

# Chapter 9

## Conclusions

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It is pertinent to doubt if it is worth to invest and investigate nowadays in *Over The Horizon Sky Wave Radar* (OTHR-SW) systems, when, at the beginning of the 21<sup>th</sup> century, the innovation-rate generally implies, especially in the radar sector, a continuous technological evolution of the systems. In fact, as we said also in the introduction, OTHR-SW systems are based on a well known technology and they were largely studied and employed since the beginning of the cold war. Yet, after more than half of a century, these systems are gaining again new attraction, certainly in virtue of their incomparably large surveillance area, their independence from meteorological conditions, their immunity to the classic stealth techniques and off course to the huge steps forward in signal processing and data storage techniques.

Moreover the LOTHAR project, based on the study and development of an OTHR-SW system for the surveillance of the Mediterranean area, is even more attractive, if considered in its Geo-political contest. As a matter of fact the Mediterranean sea presents a continuously expanding volume of maritime surface traffic. According to a study of “LegaAmbiente” the volume of big dimensions vessels in the Mediterranean sea in 2007 has been estimated to about 200000 units [33] and the data were showing an impressive growth rate.

The economic explosion occurred in China in recent years makes it necessary the availability to trade routes to and from the east. Due to the rough geomorphology and political instability of the Balkans and the Caucasus region, it seems appropriate to pursue these routes in the Mediterranean sea. In fact, as a consequence of the economic explosion in Asia, the service sector experienced a relevant growth also in Europe and the number and users of civil maritime and

aerial routes across the Mediterranean sea showed a continuous increase in the last years.

In such a scenario the realization of a large scale coverage radar seems to be a critical task and the OTHR-SW represents the only alternative solution to the prohibitive costs of a satellite radar network. Of course the main drawback in the employment of an OTHR-SW device remains the dependency from the knowledge of the actual Ionospheric structure, that it is still an impossible task on large areas and with real time constrains. That's why we decided to investigate a method to Geo-reference the OTHR-SW signal, able to overcome the lack of knowledge of the Ionospheric status.

The purpose of the presented research project was the development of a method for the real-time *Coordinate Registration* (CR) of the echo received by a pulsed and monostatic OTHR-SW system. The proposed CR method, referred to as "*Sea-Land Transition Identification*" (SLTI), is based on a really simple principle: the detection of coastline profiles within the radar echo relative to a footprint that includes sea and land regions. This method, when applied to an OTHR-SW system, transforms the radar in a "*Knowledge Based System*", allowing it to overcome the uncertainties introduced by the heterogeneous and time-varying behaviour of the Ionosphere, by taking advantage from the *a priori* knowledge of the hydro-morphology of the surveillance area. The SLTI method is based on a time-efficient algorithm that exploits the different values of the HF backscattering coefficient of sea and land regions and consequently the different power return from the two different surfaces. In fact, despite the value of the HF backscattering coefficient depends from many factors (as the operative frequency, the incidence angle of the signal and the Sea State for water regions or the terrain characteristics for land regions), it is known that it is very different for land and sea regions.

Supposing to operate with the receiving OTHR-SW antenna pointing in a fixed direction (i.e. with constants elevation and azimuth angles) and with a given working frequency, in the simplifying hypothesis of absence of multiple paths and specular reflection of the radar beam on the Ionosphere, the radar will project a certain footprint on the Earth's surface. If it is assumed that the "clutter area", i.e. the region relative to the instantaneous contribution of clutter, is limited in range by the projection on the ground of the radar pulse (and not from the projection to the ground of the beam as occurs in azimuth), then the echo resulting from the range scan of the footprint arrive to the receiver with a given delay. In a conventional radar system, this information is sufficient to extract the distance between target and radar. However, in the case of OTHR-SW system is not possible to know with precision the actual signal path, and the delay in receiving the echo gives us only a rough indication of the location of the impression. By taking advantage of one or more geographically known references, as the location on a map of a coastal profile, or FM transmitters, etc., we can Geo-reference the

radar footprint overcoming the Ionospheric uncertainties.

The SLTI approach has been here largely described. Its numerical formulation has been proposed, together with the conceptual and the mathematical models of the simulated OTHR-SW scenario. The proposed material was mostly produced during the *LOTHAR-fatt* project, that is the study and design of an OTHR-SW system for the surveillance of the Mediterranean and also during the following research to develop and apply the method. During this period of time several papers were presented to national and international conferences, describing the concept of the proposed approach, the evolution of the scenario model, the application of the SLTI in particular contexts, etc. Unfortunately it was not possible to obtain real-data from monostatic and impulsive OTHR-SW devices and consequently the method has been proved only in simulated scenarios and only for demonstration purposes. Moreover, since the results of each test, are highly dependent on the assumptions made to model the OTHR-SW scenario, it follows that a quantitative analysis of the performance of the SLTI method is to this day not very significant. We only provided rough reference requirements (in terms of both SNR and differential sea/land NRCS) for a given range coordinate registration precision. In synthesis, it was shown that a differential sea/land NRCS of about 7 dB is needed in order to identify a single sea/land transition with a down-range estimation error of 10 km and that smaller differential NRCS levels lead to higher uncertainties: incidentally, an error of 10 km is of the same order of error magnitude found by Barnum and Simpson when comparing terrain features and beacon ground range displacements based on experimental data [24]. On the other hand, a +10 km error in the identification of a sea/land transition would be more than acceptable in a OTHR-SW HF coordinate registration framework based on a single pulse analysis, considering also that several sea/land transition position estimates could be averaged based on SLTI processing of signals coming from subsequent transmit pulses. Therefore, these results obtained in ideal conditions allow to proceed with further analyses involving an increased parametric complexity of the scenario model. Note that the OTHR-SW scenario developed for demonstration purposes has been designed with a modular structure, in order to be able to singularly evolve a block of the scenario each time a new and more realistic assumption is made.

The SLTI approach developed during the present research is still under investigation. Although the method has been mathematically described, together with its main principles, the algorithm implementing the SLTI procedure could not be tested on real data, but it was only proved to be effective on a simulated OTHR-SW scenario, under a series of assumptions. Since the beginning of this research project, a modular structure has been defined for the simulated OTHR-SW scenario, in order to periodically and independently update the various blocks of the model with more realistic hypothesis. So far many improvements of the scenario have been introduced. The last implemented version of the simulated

OTHR-SW scenarios makes use of the following assumptions:

- a stable propagation Ionospheric channel is assumed to be present from the transmission of a pulse till the reception of the relative echo;
- multi-hop returns were considered too weak to be accounted for (see fig. 4.6);
- only the main propagation mode “ $F2F2$ ” is considered (see fig. 4.7);
- any eventual azimuthal drift of the ray path is neglected;
- the effects due to the Earth’s magnetic field (and accountable with a factor dependent on the geography of the system) are neglected;
- only two values for the backscattering coefficients ( $\sigma_{0S}$  for sea and  $\sigma_{0L}$  for land regions) are considered.
- sudden transitions between sea and land regions are assumed;
- clutter from mixed-surfaces (sea/land) patches is evaluated according to the percentage of sea/land within the patch;
- the echo is reconstructed at the receiver as a superposition of contributions from single clutter patches;
- the superposition of clutter contributions is evaluated in respect to the TOA of each contribution;
- the path relative to the clutter contribution from a given patch of the radar footprint is evaluated according to frequency and elevation angle of the contribution and the electron density profile of the ionosphere.
- the adopted model of the Ionosphere is analogous to the SIRM.

Until we have the possibility to apply the SLTI method directly to real radar data, it is worth to improve the simulated scenario, substituting some of the hypothesis listed above with more realistic ones, especially for what concerns the Ionospheric model. The SLTI algorithm was recently cited by Chinese authors from Xi’an University [47], and it can represent a reference for the development or improvement of any other CR technique for the OTHR-SW that takes advantages from geographically known features.

# Appendix A

## OTHR Systems and Correlated Projects

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This appendix proposes an updated list of Over The Horizon Sky Wave Radar systems located around the World and of projects that directly involve these particular sensors. The list is not intended to be comprehensive of every existing OTHR-SW apparatus, but it just represents a basic reference for any further research. The list is the result of a collection of scientific papers and of a basic web research, consequently some information can result inaccurate. The considered radar systems can be active, in stand-by mode or dismantled and whenever this information is available it is provided. The list is organized according to the nationality of the OTHR system. Note that an analogous, but more detailed, list is proposed in [58].

### USA

- **ROTHR**: “Relocatable Over The Horizon Radar”. It is a multiple radar system developed by *Raytheon* and initially located in Alaska (Amchitka), Texas (Corpus Christi), Virginia (Chesapeake) and Puerto Rico. See for reference:
  - B.T. Root, J.M. Headrick - “*Comparison of RADARC High-Frequency Radar Performance Prediction Model and ROTHR Amchitka Data*” - Naval Research Laboratory Internal Report - July 16, 1993.
  - <http://www.raytheon.com/capabilities/products/rothr>

- <http://www.fas.org/nuke/guide/usa/airdef/an-tps-71.htm>
- <http://articles.janes.com/articles/Janes-C4I-Systems/Relocatable-Over-The-Horizon-Radar-ROTHR-AN-TPS-71-United-States.html>
- **WARF**: Stanford Research Institute (SRI) “Wide Aperture Research Facility”. It is a bistatic OTHR-SW system located in California (Tx at Lost Hills and Rx at Los Banos) that employs an averaged transmitted power of about 20 MW. It was employed in a counter drug-traffic mission in the Gulf of Mexico and the Caribbean Sea. See for reference:
  - J.W Maresca Jr., C.T. Carlson - “*HF SKYWAVE RADAR MEASUREMENT OF HURRICANE WINDS AND WAVES*” - SRI International - SKYWAVE RADAR MEASUREMENT, COASTAL ENGINEERING, 1978.
  - J.W Maresca Jr., C.T. Carlson - “*High Frequency Sky-Wave Radar Track of Tropical Storm Debra*” - American Meteorological Society Vol. 109 - 1981.
  - J.R. Barnum - “*OTH Radar Surveillance at WARF During the LRAPP Church Opal Exercise*” - STANFORD RESEARCH INST MENLO PARK CA - Technical Report No 39, Sept 1975 - June 1976.
- **OTH-B**: “Over The Horizon Backscatter” radar. It a radar network consisting of 6 OTHR-SW systems (originally they should have been 12) studied to provide a complete coverage of US boundaries against any intercontinental ballistic attack. The 6 systems were grouped in two blocks: the “East Coast Radar System” (ECRS) in Maine (Moscow, Columbia Falls, Bangor) and the “West Coast Radar System” (WCRS) on the Oregon-California border, with the operative center located in Mountain Home Air Force Base, Idaho (fig. A.1). See for reference:
  - G.S. Sales - “*OTH-B RADAR SYSTEM: SYSTEM SUMMARY*” - University of Massachusetts Lowell, Center for Atmospheric Research - Scientific report No. 7 - May 1992.
  - Historic American Engineering Record - *Over-the-Horizon Backscatter Radar Network* - Library of Congress Prints and Photographs Division Washington, D.C. 20540 - Cod. HAER ME-100-O.
  - United States Air Force - *Environmental Assessment for Over-The-Horizon-Backscatter (OTHB) Radar Site at Tulelake, CA* - Technical Report for the US Forest Service. - Dec 2009.
  - M.R. Stiglitz, C. Blanchard - *Over-the-horizon backscatter radar (Special Report)* - Microwave Journal, May 1990.

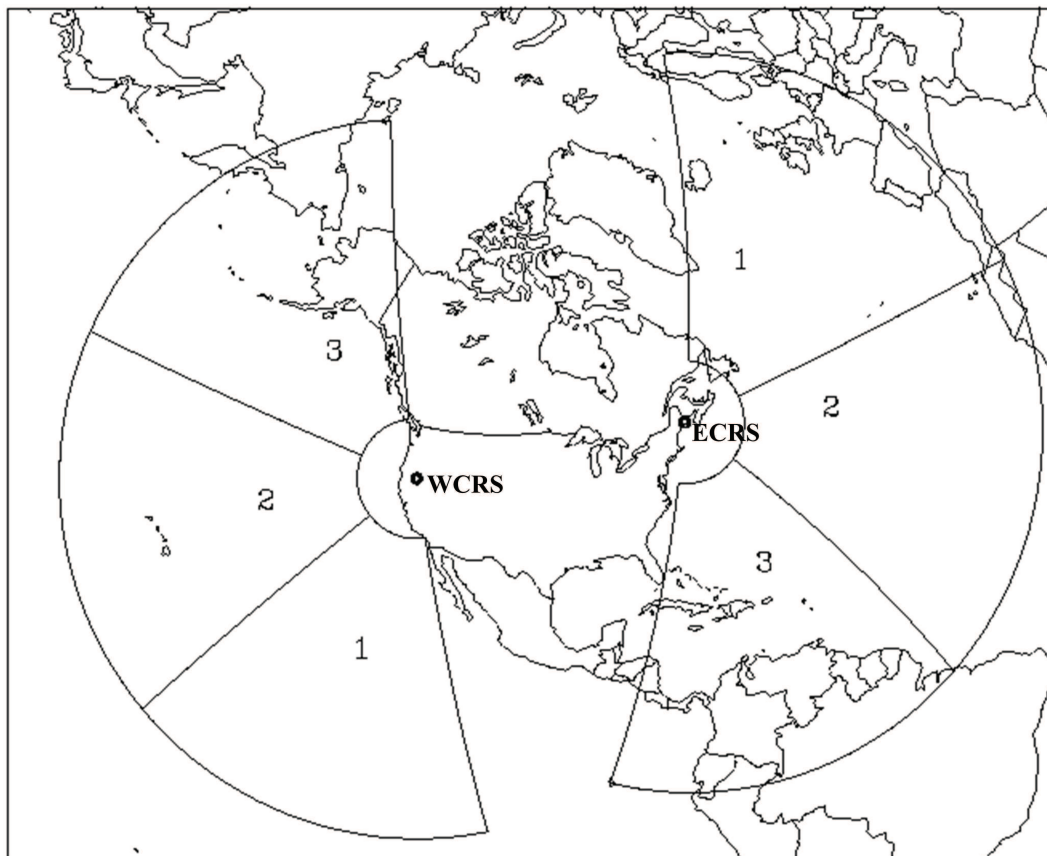


Figure A.1. Radar Coverage theoretically provided by the OTH-B HF system.

## CSI

The two OTHR-SW apparatus “Duga” of the ex Sovietic Union located in Ukraine results inactive since the 90s, while it is not confirmed the operational status of the system located in Krasnojarsk, central-Siberia. Besides their glorious history in the development of OTHR-SW systems, Russians has more recently focused on HFSWR, but it is not confirmed if they own an operative prototipe of this system.

## Australia

**JORN:** “Jindalee Operational radar Network”. More than a bi-static OTH sensor, it is a complex network of HF systems (OTH transmitters and receivers, VIS, OIS, and passive HF receivers for FMS) dislocated on the whole Australian territory. [25, 62, 73] Besides the papers listed in the bibliography we also cite:

- D.H. Sinnott - *The Development of Over-the-Horizon Radar in Australia* - Australian Department of Defence website.

## Canada

Besides its interest in the OTH sky-wave radar demonstrated in recent years, Canada has been conducting a deep study of HF surface-wave radar. Not many information are available, so the following is a really short list of references:

- R.J. Riddolls - *A Canadian Perspective on High-Frequency Over-the-Horizon Radar* - Defence R&D Canada, Ottawa - Dec 2006.
- R.J. Riddolls, M. Ravan, R.S. Adve - *Canadian HF Over-the-Horizon Radar experiments using MIMO techniques to control auroral clutter* - IEEE International Radar Conference 2010 - pp. 718-723.
- D.E. Barrick, B.J. Lipa, P.M. Lilleboe - *HF radar surface-current mapping: recent US/Canadian advances* - Proceedings of the IEEE Fourth Working Conference on Current Measurement, 1990 - pp. 22-29.
- L. Sevgi, A.M. Ponsford - *AN HF RADAR BASED INTEGRATED MARITIME SURVEILLANCE SYSTEM* - Presentation for Raytheon Systems Canada Ltd.

**CODAR** HF radars (aka “SeaSondes”), produced and managed by *OEA Technologies* are HFSWR for the study and the characterization of the ocean that are known to be employed both in Canada and in the Eastern Caribbean.

## France

**NOSTRADAMUS**: “New Transhorizon Decametric System Applying Studio Methods”. It is an OTHR-SW monostatic system located 10 km outside Paris. Thanks to its antenna’s geometry, it allows a 360° azimuthal coverage. It became fully operational in 2005, but ever since it is employed as a prototype for further researches on OTHR-SW applications. [43, 75]

Despite the previously cited references and the information provided in chapter 3, a basic description of the NOSTRADAMUS system is available also on the website of the National Center of Aero-Space Research, *ONERA*:

- <http://www.onera.fr/photos-en/instexp/nostradamus.php>



## Great Britain

According to some sources the British Royal Air-force used to operate an OTHR-SW system located in the RAF base of Akrotiri, Cyprus. Several HAMS refer of disturbances within the band  $[10 \div 28]$  MHz with a bandwidth over 20 KHz.

For what concerns the HFSWR systems, the Great Britain has to be considered in the forefront of their research and development.

## PRC

“China is one of the countries that employs high-frequency over-the-horizon radars for both military and civil applications. The first Chinese high-frequency over-the horizon backscatter radar was developed in the 1970s” [57].

Confirmed information about the activity of the PRC in the OTHR research are not available on the web. Anyway, as a sign of the interest of China to HF over the horizon systems, it is interesting to note the relevant growth in the last 15 years of the number of related papers from Chinese authors. The next list shows some of these references:

- Zhao Shuqing, Liu Yongtan, Duan Fengzeng - *Digital beamforming in the OTH radar* - ICSP-90 Beijing, 1990 - pp. 655-656.
- Zhao Shuqing, Liu Yongtan - *Frequency domain digital beamforming in the OTH radar* - SEE 13, Jan 1991 - pp. 47-51.
- Jiao Peinan - *A new method of track processing in HF skywave OTH-B radar* - ACTA CIE 19, Jan 1991 - pp. 1-6.
- Zhou Wenyu, Mao Xu - *Bistatic FMCW OTH-B experimental radar* - ICR-1991 CIE - pp. 138-142.
- Wang Jiliang, Duan Fengzeng - *Application of maximum entropy in angular superresolution of OTH radar* - SEE 15, Oct 1993 - pp. 21-30.
- Su Wei Min, Ni Jin Lin - *Development Of Sky Wave Over-the-Horizon Radar* - Aviation Journal, No.6, 2002;
- Guo Xin, Ni Jin Lin - *Ship Detection with Sky Wave over-the-Horizon Radar with Short Coherent Integration Time* - Electronics and Information Journal, No.4, 2004;
- Kong Yong, Meng Xiangzhong, et al - *Combat Efficiency Evaluation for Sky Wave Over-the-Horizon Radar Based on ADC Modeling* - Fire Control Radar Technology, No.3, 2005;

- Kong Yong, Wang Xiao Nian, et al - *A Model for Evaluating Sky Wave Over-the-Horizon Radar Combat Efficiency* - Equipment Command Institute of Technology Journal, No.1, 2006;
- Liang Yi and Wang Zhong - *Refraction effect in troposphere on OTH radar signal* - Chengdu Institute of Information Engineering Journal, No.1, 2007.

Also the number of posts on Radio HAMS blogs concerning frequent disturbances in the HF band generated in the Chinese region increased recently. There are rumours regarding a Chinese OTHR-SW system apparently located on the Hainan Island, in the south of China, who has been detected by several international HAMS. Other not-confirmed rumours refer that China acquired from Russia the “Podsolnukh-E surface-wave OTH radar”. Despite the rumours, the interest of PRC in surface-wave and sky-wave OTHR systems is evident. [74]

## Germany

Starting from a CODAR system the *University of Hamburg* developed the **WERA** (“WEllen RAdar”): an HF-SWR that operates, with a relatively low transmitted power, in the upper part of the HF band. The radar is employed for the monitoring of current and the elaboration of wave-maps.

- (<http://ifmaxp1.ifm.uni-hamburg.de/WERA.shtml>)

## Other OTHR-SW systems

Many other nations are suspected to run studies on OTHR applications or to hide a over the horizon radar prototype. Among these, not-confirmed rumours include:

- Denmark;
- Iran;
- Israeli;
- Romania;
- Turkey;
- Ukraine.

## HF sky-wave Research Facilities

Among the HF systems designed for research purposes that employ a sky-wave transmission it is worth to mention:

- **SuperDARN**: “Super Dual Auroral Radar Network”. It is not a conventional OTH radar, but a network of Ionospheric sensors, operating in HF and VHF bands, that cover the northern (9 apparatus) and southern (6 apparatus) hemispheres. Their mission is the study of the higher part of the Atmosphere, the Ionosphere and the Magnetosphere.  
(<http://superdarn.jhuapl.edu>)
- **HAARP**: “High Frequency Active Auroral Research Program”. It is an active device located in Alaska, capable to temporally and locally alter the electronic structure of the Ionospheric plasma in order to study the evolution of the medium toward the normal status.  
(<http://www.haarp.alaska.edu/>)