WHITE PAPER AP12
TECHNOLOGIES FOR AEROSPACE AND EARTH OBSERVATION

EXECUTIVE SUMMARY

Space exploration and Earth Observation have always fascinated man pushing his knowledge needs. The consequence has been the ever increasing technological development of airborne and space borne platforms, satellites for communications, instrumentation for space and Earth observations in a broad range of the electromagnetic spectrum with active and passive sensors.

Aerospace and Earth observation have always played a fundamental role in CNR. CNR is in fact accredited by sector specific studies at levels of international scientific excellence in the field of remote sensing; CNR researches are involved in several projects that concern the exploration of space and aeronautics. There are many collaborations between CNR and such space agencies as ASI, ESA, NASA, JAXA, CNES, DLR, CSA, to remember only the main ones and CE.

The Project Area (PA) has the objective of coordinating the CNR activities of the sector, of encouraging the development of innovation, research and experimentation activities, as well as maintaining and increasing the interaction with the space agencies and the industrial component, in line with the priorities defined by CE.

The main concern of the PA regards the development of the many technologies devoted at exploring the space and the Earth. Such technologies can be categorized as upstream and downstream. The former regards sending objects into space and space exploration and push the provision of technology. The latter exploits upstream for a range of different applications such as satellite broadcast services and Earth Observation and is the motivation to develop algorithms and methodologies.

The activities encompass security in space, technologies for space exploration and space telecommunications, aeronautics and navigation, Earth Observation (OT) technologies and ICT tools. With reference to EO, the skills are broad and cover sensors operating from the optical band up to the microwaves and gamma rays of cosmic origin, electromagnetic modeling and statistical data analysis with the ICT technologies and infrastructures for their management, processing and representation.

All the activities of the PA appear well established and well connected within the context of international research and technology.

1. STATE OF THE ART OF THE RELEVANT SCIENTIFIC AREA

Research and development for aerospace and Earth observation technologies is an extremely wide area, embracing a wide number of topics in the forth-and-back path involving the upstream segment, for the development of the enabling space infrastructure (launchers, platforms, sensors, etc.), and the downstream segment for the development of products and services.

As access to space is costly, involves technical risks, use of cutting edge technologies and longer times for both project development and return on investments, the sector has been traditionally government dominated by applications to environmental risk monitoring and security.

The viability of space-enabled services requires, as matter of fact, markets of large users. Notwithstanding, the increasing number of private entities currently engaged in space activities is gradually operating a shift in the traditional roles of public and private sector. This is testified by always more frequent use of the terminology “space economy”, that is the full range of activities and the use of resources creating value and benefits to human beings in the course of exploring, researching, understanding, managing, and utilizing space.

The importance of space as a privileged place from which to observe the Earth in order to know, understand and tackle important processes that impact on man life is easy to understand. Space is however not an *easy* environment, hard for technology.

Issues related to safety and the need to develop cutting-edge technologies have always been inextricably linked to space efforts. A central topic concerns the safety of space activities, both in orbit and in cases of uncontrolled reentry. The main aspects of current activities and future trends comprise modeling, mitigation and remediation of orbital debris; prediction of uncontrolled reentries in the atmosphere for civil protection purposes; spacecraft *splashdown*; astrodynamics applied to the support of space missions, scientific experiments, tracking systems and orbital determinations.
Similarly, technologies for the production and storage of energy and technologies for the space observation from the space are also of key importance especially for space exploration research.

The development of satellite telecommunications technologies, with particular reference to the next-generation High Throughput Satellite telecommunications networks is a key aspect. The activities cover the different network levels, from the study of architectures and protocols up to the modeling of the transmission channel and the design, implementation and experimental characterization of microwave components passive and active in the range of millimeter waves. Regarding to SW technologies, multiple satellite access protocols, protocols for delay and disruptive tolerant networks (DTN), future web technologies, M2M protocols via satellite and Information Centric Networking paradigms for sensor web applications, drone networks, UAVs and RPAS and communication protocols in Line of Sight and beyond Line of Sight are relevant.

Technologies for aerospace, with particular reference to power generation systems with low environmental impact, structural monitoring, safety in aeronautics, ditching, and maintenance and management of the end of life are also relevant.

Earth observation (EO) is experiencing an astonishing growth, deeply affecting both research as well as commercial outlets. To perceive the importance of this topic, it is sufficient to browse for the EO programs currently running at international level in the majority of the developed countries. Limiting to Europe, the Copernicus program is for instance playing a key role for the development of information services in several application domains. The Sentinel program, with the launch of six different families of sensors, is implementing what is referred to as “the European Observation Capability”. In parallel the Copernicus Accelerator, EO is boosting the growth of market oriented services and huge technological transfer from research to business. At the national level, the technological development of the COSMO-SkyMed constellation, currently in orbit, the COSMO-SkyMed Second Generation and several other programs such as PRISMA, gives to Italy a key role in the EO international arena.
New challenges are being addressed, the most exciting future trends being related to the development of small satellites, which are going to enable the availability of wide constellations as well as satellite formation, capable of improving revisiting time, site access and, above all, providing advanced observation diversity. Such an advance will reflect also in the need of improving R&D in the whole value added chain that goes from the data acquisition up to the serviceability levels.

Improvement of services oriented to the different application domains asks for advances on one side of methods for the statistical analysis of the EO data, including data fusion algorithms and methods for EO data interpretation, on the other side for improvements in the electromagnetic modelling. The latter is crucial for the development of retrieval algorithm to derive bio-geophysical variables for environmental monitoring and risk prevention.

During the last years, EO data have been steadily growing in volume and typology, and improving in terms of ground coverage, revisit time and spatial/spectral resolution. This provided new opportunities for application development, which, in turn, required innovative and improved methodologies for electromagnetic and statistical modelling of these new EO datasets (e.g. time series covering long periods with high temporal sampling). For instance, a great attention has been devoted to novel data fusion approaches as well as to automatic techniques able to manage large amount of data, and to extract useful information by them (e.g. deep-learning algorithms represent the newer trend in the EO big data analysis.

ICT infrastructures have led to disruptive technological advances with terrific societal implications. Topics concerning the study and development of techniques for the use, analysis and processing of Earth Observation (EO) data, and corresponding geospatial information, based on the use of advanced ICT platforms are therefore becoming more and more important. In particular, the recent availability of a huge amount of satellite data (with particular reference to those acquired on a global scale by the Copernicus Sentinel sensors) and the increasing availability of data from ground-based sensors has opened new research scenarios focused on effective and efficient processing of EO data to obtain information of the Earth's surface at very large spatial scale and in extremely short times. To this end, the use of high-performance computing infrastructures, the development of specific algorithms for processing EO data, along with the possibility of efficiently sharing these data through standardized services, becomes of central importance.

Five main topics can be identified considering the competences and skills available in CNR in such a huge area as Aerospace and EO: Space technologies and Space Safety; Space communication and aeronautics, Earth Observation Technologies; Model based data interpretation; ICT tools for the management, processing, representation and exploitation of EO data.

2. CONTRIBUTION TO THE RELEVANT SCIENTIFIC AREA

Space technologies and Space Safety

Space Safety. Modeling of space debris for the impact risk assessment in orbit, for the identification of operational procedures, standards and technologies minimizing the production of new debris, and for the evaluation of the effectiveness of technological solutions allowing the active removal of objects abandoned in space. The main objectives are to guarantee the functionality and safety in orbit of manned and unmanned systems, and the preservation of the space environment.

Space Systems Control and Astrodynamics. Studies and tests of spacecraft *splashdown*; orbital analysis for the support of space missions, with and without crew; study and modeling of non-gravitational perturbations to support fundamental physics experiments in space; orbital determination starting from radar, optical and laser observations; activities in the area of Space Situational Awareness (SSA) and Space Surveillance and Tracking (SST).

Optoelectronics, Aerospace Sensors and Power Technologies. Test systems for star trackers and of innovative compressive sensing-based prototypes using advanced optoelectronic technologies, such as micro-mirror arrays and LCD. Technologies and processes for power generation and energy storage: devices in configuration fuel cell plus electrolyzer and their integration into a single device (Regenerative Fuel Cell) for closed-loop energy generation, i.e. without emissions, being therefore suitable for the planetary robotic exploration and for energy self-sufficient space stations.

Technologies for the Observation in Space. Systems for focusing and spectral detection of X and gamma rays from cosmic emission through high efficiency lenses based on diffraction and 3D spectral detectors in the energy band. These capabilities made possible the characterization of the Gamma-ray Burst Monitor (GBM) instrument of the CALET (CALorimetric Electron Telescope) experiment, deployed aboard the International

Space Station (ISS), through simulations and data analysis of measurements of the photon bursts incident on the apparatus.

Space communications and aeronautics

Space Communications Development of technologies for satellite payloads, avionics, Unmanned Aerial Vehicles (UAVs), Remotely Piloted Aircraft Systems (RPAS), with a particular attention to the next-generation High Throughput Satellite (HTS) systems, massive Machine Type Communication (m-MTC) networks, and Command, Control & Communications (C3) systems. The interdisciplinary skills of the CNR institutes cover different levels, from bread-boarding of antenna-systems and RF front-ends, to the study of architectures and protocols, to the modelling of the transmission channel, by also considering the design, implementation, and testing of Software Defined Radios (SDRs), Software Defined Networking (SDN) architectures, and Network Function Virtualization (NFV) concepts.

Aeronautics. Emergency ditching of aircrafts: development of high-fidelity and low-fidelity computational tools for the fluid-structure interaction during the emergency ditching and support the physical understanding of the phenomena through dedicated, representative experiments.

Sloshing wing dynamics: development of advanced numerical solvers for the prediction of loads and viscous dissipation induced by sloshing fuel inside wing tanks of airplane subjected to wind gusts.

Aerodynamics and aeroacoustics, structural control: computational models for aerodynamics, aeroacoustics and for the structural monitoring in aeronautics

Earth Observation

Microwave technologies. Space borne Synthetic Aperture Radar (SAR) interferometric techniques for large area monitoring and for the 3D reconstruction and monitoring of complex scenarios such as urban areas. Airborne SAR technologies. Microwave radiometric technologies for the observation of sol, CIMR and MWI instruments.

Infrared technologies. Direct and inverse modeling of radiative transport in the Earth's atmosphere are core activities conducted for remote sounding of atmospheric temperature and composition by nadir/zenith and limb emission measurements from ground-based, high altitude and space-borne platforms in the spectral range from the infrared to the sub-mm and mm waves.

Optical band technologies. Lidar high-resolution spectral and temporal systems, Lidar imagers, Lidar 4D, optical hyperspectral systems, image interferometers in VIS-IR. Prototypes of LTA (Lighter Than Air) stratospheric platform instruments. Hyperspectral and LIDAR image simulators. Compression algorithms and blind methods to characterize the quality of the instruments. Customized signal processing methodologies for multispectral, hyperspectral, LIDAR sensors.

Platforms and integration with in situ technologies. Integration of remote sensing technologies and in-situ sensing technologies. Processing, integration and fusion of remote data sensed with different technologies, such as optical, multispectral, and SAR sensors from unmanned aerial vehicles (UAV), for smart industry and smart farming applications. Development of prototypes for in situ optical measurements. Measurement campaigns, ground truth campaigns, CalVal activities and management of test sites.

Model based data interpretation

Electromagnetic modelling. Models for interpreting EO data and retrieving bio-geophysical parameters over bare soils, agricultural and forest vegetation, snow, sea and inland waters. Time series modelling of Synthetic Aperture Radar (SAR) data for retrieving high resolution (e.g. 1km) surface soil moisture at regional/continental scale. Direct and inverse modelling of radiative transfer in the atmosphere for deriving information of its physical properties (i.e. temperature and humidity profile, LWC, pressure, chemical composition, etc.). Atmospheric data correction.

Statistical Modelling. Algorithms of signal/image processing, and data fusion (e.g. based on Bayesian Networks, pansharpening and hypersharpening) for information extraction (e.g. ship classification/identification, route prediction). Supervised (data/knowledge driven) and unsupervised methods for data clustering and classification, and for automatic change detection of land use/cover. Inversion algorithms based on statistical approaches (i.e. Bayes and Nelder-Mead neural networks) for estimating bio-geo physical parameters from EO data. Local and global scale thematic maps generation of soil moisture, agricultural and forest biomass, snow cover and snow depth. Statistical methods of multi-temporal (e.g. InSAR time series) and multi-source data analysis for mapping and monitoring natural/man-made disasters (floods, landsides, fires, oil-spills, earthquakes).

ICT tools for the management, processing, representation and exploitation of EO data
<u>Grid / Cloud computing and geospatial data infrastructures</u>. Integration of technologies and systems oriented to archiving, rendering, presenting and processing of geospatial data. Development of algorithms for processing of remote sensing data on High Performance Computing (HPC) architectures (grid-cloud computing). Computation and simulation for EO product generation and applications. Architectures and implementation of infrastructures of interoperable spatial data for research, access, exchange, and processing of geo-referenced environmental and heterogeneous (abiotic and biotic) data. Virtual laboratories for processing of geo-referenced data aimed at studying the territory through the coordinated use of web geo-services. Analysis and processing of georeferenced spatial data to support knowledge, management and planning of environmental resources. Integration and management of multiple ontologies of geospatial information for different application domains, within the framework of relevant standards. Research and development on synergistic use of EO data based on innovative data fusion techniques and assimilation models.

This line of research considers the application of Artificial Intelligence (AI) planning and scheduling technologies to increase the autonomy capabilities of current and future space missions, such as Earth Observation (EO) missions. The focus is on intelligent decision-making, such as the autonomous synthesis of spacecraft activity plans to be executed, thus enabling a spacecraft to safely achieve a set of science goals without a strict human control loop. To provide this capability, AI-based planning, scheduling, and execution techniques can be used to create, optimize and validate spacecraft plans based on a rich model of spacecraft operations. This leads also to investigate mixed-initiative planning techniques when autonomous systems and ground segment personnel are to collaborate for achieving mission objectives. A further step ahead is the design of integrated planning and learning algorithms to acquire new knowledge in (partially) unknown and unstructured environments.

3. IMPACT

Curiosity and knowledge have always been fundamental for mankind. If *science is the study of the nature and behavior of natural things* it is apparent that space is a privileged place from which to observe the Universe and the Earth to know, understand and tackle important processes that impact on man life. Unfortunately, space is not an *easy* environment: difficult and expensive to reach, hostile for man, hard for technology. Space is a real challenge.

Not surprising, many issues and competencies are involved in the PA. Instruments have to be conceived, designed, realized, launched and then managed, causing a hard technological impact on the development of such enabling technologies as propulsion, optics, mechanics, electronics, acquisition systems, telecommunication systems, data processing tools, spatial debris de-orbiting.

Modern societies heavily depend on satellite technology, for navigation, communications, meteorology and Earth observation (EO). Space technologies also affect agriculture planning, disaster management, medicine, land monitoring, transportation and are a valid tool for policy makers.

Our PA is fully inserted in the research and development of aerospace and EO technologies and all its activities have important impacts.

CNR space debris mitigation groups coordinate important EU research projects, are leaders in the space debris and represent ASI in the IADC committee. CNR is the leader in providing re-entry predictions of uncontrolled space objects and products specifically tailored for national authorities.

Compressive Sensing (CS) technologies are gaining importance. CNR has recently leaded two ESA projects for space applications, exploring the performance of novel CS-based instrumental concepts.

Optical Ground Support Equipment (OGSE) for testing multi-head Star Trackers (ST) has been recently developed by leading to the implementation of a miniaturized electro-optical device able to generate synthetic images of dynamic star fields for ST testing.

3D CZT spectro-imager module can realize the innovative high performance detectors required by new space instrument for hard X-/soft γ-rays astronomy. The configuration of the device will allow the implementation of a large variety of satellite mission.

Human space exploration, using aerial drones (AUV) for EO or surface vehicles (manned or unmanned USV) for planet exploration, based on electrochemical energy production and storage systems (FC, EZ, battery, etc.) can significantly contribute to Space Technology improvement by collaborating with the main stakeholders for power generation for stationary and surface mobility in space.

5G will deliver important features for of stakeholders, such as ultra-high bandwidth and ultra-low latency, thus enabling new applications like virtual reality and tactile Internet. The initial deployment of 5G systems is expected in 2020 and will bring significant innovations with a capacity 1000 times higher than 4G systems at a reduced energy power.

5G will allow the integration among different network segments. Terrestrial, aerial, and satellite networks will exploit seamless integration thanks to the large efforts still in place to provide such a result. Satellites will address important use causes for 5G-critical communications, i.e., future railway, maritime, and aeronautical communications.

The activities on the emergency ditching of aircrafts will make available efficient simulation-based strategies for a goal-oriented optimization and increase of handling- and approach-condition windows that secures a safe ditch. The simulation environment, developed and validated due to the testing activities of CNR, will also provide an improved understanding of physical phenomena enabling an advanced design for reducing weight.

The development of computational models for the prediction of the fuel behavior in the tank and their integration into an industrial design framework will have enormous potential if applied to upgrades of already certified aircraft

The design of new instruments and enabling technologies for EO in collaboration with the international space agencies, ESA and ASI in particular, and with the main industries is a strong asset of the PA.

Integration and synergistic use of high spatial resolution microwave and optical data allows monitoring and prevention of natural and man-forced disasters (e.g. earthquakes, floods, landslides, oil spills, pollution) providing fundamental information for designing a mitigation risk strategy, an early warning alert or addressing the post-event strategies.

High resolution monitoring of geo-bio physical variables (e.g. agricultural, forest and primary production, soil moisture, snow mass and snow condition) has an economic impact while the information provided at coarse scale (e.g. from microwave radiometers) contribute to the weather prediction and climate studies investigations.

The microwave radiometers CIMR and MWI are under development for global weather forecasting, climate monitoring and cryosphere sciences. MWI will provide data of great accuracy and resolution for ocean temperature and surface wind speed. CIMR aims at sea ice monitoring with very high spatial resolution.

CNR activities on EM and statistical modelling of EO data, impact on many applications. Surface soil moisture is of scientific, applicative and economic interest for water management, food security and agricultural production.

Forward and inverse modelling capabilities play a leading role for atmospheric monitoring and represent the key for further scientific and technological achievements and for new applications and services in view of commercial returns.

The use of HPC infrastructures allows generating fast and efficient EO processing tools and applying innovative instruments for EO data analysis, thus fostering services operated by institutions and industries that can provide value added information to such final users, as public authorities and policy makers.

The use of efficient planning and scheduling AI algorithms for managing EO activities will reduce the delays and improve the quality of the sensed data boosting the mission survival chances, extending mission lifespan and increasing science return.

Ship classification and identification have impacts on the detection of such illegal activities as unauthorized fishing, irregular migration and related smuggling activities.

All activities of design and development of novel methods for data fusion, pattern recognition, supervised and unsupervised classification, multi-temporal analysis of EO data play a key role in the interpretation of complex environmental scenarios.

Advanced methods for automatic analysis of large EO datasets are crucial for natural resource monitoring as well as for detecting warning signals related to natural/man-made disaster.

Grid / Cloud computing and geospatial data infrastructures are becoming more and more important for modeling and processing the huge amounts of EO data.

4. EMERGING RESEARCH CHALLENGES

Research challenges in space activities relate to long term sustainability. Autonomous navigation to in-orbit collision avoidance is gaining importance due the forthcoming large constellations.

Similarly, satellite constellation and formations will provide data with new unprecedented observation and diversity features. The huge amount of EO data opens new perspectives to develop innovative processing methodologies such as information extraction by exploiting artificial intelligence.

In communications, the research challenges are fostering high data rates, high reliability, and a low latency. Novel network architectures aiming at integrating ground, aerial and space networks in the so-called Space-Terrestrial Integrated Network (STIN) need investigation.

Simulation tools for aircraft ditching and fuel sloshing need a further development to improve efficiency and accuracy. Exploiting approximate models is necessary to optimize procedures to design simplified approaches (low fidelity).

5. CONCLUSIONS

The PA is substantial and well established in the framework of aerospace and EO activities at national and international level as witnessed by the large number of its projects and facilities. Projects are scientifically and technologically sound, consistent and sometimes well-funded.

Many researchers are involved in the activities of the PA. Their competences and skills are broad and significant in the fields of space technologies and space safety, space communication and aeronautics, Earth observation Technologies model based data interpretation, ICT tools for the management, processing, representation and exploitation of EO data.

The importance of the scientific programs in which the PA operates is impressive. The scientific scenario for the future appears robust and consistent since several important programs and missions are foreseen in the framework of ESA and ASI initiatives. The role of PA research is often relevant on these programs with the agencies or under contracts funded by the industries operating on the related activities. As a consequence, the procurement of resources for future PA activities appears well based.

The technological impact of the PA on modern society is unquestionable. Issues as satellite technology, for navigation, communications, meteorology and Earth observation are fundamental. It social impact is relevant since its outcomes affect agriculture planning, disaster management, medicine, land monitoring, transportation, many other fields of anthropic interested and could be a valid tool for policy makers.

A final notation concerns the expertise of people involved in the PA. The training phase for researchers involved in space activity is recognize to be long and specific. This aspect should push the maintenance of the expertizes in the PA by suitable recruitment policies.

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PROJECT AREA 12: TECHNOLOGIES FOR AEROSPACE AND EARTH OBSERVATION

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