



The VHF Alert Network of the SVOM Mission

B. Cordier¹, L. Jeannin², Ph. Lafabrie², G. Chavanas², S. Crepaldi², N. Dagoneau³ , A. Formica³, V. Garcia², L. Jolivet²,
 S. Lacour², H. Louvin³ , and E. Sabatier²

¹ CEA/Paris-Saclay, Irfu/Département d'Astrophysique, 91191 Gif-sur-Yvette, France; bcordier@cea.fr

² Centre National d'Etudes Spatiales, Centre Spatial de Toulouse, Toulouse Cedex 9, France

³ CEA/Paris-Saclay, Irfu/Département d'Électronique, des Détecteurs et d'Informatique pour la Physique, 91191, Gif-sur-Yvette, France

Received 2025 December 23; revised 2026 March 3; accepted 2026 March 7; published 2026 September 24

Abstract

The scientific success of the Space-based multi-band Variable Objects Monitor (SVOM) mission will rely on the rapid transmission of alert messages from the satellite to the scientific community, and in particular to the ground-based instruments supporting the mission. In this paper, we present the alert system developed for SVOM, which relies on the rapid transmission of alert messages through the transfer of data packets from an onboard VHF-band radio transmitter to a network of radio receivers deployed along the satellite's ground track. We will successively detail the antenna design, radio performance, network deployment, its integration within the French data center, as well as the performance achieved after one year of operation in terms of availability and latency.

Key words: space vehicles – gamma rays: stars – atmospheric effects

1. Introduction

Space-based multi-band Variable Objects Monitor (SVOM) is a French–Chinese mission dedicated to the detection and multi-wavelength study of the most distant stellar explosions: gamma-ray bursts (GRBs). The mission is composed of two sets of instruments: the first is integrated onboard a satellite, while the second is located on Earth. A part of the satellite payload is designed to detect and localize the GRB (Cordier et al. 2026).

Since a GRB is a fleeting event, the scientific success of the mission relies on the ability to rapidly transmit localization data to the community, so that other ground-based or space-based instruments can provide follow-up observations and continue characterizing the transient event. One of the main objectives of this sequence, starting in space and continuing on the ground, is to measure the luminosity distance of the burst. This quantity can only be estimated with a large ground-based telescope equipped with spectroscopic capabilities in the infrared. To achieve this goal, it is crucial to alert these ground instruments as early as possible with the most accurate information available.

One of the SVOM mission requirements is to broadcast to ground based telescopes the measured GRB celestial coordinates in no more than 30 s after localization for 66% of the localized GRBs, and in no more than 20 minutes for 95% of the GRBs. This requirement guided the entire design of the VHF alert network.

The SVOM alert network has been specifically designed to meet the requirement of rapid and continuous data transmission between the satellite and the ground. This transmission

relies on the use of radio waves: the selected approach consists of integrating a radio transmitter onboard the satellite and deploying, along its ground track, a set of radio receivers. These receivers, referred to as VHF stations, ensure the reception of the signal transmitted by the satellite, its decoding, and its conversion into digital packets. These packets are then forwarded via the internet to the French Science Center (FSC) in near real time (Louvin et al. 2026). Once received by the FSC, these digital packets are processed in order to extract the relevant information. This information is then used to generate and distribute notifications to the scientific community as well as to ground-based tracking instruments.

SVOM is a low-Earth orbit satellite placed at an altitude of 650 km, completing one orbit around the Earth in just over 95 minutes, for about 15 revolutions per day. Its orbit is inclined at 30° with respect to the Earth's equatorial plane. As a result, the satellite's trajectory oscillates between latitudes −30° and +30°. To receive the radio signal from the satellite, we have deployed around fifty radio receiver (exactly 53 as of 2025 November 7) along the satellite's ground track, distributed as uniformly as possible across the Earth's surface within this latitude range. These antennas make it possible to continuously receive the radio signal sent by the satellite, both during routine transmission and when a burst is detected, see Figure 1.

In the past, the HETE-2 space mission, which focused on GRBs, had also developed an alert system based on the transmission of radio messages and their reception on the ground by VHF stations (Matsuoka et al. 2004). The SVOM mission was largely inspired by this example but developed its

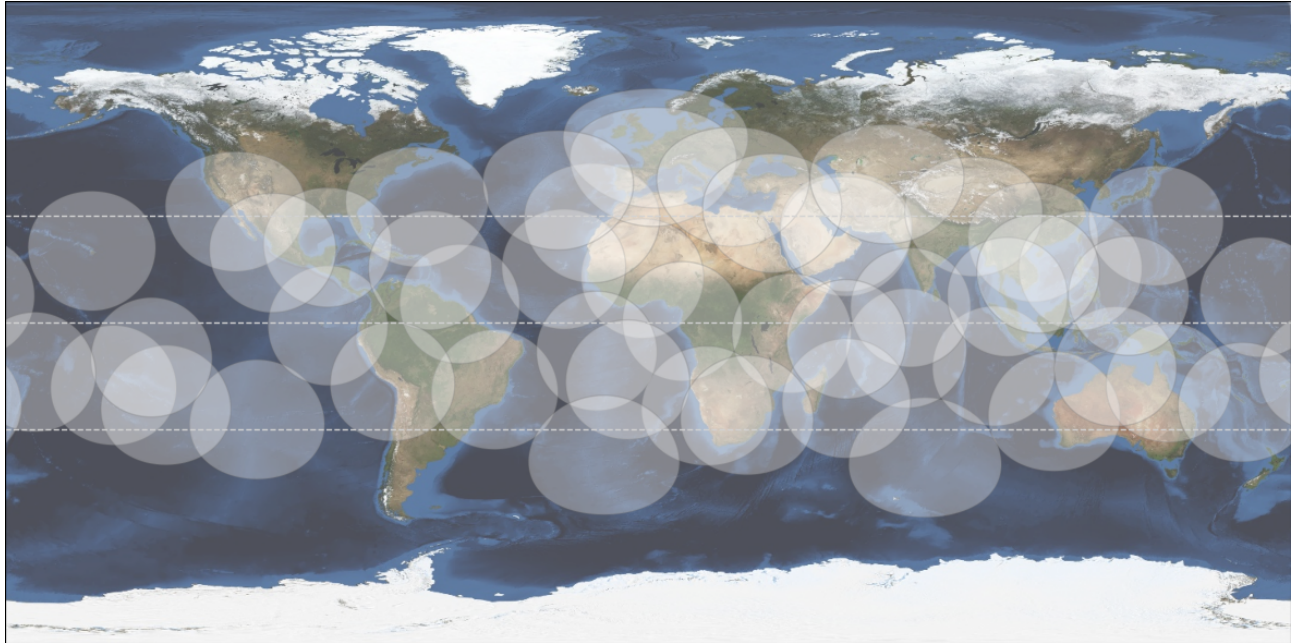


Figure 1. VHF network map (circles are drawn from a satellite elevation of 10° and a satellite altitude of 650 km).

own system. It is worth noting that, since the HETE-2 mission was in a nearly equatorial orbit, the number of stations to be deployed (around fifteen) was much smaller.

The following sections detail the station architecture, the expected radio performance, the deployment strategy for the different stations, the pre-launch testing procedures, and finally, the performance measured after one year of operation in orbit. In conclusion, we demonstrate that the SVOM VHF alert network fully satisfies the mission requirement.

2. The VHF Station

A VHF station is composed of four main elements (see Figure 2 and Figure 3):

1. two antennas to receive the SVOM emitted signal;
2. a Software Design Radio (SDR) based on a radio-frequency front-end and transceiver, which filters and digitizes the signal;
3. a processing programmable module, which demodulates and decodes the signal to transform the received radio message in digital packets;
4. an internet communication module, which ensures the real-time transmission of these digital packets to the FSC.

The key design drivers for the SVOM station were:

1. reasonable production costs;
2. ease of assembly and installation;



Figure 2. VHF operational ground station in Kourou.

3. straightforward integration with the CNES secure network;
4. reduced weight to minimize transportation costs.

The company INGESPACE, based in the Toulouse area, was selected by CNES to develop the SVOM station according to project specifications.

Given the number of stations to be deployed (50), a “low-cost” station concept was developed in order to minimize the overall cost of implementing the alert network. Otherwise, the number of stations required, coupled with the diversity of deployment sites and constraints, would have made the total completion cost prohibitive.

Particular attention was given to the installation procedures, so that local site personnel could carry out the station installation themselves without the physical presence of a CNES technical agent, requiring only phone support if necessary. It should be noted that 80% of the stations were deployed and installed during the Covid period.

With all of these constraints, the design chosen by INGSPACE consists of a very flexible and efficient SDR architecture with full remote management and upgrade capacity. The SDR receiver is packaged on a small hardened sealed metal box with only Radio Frequency (RF) connectors for antennas, and a command/control connector for internet connection to the FSC.

On the mechanical side, a range of lightweight yet robust aluminum mounts was designed to adapt to the various configurations encountered at the deployment sites. Finally, the complete station was packaged in a transport case with a total weight of 40 kg.

2.1. The Antennas

The station is equipped with two quadrifilar antennas, operating in both Left-Hand Circular Polarization (LHCP) and Right-Hand Circular Polarization (RHCP). This configuration ensures the capacity of catching the SVOM signal for all geometrical configurations.

2.2. Frequency and Modulation Scheme Choice

The selection of the RF frequency band to ensure the reliability of the alert link was a complex task that needed to account for several factors, including:

1. the overall performance of the ground station system;
2. applicable regulatory constraints;
3. the long-term sustainability of both performance and compliance throughout the mission lifetime.

Extensive studies have been conducted to assess the International Telecommunication Union (ITU) recommendations regarding the use of RF bands for space-to-ground communication in scientific missions. Several options have been identified, such as VHF, *L*-band, and *S*-band, each presenting specific technological, architectural, and environmental constraints.

The final solution was selected as the best compromise between:

1. the availability and long-term sustainability of the RF band;
2. the technological complexity of both the ground and spacecraft segments;
3. the overall costs of system design, deployment, and maintenance.

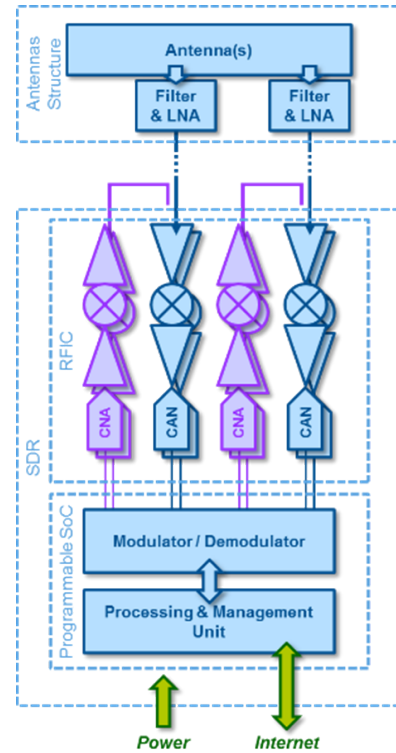


Figure 3. Ground station synoptic.

The chosen option is the space-to-Earth VHF band from 137 to 138 MHz, which benefits from global ITU protection for its use. This frequency range is sufficiently low to enable relatively simple electronic and antenna architectures, while keeping implementation costs manageable. For instance, this band has historically been used by the U.S. National Oceanic and Atmospheric Administration (NOAA) satellites to transmit real-time meteorological images.

Unlike the legacy NOAA spacecraft, the SVOM mission adopts a modern digital modulation and coding scheme to achieve robust and spectrally efficient signal transmission from the spacecraft to the ground network. Specifically, the selected modulation is 4-level Continuous Phase Frequency Shift Keying (4-CPFSK), in which each symbol encodes two bits using four discrete frequency states (Schonhoff 2003), see Figure 4.

A classic Reed-Solomon code, based on the Consultative Committee for Space Data Systems standards, has been added to the modulation to enhance its robustness and enable error correction at ground level (Reed & Solomon 1960).

2.3. Link Budget

The alert system requirements do not demand a high data rate for transmitting alert messages from the SVOM spacecraft to the ground network. A data rate of 600 bit s^{-1} has been

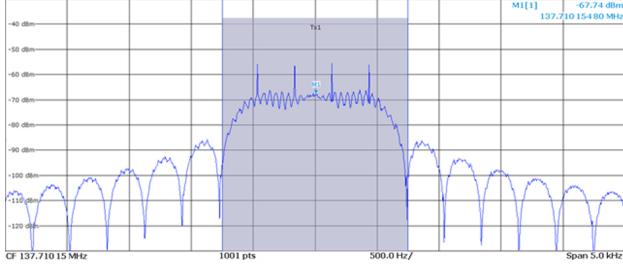


Figure 4. 4-CPFSK Modulation scheme frequency spectrum (4 possible tones = 2 bits by symbol).

specified, corresponding to $300 \text{ symbols s}^{-1}$ with the selected 4-CPFSK modulation.

A link budget has been established to achieve an E_b/N_0 of 6.9 dB at the receiver, which ensures a bit error rate of approximately 7×10^{-3} , considered acceptable for this service. In deriving this link budget and producing a complete link specification, several system constraints must be taken into account, such as spacecraft attitude and ground station geometry. However, one of the most critical considerations is the noise environment at the ground stations. As previously discussed, the selected VHF ITU band (137–138 MHz) is technologically accessible but also highly susceptible to interference or jamming from various industrial and communication equipments.

2.3.1. Ground Jamming

Several studies and measurement campaigns have been conducted to identify sources of disturbance and jamming within this theoretically reserved RF band. Two main categories of ground-based interference have been identified:

1. industrial noises, including:
 - a. electronic devices such as computers, power supplies, etc.;
 - b. communication equipment such as network devices with Ethernet links and cables;
2. ground communication noises, including:
 - a. handheld radio;
 - b. ground communication systems for aircraft and airport operations;
 - c. improperly configured or saturated VHF FM broadcasting transmitters in the 88.5–108 MHz band.

A dedicated measurement campaign was carried out in France using a mobile antenna to characterize the noise environment. Three representative scenarios were identified: a best-case scenario far from cities and industrial zones, where the noise level is minimal; an intermediate case, where the noise remains acceptable; and a worst-case scenario, where noise levels are highest, typically in urban areas or in close

proximity to industrial facilities and communication infrastructures.

Based on this campaign, the following hypotheses were adopted for link budget computations:

1. 1000 K for the best-case scenario (remote areas with minimal noise);
2. 3000 K for the intermediate case (moderate noise levels);
3. 10,000 K for the worst-case scenario (urban or industrial environments with maximum noise).

2.3.2. Link Disturbances

Along the propagation path of the VHF signal between the SVOM spacecraft and the ground stations, the signal may be affected by atmospheric disturbances and absorption phenomena. Owing to its long wavelength, the VHF signal is highly robust against tropospheric attenuation caused by water vapor in clouds and rain. However, this frequency range is susceptible to radio-frequency absorption due to ionospheric scintillation. Such scintillation effects occur predominantly at low latitudes, especially during nighttime, and can lead to localized signal fades of up to 10 dB for limited durations.

Studies conducted in the L-band region around 1 GHz provide useful references for estimating the occurrence probability of these scintillation events, and can therefore be used to support the definition of link budget assumptions (Aol et al. 2020).

2.3.3. Ground Station RF Interface

At ground level, the RF interface requirement for the stations is to have a gain of at least -15 dB at minimum elevation in all azimuth directions. This is achieved through the use of two antennas operating in opposite circular polarizations.

2.3.4. Link Budget Operating Point and Synthesis

With the modulation scheme, channel coding, and noise hypotheses defined, the spacecraft RF interfaces have been specified to ensure a reliable link under the worst-case geometrical configuration, namely low elevation angles and minimum onboard VHF antenna gain. For the computation of the spacecraft RF interface requirements, the intermediate noise scenario was selected. The spacecraft's effective isotropic radiated power (EIRP) has been set between -8 and $+4 \text{ dBW}$, assuming a 4π steradian radiation pattern achieved by two antennas operating in opposite circular polarizations.

3. Station Deployment

3.1. Ensuring Global Coverage

One of the major challenges of the project is to ensure the fastest possible alert transmission to the ground, regardless of

the satellite's position in its orbit. Even though the satellite operates only between -30° and $+30^\circ$ latitude, this region covers a vast portion of the Earth's surface, with particularly large oceanic areas where installing ground stations is extremely difficult, if not impossible.

The alerts must be transmitted to the ground immediately upon detection, without waiting for the satellite to pass over a station. This necessitates a dense and longitudinally well-distributed ground network, extending even to areas that are often overlooked, such as remote islands, politically sensitive regions, and technically challenging locations. In particular, the world's oceans—the Atlantic, Indian, and especially the Pacific—represent significant potential coverage gaps if not explicitly addressed.

3.1.1. Maintaining Satellite Visibility

Ensuring satellite visibility from the ground is a critical requirement for the immediate transmission of data, particularly critical alerts. For a satellite in a low equatorial orbit such as SVOM, this visibility is inherently brief and intermittent, limited to a few minutes during each pass over a station. This necessitates not only extensive geographic coverage but also an optimal distribution of stations so that at least one is always able to “see” the satellite.

The challenge is therefore not merely to deploy stations, but to do so in the right locations. Each station covers only a limited visibility cone, depending on its latitude, the satellite's altitude, and the local topography. Poor placement, insufficient elevation, or obstructed horizons can significantly reduce network performance. To address these constraints, precise orbital simulations were used to identify the most relevant areas and maximize the total cumulative visibility over a 24 hr period.

In parallel, the resilience of the network also relies on redundancy: if a station becomes unavailable (due to network outages, weather, or maintenance), another station must be able to take over without any loss of coverage. This ultimately ensures continuous satellite visibility and guarantees that every alert, regardless of its location along the orbit, can be transmitted immediately to the ground.

3.1.2. Finding Host Sites

Identifying suitable host sites for ground stations is one of the most complex phases of the project. Beyond purely technical constraints, this stage involves human, geopolitical, and operational considerations. The region between -30° and $+30^\circ$ latitude spans highly heterogeneous countries: some offer reliable infrastructure, a clear administrative framework, and access to connectivity, while others present major challenges in terms of stability, communication, or environment.

The priority is to identify local partners capable of hosting a station under safe, stable, and remotely accessible conditions. These partners may include universities, observatories, research institutes, or existing infrastructures already accustomed to working with space or scientific technologies. However, such collaborations take time, and involve administrative negotiations, agreement signings, regulatory compliance, equipment import logistics, and local staff training.

In certain remote areas, as in Samoa or on Easter Island, an alternative solution is to deploy a fully autonomous station, powered by solar energy and connected to the internet via satellite. While this type of deployment increases technical complexity, it enables coverage of otherwise inaccessible regions. Regional or international partnerships may also facilitate access to strategic territories, particularly islands or regions with high orbital coverage value.

3.1.3. Host Site Selection Process

The selection of a site to host a VHF station is not limited to its ideal geographic position. It depends on a multitude of technical, practical, and regulatory criteria, some of which are absolutely critical to ensure reliable and stable radio reception.

One major, often underestimated criterion is the level of RF noise in the immediate environment. For this reason, every potential site must undergo an RF survey using a wideband receiver or spectrum analyzer coupled with a calibrated VHF antenna. These measurements allow the detection of existing interference and the identification of “quiet” areas, often far from dense urban zones, technology hubs, or industrial areas.

This factor is particularly critical because the satellite signals received in VHF are extremely weak, sometimes barely above the background noise. A clean electromagnetic environment is therefore essential to ensure stable reception, even under unfavorable conditions (low elevation, distant satellite). This criterion adds to other key parameters in site selection:

1. clear horizon mask;
2. ease of maintenance;
3. reliable internet connection;
4. logistical and administrative accessibility;
5. clear regulatory framework, particularly regarding VHF reception authorization.

Taken together, these constraints require a precise and methodical selection process, sometimes at the expense of sites that are geographically attractive on paper. A fully functional station in a slightly less central location, requiring minimal maintenance support, is preferable to an ideal site on paper that is effectively blind due to excessive RF noise.

3.2. SVOM Network Deployment

The deployment of the station network began in 2019, building on a solid foundation: the existing CNES network,

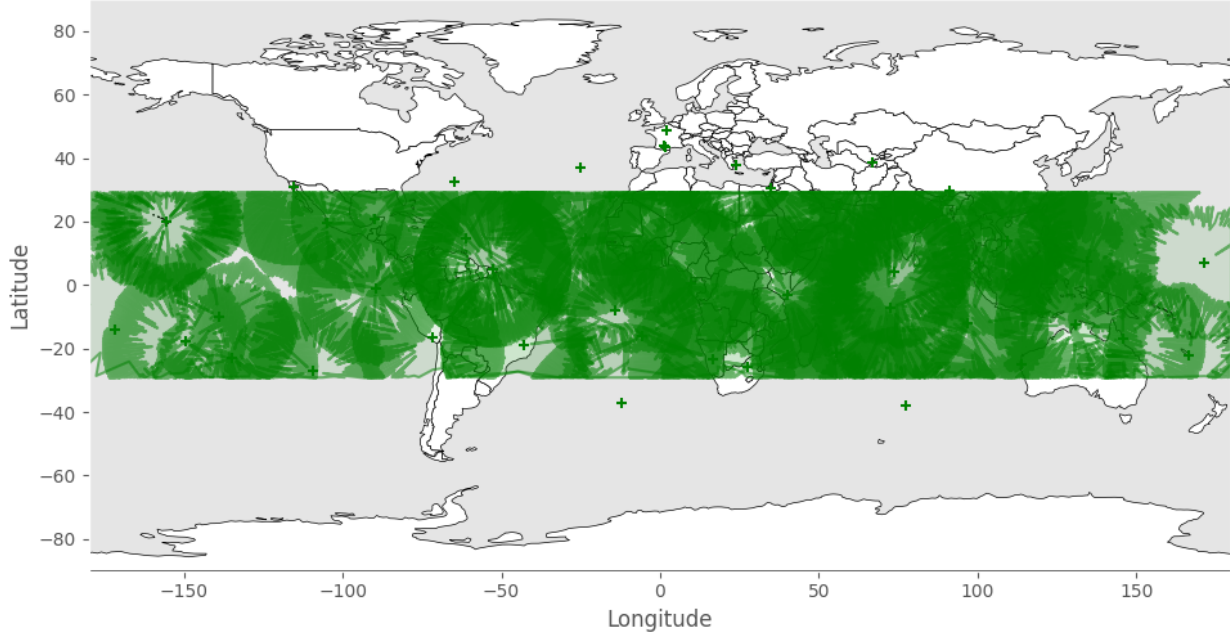


Figure 5. VHF network coverage constructed from packets received by each station. For a given station, at each pass, the position of the satellite is plotted for the first and last packets received.

which already included several strategically distributed ground stations across the globe. This initial backbone provided partial coverage and a proven architecture onto which the project could be rapidly integrated.

To extend the network, particularly within the equatorial zone, the project team leveraged an existing scientific collaboration network established over many years. Thanks to close ties with laboratories, universities, and observatories, new stations could be installed at reduced cost, often co-located with already existing infrastructure. These partnerships not only minimized hosting expenses but also provided access to local expertise for equipment monitoring and maintenance.

In more remote or difficult-to-access regions—such as isolated islands, underserved tropical zones, or politically sensitive contexts—deployment relied on technical or institutional partners already present on site. These partners played a key role by managing logistics, setting up the stations, performing first-level maintenance, and in some cases acting as intermediaries for VHF licensing or customs procedures. This collaborative model proved essential to accessing critical coverage areas without excessively increasing costs or deployment timelines. The network currently consists of 50 stations. The list of the different stations with their characteristics is presented in the Appendix A. Today, the network continues to expand following this hybrid approach: capitalizing on existing resources, developing scientific partnerships, and relying on local intermediaries in regions with low accessibility. This agile and collaborative strategy

has proven effective while also fostering international scientific cooperation around the project.

3.2.1. Coverage

The alert network currently provides coverage of 93% of the orbit (93% of the telemetry emitted by the satellite can be received at the FSC). In practice, the network's coverage is even better than theoretical estimates, as SVOM receiving stations often acquire the telemetry signal at elevations below 5° .

Figure 5 shows the actual geometric coverage of the network, derived from the packets received by each station. The uncovered areas can be quickly identified and are mainly located in the North Pacific. Table 1 provides quantitative measurements of the coverage as a function of the number of stations considered. The uncovered area represents 7.3% of the total coverage, and roughly three quarters of the area overflowed by SVOM is within visibility of at least two VHF stations.

3.3. Problems Encountered during the Deployment

The deployment of the ground station network was not free from technical and operational challenges. Several major issues were encountered during the successive deployments, requiring significant adaptations to ensure the stability and performance of the system.

Table 1
Percentage Coverage Based on the Number of Stations Considered as of 2025 December 5

Number of Stations	% of the Network Covered by Exactly N Stations	% of the Network Covered by at Least N Stations
0	7.3	...
1	18.8	92.7
2	30.0	73.7
3	23.3	43.7
4	14.0	20.4
5	5.3	6.4

Note. These Percentages are Measured from the Packets Received by Each Station at the Visibility Limit.

3.3.1. Antenna-related Issues

Thanks to measurements taken with NOAA satellites (see Section 3.4), we were able to identify a mechanical design flaw in the initially deployed antennas. Excessive thermal expansion, particularly in tropical climates, caused progressive damage to the internal structure of the antennas, leading to gain loss and malfunctions. In 2023, all antennas in the network were replaced with a new generation of antennas that are more resistant to temperature variations, ensuring stable long-term performance.

3.3.2. Network Connectivity Issues

Several sites experienced difficulties communicating through the internet, with connections that were highly unstable or extremely limited in bandwidth. In some cases, governmental restrictions made establishing a VPN to CNES nearly impossible. With the support of the CNES network team, specific solutions were implemented: routing via local relays, protocol optimization, and adaptation of systems to operate under very low data rates, while maintaining the ability to transmit critical alerts.

3.3.3. Electromagnetic (EMC) Issues

The sensitivity of the VHF system to electromagnetic noise proved particularly problematic at certain sites. The metallic structure of the station itself sometimes act as a resonant element, re-emitting disturbances onto the antennas, which then picked up parasitic signals present on the horizon. To address this issue, several measures were implemented:

1. additional shielding of coaxial cables;
2. improved cable routing within the structure to avoid ground loops;
3. installation of a ground plane beneath the antenna to reduce coupling with the structure and reflections from the ground.

These modifications reduced the noise floor by approximately 10 dB, significantly improving reception quality in complex RF environments.

3.4. Preliminary Tests with NOAA Satellites

To test the network during the deployment phase (see Section 3), the stations were configured to receive data from the polar-orbiting weather satellites NOAA-18 and NOAA-19, operated by NOAA (Goodrum et al. 2000). With an orbital period of approximately 102 minutes, these satellites complete about 14 passes over the equator each day—both ascending and descending. As a result, the same region is typically overflown at least four times per day, at intervals of roughly six hours. Their respective frequencies are 137.9125 and 137.10 MHz. They transmit analog signals using the Automatic Picture Transmission system. Earth images are derived from this signal with a fixed width and a transmission rate of 120 lines per minute. The number of lines depends on the duration of the passage. The first line corresponds to the moment the satellite becomes visible from the station, and the last line to the moment it disappears.

Using the ephemeris data from NOAA-18 and NOAA-19, together with the coordinates of a given site, we determined the start and end times of each satellite pass, as well as the corresponding start and end azimuths and the maximum elevation. Based on this information, the images were matched to their respective passes. By referencing the timestamps associated with each image file, we estimated the elevation at the end of the pass. Finally, applying the transmission rate, we inferred the acquisition start time and the elevation at the beginning of the pass.

In the presence of obstructions (buildings, mountains) or, if the station sensitivity is too low, the station's horizon may differ from the ideal 0° elevation horizon. If the signal reception is poor, signal loss may occur, resulting in missing or noisy lines in the image, including missing lines at the beginning or end of the satellite pass.

From the beginning of 2020 to the beginning of 2024, we monitored the evolution of the image quality to test how the stations evolved with the time. We also measured the real horizon of each station in order to derive the evolution of coverage throughout the deployment phase.

3.4.1. Image Quality Assessment

The quality of the images is assessed thanks to three criteria:

1. the size of the image which is directly linked with the horizon of the station;
2. the number of repeated lines when there is a loss of signal (shown in red in Figure 6);

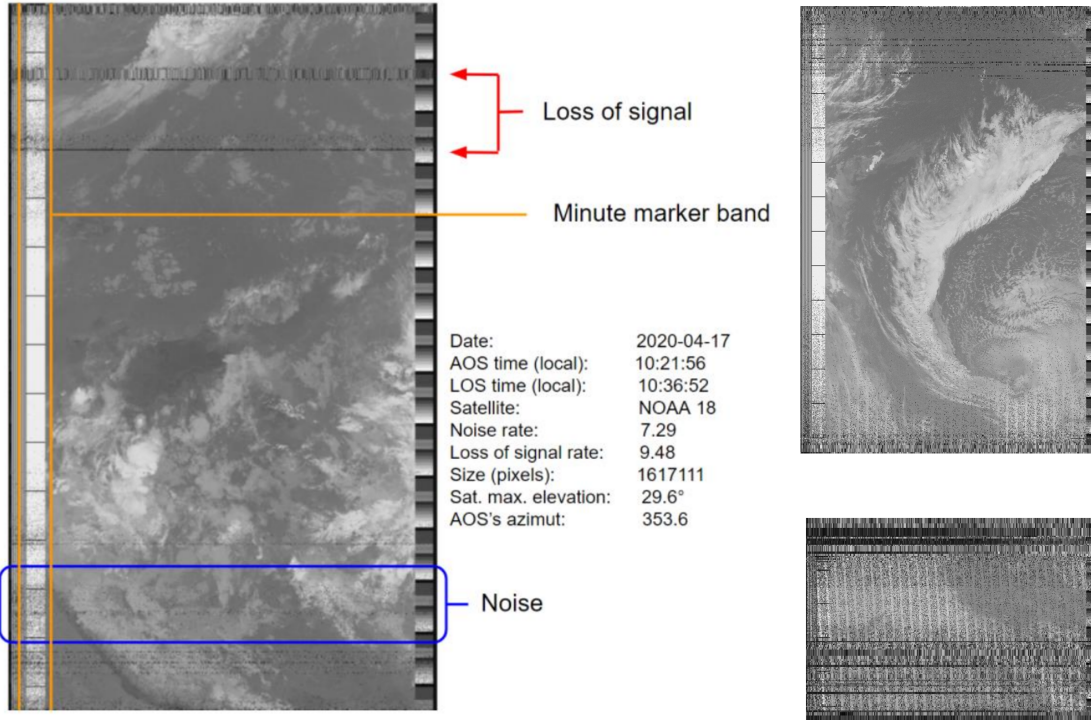


Figure 6. On the left: the three parameters extracted from the image to construct the quality score: the number of lines of signal loss, the number of black pixels in the minute mark band, and the size of the image. On the right, two images collected by the Azores station on 2024 January 7. Top: example of a good-quality image with a score of 37.5. Bottom: example of a poor-quality image with a score of 99.3.

- the noise that is measured by counting the ratio of black pixels within the minute marker band (shown in orange in Figure 6).

By linearly combining these three criteria, a global quality rating between 0 (best) and 100 (worst) is given to each image. As an example, Figure 6 provides two examples of images received by the Azores station (Portugal). The best image, rated 37.5, has many more lines and fewer noisy ones than the worst image rated 99.3 (for the first week of year 2024).

3.4.2. Contribution of Preliminary NOAA Tests

With the images received from the stations, we ran recurrent analysis to monitor the quality of the reception (through the images quality ratings) over time.

Figure 7 shows this evolution for the Hartebeesthoek station (South Africa). The evolution of the mean image rating illustrates effects that alter the quality of the reception (see Section 3.3). Gaps correspond to network issues. The fast degradation in Autumn 2021 is due to the premature aging of the antenna. Despite a replacement by a new upgraded station in Spring 2022, the quality did not fully recover due to electromagnetic issues in the environment.

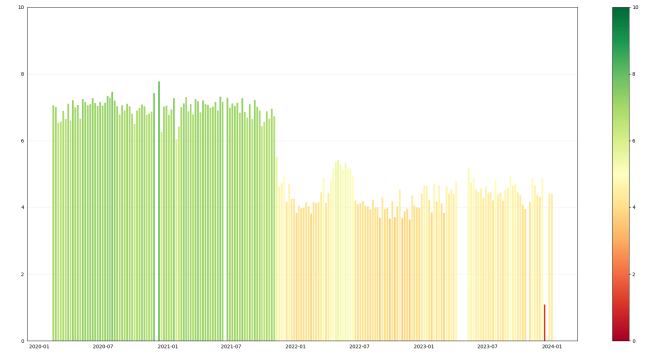


Figure 7. Evolution of the mean quality rating of the NOAA images received by the Hartebeesthoek station (South Africa).

4. FSC Integration

VHF data received from ground antennas are sent to the FSC, which hosts all services for SVOM data processing. The FSC comprises approximately 40 software components, primarily running as micro services in a Docker Swarm cloud environment built on virtual machines managed via OpenStack (Louvin et al. 2026). The production infrastructure is hosted by CC-IN2P3 in Lyon (France). SVOM FSC services depend on external systems for:

1. data storage and classification (e.g., relational databases);
2. monitoring (e.g., Grafana, Loki);
3. authentication and authorization (Keycloak).

The relational database infrastructure is maintained by CC-IN2P3 administrators, while the other components are deployed in a separate cloud and are under the responsibility of CEA FSC administrators.

The VHF binary messages (packets) are received at FSC through a dedicated REST API by the so-called *vhf-manager* service, which saves them in their raw format in a dedicated database. The *vhf-manager* allows insertions of multiple packets within one HTTP request from a given ground station.

The raw data format and rates of VHF packets are described below.

1. Total packet size is 128 bytes, with 28 bytes added by the ground station itself and 100 bytes coming from the satellite.
2. The 100 bytes are composed by a common section (packet header) of 6 bytes, and 94 bytes of data which will depend on the instrument. The packet header contains an identifier (APID) which allows to recognize the specific format of the 94 bytes. SVOM instruments have a total of 58 APIDs.
3. The emission frequency of VHF packets from the satellite is about 1 packet every 2 s.
4. The reception rates depend on the number of stations which are in the visibility range of the satellite, and we can measure over the day rates going from 0.2 packets per second to more than 1 packet per second. A comprehensive analysis of the VHF data reception is reported in Section 6 of this paper.

Even if the information from the satellite is always organized in individual packets, some APIDs have the information spread over a large number of packets. We can mention as an example the APIDs which are used to organize the light-curve content measured by ECLAIRS and GRM instruments. The information of a light-curve is organized in two APIDs (because of a different time resolution) composed by 42 and 22 packets each.

The packet processing workflow is summarized in the following paragraphs.

4.1. Raw Packet Ingestion

The raw packet is recorded, the station header and packet header are parsed and their content is organized in dedicated relational tables. The remaining 94 bytes are stored with a hash identifier which allows to detect duplicate packets (the same packet can be delivered by two different ground stations, or the satellite can repeat also relevant packets to increase the efficiency of their reception). The *vhf-manager* then calls a dedicated *decoder* service which is responsible for reading the

content of the binary VHF packets and converting them to JSON format (this depends on the APID). The JSON VHF packets are also saved in the VHF database. Once the packet ingestion is over, the system starts notifying clients about the packet reception, by sending the information (in JSON format) to a centralized messaging system hosted at FSC. Clients may subscribe to the VHF data messaging queue and act depending on the packet content (Louvin et al. 2026). The FSC provides via the *vhf-manager* an authenticated REST API allowing applications and authorized SVOM collaborators to access the VHF data (both raw and interpreted) stored in the VHF database.

For the first year of data taking, the total volume of the VHF database is about 100 GB in the Postgres database, for less than 10 GB of pure raw data.

4.2. Alert Management

Some specific APIDs contain information about satellite triggers related to the observation of a potential GRB by either the GRM or ECLAIRS instruments (or both). We call those packets “alerts.” For each alert, the localization of the GRB candidate is contained in a single 94 bytes packet we call an “alert packet.” Each alert packet is sent several times by the satellite, to maximize the probability of receiving this piece of data at the FSC level. The alert packets trigger an additional service deployed at FSC and devoted to the creation of a flag (the burst ID). After the initial alert packet, the instruments onboard SVOM broadcast more observation data in a sequence of VHF packets dubbed the “alert sequence,” which are all flagged using the burst ID for easy identification and processing by the FSC scientific pipelines.

4.3. Satellite Position and Attitude

Other APIDs contain information about satellite position and attitude, which are relevant for downstream physics analysis. This information is extracted from those packets and organized in specific tables.

4.4. From Raw Packets to Science Products

The FSC notification system allows other applications to react to the arrival of the VHF packets. Several processing pipelines are devoted to real-time VHF data analysis, combining data gathered from multiple packets.

5. In-flight Performance Measurements for the VHF Alert Network

5.1. Tests with the SVOM Satellite

An in-flight qualification measurement campaign has been run to verify the onboard requirements of the SVOM spacecraft for the VHF link.

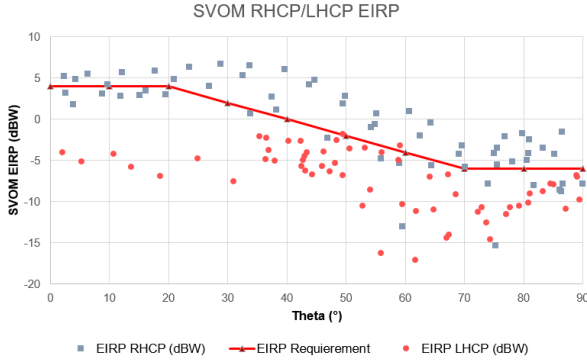


Figure 8. EIRP measurements and requirement as a function of angle theta of the antennas (0° is on axis).

Extensive testing was conducted using a ground-calibrated antenna at the CNES facilities in Kourou, French Guiana, with the objective of verifying the VHF EIRP and antenna gain of the SVOM spacecraft from a series of spectrum measurements.

Across several passes with sufficient geometrical diversity, hundreds of spectra were recorded and processed using a reverse link-budget approach to retrieve the EIRP on the spacecraft-plane.

The results presented in Figure 8 show that the SVOM spacecraft reaches the EIRP requirement with its RHCP VHF antenna with a good margin but not with its LHCP antenna. The lower performance of the LHCP part is explained by a different location of the LHCP antenna on the spacecraft. Some scientific instruments and communication equipment near the LHCP antenna result in a disturbed radiation pattern on the LHCP antenna.

The difference in performances between the antennas is clearly visible at the FSC level, where more VHF packets are received from the RHCP antenna, see Figure 9.

From the EIRP measurement, a computation is made to obtain from the quaternion attitude of the spacecraft the radiation pattern of both the RHCP and LHCP antennas.

Computations of the SVOM patterns show the expected radiation pattern for the RHCP antenna, whereas the LHCP antenna exhibits a perturbed on-axis radiation pattern, see Figure 10. We believe that this difference in results between the antennas is due to a different adaptation of RHCP and LHCP on the spacecraft.

6. SVOM VHF End-to-end Performance

The SVOM VHF emitter was turned on the day following SVOM launch in 2024 June and has been used continuously ever since as the main channel for real-time mission monitoring and alert broadcast. In this section, we will present some results regarding the end-to-end performances of the VHF network during SVOM operations.

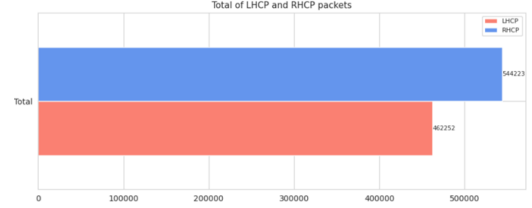


Figure 9. SVOM RHCP and LHCP packets received at FSC for a pass over the Kourou station.

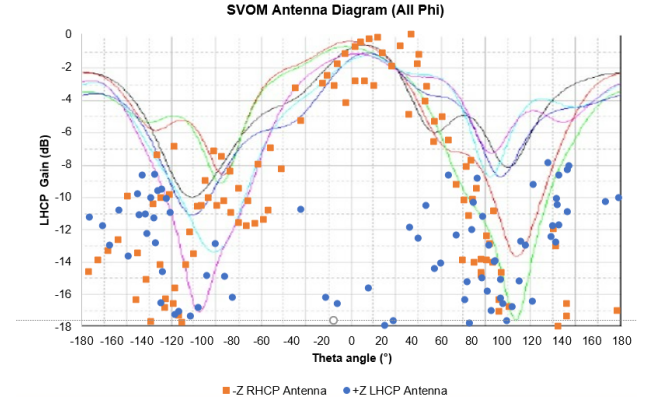


Figure 10. SVOM antenna gain as a function of antenna angle theta (0° is on axis), where continuous lines correspond to before launch measurements, and dots correspond to in-flight measured values.

6.1. Metrics and Methodology

For each VHF transmission, we define the following timestamps related to ground-to-board events:

1. the *packet time*: date and time of the VHF TM creation onboard by the instruments, encoded in the packet;
2. the *station time*: date and time at which a given station has received the VHF packet, added to the station header before transmission to FSC;
3. the *FSC reception time*: date and time at which the packet is saved at FSC, computed upon insertion in the dedicated VHF database.

Using those timestamps we compute two metrics: the ground transmission delay between the VHF antennas and the FSC which highlights the performances of the ground network, and the overall delay between the packet creations onboard and their reception at FSC which is the actual measure of end-to-end performance.

In addition to time-related metrics, we also estimate the *data completion* by computing the proportion of onboard VHF transmissions that have actually been received at FSC, using the list of all VHF packets sent by the onboard VHF emitter which is downloaded through X-Band communications every few hours alongside the complete SVOM observation data.

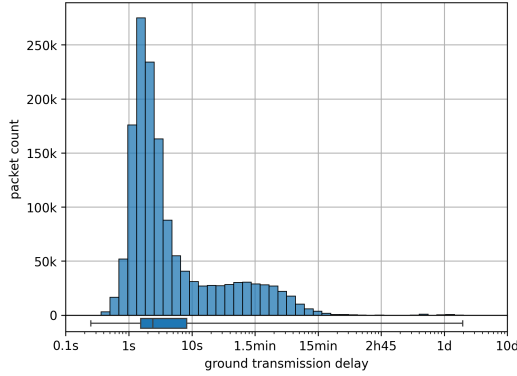


Figure 11. Distribution of stations-to-FSC transmission delays of SVOM packets received in 2025 September by all stations.

6.2. Repetition and Duplication Strategies

In order to ensure timely distribution of GRB detections and localization to the scientific community, all VHF messages containing alert-related data are sent several times by the satellite. This allows us to circumvent holes in the VHF network coverage and punctual networking issues that could lead to packet loss. This is referred to as “onboard repetition strategy.” The number and delay between repetitions depend on the packet types as identified by their APIDs.

To further improve the reliability of the SVOM downlink for alert-related data, some messages sent through the VHF network are also downloaded using the Chinese navigation satellite system Beidou. This communication subsystem has a slower rate than VHF and a much smaller bandwidth, but as we will see in the next section it allows speeding up the on-ground reception of alert data in some cases, and could even be vitally important in case the VHF network is temporarily unavailable.

All VHF packets emitted by the SVOM that are not received in real-time through the VHF network or Beidou are recovered every few hours alongside the complete SVOM observation data through the X-Band network which allows us to ensure completeness of VHF data with a few hours delay.

6.3. Ground Network Performances

The performance results presented in this section were computed using the data produced by SVOM during 2025 September. This allows us to analyze the performances of the system using the latest versions of hardware and software in place at the time of redaction.

Figure 11 shows the distribution of “ground transmission delays” between VHF antennas reception and FSC saving time for the packets received in 2025 September. The box plot at the bottom of the figure shows a median delay around 2.4 s. The box itself delimits the interquartile range representing

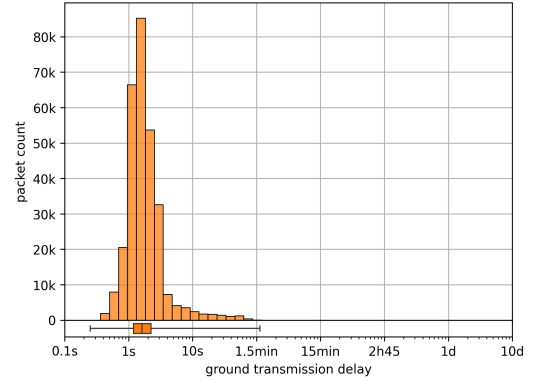


Figure 12. Distribution of stations-to-FSC transmission delays of SVOM packets received in 2025 September by the 10 most efficient stations.

50% of the data, meaning 25% of the packets were transmitted by the stations in less than 1.5 s, and 75% in less than 7 s.

In the vast majority of cases, the performance of the ground network is very good. However, we can see in Figure 11 that there are sometimes significant communication delays between the VHF stations and FSC. Those delays are due to network and bandwidth issues in some VHF station locations. In order to illustrate this, we show in Figure 12 the same plot but restricted to the 10 most efficient VHF stations. We can see that the performances are excellent and the spread hugely reduced, with a median below 2 s, more than 75% of the packets transmitted in less than 3 s and an overall maximum delay around 1 minute and 30 s.

Updates to the VHF station software as well as optimizations in the communications between the VHF stations and FSC have been developed and are currently being deployed. Those are expected to significantly reduce the ground communication delays, especially for stations which suffer from low bandwidth and internet speed. Those improvements should be implemented on all stations in the first half of 2026.

6.4. End-to-end Performances

The performance results presented in this section were computed using the data produced by SVOM during 2025 September. This allows us to analyze the performances of the system using the latest versions of hardware and software in place at the time of redaction.

In Appendix B, the table presents the contribution of the different stations to the SVOM alert system. The table is ordered in decreasing values according to the number of packets received at the FSC from each station. An inhomogeneity in performance can be observed, which can be explained by a combination of several factors: the geographical location of the station, its sensitivity as determined by the local VHF environment, and the bandwidth of its internet connection.

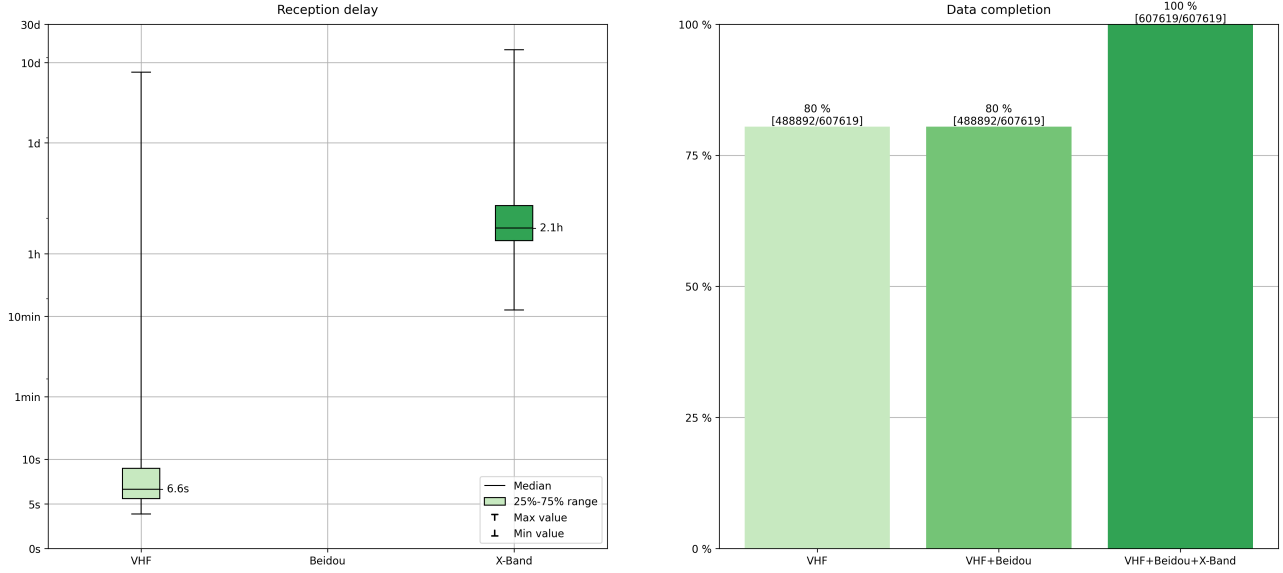


Figure 13. SVOM-to-FSC transmission delays and data completion for recurrent packets received in 2025 September.

Because the satellite is often visible from multiple stations, a given packet can be received at the FSC from several stations. The second column indicates, for each station, the number of its packets that arrived first.

Finally, the third column indicates the number of packets for which the station was the sole transmitter. This column shows that even if a station does not contribute significantly to the overall packet volume, it may fill a coverage gap in the network when it is the only station in communication with the satellite. This table clearly illustrates the complementarity of the stations within the network, balancing performance and coverage.

Regarding latencies and completion of the overall system, the figures presented below show on the left-hand side a box-and-whiskers representation of the board-to-ground delays distribution for all SVOM communication channels: VHF, Beidou and X-Band (see Section 6.2). Those delays correspond to the difference between the onboard message production and its reception and saving at FSC. The right-hand side bar plot shows the data completion for each of the communication channels for the data corresponding to the left-hand side distributions.

Figure 13 shows the board-to-ground delays distribution and data completion over 2025 September restricted to the type of VHF packets that are downlinked by SVOM as soon as they are produced and that are neither repeated by the onboard emitter nor duplicated through Beidou. Those messages are mostly used to broadcast monitoring messages from the SVOM instruments. Studying the delays and completion for those packets allows seeing the raw performance of the SVOM VHF communications without repetition strategy and Beidou replication. We can see that the delay distribution is consistent

with Figure 11 with a shift of around 4 s due to the onboard processing and VHF spacecraft-to-station communication time. The data completion is about 80%, meaning that 20% of packets are not received in the initial VHF transmission and only recovered through X-Band, the median time of which is around 2 hr. These performances are sufficient for real-time monitoring but not quite good enough to comply with the scientific goals of the SVOM mission.

Figure 14 shows the board-to-ground delays distribution and data completion over 2025 September restricted to VHF packets containing onboard trigger data. Those messages are repeated several times by the onboard emitter and also replicated through the Beidou network, and are used at FSC to automatically generate scientific products and notices which are broadcasted to the worldwide scientific community in real time. Regarding the 180 onboard triggers that occurred in 2025 September, we can see that:

1. for the VHF network, the following alert delay distributions are measured: 25% in less than 5.3 s, 50% in less than 8.9 s, and 75% in less than 215 s;
2. the onboard repetition strategy causes a spread of the time delay distribution which makes sense since the delay between packet production and reception increases with each repetition of a VHF message;
3. the onboard repetition strategy allows raising the data completion through VHF alone to 95%;
4. the Beidou replication has a median distribution delay of around 2 minutes which means that in some cases the Beidou replicated message arrives at FSC before the alert coming from the VHF communication;

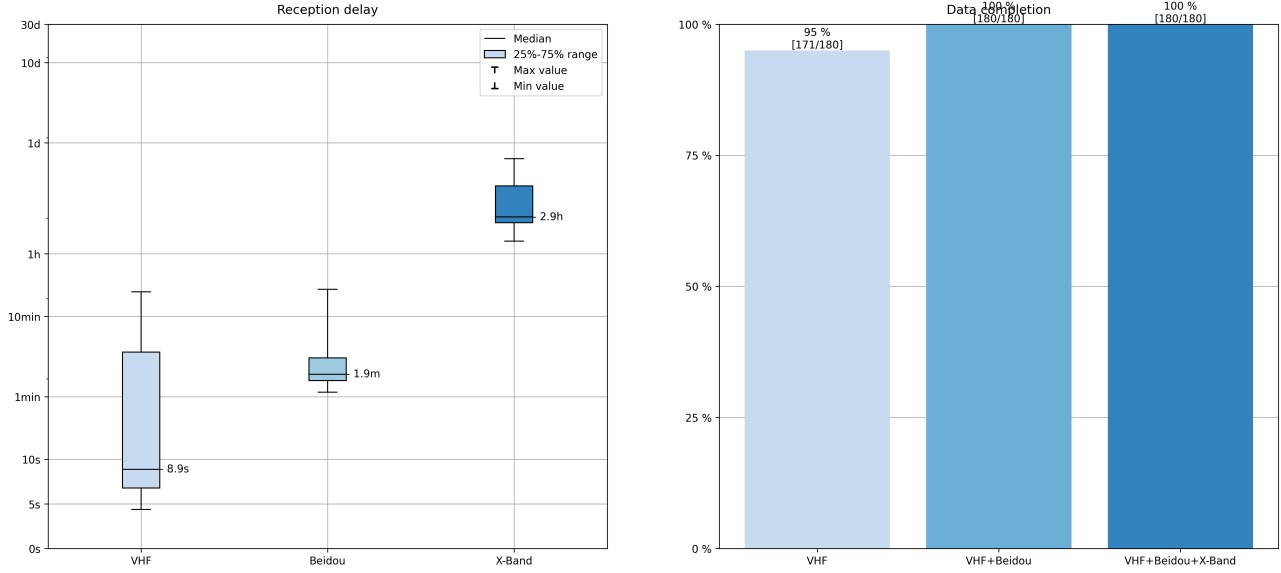


Figure 14. SVOM-to-FSC transmission delays and data completion for alert packets received in 2025 September.

- the Beidou replication allows raising the data completion to 100% meaning that we did not lose any VHF alert packets in September and never had to wait for the X-Band complete data to arrive to produce and broadcast SVOM alerts.

The latency performance of the SVOM VHF network is comparable, even slightly better for more than half of the messages, to that of the TDRSS system used by the Swift satellite. According to information given by the Swift team, TDRSS provides a median latency of 20 s (14 s/37 s for the 25%/75%) in the last few years for broadcasting the first alert message, which includes the high-energy localization of the burst. In the case of the GECAM satellite, which uses the Beidou system, latencies of about 2 minutes are observed for the first alert message.

However, it should be noted that these messaging systems, which rely on satellite relay networks, can transmit only a limited number of messages and therefore do not allow continuous contact with the scientific mission. In contrast, the SVOM VHF network enables the continuous transmission of recurrent messages that track the status of both the instruments and the spacecraft platform. This capability is a major advantage for a mission focused on the transient sky, as it allows verification of instrument operating conditions at the time of the trigger and during follow-up observations. Such information is essential for the scientific validation of the content of the alert.

Finally, taking into account the repetition and duplication strategy, 63% (113/180) of the first alert packets notifying onboard triggers were delivered in less than 30 s after the event, and 100% in less than 7 minutes. We can therefore conclude that the SVOM alert system complies with the mission requirement outlined in the introduction to this article.

7. Conclusions

The development of the VHF alert network and the first In-Flight results of the SVOM mission clearly show:

- the system requirement about the alert distribution delays is fully satisfied;
- performances at station level show that the aging of the main parts of ground stations (antennas and receivers) is better than expected after one year of operation;
- SVOM alert network should allow performing the SVOM nominal and extended operational phases.

After one year of operation, and considering both the network's performance and the scientific results obtained, it is clearly demonstrated that the VHF alert system plays a central and irreplaceable role in the daily functioning and scientific operations of the SVOM mission.

Acknowledgments

The Space-based multi-band Variable Objects Monitor (SVOM) is a joint Chinese-French mission led by the Chinese National Space Administration (CNSA), the French Space Agency (CNES), and the Chinese Academy of Sciences (CAS). We gratefully acknowledge the unwavering support of NSSC, IAMCAS, XIOPM, NAOC, IHEP, CNES, CEA, and CNRS.

We would like to thank the trainee engineers from École Centrale Lille/Lyon who worked at CEA on monitoring the VHF network: Sarah Menouni, Hugo Thiesse, Aubry De Longcamp, Elie Straumann, and Lucas Witzel Ferreira.

Appendix A

VHF Stations List

List of VHF stations deployed as of November 2025.

N°	ID	Name	Country	Installation Date	Latitude	Longitude	Implementation
1	ZAF1	Hartebeesthoek	South Africa	2019-04-29	−25.89	27.71	CNES network
2	GUF1	Kourou	France	2019-05-20	5.17	−52.69	CNES network
3	GUF2	Kourou 2	France	2019-05-20	5.17	−52.69	CNES network
4	GRC1	Athens	Greece	2019-07-15	37.98	23.78	Scientific collaboration
5	GAB1	Libreville	Gabon	2019-09-12	0.39	9.60	CNES network
6	SHN2	Saint Helena	UK	2019-11-19	−15.94	−5.67	Agreement
7	THA2	Songkhla	Thailand	2020-01-15	7.16	100.61	Scientific collaboration
8	REU1	La Réunion	France	2020-01-22	−21.20	55.57	Scientific collaboration
9	PHL1	Manila	Philippines	2020-01-23	14.54	121.04	Agreement
10	BFA1	Ouagadougou	Burkina Faso	2020-04-02	12.37	−1.51	Agreement
11	KEN1	Malindi	Kenya	2020-04-02	−3.00	40.19	CNES network
12	CPV2	Praia	Cape Verde	2020-08-31	14.92	−23.51	Agreement
13	ISR1	Tel Aviv	Israel	2020-09-10	30.60	34.76	Scientific collaboration
14	SHN1	Ascension	UK	2020-09-25	−7.92	−14.33	CNES network
15	ESP2	Maspalomas	Spain	2020-10-06	27.76	−15.63	Agreement
16	MTQ1	Le Lamentin	France	2020-10-31	14.60	−61.00	Agreement
17	ARE3	Sharjah	UAE	2020-11-05	25.31	55.49	Scientific collaboration
18	PYF2	Papeete	France	2021-02-08	−17.57	−149.60	Scientific collaboration
19	PYF3	Rikitea	France	2021-03-15	−23.13	−134.96	Agreement
20	AUS3	Carnarvon	Australia	2021-06-11	−24.87	113.70	Agreement
21	PRT1	Açores	Portugal	2021-06-30	36.99	−25.13	Agreement
22	DGA1	Diego Garcia	UK	2021-07-05	−7.27	72.38	Agreement
23	ATF1	Amsterdam	France	2021-09-13	−37.80	77.57	Agreement
24	FR4	CNES Fermat	France	2021-09-13	43.56	1.48	CNES network
25	SHN3	Tristan Da Cunha	UK	2021-10-27	−37.07	−12.31	Agreement
26	ARE1	Al Aïn	UAE	2021-11-25	24.12	55.41	Scientific collaboration
27	CHN1	Nanning	China	2021-11-26	22.51	107.78	Scientific collaboration
28	SYC1	Mahe	Seychelles	2021-12-06	−4.68	55.53	Agreement
29	USA2	Hawaii	USA	2021-12-13	20.02	−155.67	Scientific collaboration
30	UZB1	Maidanak	Uzbekistan	2022-02-26	38.67	66.90	Scientific collaboration
31	ECU2	Galapagos	Ecuador	2022-04-19	−0.90	−89.61	Agreement
32	PLW1	Palau	Palau	2022-04-29	7.46	134.53	Agreement
33	MEX1	San Pedro Martir	Mexico	2022-06-07	31.05	−115.47	Scientific collaboration
34	BMU1	Bermuda	Bermuda	2022-06-30	32.35	−64.66	CNES network
35	NCL1	Nouméa	France	2022-07-25	−22.28	166.46	Agreement
36	JPN1	Chichi-jima	Japan	2022-10-12	27.09	142.19	Scientific collaboration
37	PER1	Arequipa	Peru	2022-10-15	−16.47	−71.49	Agreement
38	PYF4	Marquises	France	2022-11-14	−9.78	−139.01	Agreement
39	FR3	CEA	France	2023-03-10	48.73	2.15	Scientific collaboration
40	MEX3	Chamela	Mexico	2023-04-11	19.50	−105.04	Scientific collaboration
41	AUS11	Coco Islands	Australia	2023-04-20	−12.19	96.83	Agreement
42	MEX2	Yucatán	Mexico	2023-05-11	20.99	−89.73	Scientific collaboration
43	CHN3	Lhassa	Chine	2023-05-31	29.64	91.18	Scientific collaboration
44	AUS7	Darwin	Australia	2023-07-06	−12.37	130.87	Agreement
45	AUS6	Cairns	Australia	2023-08-02	−16.82	145.68	Agreement
46	CHL8	Easter Island	Chile	2023-11-02	−27.14	−109.41	Agreement
47	MDV1	Male	Maldives	2024-01-25	4.19	73.53	Scientific collaboration
48	BRA8	Guanhaes	Brazil	2024-08-13	−18.79	−42.92	Agreement
49	NAM1	Windhoek	Namibia	2024-10-22	−23.27	16.50	Scientific collaboration
50	VNM3	Quy Nhon	Vietnam	2025-01-13	13.72	109.21	Scientific collaboration
51	USA3	Hawaii	USA	2025-04-02	20.02	−155.67	Scientific collaboration
52	WSM1	Apia	Samoa	2025-10-25	−13.85	−171.79	Agreement
53	MHL1	Majuro	Marshall Islands	2025-11-07	7.09	171.38	Agreement

Appendix B

Number of VHF Packets Received Per Station at the French Science Center from 2025 September 1 to 30

In 2025 September, the stations in Sharjah, Amsterdam, CNES Fermat, and Chichi-jima were not operational, and the stations in Apia and Majuro had not yet been installed. The stations are listed in descending order of packets received at the FSC.

N°	ID	Name	SVOM Packets Received from this Station	SVOM Packets Received First from this Station	SVOM Packets Received only from this Station
1	NCL1	Nouméa	46387	40502	26429
2	MTQ1	Le Lamentin	40633	9587	8378
3	AUS11	Coco Island	40083	28353	19828
4	PYF2	Papette	39019	30929	17880
5	REU1	La Réunion	38849	18607	8221
6	MEX3	Chamela	35863	22331	14459
7	ESP2	Maspalomas	34747	23835	2763
8	ZAF1	Hartebeesthoek	34315	3091	1298
9	SHN2	Saint Helena	33806	20911	2498
10	PYF3	Rikitea	32319	6074	5565
11	CPV2	Praia	32071	13655	1657
12	DGA1	Diego Garcia	30740	11233	1965
13	NAM1	Windhoek	30649	13477	719
14	THA2	Songkhla	29420	20298	2581
15	PYF4	Marquises	27471	17474	4134
16	ECU2	Galapagos	27040	17996	14586
17	ISR1	Tel Aviv	26886	20093	8365
18	AUS7	Darwin	26637	15304	13167
19	AUS6	Cairn	26320	11337	3348
20	MDV1	Male	25414	15015	4575
21	USA2	Hawai	25246	5611	4324
22	CHN1	Nanning	24753	7727	4848
23	SHN1	Ascension	24563	2246	2225
24	USA3	Hawaï	24521	22994	3866
25	GUF1	Kourou	24405	8053	956
26	GAB1	Libreville	21930	14047	3246
27	BRA8	Gunahaes	21264	17543	13964
28	GUF2	Kourou 2	21261	12495	521
29	PHL1	Manila	21002	13656	4187
30	MEX1	San Pedro Martir	20722	16539	5885
31	BFA1	Ouagadougou	18565	3819	941
32	PRT1	Açores	17119	5488	485
33	SHN3	Tristan Da Cunha	16719	4435	1840
34	CHL8	Easter Island	16176	13270	6257
35	PLW1	Palau	15479	8077	6155
36	SYC1	Mahe	13943	9910	1376
37	KEN1	Malindi	13929	8731	3128
38	BMU1	Bermuda	12886	12116	1387
39	CHN3	Lhassa	12402	2401	2299
40	GRC1	Athen	12350	8601	630
41	VNM3	Quy Nhon	11873	4082	296
42	ARE1	Al Ain	10874	4325	2672
43	UZB1	Maidanak	10832	7078	2804
44	MEX2	Yucatan	9046	4149	530
45	FR3	CEA	1359	532	13
46	PER1	Arequipa	885	584	296
47	BDV	Beidou	725	725	725
48	AUS3	Carnavon	450	290	285

Appendix C

Acknowledgments to the Contact Persons by Site

We would like to express our sincere gratitude to the individuals listed in the Table C1, who greatly assisted us in deploying and configuring the SVOM stations. Without their invaluable help, the project would not have been able to achieve its objectives.

Table C1
List of Sites and Contact Persons

Sites	Contacts
1. Açores (Portugal, Estação Geodésica Fundamental RAEGE)	Nuno MATA; Nuno Miguel SOARES da MATA
2. Al Ain (United Arab Emirates, NSSTC)	Saeed ALBLOOSHI
3. Amsterdam (France, TAAF)	Yann LE MEUR; Brendan CORBEL
4. Arequipa (Peru, UNSA)	Pablo Raul YANYACHI
5. Ascension (United Kingdom, ESA, Ariane Station)	Paul BENNETT
6. Athens (Greece, NTUA)	Maria TSAKIRI; Vangelis ZACHARIS
7. Bermuda (ESA)	Frank WILLIAMS
8. Cairns, Darwin, Carnarvon (Australia, UWA)	John MOORE; Bruce GENDRE
9. Chamela, Yucatán, San Pedro Martir (Mexico, UNAM)	Alan WATSON; Fernando ANGELES
10. Chichi-jima (Japon, KU)	Daisuke YONETOKU
11. Djibouti (CERD)	Abalyazid AHMAD; Saad IBRAHIM AHMED; Farah MAHAMOUD OSMAN; Mohamed JALLUDIN
12. Easter Island, Coco Island, Guanhaes, Tristan Da Cunha, Samoa, Marshall Islands (EnviroEarth)	Maxime Le MAILLOT; Maxime GRILLANDINI
13. Diego Garcia (United Kingdom, Sure Limited)	JoJo DELAPLANA; Paul EXALA; Dave HAWORTH
14. Galapagos (Équator, USFQ)	Luis TASIPANTA; Cristina VACA; Leo ZURITA-ARTHOS
15. Hartebeesthoek (South Africa, SANSA)	Raoul HODGES; Carlos DE OLIVEIRA; Tiisetso MASEKO; Frikkie MEYER; Tiaan STRYDOM
16. Hawaii (United State of America, CFHT)	Windell JONES-PALMA; Jean-Gabriel CUBY
17. Ho Chi Minh (Vietnam, VGU)	Hien Vo BICH; Nhu TRAN QUANG
18. Kourou (France, CNES)	Sébastien LACOUR; Julie RICHARD; Romain DELORDRE
19. La Réunion (France, IPGP)	Frédéric PESQUEIRA; Patrice BOISSIER; Christophe BRUNET; Philippe KOWALSKI
20. Le Lamentin (France, Météo France)	Ronan LE MAREC; José ODONNAT; Carole JULIARD
21. Lhassa (China, Tibet University)	Hua BAO; Tianlu CHEN; Shifeng WANG; Jianyan WEI
22. Libreville (Gabon, CNES)	Dominique-Roland DELMAS; Michel DUVERGER; Eric LE GOFF
23. Mahé (Seychelles, SMA)	Vincent AMELIE; Nelson LALANDE; Varunakumar RAJENDRAN
24. Maidanak (Uzbékistan, UBAI)	Samar ABDURAIMOV; Otabek BURKHONOV; Yusufjon TILLAYEV; Dima ALEKSEEV; Bahodir HAFIZOV
25. Malé (Maldives, MMS)	Abdul MUHSIN RAMIZ; Abdulla WAHID; Musa SAYD
26. Malindi (Kenya, BSC)	Munzer JAHJAH; Paolo ROTINI; Davide DECLEMENTE; Boniface OYENGO
27. Manila (Philippines, NAMRIA)	Donnie T. MANCERA; Maria Almaly A. BALLADARES; Charisma Victoria D. CAYAPAN; Ronaldo GATCHALIAN
28. Marquises (France, Météo France)	Serge MENDIOLA; Fabien CREPIN; William MAUREL
29. Maspalomas (Spain, INTA)	Guillermo RIVERO ARIAS; Maria DE LOS ANGELES DOMINGUEZ DURAN
30. Nanning (China, Guangxi University)	Enwei LIANG; Xiang LU; Lianzhong LÜ
31. Nouméa (France, DITTT)	Perrine DRAIN; Quentin CARDON; Cyrille DUMAS-PILHOU; Thomas MÉNARD
32. Ouagadougou (Burkina Faso, IRD)	Fabrice COURTIN; Mawelamba KATAKA; Boubakar ZEMBA
33. Oukaimeden (Morocco, OUCA)	Zouhair BENKHALDOUN; Omar OUCHAOU
34. Palau (Palau, KARI)	SoonSeob HA; DongHyun KIM; ChunWon KIM
35. Panama (UTP)	Ellis ALICIA; Rodney DELGADO SERRANO; Megan CARRERA
36. Papeete (France, UPF)	Clément MOUNE; Jean-Pierre BARRIOT; Moerani FAILLOUX; Franck MEVEL; Lydie SICHIOX; Youry VERSCHELLE; Yannick VOTA
37. Praia (Cape Verde, NOSI Data Center)	Marta ANDRADE GOMES; Antonio Carlos BARROS LOPES; Luis Carlos CORREIA; Jader SEMEDO
38. Quy Nhon (Vietnam, ICISE)	Son TRAN; Cao SON; Tran NHU; Jean TRAN THENH VAN
39. Rikitea (France, Météo France)	Gilles ORAIN; Tahiariki LEE; Sébastien HUGONY
40. Saint Helena (United Kingdom, MET Office)	Lorimar BENNETT; Marcos HENRY
41. Sharjah (United Arab Emirates, American University of Sharjah)	Georgios CHAMILOTHORIS; Nidhal GUESSOUM

Table C1
(Continued)

Sites	Contacts
42. Songkhla (Thailand)	Seksan JOMSUREE; Kanthanakorn NOYSENA; Loylip TEERAYUT
43. Tel Aviv (Israel, TAU—Wise Observatory)	Shai KASPI; Dan MAOZ
44. Windhoek (Namibia, H.E.S.S.)	Toni HANKE; Frikkie van GREUNEN

ORCID iDs

N. Dagoneau  <https://orcid.org/0000-0002-1361-2562>
H. Louvin  <https://orcid.org/0009-0006-1908-4592>

References

Aol, S., Buchert, S., & Jurua, E. 2020, *EP&S*, **72**, 164
Cordier, B., Wei, J., Zhang, S., et al. 2026, *RAA*, **26**, 104001
Goodrum, G., Kidwell, K., & Winston, W. 2000, NOAA KLM User’s Guide, Tech. rep., U.S. Department of Commerce, NOAA/NESDIS, Washington, D.C. version of September 2000
Louvin, H., Corre, D., Formica, A., et al. 2026, *RAA*, **26**, 104032
Matsuoka, M., Kawai, N., Yoshida, A., et al. 2004, *BaltA*, **13**, 201
Reed, I. S., & Solomon, G. 1960, *Journal of the Society for Industrial and Applied Mathematics*, **8**, 300
Schonhoff, T. A. 2003, *Wiley Encyclopedia of Telecommunications* (Wiley)