



HAL
open science

Key Challenges in True Multistatic OTH Radar Concepts based on HF-Radar in iFURTHER

Dominik Bok, Philippe Brouard, Anna Lisa Saverino, Amerigo Capria, Karol Abratkiewicz, Jean-Philippe Molinié, Iole Pisciotano, Alessandro Ippolito, Piotr Samczyński, Simon Vandewalle, et al.

► To cite this version:

Dominik Bok, Philippe Brouard, Anna Lisa Saverino, Amerigo Capria, Karol Abratkiewicz, et al.. Key Challenges in True Multistatic OTH Radar Concepts based on HF-Radar in iFURTHER. RADAR 2024, Oct 2024, Rennes, France. <hal-04786347>

HAL Id: hal-04786347

<https://hal.science/hal-04786347v1>

Submitted on 15 Nov 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization

Key Challenges in True Multistatic OTH Radar Concepts based on HF-Radar in iFURTHER

Dominik Bok^{*}, Philippe Brouard[†], Anna Lisa Saverino[‡], Amerigo Capria[‡], Karol Abratkiewicz[§], Jean-Philippe Molinié[†], Iole Pisciotano^{*}, Alessandro Ippolito^{||}, Piotr Samczyński[§], Simon Vandewalle^{**}, José-Luis Bárcena-Humanes^{**}, Javier Rosado-Sanz^{††}, María del Pilar Jarabo-Amores^{††}

^{*} *Fraunhofer Institute for High Frequency Physics and Radar Techniques FHR, Wachtberg, Germany*

[†] *Electromagnetism and Radar Department, ONERA – Université Paris-Saclay, Palaiseau, France*

[‡] *Radar and Surveillance Systems (RaSS), Laboratory – CNIT, Pisa, Italy*

[§] *Institute of Electronic Systems, Warsaw University of Technology – WUT, Warsaw, Poland*

^{||} *Upper Atmosphere Physics and Radiopropagation, National Institute of Geophysics and Volcanology (INGV), Rome, Italy*

^{**} *Radar department – Indra Sistemas S.A., Madrid, Spain*

^{††} *Signal Theory and Communications, University of Alcalá – UAH, Madrid, Spain*

Corresponding author: dominik.bok@fhr.fraunhofer.de

Abstract—The system concept of a multistatic network of collaborative high frequency (HF) over-the-horizon (OTH) radar nodes has been proposed and is being tested in the European Union-funded study iFURTHER. These system setups are subject to the electromagnetic situation given in the high frequency range and challenging ionospheric skywave or surface-wave propagation paths in combination with a bistatic beyond-line-of-sight (BLOS) geometry. It is foreseen to combine data from widely distributed HF sensor nodes in a cohesive OTH radar network for the coherent operation below approximately 30 MHz. Inherent technical challenges affect the choice of possible system designs and the performance in terms of target tracking and localization. Being thereby distinct to a classical OTH skywave backscatter principle in (quasi-)monostatic configurations, this idea requires conceptually new and agile system architectures, which include the support by cognitive radar principles and a sensing of the ionosphere to retrieve latest supplementary information on current propagation conditions. The possibilities are enhanced by a combined hybrid skywave and surface-wave propagation with a likely support of complementary sensor data. It may benefit from an exploitation of non-cooperative illumination by transmitters of opportunity. Successful verification of this system-of-systems concept will provide powerful radar and sensing capabilities that can be used in a wide range of upcoming OTH applications.

Index Terms—OTH, BLOS, hybrid, skywave, multistatic, PCL

I. INTRODUCTION

The EU-funded iFURTHER project [1], [2] elaborates on various concepts for a multistatic radar network to enable high frequency (HF) over-the-horizon radar (HF-OTH-R) operation. This shall achieve a wide-area monitoring for Europe that reaches beyond line-of-sight (BLOS) surveillance capabilities. The project includes a high-level architectural study of distinct system concepts that can be suitable for these types of applications, supplemented by operational use case considerations. It is extended by the experimental design and the evaluation of core-enabling technologies to verify the best approaches using simulated and experimental data to reach these goals.

Thanks to the whole iFURTHER project consortium and all partners for the exchange in the study and the EDF fund for supporting this research activity.

II. GENERAL MULTISTATIC OTH STUDY CHALLENGES

A. HF Radar Characteristics and Distinctions

The HF electromagnetic spectrum is characterized by strong ‘environmental’ noise that results from the intentional usage by a wide variety of user applications and non-intentional noise, such as human-made spurious emissions or natural atmospheric and galactic noise phenomena. Typical isolated high-powered emissions result in a high signal dynamic range. Electromagnetic waves go through distinct scattering and propagation mechanisms in the shortwave frequency range. The key mechanism that makes achieving BLOS/OTH coverage possible is the refraction of these signals at ionospheric layers to enable long-range propagation *via a skywave channel* and also the use of the diffraction in *surface-wave (SFW)* propagation over well conductive surfaces.

B. Basic operation principles of skywave HF-OTH radars

The ionosphere naturally exhibits a high level of free electrons able to affect significantly the refraction of HF radio waves so that these are propagated back to the Earth [3]. The main advantage offered by ionospheric propagation to skywave *high frequency over-the-horizon* (HF-OTH) radars is their capability to detect targets well beyond the horizon and to track these at ranges an order of magnitude greater than conventional radar systems. The *skywave* propagation is, however, equally a source of many uncertainties and difficulties in practice. Consequently, HF-OTH radar performance is not only determined by system design and operating parameters, but it is also tightly coupled with the characteristics of the ionosphere as well as of the prevailing HF environment [2].

Common skywave HF-OTH radar concepts are monostatic or quasi-monostatic *backscatter* configurations (OTH-B or OTH-BS) with a baseline between the transmitter and the receiver node of up to several tens of kilometers. These use similar forward-and-backward propagation paths [2] and their

spatial separation is mainly a logical consequence to achieve physical ‘shielding’ of the ground wave reception from the transmitter [4]. Such a backscatter configuration is referenced here as ‘quasi-monostatic’ since it appears monostatic from a target-oriented view and it is not leading to the advantages outlined for the bistatic or multistatic HF-OTH-R approaches that have been proposed in the iFURTHER study [1], [2]. The French NOSTRADAMUS OTH-R system is an actual monostatic HF transmitter and receiver setup [5], [6].

C. Collaborative multistatic HF radar network

The collaborative multistatic network of high frequency sensors extends the idea of the classical concept of OTH-B by the introduction of additional ‘HF OTH sensor nodes’. The big envisioned picture proposed by the iFURTHER study [1] is depicted in Fig. 1 below. The illustration includes three HF skywave OTH radar transmitter sites (marked with a red triangle) with a certain ‘skip zone’ of the skywave illumination around their position. These are extended by several active or covert passive receive-only OTH sensor nodes that might be co-located [2] at sites of an HF surface wave radar (HFSWR).

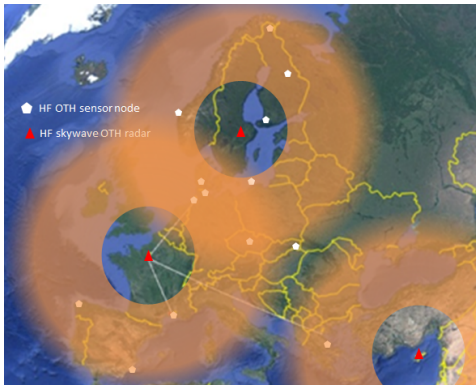


Fig. 1. Envisioned EU-wide OTH surveillance system [2].

This concept results in several functional challenges such as

- i) Dealing with ionospheric influences in bistatic skywave channels, the impact of clutter and of high noise levels.
- ii) Including *hybrid* [7, Fig. 1] setups with a combination of skywave and SFW propagation [2], requiring to match, partially conflicting, demands in terms of frequency choice, vertical receive polarization and target scattering.
- iii) Handling ‘true’ multistatic operation of HF radars with several hundreds of kilometers separation [2]. It can include ‘forward-based augmentation’ receivers [8, Fig. 1] with line-of-sight (LoS) to the targets of interest.
- iv) Coping with large baseline setups and bistatic target returns. The receiver nodes might be located multiple hundreds of kilometers apart from each other, from the targets and, certainly, from the transmitter node(s).
- v) In general, coping with quite low HF frequencies that result in comparably largely extended installations to achieve narrow beam-steering and high antenna gains.

From the functional challenges listed above, the derived ‘technical’ challenges for these multistatic configurations include:

- 1) Development of a multi-site system-of-systems (SoS) architecture and adaptive signal processing (→ Sec. III).
- 2) Resolving multistatic propagation mechanisms to retrieve ground positions and tracks of targets (→ Sec. IV).
- 3) Improving supplement aids for ionospheric characterization to support the proposed architectures (→ Sec. V).
- 4) Solving receiver node and architectural design questions to enable these approaches (→ Sec. VI).

III. ADAPTIVE RADAR OPERATION MODES / COGNITIVE NETWORK SCHEDULING POSSIBILITIES

A. Architectural multistatic OTH challenges

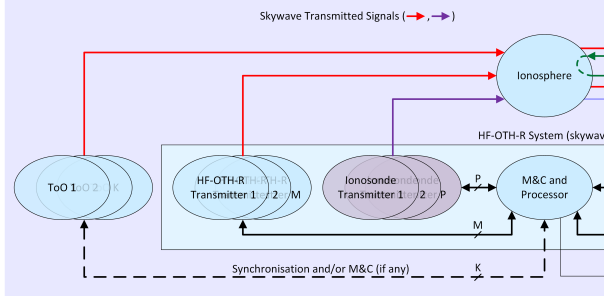
The iFURTHER concept aims to achieve multi-site and ‘true’ multistatic HF-OTH-R configurations [1], [2]. The use of sophisticated architectures, the combination of skywave, surface wave and LoS propagation modes to the receiver node increase the complexity of the system and lead to new conceptual challenges. The main ones are the following:

- a) *System Complexity*: The architecture is inherently complex due to diverse illumination, either by cooperative or by non-cooperative transmitters of opportunity (ToO), distributed receivers and processing units involved.
- b) *Signal Processing and Data Fusion*: Processing signals from multiple and spatially distributed transmitters and receivers requires advanced signal processing techniques alike. Efficient data fusion algorithms are needed to combine information from various data sources and to obtain accurate target parameter information.
- c) *Synchronization and Timing*: Distributed multistatic operation relies on transmitter and receiver sites, which will be separated by distances of several hundreds of kilometres. This leads to very stringent requirements in terms of synchronisation since data needs to be shared and coherently processed in unison at a much lower level than typically considered in the radar processing chain.
- d) *Radar modes*: The effectiveness of the radar operation in iFURTHER relies on the capability to manage a smooth transition between LoS, skywave and surface wave propagation modes in multiple transmitter-receiver pairs. Cooperative illumination must be precisely matched to the requirements of propagation and target acquisition.

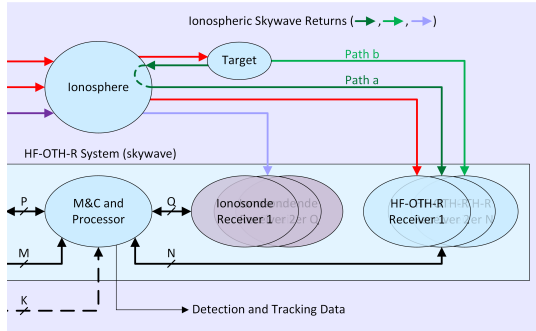
B. Cognitive networked system-of-systems scheduling

The proposed concept of the multi-site system of systems is conceived to be a cognitive one. The core principle of a cognitive radar system is that it interacts adaptively with an *environment* that it is adapted to, taking into account available resources and the target state [9]. The key cognitive radar features of the proposed distributed multi-site HF-OTH-R network are depicted in Fig. 2 below. The *ionosphere* is the environment in our case, which does not only affect the illuminating skywave signal but, equally, contributes to the target detection. Respectively, the desired capability for long-range OTH sensing is just enabled by ionospheric propagation. The system-of-systems architecture in Fig. 2 contains features for using one or multiple cooperative HF transmitter(s), the

automatic detection and exploitation of transmitter(s) of opportunity (ToO), as well as the automatic usage of ionosonde systems for the characterization of the ionospheric channels between the HF-OTH-R transmitters and the receivers. This can be additionally enhanced by *bistatic oblique sounding* at the distributed HF receiver nodes (see Sec. III-D+V).



(a) Input relations (Transmitters of Opportunity, OTH radars and ionosondes)



(b) Output relations (Ionospheric sensing plus target channel returns)

Fig. 2. High-level cognitive radar architecture with ionosphere and a target.

The high-level architecture of the multi-site multistatic cognitive HF radar network is sketched in its input and output relations. As depicted in Fig. 2a, on the input side, a central management and control (M&C) and processor system jointly manages M OTH-R transmitters, K available ToOs and P ionosonde transmitters. Fig. 2b shows N OTH-R receivers and Q ionosonde receivers being adapted on the output side. Two general types of receiving paths for target returns appear:

- The refracted skywave signal can bounce off a target and be scattered back towards the HF-OTH receiver node via an ionosphere channel ('Path a', dark green color).
- Or the target-scattered signal is received directly at an HF receiver node ('Path b', light green color) – either via direct LoS or via SFW propagation in 'hybrid' setups. SFW is here aimed at surface vessels and low-altitude air targets. It may give rise to additional hybrid sea clutter.

In addition, unoccupied frequencies need to be determined by a *frequency management system* in order to elude 3rd party emissions or frequency-selective noise at the receiver nodes.

C. Non-cooperative PCL operation mode ('passive radar')

The illumination by one or multiple ToOs can optionally be incorporated by a selection of the M&C and processor

system (in Fig. 2a) to choose and to adapt to any suitable but non-cooperative illumination. The inherently bistatic OTH-R operation requires passive coherent location (PCL) techniques after the reception, to achieve *synchronization* and to retrieve the *reference waveform* including the correct *association* of the ToO. Compared to the usage of cooperative HF transmitter(s) in a multistatic setup, *non-cooperative emissions* involve more challenges in this respect due to the lack of control over and missing information on certain emission parameters. The non-cooperative PCL mode remains subject to the *availability*, *emission* and *propagation* characteristics plus the obtainable *position accuracy* of these transmitters. This adds up to achieving OTH-R features and mitigation of bistatic HF propagation.

D. Reception of the illuminating skywave signal

An advantage of the multi-site and multistatic configurations shall be highlighted at this point. The (true) multistatic and spatially distributed OTH-R system enables the *direct reception* of the illuminating skywave signal from the distant HF transmitter, as depicted in Fig. 3 with the red path at the HF receiver node. In the shown BLOS configurations, the transmitter is far beyond the horizon and the transmitted signal reaches neither the target nor the receiver node(s) directly.

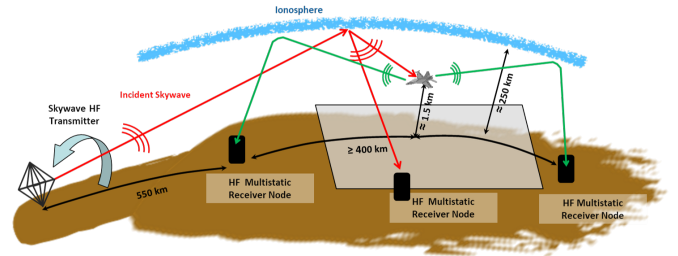


Fig. 3. Multistatic OTH setup with simplified doubly refracted paths for a target in two bistatic pairs; *bistatic oblique* skywave reception at another node.

The skywave illumination received directly after refraction can therefore be favorably used in the system architecture as a reference for the radar processing. This enables an evaluation of the *skywave illumination coverage* in this area but also an, in fact, *bistatic oblique* characterization of the skywave propagation channel between the HF transmitter(s) and the distributed multistatic receiver nodes [1] – see also Fig. 6 in Sec. V. This may be combined with the time-of-emission instance to characterize the ionospheric propagation paths. Being itself the non-cooperative illumination of opportunity (IoO), the direct skywave reception is a key step in PCL processing (Sec. III-C).

IV. CHALLENGES OF MULTISTATIC HF OTH-TRACKING AND TARGET LOCALIZATION

A. Challenges contrary to an OTH backscatter concept

The depicted multistatic OTH radar setups will raise new challenges in terms of achieving target tracking and localization. This is a consequence of the bistatic BLOS geometry that becomes contrary to the (quasi-)monostatic setups utilized in 'classical' OTH backscatter concepts (Sec. II-B), which were

based on similar forward-and-backward propagation paths to a target. The collaborative network that was sketched in Fig. 1 of Sec. II-C is composed of several bistatic pairs of HF-OTH radar nodes that instead form a ‘true’ multistatic configuration. The comparably low spatial density of HF receiver nodes causes, in general, a *large distance* and *look angle variation* to targets of interest. Thereby, the forward and the backward path to a single target will then become *highly distinct* to each other and to that of other bistatic transmitter-receiver pairs.

B. Bistatic BLOS geometry to the target positions

The high-level technical challenges 1), related to the SoS architecture, and 2), the ‘true’ multistatic OTH propagation listed in Sec. II-C, are linked to the bistatic BLOS geometry: This setup gives an ‘illumination from the top side’ on the distant targets so that *incident angles* can be comparably high.

The targets of interest might be located at traveled distances up to thousands of kilometers from the transmitter node (TX). Thereby, a potential significant distinction between the incident and the *scattered angles* toward a – presumably – ground-based receiver node (RX) may occur. The beyond line-of-sight geometry in these OTH configurations is sketched in the figures below. The bistatic radar’s baseline along x is thereby likely to cut the curved Earth’s surface. Each ionospheric path is represented by an equivalent simplified single *reflection point* at an apparent mirror-like ionospheric layer height. For multiple ionospheric transits and non-backscatter OTH configurations, their heights – and respective reflection points – are likely to differ. Especially, in widely distributed bistatic setups, even *double* ionospheric paths (shown in Figs. 3 and 6) may occur. The second distinct ionospheric skywave path results in the geometric situation that is sketched below in Fig. 4.

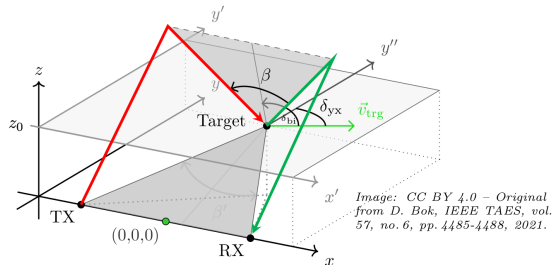


Fig. 4. Bistatic OTH configuration with double refraction to the receiver (RX) node with simplified equivalent reflection heights, i.e. ‘Path a’ case of Fig. 2b.

As outlined in [2], the proposed HF-OTH-R concepts include explicitly system configurations that are in line-of-sight (LoS) to receiver nodes, which offers several advantages, including that often the distance $R_{rx_trg} \ll R_{tx_trg}$ [1]. This is illustrated in Fig. 5, with a target in LoS to a receiver node.

In terms of the distributed radar nodes and a double (Fig. 4) or single (Fig. 5) propagation path via the ionosphere, this can lead to a *large expectable* bistatic angle β , which is measured between the incident angle at the targets and the scattered wave angle to the multistatic HF nodes. In particular, if target positions are located ‘between’ the transmitter and the receiver, also comparably large bistatic angles β may likely result.

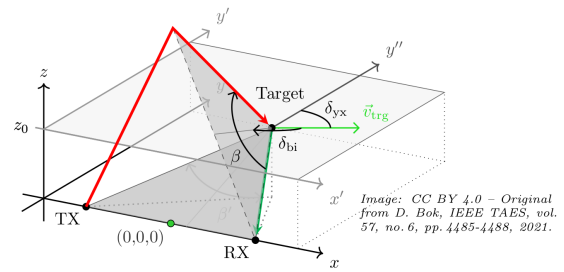


Fig. 5. Bistatic OTH configuration with skywave illumination and SFW or line-of-sight to the HF receiver (RX) node, i.e. the ‘Path b’ case of Fig. 2b.

C. Generic tracking challenges in the multistatic OTH setups

A large bistatic angle β in true multistatic setups (e.g., in LoS cases) has a direct implication on *bistatic HF scattering characteristics (RCS)*. It also lowers the *effectively measurable velocity (speed)* and it widens the *bistatic resolution cell area*. Moreover, any airborne target has often an a priori unknown target altitude, presumably located somewhere between the surface and below 80 to 100 km (lower end of the ionospheric E -layer region). If further the apparent reflection heights differ in distinct ionospheric propagation paths plus estimation errors are present, this may have a crucial implication on time-of-arrival (ToA) and Doppler-assisted multistatic methods. This should be considered along with any taken simplifications, adaptive system features’ choice to avoid *complex ionospheric propagation* (ducted multi-layer, E_s or chordal modes), combined with a demanding 3-D geometry in BLOS cases. These factors might be slightly relaxed due to the *coarse resolution* in HF radar, compared to microwave radars, whereby a certain degree of diversity in terms of look-angle, might even support OTH processing tasks. ‘Forward scattering’ for $\beta \rightarrow \pm 180^\circ$ can partly be advantageous in terms of the expectable RCS.

D. Available multistatic features and complementary info

The proposed multistatic setups with an adaptive system architecture (Sec. III) would form a collaborative network. Different cooperative emissions and bistatic pairs might assist to address or to avoid a part of these challenges. In addition, the system setup might still be supported by (quasi-)monostatic backscatter detections and/or complementary information on target echoes, which can assist the tracking and association challenges. The supplementary means for the ionospheric characterization (Sec. V) can provide further support.

Derived processing approaches to localize (to pinpoint) and to track targets will be the result of an evaluation on the sensitivity to input parameters and the possible accuracy. The achieved performance is determined by the systematic approach and the synchronization, which includes calibration procedures and usage of referencing signals. This is needed to judge on and to apply certain processing techniques to use 1-D estimates of *directions-of-arrival (DoA)*, *Doppler* and *ToA* information to refine heights of the ionospheric layers, of target altitudes along with their ground positions.

This is possibly enhanced by the usage of *complementary* sensor information (tracks from locally deployed radar, AIS or

ADS-B data) [1], which can provide an indication of certain claimed *target parameters* (speed, position and height) or a 2-D track history. Partly, this may be enhanced by *cognitive radar features* and an *adaptation of radar modes* (Sec. III). Any solution to cope with challenges of association and of spatial variations should include a certain amount of supplementary (Sec. V) and complementary information. Since it is a key feature to enable tracking aside from the detection, any demand affects the complexity of likely system architectures.

V. SUPPLEMENTARY AIDS FOR IONOSPHERIC CHARACTERIZATION

Vertical or near-vertical ionospheric sounding is a common practice, performed by a transmit antenna placed near a receive antenna (or a group of receive antennas). Operated by an ionosonde system, it provides a locally confined indication of the state of the ionosphere, such as the *critical frequency* of different ionospheric layers and their *relative virtual heights*, together with the maximal *electron density* of each layer. A *bistatic oblique* ionospheric sounding extends this concept to radar channels between widely separated TX and RX nodes. It enables the additional characterization of the bistatic channel, also using the skywave signal of an OTH-R. In order to make target detection and accurate position estimation possible, it is thereby beneficial, or even indispensable, to characterize each bistatic HF skywave channel through many oblique ionosounding systems (ionosonde or skywave reception / Sec. III-D).

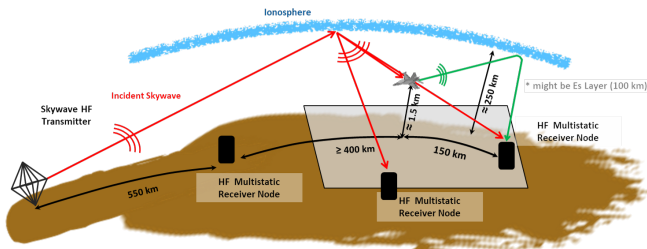


Fig. 6. Sketch of simultaneous reception of the skywave illumination at the multistatic HF receiver nodes; and high-elevation target return via an E_s layer.

The multi-site configuration of the OTH radar network in Fig. 6 permits the usage of spatially distributed HF radar receiver nodes, which allows for the concurrent *bistatic oblique* receptions of the skywave signal at spatially distributed locations. These sites may be equipped with *vertical (oblique)* ionosounding systems, as these can characterize the ionosphere above specific locations. To provide an assistance to HF channel modeling, *ray-tracing simulation studies* in the ionospheric medium have been carried out under different geophysical conditions over the European area, using two different algorithms: The INGV IONORT program [10] and the CNIT-RaSS ray tracing algorithm [11]. In order to define the propagation path of a given HF radio wave, the ionospheric electron density on the region of interest is defined by the IRI climatological model [12] and by the IRI-UP model [13], which gives close to real-time information on the modeled ionospheric medium.

This allows, in turn, the evaluation of the refractive index of the ionosphere and consequently to trace the stationary path of radio waves propagating for a given radio link. Different values can be retrieved from the ray-tracing procedures, such as coordinates of the *landing point* (latitude and longitude of the arrival point of the transmission); indicating the illumination area or ‘footprint’; *apogee* (maximum altitude reached); *group delay* of the signal; propagation *path length* and *ground range*.

VI. RECEIVER NODE DESIGN IN THE MULTISTATIC HF-OTH-R SYSTEM OF SYSTEMS

A. Technical design challenges of the HF receiver node

General iFURTHER receiver node design challenges are directly related to the intrinsic nature of the proposed cognitive multistatic OTH-R system of systems. The wide variety of possible configurations, the intrinsic variability of the propagation conditions, and the multifunction and reconfigurable capabilities at each HF receiver node, motivate the study of wideband Software Defined Radio (SDR) enabled receivers. Nowadays, there is a wide-ranging availability of commercial SDR solutions that are attractive for the HF band, being readily available, which reduces the initial design, development and maintenance costs. The operating frequencies, instantaneous bandwidths and processing architectures can be implemented using reconfigurable digital signal processing techniques.

Since the proposed concept of a long-range multistatic HF-OTH-R system with passive (covert) HF receiver nodes aims to incorporate multi-transmitter and multi-frequency operation, the receiver nodes should be able to process the whole HF band. Wideband and a kind of *ubiquitous* receiver operation enables the local reception analysis and *potential* transmitters of opportunity to be detected before selecting particular ones for OTH radar processing and target detection. In terms of cooperative transmitters, their emission parameters might be adapted according to the surrounding influences (Sec. III-B).

At the heart of this multistatic OTH radar system of systems lies an innovative antenna design, crafted to operate efficiently within the HF band. Typical antenna design for HF frequencies bases on log-periodic, monopole, dipole or loop structures, which include specific design elements, loading or a matching network to cover a wide operational bandwidth and directivity control. In general, the operating requirements impose highly demanding receiving node and antenna requirements:

- *Compact design*: For the easy deployment of the antenna systems at the different nodes, it would be necessary to consider new compact and rigid HF antenna types. The ionosonde sub-system functionality (Sec. III-B) might be integrated so that it is physically the same system, using shared antennas, RF front-end and processing hardware.
- *Acquisition bandwidth*: Wideband antennas are required for the coverage of the whole used frequency band to support the skywave propagation mode at distinct locations and under different HF propagation conditions.
- *Dynamic range*: High dynamic range is required to cope with the wide variety of signal power expected by the distinct propagation modes and a congested HF spectrum.

- *Coverage*: To provide a wide angular coverage, wide-beamwidth antennas may be selected, with the respective decrease in directivity, gain and an increase in clutter.
- *Antenna arrays*: The employment of an array will be mandatory to receive HF signals with a narrow beam (beamforming) from *different* directions at the same time, to allow simultaneously a pure reference skywave signal reception, to acquire weak echoes of distant targets and introducing a layer of diversity through spatial filtering. Adaptive 2-D digital beamforming techniques can help to reduce the direct signal interference (with clutter) of the skywave illumination in OTH-R setups. The same applies to bistatic HF sea clutter [14] mitigation in hybrid setups.
- *Single-element antenna nodes*: Multiple receiver nodes using each a single antenna element could be used for ToO *reference signal* reception (Sec. III-C), especially in surface wave or LoS propagation, or for *bistatic oblique ionosphere sounding* (Sec. V). Multistatic processing will use concurrent radar detections by these nodes [15] with overlapping coverage and multi-TX frequency diversity.
- *Synchronisation*: Secured resilient time and frequency synchronisation through dedicated software or hardware approaches with ad-hoc processing should be guaranteed.

Thereby, the receiver sites should be characterized by a low ‘environmental’ noise floor to make the SINR as high as possible and to be fully adaptable to arbitrary illumination.

B. Large-baseline, non-cooperative and bistatic radar issues

As part of a widely distributed networked system, HF receiver nodes must implement a reliable ‘capacity’ to monitor their imminent HF environment regarding interferences, available IoO and ‘local’ HF noise and to provide this information to the central management and control in a fast and adaptive cohesive way (Sec. III-B). These operation modes require an accurate time and frequency synchronization in a wide area, which is determined by the system architecture. Listed design challenges (Sec. VI-A) have to be solved for large baseline configurations over multiple hundreds of kilometers, as shown in Figs. 3 and 6. Communication links must allow for *data interchange* of network management and operation. Non-cooperative illumination adds up with typical PCL processing challenges (Sec. III-C), such as an *estimation of transmission* parameters. Interfaces with supplementary aids (Sec. V) have to be embedded in the system for *ionospheric characterization*.

VII. SUMMARY AND NEXT STEPS

In summary, the new concept of a multi-site and multistatic network of HF-OTH-R systems has the potential to enable huge benefits if it is deployed over the geographical area of the EU territory (Sec. II-C). Bistatic setups, clearly distinct to a backscatter configuration, are foreseen that would result in highly challenging propagation paths and BLOS geometries (Sec. IV-B). This shows, equally, promising possibilities, while it raises important questions on its technical realization. Challenges include thereby distinct HF propagation paths for the transits of the ionosphere and node design issues (Sec. VI).

VIII. CONCLUSION

In this paper, several key challenges have been illustrated that result in a bi- and multistatic HF-OTH-R of a collaborative networked operational concept. It has been shown that this involves multiple functional and technical challenges, which motivate an in-depth analysis and the study of finally obtainable possibilities and choices in system architectures. This is currently addressed in the on-going study project and in the evaluation of simulations and of conducted experimentations.

ACKNOWLEDGMENT

The iFURTHER study is being funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.



REFERENCES

- [1] EDF 2021 Proposal iFURTHER – DoA (Part B), Dec. 2021. Approved.
- [2] S. Saillant, D. Bok, J.P. Molinié, A. Leventis, P. Samczynski, P. Brouard, A.L. Saverino, A. Capria and Y. Paichard, “iFURTHER project - a cognitive network of HF radars for Europe defence,” 2023 IEEE International Radar Conference (RADAR), Sydney, Australia, 2023, pp. 1-6, doi: 10.1109/RADAR54928.2023.10371074.
- [3] J.M. Headrick and J.F. Thomason, “Application of high-frequency radar,” *Radio Science*, vol. 33, pp. 1045-1054, Jul-Aug. 1998.
- [4] A. Cameron, “The Jindalee operational radar network: its architecture and surveillance capability,” *Proceedings International Radar Conference*, Alexandria, VA, USA, 1995, pp. 692-697, doi: 10.1109/RADAR.1995.522633.
- [5] S. Saillant, “NOSTRADAMUS Over-The-Horizon radar, le radar transhorizon NOSTRADAMUS,” *SEE conference, 3ième journées d’études propagation électromagnétique du décimétrique à l’Angström*, Rennes (France), October 7-9, 1994.
- [6] V. Bazin, J.P. Molinie, J. Munoz, P. Dorey, S. Saillant, G. Auffray, V. Rannou, M. Lesturgie, “A general presentation about the OTH-Radar NOSTRADAMUS,” 2006 IEEE Conference on Radar, Verona, NY, USA, 2006, pp. 634-642, doi: 10.1109/RADAR.2006.1631867.
- [7] Z. Zhao, X. Wan, D. Zhang and F. Cheng, “An experimental study of HF passive bistatic radar via hybrid sky-surface wave mode,” in *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 1, pp. 415-424, Jan. 2013, doi: 10.1109/TAP.2012.2213062.
- [8] G.J. Frazer, “Forward-based receiver augmentation for OTHR,” 2007 IEEE Radar Conference, Waltham, MA, USA, 2007, pp. 373-378, doi: 10.1109/RADAR.2007.374245.
- [9] S. Haykin, “Cognitive radar: a way of the future,” *IEEE Signal Processing Magazine*, vol. 23, no. 1, pp. 30-40, Jan. 2006, doi: 10.1109/MSP.2006.1593335.
- [10] A. Azzarone, C. Bianchi, M. Pezzopane; M. Pietrella, C. Scotto and A. Settimi, “IONORT: A Windows software tool to calculate the HF ray tracing in the ionosphere,” *Comput. Geosci.*, 42, pp. 57-63, 2012.
- [11] A. Cacciamano, A. Capria, D. Olivadese, F. Berizzi, E. Dalle Mese and F. Cuccoli, “A coordinate registration technique for OTH sky-wave radars based on 3D ray-tracing and sea-land transitions,” *Progress in Electromagnetics Research Symposium*, pp. 146 - 150, 2012.
- [12] D. Bilitza, “IRI the International Standard for the Ionosphere,” *Adv. Radio Sci.*, 16, pp. 1-11, 2018, doi: 10.5194/ars-16-1-2018.
- [13] A. Pignalberi, M. Pietrella, M. Pezzopane and J.B. Habarulema, “Investigating different vTEC calibration methods for data assimilation in ionospheric empirical models,” *Advances in Space Research*, vol. 68, pp. 2138-2151, 2021, doi: 10.1016/j.asr.2020.10.040.
- [14] M. Menelle, F. Jangal, V. Bazin, D. Lecoz and G. Auffray, “Bi-static and multi-frequency experiments of HFSWR,” *OCEANS 2009, Biloxi*, MS, USA, 2009, pp. 1-4, doi: 10.23919/OCEANS.2009.5422121.
- [15] K. Abratkiewicz, P. Samczynski, G. Mazurek, M. Bartoszewski and J. Julczyk, “Passive Radar Using a Non-Cooperative Over-the-Horizon Radar as an Illuminator - First Results,” 2024 IEEE Radar Conference (RadarConf24), Denver, CO, USA, 2024, pp. 1-6.