

VOLCANICA Article in Press

This is an uncorrected proof, meaning that this manuscript has not been copyedited or formatted according to Volcanica's styles and standards. In turn, this means that article content, including text, may still change prior to final publication. Although articles in press do not have all bibliographic details available yet, they can be cited using the year of online publication and the DOI, as follows: author(s)(year), article title, Volcanica, DOI.

Moiroux Arvis, L., Royer, L., Sudre, J., Lafarguette, P., Mezhoud, J., Breton, V., Terray, L., Cariou, C., Chanet, J.-P. and Donsez, D. (2026) "Satellite IoT, a new opportunity for the monitoring of active volcanoes", <i>Volcanica</i> , 9(2). doi: 10.30909/vol/ttq1469.

Satellite IoT, a new Opportunity for the Monitoring of Active Volcanoes

 L. Moiroux Arvis^{*α},  L. Royer^β,  J. Sudre^γ,  P. Lafarguette^β,  J. Mezhoud^δ,  V. Breton^β,
 Luca Terray^β,  C. Cariou^α,  J.P. Chanet^α, and  D. Donsez^ε

^α Université Clermont Auvergne, INRAE, UR TSCF, Aubière, France.

^β Université Clermont-Auvergne, CNRS, LPCA, 63000 Clermont-Ferrand, France.

^γ Université Clermont Auvergne, 63000 Clermont-Ferrand, France.

^δ Université Clermont-Auvergne, Mésocentre, 63000 Clermont-Ferrand, France.

^ε Université Grenoble Alpes, LIG, 38058 Grenoble cedex, France.

ABSTRACT

This paper presents an evaluation of satellite-based Internet of Things (IoT) communication solutions for the monitoring of active volcanoes, focusing on two major satellite architectures: Low Earth Orbit (LEO) and Geostationary Earth Orbit (GEO) systems. Satellite IoT technologies enable the rapid deployment of low-power sensor networks in harsh and remote environments where conventional communication infrastructures are ineffective. Field and laboratory experiments were conducted to assess the quality of service provided by representative LEO and GEO solutions, illustrated through the use of the Kinéis LEO constellation and the EchoStar Mobile GEO satellite platform. The results show that LEO-based systems offer worldwide coverage but are constrained by intermittent satellite visibility, requiring the integration of satellite pass schedules into device operation. Transmission success rates were found to strongly depend on satellite elevation, ranging from approximately 20% at low elevation angles to over 80% at high elevation angles. In contrast, GEO-based systems provide continuous connectivity within their coverage area and exhibit a stable transmission success rate of up to 94%, provided that a clear line of sight toward the satellite is maintained, although their coverage is geographically limited. Power consumption measurements for both architectures demonstrate the feasibility of multi-year battery autonomy for volcano monitoring applications.

KEYWORDS: Satellite iot; Geo satellite; Leo satellite; Network performance evaluation; Monitoring of active volcanoes; Environmental monitoring.

1 INTRODUCTION

This article presents an evaluation of the possibilities and limitations offered by two satellite IoT (Internet of Things) communication solutions applied to the observation and monitoring of active volcanoes. The interest of deploying wireless sensor networks on volcanic edifices to improve their surveillance has been identified more than 20 years ago [Werner-Allen et al. 2006]. At that time, the first IoT systems deployed on the Reventador volcano in Ecuador achieved high availability, precise timestamping, and effective seismic and acoustic data collection despite harsh environmental conditions. Since then, several on-site experiments have confirmed the feasibility and benefits of deploying ground-based wireless sensor networks for monitoring volcanoes. An IoT-based LoRa network monitoring soil temperature at the Teide volcano in Tenerife provided reliable real-time data transmission with minimal energy consumption [Awadallah et al. 2019]. A network of sensors, communicating

*✉ laure.moiroux-arvis@inrae.fr

nodes, and gateways was successfully deployed on the Etna Volcano in Sicily from 2019 to 2022, including a period of intense volcanic activity in 2021 [Terray et al. 2020; Royer et al. 2024]. Indeed, the Low-Power Wide-Area Network (LPWAN) technologies enable the rapid deployment of autonomous, low-cost sensor networks at key monitoring points that are highly strategic but difficult to access via commercial terrestrial communication infrastructures. This difficulty is mainly due to the particularly rugged topography of volcanic edifices, marked by the presence of deep, enclosed craters whose walls significantly hinder the propagation of radio frequency signals to terrestrial relays, even when they are nearby. Furthermore, the extreme weather conditions of these sites often make access difficult or even impossible and expose the instruments to severe constraints. The presence of acidic gases, combined with the risk of eruptions, also jeopardizes the proper functioning and longevity of the measurement devices deployed in the field [Royer et al. 2024]. The use of robust, low-cost systems that are easy to deploy and maintain is therefore essential to ensure continuous and long-term monitoring. Additionally, data telemetry not only helps to secure information in the event of equipment failure or destruction, but also allows near real-time tracking of parameter evolution, thereby facilitating preventive and maintenance actions.

However, the deployment of wireless sensor networks in rugged volcanic topographies is also faced with challenges, especially related to the signal quality between gateways and nodes to collect sensor data and to the access to internet required for data transfer from the gateways to the end-point where it will be analyzed [Rawat et al. 2014]. In such contexts, satellite IoT offers a unique advantage as it provides global coverage, high reliability, and the ability to operate in environments where terrestrial communication is impractical or impossible [Shutao 2024]. Recent studies have highlighted the potential of integrating satellite and terrestrial IoT networks to create hybrid architectures capable of ensuring data continuity in real time, even in extreme or disaster-prone environments [Fraire et al. 2021]. These developments open new perspectives for active volcano monitoring, where rapid deployment and resilience of the communication network are critical. It is in this context that the quality of service offered by two satellite telecommunication operators was evaluated: on the one hand, Kinéis, which relies on a constellation of Argos nanosatellites in Low Earth Orbit (LEO), and on the other, EchoStar Mobile, which operates using a Geostationary Earth Orbit satellite (GEO). The GEO satellite is positioned above the equator and remains fixed relative to a given point on the Earth's surface, while the LEO satellites, located closer to Earth, make rapid revolutions covering different areas, as illustrated in Figure 1.

While most studies on satellite IoT focus on the performance of these communication networks in the context of large-scale deployment of connected devices across a wide range of application domains [Hassan et al. 2020], our work aims to

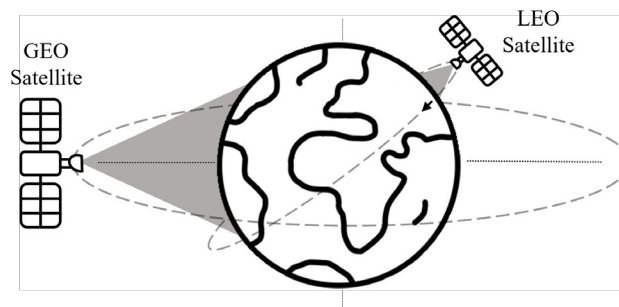


Figure 1: LEO and GEO satellite orbits

assess the actual quality of service of these technologies in the concrete application of monitoring of active volcanoes. LEO and GEO connectivity options are compared based on both field experiments conducted on Mount Etna and long-duration open-sky measurements. Beyond comparing functionalities, key performance factors are analyzed, including the influence of terrain topography, satellite elevation, message integrity, and the energy cost per transmitted message.

This paper is organized as follows: after a brief overview of the opportunities offered by IoT, the materials and methods used to conduct our experiments are described. The results obtained are then presented in detail and discussed.

2 OVERVIEW OF CONNECTIVITY OPTIONS FOR REMOTE IoT MONITORING

The IoT has quickly established itself and continues to experience strong growth across numerous sectors [Hassan et al. 2020], ranging from industry and logistics to everyday applications such as smart cities, healthcare, sports, air pollution monitoring [Bathiya et al. 2016] and home automation, as well as in the field of agriculture [Elijah et al. 2018]. Although its adoption has been slower in environmental monitoring and observation, IoT is gradually finding applications there and is generating growing interest [Radha et al. 2024]. Indeed, it represents a key tool for better understanding how ecosystems function, particularly in the context of climate change [Salam 2020]. By enabling effective monitoring, these technologies allow for the automated measurement of various atmospheric, physical, chemical, and biological parameters over the long term, with high temporal resolution [Narayana et al. 2024].

IoT involves a set of technologies that enable the collection, transmission, and analysis of data from various sensors deployed in diverse environments. Among them, LPWAN and more recently satellite technologies are particularly relevant to environmental applications requiring wide coverage. These solutions aim to meet the requirements of massive Machine Type Communications (mMTC) systems, an essential pillar of IoT defined by their ability to manage a very large number of connected devices while adhering to strict constraints in terms of latency, robustness, coverage, and energy efficiency. Each of these technologies offers varying degrees of optimization depending on the use case, the type of data to be transmitted and the deployment environment. LPWAN technologies, such as LoRaWAN and Sigfox, have experienced significant growth, reaching approximately 1.3 billion connections in 2023 [Sinha 2024]. This expansion is largely due to their suitability for environmental instrumentation requirements, namely, low data rates, long range, low energy consumption, and low cost [Moiroux-Arvis et al. 2023]. In the absence of an operated public network, deploying a private network requires the installation of dedicated gateways. This process is often complex and costly, particularly when no wired electrical infrastructure is available to power them. These gateways are also vulnerable to damage caused by human activity or natural events, especially in active volcanic areas [Awadallah et al. 2019]. They also need to be connected to the Network Server using a backhaul such as Cellular (3G/4G/5G), Wi-Fi, Ethernet, fiber-optic, or 2.4 GHz radio links. Without Internet connectivity in so-called “white zones”, it becomes impossible to implement a LoRaWAN network [Rafi et al. 2025]. Lastly, topographic constraints, such as those found in watersheds, high mountain areas, volcanic edifices, or riverbeds, limit the effectiveness of terrestrial networks due to the signal attenuation affecting radio-frequency communication between ground-based devices. Mesh or multi-hop approaches have been proposed as an alternative means to mitigate the lack of direct connectivity to a gateway by allowing nodes to forward messages to one another, thereby extending coverage without requiring continuous Internet access at every hop. However,

while such architectures can increase reach, they still require the deployment of multiple relay nodes distributed across the monitored area, which adds system complexity and increases exposure to harsh environmental conditions. Moreover, multi-hop routing introduces additional dependencies on intermediate nodes, higher cumulative energy consumption, and potential latency and reliability issues, since end-to-end delivery depends on the availability of all relaying nodes, as discussed in multihop LoRaWAN mesh studies [Cotrim and Kleinschmidt 2020].

Satellite technology makes it possible to overcome dependence on terrestrial telecommunications infrastructure, notably relay facilities such as gateways, base stations, or backhaul links. It is therefore of major interest in areas where such infrastructure is lacking or difficult to deploy and maintain. It is why communications operated with satellites offers a solution for a wide range of applications [ECC 2020; Centenaro et al. 2021], whether located in urban, rural, or remote areas [De Sanctis et al. 2016; Kodheli et al. 2020]. This technology opens new opportunities, particularly for environmental observatories, which are often situated in remote regions. It enables the monitoring of air and water pollution, wildlife tracking, forest fires, floods, earthquakes, cyclones, hurricanes, landslides, and avalanches [Chippalkatti and Biradar 2021]. A concrete example in the context of forest fire monitoring is provided by [Desk 2024]. However, the use of satellite technology does not completely overcome local constraints related to terrain and environmental conditions, such as topographic masking, natural obstacles, or weather, which can affect the quality of the radio link between a ground sensor and the satellite. Nevertheless, by ensuring connectivity for devices distributed across vast geographic areas, including remote environments, without relying on terrestrial infrastructure, this technology also offers a promising solution for volcano instrumentation. The principle is based on the use of satellites to relay data between ground-based devices and remote processing infrastructures. Thus, thanks to LEO or GEO satellites, IoT sensors can transmit their data to ground stations, where it is then processed and analyzed. Figure 2 illustrates the different stages of satellite communication.

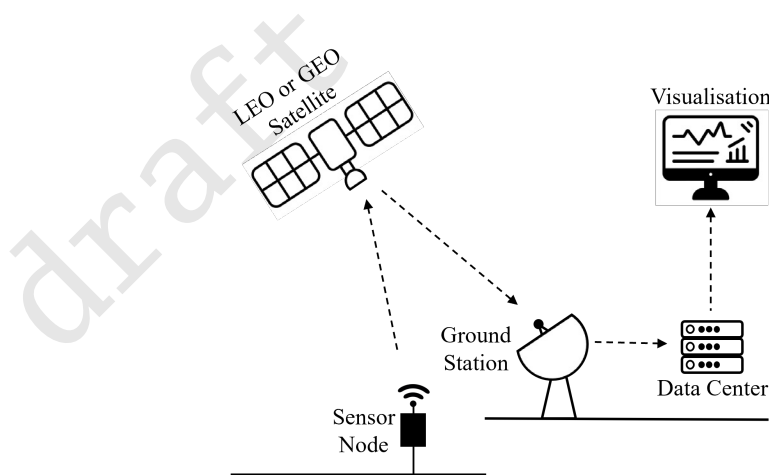


Figure 2: Fundamentals of IoT satellite communication

The communicating sensor-nodes, to which the measurement probes are connected, are deployed on the ground. These nodes transmit their data to a satellite, which then relays the information to a ground station. The data is subsequently managed within a data center type infrastructure, allowing end users to access it. In recent years, many industrial players have heavily invested in the development of satellite-based solutions dedicated to IoT, aiming to provide low-power, cost-

effective connectivity directly from space. The list of operators presented by [SatelliteIoT 2025] shows that most rely on constellations of nanosatellites in LEO, which help reduce latency and launch costs while offering broad coverage suited for intermittent transmission of small data volumes [Qu et al. 2017]. However, to ensure long-term hourly coverage at a continental scale, a constellation of more than 10 LEO satellites is required [Lahoz et al. 2012]. On the other hand, GEO satellite-based solutions represent about a quarter of the global market. Yet, GEO satellites provide wide coverage, with a single satellite capable of covering up to one third of the Earth's surface, although polar regions remain inaccessible [Jung et al. 2024]. In terms of latency performance, LEO constellations have an advantage over GEO satellites: GEO systems typically experience latency between 240 ms and 280 ms, whereas LEO systems range from 30 ms to 150 ms [Adiprabowo et al. 2025]. But this characteristic is not critical in the case of environmental applications, as the time constants of the observed phenomena are generally greater than one second. For this reason, we explored the two options in our context.

3 MATERIAL AND METHODS

To evaluate the performance offered by satellite IoT, the solutions provided by the operators Kinéis [Kinéis 2018] (LEO-based service) and Echostar Mobile [Satellite-based LoRa® Unlocks Europe-Wide IoT 2022] (GEO-based service) were tested. The choice of these two operators allows for assessing and comparing the services provided by a low Earth orbit satellite network with those of a geostationary configuration. The tests and measurements conducted over several weeks made it possible to evaluate the performance of each of these technologies in terms of features, quality of service, data rate, and energy consumption.

3.1 LEO-based Spatial IoT connectivity proposed by Kinéis-Argos

The Kinéis offering evaluated in this paper is based on a constellation of operational Argos satellites in low Earth orbit, at an altitude of approximately 650 km, as shown in Figure 3. Connectivity between the sensor nodes and the satellites is not continuous but depends on the satellite location above the horizon at the sensor node's position. Each satellite travels at an average speed of about 7.8 km per second, and its pass duration varies between 3 and 12 minutes, depending on its elevation relative to the horizon. To establish a connection with a satellite, a minimum elevation is required. Terrestrial obstacles can significantly affect signal quality, with a minimum threshold of 5° defined by the operator.

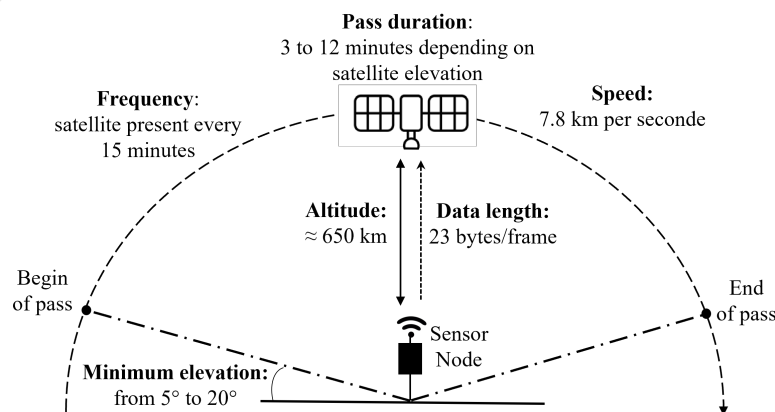


Figure 3: Illustration of satellite communication using the Kinéis LEO constellation

Synchronizing communications with satellite pass windows is essential for optimizing quality of service by avoiding unnecessary data transmissions when no satellite is in the sky at the sensor node geolocation. This approach also helps minimize energy consumption, as the nodes can remain in sleep mode and activate only to perform measurements and transmit data during satellite overpasses. Therefore, it is necessary to integrate a satellite pass schedule directly into the communicating nodes. To support this, Argos offers the ability to upload a schedule generated for a given geolocation, valid for up to six months.

3.2 GEO-based Spatial IoT connectivity proposed by Echostar Mobile

Echostar Mobile provides a satellite communication service with continuous coverage across Europe, the UK, and Scandinavia, thanks to the EchoStar XXI geosynchronous satellite launched in 2017 [ISS Tracker 2015]. This satellite is positioned in a geostationary orbital slot at 10.25 degrees East, at an altitude of approximately 36,000 km. Unlike LEO satellites, connectivity between sensor nodes and a geostationary satellite is continuous and therefore does not require synchronization with satellite passes (Figure 4).

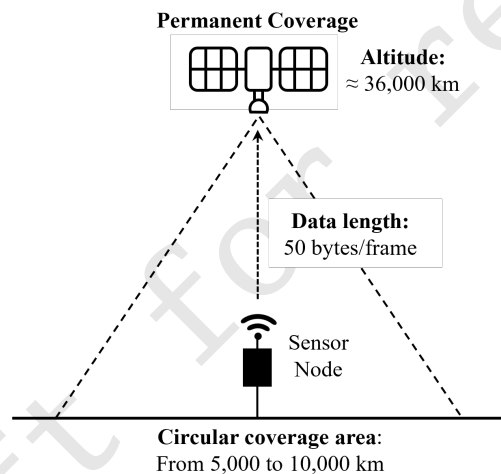


Figure 4: Illustration of satellite communication using the Echostar Mobile GEO satellite

The uniqueness of the offering provided by Echostar Mobile lies in its use of communication based on LoRa® Frequency Hopping Spread Spectrum (LR-FHSS) in the licensed S-Band, which combines the long-range and low-power features of the LoRa physical layer. This choice allows for complementing and extending terrestrial LoRa infrastructures in areas that are difficult to equip.

3.3 Summary of the features of LEO (Kinéis/Argos) and GEO (EchoStar Mobile) satellite IoT solutions

Table 1 presents the main characteristics of the technologies deployed by the two satellite communication operators targeted in this study and terrestrial LoRaWAN technology, which is provided as a reference for comparison. The table also distinguishes the characteristics of the experimental 8-satellite Argos constellation from those of the final operational 25-satellite Kinéis constellation. In particular, the average interval between successive communication opportunities is expected to decrease from approximately 26.8 minutes with the 8-satellite configuration to about 15 minutes with the complete constellation. The

Table 1: Summary of the Communication Technology Characteristics of Kinéis, EchoStar Mobile and LoRaWAN from publicly available sources

	Kinéis	EchoStar Mobile	LoRaWAN
Features of satellites			
Orbit	LEO	GEO	—
Altitude	≈650 km	≈36 000 km	—
Number	8 sat.: during experiments 25 sat.: final constellation	1	—
Size	0.2 × 0.2 × 0.4 m	18 m antenna	—
Weight	≈25 kg	—	—
Service life	8 years	15 years	—
Features of the communication			
Coverage	Global	Pan-European	Gateway and antenna dependent (typically a few kilometres)
Radio band	401 MHz	Licensed 2 GHz S-band	ISM bands (868 MHz EU, 915 MHz US)
Communication availability	According to satellite passages	Continuous within coverage area	Continuous if gateway reachable
Transmission constraint	Minimum 1 min between transmissions	Not specified in public documentation	1% duty cycle (EU868 regulation)
Average time between successive satellite passes according to $E_{\min}^{(1)}$	8 sat.: 26.8 min ($E_{\min} > 5^\circ$) ≈80 min ($E_{\min} > 30^\circ$) ⁽²⁾ 25 sat.: 15 min ($E_{\min} > 5^\circ$) ≈45 min ($E_{\min} > 30^\circ$) ⁽²⁾	Continuous	—
Modulation	KIM1: LD-A2 ⁽³⁾ KIM2: LD-A2 or LD-K ⁽³⁾	LR-FHSS	LoRa (SF7–SF12)
Maximum payload per message (excluding protocol overhead)	30 bytes raw or 23 bytes encoded	50 to 115 bytes ⁽⁴⁾	Up to 242 bytes
Transmission power	20 to 30 dBm	Up to 27 dBm	Up to 14 dBm (EU868)
Supply voltage	KIM1: 4.5–5.5 V (5 V typ.) KIM2: 3.3–5.0 V (3.6 V typ.)	3.3 V ±10%	SX1272 circuit: 1.8–3.7 V
Communication module operating conditions			
Temperature operation	-20°C to +55°C	-30°C to +70°C	-40°C to +85°C
Humidity	Up to 90%	Up to 90%	Up to 90%

(1) $E_{\min}$ denotes the minimum satellite elevation angle above the local horizon.

(2) values reported for a minimum satellite elevation angle of 30° are estimates derived from the experimental communication success rates obtained with the 8-satellite constellation and from the operator specifications for the final 25-satellite constellation.

(3) KIM1 and KIM2 denote the first- and second-generation Kinéis communication modules, respectively.

(4) depending on data rate [LoRa Alliance Resource Library 2026]

major difference between the satellite solutions lies in the continuity of the communication link, which is inherent to the type of orbit, GEO or LEO, followed by the deployed satellites. Regarding the payload available per message sent, the value is significantly higher with EchoStar Mobile (from 50 bytes to 115 bytes) compared to Kinéis (from 23 bytes to 31 bytes). Lastly, both satellite communication systems support adjustable transmission power levels, ranging from 24 to 30 dBm for Kinéis and up to 27 dBm for EchoStar Mobile. The actual power consumption of each communication module has been measured and is presented in Section Evaluation of energy autonomy.

165

170

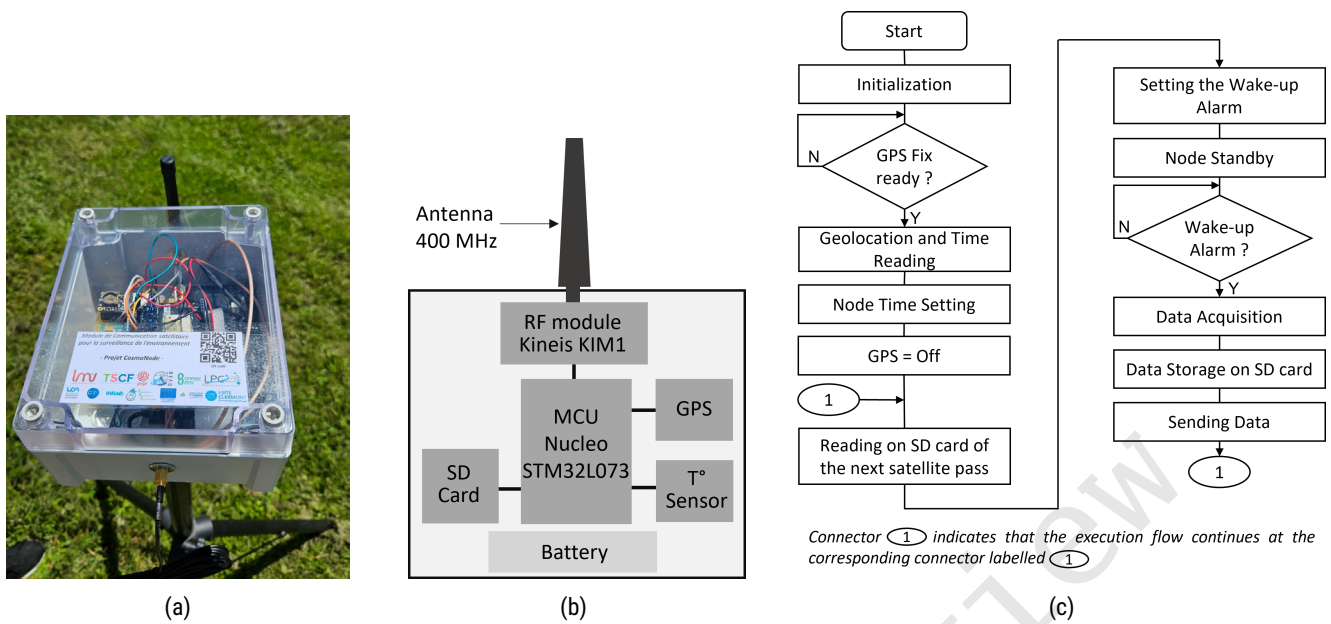


Figure 5: Kinéis Communication node: a) picture of the node b) different elements integrated in the node c) Diagram of the program embedded in the Kinéis Node

3.4 Materials

3.4.1 Kinéis Satellite-connected IoT device

To test the communication service offered by Kinéis based on the Argos constellation, a device was developed to both take and store air temperature and geolocation measurements, and to transfer data frames to an Argos satellite when it is in range. This sensor node is controlled by a program running on an STM32L073RZ microcontroller embedded on a Nucleo development board (from STMicroelectronics), as illustrated in Figure 5.b. The sensor node is powered by a rechargeable 3.6 V/8.8 Ah lithium battery, aiming for energy autonomy during a data acquisition campaign. Most of the time, the sensor node operates in deep sleep mode and is active only during satellite passes. Measurements are stored on an SD card memory. RF communication relies on the Kinéis KIM1 shield module equipped with a 400 MHz antenna. The transmission power was set to the maximum value of 1 W. The microcontroller communicates with the KIM1 module and GPS module (FGPMMOPA6H from GlobalTop Technology) via a UART interface, with the TMP102 (from Texas Instruments) temperature sensor via an I2C bus, and with the SD card via an SPI bus. All components were interconnected and integrated into a waterproof protective enclosure (Figure 5.a). The diagram of the embedded program in the node is shown in Figure 5.c. This program controls all node operations, including the management of sleep and wake-up cycles based on satellite passes, as well as data acquisition and transmission. For data transmission, the microcontroller controls the Kinéis communication module by sending specific text-based AT commands via a serial interface.

To ensure the node communicates only during satellite pass windows, a pass schedule is implemented on the SD card. This schedule synchronizes the node with the satellite passes, specifying the start and end times for each window. During each window, the node transmits a data frame to the satellite every minute. The raw frame format limits the payload to a

maximum of 31 bytes encoded in hexadecimal. The data frame structure we defined contains 27 bytes and is detailed in Table 2.

Table 2: Structure of the Kinéis Node data frame (27 bytes)

Bytes	Description
1 byte	Sensor node identifier
2 bytes	Counter (Auto increment of the frame)
6 bytes	Measurement Timestamp (UTC time)
2 bytes	Temperature
12 bytes	GPS position (latitude, longitude, altitude)
4 bytes	Battery voltage of the node

3.4.2 EchoStar Satellite-connected IoT device

To test the EchoStar Mobile technology, a communication node integrating the EchoStar EM2050 communication module was developed. It features an architecture similar to the Kinéis node and, like it, includes a GPS module (FGPMMOPA6H), an SD card and a 3.6 V/8.8 Ah rechargeable lithium battery, as illustrated in Figure 6.a and Figure 6.b. It is also controlled by a microcontroller from the STM32 family (STM32L476RGT). However, unlike the Kinéis node, which is based on a set of development boards, a dedicated electronic board was designed by our laboratory. This board was developed to be optimized for both compactness and energy consumption. Notably, a 2.4 GHz ceramic antenna (M310220) is directly integrated onto the board. This node also enables interfacing with a PT100 temperature sensor and a water level probe using the SDI-12 protocol, for applications in water resource management. As with the Kinéis node, the system remains in deep sleep mode most of the time. It is only active during data acquisition and transmission, which occur at configurable intervals based on specific needs. The electronic board and the battery are housed in a waterproof protective casing (Figure 6.a).

The diagram in Figure 6.c illustrates the embedded program within the node. This program oversees all operations of the node, such as managing sleep and wake-up cycles, as well as handling data acquisition and transmission.

As EchoStar modules use LoRa® technology to communicate with satellites, the maximum size of the transmitted data frames depends on the Spreading Factor (SF) used in the LoRa modulation. The frame is encoded in hexadecimal. The data frame structure we have defined is provided in Table 3.

Table 3: Structure of the Echostar Node data frame (30 bytes)

Bytes	Description
4 bytes	Timestamp (UTC time)
6 bytes	Battery data (capacity, voltage, current, temperature)
2 bytes	Probe temperature
10 bytes	Water probes (temperature, level, conductivity)
8 bytes	GPS position (latitude, longitude)

3.4.3 Tests and measurements carried out

Two scientific missions were conducted in September 2023 and September 2024 on Mount Etna volcano in Sicily, providing a first opportunity to test the communication devices in an active volcanic site (Figure 7). The modules were transported in

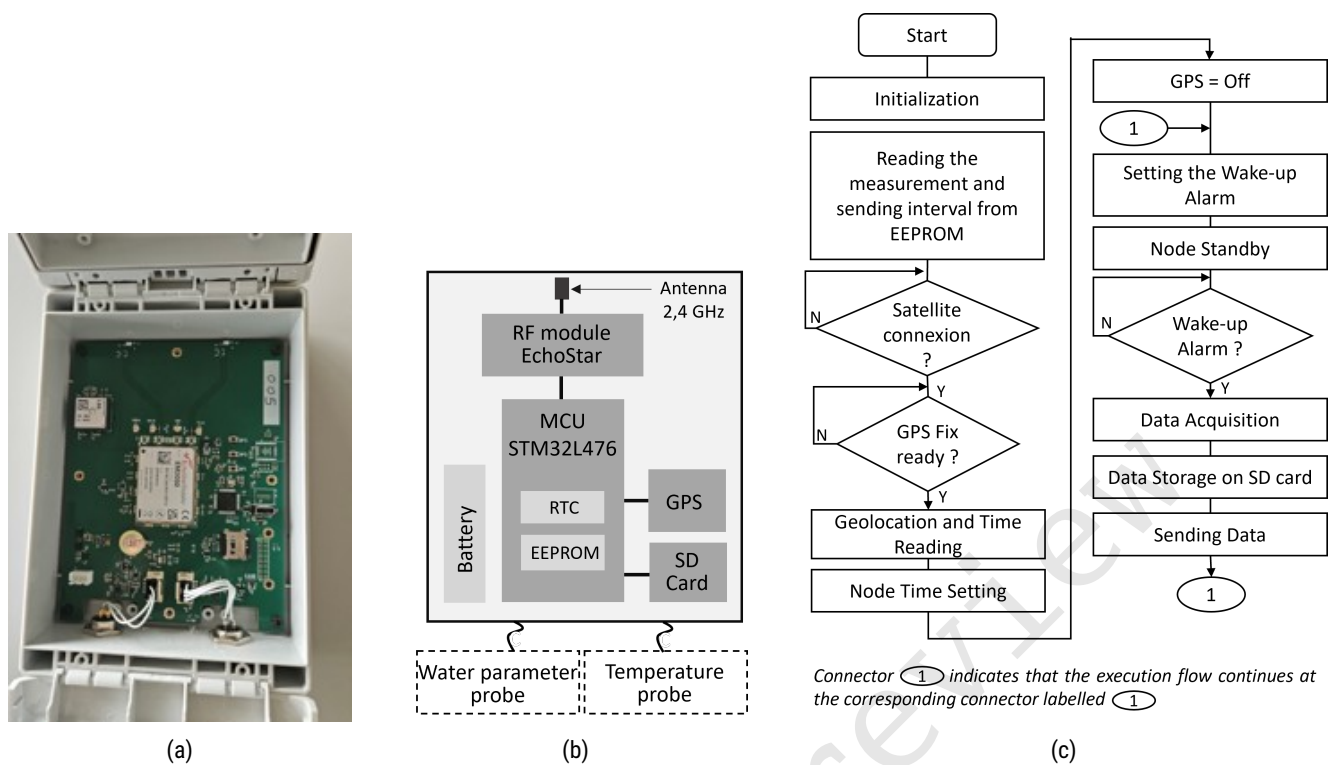


Figure 6: Echostar Communication node: a) picture of the node with the EM2050 module at the center b) different elements integrated in the node c) Diagram of the program embedded in the Echostar Node

the main areas of interest for volcano monitoring (South and North rift zones, summit craters) and on the main roads around the edifice during a mobile survey (by car and on foot). Fixed points lasting several tens of minutes were also established at relevant monitoring sites, particularly at the summit craters. However, the limited duration of the campaigns and the difficulty of accessing scientifically relevant areas did not allow a long-term assessment of the quality of service. Therefore, these field experiments should be regarded as a snapshot evaluation of the communication systems under representative volcanic conditions rather than as a long-term validation of their performance for continuous monitoring applications.



(a)



(b)

Figure 7: Kinéis module being deployed on Mt. Etna volcano: a) on the rim of Bocca Nuova crater at the summit, b) on the flank of the volcano at 3000 m of altitude

In such a volcanic environment, satellite communication performance can be impacted by terrain masking and line-of-sight obstructions caused by crater rims and steep slopes, which may reduce satellite visibility, especially at low elevation angles. Communication quality can also be affected by extreme weather conditions (humidity, rain, wind, temperature), which can degrade signal quality. Finally, chemically aggressive volcanic gases can gradually degrade exposed components (e.g., antenna and connectors), potentially affecting long-term reliability.

To better isolate the intrinsic performance of each communication solution from terrain and environment induced effects, additional outdoor tests were conducted in a less constrained setting. To this end, measurements were carried out on the campus of the University Clermont-Auvergne (UCA) in Cézeaux-Aubière (France) at an open site offering a clear radio horizon. These measurements made it possible to evaluate the quality of service provided by the operators over several weeks. The communication nodes were placed on the roof of the laboratory, a location offering few obstacles to radio frequency communication, as shown in Figure 8.



Figure 8: Satellite modules installed in the roof of the laboratory located on the campus of the University Clermont-Auvergne

4 RESULTS

4.1 Evaluation of the transmission efficiency

4.1.1 *Evaluation on the Mount Etna volcano*

Figure 9 and Figure 10 illustrate the path followed during the mobile survey with the Kinéis nodes. Figure 9.a shows the points where communication was established, and Figure 9.b shows the points where communication failed.

During the field campaign, communication attempts were performed every minute during satellite visibility windows. Most measurements were acquired while the nodes were moving, either by car along the main roads surrounding Mount Etna or on foot in the summit areas. The communication nodes were stationary only during fixed observation periods lasting several tens of minutes at the summit craters.

Overall, these results show that communication via the Kinéis node is effective around most of the perimeter of Mount Etna, with many successful transmissions across a wide area. The coverage in and around the Bocca Nuova summit crater displayed in Figure 10 is particularly important because previous experiments showed connectivity issues with an LPWAN

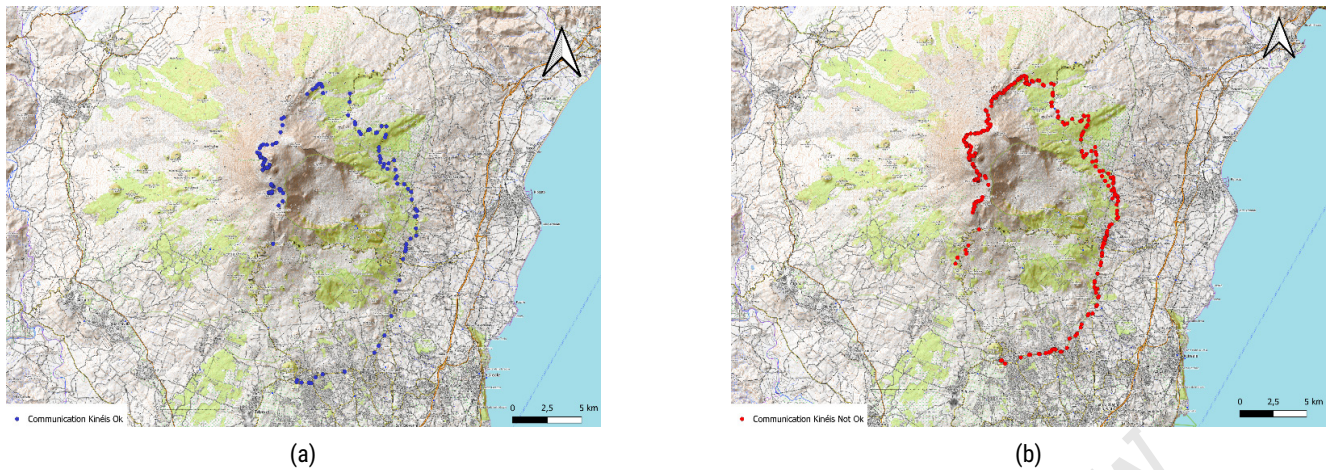


Figure 9: Maps of the Etna site with the location of the successful communications (map (a) with blue dots) and failed communications (map (b) with red dots) along the way with Argos satellites

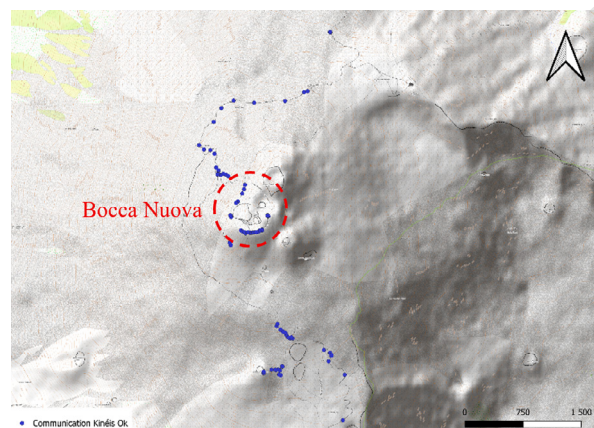


Figure 10: Map of the Bocca Nuova zone of the Etna; the circle with red dashes corresponds to the location of Bocca Nuova central crater while blue dots represent the locations of the successful communications with Argos satellites along the way

network in this same area, as reported in [Royer et al. 2024]. This study presents the deployment of a LoRaWAN infrastructure on Mount Etna and demonstrated the feasibility of terrestrial LPWAN communications. However, it also highlighted several operational limitations, including incomplete coverage due to the complex volcanic topography, the need for a locally deployed gateway and cellular backhaul, and reduced communication range caused by gateway installation constraints. Overcoming these limitations is particularly important because this area is of major interest to scientists, particularly due to the persistent magmatic degassing from the Bocca Nuova summit crater, whose gas plume provides valuable information but remains difficult to monitor continuously. [Aiuppa et al. 2007].

However, as shown in Figure 9.b, numerous communication failures were also observed along the road to reach the central crater, particularly in areas with rough topography. Nevertheless, these failures should also be put into perspective, as the campaign was conducted in a mobile configuration, with the communication node placed at the front of the vehicle, behind the windshield, which may have introduced additional signal masking during some communication attempts. These field observations are consistent with the specific challenges associated with the use of LEO satellite nodes in environments characterized by rugged terrain that can block radio wave propagation. Indeed, although LEO satellites offer extensive coverage,

their orbit close to Earth implies a variable angular elevation with respect to a given geolocation point on Earth. For elevation values that are too low, the direct line of sight between the ground-deployed communication node and the satellite can be obstructed by natural obstacles, such as volcanic structures or any other geological formation. To limit the transmission failure rate, the choice can be made to program message emission from the node to the satellites only for elevation values that limit the masking effects of the terrain. However, removing from the schedule the passage times below a given elevation threshold reduces the time windows available for communication. To quantify this effect, tests were conducted over several weeks on the roof of a UCA campus building, an open area without obstacles.

In the same way as for the Kinéis node, the EchoStar Mobile node was deployed on the Etna site during a field trip, although it was not possible to reach the summit craters due to volcanic unrest. At the Mount Etna experimental site (37.75°N, 15.00°E), the EchoStar 21 geostationary satellite is visible at an elevation angle of approximately 46°, which limits the risk of terrain masking.. As shown in Figure 11, this initial brief exploration confirmed the communication potential offered by the EchoStar Mobile operator for this type of site as communication was successfully achieved in every location on the volcanic edifice.

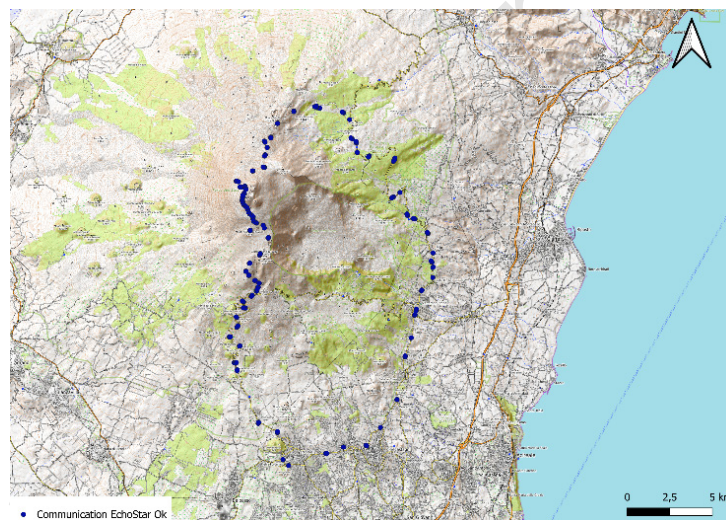


Figure 11: Map of the Etna site with the location of the successful (blue dots) communication with the Echostar Mobile satellite along the way

4.1.2 Evaluation of the Kinéis node in an open area

The tests conducted on the laboratory roof at the University of Clermont-Auvergne took place from January 31 to February 26, 2025. This location is open at 360 degrees, without obstacles. During this period, the Argos satellite constellation had 8 operational satellites, named 'CS', 'MB', 'MC', 'NK', 'NN', 'NP', 'O3', and 'SR'.

Table 4 presents the data extracted from the satellite schedule. Over the period of more than 26 days considered, at least one satellite was present 27.5% of the time, which is an average of 6.6 hours per day. The average time without a satellite is 26.8 minutes, with a maximum of 4.1 hours. Over a range of 5° to 90°, the average elevation of the satellites considered is 31.3°.

Table 4: Data extracted from the Argos satellite calendar provided by Kinéis corresponding to the period of test

Location	Campus des Cézeaux 63170 Aubière – France
Number of satellites considered	8
Duration of test	641.8 hours
Cumulated time with satellite	176.6 hours
Ratio	27.5%
Mean time with presence of satellite per day	6.6 hours
Mean time without satellite	26.8 min
Maximal time without satellite	4.1 hours
Mean middle elevation	31.3°
Minimal elevation	5°
Maximal elevation	89.8°

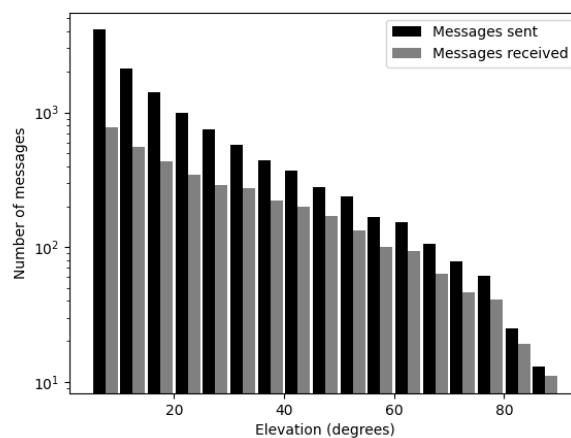


Figure 12: Numbers of messages sent by the node (black) and received by the Kinéis ground station (grey)

Figure 12 shows the number of messages transmitted and the number of messages received during the test period. Based on the schedule provided by Argos and used by the communication node, a message is sent every minute during the passage of a satellite with a minimum elevation of 5°.

As expected, the number of messages sent is significantly higher when the satellites are at a low elevation. This trend can be explained by the fact that all satellites pass through low elevations, whereas only a few reaches high elevations. Thus, transmission opportunities are more numerous at low elevations. At higher elevations, the number of visible satellites decreases considerably, reducing the available transmission windows. Furthermore, Figure 12 highlights the gap between the number of messages sent and the number of messages received, which varies with satellite elevation and suggests a strong elevation-dependent reception performance.

Indeed, as illustrated in Figure 13, the percentage of successful transmissions increases significantly with the elevation of the satellite at the time the message is sent. A reception rate exceeding 50% is only achieved when the elevation exceeds 30°. At a maximum elevation between 85° and 90°, the message reception success rate exceeds 80%.

This analysis of transmissions highlights the significant impact of satellite elevation on the probability of successful communication between the node and the satellite. These results emphasize the importance of integrating this parameter into

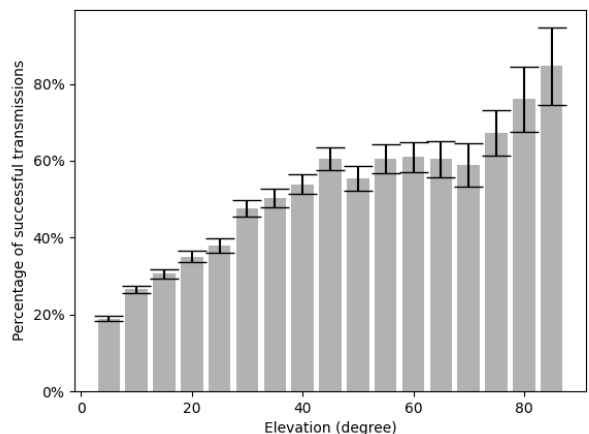


Figure 13: Percentage of successful transmissions as a function of satellite elevation at the time of message transmission by the node

transmission planning. By avoiding message emissions when the satellite is at low elevation, it is possible to significantly increase communication efficiency, at the expense of the available passage time for communication.

To obtain these results, we estimated, for each message sent by the node, the corresponding satellite elevation. This estimation is based on the satellite pass schedule provided by Argos. An excerpt from the schedule is given in Table 5 for the satellite 'O3'. Depending on the geolocation, Argos provides, for each satellite pass, the satellite's name, its pass duration, the date and time of the start and end of the pass, as well as the date and time of the maximum elevation, which occurs midway. Since the operator schedule provides only these key pass parameters and not a full elevation time series, an interpolation-based approximation was used to estimate the elevation at each transmission timestamp. Thus, a simple linear function estimating the elevation as a function of time is established by the 'Start date/time', the 'Middle date/time', and the 'Middle elevation' data. However, this method remains approximate because a satellite's elevation evolves non-linearly due to its orbital trajectory. Despite this approximation, this method simply illustrates the influence of elevation on communication quality.

Table 5: Example of data provided for the satellite 'O3'

Satellite	O3
Start date/time	01/31/2025 00:11:25
Middle date/time	01/31/2025 00:16:39
End date/time	01/31/2025 00:21:53
Duration	00:10:28
Middle elevation (°)	24.52
Start azimuth (°)	203.74
Middle azimuth (°)	265.99
End azimuth (°)	328.67

The integrity of the messages received compared to the transmitted frame was also evaluated. Indeed, during transmission, bit-flip errors can occur with a bit inversion (from 0 to 1 or from 1 to 0) due to disruptions in radio communication. The message may also be incomplete with missing bits. Therefore, it is necessary to decode the received frame and compare it with the sent frame bit by bit. Initially, the analysis of message integrity was carried out with the Kinéis node over the period

from January 30, 2025, to February 26, 2025. In the transmitted frame described in Table 2, only the first 7 bytes (i.e., 56 bits) whose value was known a priori, were considered for this analysis. However, the following bytes of the frame were not analyzed because their values vary depending on the sensor data. The results obtained are presented Table 6.

Table 6: Number of bit-flip errors considering the 7 first bytes of the message

Number of received messages	5166
Number of received bits	289,293
Number of bit-flips	2505
Ratio of bit-flips to the total	0.9%
Mean bit-flips per message	1.9 bit
Incomplete messages (ratio)	30 (0.6%)

Out of the 5166 messages received, only 30 were incomplete, representing a rate of 0.6%. A total of 2505 bit-flips were recorded in the first 56 bits of the 5166 messages received. By extrapolating over the entire frame, the average error rate is 1.9 bit-flips per message. In the second phase, the analysis of message integrity was performed on a data frame of 27 bytes (i.e., 216 bits), containing a sequence of bits alternating between 0 and 1. Thus, the resulting message consists of 27 bytes, each having the binary value '1010 1010', or 55 in hexadecimal. The results obtained for 1122 messages received are reported in Table 7.

Table 7: Number of bit-flip errors observed with a frame message of 27 byte "01010 0101" sent by Kinéis node

Number of received messages	1122
Number of received bits	242,352
Number of bit-flips	1742
Ratio of bit-flips to the total	0.7%
Mean bit-flips per message	1.5 bit
Incomplete message (ratio)	12 (1.1%)

Across these messages, 1742 bit-flip errors were recorded, resulting in a bit-flip rate of 0.7%. The average number of bit-flip errors per message is 1.5 bits. It should be noted that 12 incomplete messages were not considered. The relative distribution of the number of erroneous messages as a function of the number of bit-flip errors per message is given in Figure 14.

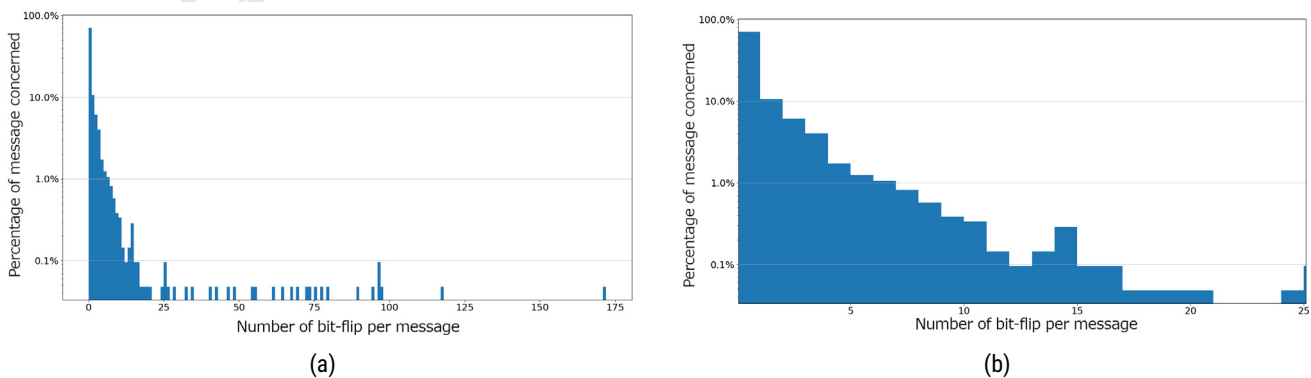


Figure 14: Percentage of messages received depending on the number of bit-flip errors: a) per message, b) with zoomed part from 0 to 25 errors

Figure 15 shows the number of bit-flips measured for each bit position in the frame. A correlation appears between the bit position and its error probability. The graph shows the progressive increase in the number of bit-flips as we advance through the frame.

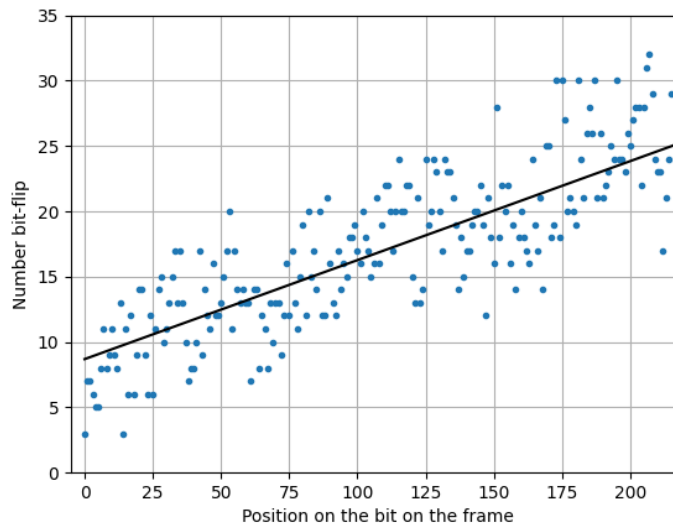


Figure 15: Number of bit-flip depending on the position of the bit in the message

At the cost of a reduction of the maximum payload from 31 to 23 bytes, Kinéis offers a CRC-type encoding option that allows for corrections of up to 4 bit-errors. Figure 16 shows the effectiveness of this encoding obtained upon receiving messages containing a series of 23 bytes with a value of 55 in hexadecimal. The results exhibit a correction efficiency of over 80% for messages containing 1 to 3 bit-flips, which represents 20% of the received messages as shown in Figure 14.b. Beyond 4 errors per message, which is about 10% of the received messages, correction is no longer effective. This highlights the benefit of enabling error correction mechanisms when available, as they can significantly improve the integrity of received data without increasing transmission power compare to a redundant transmission scenario. However, the reduced payload capacity associated with such mechanisms must be considered when defining the application message format.

4.1.3 Evaluation of the Echostar node in an open area

The tests conducted with an Echostar Mobile module on the rooftop of the University of Clermont-Auvergne's laboratory took place in July 2025, at the same location as the Kinéis node test (Figure 10). At the Aubière test site (45.759°N, 3.108°E), the corresponding elevation angle toward the EchoStar 21 satellite was approximately 37°. Since the satellite operated by EchoStar Mobile is geostationary, the assessments carried out in the context of a low Earth orbit satellite constellation are no longer relevant. The tests were therefore limited to evaluating communication efficiency over a continuous period under clear line-of-sight conditions. For this purpose, 3,538 messages were sent every 66 seconds by the EchoNode device. Each message consists of 30 bytes, each byte containing the binary value '10101010'. Among the 3,538 transmissions, 3,321 were successfully received, resulting in a success rate of 94% with no bit-flip errors detected in the frames received. Figure 17 shows the variation in the number of unreceived messages over time, which seems correlated with the Received Signal Strength Indicator (RSSI)

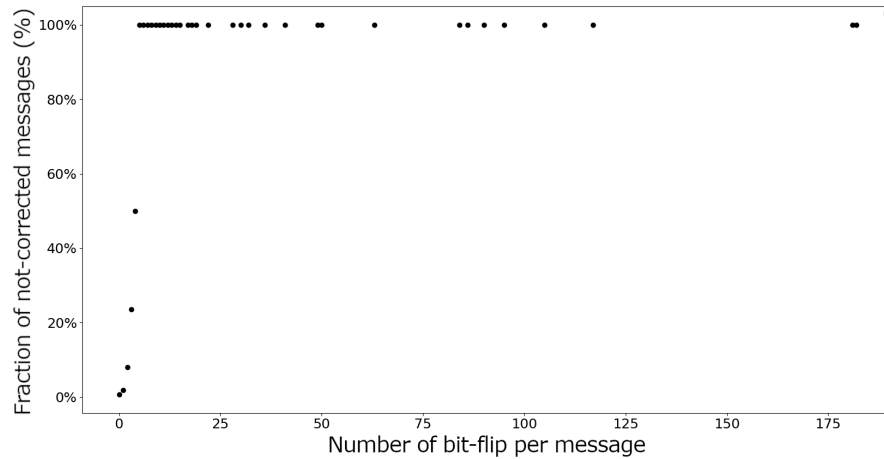


Figure 16: Proportion of uncorrected messages after processing by Kinéis as a function of the number of error bits contained in the message

value of the radio communication signal. During the time slot between 5 PM and 1 AM, very few messages were lost, resulting in a success rate close to 100%. Since the radio configuration remained unchanged throughout the experiment, this recurring pattern cannot be attributed to changes in the transmission parameters. Possible explanations include environmental factors or internal mechanisms of the communication service. This behaviour needs to be confirmed with a longer observation period, but it opens up the possibility of adapting transmission schedules to the most favorable communication conditions.

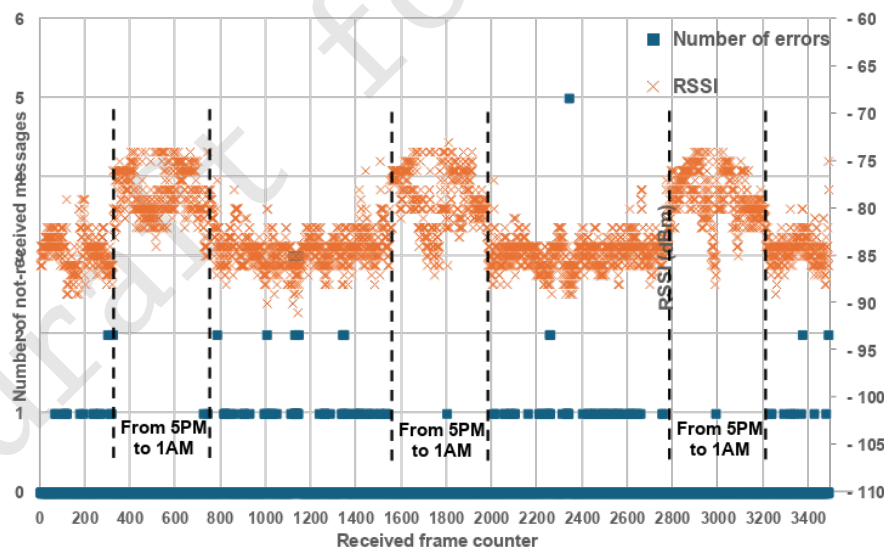


Figure 17: Variation in the number of unreceived messages and RSSI values during the transmission testing period

4.2 Evaluation of energy autonomy

The Kinéis and EchoStar Mobile sensor nodes developed in this work operate according to a measurement and transmission cycle composed of several successive phases, including sleep, wake-up, data acquisition and preparation, data transmission,

and return to the sleep state, corresponding to the programmed cycles show in Figures 5 and 6. The chronology of these phases and their typical duration are summarized in Table 8.

Table 8: Chronology and duration of the main operations performed during one measurement and transmission cycle

Power state	Operation	Kinéis	EchoStar Mobile
Sleep	Deep sleep while waiting for the next transmission cycle	$T_{\text{cycle}} - T_{\text{active}}^{(1)(2)}$	$T_{\text{cycle}} - T_{\text{active}}$
Active	Wake-up + Data acquisition + Payload preparation + Data storage	≈ 200 ms	≈ 200 ms
	Sending Data	≈ 11.6 s	≈ 3.6 s
	Satellite pass schedule programming (read next satellite pass from the SD card and program the RTC wake-up) ⁽³⁾	≈ 80 ms	Not required
	Return to Sleep	≈ 3 ms	≈ 3 ms

⁽¹⁾ T_{cycle} denotes the reporting period between two consecutive transmissions.

⁽²⁾ T_{active} is the sum of the wake-up, data acquisition, storage, transmission, scheduling and return to sleep duration.

⁽³⁾ The Kinéis implementation requires periodic RTC resynchronization using the GPS receiver to compensate for RTC drift (approximately 1 s/day). This operation is performed periodically rather than before each transmission and is therefore not included in the typical active cycle.

The difference between the two implementations is that the Kinéis node requires an additional satellite pass scheduling operation, whereas the EchoStar Mobile node benefits from continuous GEO connectivity and can transmit immediately. Furthermore, the Kinéis node must be periodically re-synchronized with the time provided by the GPS module to compensate for RTC drift and maintain the timing accuracy required for satellite pass scheduling. In contrast, the GPS receiver of the EchoStar Mobile node is only activated once during node start-up to determine the sensor position and to perform the initial node time setting.

In this study, in order to compare the intrinsic energy cost of each connectivity solution independently of the contributions from the node's complete electronic and embedded software components, the measurements were focused on the satellite communication phase (message transmission). The average current consumed during the communication time is summarized in Table 9 for the two modules. The Kinéis (KIM1) and EchoStar modules were configured with their maximum transmission power values, respectively 30 dBm and 27 dBm. Precise current consumption measurements were carried out using a high-precision Keithley DMM7510 multimeter.

Table 9: Average current consumed during message emission

Communication module	Mean current (I)	Duration (t)
Kinéis	48.4 mA	11.6 s
EchoStar Mobile	401.6 mA	3.6 s

The energy consumed during a message transmission is calculated using the following formula:

$$E(\text{Wh}) = P(\text{W}) \times t(\text{h}), \quad (1)$$

where E is the energy required for one message transmission, P is the power and t is the communication duration.

Then,

$$E(\text{Wh}) = U(\text{V}) \times I(\text{A}) \times t(\text{h}) \quad (2)$$

where E is the energy required for one message transmission, U is the supply voltage, I is the current consumption and t is the communication duration.

The corresponding energy consumption are summarized in Table 10. In the case of the Kinéis module, the efficiency of the DC/DC boost converter powering it is taken into account.

Table 10: Energy consumption per message sent

Communication module	Energy consumed (E)
Kinéis	0.87 mWh
EchoStar	1.44 mWh

Considering the use of a rechargeable lithium-ion battery pack with a capacity of 8.8 Ah at a voltage of 3.6 V, which corresponds to a total available energy of 31.7 Wh, the estimation of node autonomy depending on the message emission periodicity is provided in Table 11. These estimates are based on the typical capacity of power cells, which can vary significantly with aging and temperature.

Table 11: Estimated autonomy according to message emission frequency

Communication module	Message sending periodicity	Energy used per hour	Autonomy
Kinéis	1 message per hour	0.87 mWh	1518 days
	4 messages per hour	3.48 mWh	379 days
EchoStar	1 message per hour	1.44 mWh	916 days
	4 messages per hour	5.76 mWh	229 days

The battery life estimate presented above is only based on energy consumption related to data communication with satellites. This estimate does not consider the total consumption of the sensor node, which includes, among other things, the processing unit and the sensor measurement unit. Moreover, additional power consumption for the Kinéis node must be considered compared to the Echostar version due to the management of the satellite pass schedule (about 80 ms of additional node activity as reported in Table 8) and due to a daily GPS-based RTC resynchronization..

In practice, the battery autonomy will be lower than the values estimated in Table 11 and will depend on the actual usage scenario.

5 DISCUSSION AND LESSONS LEARNED

The opportunity to conduct tests during two experimental field campaigns, even if of short duration, allowed us to confirm the feasibility of instrumenting sites of interest with communicating sensors using satellite technology, in situations where other terrestrial solutions show their limitations. Additional tests and measurements carried out under more controlled conditions and over a longer period enabled a deeper evaluation of the intrinsic behavior and performance of the two different technologies.

In practice, the two solutions exhibit complementary behaviors that lead to different deployment constraints and operational trade-offs, as summarized in Table 12.

Table 12: Practical comparison of satellite IoT solutions

	LEO satellite IoT (Kinéis/Argos)	GEO satellite IoT (EchoStar Mobile)
Main advantage	Global coverage	Continuous access within the coverage area
Main limitation	Satellite elevation + terrain masking	Line-of-sight toward GEO direction
Communication scheduling requirement	Yes	No
Deployment implications	Prefer open horizon; elevation-aware transmissions improve reliability	Ensure stable line-of-sight toward GEO direction
Satellite availability / visibility during the test period	Intermittent: satellites visible 27.5% of the time (open-sky)	Continuous (within the coverage area, no pass constraint)
Transmission success (open-sky test)	Elevation-dependent: > 80% for elevation $\geq 85^\circ$	94% when line-of-sight is ensured
Message integrity (received frames)	Bit-flip rate < 1%	No bit-flip errors detected
Estimated autonomy (3.6 V, 8.8 Ah battery)	1 message per hour → 1518 days 4 messages per hour → 379 days	1 message per hour → 916 days 4 messages per hour → 229 days

From a practical deployment perspective, the overall hardware cost of the developed sensor nodes is approximately €200 per unit. In addition to the hardware cost, both satellite communication solutions require a service subscription of the order of a few euros per node per month, depending on the selected commercial plan and the expected communication volume.

For the LEO service (Kinéis/Argos), link availability is inherently time-dependent and strongly influenced by satellite passes and their elevation above the horizon. The open-sky experiment shows that satellite presence is intermittent (27.5% of the time on average over the test period), with significant time between consecutive passes. This confirms that, beyond raw coverage, operational performance depends on the ability to align transmissions with pass opportunities. In addition, the elevation-dependent analysis demonstrates that reception performance significantly improves at higher elevation angles, with successful reception exceeding 50% only above 30° and reaching over 80% at maximum elevation. Considering only satellite passes above 30° , the average interval between communication opportunities increases from 26.8 min to approximately 80 min for the 8-satellite constellation used during the experiments. Extrapolating to the final 25-satellite Kinéis constellation, this interval is expected to decrease to approximately 45 min, providing more frequent communication opportunities while maintaining improved link reliability. These results highlight a key lesson for rugged volcanic terrain: low-elevation transmission windows are less suitable because they are more exposed to topographic masking, and thus lead to reduced efficiency. Consequently, the deployment location is a critical parameter, and elevation-aware transmission strategies improve reliability and limit unnecessary transmissions. It therefore appears essential to develop, for a given location, a pass schedule that accounts for the minimum required elevation angle as well as topographic masking, in order to increase the likelihood of successful transmissions. However, the acceptable packet loss rate ultimately depends on the monitoring application. For environmental

monitoring applications involving slowly varying parameters, such as temperature or long-term gas concentration trends, a moderate packet loss rate may remain acceptable provided that measurements are acquired periodically. In contrast, applications requiring near-real-time alarms or guaranteed data delivery require higher communication reliability, which may be achieved through repeated transmissions or adaptive transmission scheduling based on the predicted satellite elevation. In contrast, the GEO service (EchoStar Mobile) does not require pass scheduling and provides more predictable connectivity when line-of-sight is ensured. Under open-sky conditions, the GEO solution achieved a transmission efficiency of 94%, confirming that continuous satellite availability can simplify operational deployment compared to LEO services. Nevertheless, this advantage comes with two practical limitations: (i) coverage is restricted to the operator service area (e.g., Europe for EchoStar Mobile), and (ii) the measured energy cost per transmitted message is higher than for the LEO solution evaluated in this study. In addition, because the satellite remains in a fixed position in the sky, reliable communication requires a clear line of sight toward the satellite throughout the deployment. Consequently, the local topography and any permanent obstacles in that direction must be carefully considered when selecting the installation site.

Beyond transmission efficiency, message integrity and energy consumption are key factors for the design of long-term volcanic monitoring systems. The Kinéis integrity analysis shows that successfully received frames may still contain bit errors (with bit-flip rates in the 0.9% range depending on the test configuration), meaning that the message delivery ratio alone is not sufficient to fully characterize data usability. Enabling error-correction mechanisms provides a practical benefit, as it improves the usability of received data without increasing transmission power, at the cost of a reduced payload capacity that must be considered when defining the application message format. Communication-only energy consumption measurements confirm that the data reporting strategy is a key driver of node autonomy. With a 3.6 V / 8.8 Ah battery, the estimated lifetime ranges from 1518 to 379 days for Kinéis (1 to 4 messages per hour) and from 916 to 229 days for EchoStar Mobile, for the same reporting rates. This highlights that the transmission frequency, as well as repetition policies when required, must be adapted to the monitoring objective: a low reporting rate may be sufficient during routine operation, whereas higher rates may be needed during crisis phases to enable closer monitoring.

6 CONCLUSION AND PERSPECTIVES

This article presents a comparison of the services and performance offered by two satellite IoT communication solutions in the perspective of monitoring active volcanoes. It is based on tests and measurements carried out using two communication nodes: LEO-based service (Kinéis/Argos) and a GEO-based service (EchoStar Mobile), which operate, respectively, a constellation of low Earth orbit nano satellites and a geostationary satellite. Our results confirm that IoT satellite technologies are indeed very promising for the challenging environments of active volcanoes. For the LEO-based service (Kinéis/Argos), communication opportunities remain intermittent due to satellite pass dynamics. This limitation can be partially mitigated by integrating a satellite pass schedule into the communication node, which avoids unnecessary transmission attempts when no satellite is in view. The experiments also show that transmission efficiency is strongly site-dependent, as it is affected by surrounding topography and by satellite elevation at the time of transmission. In this context, developing a pass schedule that accounts for the minimum required elevation angle as a function of azimuth for a given location could help better anticipate outages

caused by terrain obstructions. Future work will focus on integrating digital elevation models into satellite pass prediction in order to identify communication opportunities affected by terrain masking and optimize transmission scheduling for a given deployment site. In contrast, the GEO-based service (EchoStar Mobile) provides more predictable connectivity when line-of-sight is ensured and achieved a transmission efficiency of 94% under open-sky conditions. Nevertheless, this solution remains constrained by regional coverage (e.g., Europe for EchoStar Mobile) and may involve a higher communication energy cost than the LEO-based option. Beyond the comparison of the two communication technologies, future work should include a more systematic evaluation of deployment conditions, including controlled terrain masking scenarios, different topographic configurations, and long-term field deployments, in order to establish practical deployment guidelines for satellite IoT systems in volcanic environments. Moreover, satellite connectivity does not eliminate the exposure of sensing nodes to harsh volcanic conditions, which could still constrain long-term deployment. Although these aspects were not specifically evaluated in the present study, node robustness remains a key factor for long-term deployments under acidic gases, ash deposition, strong winds, temperature extremes, and potential mechanical damage during eruptive activity. In addition, practical deployment constraints such as wildlife interactions (e.g., damage to cables) and human interference (e.g., theft or vandalism) should also be considered. Addressing these constraints requires appropriate hardware protection, including protective enclosures, antenna and connector protection, corrosion-resistant materials) as well as operational strategies such as redundancy and maintenance planning.

At the time of writing this article, Kinéis is finalizing the deployment of a new constellation of 25 nanosatellites to replace the Argos satellites. They will be distributed across 5 orbital planes, with 5 satellites per plane. According to Kinéis, this configuration will enable satellite passes every 15 minutes. At the same time, a new communication module (model KIM2) will be introduced to replace the KIM1 model used in our tests. The new KIM2 module brings several enhancements, including a lower-power modulation (LD-K), additional downlink capabilities (application messages, satellite detection, and AOP reception), and configurable message repetition strategies to enhance reception performance. A new study will be needed to assess the improvement in quality of service offered by these enhancements in particular in the context of the monitoring of active volcanoes.

Overall, this study highlights that satellite IoT has a role to play in monitoring volcanoes, by ensuring near real-time data availability in overexposed and/or remote environments where costly traditional infrastructures do not present a favorable risk-benefit balance. Beyond volcanology, these technologies open new perspectives for environmental monitoring in domains in areas such as early warning systems for floods, biodiversity tracking in inaccessible regions, as well as agricultural monitoring to optimize crop and irrigation management and yield forecasting. Upcoming advances in the deployment of satellite constellations and communication modules will therefore play a key role by providing valuable data to improve environmental understanding and monitoring in the context of climate change, while strengthening resilience and preparedness against hazards on a global scale.

AUTHOR CONTRIBUTIONS

L.M.A., L.R., and J.S. led the conceptualization, methodology design, node deployment, investigation and writing original draft. L.M.A., L.R., and P.L. developed the software. L.M.A., L.R., J.S., J.M., and L.T. led data collection and data analysis. D.D. provided expertise and technical input on Satellite IoT systems. L.M.A., L.R., V.B., J.P.C., L.T., and C.C. led funding acquisition and reviewed the manuscript. All authors provided critical feedback and actively participated in the writing and revision of the manuscript.

ACKNOWLEDGEMENTS

The authors thank the EAU Research Federation (FR EAU), and the DATA Program of the CAP 20-25 UCA project for their financial support.

This study was partly carried out as part of the SPAGHETTI project, funded by the ANR (French National Research Agency). This work contributes to the ClerVolc program of the International Research Center for Disaster Sciences and Sustainable Development of the University of Clermont Auvergne.

This work was supported by the International Research Center "Innovation Transportation and Production Systems" of the I-SITE CAP 20-25.

This work was also supported by the French National Program (ANR) "Investment for Future - Excellency Equipment" project TERRA FORMA with the reference ANR-21-ESRE-0014.

The maps in this publication use data from OpenStreetMap contributors, © OpenStreetMap contributors. For more information, visit openstreetmap.org/copyright.

DATA AVAILABILITY

The datasets generated and analyzed during the current study are publicly available at the following repository: <https://git.mesocentre.uca.fr/connecsens/volcano-monitoring-iot-satellite-dataset>.

COPYRIGHT NOTICE

REFERENCES

- Adiprabowo, T., D. Ramdani, P. Daud, A. Andriana, Z. Zulkarnain, N. Nasrullah, O. Vertus, S. A. Rahman, and M. T. A. Simarmata (2025). "Satellite technology for Internet of Things: an overview". *Internet of Things and Artificial Intelligence Journal* 5(1), pages 58–68. DOI: 10.31763/iota.v5i1.758.
- Aiuppa, A., R. Moretti, C. Federico, G. Giudice, S. Gurrieri, M. Liuzzo, P. Papale, H. Shinohara, and M. Valenza (2007). "Forecasting Etna eruptions by real-time observation of volcanic gas composition". *Geology* 35(12), pages 1115–1118.
- Awadallah, S., D. Moure, and P. Torres-González (2019). "An Internet of Things (IoT) Application on Volcano Monitoring". *Sensors* 19(21). DOI: 10.3390/s19214651.
- Bathiya, B., S. Srivastava, and B. Mishra (2016). "Air pollution monitoring using wireless sensor network", pages 112–117. DOI: 10.1109/WIECON-ECE.2016.8009098.

- Centenaro, M., C. E. Costa, F. Granelli, C. Sacchi, and L. Vangelista (2021). “A survey on technologies, standards and open challenges in satellite IoT”. *IEEE Communications Surveys & Tutorials* 23(3), pages 1693–1720. DOI: 10.1109/COMST.2021.3078433. 500
- Chippalkatti, V. S. and R. C. Biradar (2021). “Review of Satellite based Internet of Things and Applications”. *Turkish Journal of Computer and Mathematics Education* 12(12). <https://www.proquest.com/scholarly-journals/review-satellite-based-internet-things/docview/2622821625/se-2>, pages 758–766.
- Cotrim, J. R. and J. H. Kleinschmidt (2020). “LoRaWAN Mesh Networks: a review and classification of multihop communication”. *Sensors* 20(15). DOI: 10.3390/s20154273. 505
- De Sanctis, M., E. Cianca, G. Araniti, I. Bisio, and R. Prasad (2016). “Satellite communications supporting internet of remote things”. *IEEE Internet of Things Journal* 3(1), pages 113–123. DOI: 10.1109/JIOT.2015.2487046.
- Desk, N. (2024). “Dryad networks and Kinéis partner for satellite-enabled wildfire early detection”. <https://geospatialworld.net/news/dryad-networks-kineis-satellite-wildfire-early-detection/>.
- ECC (2020). *M2M/IoT Operation via Satellite*. Technical report ECC Report 305. <https://docdb.cept.org/download/1403>. 510
- Elijah, O., T. A. Rahman, I. Orikumhi, C. Y. Leow, and M. N. Hindia (2018). “An overview of Internet of Things (IoT) and Data analytics in agriculture: benefits and challenges”. *IEEE Internet of Things Journal* 5(5), pages 3758–3773. DOI: 10.1109/JIOT.2018.2844296.
- Fraire, J. A., O. Iova, and F. Valois (2021). “Space-terrestrial integrated Internet of Things: challenges and opportunities”. Version Number: 3. DOI: 10.48550/ARXIV.2110.11518. 515
- Hassan, R., F. Qamar, M. K. Hasan, A. H. M. Aman, and A. S. Ahmed (2020). “Internet of Things and its applications: a comprehensive survey”. *Symmetry* 12(10). DOI: 10.3390/sym12101674.
- ISS Tracker (2015). <https://isstracker.pl/en/satellites/42749>.
- Jung, D.-H., H. Nam, J. Choi, and D. J. Love (2024). “Modeling and analysis of GEO satellite networks”. *Trans. Wireless Comm.* 23(11part1), pages 16757–16770. DOI: 10.1109/TWC.2024.3447229. 520
- Kinéis (2018). *Kinéis technology: the future of IoT starts here*. <https://www.kineis.com/en/technology-kineis-iot/>.
- Kodheli, O., E. Lagunas, N. Maturo, S. K. Sharma, B. Shankar, J. F. M. Montoya, J. C. M. Duncan, D. Spano, S. Chatzinotas, S. Kisseleff, J. Querol, L. Lei, T. X. Vu, and G. Goussetis (2020). “Satellite communications in the new space Era: a survey and future challenges”. Version Number: 2. DOI: 10.48550/ARXIV.2002.08811.
- Lahoz, W. A., V.-H. Peuch, J. Orphal, J.-L. Attié, K. Chance, X. Liu, D. Edwards, H. Elbern, J.-M. Flaud, M. Claeysman, and L. E. Amraoui (2012). “Monitoring air quality from space: the case for the geostationary platform”. *Bulletin of the American Meteorological Society* 93(2). Publisher: American Meteorological Society, pages 221–233. DOI: 10.1175/bams-d-11-00045.1. 525
- LoRa Alliance Resource Library (2026). <https://resources.lora-alliance.org/technical-specifications>.
- Moiroux-Arvis, L., L. Royer, D. Sarramia, G. De Sousa, A. Claude, D. Latour, E. Roussel, O. Voldoire, P. Chardon, R. Vandaële, T. Améglio, and J.-P. Chanet (2023). “ConnecSenS, a versatile IoT platform for environment monitoring: bring water to cloud”. *Sensors* 23(6). DOI: 10.3390/s23062896. 530

- Narayana, T. L., C. Venkatesh, A. Kiran, C. B. J, A. Kumar, S. B. Khan, A. Almusharraf, and M. T. Quasim (2024). “Advances in real time smart monitoring of environmental parameters using IoT and sensors”. *Heliyon* 10(7), e28195. DOI: 10.1016/j.heliyon.2024.e28195.
- Qu, Z., G. Zhang, H. Cao, and J. Xie (2017). “LEO satellite constellation for Internet of Things”. *IEEE Access* 5, pages 18391–18401. DOI: 10.1109/ACCESS.2017.2735988.
- Radha, M. C., M. M. Madheswaran, M. M. Lokesh, and M. M. M. Althaf (2024). “Environmental monitoring in Internet of Things (IOT)”. *International Journal for Research in Applied Science and Engineering Technology* 12(4), pages 1658–1663. DOI: 10.22214/ijraset.2024.60086.
- Rafi, M. S. M., M. Behjati, and A. S. Rafsanjani (2025). “Reliable and cost-efficient IoT connectivity for smart agriculture: a comparative study of LPWAN, 5G, and hybrid connectivity models”. Version Number: 1. DOI: 10.48550/ARXIV.2503.11162.
- Rawat, P., K. D. Singh, H. Chaouchi, and J. M. Bonnin (2014). “Wireless sensor networks: a survey on recent developments and potential synergies”. *The Journal of Supercomputing* 68(1), pages 1–48. DOI: 10.1007/s11227-013-1021-9.
- Royer, L., L. Terray, M. Rubéo-Lisa, J. Sudre, P.-J. Gauthier, A. Claude, S. Giammanco, E. Pecora, P. Principato, and V. Breton (2024). “Lessons learnt from monitoring the Etna volcano using an IoT sensor network through a period of intense eruptive activity”. *Sensors* 24(5). DOI: 10.3390/s24051577.
- Salam, A. (2020). “Internet of Things for environmental sustainability and climate change”. Series Title: Internet of Things, pages 33–69. DOI: 10.1007/978-3-030-35291-2_2.
- Satellite-based LoRa® Unlocks Europe-Wide IoT (2022). Technical report. https://echostarmobile.com/wp-content/uploads/2022/04/EchoStar_Mobile_White_Paper_compressed.pdf. EchoStar Mobile.
- SatelliteIoT (2025). *Satellite Operators for the Internet of Things (IoT) – an overview*. <https://satelliteiot.space/satellite-iot-operators/>.
- Shutao, Z. (2024). “Satellite Internet of Things research report”. arXiv:2407.17696 [eess]. DOI: 10.48550/arXiv.2407.17696.
- Sinha, S. (2024). “LPWAN market 2024: licensed technologies boost their share among global 1.3 billion connections as LoRa leads outside China”. <https://iot-analytics.com/lpwan-market/>.
- Terray, L., L. Royer, D. Sarramia, C. Achard, E. Bourdeau, P. Chardon, A. Claude, J. Fuchet, P.-J. Gauthier, D. Grimbichler, J. Mezhoud, F. Ogereau, R. Vandaële, and V. Breton (2020). “From sensor to cloud: an IoT network of radon outdoor probes to monitor active volcanoes”. *Sensors* 20(10). DOI: 10.3390/s20102755.
- Werner-Allen, G., K. Lorincz, M. Ruiz, O. Marcillo, J. Johnson, J. Lees, and M. Welsh (2006). “Deploying a wireless sensor network on an active volcano”. *IEEE Internet Computing* 10(2), pages 18–25. DOI: 10.1109/MIC.2006.26.