augmentation of EO systems                              | Testing and benchmarking quantum devices as quantum gravimeters, magnetometers, gyroscopes, accelerometers, antennas                        | Middle term (5÷10 y.) | • New generation quantum payload to enhance sensing capabilities for navigation, EO and SSA.  
(Augmented Orbit Determination systems, Magnetic/gravimetric field Mappings)  
• Augmenting capabilities of EO imaging systems with quantum physics (Entangle-Enahanced SAR, LIDAR) |
|                             |                                                         | Testing Microwave Photonics for RF Signal Manipulation (in SAR Satellite systems )                                                              | Middle term (5÷10 y.) | • New generation quantum payload to enhance sensing capabilities for navigation, EO and SSA.  
(Augmented Orbit Determination systems, Magnetic/gravimetric field Mappings)  
• Augmenting capabilities of EO imaging systems with quantum physics (Entangle-Enahanced SAR, LIDAR) |
|                             |                                                         | Evaluating new system for EO augmentation based on Quantum Mechanics: Quantum Illumination, Radar, Ghost Imaging                             | Long term (> 10 y.) | • New generation quantum payload to enhance sensing capabilities for navigation, EO and SSA.  
(Augmented Orbit Determination systems, Magnetic/gravimetric field Mappings)  
• Augmenting capabilities of EO imaging systems with quantum physics (Entangle-Enahanced SAR, LIDAR) |
TECHNOLOGY READINESS LEVEL

ESA TRL For Space Technologies

Quantum TRL

QTRL
Quantum Technology Readiness Levels describing the maturity of Quantum Computing
Technology

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PART 3: TASI ROADMAPS FOR QUANTUM TECH
ROADMAP 2/3: HYBRID QUANTUM / CLASSICAL COMPUTING

- Quantum computing to Speed up ground and on-board processing for EO
- Constellation of Satellites for in space HPC by means of distributed hybrid computing

Photonic Processing

Quantum Computing

In-orbit validation and benchmarking of an hybrid quantum / classical platform

Study and identification of potentials quantum based applications and algorithms for space related tasks, independently on the adopted platform.

Identify trade-off between Q. Computing platforms (Superconducting, Photons, Ion, atoms) and mapping with quantum applications over space domain.

Study quantum distributed protocols enabling new Features and applications (Blind Quantum Computing, Leader Election, Position Verification)

2023

Testing & Benchmarking Photonic processors (classical) for Space

2024

2025

2026

2027

2028

2029

2030

2035

Implementation and testing of PoC to demonstrate relevant End-User Applications for Earth Observation and Navigation

Space Validation of Photonic based Processors

Funded activity

Submitted proposal

Date:
Ref:
Template: 83230347-DOC-TAS-FR-009

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ROADMAP 1/3: QUANTUM COMM. & TIME METROLOGY

- Highly Secure time generation and distribution systems for **GALILEO** (impacting both ground and space segment)
- Highly Secure EO data transfer (TT&C & EO data)
- New payload for scientific missions in EO; Optical Synthetic aperture telescope

- **2023**
  - Quantum Key Distr. (Fiber-FSO) with TASI acting as Trusted node

- **2024**
  - Testbed for QKD based Time Transfer

- **2025**
  - Study of quantum photonic systems for new generation clocks
  - Optical Synch of TASI buildings

- **2026**
  - Entanglement Based Quantum Synchronization protocols
  - Fiber QKD Secure time transfer between Operative Ground Stations (demonstrating chains of Trusted Node)

- **2027**
  - In-orbit Satellite QKD Benchmarking and Validation
  - Space validation of quantum photonic clocks & Synchronization Protocols

- **2028**
  - In-Orbit validation of optical synch via ISL

- **2029**
  - In-orbit technology demonstration of Photonic Clock concept

- **2030**
  - Unconditionally Secure Time Transfer
  - Hybrid Free space \ fiber QKD
  - Photonic quantum clocks

**Funded activity**

**Submitted proposal**
ROADMAP 2/3: QUANTUM SENSING

- New EO imaging Systems augmented with quantum capabilities (Cosmo SKyMed, Sentinel)
- New generation quantum payload to enhance sensing capabilities for Navigation, EO and SSA

- Study of Quantum photonic systems for microwave generation
- Study of inertial quantum sensors based on Cold Atom and BEC for Space
- Test Case definition and Testing of devices as quantum magnetometers, gyroscopes, gravimeters, antennas
- Study and characterization of NV center devices for Space
- Feasibility analysis and Evaluation of Actively Optical and Quantum Illumin. EO
- Space Qualification and In-Orbit Testing validation of quantum devices
- Test of Quantum Illumination & LIDAR/Ghost Imaging systems for EO
- Missions including quantum payload for sensing

Date: Ref: Template: 83230347-DOC-TAS-FR-009

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THALES ALENIA SPACE OPEN
PART 4: WHAT WE ARE DOING
Objective: Develop next-generation programmable, large-scale atomic quantum simulators operating with up to 10000 atoms

TASI role: End user

Develop one (or more) representative case studies to take advantage of several different computational paradigms and computational platforms (NISQ, real and emulated quantum computers)
**QC4EO – QUANTUM COMPUTING FOR EARTH OBSERVATION**

**Objective:** identification of interesting quantum computing use cases for space (within next 15 years) and roadmap definition

- Scenarios n°1 and n°4: The mission planning problem
- Scenarios n°11: SAR antenna design optimization
- Scenarios n°13: Large constellation design
- Scenarios n°7: Radar digital beam-forming
- Scenario n°3: QFT for SAR raw data processing
- Scenario n°5: Multiple-view Geometry on optical images
- Scenario n°6: The phase unwrapping problem
- Scenario n°10: Algorithms for InSAR Co-registration
- Scenario n°12: SAR raw data compression
- Scenario n°2: Classification of time series optical image
- Scenario n°8: SAR image segmentation
- Scenario n°9: Optical and radar data fusion
**Objective:** build a world-class supercomputing cloud infrastructure to store, manage and process all the produced data. Set up strong links between Academia, Industry.
**QU-PILOT**

**Objective:** develop and provide access to the first, federated European fabrication (production) capabilities for quantum technologies. Provide experimental production capabilities for quantum technologies on the superconducting, photonics, semiconducting and diamond platforms, which will find application in computing, communication and sensing.

**TASI role:** end user, benchmarking. Develop a highly sensitive superconducting magnetometer for space applications.

**Quantum Antenna or Magnetometer**
1. Wideband sensor
2. Sensitive to the magnetic component of EM waves
3. Determination of the direction of arrival
NATIONAL QUANTUM SCIENCE AND TECHNOLOGY INSTITUTE

Objective: strengthening and coordinating the low-TRL research up to its translation into prototypes, favoring interfacing with industrial needs thanks to outreach and continued-education programs.

TASI is part of the Spoke 7, being interested in:
• Quantum devices for sensing (magnetometer)
• Quantum illumination
• QKD

[Lanzagorta, Marco, and Jeffrey Uhlmann. “Space-based quantum sensing for low-power detection of small targets.” Radar Sensor Technology XIX; and Active and Passive Signatures VI. Vol. 9461. International Society for Optics and Photonics, 2015]
Objective: to industrially evaluate and demonstrate a set of enabling technologies in the field of Satellite based network security. More specifically:

- **Satellite FSO QKD**
- **Hybrid Fiber & FSO QKD**
- **Unconditional Cyphering of a Timing Distribution signal**
- **Trusted node over Satellite assets**
**Objective:** to develop a simulator of QKD constellations for secret key distribution

- **HW resources** optimization (number of satellites, size of ground and space optical terminals, …)
- **Costs** optimization
- **Performance** evaluation of different scenarios
- **Risk** analysis;
- Realization of a **digital twin** of the system.
PART 5: QUANTUM COMPUTING USE CASES
THE MISSION PLANNING PROBLEM (1/2)

Optimal scheduling of satellite observations for a given list of user requests (Knapsack problem)

\[2^{(N \times M \times \vartheta)}\] possible solutions

- \(N\) is the number of satellites \(\sim 100\)
- \(M\) the number of AR for each satellite \(\sim 1000\)
- \(\vartheta\) the number of DTO for each pair of satellite-AR \(\sim 10\)
THE MISSION PLANNING PROBLEM (2/2)

Full quantum solution


Hybrid approach

SAR raw data are processed on ground because of the huge computational power needed. Main bottlenecks is the number of FFT / IFFT needed to focus a SAR image.

QFT does not offer a direct quantum speedup compared to FFT. However, a speedup can be achieved by incorporating multiple classical processing steps in a more complex quantum circuit and exploiting the quantum representation of data.
MULTIPLE-VIEW GEOMETRY ON OPTICAL IMAGES

Alignment of multiple images of a given area of interest to analyse the changes that have occurred on the area of interest as time has passed and perform terrain reconstruction. This problem can be tackled with bundle adjustment, which consists in estimating the different changes by minimizing the re-projection error.

THE PHASE UNWRAPPING PROBLEM

recovering unambiguous phase values from a two-dimensional array of phase values known only modulo $2\pi$ rad

$$\phi_i = \varphi_i + 2\pi k_i$$

$$E = \sum_{(s,t) \in A} W_{st} (k_t - k_s - a_{st})^2 + \sum_{s \in A} \omega_s (k_s - a_s)^2$$

find the best array ok k (one k value for each pixel in the InSAR image) that minimizes the energy cost function E

Full quantum solution $\rightarrow$ QUBO
Simulate the EM response of a complex-shaped target for SAR
• Improving target detection
• Improving system calibration with non-conventional target

Antenna design optimization
• Improving overall performances of SAR systems
• Improving beamforming

QUANTUM COMPUTING FOR EM SIMULATION (2/2)

/// Cast the problem into the solution of a linear system of equations:

/ Help in solving PDEs based on **FEM techniques**

/ Based on **HHL algorithm**

/ It has been proven that calculation of EM scattering cross section of an arbitrary target is exponentially faster than the best classical algorithm
PART 6: CONCLUSIONS
CONCLUSION

Is Space ready for the Quantum Leap?
CONCLUSION

Is Space ready for the Quantum Leap?

NO
CONCLUSION

Is Space ready for the Quantum Leap?

NOT ENTIRELY NO

...but we are working for turning this answer into “yes” within next few years
CONCLUSION

Is Space ready for the Quantum Leap?

/// **Quantum tech** is a huge word encompassing a large area of applications and not all of these share the same maturity

/// **Quantum communication** is ready for the market with several industrial applications, while quantum **sensing** is approaching this status with high value demonstrations

/// **Quantum computing** is still in its infancy, in particular when applied to space systems. However, interesting applications are emerging also in space area and these could be potential breakthrough

/// There is a growing global **trend** of investing resources in quantum applications for space. Europe and our company are strongly involved in this trend

/// Space companies are looking to make their systems as independent as possible and to move computation in orbit. **Hybrid model** that combines classical HPC tasks with quantum properties could be the winning solution
**ARE YOU READY FOR THE QUANTUM LEAP?**

///Do you want to contribute to develop new technologies for space?

///Join us at Thales Alenia Space in Italy, where we have a lot of opportunities for students and seniors:

- Staff position within our team in Rome
- Industrial PhD
- Thesis
- Stages

///Don’t hesitate to get in touch with us for further information
THANKS FOR YOUR ATTENTION

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