Next Generation Electromagnetic Measurement Instruments

Engineering Development and Validation Plan

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Reference proposal supporting the National Electromagnetic Monitoring Plan
Proposing organization EFEIA Foundation
Development horizon 24 months
Reference version 1.0

Executive Summary

EFEIA Foundation proposes a modular instrument development program to resolve specific gaps between routine electromagnetic surveys and the detailed physical characterization of real exposure. The program translates Joaquin Machado's article Radiofrequency micro-peaks, dynamic 5G, and the limits of regulatory measurement into an engineering architecture, measurable requirements, construction work packages, and independent validation. [1]

The central requirement is to preserve information that may be lost through slow display updates, long averaging intervals, sequential frequency sweeps, incomplete field sensing, or undocumented assumptions. The platform would capture short events, retain calibrated waveforms, measure electric and magnetic fields separately where necessary, map spatial variation, and report its own detection limits.

The proposed system combines a low-frequency electric and magnetic field module, frequency-selective RF receivers, a fast event recorder, high-GHz receiver heads, a research module for coherent vector measurements, and a common data and calibration framework. It is a family of instruments rather than a single universal probe.

Existing real-time analyzers already capture many transients. The proposed contribution is an exposure-focused, calibrated integration of these capabilities with field probes, spatial information, event retention, and independently tested performance. Any claim of novelty would require a separate technical and intellectual-property review. [2]

The initial 24-month cycle would deliver a validated core prototype and a first engineering report. Advanced vector and high-GHz capabilities would progress through separate feasibility gates. The program would not promise simultaneous, phase-coherent coverage of the entire spectrum.

All numerical specifications in this proposal are preliminary engineering targets, not demonstrated performance or health thresholds. They would be frozen, revised, or rejected through design review and testing. Greater measurement detail supports research; it does not establish that a detected micro-peak causes biological harm.

1 Measurement Problem and Design Basis

The source article identifies three distinct tasks: assessing compliance, characterizing physical exposure, and testing clinical hypotheses. This development program addresses the second task while retaining measurements useful for the other two. The article is a critical narrative analysis, not an original instrument-validation dataset. [1]

The program must preserve the article's correction that ICNIRP 2020 includes brief-exposure restrictions. It would therefore be inaccurate to claim that all standards disregard pulses. The gap must be demonstrated for a particular instrument, acquisition mode, averaging window, and retained dataset. IEC 62232 supplies assessment methods; it is not itself a set of exposure limits. [3, 4]

Information gap	Engineering response
Long averages conceal event structure	Retain waveforms and event summaries alongside averages at explicitly stated windows.
Sweeps and acquisition gaps miss events	Use continuous acquisition within declared instantaneous bands; record retuning and dropped-data intervals.
Electric field substituted for full field state	Measure E and H separately; permit vector power-flow calculations only in a validated coherent mode.
Spatial variation reduced to one reading	Use calibrated small probes, documented effective sensing volume, and repeatable spatial mapping.
Traffic and beam conditions unknown	Time-stamp measurements and distinguish passive observation from authorized controlled traffic.
Peaks lack measurement context	Attach bandwidth, detector, calibration, clipping, noise, and detection-confidence metadata to each event.

2 Operational Definition of a Micro Peak

A micro-peak is an operational event descriptor, not a recognized health endpoint or an assumed microsecond duration. Each study must define the measured quantity, analysis bandwidth, envelope or RMS window, amplitude threshold, minimum duration, hysteresis, and event-merging rule.

The system would distinguish an RF carrier-cycle maximum, a channel-envelope peak, a short-window RMS maximum, and a maximum across a long observation interval. These are different quantities. A peak without its bandwidth and time definition would not be an acceptable reportable result.

3 Modular System Architecture

Module	Construction scope and outputs
A Low-frequency fields	Separate triaxial electric and magnetic sensors, low-noise conditioning, anti-alias filtering, simultaneous digitization, harmonics and transient recording.
B RF survey and selection	Calibrated field probes or antennas, preselection filters, protected dual-gain inputs, tunable receiver paths, and spectrum identification.
C Fast event recorder	FPGA processing, circular memory, multilevel triggers, raw IQ retention, event counters, and explicit acquisition-gap accounting.
D High-GHz heads	Band-specific antennas and frequency converters with individual amplitude, polarization, pattern, and timing calibration.
E Coherent vector research	Six synchronized field components within a validated sub-band; probe geometry correction and phase calibration for E and H reconstruction.
F Spatial and timing unit	Position and orientation recording, calibrated probe fixtures, common clock distribution, and synchronized mapping nodes.
G Data and metrology software	Calibration registry, uncertainty propagation, event replay, interoperable export, audit records, and reproducible analysis.

Measurement chain: field sensor → protection and filtering → calibrated gain or frequency conversion → synchronized digitizer → continuous processing and circular buffer → event and background archive → analysis and reporting.

The fast recorder would integrate established receiver and digitizer technology first. Custom development would focus on probes, synchronization, event retention, calibration transfer, field deployment, and software integration. A fully custom wideband RF chipset is outside the initial scope.

4 Proposed Frequency Coverage

The core low-frequency module would target 1 Hz to 100 kHz. A separate RF receiver path would target 9 kHz to 6 GHz, providing an overlap for cross-checking. LF phase and amplitude performance would be specified by sub-band rather than assumed uniform.

Optional receiver heads would address 6–18 GHz and 18–40 GHz. A 40–110 GHz research extension would cover selected validated sub-bands only. Frequencies above 110 GHz would remain outside the first program unless separately approved and resourced. Nominal tuning range would never be represented as simultaneous acquisition bandwidth.

The coverage register would distinguish calibrated, characterized but unqualified, and unmeasured ranges, including filter transitions and antenna limitations. Static fields below the 1 Hz core limit would require a separate sensor module.

5 Temporal Capture and Event Retention

The initial fast RF path would target at least 200 MHz of usable instantaneous complex bandwidth and approximately 250 MS/s complex sampling per active channel. Usable bandwidth must be verified after filtering and equalization; an ADC sample rate alone is not proof of flat response or transient fidelity.

A standard acceptance waveform would be a 1 µs RF-envelope burst within the qualified passband, at least 20 dB above the integrated noise level and at least 6 dB below measured compression. Proposed targets are at least 99% probability of intercept, with a one-sided 95% confidence lower bound, and peak-envelope amplitude error within 1 dB relative to a calibrated reference under the stated test conditions.

These targets apply only to qualified waveforms, settings, and bands. Performance for shorter bursts, weak signals, passband edges, overlapping signals, and high-GHz converter modes would be measured separately. The system would not infer a universal 1 µs capability from a single successful demonstration.

A continuously updated circular buffer would retain nominally 1 ms before and 9 ms after a trigger, with configurable windows. Trigger classes would include amplitude, rate of change, spectral occupancy, and externally synchronized events. Rate-of-change triggers would use a stated smoothing bandwidth to avoid treating noise as a physical transient.

Continuous background summaries and randomized waveform captures would accompany triggered data to reduce selection bias. Under high event rates, the system would record buffer occupancy, discarded-event counts, and loss intervals. A saturated recorder must not report an apparently quiet environment.

6 Quantities and Analysis Windows

- Retain field units such as V/m and A/m, or magnetic flux density in tesla, before any power-density conversion.
- Report channel-envelope peaks, short-window RMS, duty cycle, event duration, repetition intervals, rise and fall times, and crest factor with explicit definitions.
- Provide optional analysis windows such as 1 µs, 10 µs, 100 µs, 1 ms, 10 ms, and 1 s, plus longer study or compliance windows where applicable.
- Flag a window as unsupported when analog response, filtering, signal-to-noise ratio, or capture duration cannot support it.
- Treat measured modulation features as physical descriptors. Do not automatically assign biological weights to them.

Time resolution of a downconverted envelope must not be confused with direct digitization of a tens-of-GHz carrier. Converter response, local-oscillator stability, image rejection, and bandwidth are part of the measurement model.

7 Electric and Magnetic Field Reconstruction

The core platform would report electric and magnetic fields separately whenever the field regime or source geometry does not justify a plane-wave approximation. A value derived from E alone using a free-space impedance assumption would be labeled equivalent plane-wave power density, with the assumption displayed.

The vector research module would target simultaneous Ex, Ey, Ez, Hx, Hy, and Hz acquisition within an initial selected sub-band between approximately 0.7 and 6 GHz, using a narrower qualified bandwidth such as 20 MHz. This is a feasibility target, not a promise of six-component coherence across the full tuning range.

Active power-flow reconstruction requires relative amplitude, relative phase, orientation, and effective spatial co-location. Three electric-field magnitudes and three magnetic-field magnitudes are insufficient. Sequentially multiplexed axes cannot establish instantaneous vector relationships for an arbitrary transient.

The research workflow would use complex field components with an explicit RMS phasor convention. Mean active flux is the real part of the complex E cross conjugate-H product; peak-amplitude phasors require a factor of one half. Broadband transient calculations require adequately aligned waveform reconstruction, not one phasor for the entire signal. [1]

Probe separation and coupling can produce significant errors near sources and in steep gradients. Small electric probes and magnetic loops would be evaluated in controlled fields; optical or isolated links would reduce cable perturbation. Corrections would be limited to geometries for which validation supports them.

8 Phase and Timing Performance

A proposed vector-mode target is residual interchannel phase error within 5 degrees under a specified reference-field test, with uncertainty and frequency dependence reported. At 6 GHz, 5 degrees corresponds to approximately 2.3 ps of equivalent delay. This illustrates the calibration challenge; ordinary network time synchronization cannot establish RF phase coherence.

Coherent channels would share a reference oscillator, local-oscillator architecture where required, and repeatable calibration of channel delay and phase. Acquisition would stop being labeled coherent if drift or calibration status exceeded the qualified limits.

For cross-site event association, a separate target is timestamp alignment within 100 ns under validated synchronization conditions. Clock lock, uncertainty, holdover, and synchronization loss would be logged. Cross-site timestamps support temporal association, not phase-based E/H reconstruction.

9 Spatial Mapping and Dynamic Network Context

Spatial surveys would record probe position, orientation, sensing volume, nearby surfaces, source distance where known, and operator placement. Measurement height and grid spacing would be selected from the anticipated field gradients and probe response rather than fixed nationally without validation.

At 40 GHz the free-space wavelength is approximately 7.5 mm. Millimeter-scale structure may therefore require laboratory positioning and very small probes. A handheld survey or a large probe cannot claim to resolve arbitrary millimeter-scale exposure variation. Spatial resolution would be an independently verified specification.

Sequential scans confound changes over space with changes over time. Controlled mapping would use stable or repeatable source conditions; field mapping would include a stationary reference sensor or synchronized nodes. Residual ambiguity would be retained in the report.

For beamforming and TDD systems, passive ambient observation and authorized induced-traffic sessions would be labeled separately. Available metadata could include channel, bandwidth, timing structure, traffic-test schedule, and observation point. A received burst alone would not prove its source identity or technology.

10 Storage and Data Architecture

At 250 MS/s, 16-bit I plus 16-bit Q requires approximately 1 GB/s per channel. Six such channels would produce 6 GB/s, or 21.6 TB per hour, before file and metadata overhead. A 10 ms six-channel capture would require approximately 60 MB. These are illustrative uncompressed payload calculations, not a claim that every mode runs at that rate.

The platform would therefore combine continuous summaries, event buffers, configurable raw captures, and laboratory streaming. The narrower vector mode would have its own throughput budget. Data-rate limits would be measured end to end, including storage stalls and concurrent processing.

Each event would retain a unique identifier; UTC and monotonic timestamps; raw sample links; active frequency range; sample rate; filters; gain path; probe and calibration identifiers; position and orientation; noise estimate; trigger settings; clipping and loss flags; uncertainty; and processing version.

Raw arrays and metadata would use documented formats such as HDF5 or Zarr with a published schema. Calibration corrections would remain reversible and original samples immutable. Payload demodulation would not be required; raw IQ handling would follow access, retention, and applicable legal requirements.

Research outputs would distinguish direct measurements, corrected measurements, model-derived quantities, and unresolved intervals. No automated dashboard would translate a micro-peak into a health-risk score without separate scientific validation.

11 Calibration and Measurement Uncertainty

A calibration plan would cover probes, antennas, cables, converters, filters, amplifiers, digitizers, timing references, and software. Traceability would be established through qualified laboratories and appropriate reference fields. Uncertainty evaluation would follow the JCGM framework. [5]

Controlled tests would use suitable field cells, coils, chambers, reference antennas, calibrated generators, pulse or vector signal generators, power references, oscilloscopes, and network analysis. Each apparatus would be used only within its validated frequency and field regime.

The uncertainty budget would include amplitude and phase response, isotropy, polarization, mismatch, sensor positioning, probe perturbation, finite sensing volume, temperature, noise, quantization, compression, aliasing, filtering, timing drift, and repeatability. Correlations among channels would be considered in vector calculations.

Separate budgets would apply to CW amplitude, burst peaks, RMS windows, duration, integrated incident energy where valid, and derived active flux. A single uncertainty number would not be attached indiscriminately to all quantities. Expanded uncertainty would state coverage factor and interpretation.

12 Preliminary Qualification Targets

Parameter	Proposed target and reporting condition
RF burst amplitude	Error within 1 dB for the qualified 1 µs reference burst; specify reference uncertainty and applicable settings.
Calibrated field amplitude	Expanded uncertainty goal no greater than 3 dB in qualified core bands; revise by sub-band if unsupported.
Event capture	At least 99% POI with a one-sided 95% confidence lower bound for a predefined burst population and operating mode.
Dynamic range	At least 60 dB usable in a stated fixed configuration; report spur-free performance, noise floor, compression, and gain-switch blind intervals separately.
LF acquisition	At least 500 kS/s per simultaneous real channel for the proposed 100 kHz passband, subject to measured anti-alias performance.
Clock and vector modes	Cross-site timestamp target within 100 ns; local vector phase target within 5 degrees in a qualified sub-band. These are separate specifications.

Every target must have a test method, operating conditions, uncertainty budget, and disposition. Specifications that fail qualification would be narrowed or withdrawn rather than hidden through averaging.

13 Validation Experiments and Acceptance Gates

Validation would compare the integrated prototype with calibrated reference equipment and with a representative conventional survey workflow. This comparison would establish what information the new workflow retains beyond a particular existing configuration, not claim that all existing instruments miss the same events.

Test	Acceptance evidence
Short-event interception	At least 1,000 randomized bursts per representative test condition; exact binomial confidence analysis; amplitude error and missed-event logs. Increase sample size or narrow claims if needed.
Peak and average separation	Equal-average signals with different burst structure; reproduce average within uncertainty and distinguish peak, duty cycle, and duration without conflation.
Overload and interference	Strong adjacent signals, impulsive interference, and overload recovery; identify clipping, compression, false events, and unusable intervals.
Vector reconstruction	Known traveling-wave and controlled reactive-field cases; compare component phase and active flux against reference or validated models with uncertainties.
Spatial resolution	Controlled gradients and repeatable position scans; quantify smoothing, probe-volume effects, repeatability, and temporal ambiguity.
Sustained field operation	72-hour recording per qualified deployment configuration; reconcile expected and recorded data, losses, thermal drift, clock status, and storage load.
Independent replication	A second laboratory repeats selected qualification tests using frozen firmware, calibration files, raw data, and published analysis.

The reference-burst tests would randomize arrival relative to processing cycles and include high event-rate stress. POI would mean successful retained capture, not merely a transient appearing on a display. False-trigger rates would be measured in terminated-input, controlled-noise, and live-field conditions.

For a claimed absence of events, reporting must state the frequency coverage, monitoring duration, threshold, qualified pulse duration, and acquisition uptime. Non-detection outside these conditions would remain unresolved.

14 Construction Work Packages

WP1 Requirements and metrology. Freeze use cases, gap matrix, measurands, benchmark methods, numerical target conditions, and safety requirements. Produce a requirements-to-test register and reference signal library.

WP2 Sensors and analog electronics. Select or develop LF sensors and RF probes; design shielding, protection, filters, calibrated gain paths, converter interfaces, and mechanical fixtures. Characterize self-emissions and field perturbation.

WP3 Acquisition and firmware. Integrate synchronized digitizers and FPGA processing; implement circular buffers, triggers, loss counters, timestamps, and streaming. Verify operation under worst-case input and storage load.

WP4 Calibration and vector feasibility. Establish correction models, uncertainty budgets, automated test fixtures, and the phase-coherent sub-band demonstrator. Decide whether vector power-flow reporting is supportable.

WP5 Software and reporting. Build acquisition control, calibration registry, waveform replay, multiscale analysis, spatial registration, machine-readable export, and a report that separates measured and inferred quantities.

WP6 System integration and qualification. Assemble engineering units, assess environmental and electrical performance, test reference waveforms, and commission independent laboratory replication.

WP7 Field pilot and transfer. Deploy qualified units in consenting research settings; compare workflows; document usability and maintenance; release the engineering report, manufacturing package, and transfer recommendations.

15 Team and Build Strategy

The program requires a technical lead, RF and antenna engineers, analog and LF instrumentation expertise, FPGA and embedded developers, data-software engineers, a metrologist, a mechanical designer, a field lead, and independent test partners. Clinical collaborators would advise on research interfaces rather than set unvalidated instrument risk thresholds.

Procurement would favor characterized commercial receiver, digitizer, timing, and compute components where they meet requirements. Custom parts would be justified by an unresolved measurement need. The build package would include schematics, PCB files, bill of materials, mechanical drawings, source and firmware versions, test fixtures, calibration procedures, and service documentation.

Electrical safety, battery protection, electromagnetic compatibility, and enclosure requirements would be assigned according to the actual use environment. The proposal does not classify the platform as a diagnostic medical device or certify it as a regulatory compliance instrument.

16 Development Schedule and Monitoring Integration

Period	Engineering milestone	Release gate
Months 1–3	Requirements, current-tool benchmark, architecture, procurement plan	Approve testable scope and initial cost baseline.
Months 4–6	Bench integration and initial probes; protocol interface	Core receiver and recorder feasibility demonstrated.
Months 7–12	Alpha core units, triggers, LF module, calibration work	Qualified bands may enter a supervised research pilot.
Months 13–18	Beta hardware; high-GHz and vector feasibility decisions	Core performance verified; advanced modes qualified separately.
Months 19–21	Independent laboratory tests and corrected release candidate	Close major measurement failures or restrict specifications.
Months 22–24	Engineering report, manufacturing transfer, field lessons	Publish validated performance, limitations, and next-stage plan.

The National Monitoring Plan has six months of preparation, twelve months of monitoring, and six months of analysis. It cannot depend on a new instrument that will only be fully qualified at Month 24. Early monitoring must use calibrated existing equipment, with prototype measurements introduced only after the applicable gate.

Prototype records would identify hardware, firmware, calibration, and coverage changes. Measurements from different generations would not be pooled as a continuous trend without comparability tests. The first engineering report and the first monitoring report can be coordinated, while their evidentiary scopes remain distinct.

17 Funding and Procurement Basis

Funding would be released by milestone. The initial cost model would separately identify personnel effort, commercial receivers and digitizers, custom sensors, prototype fabrication, high-GHz converters, laboratory access, calibration, software and storage, field operations, independent replication, manufacturing transfer, and contingency.

A credible total requires supplier quotations, laboratory rates, staffing effort, and design choices from WP1. This proposal therefore establishes a budgeting method rather than an unsupported dollar estimate. Advanced vector and 40–110 GHz work would have optional budgets so that unresolved feasibility does not prevent delivery of the core platform.

The build-versus-buy review would compare acquisition cost, calibration burden, supportability, openness, and proven performance. Production unit cost would be estimated after the prototype bill of materials and assembly process are stable.

18 Technical Risks and Decision Rules

Risk	Mitigation and decision
Wide tuning range mistaken for continuous coverage	Publish an active-band map; use parallel paths only where funded and qualified; disclose retuning gaps.
False or distorted micro-peaks	Test overload, ringing, aliasing, trigger artifacts, and noise; retain raw evidence and reject invalid events.
Vector sensing cannot meet phase or spatial accuracy	Restrict to qualified sub-bands and geometries; otherwise report E and H separately and disable active-flux output.
High-GHz sensitivity or calibration is inadequate	Narrow to validated bands; report detection limits and angular response; defer unsupported extensions.
Data volume overwhelms capture	Use circular buffers and loss accounting; stress-test event storms; publish discarded-event statistics.
Prototype self-emissions alter the measurement	Use separation, shielding, optical links, battery tests, and powered versus unpowered background comparisons.
A physical event is presented as a health conclusion	Keep waveform characterization separate from clinical research and regulatory interpretation.

19 Deliverables and Final Acceptance

- A validated core instrument configuration and a register of qualified optional modes.
- A benchmark report showing retained and missed information under defined conventional and new workflows.
- A calibration and uncertainty dossier with independent replication results.
- An open event schema, reference waveform library, and reproducible analysis package.
- A construction and maintenance package sufficient for authorized manufacturing transfer.
- A field-pilot report documenting reliability, limitations, and integration with national monitoring.
- A first engineering report by Month 24, including unresolved requirements and an evidence-based continuation decision.

The program succeeds when it demonstrates additional, reproducible measurement capability under defined conditions and makes residual blind spots explicit. It would replace unsupported inference with retained physical evidence wherever the validated architecture permits, while identifying what still cannot be measured reliably.

References and Technical Basis

The source article establishes the proposed research problem. External sources below support selected technical capabilities, standards context, and metrology practice. They do not validate this proposed instrument. Numerical targets, architecture, and schedule are engineering proposals requiring review and testing.

[1] Machado J. Radiofrequency micro-peaks, dynamic 5G, and the limits of regulatory measurement. User-supplied reference manuscript, RF_article_en_rebuilt_verified.docx. No publication date stated in the supplied manuscript.

[2] Keysight Technologies. Real-Time Spectrum Analyzers. Existing real-time acquisition capabilities and configuration-dependent probability of intercept. https://www.keysight.com/es/en/products/spectrum-analyzers-signal-analyzers/real-time-spectrum-analyzers.html

[3] ICNIRP. Guidelines for Limiting Exposure to Electromagnetic Fields 100 kHz to 300 GHz. Health Physics. 2020;118(5):483–524. https://www.icnirp.org/cms/upload/publications/ICNIRPrfgdl2020.pdf

[4] IEC. IEC 62232:2025. Determination of RF field strength, power density and SAR in the vicinity of base stations for the purpose of evaluating human exposure. Official catalogue summary. https://webstore.iec.ch/en/publication/89073

[5] JCGM. Evaluation of measurement data Guide to the expression of uncertainty in measurement. JCGM 100:2008. BIPM publications and associated supplements. https://www.bipm.org/en/committees/jc/jcgm/publications

[6] ITU-T. Recommendation K.61. Guidance on measurement and numerical prediction of electromagnetic fields for compliance with human exposure limits for telecommunication installations. Edition 10/2025. https://www.itu.int/rec/t-rec-k.61/en

[7] Keysight Technologies. Spectrum Analyzer application documentation. Distinction between frequency range and instantaneous IF bandwidth. https://helpfiles.keysight.com/csg/NA520xA/Applications/Spectrum_Analyzer.htm

Design Review Record

At the requirements review, the consortium would obtain the applicable full standards, select the relevant clauses and operating regimes, and produce a clause-to-test mapping. Catalogue descriptions and general product documentation do not establish conformity. ITU-T K.61 and IEC 62232 would inform applicable assessment workflows; qualification would also require the laboratory methods specific to each new measurement mode. [4, 6]

The first review would resolve the exact frequency boundaries, active channel count, usable bandwidth, qualified pulse classes, probe geometry, calibration routes, timestamp architecture, data-retention policy, prototype quantity, and independently quoted budget. This record would become the controlled baseline for construction.