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Ingegneria e diritto internazionale dello spazio nei sistemi di comunicazione, navigazione e sensing satellitare – Engineering and International Space Law in Communications, Navigation and Sensing Satellite Systems

Modelling and simulation of space electromagnetic operations in a synthetic scenario: development of multi-domain platforms and systems

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CHAPTER 1: NATO OPERATIVE CONTEXT

EMSO (Electromagnetic Spectrum Operations)

Since the Cold War, the potential for the EMS (Electro-Magnetic Spectrum) to support conventional military forces has been clearly understood by both Western and Eastern countries. Hence, both parties have invested in Spectrum Dependent Systems (radars, radios, EW and SIGINT systems and systems of systems) for military and national security purposes.

Recently, the lessons learned from the conflicts in Ukraine and Syria provide a unique insight into the complexity of conducting military operations in a congested and contested Electro-Magnetic Spectrum (EMS). Even though the term 'spectrum' is well understood by the majority, it is the Electro-Magnetic Environment (EME) which best captures the message NATO tries to convey when it comes to operating, exploiting, transmitting and receiving, or sending electromagnetic energy in time and space. In this vein, NATO nations have agreed to define EME as electromagnetic phenomena occurring in a given place. Phenomena more than radio frequencies are better aligned with the essence of EME.

The EMS has always been militarized, but the dual use nature of the EMS, the enormous dependency that the global economy has developed on EMS-based services and the impacts of technology miniaturization are combining to create challenges for all nations because of their reliance on services tied to the EMS. Furthermore, adversaries are aggressively fielding electronic attack and cyber technologies that erode the ability to use the spectrum for joint operations, while the global wireless broadband industry is seeking to reallocate spectrum from defence use to commercial uses, to meet consumer demands for greater mobility and data connectivity.

Freedom of movement and action in the EME have until recently been commonly accepted as a prerequisite for military operations. Success in modern military operations depends on making the most effective and efficient use and exploitation of the EME. NATO forces will operate within an increasingly complex and challenged EME in the future; therefore, NATO should articulate proper procedures for the complex and unexpected EME Environment of the future.

For a long time, NATO accomplished different lines of activity to ensure freedom of movement in the EME, where a loss of control will inevitably lead to mission failure. Many forums call for consideration of the spectrum as a battlefield since it has significant influence in the aptitudes and procedures of the other domains (land, maritime, air and cyberspace), showing a transversality impact on the whole multi-domain operative environment. These domains must inexorably work within the spectrum to accomplish their missions effectively and to allow interconnectivity between them to outline concretely a military comprehensive approach.

Ukraine and Syria provide good examples and a greater understanding of this new form of conflict. It was unveiled as a new facet of armed conflict, which can be labeled as 'hybrid' or 'new generation' with EW as a key capability in paradigms.

In 2007 NATO promulgated a concept with the purpose to prepare for the transformation of the future electronic war. EMO (Electromagnetic Operations) was one of the cornerstones of this concept. NATO doctrine recognizes that NATO operations are complicated by an increasingly congested and contested EME. In the transformation document, NATO declared the EME as an operational environment, but not a domain, as referenced in MC 64/11 "NATO recognizes the Electromagnetic Environment as an operating environment".

All modern forces conduct operations that depend on the use of the EME. The recognized need for military forces to have access to and utilize the EME creates vulnerabilities and opportunities for EM spectrum warriors.

Therefore, a new operational discipline has been set up accordingly, named Electromagnetic Spectrum Operations or EMSO. EMSO consist not only of "traditional" Electronic Warfare (EW), but includes several other disciplines, which operate in the Electromagnetic Environment, such as Signals Intelligence (SIGINT) as part of Information Operations, Spectrum Management and Cyber Electromagnetic Activities (CEMA).

The EME cuts across all levels of warfare and must therefore be considered for the conduct and planning of every single operation. EMO models and exploits the EME, using it to attack or defend and includes the use of EME as supporting operations in all other operational environments (e.g. spectrum management and Position, Navigation & Time [PNT]).

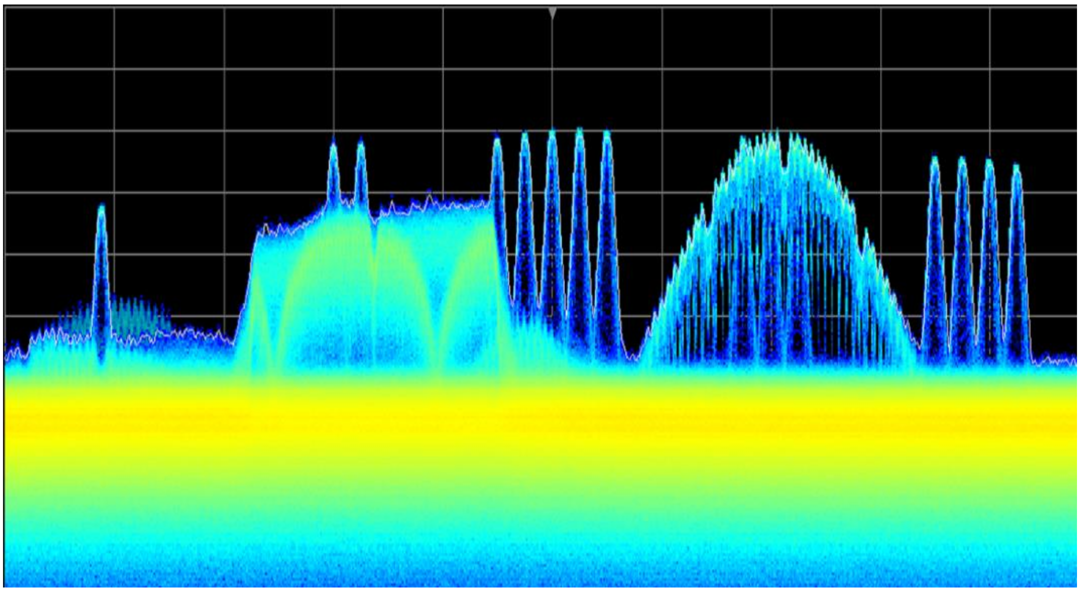

Figure 1: Electromagnetic spectrum of many signals with different timing and frequential characteristics detected in the surrounding environment.

Space EMSO

Operations are a military action or the carrying out of a strategic, operational, tactical, service, training, or administrative military mission. Space operations are military actions, conducted across the competition continuum. They include both traditional and irregular warfare, to deliver effects to the joint force, to create a period of a relative degree of advantage of one force over another, and to support an environment of security that enables freedom of action for the Armed Forced.

Military space forces operate in the space domain, the dynamic and complex environment above the altitude where atmospheric effects on airborne objects become negligible. The Space Domain is very important in strengthening NATO's deterrence posture.

The space operations can perform many actions using the electromagnetic environment, which can have a huge operative impact on military operations. Space technologies are included in the so-called Emerging Disruptive Technologies (EDT), which represent technologies with strategic impact on the future operating environment. Space technologies mainly includes earth observation, on-board processing, low latency and broadband satellite communications, position, navigation & timing,

space situational awareness (SSA) and space surveillance and tracking (SST), space domain awareness (SDA).
The fundamental capabilities implementable using space assets have been modelled and simulated in the synthetic developed scenario, which can be associated to GEO (Satellite Communication), MEO (Positioning Navigation and Timing) and LEO (Intelligence Surveillance and Reconnaissance) satellite platforms.
Electronic Warfare and Cyber may be the preferred way to attack space capabilities, because they don't have the same long-term consequences as kinetic attacks on satellites (space debris) and they can't be tracked without a dedicated monitoring system.
For this reason, it is important to start thinking to equip satellite platforms with EMSO payloads, in order to extend space domain capabilities for military operations. Considering the electromagnetic and cyber-attacks increasing against satellite platforms, it is necessary to have counter-measure systems on board, to protect assets by inefficiencies and ineffectiveness behaviours. This assumption defines and confirms a purely (electromagnetically speaking) defensive role of space domain, in compliance with international space law, where the space actions must be conducted with a perspective to maintaining international peace and security and to promote cooperation and understanding among States (peaceful use of space). The development of space electronic monitoring devices and counter measures capabilities represent a technology cornerstone with huge operative impacts, paving the way to a comprehensive vision of "Space EMSO" concept, which is a crucial enabling factor for military mission operations, increasing the battlefield situational awareness and fostering decision-making processes. The developed project has the objective to highlight space domain importance in a simulated military scenario, harmonizing multi-domain actions by modelling systems exploiting the electromagnetic operative environment potentialities.

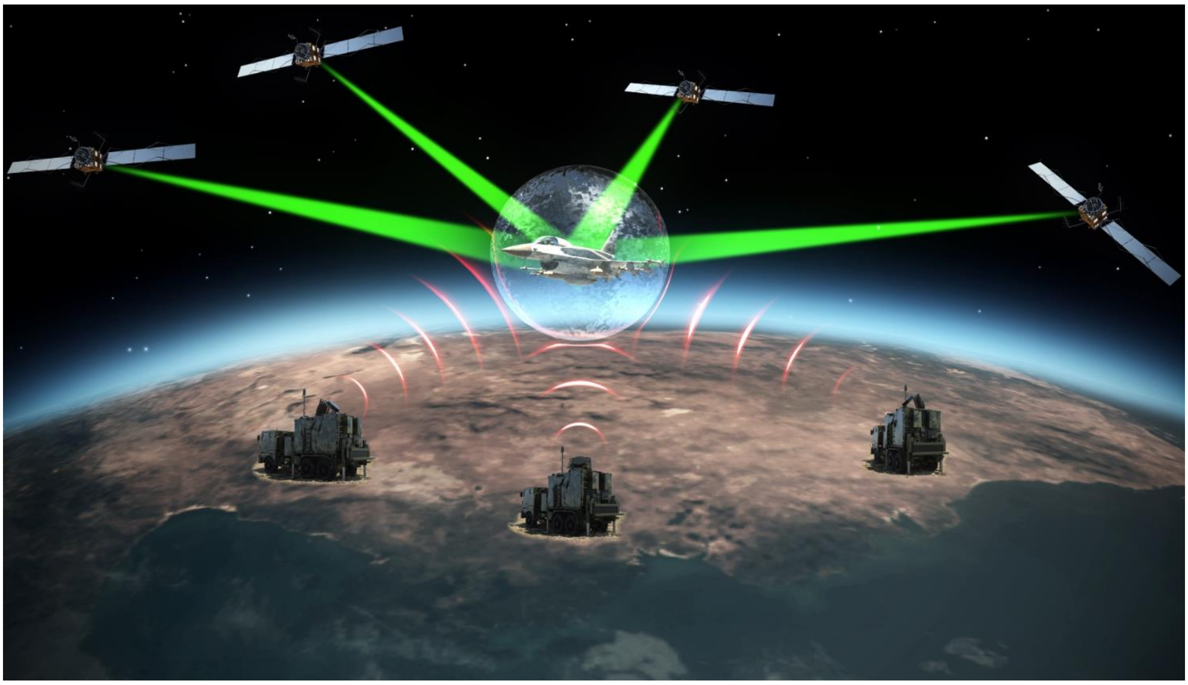

Figure 2: Animation of a multi-domain assets using electromagnetic operating environment.

CHAPTER 2: ELMO (ELECTROMAGNETIC LAYER FOR MULTI-DOMAIN OPERATIONS)

Project conceptual idea

The conceptual idea of the ELMO project is described by an architecture that explains the functional interconnection of the main blocks used for the implementation. The modelling and simulation (M&S) architecture consists of the following elements of interest:

- Matlab/Simulink: used to perform the mathematical modelling of the fundamental electromagnetic blocks to build the virtual objects in the synthetic scenario. This modelling phase mainly focuses on the constitution of the functional and behavioral algorithms of the systems.
- AGI STK (Systems Tool Kit): used for the construction of the synthetic environment useful for scenario configuration and for electromagnetic simulations calculations. This is important for the definition of the electromagnetic component that, in military operations, affects the four fundamental domains (land, air, maritime and space - multi-domain impact of the electromagnetic component).
- Matlab-STK interconnection: the project is based on dynamic and continuous data exchanging between EM (Electromagnetic) models synthesized in Matlab and simulation results provided by the STK tool. In particular, an interaction is carried out between the functional algorithms of the models and the real-time results of dynamic EM propagation provided by the simulators.
- Artificial intelligence: considering a possible long-term future development, it was conceptualized to merge potentialities offered by EDT (Emerging Disruptive Technologies), such as artificial intelligence, with the described project, creating specific neural networks in feedback with the synthetic environment. In particular, by receiving data from STK, the neural network could be trained on multiple simulations (versatility offered by M&S applications that allow obtaining stochastic results according to specific operating algorithms – Computer Assisted Wargaming). Furthermore, the deductive results produced by the neural network, could provide, among the other things, the configuration parameters of the EM models, maximizing an objective function that considers new threats, scenario parameters, level of effectiveness and level of interoperability to be obtained.

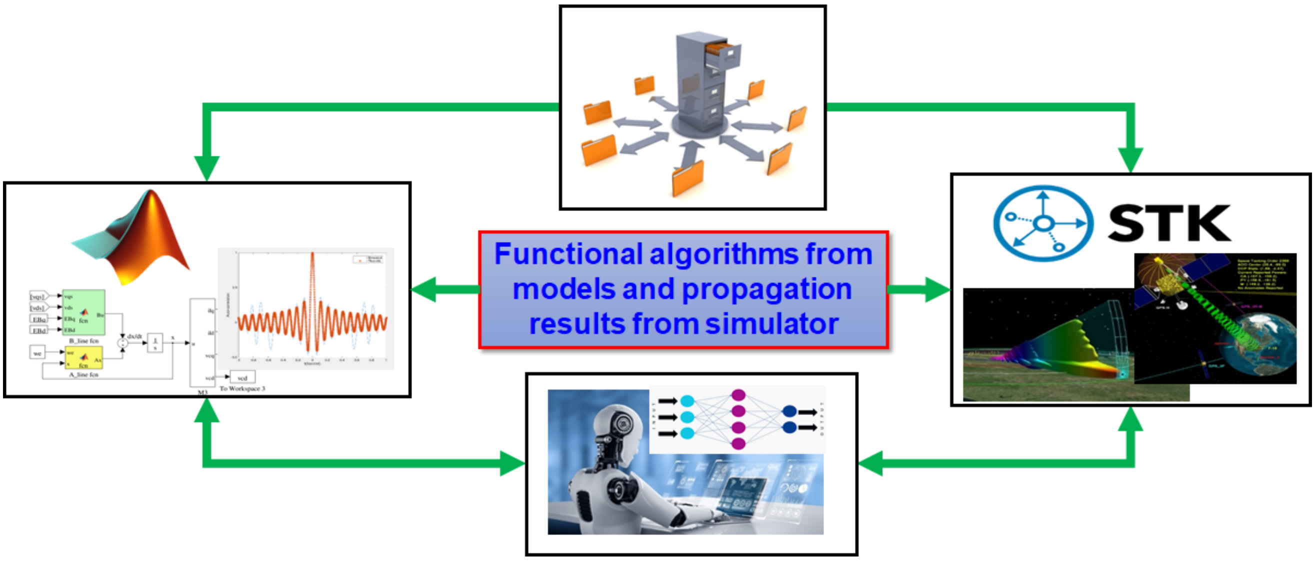

Figure 3: Conceptual idea of ELMO project (functional-logical architecture).

ELMO data integration

To make an example, in order to replicate a complete operating cycle of the proposed synthetic electromagnetic environment, the following logical operations are reported, based on the creation of two generic models of receiver and transmitter:

- The transmitter model is based on the programming of a specific operating algorithm, which, depending on the input parameters, will provide a specific output. In particular, the spectrogram matrix of the generated output signal (time, frequency, power) could be calculated as output.
- Through a connection between the STK tool and Matlab, made for example with special APIs (Application Programming Interfaces), with bi-directional characteristics (input/output), the matrix values of the output signal, associated with a specific virtual object inserted in the simulator, constitute the input of the antenna to proceed with the calculation of the propagation results. The bidirectionality of the mentioned connection between a mathematical simulator and a scenario simulator, with mainly propagative purposes, would allow generating results in terms of input data for further mathematical models.
- The receiver model is based on the programming of a specific operating algorithm, which, depending on the input parameters, will provide a specific output. In particular, certain behavioral feedback connected to the functioning of the modeled receiver device could be provided as output. This information will be transmitted within the synthetic environment to provide electromagnetic situational awareness and, possibly, carry out actions of an operational, technical and/or informative nature.

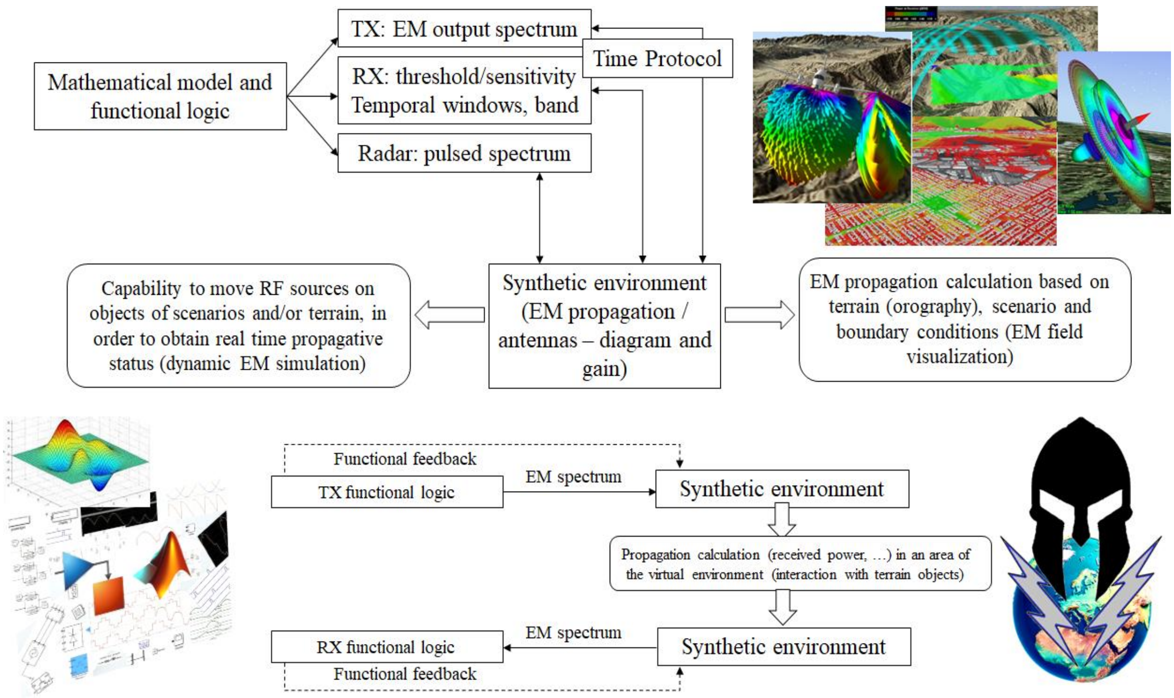

Figure 4: Flow chart (example) for data integration implementation between the modelling and simulation component.

Therefore, Matlab/Simulink tool is a fundamental component of the ELMO project, especially in the modelling phase of peculiar EM systems, such as those used in a multi-domain electronic warfare context. In this case it is important to be able to create a behavioral model that reflects the functional logic of systems used in military operations (digital twin), defining the architectural blocks of a transceiver chain, except the radiating elements. In fact, the antennas will be inserted directly into the

virtual environment defined by STK, obtaining the radiation pattern desired for the specific electronic system to which it is connected.
The construction of models is a complex engineering operation because it is important to define a specific technical level on which structure logical operations of behavioral algorithm and, moreover, to make a general-purpose model. This last feature is significant since it enhances the importance of the M&S tool applied to the military technological sector, ensuring, firstly, versatility of use through the virtualization process. Having a generic model available allows performing multiple technical-operational configurations, easily replicating different system architectures that could be assimilated to specific types of equipment supplied to the Armed Forces. Results obtained by the ELMO system are therefore related to a specific behavioral models of EM systems defined in Matlab and, therefore, take on greater technical-operational value with respect to EM layer in multi-domain military operations characterization. The versatility inherent in the models is also a key point in the experimental phase of ELMO synthetic environment, concerning the definition of systems of systems, such as gap filler type. The availability of electronic system models allows interfacing different apparatuses designed to cooperate for a common purpose, for example in Forces protection, and to exploit the ELMO synthetic environment to carry out technical and operational verifications, on the premise of any experimental activity in the field. This would have a benefit to analyze and maximize awareness of activities that, albeit with experimental premises, have a direct impact on operational and information structure.

Project applications

The creation of a synthetic environment for electromagnetic operations provides an increasingly crucial aspect for the fulfillment of multi-domain missions complying with progressive technological increase of threats, in a context of Electronic Warfare. The virtualization of the EM operating environment and interconnection intrinsic transversal feature with the main military domains allows performing a computer assisted wargaming, in order to achieve the so-called best CoA (Courses of Action). In this regard, the conceptual analogy between a best CoA approach and obtaining technical, operational and information awareness aimed at defining the most effective electronic countermeasure (best countermeasure) is interesting. Once a scenario is virtualized, in terms of factions, types of platforms and systems, rules of engagement and objectives to be pursued, in line with the operation plan, by applying the concepts of computer-assisted wargaming, it is possible to develop technical and training skills to better manage the EM component, correlated to friendly and enemy Tactics, Techniques, and Procedures (TTPs). In addition, this situational approach would allow studying the perpetration of EM actions, from a multi-disciplinary point of view, mitigating any side effects (e.g. characterizing impacts in the cyber space used for the civil population).
The ELMO project can be used to integrate technical, operational and informative data. For instance, in an Electronic War context, the main identified impacts of using ELMO can concern using of electromagnetic countermeasures for Forces protection. The visualization and quantification of the electronic protection performance, albeit simulated, represents the starting point for expressing subsequent operational considerations and facilitating the decision-making process of the Commanders, providing it with information and feedback obtained from the electromagnetic component.

CHAPTER 3: ELMO SCENARIO

STK overview

The synthetic environment for studying and analyzing Electromagnetic Spectrum Operations has been created interfacing Matlab and STK, exploiting an interface communication in order to be able to implement a bi-directional link between the two tools. This integration represents the core part of the whole project.
STK is a software for digital mission engineering and systems analysis, which allows to model and simulate complex systems in their operational environments. With STK, it is possible to model complex systems inside a realistic and time-dynamic three-dimensional simulation that includes high-resolution terrain, imagery, RF environments, and more.
STK enables to create multi-domain scenarios that extend simulation beyond systems to an interactive model of the operational environment. Define and understand complex relationships between objects and analyze their performance over time. STK is composed of different modules, which have been developed with the aim to go deeper in several fields of application of digital mission engineering. The STK tool and its related modules allows building and using a synthetic environment both for support operations and for concept/capability development. In this regard, STK has been used to build, plan and analyze a multi-domain scenario based on EMSO, where the role of the Space Domain is highlighted as a key factor for obtaining a military advantage on the battlefield.
Within ELMO project conceptual idea, STK is also used for managing all the antennas involved in the military mission. These antennas include both the ones connected to internal STK model and the ones connected to Matlab external models. This represents an important aspect conceptualize for the project implementation, since it defines a clear technical border between STK and Matlab main functions, centralizing in STK all the electromagnetic propagation aspects, including electronic to electromagnetic transduction, visualizing antennas propagation diagrams. This technical conceptual choice has been done, firstly, for simplifying the STK and Matlab coherent integration, which represents a good starting point for implementing practical steps within an initial proof of concept realization and, secondly, because the models of antennas available in STK cover a significant range of application in EMSO. The capabilities of creating and managing antennas and the basic concepts embedded in the Communication module of STK tool are reported, since they represent the main technical fundamentals on which base the electromagnetic propagations simulations used for this project.

Embedded Antenna

When an embedded antenna component is selected, the component definition is copied into the transmitter, receiver, or radar object. Additional changes made to the transmitter, receiver, or radar object will not affect the original antenna component.

Linked Antenna

When a linked antenna object is selected, the antenna definition is available only for viewing with the transmitter, receiver, or radar object. Any modifications made will affect all transmitter, receiver, and radar objects that are linked to the antenna object.

Linking to an Antenna that Resides on a Sensor

In order to model actual, real-world configurations as closely as possible, STK anticipates that the antenna object will be placed on the sensor, so it can inherit sensor properties such as location and pointing. On the other hand, radar, receiver, or transmitter objects that link to this antenna must reside on the sensor's parent object, not on the sensor itself. It is helpful in this context, to think of the sensor as the gimbal for the antenna, while radar, receiver, or transmitter merely represent electronic components that do not require pointing and whose location does not affect RF properties.

STK communication link

STK allows a radar, receiver, or transmitter object to be placed directly on a sensor, the use of embedded antennas is the only available option in this case.

Moreover, STK allows to determine the times one object can "access," or see, another object. It is possible impose constraints on accesses between objects to define what constitutes a valid access. These constraints are defined as properties of the objects whose accesses are being calculated. This capability is used in STK Communications to define communications links.

Two types of communications links can be modeled: basic and multi-hop. To create a basic communications link, simply an access between a transmitter and a receiver has to be defined. By changing the receiver constraints, it is possible to define the limiting characteristics of the link to analyze.

Communications links can only be defined between receivers and transmitters. Although an access can be calculated between a receiver or transmitter and other objects in STK, the communication parameters are not used to determine whether an access exists and the communications link data is unavailable.

To create a multi-hop communications link, it is possible to define a group of communication objects consisting of a transmitter, receiver, re-transmitter, and another receiver. The group of objects is specified by creating a chain object using a chain, where the transmitters and receivers are listed in the chain in the order that the signal must pass through. More complex multi-hop links may be analyzed by creating constellations of receivers and transmitters for use when creating the chain.

Link Budget Report

The Link Budget report includes the entire link parameters associated with the selected receiver or transmitter. Link budget reports consider light speed delay. Link budget reports take computed refraction into account if enabled on the transmitter or receiver objects. The model settings used to compute refraction for the transmit side of the link will be taken from the transmitter object and the model settings for the receive side will be taken from the receiver object. Depending on the model types of the objects involved, some parameters may be blank when the report is generated.

Main fields in the basic Link Budget report are:

- Time: Scenario time.
- EIRP: The effective isotropic radiated power in the link direction. This value is the power of the transmitter (in dBW), plus the antenna gain (in dB), plus any filter and post-transmit gains/losses (in dB).
- Rcvd Iso Pwr: Received Isotropic Power at the receiver antenna. The value is defined in the bandwidth of interest and therefore includes bandwidth overlap factor.
- Flux Density: Power flux density at the receiver antenna. The units for this are dBW/m2.
- g/T: Receiver gain over the equivalent noise temperature. Units are dB/K.
- C/No: Carrier-to-Noise density at the receiver input.
- Bandwidth: The receiver's RF bandwidth will be equal to the user specified bandwidth if the autoscaling option is disabled for the receiver. Otherwise, it will show the bandwidth that the receiver is using to match the transmitted signal. If spread spectrum/CDMA is enabled, the bandwidth will be the spread bandwidth.
- C/N: Carrier-to-Noise ratio at the receiver input.

- Eb/No: Signal-to-Noise ratio at the receiver.
- BER: Bit Error Rate.

Communication system

The communication system is an object defined in the scenario, useful to perform an analysis on a complex communication system involving receivers, transmitters and interferences deployed in the virtual environment. To manage many receivers and transmitters of the same type, through constellations objects in STK is possible to group many electromagnetic devices and define the link budget conditions. For example, the constellation of transmitters composed of satellite GPS payloads can be grouped in the same virtual object in the scenario and subsequently perform a link access towards a GPS receiver. Using the communication system, STK automatically can provide the link budget using the minimum range or the maximum C/N criteria. Nevertheless, STK communication system object represents the key factor for analyzing the propagation and signal effects of a radio frequency interference (such as a jammer). In this context, STK tool is able to provide many data, reporting several parameters useful for analysis of an electromagnetic communication considering also wanted or unwanted interference, which can affect the information at the receiver. In particular, the simulation analysis has been focused on the following parameters of communication system object:

- Eb/(No+Io): The energy per bit to noise-plus-interference ratio (Eb/(No+Io)), where Eb is the energy per bit, No = kT (Boltzmann's constant * system temperature), and Io = interference power spectral density.
- BER+I: Bit error rate in the presence of interference (BER+I) is the probability that a bit is in error (i.e. a zero is transmitted but a one is received) in the interference environment. The BER+I is the number of bits in error divided by the total number of bits sent. STK uses table lookup from a modulation file to extract a BER+I given an Eb/(No+Io). STK interpolates the table as necessary to determine the appropriate bit error rate for a particular bit energy level. If the bit energy is smaller than the first value in the table, the bit error rate for the first value is used. If the bit energy is larger than the last value in the table, a default bit error rate of 1.0e-30 is used to indicate no errors.
- J/S: J/S is the jammer to signal ratio.

STK makes available a spectrum analyzer that has been very useful to verify the synthetic radio frequency signals emitted by each internal or external transmitter models. Moreover, this simulator embedded functionality allows also to virtually lock the spectrum analyzer in available receivers defined in the scenario, monitoring the radio frequency situation after first stage receiver (antenna, low noise amplifier and channel filter).

STK Object Model

The STK Object Model is a collection of COM (Component Object Model) libraries (STK Objects, STK X, STK Util, STK Graphics Primitives, STK VGT (Analysis Workbench), and STK Astrogator) containing types, interfaces, events and classes representing various aspects of the STK application structure, which is designed to make it easy for building custom solutions using STK and the STK Engine. The various components provide developers with capabilities to control and automate STK objects, manage the lifetime of STK objects, access Data Provider Tools, perform access and coverage computations, and respond to events generated by STK.

The STK Object Model is built on Microsoft COM technology and can be used in environments supporting standard COM automation. The STK Object Model is available for use with STK as well as custom-built STK Engine applications.
STK and MATLAB can be integrated using connectors developed by AGI or by accessing STK's COM interface.
Advantages of STK-MATLAB integration mainly concerns analysis's automatization, extension or visualization.

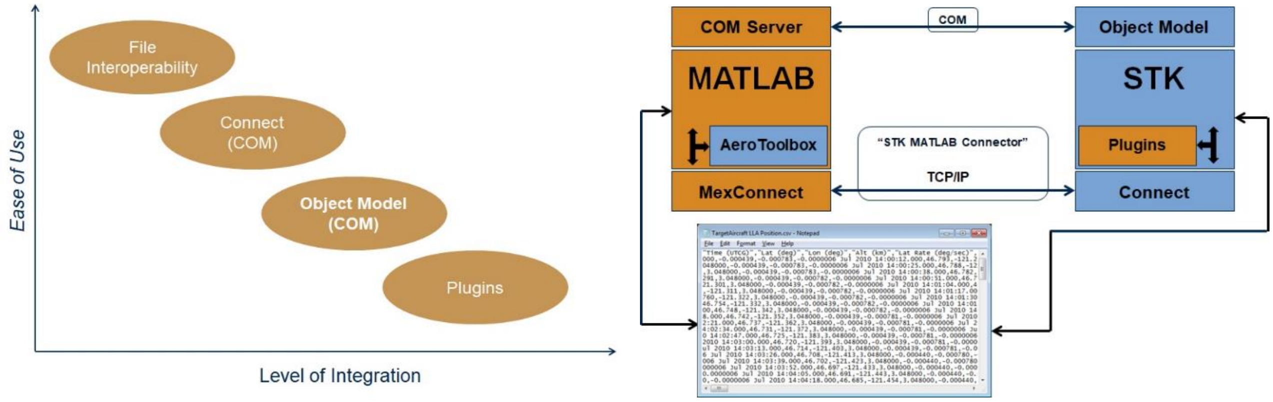

Figure 5: STK and Matlab level of integration graph and conceptual schematic interface.

Conceptual ELMO scenario

In order to implement a proof of concept for the project ELMO, a simulated scenario has been created. The main characteristics of this scenario are the following:

- The creation of a vignette in a multi-domain environment.
- The importance of the space domain for situational awareness increasing in the future operating environment.
- The key role of the electromagnetic spectrum operations for a military operation mission's accomplishment through the generation of tangible and multi-factorial effects on all the military domains, acting on operative and informative elements.

The space domain has been highlighted for its intrinsic peculiarities, which make it very suitable for new concept development and for mission conduction, involving non kinetic effects through the use, the management and the control of the electromagnetic spectrum.
The implemented scenario has been developed in Orlando city, in Florida, where a digital terrain has been created for the simulation analysis and propagation calculations. Generally, a synthetic terrain in a modeling and simulation tool is composed of:

- Shape files, which contain vectorial data for geometric elements definition, such as lines, points, polygons, etc.
- Elevation files, which can include ASCII values with information of the terrain profile.
- Raster files, which is a georeferenced picture of the selected terrain.

Each modelling and simulation tool manages the terrain generation files in different ways. In STK, a synthetic terrain for analysis has been created from a jpeg file. In addition to the terrain file, a satellite photo has been overlapped to have a fully visualization of the synthetic scenario which is going to be created. In STK, it is also possible to add buildings present in a city, configuring a shape file containing, for instance, the polygons describing the buildings. The described operations have been done in Orlando city, in order to set the virtual terrain for analysis and for visualization of the

simulation in a 3D perspective. Moreover, has been inserted a 3D tile object in the simulator, which simulates a military headquarter, in Exton, USA.
After the synthetic terrain definition, the virtual mission has been configured and, consequently the digital platforms with several attached devices.
To better understand the implemented scenario, it is important to specify that the units are presented in two factions, blue and red forces, according to the electromagnetic military actions that are going to conduct in the synthetic environment.

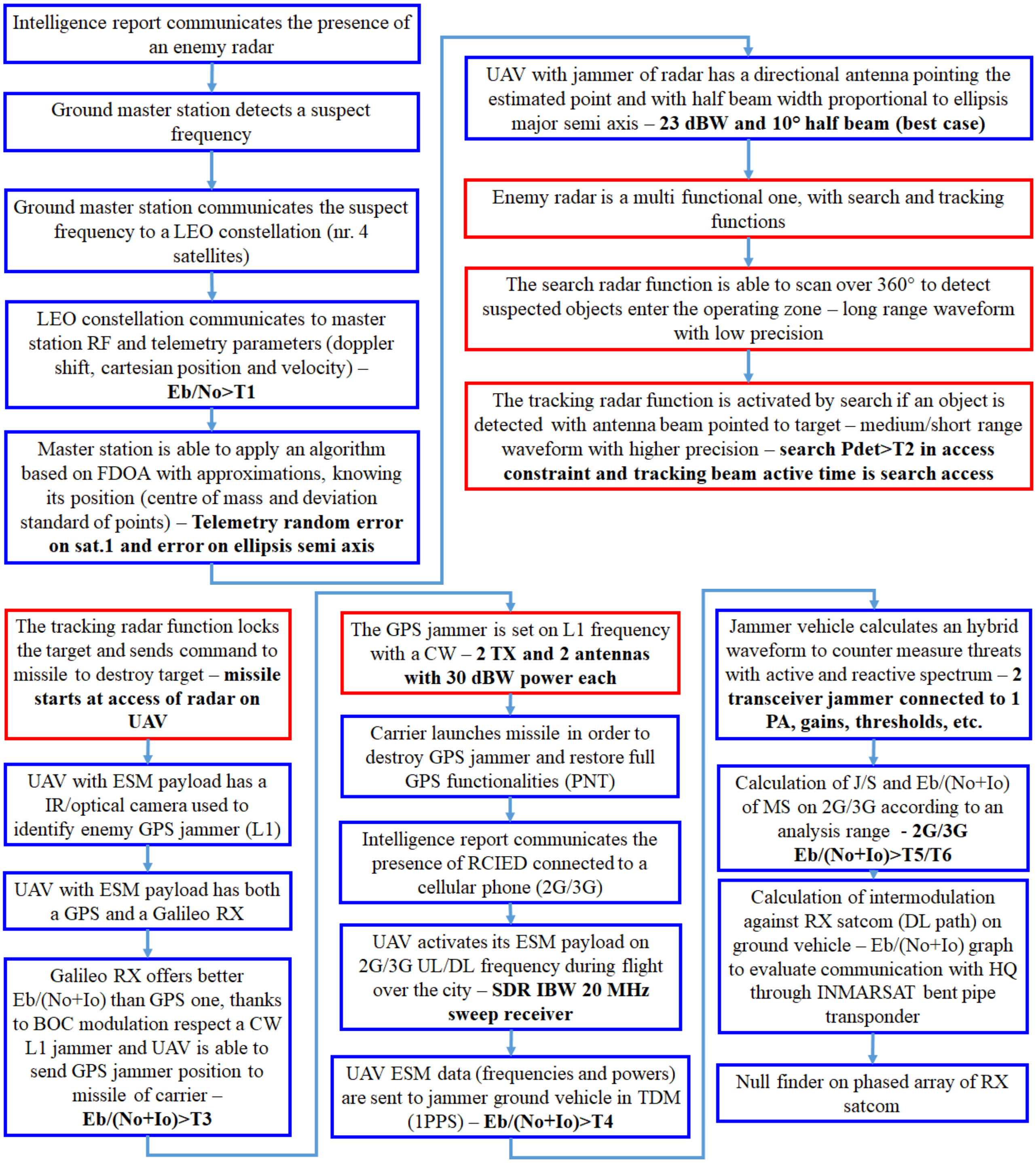

Figure 6: Scenario main actions (blue or red boxed indicate if an action is performed by blue or red forces units).

This scenario contains several EMSO actions, in particular:

- EA (Electronic Attack): the UAV performs an EA activating the on-board jammer toward the enemy radar;
- ESM (Electronic Support Measurement): the ground master station is able to send suspicious threats detected after a spectrum monitoring to LEO constellation for direction finder to geo-localize the enemy radar. In addition, the UAV is able to monitor the electromagnetic spectrum in an urban area, in order to send information to a ground vehicle jammer;
- ED (Electronic Defense): the ground vehicle is equipped with a hybrid jammer, automatically configuring system's reactive phases through UAV ESM actions and with a pre-programmed waveform in the active phases. These actions can be performed both in time sequence and in time parallel.
- Electromagnetic interoperability:
  - Time domain: 1PPS generated by GPS receivers of the platforms allows creating a synchronized time protocol regardless the military domain where the platform operates;
  - Modulation: the use of Galileo signal for Positioning purpose allows having a lower interference with respect to a high power and continuous wave L1 GPS jammer;
  - Antenna beam forming: the ability of a simulate phased array to create a null finder toward an interference source, providing, at the same time maximum gain in satellite direction, can improve the Signal to Noise Ratio of the communications.

External Matlab models

Matlab tool has been used to build digital models of electromagnetic systems, which are not available in STK. In particular, STK despite provide many embedded models for different electromagnetic systems, is not able to cover the overall spectrum of military electronic devices that can be employed in the future operating multi-domain environment. In particular, the military electronic devices are often designed as system of systems, implementing custom algorithms and based on specific logic connections and hardware architecture. For instance, at the same transmitter power and bandwidth, two different electronic counter systems designed with two different circuital architectures and with two functional logics, can show a wide difference performance in terms of level of effectiveness against the same threat, in the same scenario boundary conditions. Another important aspect to consider is the electronic waveform programmed and implemented inside the system defining methods for receiving and transmitting electromagnetic signals.

In this context, Matlab is considered as an expert modelling and simulation system where, through a code-based approach, it is possible to create a digital model of any specific device which can be used in the EMSO context. The models are created as digital twin of a real system, in terms of behavioral and functional algorithms, for experimenting and verifying many results, obtained implementing different technical or operative configurations in the synthetic environment.

Among the models created within the ELMO project, two digital models of systems are reported below, in order to better clarify the concept expressed for the M&S supporting EMSO and to show potential capabilities defined by Matlab and STK integration. These Matlab models have been based on a specific and simple characteristic which links the current and the future digital systems in the virtual environment: the flexibility of a general-purpose architecture, which represents the cornerstone for further considerations and experimentations. The achievement of the general-purpose characteristic is essential in a modelling and simulation project, since, in this way, it is possible to test many hardware and software configurations of the same systems, by changing input variables or applying minor changes in Matlab scripts, allowing to conduct a multi-factorial analysis through the simulation. Furthermore, the need to be versatile and general purpose is crucial in the concept development and experimentation field, mostly for studying and analyzing a complex problem using a comprehensive approach method.

As first proof of concept, a military jammer has been created in Matlab, which integrates different functionalities:

– Active jammer: a device that involves only transmitter chains and it works, usually, with an electronic waveform created in pre-mission phase, according to radio frequency information of operation area.
– Reactive jammer: a device that involves both transmitter and receiver chains, able to create a radio frequency spectrum in response to the electromagnetic environment in the operation area, according to configured timing and frequency parameters.
– Hybrid jammer: a device that can perform both active and reactive phases, using a single chain (time sequence) and/or a multi chain configuration (time simultaneity).

The realized digital model of jammer system defined in Matlab corresponds to a hybrid system, since this is the most complex architecture, in terms of functional phase’s integration. For this reason, a specific setting of the input and control variables allow to simulate also an only active and an only reactive jammer. Furthermore, in this digital model is possible to choose the hardware configuration of the electronic counter measure system, in terms of number of transceivers and power amplifiers, and the software configuration expressed as configuration typology (single or multiple chain). These technical aspects make the model general-purpose and its scripts composition gives usage modularity, providing an easy way to create different system architectures.

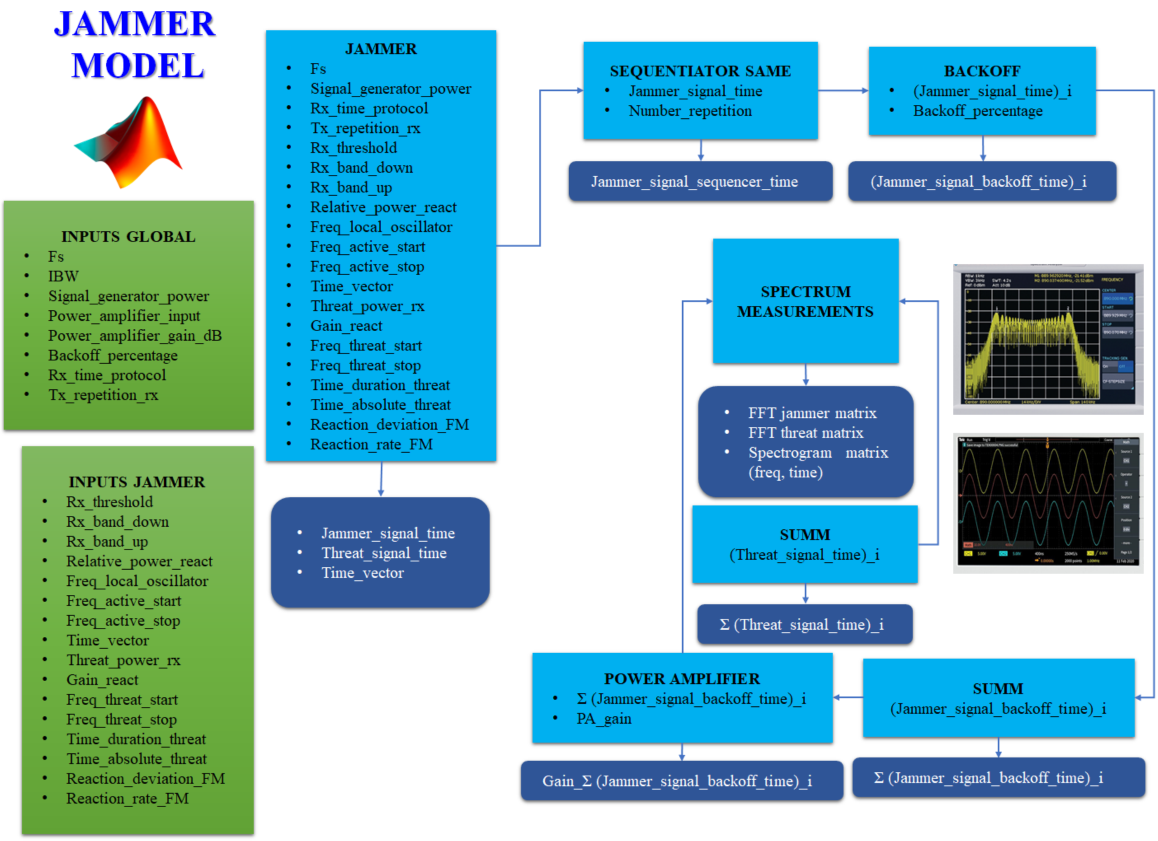

Figure 7: External Matlab jammer model – input variables, functional blocks and related outputs.

Another digital model created in Matlab is a Radar Warning Receiver (RWR), an electronic system installed on board an aircraft or a helicopter, as a radio frequency sensor for the radar threats. The system is configured in a specific band of interested and with a pre-mission library, which is used to classify a further incoming threat. The expected output is to provide information both to pilot and crew, in order to make related flying procedures and to release manually or automatically counter measures (jammer signal or chaff), thus building an electronic defense against missiles with a radar guiding. Although the RWR model has been created and tested, it has not been used for the developed scenario.

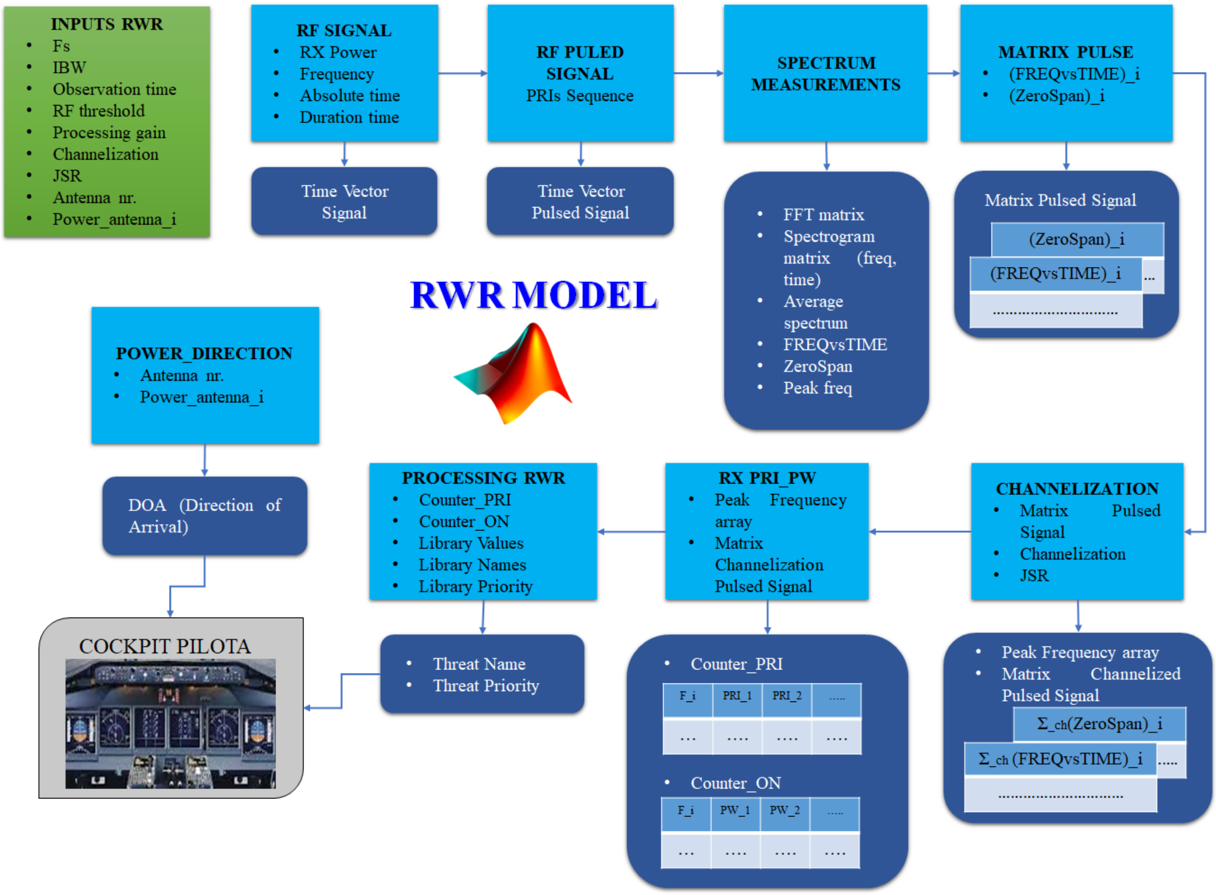

Figure 8: External Matlab RWR model – input variables, functional blocks and related outputs.

The electromagnetic device used in STK have been built on the available models of complex receiver and transmitter available in the simulator. This choice is essentially due to the highest level of versatility offered by these models' configurations, in terms of device specifications, antenna, modulator/demodulator, filter components, additional gains or losses inserted in the radio frequency chain and system temperature characteristic (only for receiver objects).

Technical insight on space domain and electromagnetic environment

<u>DF LEO constellation</u>

A LEO constellation has been created in order to perform an electronic intelligence (ELINT) action on the adversary devices in the battlefield. In particular, a constellation composed of 4 satellites has been inserted in the STK simulator, at 500 km altitude, designing circular orbits with 75 degree inclination, in parallel planes. The four orbit planes are separated, in terms of RAAN (right ascension of ascending node), with a fixed value equal to 1 degree. At the start time of simulation, it is assumed that these satellites are passing over the operating area, performing their measurements for ELINT purposes. In a real scenario, the overall military mission, being its effectiveness consequence of the direction finder result, has to be planned, in the same way, when the LEO satellites passage will cover the operating area. The ELINT system created in this scenario reflects a multi-domain approach, since it is composed of the 4 mentioned LEO satellites with their related radio frequency measurements and of one ground master station installed in the operating area. The ground master station's main functions concern the command/control of the space assets and geo-localization algorithm implementation.

In particular, the logic processes and the technical elements of the modelled ELINT system is reported below:

- Ground master station is equipped with a radio frequency receiver, able to scan the electromagnetic spectrum in a wide frequency band. This is a sweeping receiver, whose configured scan band are evaluated by a pre-mission intelligence report about the possible presence of an enemy radar working in C band. The master station receiver is able to detect a suspicious signal in the radio frequency spectrum, knowing that a potential threat is present in the operating area, which can be placed in a theoretical circular area with around 100 km radius. This assumption is based on the orographic characteristic of the terrain, the frequency band communicate by intelligence cell and the gain of the receiver chain (antenna and low noise amplifier) configured in the model. Once the suspected signal is detected, the master station asks to the LEO constellation to collect further information, providing them the received frequency value, in order to estimate the position of the enemy threat and plan, subsequently, the future military actions. In addition, the ground master station has been equipped in the simulator with another receiver connected to a hemispherical antenna whose function is to communicate with LEO constellation and collect the information after its passage over the operating zone.
- LEO satellites are equipped with a radio frequency sensor, composed of a software-defined receiver and a parabolic antenna with 15 degree half beam width mounted in nadir configuration. The satellite receivers are able to calculate the Doppler shifts of the incoming signals, with a configurable sampling frequency (time step of the simulation section). Moreover, each satellite sends to the master station also its own telemetric status, in terms of Cartesian position (x, y, z) and Cartesian velocity (vx, vy, vz). The effective time useful for estimating the target position by master station, in this situation is around 40 seconds.

  The satellite communication of the satellite constellation with the master station has been also simulated in this scenario, where a fixed threshold has been set in Matlab script for evaluating if the information will arrive to the master station. The threshold has been defined on Eb/No parameter. The current threshold test for this scenario is 10.5 dB, considering that for this satellite communication a QPSK has been chosen, since the amount of exchanging data is small, obtaining more robustness if compared to other higher order modulations.

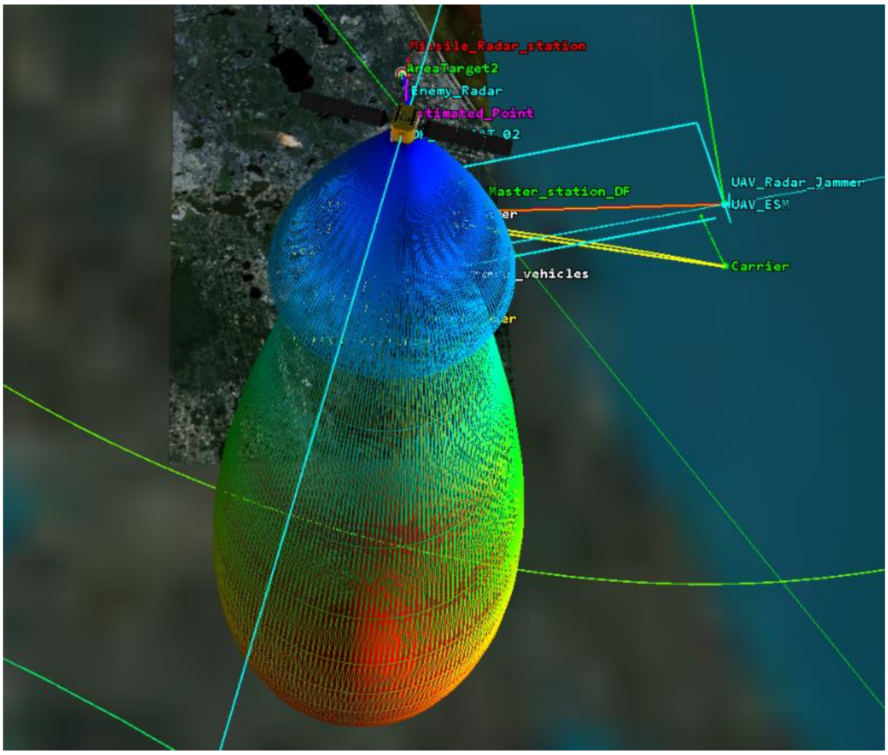

Figure 9: LEO satellite 3D object and antenna pattern view.

- To complete the direction-finding process, the ground master station is able to implement a FDOA-based algorithm with the received satellites data. This algorithm derives from the FDOA formulas, which link the measured Doppler shifts to related geometric parameters of receivers' pairs.

$$f_{i,j} = \frac{r_i\left[vx_j\left(x_j - x\right) + vy_j\left(y_j - y\right) + vz_j\left(z_j - z\right)\right] - r_j\left[vx_i(x_i - x) + vy_i(y_i - y) + vz_i(z_i - z)\right]}{r_i r_j}$$

$$r_i^2 - (x^2 + y^2 + z^2) - \left(x_i^2 + y_i^2 + z_i^2\right) + 2(xx_i + yy_i + zz_i) = 0$$

where

$$f_{i,j} \textit{ is the delta Doppler shifts between satellite } i^{th} \textit{and } j^{th}$$
$$r_i \textit{ is the range of satellite } i^{th} \textit{with respect to signal to localize}$$
$$(vx_i, vy_i; vz_i) \textit{ are Cartesian velocity components}$$
$$(x_i, y_i, z_i) \textit{are the Cartesian position components}$$
$$(x, y, z) \textit{ are the Cartesian position components of the target source}$$
$$\textit{same variables for each satellite present in the constellation}$$

In particular, rather than calculate the position of the transmitter to be localized respect to the measured Doppler shift solving a nonlinear equations system, has been implemented another mathematical approach, essentially applying a reverse formula of this canonical approach for FDOA. In this way, has been implemented an iterative approach, because the simulated algorithm is based on a target transmitter position guessing associated with a minimum finder applied measured satellites Doppler shift and calculated ones. The starting point of the first area guessing is the position of the ground master station, which detects the suspicious signal in the operative zone. Many guessing areas are created with subsequent tuning and refinements of the point's granularity, according to the variables set in the Matlab script.

The described approach for localization of a radio frequency source has been defined for this ELINT system employed in the virtual scenario, which involves conjunction action of satellite

and ground assets and, albeit with a loss of precision in the estimation results, it is suite for the system configuration to reduce the processing time of calculation.
Through addition of a Doppler shift threshold referred to each measured satellite data for algorithm calculation, is possible to increase the estimated point precision, avoiding for example particular orbital points affected by less geometric dilution of precision (considering the whole geometric system, which includes satellite and target transmitter).
The calculation of the algorithm is performed several times, according to suitable passage of satellites defined by master station and time step set in the simulation section. The estimated target transmitter point represents the center of mass of points' distribution, where has been also reported the standard deviation on latitude and longitude, to consider the width of this probability distribution in the simulated scenario. The final outputs are visualized also in the 3D visualization in STK, with the target estimated point and an ellipsis area where the semi-axis are the described deviation standards.

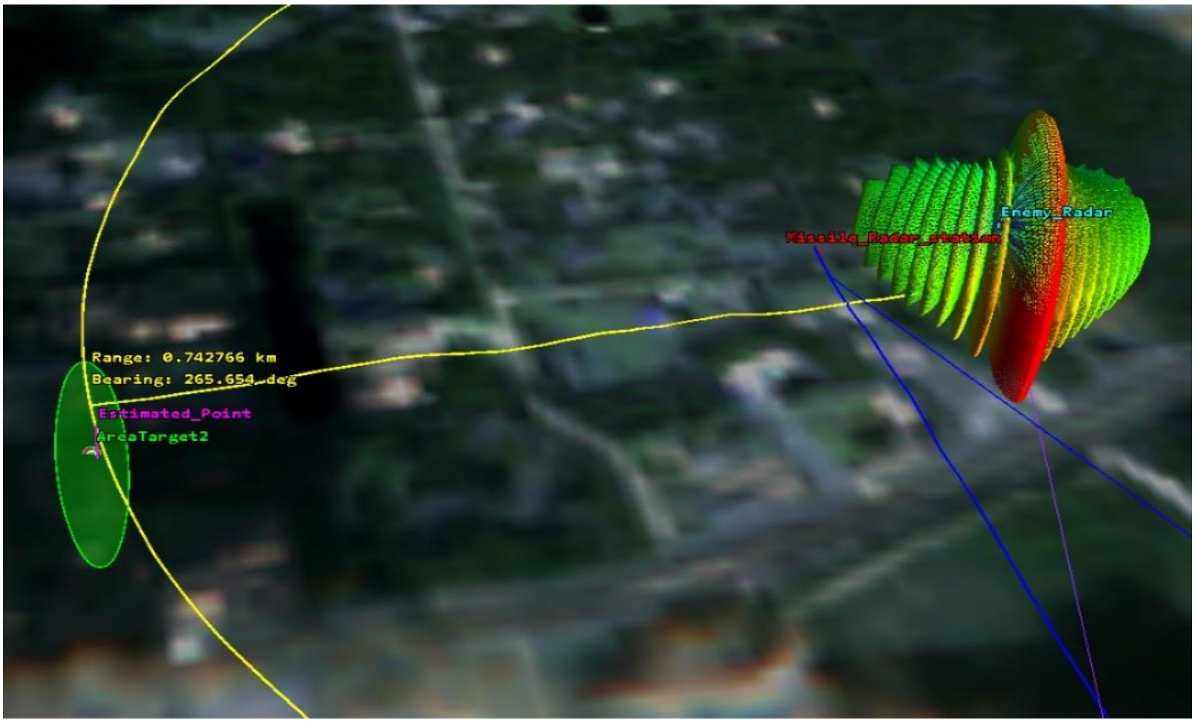

Figure 10: Estimated point and uncertainty area 3D object view.

- This space domain system for ELINT is essential for the blue forces actions. In particular, in the scenario another UAV has been placed, moving on the same flight route of the UAV ESM but with a different altitude. This UAV is equipped with a specific electronic system, which implements a narrow band jammer and a software defined antenna, in order to perform an electronic attack on the enemy radar in the operating area and to be not detected by it. The jammer has been modeled as a high power and single frequency device, to have electromagnetic effects in a wide range. It is configured in the pre-mission phases, knowing the suspicious threat frequency detected by the ground master station, carrying out a non-kinetic action on the enemy radar.
  The characteristic of jammer designed for enemy radar inhibition are the following:
  - Transmitter frequency: 3 GHz
  - Transmitter power: 23 dBW
  - Modulation: Narrowband Uniform

- Antenna type: Parabolic
- Antenna gain and half beam width: dynamically calculated by simulator.

Thanks to the LEO satellites, the blue forces are able to estimate the position of the enemy source in the operating area, providing also a level of algorithm uncertainty expressed by latitude and longitude standard deviation calculated on points' probability distribution. These information are provided by ground master station to this UAV, which is able to automatically concentrate the main lobe of the jammer antenna in the estimation area provided by ELINT system. The pointing of this dynamically changed directive antenna is in the estimated target point direction and the half beam width has been proportioned linked to the major semi-axis of the described uncertainty ellipsis area. For this aspect, many considerations have been done in the designing phase of this software-defined element, highlighting a trade-off between the directivity of the antenna and the precision of the FDOA based algorithm implemented for target estimation. The directivity dependence has been obtained starting from a best case, in terms of minimum obtained error of ELINT system, using an empirical approach by making many simulation and changing models' and scenario's parameters. These tests have provided a best-case error of 0.02%, expressed in terms of satellite altitude (500 km) and major semi-axis of the ellipsis area. Knowing this data, it has been set a half beam width of directive antenna equal to 5°. This represents the initial configuration made for this system, from which other directivity antenna values are automatically configured, according to results obtained by ELINT estimation algorithm. To be more directive means to be more effectiveness inhibiting the radar threats (less probability to be detected), but it also means to have a higher data trust (high precision ELINT geo-localization system).

Since the ELINT algorithm is based on the telemetry data of the LEO satellites' constellation transmitted to the ground master station, some errors can be introduced in Matlab code, in order to characterize the estimated target precision with respect to a data perturbation. The availability of different models in the synthetic environment allows to easily conduct these verifications, for instance, introducing a weighted random error on Cartesian positions and Cartesian velocities of satellite nr. 1. Another error source is represented by the frequency value detected by the ground master station and sent to the satellites' payload configuration. These introduced errors are very important to evaluate the whole multi-domain system performances.

- The enemy radar system has been modeled with a multi-function approach. The main functions embedded in this radar are search and tracking, changing different radar waveforms according to a strategy defined in the model definition. Search radar is a sub-system defined with a long-range waveform, designed to detect blue forces assets flying in the operating area. The main characteristics of search radar are the following:
  - Transmitter frequency: 3 GHz
  - Transmitter power: 40 dBW
  - Pulse Repetition Frequency: 0.001 MHz
  - Pulse Width: 1e-07 s
  - Antenna type: Uniform Aperture Rectangular
  - Antenna gain: 60 dB
  - Antenna polarization: vertical
  - Antenna half beam width: X = 52.17°, Y = 5°

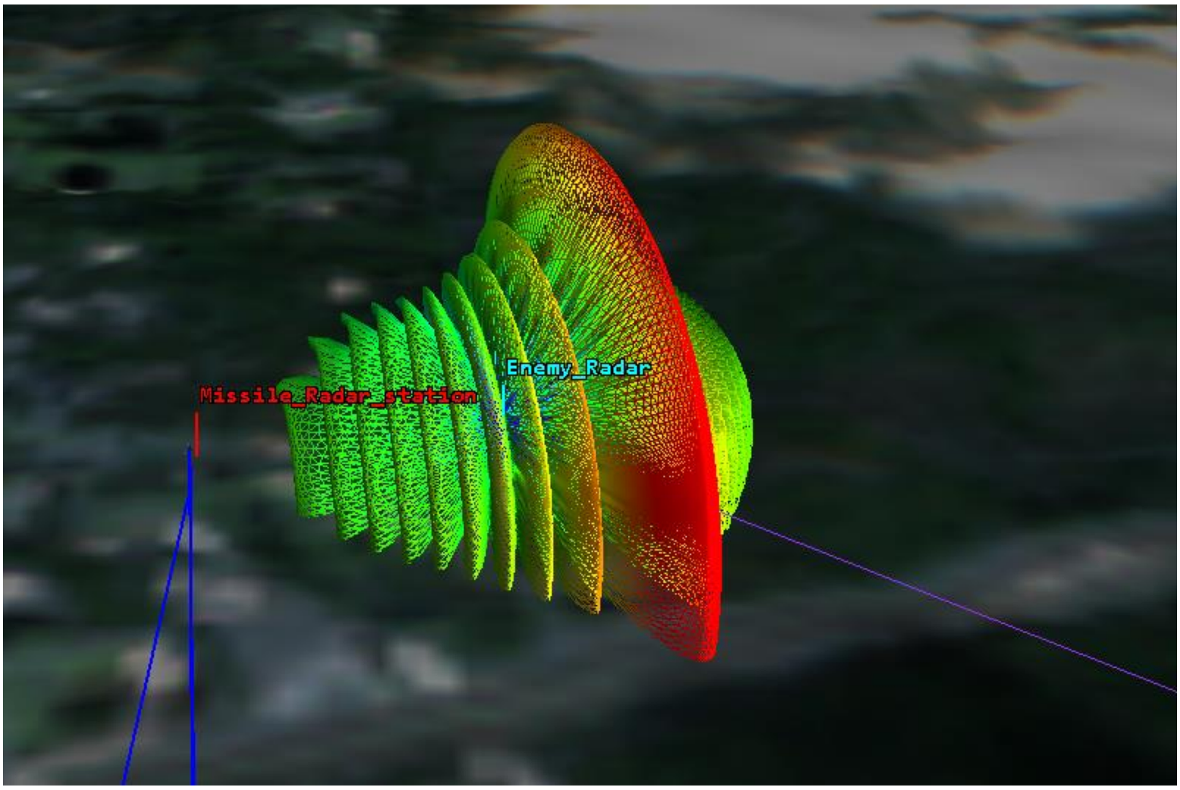

Figure 11: Search radar 3D object and antenna pattern view.

In this scenario, the radar targets are represented by blue forces UAVs, whose Radar Cross Section has been modeled in order to obtain a specific back scattered power at the radar antenna receiver. The search radar is the first layer of enemy protection, which implements an electromagnetic signal with timing and frequency characteristics aimed to obtain a long-range detection but with less precision (high ambiguity cell). In addition to a search signal waveform, a scanning radar antenna has been implemented, using a servo motor which is able to simulate an antenna movement in 360° azimuth zone. This scanning behavior is fundamental since the enemy radar does not know a priori the blue forces UAVs or aircrafts directions of arrival. The last layer of radar protection is simulated by implementing a tracking function, using a long/medium/short range waveform signal, with an increasingly wider pulse width and, therefore, a better range precision (low ambiguity cell). These functionalities are implemented by setting a radar waveforms strategy, whose decisional process is based on range from target object.

The tracking radar sub-system characteristic are reported below:

- Antenna type: Parabolic
- Antenna gain: 30 dB
- Antenna polarization: vertical
- Antenna half beam width: 1.4°
- Long range strategy: < 200 km
- Transmitter power (long range): 40 dBW
- Transmitter frequency (long range): 2 GHz
- Pulse Repetition Frequency (long range): 0.005 MHz
- Pulse Width (long range): 0.002 s
- Medium range strategy: < 60 km

- Transmitter power (medium range): 30 dBW
- Transmitter frequency (medium range): 3 GHz
- Pulse Repetition Frequency (medium range): 0.002 MHz
- Pulse Width (medium range): 0.0005 s
- Short range strategy: < 18 km
- Transmitter power (short range): 23 dBW
- Transmitter frequency (short range): 8 GHz
- Pulse Repetition Frequency (short range): 0.005 MHz
- Pulse Width (short range): 0.0002 s

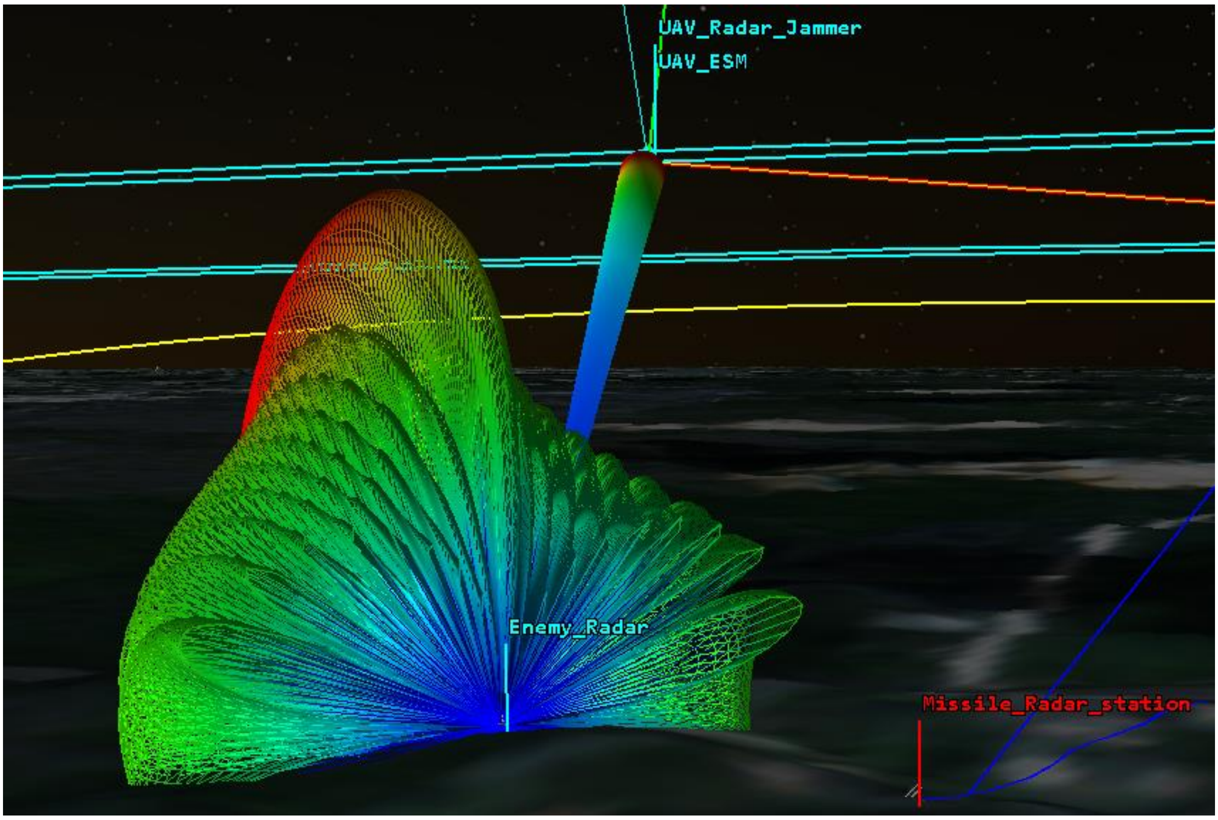

Figure 12: Search and tracking radar 3D object and antennas pattern view.

The tracking function is very important after a suspicious target has been detected by search phase, in order to follow the assets' movement and to provide missiles' guiding toward targets. An important feature of this multi-functional radar is the logical connection between search and tracking phases. In fact, the tracking function is only activated by a specific value of search function probability of detection. It means that the tracking waveform is triggered by the scanning searching one, because:

- the missiles before being launched need a precise guiding signal;
- the full-activated tracking waveform could result a higher electromagnetic visibility, making the radar system more detectable by electromagnetic monitoring systems.

For these considerations, it is very important to analyze search radar probability of detection and to insert a threshold value above which the subsequent tracking function can be activated. The radar parameter used for this simulation is the integrated probability of detection, that is a time integration of many radar's echoes, useful to achieve the most suitable signal to noise ratio. A suitable dimensioning of STK’s radar device is fundamental for studying both radar’s performances to detect a target asset and electronic attack effects on radar’s receiver stages.

GPS and Galileo constellations

The scenario includes both GPS and Galileo satellite constellations, which have a crucial role in the overall military simulated mission. The PNT (Position, Navigation, and Timing) technologies are progressively becoming more important to accomplish military tasks in an operative environment. STK allows easily inserting and managing satellites or constellations through an access to its satellites database and using related TLE epoch time. A two-line element set (TLE) is a data format encoding a list of orbital elements of an Earth-orbiting object for a given point in time, the epoch. Using a suitable prediction formula, the state (position and velocity) at any point in the past or future can be estimated to some accuracy. The TLE data representation is specific to the simplified perturbations models (SGP, SGP4, SDP4, SGP8 and SDP8), so any algorithm using a TLE as a data source must implement one of the SGP models to correctly compute the state at a time of interest. TLEs can describe the trajectories only of Earth-orbiting objects. TLEs are widely used as input for projecting the future orbital tracks of space debris for purposes of characterizing "future debris events to support risk analysis, close approach analysis, collision avoidance maneuvering" and forensic analysis. Having the orbits built, the next step has been to define a transmitter payload for both GPS and Galileo, in order to emit the related L1 and E1 signal for PNT purposes.

The GPS transmitter has been modelled with the main following characteristics:

- Transmitter frequency: 1.57542 GHz
- Transmitter power: 14.3988 dBW
- Modulation: BPSK
- Data rate: 50 b/s
- CDMA spreading factor: 20460
- Antenna type: GPS Global
- Antenna gain: 13 dB
- Antenna polarization: RHCP
- Antenna half beam width: 30°

The Galileo transmitter has been modelled with the main following characteristics:

- Transmitter frequency: 1.57542 GHz
- Transmitter power: 14.3988 dBW
- Modulation: BOC
- Data rate: 50 b/s
- CDMA spreading factor: 20460
- Sub-carrier frequency: 10.23 MHz
- Antenna type: GPS Global
- Antenna gain: 13 dB
- Antenna polarization: RHCP
- Antenna half beam width: 30°

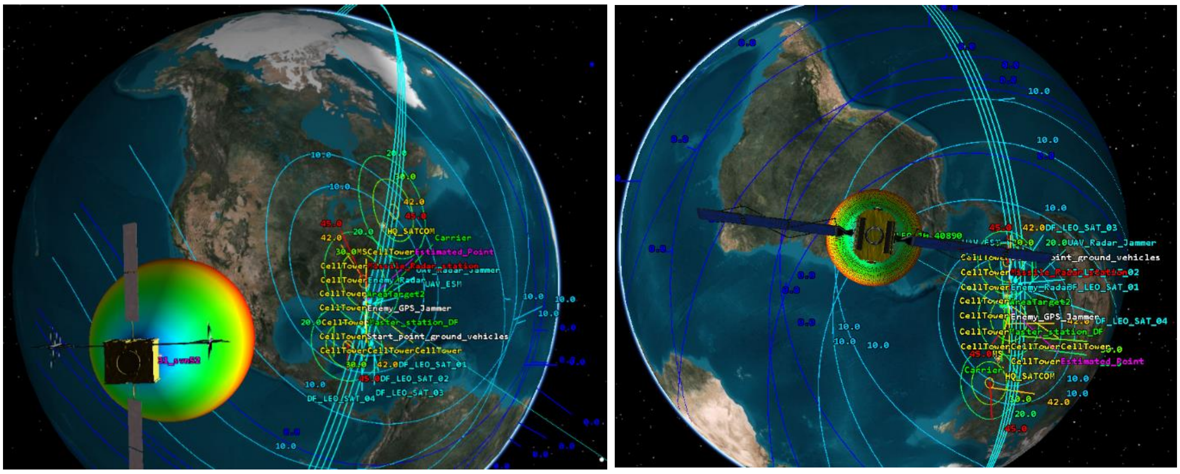

Figure 13: GPS satellite (left) and Galileo satellite (right) 3D objects and antennas pattern view.

The antenna used for both constellations has been chosen within STK antennas library, selecting a GPS Global type with nadir orientation. Associated with these GPS and Galileo satellite transmitters, corresponding receivers have been created in the scenario. In particular, the UAV for ESM is equipped with receiver able to detect and process both GPS and Galileo signals (multi-constellation receiver). Instead, the jammer ground vehicle is equipped only with a GPS receiver. All the units using a GPS or Galileo receiver have been connected to a GPS Fixed Reception Pattern Antenna (FRPA) available in STK library and oriented to zenith direction. The insertion of GPS and Galileo receivers is fundamental for the further technical considerations of the scenario, allowing conducting an analysis of the links budget, using the described STK communication system object. In fact, for each communication system, three constellation objects have been created:

1. GPS/Galileo transmitter which groups all the satellites payload defined in the scenario;
2. GPS/Galileo receiver which includes the single receiver;
3. GPS/Galileo interference, which includes an enemy GPS static L1 jammer, defined in the scenario.

Therefore, the utilization of communication systems in this scenario section is crucial to perform an evaluation on the possible effects of an interference device that acts on GPS and Galileo carrier frequency and analyzing the related robustness of each signal, with respect to the operative parameters that define the synthetic environment (routes of the platforms, type of antennas, distance of L1 jammer with respect to the receivers, etc.).

In this simulation, the technical objectives for this simulation section are described below:

– The UAV for ESM is able to send to the carrier the position of the L1 enemy jammer acquired with an on-board simulated infrared/optical camera with a specific field of view, triggering a kinetic action against this threat (launch of a missile). Although is present an enemy L1 jammer, the geographic position of enemy asset can be processed with UAV multi-constellation receiver (GPS and Galileo), showing the better Galileo signal resilience with respect to a continuous waveform jammer signal centered to carrier frequency (L1/E1). The described resilience, expressed in terms of Eb/(No+Io) measurements is connected to the specific modulation chosen for Galileo system, designed to be interoperable with GPS L1, working in the same carrier frequency. The results quantify Galileo received signal robustness with respect GPS one, through a differential Eb/(No+Io) parameter equal to 7 dB (including the received power difference adjustment between the two received signals). Therefore, by setting a specific threshold in Matlab script, it is possible to define an operative situation including GPS signal jammed and Galileo signal not jammed by adversary electronic attack.

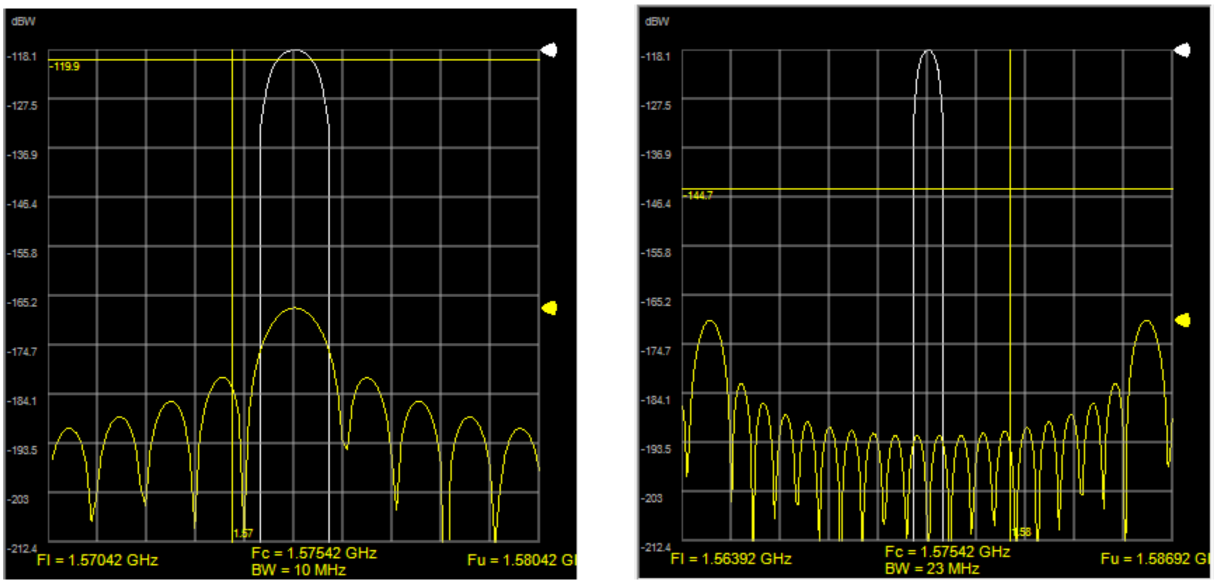

Figure 14: STK spectrum analyser in GPS receiver (left) and Galileo receiver (right) showing the jammer signal (white) and navigation signal (yellow).

The enemy L1 jammer has been configured with the following characteristics:

- Transmitter frequency: 1.57542 GHz
- Transmitter power: 30 dBW
- Modulation: BPSK
- Data rate: 1 Mb/s
- CDMA spreading factor: //
- Antenna type: Hemispherical
- Antenna gain: 3 dB
- Antenna polarization: linear
- Antenna half beam width: //

Figure 15: Enemy GPS L1 jammer station 3D objects and antennas pattern view.

- The kinetic action performed on L1 jammer destroyed this electromagnetic threat, restoring the functionalities of blue forces assets' GPS receivers. In this regard, a new simulation section is defined, involving the timing capabilities of GPS receivers mounted on-board the UAV ESM and jammer ground vehicle. These two GPS receivers are able to provide to other electronic devices composing platform's payload, a high-precision common timing reference, using the 1 PPS (one pulse per second) digital signal. As result, the systems receiving 1 PPS have synchronized each other, in order to be interoperable using a time division multiplexing approach. Therefore, a time protocol is generated in Matlab, alternating receiver and transmitter windows, within which different systems can exchange data accordingly. The simulated timing synchronized systems are:
    - The radio frequency receiver on-board UAV used for EMS purposes, scanning the urban area of the operating area, with receiver devices set to 2G and 3G uplink and downlink cellular bands. This information, used to configure the virtual receiver for ESM, has been simulated coming from an intelligence report about RCIED (radio controlled improvised explosive device) placement against the blue forces, connected to a 2G/3G mobile station. The UAV ESM receiver collects the radio frequency information according many input parameters that can be set in the model created in Matlab, among which it is important to mention the instantaneous bandwidth (Software Defined Radio simulated model), the total scanning bandwidth, the antennas characteristics (gain, directivity, beam width) and the pre-defined route of the asset.
    - The receiver sub-system of the hybrid jammer model architecture is able to receive the radio frequency information by UAV ESM action over the city and automatically generate a waveform with active and reactive characteristics, according to the programming and configuration of the electronic counter measure system. The final spectrum responds to a multiple chain hybrid jammer, which has been configured in the digital twin model for this specific scenario. This system can adapt its available power and frequency resources in response to a particular radio frequency situation captured by UAV flight. This is another example of a new concept system of system employed in a synthetic EMSO scenario, which acts in a multi-domain perspective, hence using air and land domain assets. To sum up, the receiver stage of the reactive jammer phase has been virtually and practically distributed and de-localized in the operating zone. The main technical and operative choice behind this complex jammer system (UAV and ground vehicle) relies on the better receiver performances offered by an UAV flying over a high-density city to receive potential radio frequencies threats, such as base transmitter stations and active mobile stations (congested and contested EME). The processing phase of the hybrid jammer implemented in Matlab is based on a repeater approach, so that the received spectrum is replicated in the transmitter window, managing the resources between active and reactive part and spreading the samples over a specific timing length. This reactive spreading means how the received samples are distributed inside the subsequent transmitter window, whose length is a multiple number of the receiver one. The created model can be configured to make a pure repeater waveform, where the timing sample length is not changed, meaning that the timing sample length is the same multiple number coming from the ratio between time protocol TX and RX windows. Moreover, the reaction of the jammer has been defined using a proportional principle, which correspond to the most general-purpose system configuration suitable to many different

scenarios. This proportional principle deals with a modulation of the maximum signal level of power amplifier, according to power of the received threat to be jammed, normalizing the processing gain of the active and reactive signal to the saturation point. This saturation point is normally identified as the 1 dB compression point of the power amplifier. The power amplifier has been modeled to amplify the signal, generating spurious until the fifth order harmonics.

That said, in an urban environment, a hybrid jammer can show low performances in terms of effectiveness levels, since it can receive a very low power from the real threats, especially in a scenario where the jammer has to allocate its resources on other radio frequency signals (this situation is more probable in an urban environment). For these reasons, the poor received level of the signal corresponds, generally, to a low effectiveness reaction, which it is reflected to a short range of force protection. In fact, in an urban environment, besides the spectrum congestion due to the presence of many potential signal threats, the effective signal can be attenuated by artificial objects present in the scenario (e.g. building, artificial structures, etc.), which can cause a destructive interference and a high attenuation of received power. The virtual de-localization of the receiver stage on-board UAV allows having a better signal level, thanks both to geometric and electromagnetic aspects (such as the use of a directive and high gain antennas pointed in nadir orientation).

The integration of the output jammer spectrum has been performed using PSD (Power Spectral Density) technique, where the signal samples are formatted in a specific modulation file and then loaded in the STK complex transmitter model, in the external modulator tab. This technique has been evaluated with respect to other possible integrations between Matlab and STK because the jammer waveform has been generated with timing characteristics very fast (microsecond order of magnitude). The PSD integration is very good integration technique where the Matlab complex spectrum is totally replicated by STK digital objects, hence virtually alive, but all the related results have to be contextualized to the assumption that the effects of the most important contribution of jamming signals can be considered as time average spectrum. This consideration is true when the jamming signals vary very fast with respect to expected threat at the target receiver device.

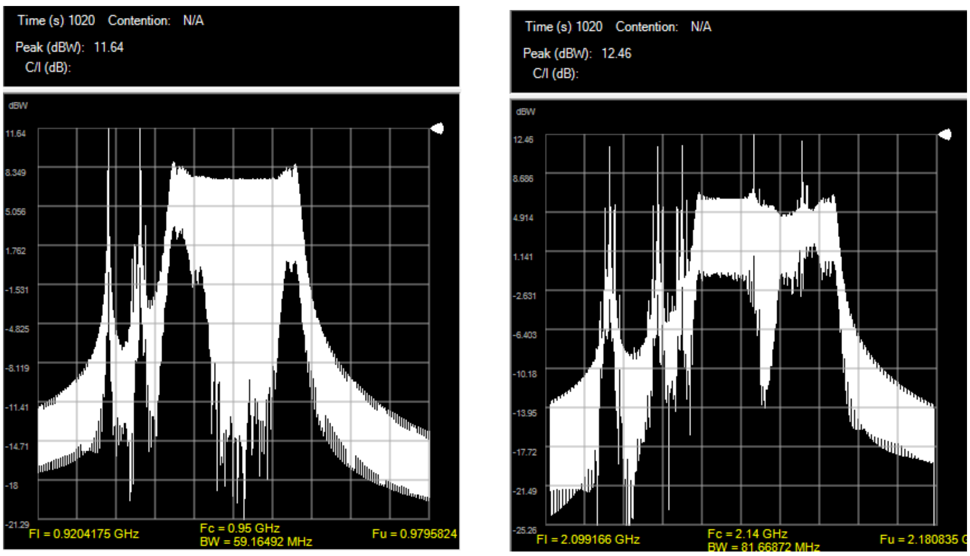

Figure 16: STK spectrum analyser of 2G hybrid waveform (left) and 3G hybrid waveform (right) at the ground vehicle jammer transmitter.

– The synthetic urban area in the scenario has been modeled with several base transceiver stations, spread all over the city and used to test cellular communication, which simulates an a-symmetric enemy military actions planned against blue forces ground vehicles. Each base transceiver station has been composed of three GSM900 and three UMTS (band 1) transceiver chains, connected to six antennas in total, placed in a clover configuration (each antenna has a 120° illumination sector). In addition, GSM and UMTS channels have been distributed in Orlando city by different cellular stations.

  The GSM base transceiver station characteristics (involved in the cellular communication) are below reported:
  - Transmitter frequency: 0.931 GHz
  - EIRP: 40 dBW
  - Modulation: MSK
  - Data rate: 0.133 Mb/s
  - CDMA spreading factor: //
  - Antenna type: Sinc Integer Power Aperture Rectangular
  - Antenna polarization: linear
  - Antenna half beam width: 60°

  The UMTS base transceiver station characteristics (involved in the cellular communication) are below reported:
  - Transmitter frequency: 2.1275 GHz
  - EIRP: 40 dBW
  - Modulation: 64QAM
  - Data rate: 0.015 Mb/s
  - CDMA spreading factor: 512
  - Antenna type: Sinc Integer Power Aperture Rectangular
  - Antenna polarization: linear
  - Antenna half beam width: 60°

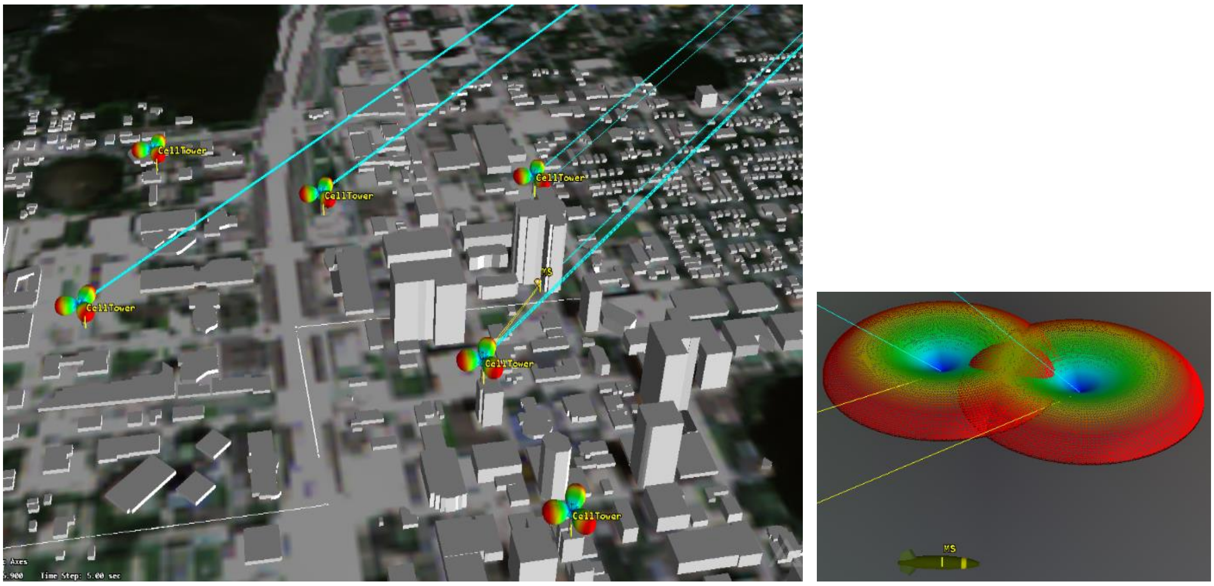

Figure 17: Urban area BTSs (left) and MS bomb RCIED (right) 3D objects and antennas pattern view.

The mobile station has been simulated to be connected to an improvised explosive device, implementing a specific operative and technical procedure. The cellular communication is already established and the bomb is activated by an activation command sent over the downlink path (from a triggerman to mobile station), for instance a multi-tone audio signal. These tactic procedures have to be considered when levels of effectiveness evaluation have to be calculated.
In this context, it is important to mention that jammer effectiveness levels are measured in terms of J/S parameter for each radio controlled device, measured at inhibition condition of the threat. The J/S value is correlated to a force protection range of the electronic counter measure system and to Eb/(N0+I0) level.
The GSM/UMTS jammer characteristics are below described:

- Transmitter central frequency: 0.95 GHz, 2.14 GHz
- Transmitter power: 30 dBW
- Modulation: external file (PSD integration)
- Antenna type: Dipole
- Antenna polarization: linear

<u>Geostationary satellite for Communication (INMARSAT)</u>

In this project scenario has been inserted a geostationary satellite, to test and verify a satellite communication during the described military mission. The used geostationary satellite is the Inmarsat 3-F2 since this asset coverage area correspond to the area of the Earth where the scenario has been planned. In this section, it is simulated a satellite communication between the military headquarter placed in Exton, USA and a command post ground vehicle which is performing its mission in Orlando city. Hence, these two assets to connect are around 1500 km far away.
Therefore, the main elements involving in this simulation part are described below:

- Military Headquarter: this unit has been modeled with 3D tiles functionality, where a 3D model has been prepared and placed in the synthetic environment. This functionality is appreciated in 3D graphic visualization, offered by STK simulator. In this synthetic infrastructure, a satellite transmitter connected to a parabolic antenna has been placed on the roof of building. The antenna is linked to a servo motor which is able to point to the geostationary satellite, implementing the uplink communication. The main characteristics of this transmitter chain are reported below:
  - Transmitter frequency: 1.555 GHz
  - Transmitter power: 10 dBW
  - Modulation: 16PSK
  - Data rate: 0.4 Mb/s
  - CDMA spreading factor: //
  - Antenna type: Parabolic
  - Antenna gain: 45 dB
  - Antenna polarization: Circular
  - Antenna half beam width: 1°

  According to the operative context, it is simulating that the military HQ needs to exchange data continuously with the ground vehicle, in order to provide information about adversary forces, to monitor the situation during execution phase of operation and to increase the Commander situational awareness of the battlefield. Since the command-and-control functions have a meaningful importance in the military operations, maintaining satellite communication is crucial for the mission's objectives achievement and to maintain an operative advantage over the adversary.

Figure 18: Military HQ building with satellite communication antenna 3D objects and antenna pattern view.

- Geostationary satellite for communication: this unit has been retrieved by STK satellites database, defining the satellite position and orbits. Once space asset has been place, it has been associated to a high-fidelity 3D model, which details the Inmarsat satellite physical characteristics. Then, the modeling phases have been focused on the payload creation and configuration, to have a bent pipe transponder on-board the satellite.

  A communications satellite's transponder is the series of interconnected units that form a communications channel between the receiving and the transmitting antennas. It is mainly used in satellite communication to transfer the received signals. A transponder is typically composed of:

  - an input band-limiting device (an input band-pass filter),
  - an input low-noise amplifier (LNA), designed to amplify the signals received from the Earth station (normally very weak, because of the large distances involved),
  - a frequency translator (normally composed of an oscillator and a frequency mixer) used to convert the frequency of the received signal to the frequency required for the transmitted signal,
  - an output band-pass filter,
  - a power amplifier (this can be a traveling-wave tube or a solid-state amplifier).

  Most communication satellites are radio relay stations in orbit and carry dozens of transponders, each with a bandwidth of tens of megahertz. Most transponders operate on a bent pipe principle, sending back to Earth what goes into the conduit with only amplification and a shift from uplink to downlink frequency. However, some modern satellites use on-board processing, where the signal is demodulated, decoded, re-encoded and modulated aboard the satellite. This type, called a "regenerative" transponder, is more complex, but has many advantages, such as improving the signal to noise ratio as the signal is regenerated from the digital domain and permits selective processing of the data in the digital domain.

It is important to distinguish between a "transceiver" and "transponder". A transceiver has an independent transmitter and receiver packaged in the same unit. In a transponder the transmit carrier frequency is derived from the received signal. The frequency linkage allows an interrogating ground station to recover the Doppler shift and thus infer range and speed from a communication signal without allocating power to a separate ranging signal.

STK simulator allows modeling and simulating satellite transponder, making available two main transponder typologies: analog transponder and digital transponder.

In an analog transponder, the transmitted signal is essentially a reflection of the received signal, with the added possibility of frequency translation or power amplification. STK Communications models an analog transponder as a combination of a receiver and a re-transmitter. To model a link that includes an analog transponder, a chain is set-up with links to the receiver and from the re-transmitter. For example, to model a simple one-hop link from a ground transmitter to a ground receiver via an analog satellite transponder, a chain with the following constituent links is defined:

- ground transmitter to satellite receiver (uplink)
- satellite receiver to satellite re-transmitter (downlink)
- satellite re-transmitter to ground receiver

In a digital (or regenerative) transponder, there is complete demodulation and re-modulation of the incoming signal before it is sent on its way.

STK Communications models a digital transponder as a combination of a receiver and a transmitter. To model a link that includes a digital transponder, a chain with links to the receiver and from the transmitter is set up. For example, to model a simple one-hop link from a ground transmitter to a ground receiver via a digital satellite transponder, a chain with the following constituent links is defined:

- ground transmitter to satellite receiver (uplink)
- satellite receiver to satellite transmitter (downlink)

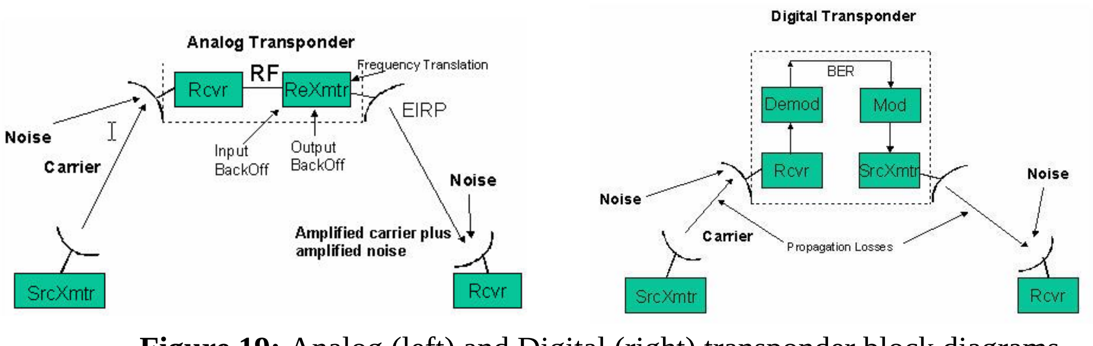

Figure 19: Analog (left) and Digital (right) transponder block diagrams.

As known, the Inmarsat communication happens in L band where a 12m diameter reflector is used, with a very high gain. These peculiarities of Inmarsat satellite have been mirrored in the transponder model parameters, in order to obtain subsequent results very close to a real application. The receiver and transmitter composing the transponder system have been created based on a multi-beam device, as the real satellite system. For testing the multi-beam functionalities of the simulator, 3 beams of radio frequency chain have been set. The result can be also visualized in 2D or 3D window of STK, where a contour graphics has been generated. This visualization is very important to manage each communication beam in the virtual environment, in terms of receiver/transmitter gain (antenna physical gain and beam processing gain) projection on the Earth, frequency bandwidth of the communication channel and orientation by setting proper azimuth and elevation values.

The electronic characteristics of the modeled bent pipe transponder are:

- Receiver type: multi-beam receiver
- Receiver frequency: 1.535 GHz, 1.545 GHz, 1.555 GHz
- De-Modulation: 16PSK
- Antenna type: 12m diameter reflector
- Antenna gain: 45 dB
- Antenna polarization: Circular
- Antenna half beam width: 1°

- Transmitter type: multi-beam transmitter
- Transmitter frequency: 1.636 GHz, 1. 646 GHz, 1. 656 GHz
- Transmitter power: 20 dBW
- Modulation: 16PSK
- Data rate: 0.4 Mb/s
- CDMA spreading factor: //
- Antenna type: 12m diameter reflector
- Antenna gain: 45 dB
- Antenna polarization: Circular
- Antenna half beam width: 1°

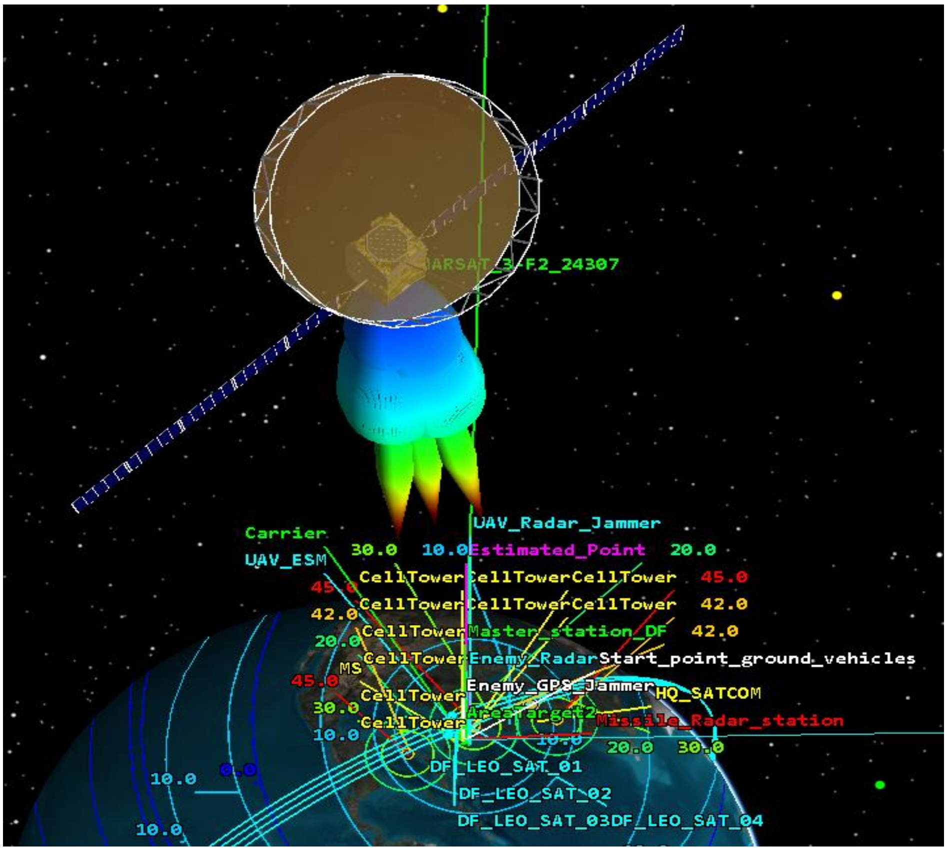

Figure 20: Inmarsat satellite with bent pipe transponder 3D object and antenna pattern (multi-beam) view.

The current simulation involves a ground transmitter (HQ) and a ground receiver placed between 45 dB and 42 dB contour lines. After the modeling phases, concerning the simulation functionalities of transponder, the STK simulator offers suitable objects for evaluating the composite link budget.

Chains are used to determine access through a string of serially linked objects. Constellations allow a single object in the chain to be represented by a defined set of objects. For the developed scenario, a chain has been configured in order to virtually connect all the systems involve in the satellite communication (both uplink and downlink path).

- Command post ground vehicle: this unit is equipped with a satellite communication receiver and it represents the lead vehicle in a convoy with the aforementioned jammer vehicle. In this vignette, command post ground vehicle is the potential target of the enemy forces, which have planned to activate the radio controlled improvised explosive device. In fact, operatively speaking, it represents the worst-case situation, since the Command post ground vehicle has not been equipped with an electronic counter measure system. This choice has been done because of convoy leader vehicle main function, which is a receiver node of satellite communications with the HQ. For the described reasons, the vehicles are moving on the same route, just with a pre-defined inter-vehicular distance. So, the convoy configuration has been studied in order to analyze the effect of the jammer not as self-protection device, but mostly to quantify the level of effectiveness in relation to another vehicle without any electromagnetic defense device. In this context, are very important the pre-defined inter-vehicular distance, the characteristics of the scenario and the radio frequency threat to inhibit.

  The receiver chain on the command post vehicle has been modeled with the following main characteristics:

  - Receiver frequency: 1.636 GHz
  - De-Modulation: 16PSK
  - CDMA spreading factor: //
  - Antenna type: Phased Array
  - Antenna elements: X = 9, Y = 11 (hexagonal configuration)

  The modelled phased antenna can generate a radiation diagram following satellite transmitter with its main lobe, showing the biggest gain in the downlink path direction. Furthermore, the presence of the vehicular jammer in its proximity can unintentionally degrade the satellite communication, leading to possible operative problems in mission objectives achievement. This section answer to a crucial question: in a military operation, is it more important to be (electromagnetically) protected or communicate? My answer is both. Although the answer seems to be obvious and simple, the practical implementation is very complex, above all in a complex electromagnetic operating environment. The progressive evolution of electromagnetic threats pushes to have electronic counter measure systems increasingly performing and technologically advanced. The necessity to jam widely many threats is another key element to take into consideration. For these considerations, a full electromagnetic interoperability achievement is a cornerstone in the current and in the future spectrum operations.

  In this regard, the aspects concerning a possible electromagnetic interoperability between receiver satellite communication and the jammer for electronic defense have been simulated and evaluated. As described above, the configured jammer in this scenario mainly works on 2G and 3G cellular communication bands and the receiver for satellite communication has been set in L band at 1636 MHz. Theoretically, there are no interoperability problems between the two electronic devices, since the jamming signal waveform has been generated to allocate power in completely different frequency bandwidths. However, a real situation can be very different. The hardware and software architecture of the modelled jammer is very important in this perspective, since a jammer with two transceivers and one power amplifier has been configured, in order to emulate a possible real situation, not necessarily a good one. The combination of two different transceiver sources to the same amplifier generates unintentionally electromagnetic emissions, located in different bandwidths with respect to the wanted jamming signal. Among these non-linearity effects, it is important to mention, for instance, the second and third orders intermodulation products, generating unwanted noise in the receiver satellite communication band.

The external jammer model created in Matlab considers the defined hardware and software system configuration, creating a radio frequency spectrum in the entire instantaneous bandwidth (half sampling frequency), replicating also further intermodulation or spurious of signal. These unintentional frequency contributions are passed to a dedicated transmitter modelled on-board the jammer ground vehicle in the desired bandwidth under analysis. For this emission, a dipole antenna has been chosen and a 0 dBW power, since in a real configuration it is important to take into account losses of real omnidirectional antennas with respect to the central frequency of the receiver satellite communication. The antennas are designed to emit in specific bands (e.g. cellular band jammer antennas).

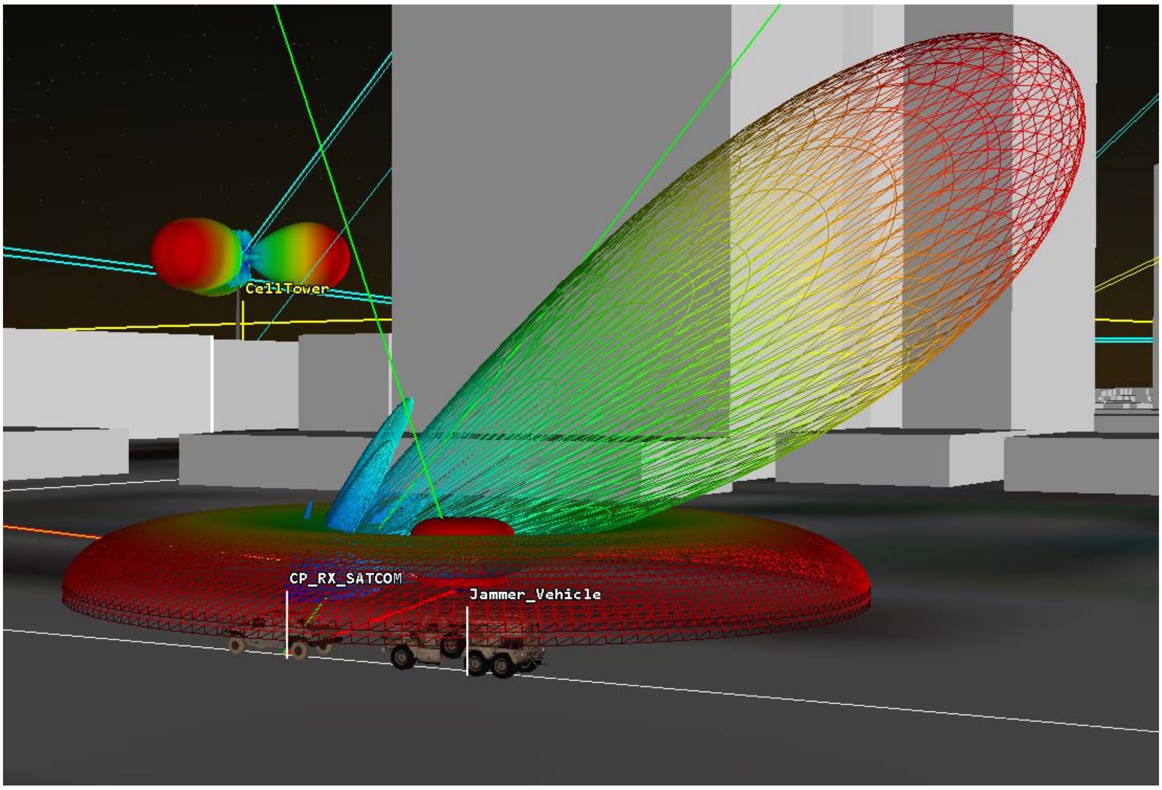

Figure 21: Ground vehicle convoy (command post as first vehicle and jammer as last vehicle) 3D objects and antennas pattern view.

Once the (unintentionally) interference has been created in the virtual scenario, a communication system object has been configured in order to evaluate the quality of downlink path communication in presence of an electronic protection. In this case, the Eb/(No+Io) parameter

has been retrieved from the electromagnetic propagation analysis, drawing a graph where it is showed the Eb/(No+Io) envelope with respect to simulation time.
The phased array antenna modeled on the ground receiver for satellite communication is able to dynamically point toward the downlink satellite transmitter, by modifying its radiation diagram. In addition, it has been also inserted an antenna null finder capability towards the radio frequency interference source direction (electronic force protection ground vehicle in the rear – known direction). Therefore, the overall effect is to maximize the receiver gain through satellite pointing and, at the same time, to create an antenna null in the interference direction, in order to minimize noise effects on the downlink communication. The systems' interoperability can be reached with a complex antenna radiation pattern, able to adapt to a complex electromagnetic environment, such as a phased array antenna defined on-board command post ground vehicle.

Figure 22: Receiver phased array antenna without null finder functionality (left) and with null finder functionality (right) 3D antennas pattern view.

Scenario different course of actions

The modelling and simulation supporting electromagnetic spectrum operations is a key technology, which allows studying and analyzing how this operating environment will influence transversally the military domains, in terms of informative, technical and operative aspect. In this scenario, although the multi-domain assets represented, the space domain has been highlighted, through which, in conjunction with the electromagnetic environment, it is possible not only to increase the situational awareness, but a comprehensive operative management of the future battlefield.
The synthetic scenario allows reaching a high level of versatility, meaning that by changing particular configuration variables of systems' models it is possible to obtain completely different operative results. Different results will lead to several courses of action, which correspond too many scenario ramifications. The following situations can be easily generated and verified.
<u>Master station does not receive suspicious frequencies:</u> the LEO satellites constellation cannot be configured with received frequency and the estimation algorithm cannot be processed. Any UAV missions in the operating area can be detected and be destroyed by radar guided missiles.
<u>Master station receives suspicious frequencies:</u> the LEO satellites constellation can be configured with received frequency and the estimation algorithm can be processed. As a result, an estimation point is obtained associated to an uncertainty area.
<u>UAV jammer is not able to inhibit enemy radar:</u> the on-board single frequency jammer is connected to a dynamically change antenna, pointing to the estimated point of the target and whose directivity is proportional to maximum obtained uncertainty error. The uncertainty level of the ELINT system is able to change automatically jammer antenna gain and directivity, so it means that the EIRP can be strongly affected by FDOA results' precision. The inhibition of the radar is connected to the jammer

parameters, to radar technological architecture implemented in the model and to the radar cross section of the target asset.
UAV jammer is able to inhibit enemy radar: the two UAVs of blue forcers are not detected, hence not destroyed, by enemy radar thanks to the electromagnetic attack performed through the UAV jammer. The search function is completely jam and the subsequent tracking phase for missile launching is not activated.

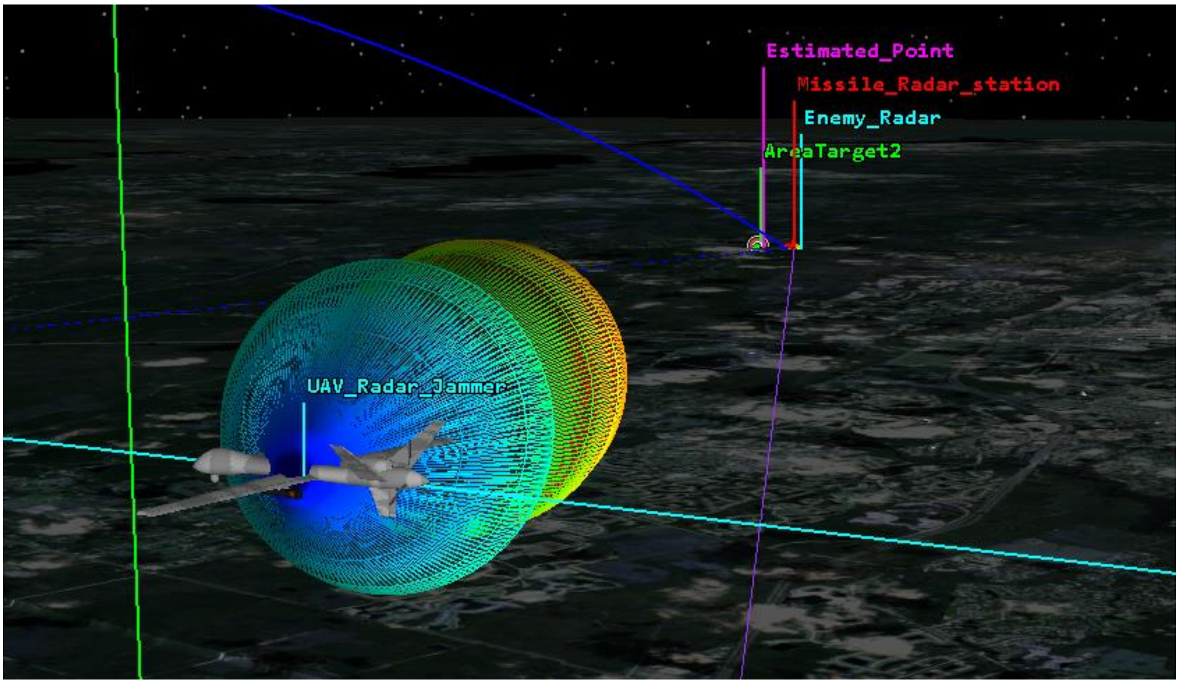

Figure 23: UAV radar jammer 3D object and antenna pattern view.

Galielo L1 modulation is affected by jammer: the use of a multi-constellation receiver on-board UAV ESM is a very important aspect in this simulation. A specific BOC modulation configuration has been chosen for satellite transmitters, in order to highlight Galileo signals resilience in a noisy environment (narrow band L1 jammer signal) with respect to GPS ones. The capability to use Galileo allows to UAV ESM to send the precise target (enemy GPS jammer) position to conduct a kinetic action on it and restore GPS receivers in the operating area.
UAV ESM detects BTSs and MSs: one of the mission performed by UAV ESM is to monitor radio frequency spectrum, in specific bands, over a high-density urban area. This electromagnetic surveillance is part of the a multi-domain architecture to implement a hybrid jammer waveform, where receiver stage has been conceptually de-localized with respect to the ground vehicle used for electronic force protection. The ESM receiver electronic configuration (e.g. instantaneous bandwidth and scanning technique) and the collected signals samples are fundamental for subsequent electronic defense actions. Based on an incorrect intelligence information or an incorrect model configuration, the effective threat signal cannot be detected or to many (environment) signals are collected. The latter situation is typical in an electronic support measure action performed in an urban environment and can result a jammer device to be completely ineffective, since it needs to spread its (limited) resources over many suspicious threats.

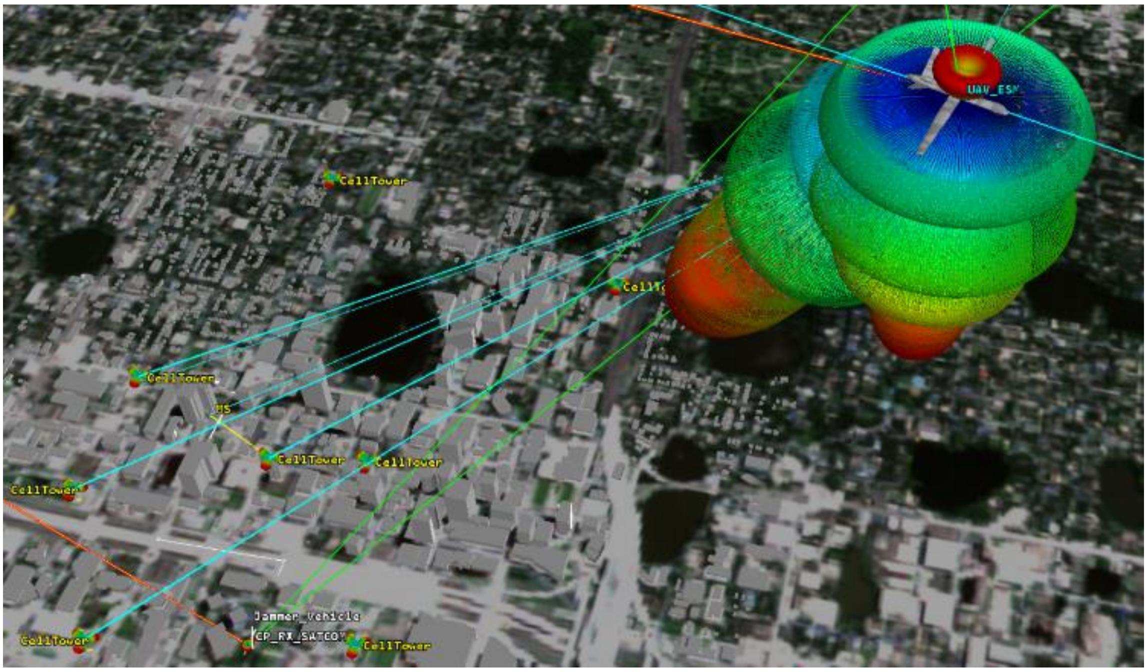

Figure 24: UAV ESM 3D object and antennas pattern view.

GPS jammer is not destroyed: the enemy GPS L1 jammer is placed in the operating area in order to avoid use of PNT devices by blue forces. The GPS jammer continuously disturb the electromagnetic environment making ineffective blue forces devices using L1 signal functionalities. In this situation, the ground vehicles mission is performed anyway, albeit with technical and operative limitations. As result, the jammer reactive part is filled with blank information, generating an only active waveform. The active waveform is configured in pre-mission phases and it is fixed, meaning that there is not a dynamic spectrum adaption according to the specific electromagnetic environment of the operating area. Since the resources of the jammer are limited in time, in frequency and in power, using an active waveform needs to have suitable informative support, in order to be effective inhibiting several possible threats. Mostly in an urban scenario and for multi-purposes devices (e.g. cellular phones), it is very difficult to have a priori detailed information concerning radio frequency possible threats.

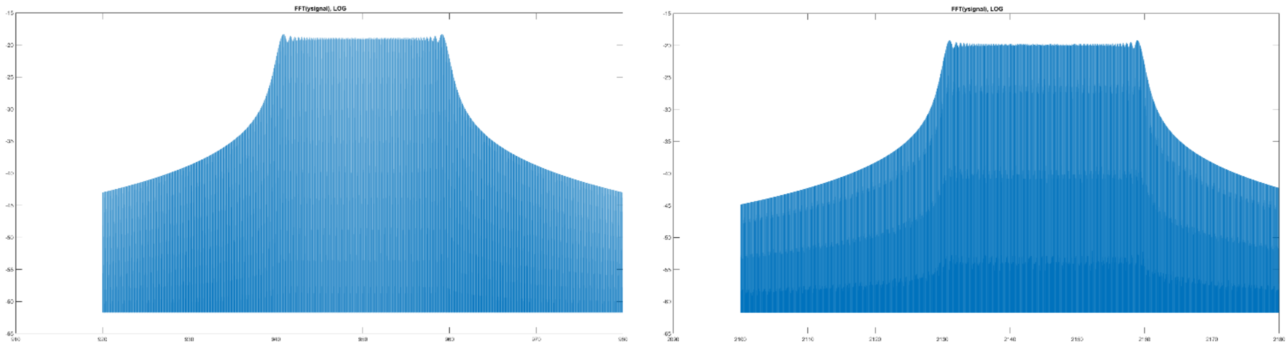

Figure 25: Matlab jammer external model spectrum in active waveform mode (2G left and 3G right).

GPS jammer is destroyed: the multi-domain electronic warfare system works properly, meaning that UAV ESM and ground vehicle are perfectly synchronized in time, sharing the same time protocol for data exchanging. The ground vehicle can receive data collected after UAV ESM action over the city, automatically generating its waveform in hybrid mode (reactive and active at same time). Jammer reactions are created on the detected frequency contributions, dynamically adapting the system's resources and transmitting an electromagnetic signal with specific characteristics, according to model configuration.

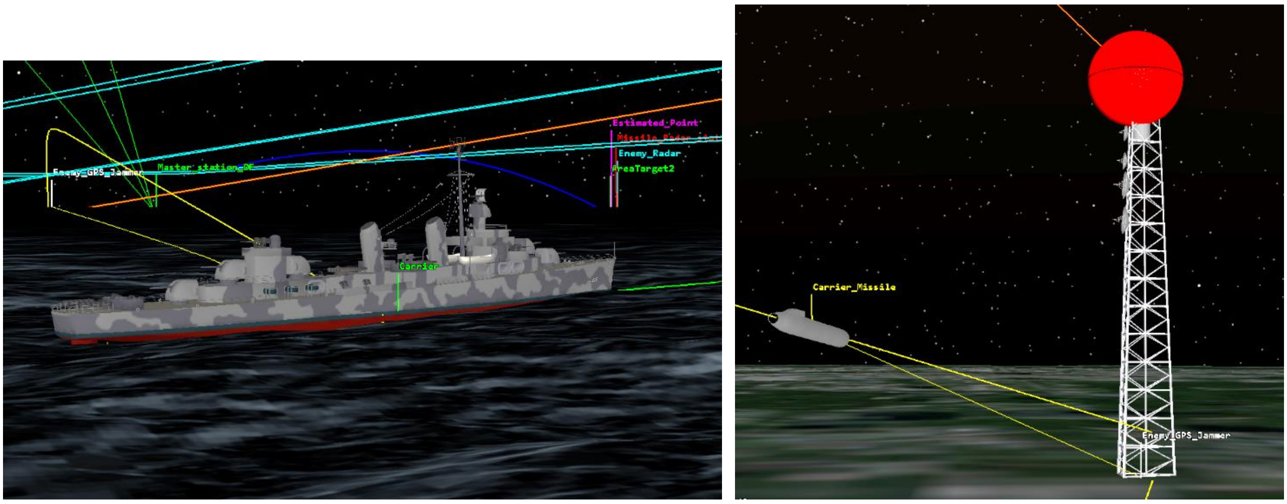

Figure 26: Military ship (left) and tomahawk missile (right) launched towards GPS jammer station 3D objects' view.

<u>Ground vehicle jammer inhibits 2G/3G threats:</u> depending on jammer waveform transmission (hybrid or purely active) the effects on radio controlled improvised explosive device threats can be very different. In this context, the obtained results are range of effectiveness with respect to the target vehicle (command post with satellite receiver), calculated in this specific scenario and using both J/S and Eb/(N0+Io) thresholds. These thresholds have to be set correlating to threat's signal characteristics to jam (e.g. modulation, frequency, multiplexing, data rate, etc.). For these reasons, according to the jamming thresholds set in this scenario, it is possible to verify performance differences of using an active or a hybrid jammer waveform. At the same power, frequency, timing system resources, have a theoretical waveform configuration better than another is impossible, since the informative, operative and technical variables that concur to force protection level are too many and not known a priori. Therefore, a creation of a synthetic environment able to model and simulate these peculiar aspects is important to manage the current and the future electromagnetic spectrum operations, increasing operational value of the M&S supporting military sector, through a representation of these non-kinetic effects.

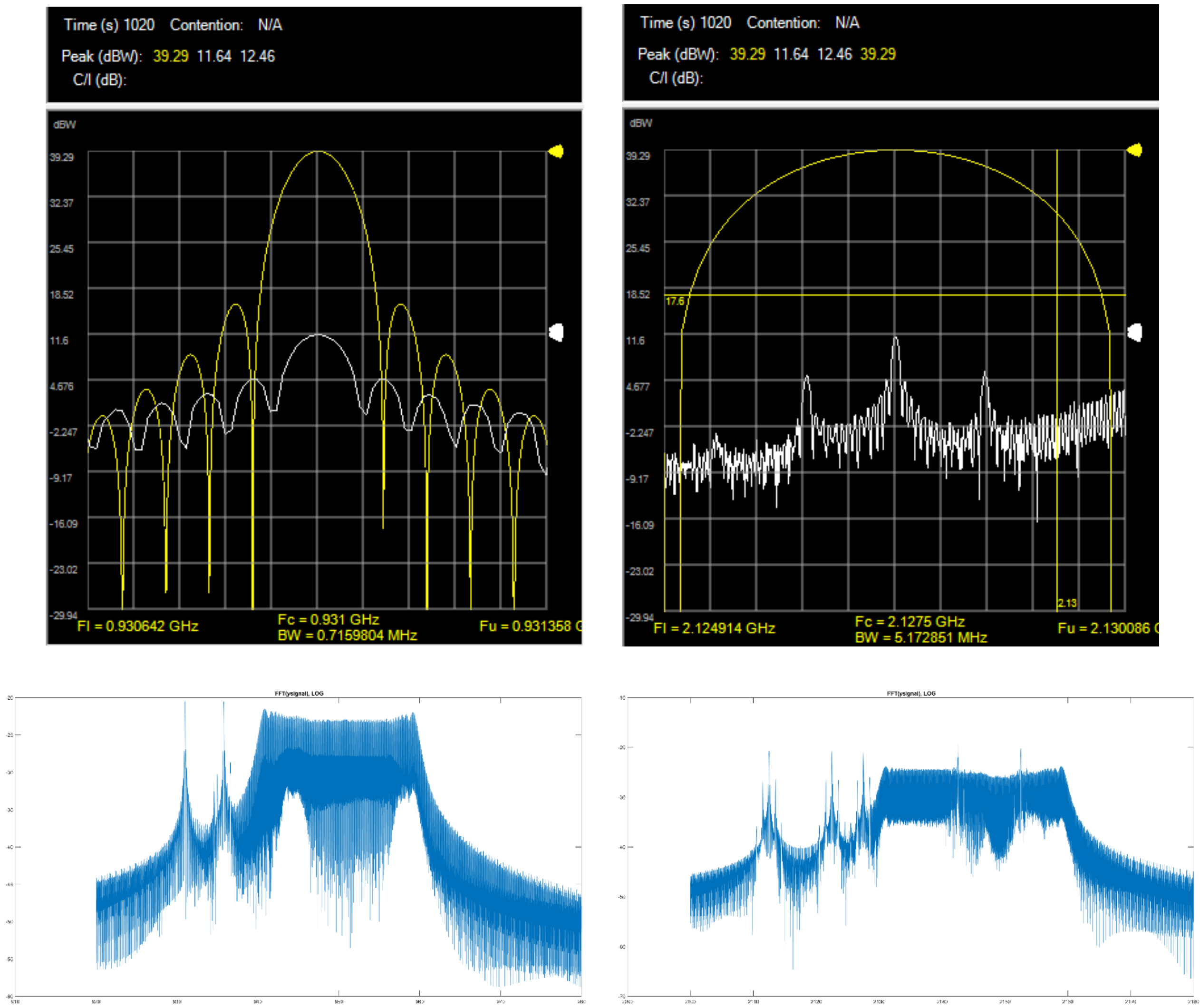

Figure 27: STK spectrum analyser in MS GSM receiver (top-left) and MS UMTS receiver (top-right) showing the jammer waveforms (white) and cellular communication channels (yellow). Matlab jammer external model spectrum in hybrid waveform mode (2G bottom-left and 3G bottom-right).

<u>Ground vehicle's satellite receiver communicates with HQ:</u> depending on jammer waveform transmission (hybrid or purely active) the effects on the command post ground vehicle's satellite receiver can result very different. A more effective jammer system and its waveform can unintentionally increase the noise interference level towards a friendly communication device. In this case, since the inter-vehicular distance is very close, in order to provide better electromagnetic protection by jammer actions, and due to a very low level received signal coming from satellite downlink connection, it is very important to simulate the devices electromagnetic interoperability. The interoperability evaluation is obtained by calculating quality of satellite communication, according to vehicles' mission, interference contribution and satellite communication receiver configuration. This configuration is conducted essentially by changing phased array antenna pattern, defining a null finder capability, showing its effect on radio frequency source attenuation with respect to desired signal.

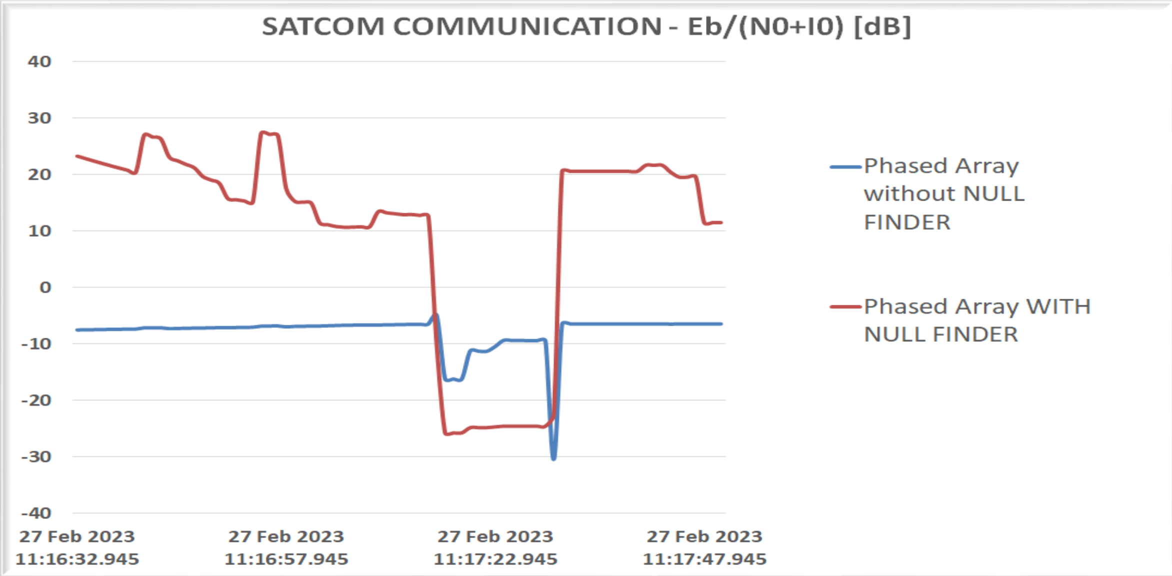

Figure 28: STK graph of satellite communication Eb/(N0+I0) parameter configuring the phased array antenna without null finder capability and with null finder capability.

The electromagnetic interoperability has been studied using the Eb/(N0+I0) temporal envelop, shown in two dirrent situational scenarios:

1. Phase array receiver antenna does not implement the null finder functionality: maximum Eb/(N0+I0) value is around -8 dB, meaning that there is no satellite communication, since the downlink path is distorted by jammer interferences;
2. Phase array receiver antenna implements the null finder functionality: maximum Eb/(N0+I0) value is around 27 dB, meaning that there is satellite communication and the command post ground vehicle is able to receive all the military information by military HQ. In this case, the jammer interferences in L band are strongly attenuated by antenna radiation diagram.

Therefore, by using the null finder algorithm capability on a phased array antenna is possible to earn around 35 dB on Eb/(N0+I0), meaning that the satellite communication using the GEO satellite transponder is affected by a low bit error rate.

In STK simulator, a phased antenna model has been implemented using a MVDR (Minimum Variance Distortionless Response) beam former algorithm. Beam former algorithm can compute the weights of each array element, for shaping antenna's gain pattern. MVDR changes the amplitude and phase across the array elements to steer and shape the beam as well as the nulls. Therefore, the MVDR goal is to minimize the variance of the beam former output. If the noise and the underlying desired signals are uncorrelated, as is typically the case, then the variance of the captured signals is the sum of the variances of the desired signal and the noise. Hence, the MVDR solution seeks to minimize this sum, thereby mitigating the effect of the noise. In this model, a MVDR constraint of 3 dB has been set. This value is used to constraint the amount of main gain reduction, which can take place to null interference.

Matlab code description

Matlab code developed for this scenario has been divided in five different simulation sections, replicating the logic flow chart of the ELMO scenario. In particular, these sections are the following:

– GET & CREATION: it is the section able to initialize variables and objects. This section has to be run with ELMO scenario already open in STK. In this way, the section is able to read all the simulated entities defined in the virtual environment, their structure and the attributes of the all the objects composing the “top level” unit. In addition, there is also a creation phase, which, through Matlab, is able to create automatically several units, place them in the scenario and setting the physical characteristics. Conceptually the get phase includes all the platforms and devices defined in STK, instead the creation phase deals with all the “custom” objects (such as specific electromagnetic systems) transferred to STK simulator and whose data are managed by Matlab. Moreover, the creation part of the code includes radio frequency access objects and constellations used to create respectively link budgets and communication systems between several assets in the simulator.

- LOGIC SECTION DF: it is the simulation section responsible to read LEO satellites’ Doppler shift and telemetric parameters, in order to use this information for FDOA algorithm implementation. The master station is able to receive these data, by creating a communication link with LEO satellites and, in this regard, each link budget is evaluated. This simulation section includes the configuration variables of the FDOA algorithm and the possibility to insert errors affecting frequency data and telemetry states of satellites, in order to characterize the algorithm precision with respect to scenario’s perturbations.
- ACCESS MISSILE RADAR and CARRIER: it is the simulation section where the kinetic actions are evaluated (missile launches). In particular, is simulated if the radar is able to detect UAVs, which are performing an electronic attack (jammer) whose EIRP and radio frequency directivity is configured according to FDOA geo-localization algorithm results. The subsequent kinetic action, performed by blue forces, by launching a missile from a ship to destroy the GPS L1 jammer, is linked to the previous one. The UAV is able to detect (if it is not destroyed by enemy radar guided missiles) GPS L1 jammer using its camera payload and to communicate the target position through a multi-constellation receiver (using Galileo signal). In this regard, many further considerations can be done according to GPS L1 jammer characteristics (EIRP, antenna type, position, etc.) and to BOC modulation types simulated in the scenario. A scenario’s parameter change can result in a different situation (e.g. Galileo is also affected by jammer action, considering the same defined threshold level), leading to completely different technical and operative subsequent situations.
- LOGIC UAV ESM: it is the simulation section able to collect the radio frequency information by UAV flying over the urban area. This code is also able to dynamically change the ESM receiver characteristics, coherently with STK simulation time, for implementing a receiver model SDR-based. In particular, knowing a priori the bands to scan, setting a specific value of SDR instantaneous bandwidth (IBW), Matlab drives STK receiver objects to implement a defined timing and frequency scheduler, to cover all the target bands. Changing these receiver parameters means to obtain different results, in terms of received frequencies and power levels. They have specific operative effects on overall mission. Linked to the previous simulation section, the GPS received signal restoring (after GPS L1 jammer destruction) is used in this portion of Matlab code, to implement a time division interoperability between UAV ESM and ground vehicle. In this way, these units are able to share the same time protocol in a synchronized way (1 PPS-based approach).
- LOGIC JAMMER: it is the section that is call the external jammer model, by providing radio frequency information collected and received in the previous stage. The jammer is configured with:

1. UAV collected radio frequency data used to generate the transmitted spectrum (waveform);
2. architectural logic data defining its functionalities and its behavioral processes.

According to previous section results, the emitted waveform can be fully active or hybrid (combination of reactive and active stages of jammer system). The output of this Matlab simulation section is a Power Spectrum Density file generation in a particular format, which is associated to a STK transmitter modulator stage, therefore, used for level of effectiveness and electromagnetic interoperability calculations.

During each simulation section running, Matlab code is able to provide pre-defined messages to user, which have been defined to give a quick result of the activated logic simulation branch.

```
message_DF =

    'RADIO FREQUENCY INTERFERENCE ESTIMATED - ANTENNA RADAR JAMMER ANGLE IS 10.0295'


message_missile_uav =

    'MISSILE OF RADAR SEARCH AND TRACKING NOT LAUNCHED - RADAR JAMMED'


message_missile_carrier =

    'MISSILE OF CARRIER LAUNCHED - BOC SIGNAL FOR GALILEO POSITION IS NOT JAMMED'


message_missile_carrier =

    'MISSILE OF CARRIER LAUNCHED - ENEMY GPS JAMMER DESTROYED'


message_jammer_signal =

    'UAV ESM COMMUNICATES WITH JAMMER VEHICLE THROUGH TDM (GPS 1PPS) - JAMMER WAVEFORM IS HYBRID - REACTIVE + ACTIVE'


message_jamm_2g =

    'JAMMED 2G'


message_jamm_3g =

    'JAMMED 3G'
```

Figure 29: Example of Matlab messages during the simulation.

Conditional thresholds and scenario decision tree

The conceptual map of this scenario is very complex, since it involves multi-domain assets in blue and red forces side, several electromagnetic actions (offensive, defensive and monitoring) and logic nested situational processes. In fact, the potential branches, in terms of Course of Actions potentially occurring, can include hundreds of cases. Just think about the possible electronic configurations that can be develop models in STK and in Matlab, for systems' performances characterization in many technical simulated situations. In addition, fixing a specific electronic models' architecture and configuration, further results are obtained changing operative scenario's conditions (e.g. position of units on the terrain, employed physical assets features, doctrinal aspects, type of mission, etc.), which have a direct impact on electronic systems performances in terms of levels of effectiveness. This is the powerful of Modelling and Simulation applications, the versatility embedded in a digital twin representation of real world: once the modelling phases have been concluded, the simulations that can be run to study and analyze different multi-factorial situations (technical, operative and informative) can be so many.

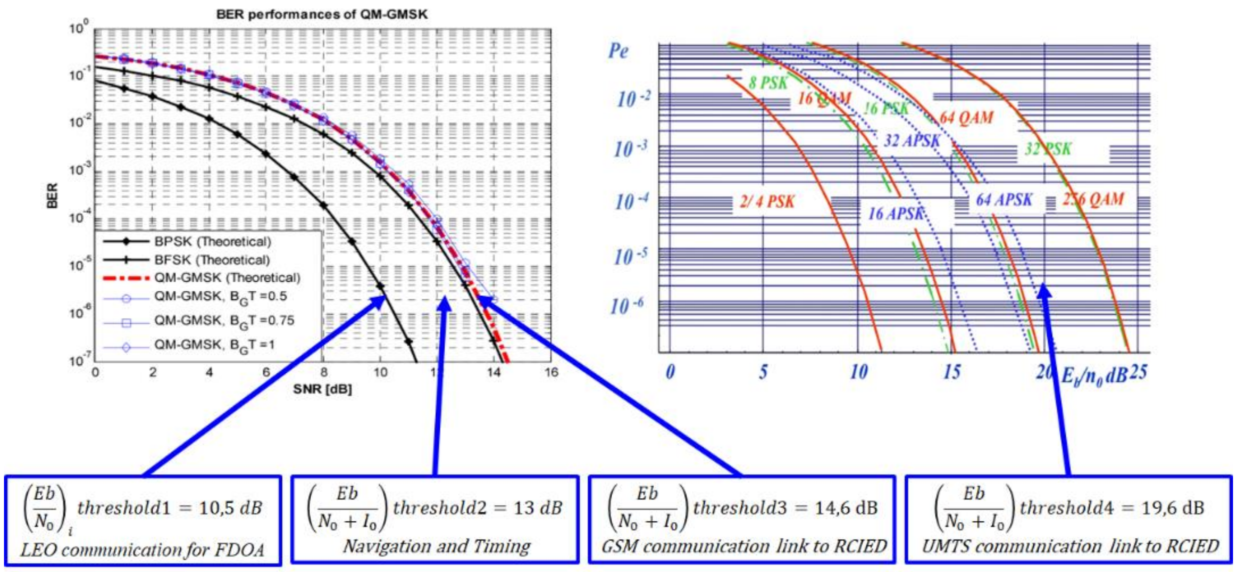

Figure 30: Scenario's threshold levels with respect to BER vs Eb/(N0) graph for different communication modulations.

The decisional branches of this scenario are managed by Matlab code, whose effects are projected into STK simulator, structuring a conceptual decision tree diagram based on communication parameters thresholds. To evaluate a quality of a link budget, Eb/N0 (in normal situation) and Eb/(N0+I0) (in presence of radio frequency interference) have been calculated and verified. On these parameters the thresholds have been set considering a common BER value (e.g. 1e-6) and considering the modulation chosen for communication links. This approach has been adopted to simply the decision tree conditional phases, although it can be easily modified with different threshold values and BER considerations.

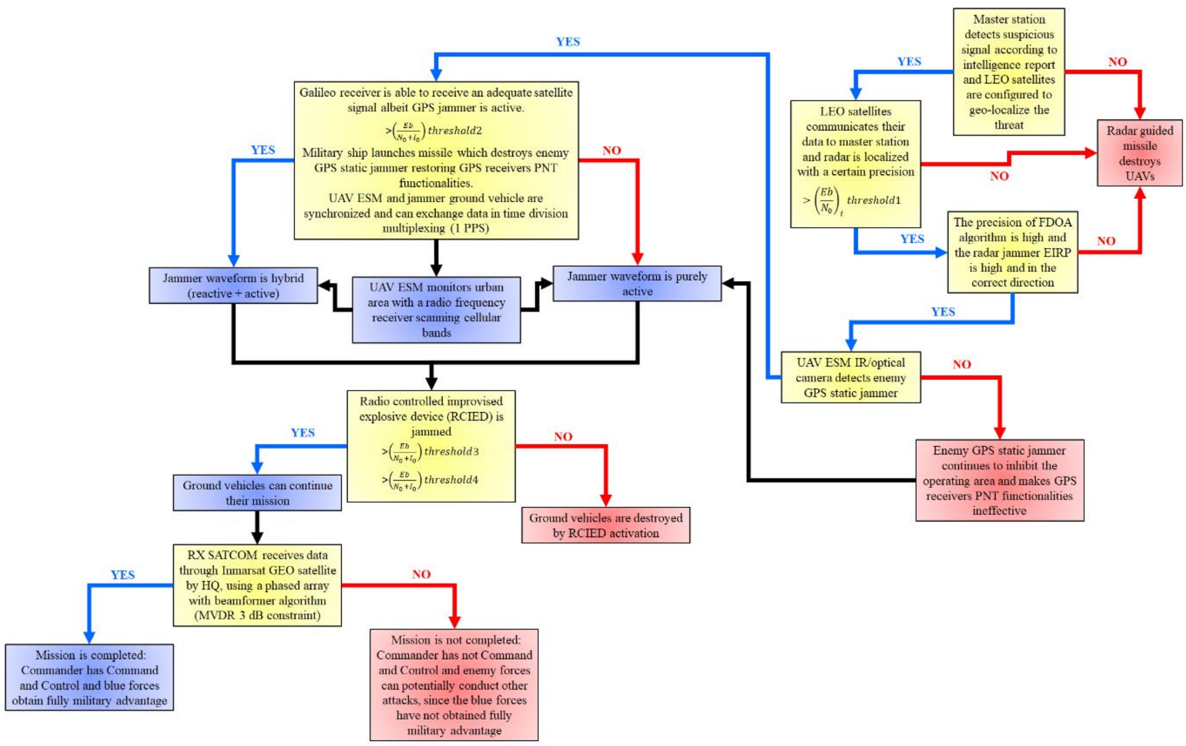

Figure 31: Scenario's decision tree developed based on conditional thresholds (yellow boxes are the conditions, blue and red boxes are respectively blue and red forces actions).

CHAPTER 4: CONCLUSION AND FUTURE DEVELOPMENTS

Hardware/Software in the loop applications

A peculiarity of the ELMO synthetic environment lies in the hardware and software in the loop connection. As a starting point, it is possible to consider a physical apparatus supplied or being tested by the Armed Forces, where emitted spectrum is obtained (for example of a transmitter) through a measuring instrument (e.g. spectrum analyzer). The spectrum actually emitted by the device, expressed as a function of raw data (e.g. time matrix, frequency, power of the emitted signal) could be input for STK tool. In this way, through hardware in the loop, simulations would be obtained in which a spectrum transmitted by a real system and, therefore, used in operations, is locked to simulated objects, exploiting the versatility of M&S in the construction and configuration of operational scenarios.

Furthermore, it is important to highlight that the virtualization of an environment for electromagnetic operations is also in line with the technological paradigm that characterizes the missions in the future operating environment, the so-called software defined missions (S.D.M.). With the available antennas models (radiation diagram) and with STK virtual electromagnetic propagation, it is possible to explore an interface with a digital sub-system developed in Matlab and with a real software-defined radio (SDR). The Matlab interfacing sub-system could initially implement converters (analog and digital) to receive data of interest from the synthetic environment (STK) and send them to the real electronic board. In this way, hybrid experiments could be achieved, involving real and simulated devices.

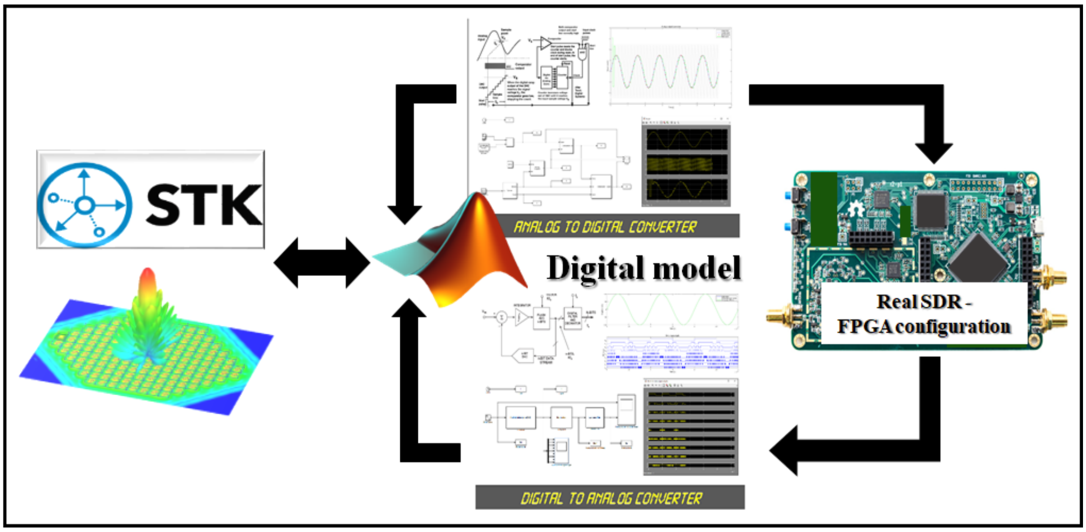

Figure 32: Hardware in the Loop (HIL)/ Software in the Loop (SIL) potential integration.

The ELMO project can be essential for the definition and study of SDMs, providing a virtual arena in which develop and verify innovative technological capabilities suited to real informative/operational contexts. The potential ELMO outcomes deriving from the simulated electromagnetic multi-domain scenarios could be important for the realistic definition and verification of hardware and software applications.

Models and scenarios verification and validation

Verification and validation of simulation models is conducted during the development of a simulation model with the ultimate goal of producing an accurate and credible model. Simulation models are being used increasingly to solve problems and to aid in decision-making. The developers and users of these models, the decision makers using information obtained from the results of these

models, and the individuals affected by decisions based on such models are all rightly concerned by the fact that a model and related simulations results are "correct" or not. This concern is addressed through verification and validation of the simulation model.
Simulation models are approximate imitations of real-world systems and they never exactly imitate the real-world system. Due to that, a model should be verified and validated to the degree needed for the model's intended purpose or application.
The verification and validation of a simulation model starts after functional specifications have been documented and initial model development has been completed. Verification and validation is an iterative process that takes place throughout the development of a model.

<u>Verification</u>

In the context of computer simulation, verification of a model is the process of confirming that it is correctly implemented with respect to the conceptual model (it matches specifications and assumptions deemed acceptable for the given purpose of application). During verification the model is tested to find and fix errors in the implementation of the model. Various processes and techniques are used to assure the model matches specifications and assumptions with respect to the model concept. The objective of model verification is to ensure that the implementation of the model is correct.
Many techniques can be utilized to verify a model. These include, but are not limited to, having the model checked by an expert, making logic flow diagrams that include each logically possible action, examining the model output for reasonableness under a variety of settings of the input parameters, and using an interactive debugger. Many software engineering techniques used for software verification are applicable to simulation model verification.

<u>Validation</u>

Validation checks the accuracy of the model's representation of the real system. Model validation is defined to mean "substantiation that a computerized model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model". A model should be built for a specific purpose or set of objectives and its validity determined for that purpose. Many approaches can be used to validate a computer model. The approaches range from subjective reviews to objective statistical tests. One approach that is commonly used is to have the model builders determine validity of the model through a series of tests.
Therefore, Subject Matter Experts in each military domain that employ several assets or electromagnetic systems in operations can perform these fundamental phases in M&S simulations. The result is a synthetic versus real world gap characterization, in order to correlate any M&S results with related operative considerations.

Future M&S developments

The presented scenario represents a proof of concept of ELMO project, useful to provide an initial demonstration through a technical feasibility of the overall concept. The synthetic environment is a reference framework for analyzing electromagnetic layer in military multi-domain operations, where:

– several models implementing behavioral functionalities of EMSO systems can be developed using the versatility offered by Matlab/Simulink;
– several scenarios can be configured in a virtual terrain, employing different electromagnetic propagation models, in order to obtain high-fidelity results in terms of data and of simulation visualizations.

In this regard, it is fundamental the capability of custom models development, respecting the aforementioned main architecture criteria: modularity and general-purpose. Referring to the created scenario, for instance, the following future developments can be identified, to improve the modelling and simulation results:

- use a high-fidelity and high-resolution synthetic terrain, including natural terrain structure (orography) and artificial objects which can impact on electromagnetic propagations;
- integrate ELMO proof of concept with CGF- Computer Generated Forces (constructive/virtual military simulators), using standard base protocol (e.g. High Level Architecture) and/or custom connections (e.g. Application Interfaces). The described M&S interoperability aspect is very useful to project electromagnetic layer results on Armed Forces scenarios and to use high fidelity digital twin platforms (e.g. ground vehicle, aircraft, satellite, ship, etc.), in terms of physical and behavioral databases parameters (e.g. rules of engagement). Once mirrored in ELMO synthetic environment platforms' military actions, it can be possible to attach on them available models created for electromagnetic systems. This integration with military simulators is very important for increasing situational awareness of assets increasingly employed in future scenarios, such as satellites for remote sensing, communication, navigation and foster management of electromagnetic environment to achieve mission's objectives. Moreover, the CGF analysis capabilities of different Courses of Action, correlated to ELMO electromagnetic multi-domain layer, is an essential component for next generation programs of M&S, mostly concerning the simulation of non-kinetic effects on the battlefield;
- design and development of new Matlab models to increase electromagnetic analysis. The creation of Base Transceiver Station and corresponding mobile station behavioral models are very important for level of effectiveness enhancement of a jammer system, taking into consideration specific receivers' stages and the timing/informative signal envelope (multiplexing). In addition, the creation of a GPS/Galileo receiver in Matlab would elevate technical and operative values of ELMO scenarios, where many considerations can be conducted both for evaluating best radio frequency interference effects on a receiver (calculating the distorted S-curve of receiver discriminator and the Delay Doppler maps) or, on the contrary, for mitigations techniques assessment.

The ELMO scenario is based on different thresholds, which have been useful to structure the overall project basement, on which create further capability functionalities. The values used are both for thresholds setting and for models' input variables configuration have to be determined or tuned in the verification and validation phases, leading to a classified scenario's data and virtual environment.

Conclusions

The Modeling & Simulation in support of electromagnetic operations could also allow system configurations, in order to understand how to counter new electronic threats, studying and characterizing, for example, the effectiveness of gap filler systems. The creation of a complex urbanized virtual scenario is an essential component in the analysis of the technical-operational effectiveness of the electromagnetic devices used in operation, both from a spectral and a physical point of view. In particular, the physical virtualization of the surrounding environment allows simulating the main propagative effects provided by the physical objects defined in the scenario, whose understanding and analysis allows obtaining a quantification of the performance effectiveness, in relation to the maximization of the efficiency of the technical and operational processes of the employed electromagnetic equipment.

Concerning to the ever-expanding technological dynamism within the military context, a winning approach will surely be a comprehensive one, where military professionals able to carry out interdisciplinary and heterogeneous analysis and assessments will increasingly a have fundamental role, in order to synthesize, within a single technical direction, declinations and operational applications. Shortly, it will become essential to model and to manage the future complex military challenges within a vast and diversified technological substrate, through capability developments characterized by a high technological level but with a direct and simple operational projection to support military operations.

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