**Borsa di studio attivata ai sensi di quanto disposto dal D.M. n. 1061 del 10/08/2021**

Titolo del progetto: Clim4CubeSat – Impatto del cambiamento climatico sulle future radiocomunicazioni satellitari ad alta frequenza: valutazione degli effetti atmosferici del riscaldamento globale sulla costellazione di satelliti CubeSat a onde millimetriche

La borsa sarà attivata sul seguente corso di dottorato accreditato per il XXXVII ciclo:
TECNOLOGIE DELL'INFORMAZIONE E DELLE COMUNICAZIONI (ICT)

Responsabile scientifico: Prof. FRANK S. MARZANO
Area per la quale si presenta la richiesta: GREEN
Numero di mensilità da svolgere in azienda: 6
Numero di mensilità da svolgere all'estero: 6 presso European Space Agency (ESA) -ESTEC https://www.esa.int/About_Us/ESTEC, Keplerlaan 1, Postbus 299, 2200 AG Noordwijk (The Netherlands) Referente: Dr. Antonio Martellucci, antonio.martellucci@esa.int
Azienda: Telespazio SpA https://www.telespazio.com/it/home, Via Tiburtina, 965, 00156 Roma RM Referente: Dr. Luffarelli Valter, valter.luffarelli@telespazio.com

Progetto di ricerca:
Millimeter wave - matter interaction is an important topic for both low-Earth orbit (LEO) satellite radiopropagation and Earth remote sensing from active and passive sensors. Frequency bands of interest are those beyond 60 GHz, namely the so-called W band (75-100 GHz). At millimeter wave (MMW) both electromagnetic absorption due to gases and scattering due to precipitating clouds, as well as atmospheric sky noise temperature, are essential phenomena to quantify the atmospheric effects on MMW signals. Usual theoretical models for signal propagation and emission in cloudy and rainy atmosphere are available and tested up to 50 GHz (Q band), Microphysical issues arise when considering MMW wavelengths at V and W band due to the resonant Mie scattering effects due to cloud droplets and hydrometeor particles on signal amplitude. The radiative transfer integro-differential equation is considered a general framework where both extinction and multiple scattering can be treated, even though only via numerical solutions in complex cases. Moreover, microphysical-radiative numerical models need to be parameterized and tuned to local climatology in order to be representative of measured statistics of tropospheric extinction and emission. From ground, a very promising approach to test W band model-based predictions is the MMW Sun-tracking radiometry using the Sun as natural signal emitter. Ground-based MMW Sun-tracking campaigns have been carried out and/or are running mainly in the US and in Italy, but the acquired data sets have still to be fully exploited for testing the model-based propagation predictions at MMWs. Verification of tropospheric signal attenuation and sky noise temperature models and statistical behavior at MMWs is quite cumbersome since it requests space transmitters at W band within dedicated campaigns. The latter are quite costly and rare, even though recently cubesat spacecraft payloads are becoming available.

CubeSats are cube-sized nanosatellites that typically weigh between 1 and 10 kilograms and follow the popular ‘CubeSat’ standard, which defines the outer dimensions of the satellite within multiple cubic units of 10x10x10 cm. For instance, a 3-unit CubeSat has dimensions of 10x10x30 cm and weighs about 3-4 kg. This is typically the minimum size which can accommodate small technology payloads. Fixing the satellite body dimensions promotes a highly modular, highly integrated system where satellite subsystems are available as ’commercial off the shelf’ products from a number of different suppliers and can be stacked together according to the needs of the mission. Due to their high degree of modularity and extensive use of commercial off the shelf subsystems, CubeSat projects can be readied for flight on a much more rapid basis compared to traditional satellite schedules, typically within one to two years. CubeSats have already proved their worth as educational tools. In addition, they have various promising applications. For large broadband satellite networks, the number of gateways may be such that the cost of the ground segment exceeds the cost of the satellite, even when using Q/V band in the gateway feeder link. The usage of the spectrum available in W-band (70/80 GHz) for Satcom systems feeder link in future High-Through-Put systems will significantly reduce the number of required gateways and consequently the overall cost of the ground segment. However, the atmospheric channel- propagation models available from the International Telecommunication Union (ITU) are known to be accurate up to 30-40 GHz. Therefore, new measurement campaigns and atmospheric modeling are needed to characterize the atmospheric channel propagation at W-band.

The recently published IPCC (International Panel on Climate Change) sixth Assessment Report (AR6) provides new estimates of the chances of crossing the global warming level of 1.5°C in the next decades, and finds that unless there are immediate, rapid and large-scale reductions in greenhouse gas emissions, limiting warming to close to 1.5°C or even 2°C will be beyond reach. The AR6 report shows that emissions of greenhouse gases from human activities are responsible for approximately 1.1°C of warming since 1850-1900, and finds that averaged over the next 20 years, global temperature is expected to reach or exceed 1.5°C of warming. This assessment is based on improved observational datasets to assess historical warming, as well progress in scientific of the response of the climate system to human-caused greenhouse gas emissions. The AR6 focuses on the physical science behind climate change, considers five scenarios that game out how humanity will respond, or not, to the specter of warming. They reveal that some of the more extreme projections of the past are less likely to come to fruition. These AR6 can be transformed into radiopropagation scenarios for LEO CubeSat constellation communications, which will be also the space segment of the Internet-of-thins (IoT) infrastructure. This means that any AR6 scenario, from the SSP1-1.9 “Taking the green road” up to SSP5-8.5 “No mitigation”, will have a direct impact on future radiocommunications at W band using LEO satellites.

The objectives of the PhD project are manifold: i) to extend the Eddington radiative model to include non-spherical ice particle scattering effects and, at least in a statistical sense, the impact of horizontal inhomogeneity of fractional cloud coverage. For a single layer atmosphere, the solution can be expressed analytically, but for a stratified medium the most effective Eddington approach is the iterative one. MMW single-scattering properties of ice particles can be modeled in terms of extinction, volumetric albedo and asymmetry factor, to be parametrized in terms of particle concentration and mean sizes; ii) to apply the MMW microphysical-radiative model to cloud structures, statistically generated under first and second order statistics of particles concentration spatial distribution. These vertical structures are embedded within randomly varying clear-air vertical profiles of temperature, humidity and pressure, derived from RaOb data. Moreover, the measured statistics of rain gauges (if available) or global-scale reanalyses can be used to match the rain rate effects on a monthly or yearly basis. Exploiting and optimizing the ANN topologies, an ANN-based advance predictor of MMW signal extinction and emission from frequency-scaled attenuation and antenna noise temperatures can be designed, taking into account the elevation angle variability; iii) to apply the W-band developed models to IPCC AR6 scenarios by computing the variability and expected increase of the atmospheric attenuation in the various conditions. The scope is to evaluate how much the current design of W-band CubeSat constellation will be unsustainable if an AR6 scenario will happen and to what extent the economic investment will be affected and IoT space-based connections degraded. On the other, W-band radiopropagation link mapping can be used to monitor the atmospheric extinction at global scale as an indicator of climate change trend.

The PhD project time plan is as follows:
Year 1. Experimental data and theoretical modeling at millimeter wave
-1.a Exploration of available W band datasets from ground-based Sun-tracking microwave radiometers as well as MMW collocated beacons together with meteorological surface stations and radiosounding profiles.

-1.b Electromagnetic modeling of ice hydrometeors as equivalent spherical particles with effective permittivity considering the mixed air-ice composition and their impact on Mie scattering effects.
-1.c Formulation of MMW microphysical-radiative models in a cloudy atmosphere, including the effects of ice hydrometeors as well as the horizontal inhomogeneity, to express MMW signal extinction and emission
Year 2. Statistical prediction and machine-learning approaches for W band CubeSat constellations
-2.a Investigation of the MMW microphysical-radiative models to consider the local climatology considering local atmospheric radiosounding and parametric approaches
-2.b Exploration of model-based machine-learning oriented prediction methods of MMW signal extinction and emission, based on new artificial neural network (ANN) topologies
-2.c WP2.3Evaluation of the intrinsic uncertainties within the statistical multivariate prediction methods and those based on artificial neural networks
Stage of 3 months at the selected institute (Politecnico Milano)
Year 3. Impact of climate change of W-band CubeSat radiocommunication networks
-3.a Collection of AR6 scenario datasets in terms of atmospheric variables and evaluation of methods to initialize MMW radiopropagation models
-3.b Coupling of AR6 scenario data with radio-meteorological models to transform AR6 maps into W-band attenuation and sky-noise temperature datasets
-3.c Analysis of the impact of AR6 radiometeorological scenarios on the current design of W-band CubeSat constellation and IoT space-based degradation as well as global monitoring of atmospheric extinction.
Stage of 3 months at the selected foreign institute (ESA, NL)

These PhD goals are strictly related to the Sustainable Development Goals (SDG) and, in particular, to SDG13 (Climate action). The PhD objectives are also coherent with the aims of the Italian plan PNRR (Piano Nazionale Ripresa e Resilienza) and, in particular, with the mission component M2C4 (Tutela del territorio e della risorsa idrica) and its Topic 1 (Rafforzamento della capacità previsionale degli effetti del cambiamento climatico tramite sistemi avanzati ed integrati di monitoraggio e analisi) as well as with mission component M1C2 (Digitalizzazione, Innovazione e Competitività nel sistema produttivo) and its Topic 3 (Rafforzare la partecipazione allo sviluppo dell'economia dello spazio e i sistemi di osservazione della Terra).

Titolo del progetto (inglese): Clim4CubeSat – Climate change impact on new high-frequency satellite radiocommunications: evaluating the global warming atmospheric effects on low-Earth CubeSat satellite constellation at millimeter waves

Progetto di ricerca (inglese):
Millimeter wave - matter interaction is an important topic for both low-Earth orbit (LEO) satellite radiopropagation and Earth remote sensing from active and passive sensors. Frequency bands of interest are those beyond 60 GHz, namely the so-called W band (75-100 GHz). At millimeter wave (MMW) both electromagnetic absorption due to gases and scattering due to precipitating clouds, as well as atmospheric sky noise temperature, are essential phenomena to quantify the atmospheric effects on MMW signals. Usual theoretical models for signal propagation and emission in cloudy and rainy atmosphere are available and tested up to 50 GHz (Q band), Microphysical issues arise when considering MMW wavelengths at V and W band due to the resonant Mie scattering effects due to cloud droplets and hydrometeor particles on signal amplitude. The radiative transfer integro-differential equation is considered a general framework where both extinction and multiple scattering can be treated, even though only via numerical solutions in complex cases. Moreover, microphysical-radiative numerical models need to be parameterized and tuned to local climatology in order to be representative of measured statistics of tropospheric extinction and emission. From ground, a very promising approach to test W band model-based predictions is the MMW Sun-tracking radiometry using the Sun as natural signal emitter. Ground-based MMW Sun-tracking campaigns have been carried out and/or are running

mainly in the US and in Italy, but the acquired data sets have still to be fully exploited for testing the model-based propagation predictions at MMWs. Verification of tropospheric signal attenuation and sky noise temperature models and statistical behavior at MMWs is quite cumbersome since it requests space transmitters at W band within dedicated campaigns. The latter are quite costly and rare, even though recently cubesat spacecraft payloads are becoming available.

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