

Spaceborne High Frequency Mission: Hearing the Shortwave Radio beyond the Ionosphere

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Spaceborne High Frequency Mission:

Hearing the Shortwave Radio beyond the Ionosphere

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Abstract

The high-frequency (HF) shortwave band, approximately 3-30 MHz, together with adjacent upper-medium-frequency extension down to about 0.3 MHz form one of the least explored radio windows in near-Earth space. From the ground, this band is both a resource and a barrier: the ionosphere enables long-distance shortwave communication by refraction, but the same dispersive and magnetized plasma blocks, bends, absorbs, scintillates and depolarizes extraterrestrial radio waves. Above the main ionospheric layers, shortwave signals from the Sun, planetary magnetospheres, lightning, terrestrial transmitters, and the Galactic radio background can be measured directly under conditions unavailable to ground-based instruments. A spaceborne HF mission can therefore serve three communities at once: heliophysics and space weather, low-frequency radio astronomy and planetary science, and ionospheric radio-propagation and spectrum-environment monitoring.

We propose the Spaceborne High Frequency Mission (SHFM) as a staged constellation mission for receiving, classifying and locating shortwave radio signals above the ionosphere. The present concept

deliberately adopts a conventional and technically mature payload architecture: deployable electrically short HF antennas, high-impedance low-noise preamplifiers, broadband high-dynamic-range receivers, multi-channel synchronized digitizers, onboard intelligent signal processing, precision timing, and calibrated ground-space experiments. The baseline constellation consists of multiple small satellites in controlled relative orbits, forming a spaceborne HF receiving array. By combining signals coherently or non-coherently, the array will improve sensitivity, enable direction finding and source separation, suppress interference through spatial filtering, and establish the measurement basis for future low-frequency radio imaging missions.

The mission has four primary scientific objectives: (1) characterize the orbital shortwave radio environment and its dependence on local time, geomagnetic latitude and space weather; (2) observe solar, heliospheric, planetary and Galactic radio sources in a band severely distorted or inaccessible from the ground; (3) determine upward trans-ionospheric HF propagation using calibrated ground beacons and natural impulsive sources; and (4) demonstrate multi-satellite HF array reception above the ionosphere. In addition, SHFM has clear application value: it can monitor the global HF spectrum environment, identify and locate strong shortwave radiation sources, support interference diagnosis and radio-environment awareness, and provide data products useful for HF communication resilience during disturbed space-weather conditions. This paper defines the scientific rationale, mission objectives, measurement requirements, key technologies and staged mission profile for SHFM.

Keywords: space mission design; high-frequency radio; shortwave radio; ionosphere; spaceborne antenna; constellation; radio interferometry; onboard signal processing; radio-source monitoring; heliophysics

1. Background and scientific rationale

Radio observations have opened new windows for plasma physics, energetic particles and magnetic fields. At centimeter, decimeter and meter wavelengths, ground-based observatories now measure the Sun, pulsars, supernova remnants, active galaxies, transient radio sources and the diffuse Galactic synchrotron background with high fidelity. At lower frequencies, especially below about 30 MHz, the observation situation changes dramatically. The terrestrial ionosphere becomes a time-varying, anisotropic and absorbing propagation medium. Its electron density, collision frequency and geomagnetic-field coupling change with solar illumination, latitude, season, geomagnetic activity and traveling ionospheric disturbances. As a result, radio waves in the shortwave band experience frequency-dependent group delay, phase distortion, refraction, Faraday rotation, scintillation, absorption and multipath propagation. Below the local plasma cutoff, extraterrestrial radiation cannot reach the ground at all.

This limitation is scientifically costly because the 0.3-30 MHz band carries rich plasma information. Solar type II and type III radio bursts trace shocks and energetic electron beams from the outer corona into interplanetary space^[1~3]. Planetary auroral emissions, generated mainly through cyclotron-maser instability, provide a remote diagnostic of magnetospheric plasma processes and magnetic-field strength. The Galactic background and bright low-frequency sources contain information about cosmic-ray electrons, absorption, scattering and magnetized interstellar plasma^[4]. Lightning and other impulsive terrestrial sources provide natural broadband probes of trans-ionospheric propagation^[5~11]. Ground transmitters, ionosondes and HF radars provide controlled signals that can be used to validate ray tracing, data assimilation and ionospheric models from a spaceborne vantage point^[12~19].

The need for spaceborne low-frequency radio measurements has been recognized for decades. The radio astronomy explorer missions showed that radio astronomy below the ionosphere is possible, but their angular resolution and calibration capability were limited by the technology of the time. Later studies proposed evolutionary space-based low-frequency telescopes, two-element interferometers, orbiting arrays, lunar-farside arrays and distributed aperture arrays^[20~27]. Modern low-frequency ground arrays such as LOFAR have demonstrated the scientific power of large digital aperture arrays above the ionospheric cutoff, while also revealing the calibration difficulty caused by the ionosphere^[28~29]. Recent spacecraft and mission concepts, including CASSIOPE/e-POP RRI, AERO, VISTA and HF vector-sensor studies, demonstrate that compact spacecraft can carry multi-channel digital receivers and vector antennas for LF/HF science and technology validation^[30~38].

The remaining gap is no longer simply the existence of a receiver in orbit. What remains missing is a mission architecture that treats the shortwave band as a calibrated spaceborne observing system: a system that measures the environment, separates natural and artificial sources, uses multiple satellites for array gain and direction finding, and closes the loop with ground-based ionospheric measurements. A single satellite can measure spectra and waveforms, but it cannot fully determine source direction, suppress terrestrial interference spatially, or build a receiving aperture with higher gain. A constellation can do these things. For this reason, SHFM is conceived not as a one-off payload but as a staged spaceborne HF receiving array. Therefore, we have presented the overall logic framework of the SHFM concept, as shown in Figure 1.

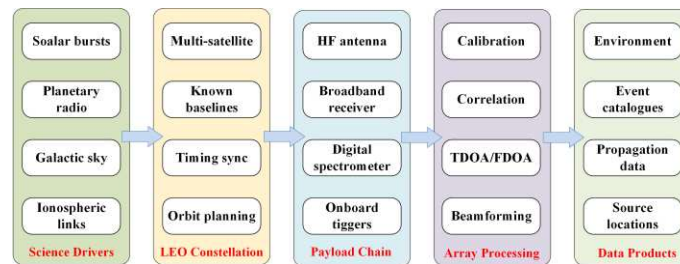


Figure 1. Overall logic framework of the Spaceborne High Frequency Mission Concept.

The mission concept follows a conservative technology path. The payload uses conventional electric antennas, low-noise analog front ends, broadband digitization and digital signal processing. The central technical challenge is therefore not speculative sensing physics, but system integration: how to deploy and calibrate short HF antennas on small spacecraft, how to maintain receiver linearity in a strong and variable radio environment, how to process wideband data onboard, and how to preserve the timing, phase and baseline knowledge needed for multi-satellite array reception. The conceptual observation geometry of the SHFM for receiving high-frequency signals above the ionosphere is shown in Figure 2.

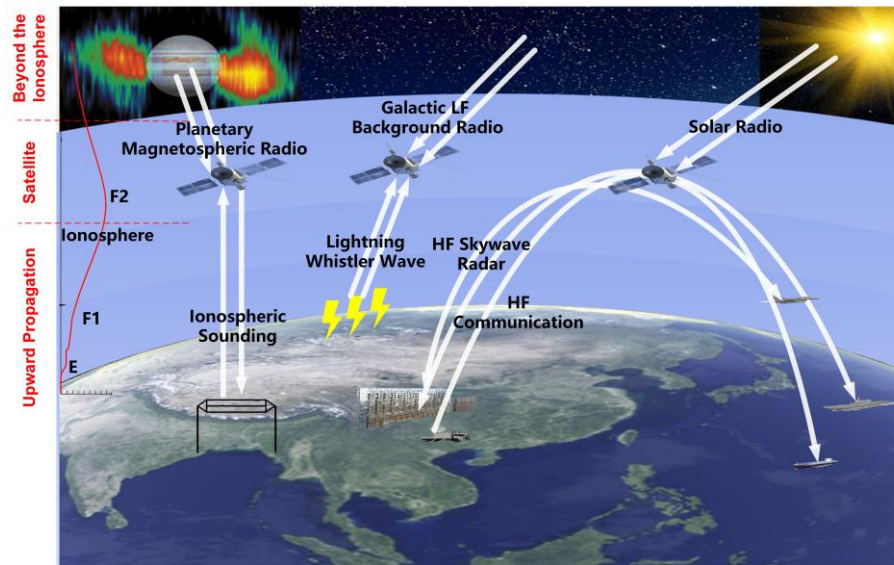


Figure 2. Conceptual observation geometry for receiving HF signals above the ionosphere.

2. Scientific questions, application objectives and mission objectives

2.1. Scientific questions

SHFM is driven by four groups of scientific questions.

First, how do solar eruptions generate and transport shortwave radio emission through the corona and inner heliosphere? Type II radio bursts are associated with shocks, while type radio III bursts are produced by energetic electron beams. Their frequency drift reflects the ambient plasma density and the motion of the emitting source. The 0.3-30 MHz range corresponds to source regions extending from the outer solar corona into interplanetary space. Observations above the ionosphere can provide dynamic spectra, polarization information and, with a constellation, source direction and propagation signatures that are essential for space-weather interpretation^[1~3].

Second, how can planetary and possible exoplanetary radio emissions be used to diagnose magnetized plasma environments? Auroral radio emission is linked to the electron cyclotron frequency,

$$f_{ce} = \frac{eB}{2\pi m_e} \approx 2.8 \times 10^{10} \cdot B(\text{Hz}),$$

Where, f_{ce} is the electron cyclotron frequency, B is the magnetic field strength, with the unit being tesla (T), e is the elementary charge, and m_e represents the rest mass of the electron. The maximum emission frequency therefore constrains the source magnetic field. Solar-system planets (e.g. Jupiter, Saturn) emit strongly at low radio frequencies, and candidate exoplanetary emissions are expected to occur in or below the terrestrial shortwave window. A spaceborne receiver can search for polarized, periodic, beamed and bursty emissions under observing conditions unavailable to ground instruments.

Third, what does the low-frequency sky reveal about Galactic plasma and energetic particles? Dispersion, scattering, absorption and Faraday rotation are stronger at long wavelengths. Observations of the Galactic background, bright supernova remnants, pulsars and transient sources can therefore constrain electron density, magnetic fields, plasma turbulence and low-energy cosmic-ray populations. A pathfinder constellation will not replace a future lunar-farside or deep-space radio array, but it can measure the sky background, interference environment and calibration requirements needed to design for the observatory^[4].

Fourth, how do shortwave signals propagate upward through a realistic ionosphere? Existing propagation tools rely on ionosondes, Global Navigation Satellite System (GNSS) total electron content, empirical climatologies and ray-tracing^[12~19]. Spaceborne reception of controlled beacons and natural impulsive sources can directly measure frequency-dependent delay, amplitude fading, Doppler shift, polarization change and waveform dispersion along known or reconstructable paths. This provides a direct test of trans-ionospheric propagation models during quiet and disturbed conditions.

The four scientific questions driving SHFM can be generally summarized in Figure 3 below.

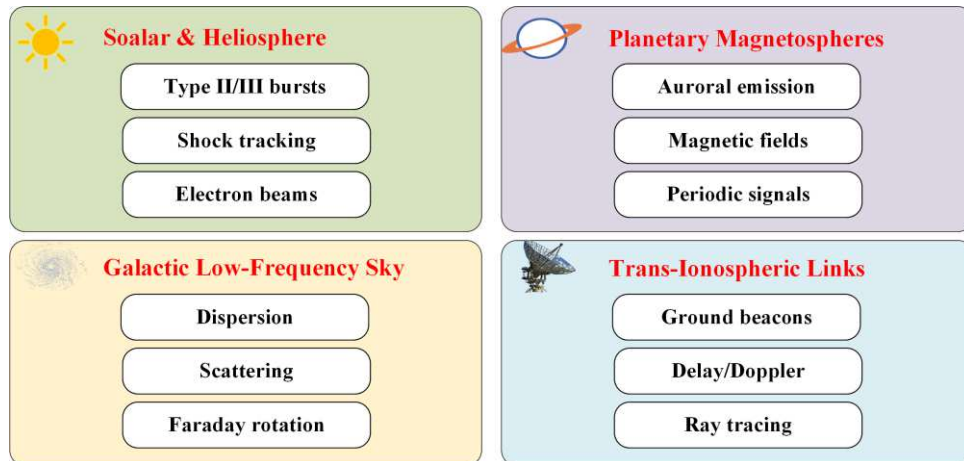


Figure 3. Scientific question map for the proposed spaceborne HF constellation.

2.2. Application value: monitoring HF radiation sources

Beyond the scientific objectives, SHFM can provide a new class of practical radio-environment data products. The HF band is used for long-distance communication, over-the-horizon sensing, ionospheric sounding, timing and frequency services, maritime and aviation communication, emergency communication and amateur radio. The same ionospheric propagation that makes these applications possible also makes the global HF environment difficult to characterize from the ground. A spaceborne constellation can observe the upward leakage of shortwave radiation over broad geographic regions and can build global maps of spectral occupancy, source occurrence, propagation conditions and interference events.

A multi-satellite HF array is particularly valuable because source monitoring is fundamentally a geometry problem. A single satellite can detect a signal and record its spectrum, but source localization requires directional information or multiple observing points. SHFM can combine several complementary methods: interferometric direction finding for far-field sources, time-difference and frequency-difference measurements for transient or narrowband emitters, multi-pass orbital geometry for source tracking, and adaptive beamforming or nulling for source separation^[39~49]. The objective is not merely to collect stronger spectra, but to convert spectra into geophysical and application-relevant information: where the radiation came from, how it propagated, how stable it was, and how it affected the surrounding HF environment.

The application products should be framed as civil and scientific services. They include global HF spectrum-environment maps, ionospheric propagation diagnostics, interference-source identification for scientific observations, support for emergency communication planning, space-weather nowcasting inputs, and validation data for HF propagation models. These products also feed back into the scientific mission because separating terrestrial sources from solar, planetary and Galactic signals is one of the core requirements for low-frequency radio astronomy from space.

In summary, SHFM can perform tasks such as orbit environment monitoring, detection of natural signal sources, and positioning of ground signal sources based on the observed (received) signals and the differences in the targets. The architecture relationship can be seen in the following Figure 4.

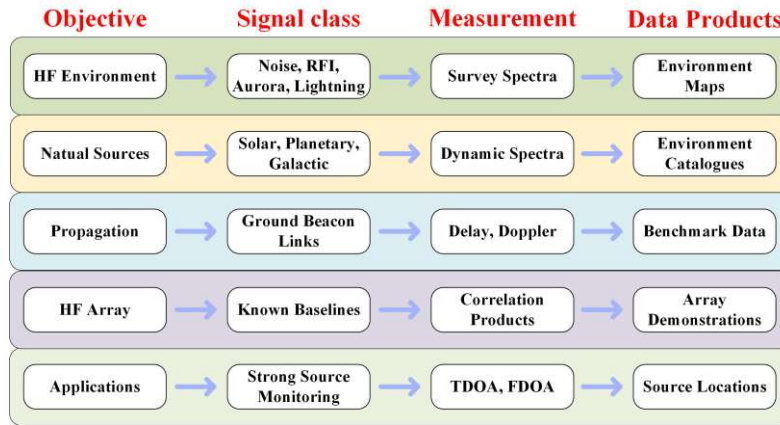


Figure 4. Relationship among application objectives, measurements, processing steps, and products.

2.3. Mission objectives

The core goal of SHFM is to build a calibrated spaceborne capability for receiving, interpreting and locating shortwave radio signals above the ionosphere. The mission objectives are as follows.

1. Characterize the orbital HF radio environment. The constellation will measure background noise, terrestrial radio-frequency interference, lightning-related transients, auroral emissions, spacecraft self-noise and their dependence on orbit, local time, geomagnetic latitude, attitude and space-weather conditions^[5~11,13~15,50~51].
2. Observe natural shortwave radio sources. The mission will monitor solar and heliospheric radio bursts, planetary emissions, bright Galactic sources, selected pulsars, supernova remnants and transient events. Initial products will emphasize dynamic spectra, event timing, polarization-sensitive measurements and source classification; later products will include direction finding and coarse imaging where geometry permits.
3. Validate trans-ionospheric propagation. SHFM will receive calibrated ground beacons, coordinated ionosonde and HF-radar transmissions, and natural impulsive sources such as lightning. The data will be compared with ionospheric models, GNSS total electron content, ionosonde measurements and ray-tracing results.
4. Demonstrate a spaceborne HF receiving array. Multiple satellites will operate as a controlled array with common timing, known baselines and calibrated receiver responses. The array will demonstrate coherent and non-coherent combination, source direction finding, adaptive interference rejection and sensitivity improvement.
5. Deliver application-ready HF radio-environment products. The mission will provide global spectrum occupancy maps, strong-source event lists, source-localization products where geometry and signal quality permit, and data products useful for space-weather and HF communication studies.

3. Measurement requirements, payload and key technologies

3.1. Measurement requirements

The baseline science band is 2-30 MHz, with an engineering goal to extend downward toward 0.3 MHz when the local plasma environment, antenna coupling and receiver noise permit. This range covers the main HF shortwave band and overlaps the upper medium-frequency regime important for ionospheric and solar radio studies. The payload should support continuous dynamic spectra, triggered waveform capture, multi-channel phase-coherent sampling, and calibrated field-strength estimation.

Table 1 connects the principal objectives to measurement methods and required payload functions.

Table 2. The Scientific goals in the SHFM system, along with their corresponding key question, measurement methods, and required payload functions

Scientific or application goal	Key question or objective	Measurement method	Required payload and system elements
Solar and heliospheric radio emission	How do shocks, coronal mass ejections (CMEs), and electron beams generate and transport from the corona to 1 AU?	Dynamic spectra, burst triggering, polarization-sensitive reception, multi-satellite direction finding, coordination with solar monitors	Deployable HF antenna, broadband receiver, digital spectrometer, precision timing, array processing
Planetary magnetospheres and exoplanet candidates	Can low-frequency radio emission constrain magnetic fields, rotation and star-planet interaction?	Long-duration monitoring, search for polarized periodic emissions, comparison with ephemerides, source-direction consistency checks	Low-noise receiver mode, vector or crossed-dipole reception, stable calibration, event classifier
Galactic plasma and low-frequency sky background	What are the spectra and variability of bright low-frequency sources above the ionosphere?	Sky-background survey, selected-source monitoring, dispersion/scattering analysis for bright impulsive sources	Calibrated antenna effective length, stable receiver gain, quiet observing modes, sky and interference catalogues
Ionospheric propagation	How do ground HF signals penetrate to orbit under realistic ionospheric conditions?	Reception of calibrated beacons and natural impulsive sources, delay and Doppler estimation, comparison with TEC, ionosonde and ray tracing	Ground-beacon coordination, waveform capture, accurate time tagging, propagation inversion pipeline
HF spectrum monitoring	Where are strong shortwave radiation sources, and how does the global HF environment vary?	Spectral occupancy mapping, source detection, TDOA (time difference of arrival)/FDOA (frequency difference of arrival), interferometric direction finding, multi-pass tracking	Constellation geometry, onboard classification, array processing, source-localization products
Future low-frequency observatory pathfinder	What architecture is needed for a science-grade spaceborne radio array?	Array calibration, coherent/non-coherent combining, RFI rejection, baseline and timing error analysis	Multi-satellite timing, inter-satellite calibration, orbit maintenance, ground correlation and beamforming

The mission should not over-constrain early implementation. In a first constellation phase, robust dynamic spectra and triggered waveform snippets may be more important than continuous full-band raw sampling. Raw wideband data should be captured only around high-value events, calibration passes

and selected array experiments. For routine survey operations, onboard channelization and event-driven data selection are required to keep downlink demand realistic.

The baseline science band of SHFM and the priority observables in the early implementation are shown in Figure 5.

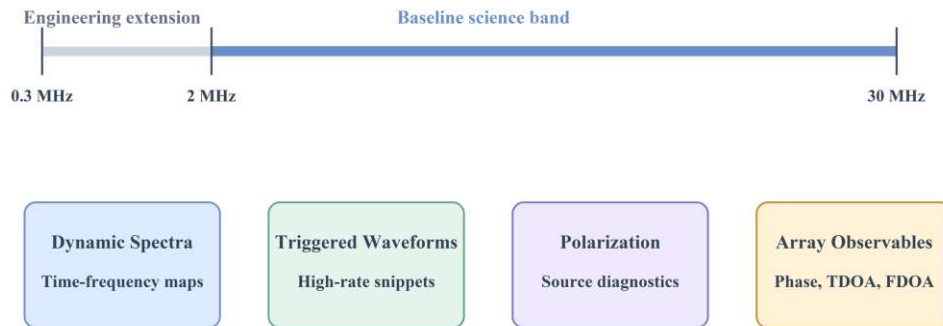


Figure 5. Baseline measurement requirement architecture and priority observables.

3.2. Key technologies and preliminary requirements

The SHFM system has five mission-driving technologies: the spaceborne HF antenna, the broadband receiver, onboard intelligent signal processing, constellation orbit maintenance and array reception. Table 2 summarizes the preliminary requirements.

Table 2. The mission-driving technologies in the SHFM system, along with their corresponding functions and preliminary requirements

Key technology	Function	Preliminary requirement or design driver
Spaceborne HF antenna	Couple 2-30 MHz fields into a small spacecraft receiver	Electrically short deployable dipoles or crossed monopoles; calibrated effective length; high-impedance preamplifier; stable impedance model in plasma; electromagnetic compatibility with spacecraft
Broadband HF receiver	Preserve weak natural signals while tolerating strong terrestrial signals	High dynamic range; selectable gain; low-noise front end; anti-alias filtering; multi-channel digitization; external-noise-limited performance where possible
Onboard intelligent signal processing	Convert wideband RF data into useful science and application products	Polyphase channelization, dynamic spectra, transient detection, RFI excision, source classification, adaptive compression, event-triggered waveform capture
Precision timing and calibration	Enable multi-satellite array reception and propagation measurements	GNSS-disciplined or space-qualified clock, inter-satellite time transfer where feasible, calibration tones, phase and gain tracking, baseline knowledge compatible with HF phase requirements
Orbit maintenance and formation control	Keep useful relative geometry for the in-orbit receiving array	Controlled baselines from several kilometers to hundreds of kilometers depending on phase; differential drag and/or low-thrust control; relative navigation; geometry planning for coverage and source localization
Array reception and source	Improve sensitivity, reject interference	Coherent beamforming when phase calibration is sufficient;

localization	and determine source direction	non-coherent combining for robust detection; cross-correlation; TDOA/FDOA; adaptive nulling; ground and onboard processing options
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Spaceborne HF antenna. The wavelength is about 10 m at 30 MHz, 100 m at 3 MHz and 1000 m at 0.3 MHz. A resonant antenna is impractical for most small spacecraft at the lower part of the band. The mission therefore uses electrically short receiving antennas, such as deployable tape-spring dipoles, crossed monopoles, tip-to-tip wire elements or compact vector-sensor geometries^[24,32~38,52]. For example, a simple and reliable deployment mechanism and hold-down and release mechanism (HDRM) may be adopted. The antenna is fabricated from lightweight tubing or wire, providing adequate shape-retention stiffness while minimizing mass. The deployment mechanism employs an integrated three-axis deployment unit featuring a simple structure, a high degree of integration, and ease of testing and ground verification. The HDRM uses a thermal-knife device, with a high-strength restraint cord securing the antenna to the support structure. After the satellite reaches orbit, the device is energized to sever the restraint cord, thereby releasing the antenna. The antenna HDRM uses a mature thermal-knife release design that offers low mass, compact construction, easy reset, and suitability for repeated ground testing.

A schematic of the antenna in its stowed and deployed configurations is shown in Figure 6 below. The antenna is not merely a mechanical appendage. It defines the effective length, polarization response, impedance, noise coupling, plasma sheath interaction and spacecraft scattering environment. Its calibration must combine ground measurements, electromagnetic simulation, in-orbit maneuvers, beacon reception and sky-background comparisons^[24,32~38,52].

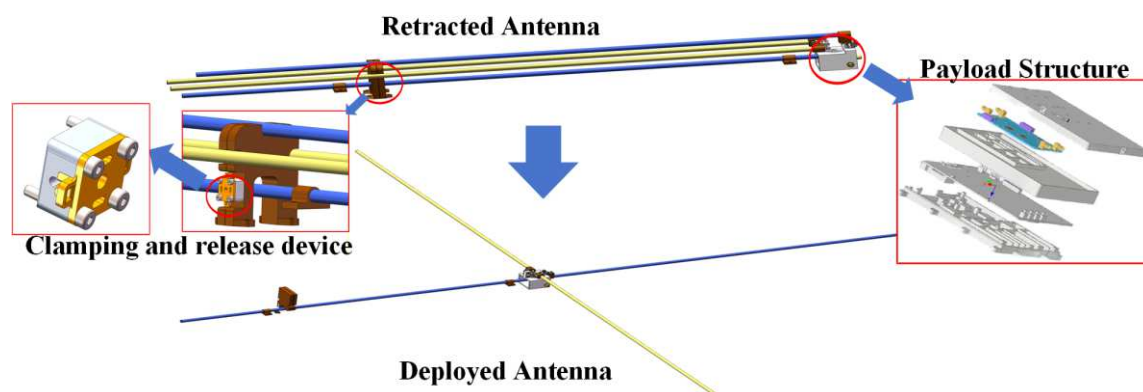


Figure 6. HF receiving antenna and payload design

Broadband receiver. The receiver must be linear and stable in an environment where strong terrestrial signals, lightning impulses and spacecraft self-emission may coexist with weak natural emissions. A conventional architecture includes high-impedance low-noise preamplifiers close to the antenna feed,

switchable gain and protection, band selection or direct sampling, high-resolution analog-to-digital conversion, and a digital back end. The receiver should support both survey spectra and high-rate waveform capture. Multi-channel synchronization is essential for crossed antennas, polarization analysis and array experiments^[30~35,38]. The key specifications of the antenna and wideband receiver are listed in Table 3 below.

Table 3. The key specifications of the antenna and wideband receiver

Parameter Category		Typical Value
Overall System	Frequency	Nominal: 2 MHz to 30 MHz If feasible: 0.3 MHz to 30 MHz
	Power Consumption	≤ 20 W
	Mass	≤ 2 kg
	Power Supply	28 VDC
Antenna	Mass	≤ 1 kg
	Dimensions	Stowed: 1.5 m $\times$ 10 cm $\times$ 3 cm Deployed: 3 m $\times$ 3 m $\times$ 3 cm
	VSWR	≤ 2.5
	Connector	SMA-K (female)
Receiver Payload	Mass	≤ 1 kg
	Dimensions	20 cm $\times$ 20 cm $\times$ 10 cm
Antenna HDRM	Mass	≤ 40 g
	Reliability	$R \geq 0.999$
	Dimensions	≤ 21 mm $\times$ 15 mm $\times$ 10 mm
	Response Time	≤ 6 s

Onboard intelligent signal processing. The HF band is data-rich and interference-rich. Continuous raw downlink from several satellites is not practical for routine operations. The payload therefore requires onboard processing that is scientifically transparent and calibratable. A polyphase filter bank or equivalent channelizer can form dynamic spectra. Burst detectors can trigger high-cadence modes for solar bursts, lightning, auroral events and unusual narrowband signals. Classification algorithms can separate natural bursts, ground transmitters, spacecraft interference and instrumental artifacts^[50~51]. Radio frequency interference (RFI) excision and adaptive compression should preserve calibrated measurement products rather than only reducing data volume.

Orbit maintenance and constellation geometry. The constellation is an instrument. Its baselines determine angular response, localization capability and array gain. In LEO, differential drag, J2 precession, atmospheric variability and station-keeping limitations must be part of the measurement design. The mission should maintain a controlled relative geometry rather than an uncontrolled

cluster[53~56]. For early operations, baselines of several kilometers to tens of kilometers are sufficient for time difference of arrival (TDOA)/frequency difference of arrival (FDOA) experiments, coarse direction finding and non-coherent combining^[39~49]. Longer baselines, from tens to hundreds of kilometers, improve angular resolution but demand stronger timing, ephemeris and calibration control. Position knowledge at the sub-meter to meter level and timing knowledge at the nanosecond to few-nanosecond level are desirable for coherent experiments in the upper HF band; less stringent knowledge is acceptable for non-coherent monitoring and many propagation products.

Array reception. For N similar satellites, coherent combination can in principle improve array sensitivity by about $10 \log_{10}(N)$ dB in power signal-to-noise ratio when phase calibration is adequate, while non-coherent combination provides a more robust but smaller gain. Cross-correlation among satellites provides source-direction information and can help distinguish far-field astronomical signals from near-Earth or spacecraft-local interference. Adaptive beamforming and nulling can suppress persistent terrestrial sources, improving the radio-quietness of selected observing modes. The mission should be designed so that array products can be generated both onboard for rapid event selection and on the ground for high-fidelity science analysis.

3.3. Calibration and data products

Calibration is the difference between detecting shortwave power and making a scientific measurement. SHFM requires instrument calibration, array calibration and propagation calibration.

Instrument calibration includes receiver gain, noise figure, linearity, antenna effective length, polarization response, spacecraft electromagnetic compatibility and temperature dependence. Internal calibration tones provide stability checks, but they cannot alone determine the incident free-space field. In-orbit calibration should use known transmitters, spacecraft attitude maneuvers, sky-background models and repeated observations over different geometries.

Array calibration includes clock offsets, phase delays, antenna orientation, baseline vectors, receiver gain mismatch and polarization leakage. The calibration products must be carried through the data pipeline so that users can distinguish raw spectra, calibrated field strength, direction-of-arrival estimates and source-localization products.

Propagation calibration uses coordinated ground beacons and independent ionospheric measurements. Where available, standard frequency stations, ionosondes, HF radars and dedicated beacon campaigns can provide controlled signals^[12~15,19]. GNSS electron total content (TEC), ionosonde profiles, magnetometer data and space-weather indices provide context. The goal is to create benchmark events in which the source, path, receiver geometry and ionospheric state are all constrained.

The mission will generate five data product families: (1) orbital HF radio-environment maps; (2) natural-source event catalogues for solar, planetary, Galactic and lightning-related signals; (3) calibrated ground-space propagation data sets; (4) source-monitoring and localization products for strong HF radiation sources; and (5) array-performance and calibration data needed for future low-frequency space observatories.

The three calibration steps described above and the generation of five products can be summarized as shown in Figure 7.

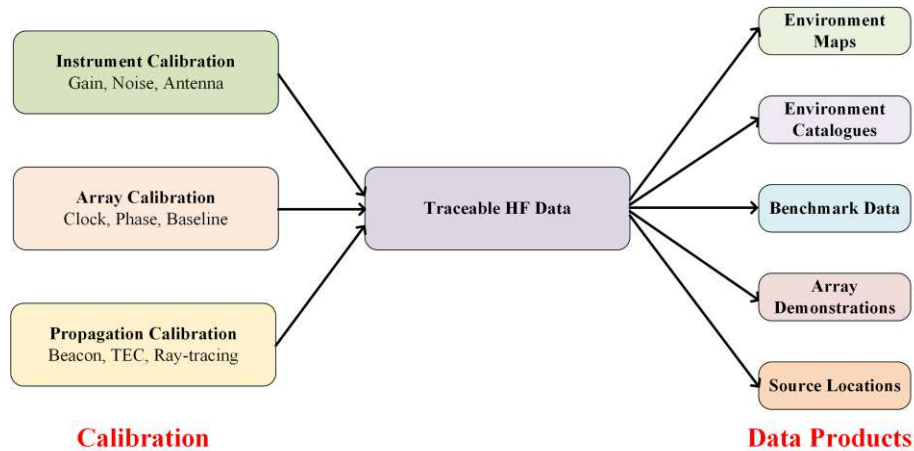


Figure 7. Calibration and data-product flow for traceable HF measurements.

4. Mission profile and constellation design

4.1. Orbit and constellation configuration

The baseline SHFM architecture is a multi-satellite constellation in low Earth orbit above the densest ionospheric layers. A high-inclination or near-polar orbit is attractive because it samples auroral regions, high-latitude propagation, a wide range of geomagnetic coordinates and global HF source distributions. A moderate altitude, for example several hundred kilometers to around 1000 km, balances mission lifetime, drag, radiation, GNSS availability, downlink and sensitivity to the topside ionosphere. Very-low-Earth orbit is valuable for in situ ionospheric studies but increases drag, atomic oxygen exposure, antenna-plasma coupling complexity and formation-maintenance demand.

The first constellation phase can consist of three to six satellites. Three satellites are the minimum for two-dimensional localization experiments with time-difference measurements under favorable geometry; four or more improve ambiguity resolution, array robustness and calibration^[39~49,53~56]. A later science phase can expand to 12 or more satellites, enabling better UV (ultraviolet wave) coverage, improved sensitivity, stronger RFI rejection and more persistent global monitoring. The constellation

may use multiple orbital planes or controlled along-track separations depending on whether the priority is global monitoring, interferometric coverage or coordinated beacon experiments.

The Constellation geometry and array-operation concept of the first stage of SHFM can be summarized as shown in Figure 8.

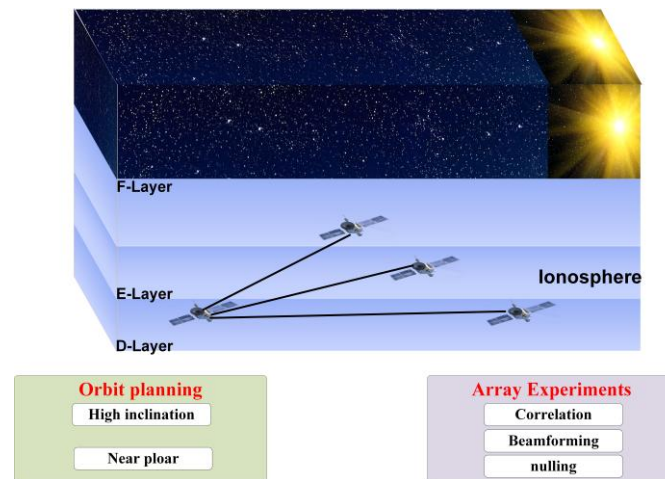


Figure 8. Constellation geometry and array-operation concept for LEO HF observations.

The mission should keep a clear growth path. The first phase demonstrates reception, calibration, source classification and limited array experiments. The second phase expands the number of spacecraft and baselines, improving direction finding and source separation. A future phase could move toward a low-Earth, cislunar or lunar-farside architecture for a truly radio-quiet low-frequency observatory.

4.2. Observing modes

SHFM should operate in several modes.

In survey mode, it continuously measures the orbital HF environment with moderate time-frequency resolution. This mode produces spectral occupancy maps, noise statistics, spacecraft self-noise diagnostics and global interference products.

In solar and space-weather mode, the cadence and burst-trigger sensitivity increase when solar activity is enhanced. This mode records dynamic spectra and waveform snippets for type II, type III and complex solar radio bursts and supports rapid event reporting^[1~3].

In planetary and deep-space mode, long integrations are scheduled when the spacecraft geometry points away from Earth-limb interference or when planetary ephemerides are favorable. This mode emphasizes stable calibration, low-noise operation and rejection of terrestrial leakage.

In ground-beacon and ionospheric mode, it records known transmitters, ionosondes, HF radars and coordinated beacon campaigns^[12~15,19]. It stores phase, delay, Doppler, amplitude and polarization-sensitive products for propagation inversion.

Source-monitoring mode detects and tracks strong HF radiation sources. It uses onboard classifiers to flag persistent narrowband emitters, impulsive sources and anomalous events, then schedules high-rate capture or multi-satellite correlation when the geometry is favorable^[5~11,50~51].

Array experiment mode activates phase-coherent or correlation processing among satellites^[39~49]. This mode is used for beamforming, nulling, TDOA/FDOA localization, inter-satellite calibration and demonstrations of array gain.

Notably, for ground-beacon and ionospheric mode, source-monitoring mode and array experiment mode, ground-based signals propagate upward and are received by satellites. However, not all ground-based signals can be received by satellites. For example, as shown in Figure 9 below, shows the HF signals transmitted from Wuhan (30.35N, 114.17E) on June 20, 2026 (red dots indicate the transmitting points) and the regions at satellite altitude where the signals can be received by satellites (blue regions). It can be seen that satellites may receive more HF signals from the ground at night and are more likely to receive HF signals. This is because a signal can penetrate the ionosphere and then be received by a satellite only when its frequency is higher than the critical frequency of the ionospheric F2 layer. Moreover, the daytime critical frequency of the ionospheric F2 layer is higher than that at night.

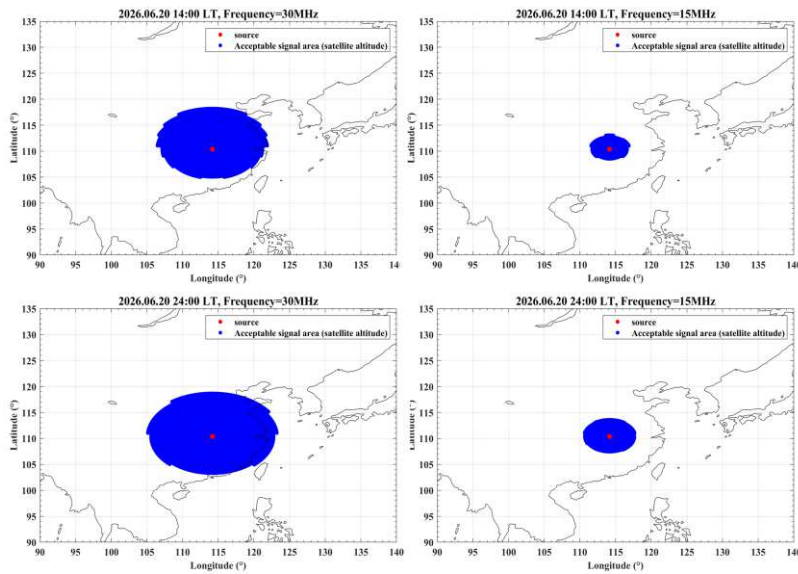


Figure 9. HF signals transmitted from Wuhan (30.35° N, 114.17° E) on June 20, 2026 (red dots indicate the transmitting points) and the regions at satellite altitude where the signals can be received by satellites (blue regions). 14:00 LT, 30 MHz transmitting frequency (upper left panel); 14:00 LT, 15 MHz transmitting frequency (upper right

panel); 24:00 LT, 30 MHz transmitting frequency (lower left panel); 24:00 LT, 15 MHz transmitting frequency (lower right panel).

4.3. Orbit maintenance, timing and in-orbit array operation

The orbit-control system must be treated as part of the radio instrument. For ordinary spectrum monitoring, precise absolute formation is less critical; for coherent reception, direction finding and interferometry, baseline knowledge and time synchronization directly set measurement quality^[39~49,56]. The constellation should therefore include relative navigation, orbit prediction, maneuver planning and formation-health assessment as mission-level data products.

A practical approach is staged. During commissioning, satellites fly in a safe separated configuration and perform individual antenna deployment, self-noise surveys and receiver calibration. After the single-spacecraft performance is understood, the constellation enters controlled relative-orbit operations. Differential drag can provide propellant-efficient along-track spacing in low orbit, while small propulsion systems improve reconfiguration, collision avoidance and long-term baseline maintenance. Inter-satellite links are scientifically useful but not mandatory for all products; where they are not available, precise time tagging and ground correlation can still provide high-value array measurements.

Timing is equally important. HF periods range from about 33 ns at 30 MHz to 333 ns at 3 MHz. Coherent combination at the upper end of the band therefore benefits from nanosecond-class time knowledge after calibration. This requirement can be met through a combination of stable onboard oscillators, GNSS timing, inter-satellite time transfer where available, calibration transmitters and post-processing corrections. The mission should also include a non-coherent processing path so that useful science and monitoring products are available even when phase coherence is not maintained.

4.4. Development approach

The development should proceed through four steps, as shown in Figure 10..

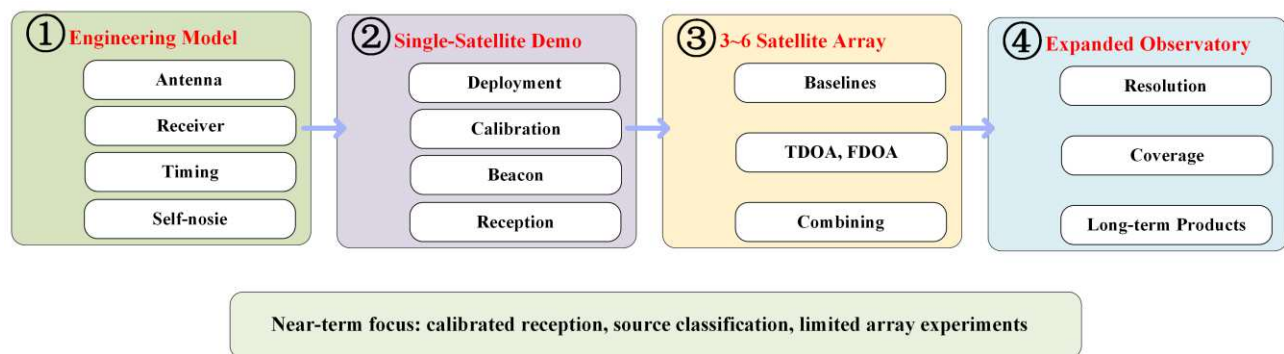


Figure 10. Staged development roadmap from engineering model to expanded constellation.

The first step is an engineering model that validates the antenna, receiver, channelizer, timing chain and self-noise control on the ground. This step should include plasma-coupled antenna simulation, anechoic and open-site antenna measurements, receiver linearity tests with strong-signal scenarios, and end-to-end digital processing tests using recorded HF environments.

The second step is a single-satellite or hosted-payload demonstration. Its goals are antenna deployment, receiver calibration, orbital HF environment measurement, ground-beacon reception and onboard event detection. Even one satellite can produce valuable radio-environment and propagation data.

The third step is a three-to-six-satellite array demonstration. The constellation diagram and the ground coverage area by the satellites are shown in Figure 11. This phase establishes relative timing, baseline calibration, TDOA/FDOA localization, non-coherent and coherent combining, and adaptive source separation. It is the critical step that turns SHFM from a receiver mission into an in-orbit array mission.

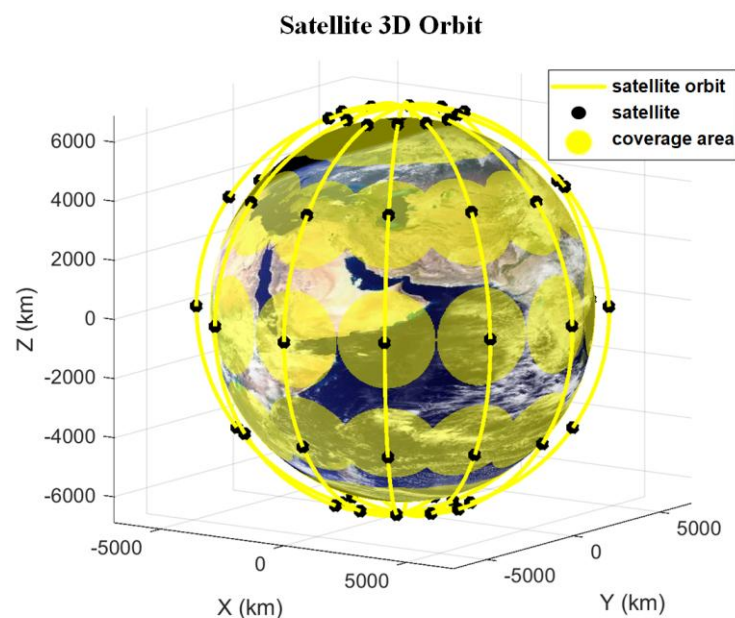


Figure 11. three-to-six-satellite array performs tasks such as relative timing, baseline calibration, TDOA/FDOA localization.

The fourth step is an expanded constellation or future observatory. The constellation diagram and the ground coverage area by the satellites are shown in Figure 12. The expanded system would provide better angular resolution, stronger array gain, more complete sky and Earth coverage, and a clearer path toward spaceborne low-frequency imaging^[20~27].

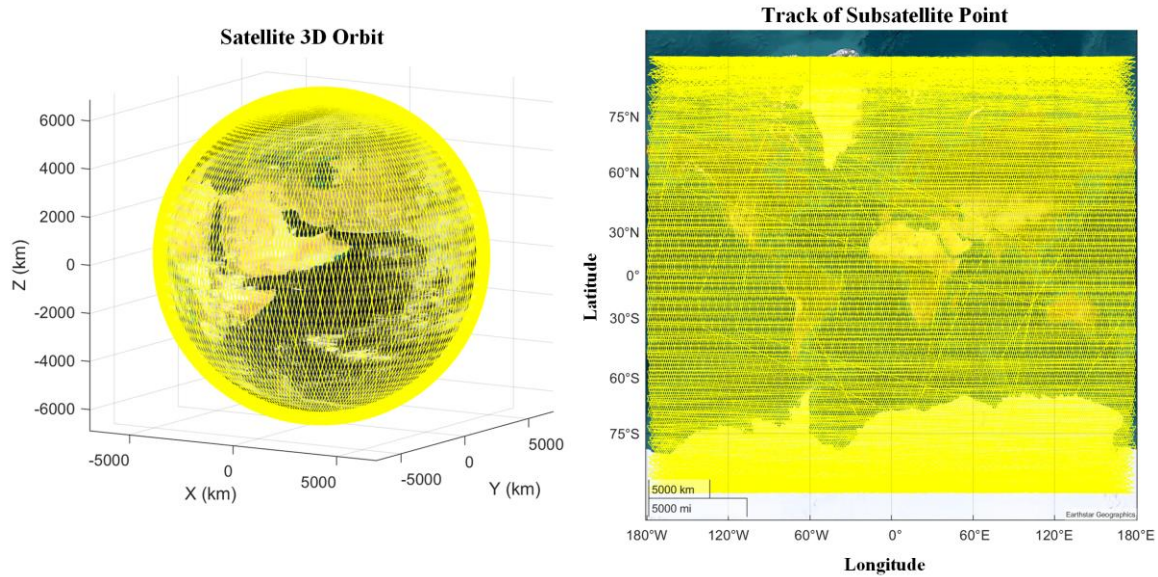


Figure 12. 20-satellite array achieves complete sky and Earth coverage, with a 3D orbital schematic on the left panel and sub-satellite tracks on the right panel.

5. Summary

SHFM is a mission concept for opening the shortwave radio window above the ionosphere with a technically mature and scalable architecture. It combines conventional deployable HF antennas, broadband low-noise receivers, multi-channel synchronized digitization, onboard intelligent processing and a controlled satellite constellation. Designed to serve both science and applications, the SHFM observes natural low-frequency radio sources, measures trans-ionospheric radio wave propagation, characterizes the orbital HF environment, and monitors strong shortwave radiation sources from space.

The essential innovation is system-level. A single spacecraft can detect shortwave signals, but a constellation can form a receiving array. With multiple satellites, SHFM can improve sensitivity, separate sources, estimate direction, reject interference and build calibrated data products that are directly useful for future low-frequency radio astronomy. Orbit maintenance, timing, antenna calibration and onboard processing are therefore not supporting details; they are the core enabling technologies of the mission.

The near-term mission should focus on four deliverables: a calibrated orbital HF radio-environment atlas, a catalogue of solar and natural radio events, benchmark data sets for upward HF propagation through the ionosphere, and a demonstration of multi-satellite HF array reception. These deliverables would establish the knowledge and technology foundation for future larger spaceborne low-frequency arrays, including high-Orbit, cislunar and lunar-farside observatories^[2~4,20~27,53~55].

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The authors declare no conflicts of interest.

Reporting standards and availability of data, materials, code and protocols:

This article does not produce any products such as data, algorithms, or codes.

Ethics and Biosecurity

This research does not involve any issues related to biological experiments or ethics.

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