PIANETA DINAMICO
WORKING EARTH

GEO-DREAM

Geohazard and Environmental Observation for Data-driven Assessment of Monitoring, Research, and Evaluation

Project Coordinator

Elisa Trasatti

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ISTITUTO NAZIONALE
DI GEOFISICA E VULCANOLOGIA

Politecnico di Torino
International University

GFZ Helmholtz-Zentrum Potsdam

CSIC
Consejo Superior de Investigaciones Científicas

GEO-DREAM in numbers

- Call 2026-2029 Pianeta Dinamico - **Thematic Line 1**

  "*Advanced Earth geo-observation with remote sensing, proximal, and in situ data for the development of Earth System Digital Twins*"
- Funded with **1.951.970,00** €
- GEO-DREAM Ob.Fu. 1020.030 (Personnel is AC - 1020.010)
- Seven Divisions (*sezioni*) + two Units (*sedi*) involved → five CRA
  - ONT (+ RM1, Bologna, Ancona, Rende, and non-INGV personnel)
  - RM2
  - OE
  - OV
  - PI
- About 60 INGV researchers, technologists and technicians
- 7 External Participants
- 3 PhD, 5 Research contracts, and 2 scholarships starting and planned

PIANETA DINAMICO GEO-DREAM

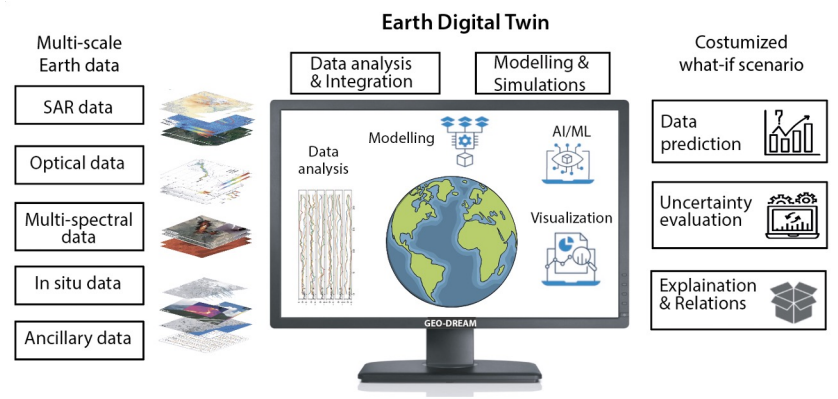
Concept

→ GEO-DREAM investigates the feasibility of developing an **Earth Digital Twin** (DT) built from multiple thematic DTs addressing diverse **natural hazards** through remote sensing and in situ observations, and AI/ML analysis

→ **DTs will generate simulation scenarios** to support recognition and forecasting

→ The **platform VISTA enables interactive what-if analyses** for uncertainty assessment, hazard management, and decision-making, ultimately improving **warning capabilities and disaster preparedness**

→ The **prototype Earth DT** starts from an **AI-based foundation model and progresses through concrete applications and iterative enhancements**



Development and implementation of four operational Digital Twins

- **open conduit volcano** (Mt Etna)
- **closed conduit volcano** (Campi Flegrei)
- **earthquakes and landslides**
- **space weather**



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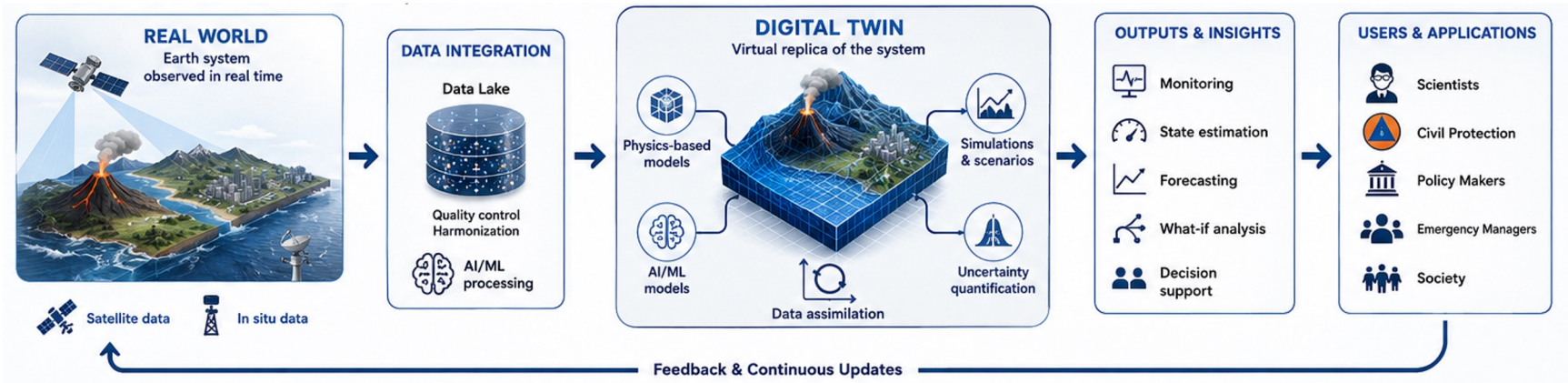
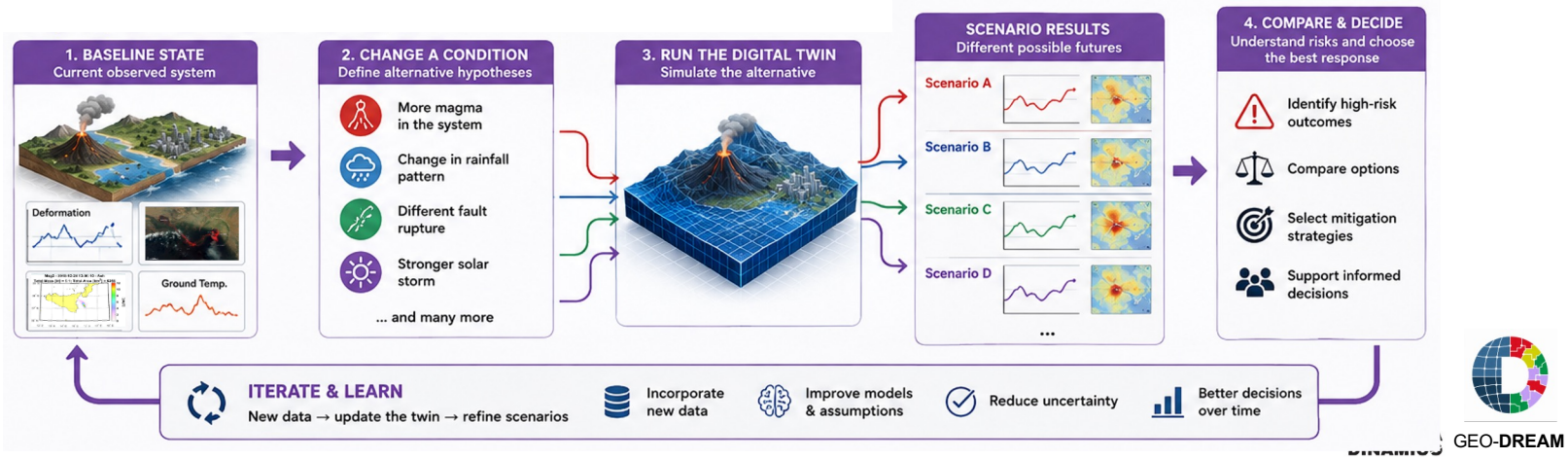
What is a Digital Twin? What is a what-if scenario?

WHAT IS A DIGITAL TWIN? A virtual, dynamic replica of a real system, continuously updated with real data to **understand, simulate and predict its behavior**.



WHAT IS A WHAT-IF SCENARIO? A virtual experiment where we change conditions or assumptions to **explore possible futures and their consequences**.

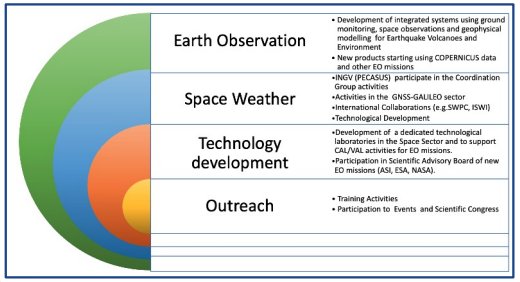


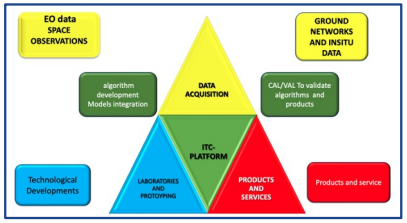
GEO-DREAM

Basecamp

Pianeta Dinamico 2021-2022
ATTEMPT - integrated system for multi-hazard from space over mediterranean

COS (est. 2020) coordinates space and aerospace activities - monitoring, surveillance, research, and societal services - across the INGV Deps: Volcanology, Seismology, and Environment





n.	COS Modules	n.	COS Modules
1	Space weather for aviation - PECASUS	11	Data Assimilation of Volcanic Ash Clouds monitoring
2	Space weather service for SWESNET	12	Volcanic hazard monitoring from space
3	Technological development for aero-space systems and grounding equipment	13	MeteoSAT Rapid Response Web Service (MS2RWS)
4	GNSS archiving facility and standard geodetic products	14	Multi/Hyper -spectral observations for volcanoes and environmental applications
5	Earthquake Damage Mapping	15	Digital Surface Models from EO data processing
6	SAR products for geophysical applications	16	Characterization of forest fires and burnt areas
7	Geodetic scenarios and modeling from geodetic data	17	UAS based for CAL/VAL activities
8	3D displacement field mapping from geodetic data	18	Remote Ground-based observation of volcanic degassing
9	Lithosphere-Atmosphere-Ionosphere Coupling (LAIC) analysis	19	Magnetic Methods for the Source Apportionment of PM in the urban environment
10	ASH_ICE_SO2 from Volcanoes	20	Optical Satellite data acquisition system – MAST infrastructure

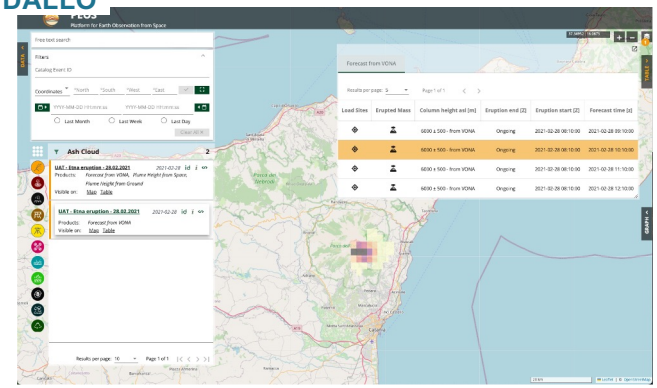
MEET MONITORING EARTH'S EVOLUTION AND TECTONICS
Finanziato dall'Unione europea NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

Ends in mid-2026

PEOS - Platform for Earth Observation from Space https://portal.peosdev.ingv.it/it/

WP9 - PIATTAFORMA PER L'OSSERVAZIONE DELLA TERRA DALLO SPAZIO

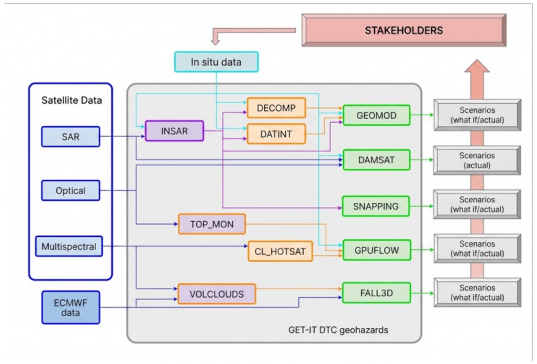
- **3D Models** – reconstruction of digital ces through very high spatial resolution of optical satellite imagery.
- **Volcanic Hazard** – Detection, tracking and quantification of hazardous phenomena during volcanic eruption from multispectral satellite data.
- **Ash Clouds** – Forecasting products for volcanic ash dispersion, deposition on the ground, erupted mass and plume height.
- **Volcanic clouds** – Detection, quantification and mapping of volcanic ash and SO2 clouds from geostationary and polar satellite platforms data.
- **Volcanic source modeling** – Information and scenarios about deformation sources in volcanic areas (magmatic camera, magma/gas reservoirs etc.)
- **CAL/VAL volcanic plumes** – Ground-based validation of volcanic plumes to evaluate the accuracy and reliability of remote-sensing products.
- **Temperature estimation on volcanic area** – Thermal monitoring of High Temperature Events (HTE), such eruptions or forest fires.
- **Geodetic data modeling** – Prediction of induced permanent deformation from seismic events from geodetic, InSAR and GNSS data.
- **SAR products** – Surface deformation maps induced by seismic events using satellite data acquired by SAR sensors.
- **Surface temperature** – Surface temperature maps using thermal bands data of optical satellite.
- **LAIC** – Anomalies detection from satellite and magnetic data related to Lithosphere-Atmosphere-Ionosphere Coupling (LAIC) phenomena.
- **Damage mapping** – Damage map products for urban and metropolitan areas following earthquakes through satellite images analysis.
- **Displacement mapping from geodesy** – 3D ground displacement components obtained by combining GNSS and SAR data.
- **Cal/Val by UAS** – Calibration and validation of satellite data by means of Unmanned Aircraft System.
- **Forest fire front** – Characterization of active fires and their impact on vegetation and soil erosion.
- **Space Weather ESA** – Ionospheric nowcasting and forecasting products for the pre-operational space weather service of the European Space Agency
- **Space Weather PECASUS** – Ionospheric condition advisories for the PECAUS operational service for the International Civil Aviation Organization (ICAO)
- **eSWua** – Nowcasting and forecasting data and products for HF communication and GNSS positioning from INGV ionospheric global monitoring network.



esa
DestinE Platform
Your gateway to a sustainable future
A unique ecosystem of services harnessing the power of Destination Earth.

GET—IT Geohazards Early Digital Twin Component

GET-IT designs a Geohazard DT
Design and test a Digital Twin Component (DTC) for geohazards (volcanoes, earthquakes, landslides) exploiting multi-sensor EO data and AI techniques (end of 2024 - end of 2027)



Objectives of GEO-DREAM

- *Objective 1 (Scientific)*

  Develop and implement four operational Digital Twins: i) open conduit volcano, ii) closed conduit volcano, iii) earthquakes and landslides, and iv) space weather

- *Objective 2 (Scientific)*

  Build an AI-Driven Data Integration Framework for the Earth DT Prototype

- *Objective 3 (Scientific)*

  Demonstrate the GEO-DREAM approach across high-risk natural environments

- *Objective 4 (Technological)*

  Enhance INGV operational preparedness via the VISTA platform

- *Objective 5 (Transversal)*

  Boost Remote Sensing uptake and Open Science for community benefit

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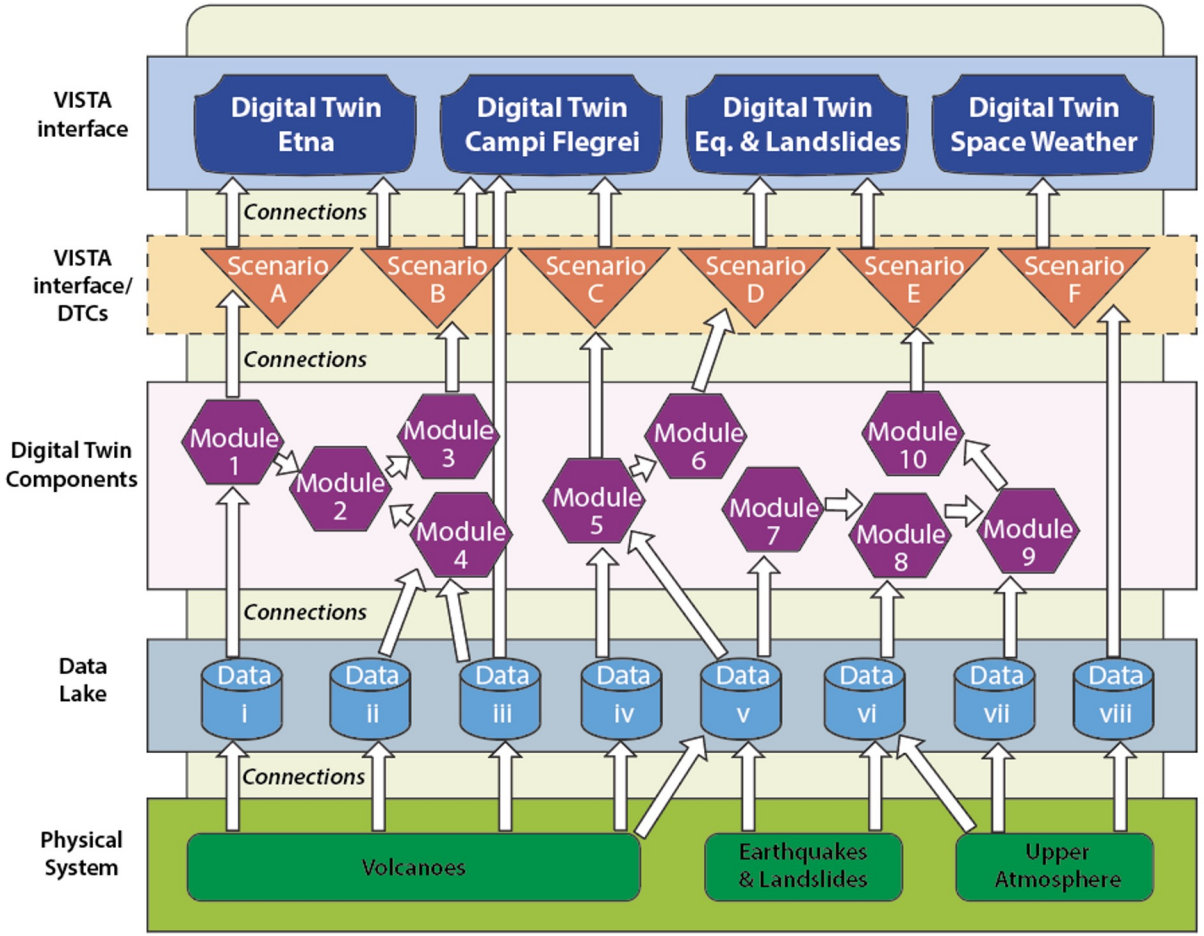
Inside the GEO-DREAM Digital Twins



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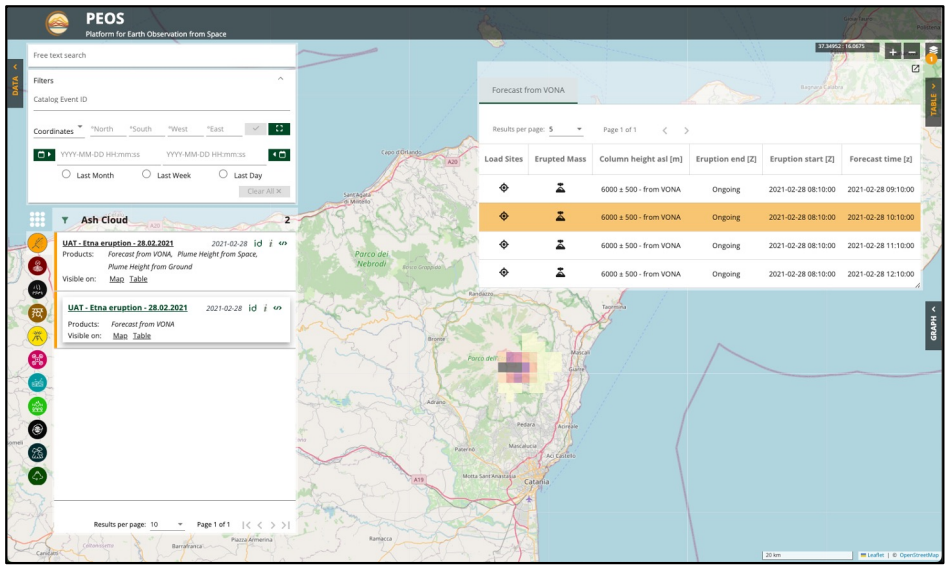
Modules

	Module	Ref. person	Description
Lev. 1	**Rende satellite data provider**	Falcone, Musacchio	Satellite data acquisition and pre-processing system located in the Rende branch of INGV (PEOS: yes)
	MAST satellite data provider	Stelitano, Merucci	New implementation of the MAST satellite data acquisition and pre-processing system for redundancy (PEOS: MAST service not included)
	SAT2LST	Silvestri, Musacchio	Land surface temperature map from thermal data (PEOS: yes. Extension to cover the Italian territory and focus on specific environments in GEO-DREAM)
	SAR data products	Polcari	Surface deformation map and displacement time series (PEOS: only co-seismic interferograms, extension to time series in volcanic and seismic areas)
	GNSS data products	Avallone	GNSS time series and mean velocities. Sensitivity of the RING GNSS network to moderate earthquakes (M>5.5) (PEOS: GNSS data were not included)
	Surface temperature measurements	i) Iarocci, ii) Sansivero, iii) Marotta	i) development of ground instrumentation for experiments of cal/val (PEOS: no); ii) ground thermal data collection and pre-processing for cal/val (PEOS: no); iii) soil thermal data from mobile thermal cameras and UAS for cal/val (PEOS: yes)
	Gravimetry data	Pivetta, Carlino	Gravimetry data from the Campi Flegrei ground network (PEOS: not present)
Lev. 2	**CL_HOTSAT**	Ganci	Thermal monitoring of active volcanoes via multispectral satellite data (PEOS: yes)
	VOLCLOUDS	Corradin, Guerrier, Naranjo	Detection & retrieval of volcanic clouds (PEOS: only products, no data processing)
	3D Models	Spinetti, Bisson	Generation of 3D terrain digital models (PEOS: only products). Development of procedures for digital model analysis and new DEM in the Campi Flegrei area
	GNSS data analysis	Pintori, Devoti, De Martino, Silverii	Exploration and application of multivariate statistical analysis and change point detection techniques (PEOS: not included, new tools developed in GEO-DREAM)
	SAR data analysis	Polcari, Tolomei	InSAR dataset cal/val and multivariate statistical analysis (PEOS: no, new tools)
	SISTEM	Guglielmino	Integration of GNSS and InSAR data for 3D displacement and strain maps (PEOS: only products, in GEO-DREAM data processing)
	DAMSAT	Bignami	Earthquake damage mapping by change detection (PEOS: only products, in GEO-DREAM data processing)
	Surface temperature cal/val	Bellucci, Caputo	Surface temperature cal/val between ground thermal data and SAT2LST (PEOS: partially. Now carried out in different environments)
	Fire Front	Amici	Delineation of active fire fronts (PEOS: only products, now data processing)
	LAIC	Cesaroni	Measuring and modeling of ionospheric parameters to highlight ionospheric disturbances induced by lithospheric events (PEOS: no)
Lev. 3	**VSM**	Trasatti, Silverii, Nikkhoo, Pivetta	Surface deformation and gravity modelling/inversion by analytical sources (PEOS: products from only deformation data). Extension of VSM for joint deformation and gravity data inversion
	VSMFEM	Trasatti, Astort	Surface deformation and gravity modelling and inversion by Finite Element Models - FEM (PEOS: no)
	EnKF_FEM	Silverii, Trasatti	EnKF data assimilation of FEM models based on geodetic data (PEOS: no, methodology to be developed in GEO-DREAM)
	DIKE-CODE	Maccaferri	2D model for the propagation and arrest of a magmatic dyke in interaction with crustal stress (PEOS: no)
	GPUFLOW	Bilotta	Lava flow modeling by cellular automata model running on GPU (PEOS: no)
	Fall3D	Pardini	Numerical simulations to forecast the movement of volcanic clouds (PEOS: only products from a different tool. GEO-DREAM implements the Fall3D code)
	Eq scenario modelling	Atzori	Primary (deformation) and secondary (gravitative) effects induced by an earthquake, either from scratch or from a distributed slip model (PEOS: no)
	Landslides	Albano, Moro	Analytical modelling of seismically induced landslides (PEOS: no, new tools developed in GEO-DREAM)
	CFF	Antonioli	Simulation of stress transfer and triggering mechanisms (Coulomb Failure Function, CFF) of fault interaction (PEOS: no, code implemented in GEO-DREAM)
	PDC-MAP	De' Michieli Vitturi, Esposti Ongaro	Simulation workflow for dilute Pyroclastic Density Currents – PDC (PEOS: no, code implemented in GEO-DREAM)
	Space weather	Cesaroni	Impact of the Sun-Earth interaction into the ionosphere (PEOS: only products, new IONORING IRI-UP model)

GEO-DREAM has a dual nature

It is both a **research project** and an **infrastructural initiative** supporting natural hazards monitoring

Product Discovery & Visualization



https://portal.peosdev.ingv.it/it/

VISTA - Interactive Platform



Virtual Interactive Visualization, Simulation and Twin Analysis

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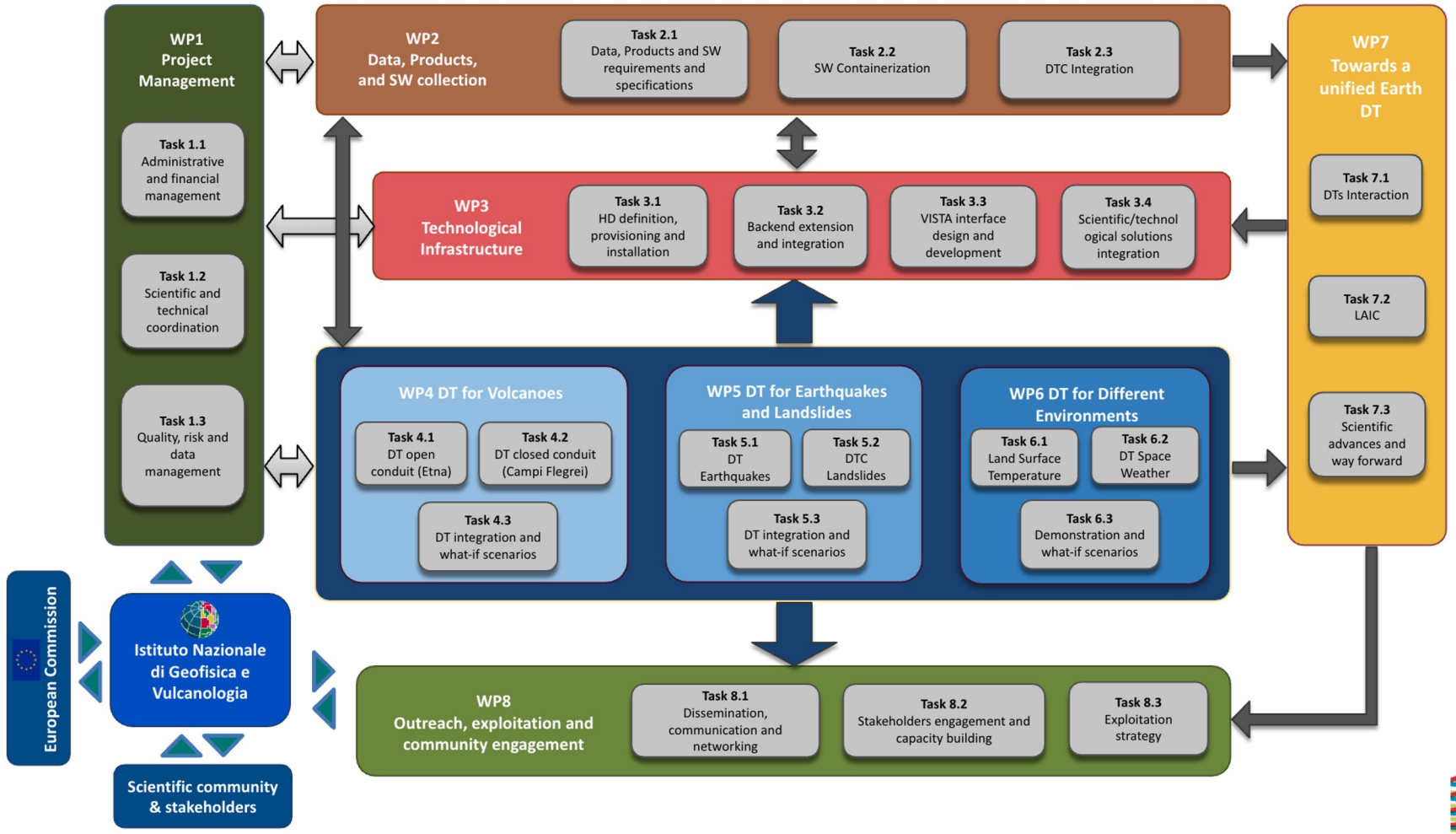
WP breakdown



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WP 4 Digital Twins for Volcanoes

Open Conduit DT
Mt Etna



Rende satellite data provider
MAST satellite data provider

- **Geodetic & Source Modelling**
  - data: SAR, SISTEM
  - simulations: VSM, VSMFEM, EnKF_FEM, DIKE_CODE
- **Volcanic Plume / Ash Cloud**
  - Detection & retrieval: VOLCLOUDS
  - Forecasting: Fall3D
- **Lava Flow Modelling**
  - Detection & retrieval: CL_HOTSAT
  - Forecasting: GPUFLOW
- **Thermal State & Calibration/Validation**
  - SAT2LST

Close Conduit DT
Campi Flegrei



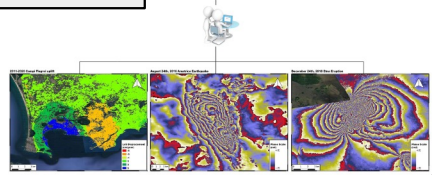
Rende satellite data provider
MAST satellite data provider

- **Geodetic & Source Modelling**
  - data: SAR, GNSS, gravimetry
  - simulations: VSM, VSMFEM, EnKF_FEM, DIKE_CODE
- **Volcanic Plume / Ash Cloud**
  - Detection & retrieval: VOLCLOUDS
- **Thermal State & Calibration/Validation**
  - SAT2LST
  - CL_HOTSAT
  - Surface temperature cal/val
- **PDC Modelling**
  - 3D MODELS
  - PDC-MAP

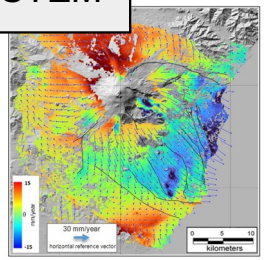
WP 4 Modules

SAR data and products

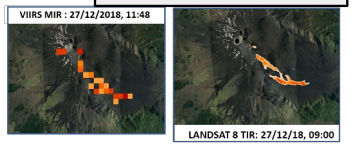




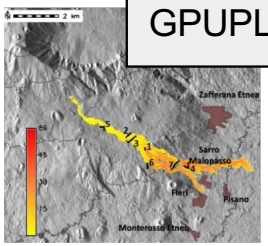
SISTEM



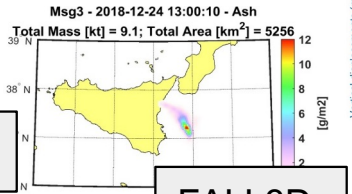
CL-HOTSAT



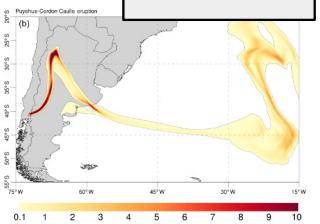
GPUPLOW



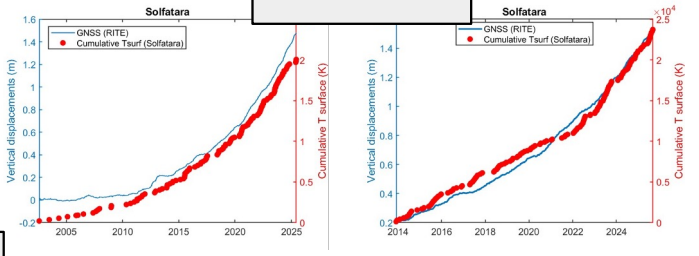
VOLCLOUDS



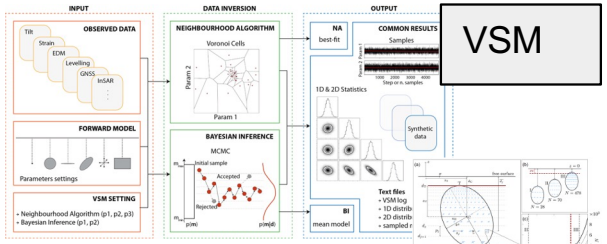
FALL3D



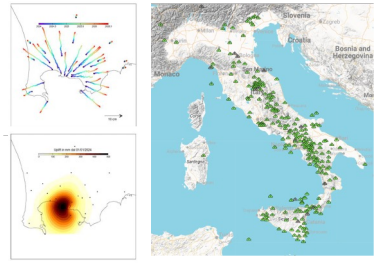
SAT2SLT



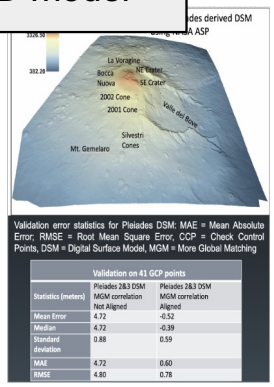
VSM



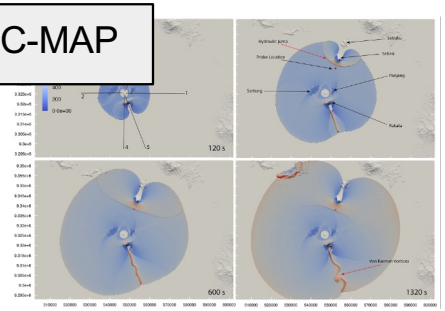
GNSS data and products



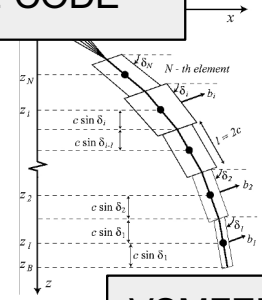
3D model



PDC-MAP



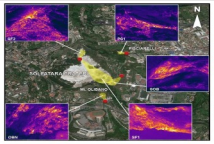
DIKE-CODE

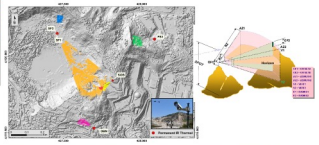


Surf. Temp. Cal/Val

Fixed thermal cameras at *Solfatara-Campi Flegrei*:

SF1 = *Solfatara* Station 1;
SF2 = *Solfatara* Station 2;
SOB = *Solfatara* OB Station;
OBN = *Olibano* Station;
PS1 = *Pisciarelli* Station

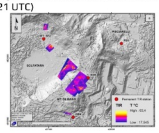


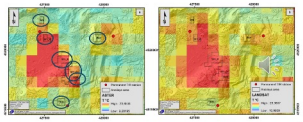


TIRNet
Thermal Infrared Permanent Volcanic Surveillance Network

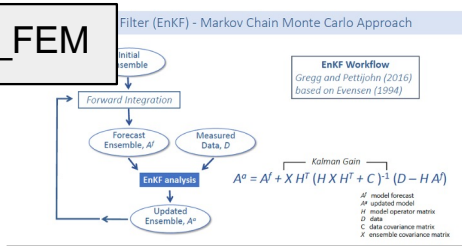


Fixed thermal cameras acquire every day, at least three time during night and one in synchronous with nighttime satellite acquisition (about 21 UTC)

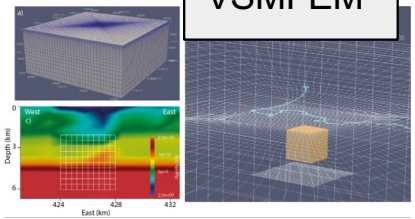




EnKF_FEM



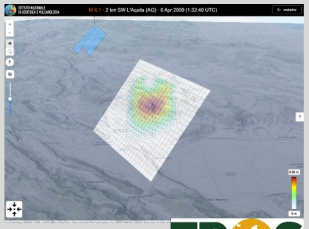
VSMFEM



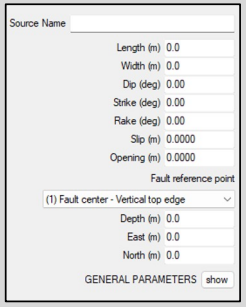
WP 5 Digital Twin for Earthquakes & Landslides

Fault distributed slip

Portale Sorgente Estesa
https://finitesource.ingv.it/

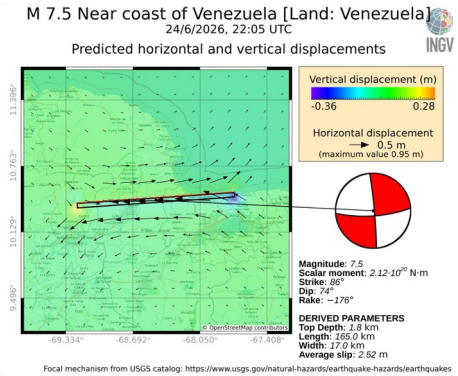


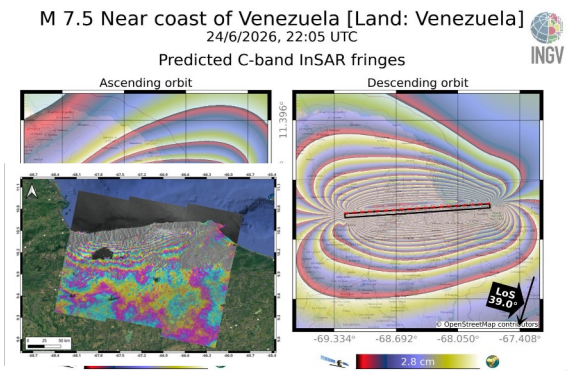
ad hoc interface



local file

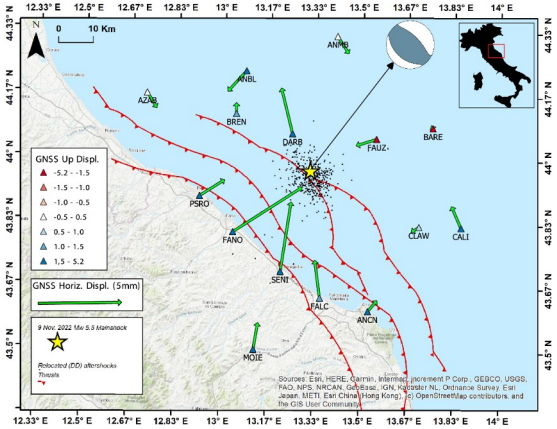
Forward Modeling





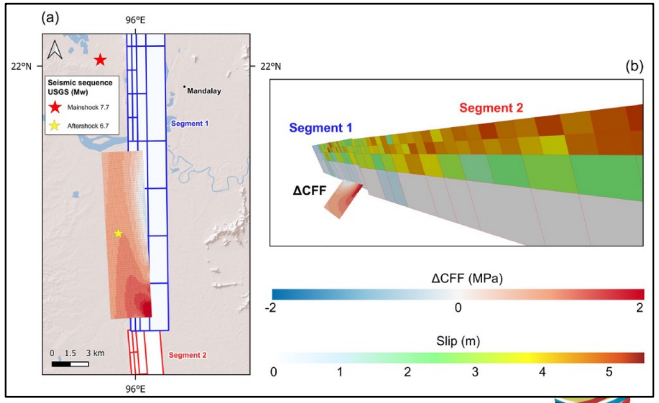
what if seismic scenario

+ GNSS stations
Forward Modeling



Scenario and test GNSS network (RING) sensitivity

+ receiver fault



what if stress transfer scenario

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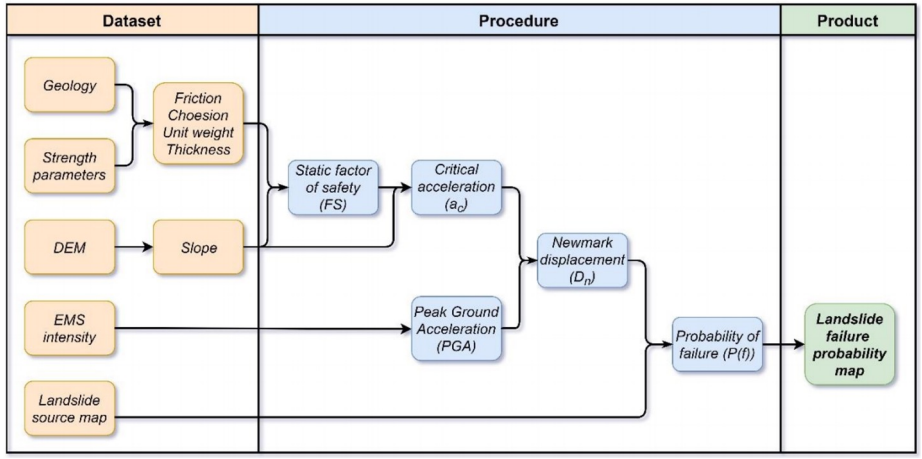
WP 5 Digital Twin for Earthquakes & Landslides



Probability of occurrence of earthquake-induced slope instability phenomena *(Jibson 1993, 2007, 2011)*

DT Earthquakes/landslides

- **Geodetic & Source Modelling**
  - data: SAR, GNSS
  - data analysis: SAR, GNSS, SISTEM
  - simulations: Eq scenario modelling, Landslides, CFF, VSM
- **Damage**
  - DAMSAT

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WP 6 DTC for different environments (SWX, heat islands, and fires)

This WP is related to environmental phenomena such as

- extreme thermal events (thermal state, heat islands, fires) at local and National scale
- dedicated to build and deploy a DT for space weather phenomena, simulating the impacts of the solar and geomagnetic activity on the Earth's ionosphere

- **Thermal state**
  - SAT2LST
  - Surface temperature measurements
  - Surface temperature cal/val
  - Fire Fronts
- **Space weather**
  - LAIC
  - Space weather

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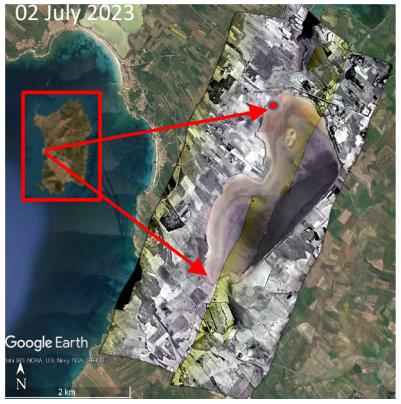
WP 6 Thermal state

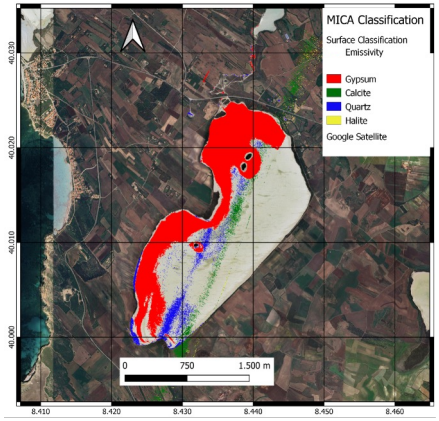


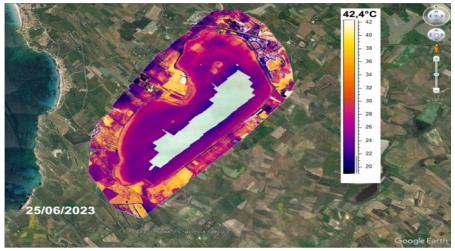
Test Campaign of a Ground-Based Thermal Calibration Network

Test-site: Stagno Sale ‘e Porcus (Sardinia)

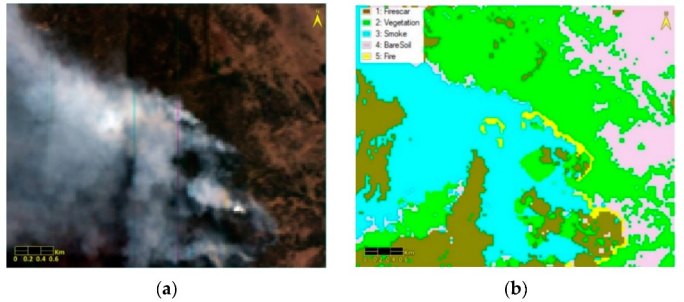


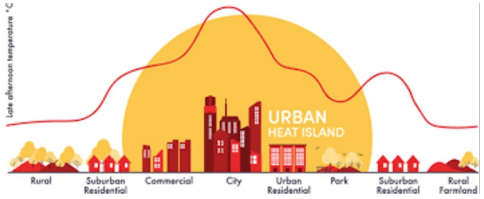


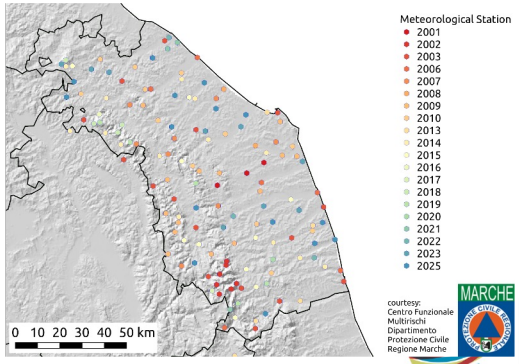




LST retrieval with multi-source approach







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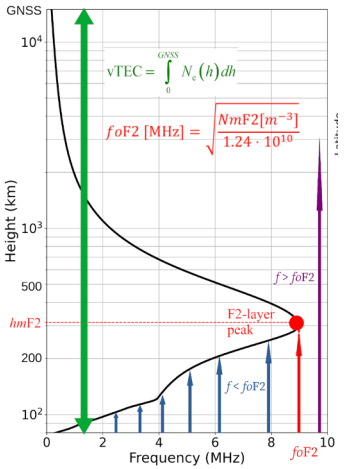
WT 6 Space Weather

***fo*F2 is the ordinary critical frequency of the ionospheric F2 layer.**

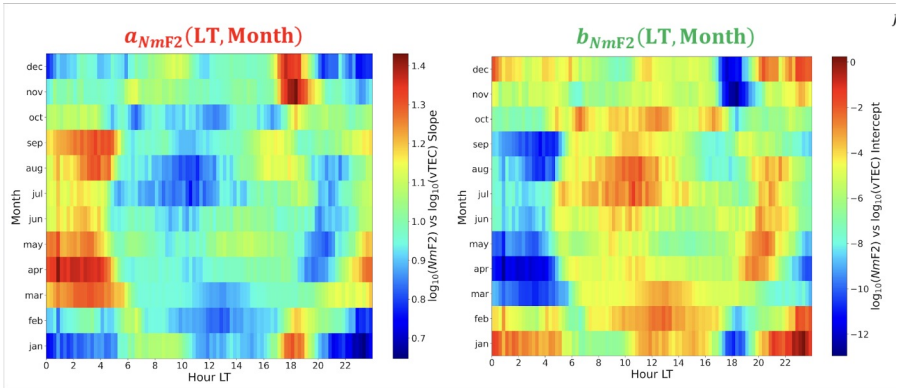
Maximum frequency of electromagnetic waves reflected by the ionosphere.

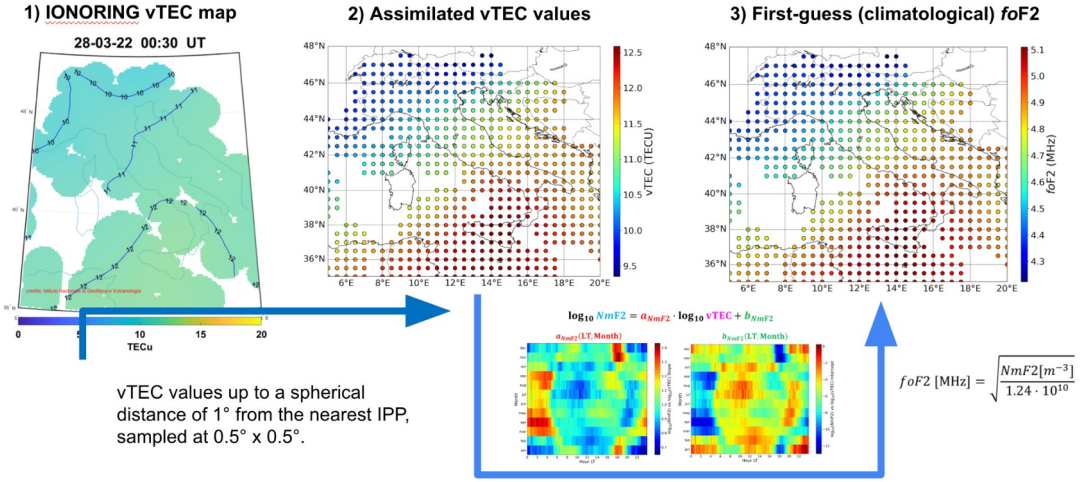
*fo*F2 knowledge is of utmost importance for High-Frequency (HF) radio communications and many Space Weather applications.

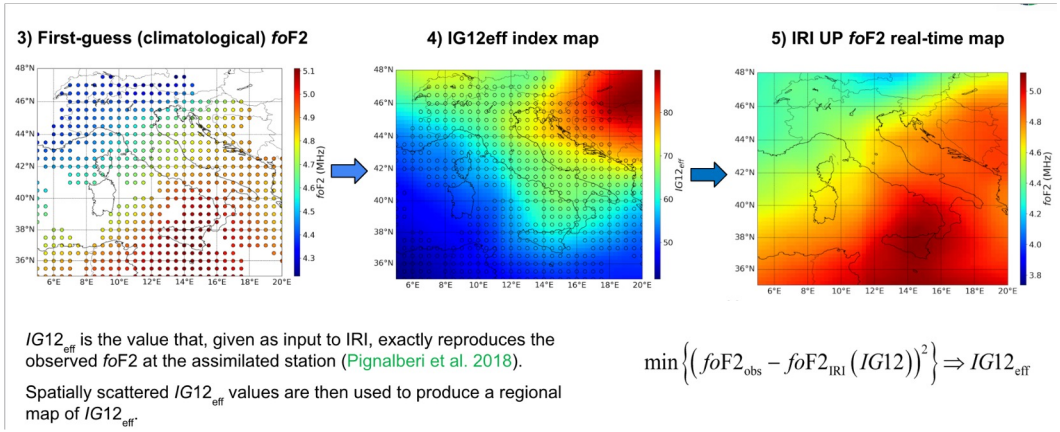
F2-layer peak frequency real-time mapping and alert through data assimilation.



Assessing *fo*F2 from GNSS vTEC







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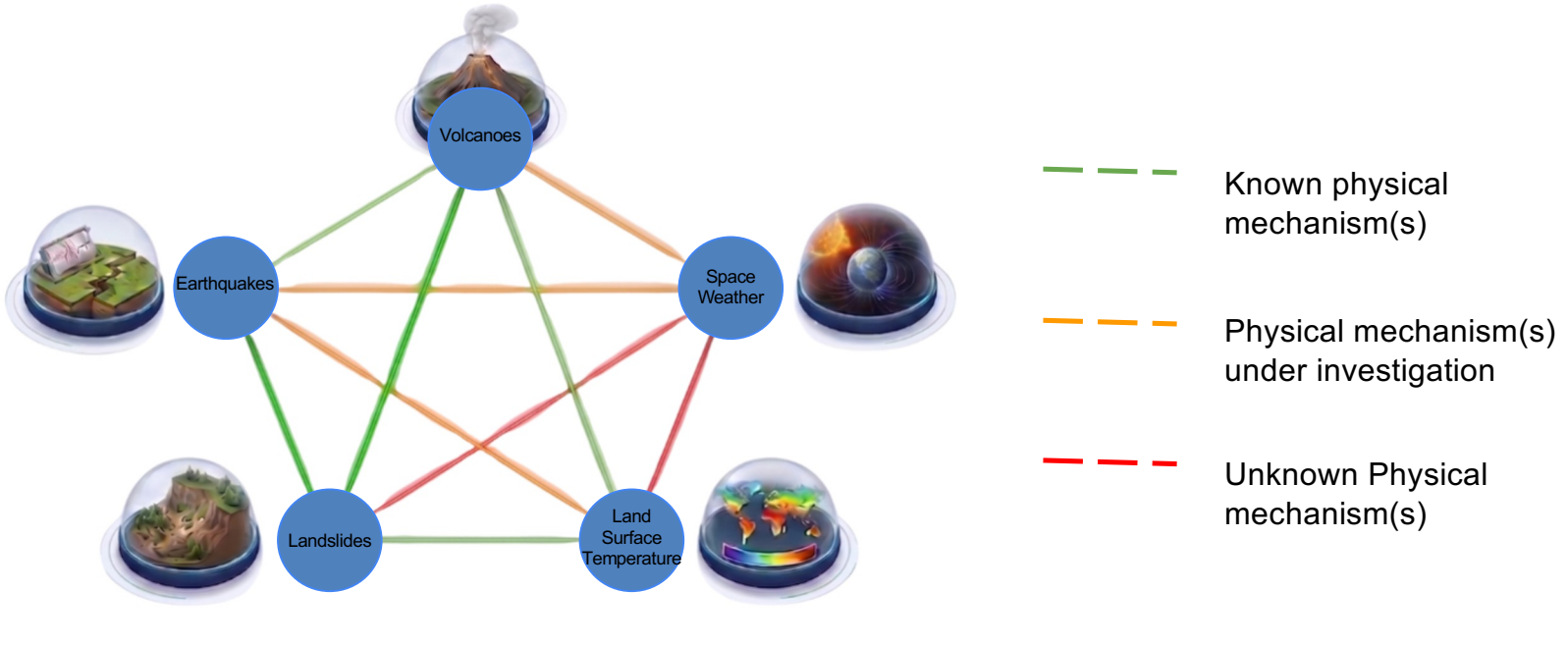
WP 7 Earth Digital Twin



- Interaction among the thematic DTs for **volcanoes**, **earthquakes**, and the **environment**
- Investigation on **Lithosphere-Atmosphere-Ionosphere coupling** to identify correlations among lithosphere and atmosphere from observations processed in WP4-5-6, supporting the interpretation of **complex, coupled scenarios**
- Using an **AI-driven data integration framework**, the aim is to move beyond single-hazard analyses **to uncover cross-process linkages between diverse phenomena**

GEO-DREAM Scientific Challenges

→ ***Etna:*** *relation between intrusions and erupted products under varying gas content and eruptive styles (effusive/explosive) and examine links between East flank dynamics and the 2018 lateral eruptions.*

→ ***Campi Flegrei****: assessment of the significance of observed changes (geodetic and thermal time series) for early detection of source variations and possible dike propagation, RT network sensitivity and supporting vent-opening scenarios for PDC simulations. Exploration of volcanic plume detection/retrieval.*

→ ***Earthquakes****: AI/ML identification of InSAR patterns of primary (co-seismic deformation) and secondary (seismo-induced landslides) effects.*

→ ***Space weather****: impact of solar and geomagnetic storms on the Mediterranean ionosphere under different simulated solar-wind and geomagnetic-field conditions.*

→***GEO-DREAM****: connections between these distinct hazards.*

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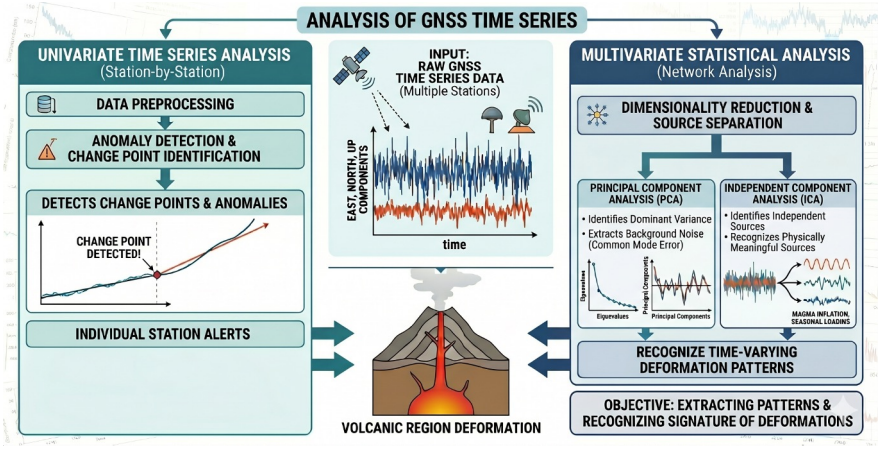
Fostering AI/ML in geohazards and space weather

Statistical analysis and change point detection on deformation time series

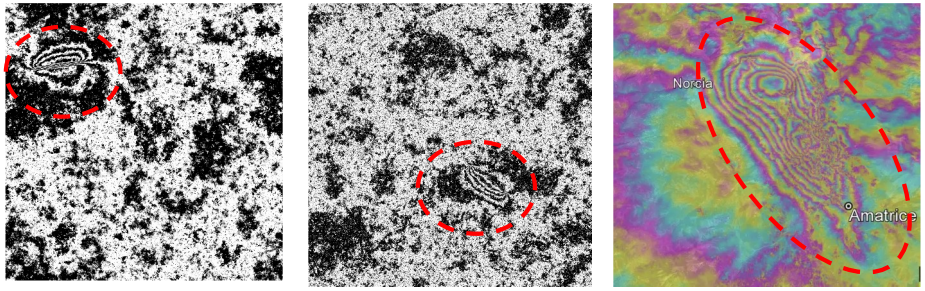
- Automatic anomaly detection in surface deformation time series
- Dimensionality reduction to separate sources



Automatic recognition of seismic signals on SAR interferograms

- Generation of synthetic interferograms of coseismic deformation and seismo-induced landslides.
- AI network training
- Testing on real cases

synthetic **synthetic** **real**



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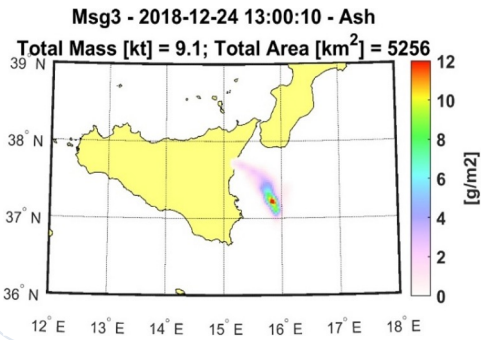
Fostering AI/ML in geohazards and space weather

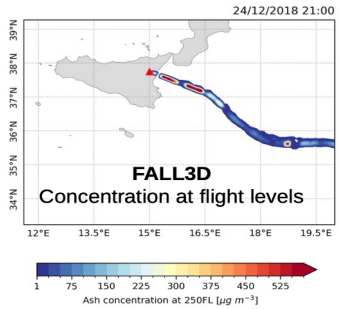
Volcanic ash cloud retrieval by satellite data, simulation and data assimilation

- Ensemble simulations of volcanic ash clouds and data assimilation
- Real time ash and SO2 detection and retrieval by satellite data
- Real time forecasting
- Data assimilation and forecast via HPC resources

detection/retrieval



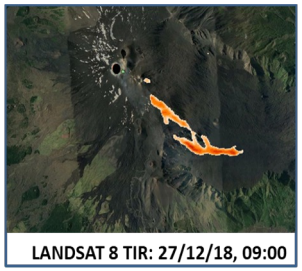
simulation/forecast

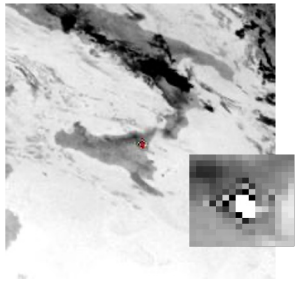


Lavaflow detection and retrieval with satellite data and simulation and forecast

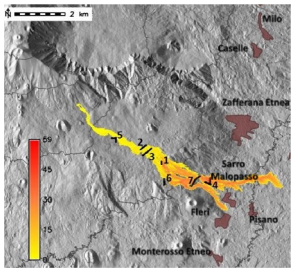
- Multi-spectral satellite imagery to automatically locate thermal anomalies
- Simulate lavaflow from 2D cellular automaton by assimilating satellite data
- 7-day forecasts for lava flow obtained in a few seconds with GPUs

detection/retrieval





simulation/forecast



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Fostering AI/ML in geohazards and space weather

Volcano deformation time serie assimilation with Ensemble Kalman Filter

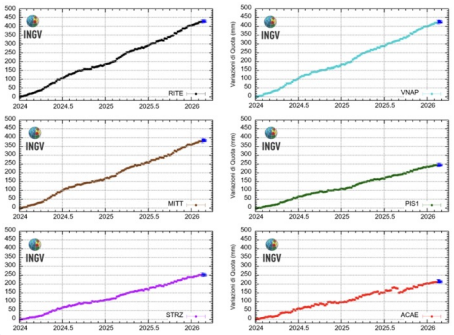
- Markov Chain Monte Carlo retrieval of magmatic source parameters
- Near real time data assimilation and parameters forecast

$$A^a = A^f + X\,H^T\,(H\,X\,H^T + C)^{-1}\,(D - H\,A^f)$$

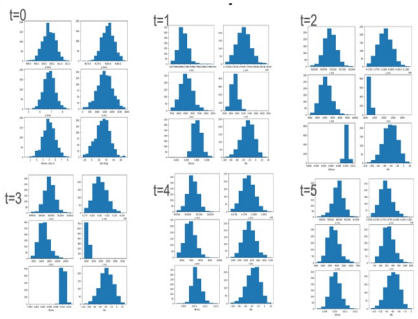
(Kalman Gain)

A^f model forecast
A^a updated model
H model operator matrix
D data
C data covariance matrix
X ensemble covariance matrix

Geodetic data TS



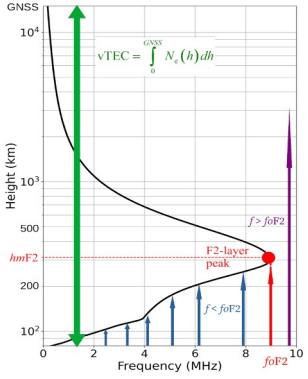
simulation/forecast



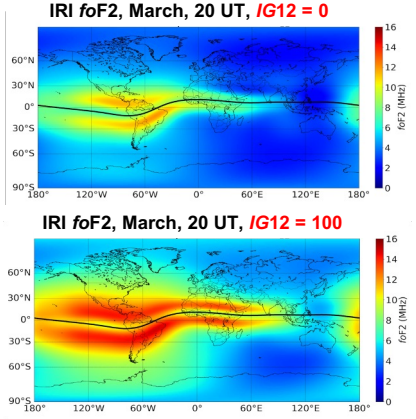
Ionospheric electron density & IRI UP data assimilation

- F2-layer peak frequency real-time mapping
- Empirical data assimilation by IRI UP to update the F2-layer description
- Obtain a nowcasting of *fo*F2 for Space Weather

F2-layer frequency



simulation/nowcast



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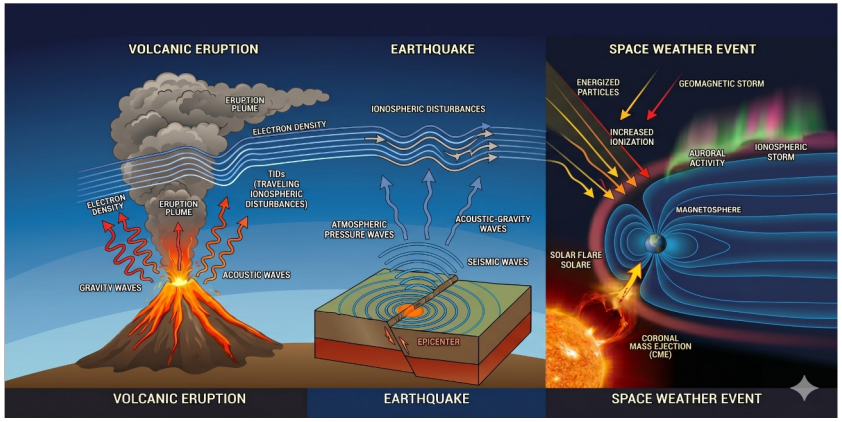
Fostering AI/ML in geohazards and space weather



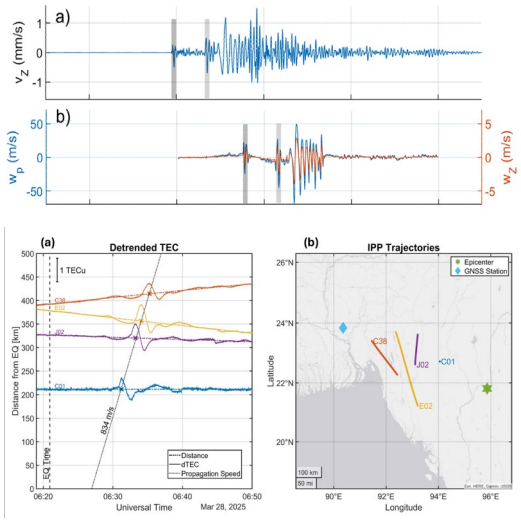
Towards a unified vision of the Earth System

- Exploration of connections among distinct hazards (**volcanic, seismic, environmental and space weather**), potentially using the ionosphere as a global probing medium
- Prototype a Earth DT, starting from an **AI-based foundation model**
- Progressing through concrete applications and iterative enhancements
- Delineate **guidelines** to scale the prototype towards **global infrastructures**

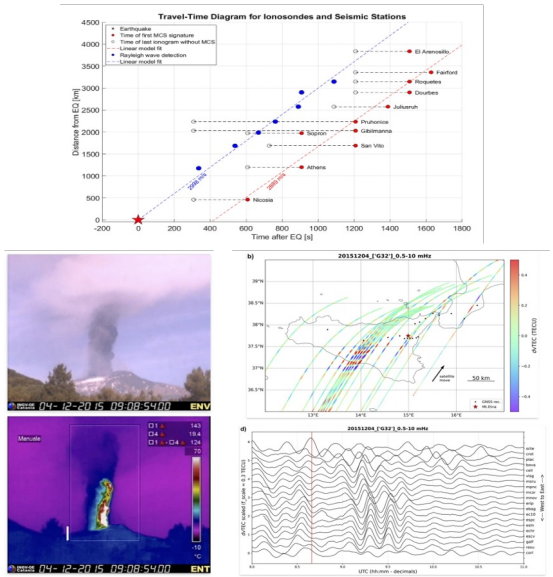
Lithosphere-Atmosphere-Ionosphere coupling investigation

- Strong earthquakes produce infrasound and elastic waves possibly reaching ionosphere heights
- Medium-size to major volcanic events disturb the ionosphere

Multi-source time series



Common patterns



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THANK YOU!

GEO-DREAM

