# NWRA Principal Results from IARPA HFGeo Program Phases 1A and 1B 

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Zunicalc (1A and 1B): Dr. George Zunich

ASTRA (1B): Dr. Geoff Crowley and his staff

## NWRA NWRA's Phase 1A and 1B Approaches

- NWRA was selected as a performer on both HFGeo Phase 1A and 1B
- NWRA was the only Phase 1B performer
- Phase 1A focused on Dr. Chad Spooner's expertise in cyclostationary signal processing, signal separation, and angle-of-arrival (AoA) estimation
- Sub-focus on examining effects on AoA due to smallscale ionospheric structure and medium-scale TIDs
- Phase 1B approach is to apply assimilative ionospheric modeling to account for mediumscale TIDs


# Phase 1A Principal Results 

NorthWest Research Associates<br>Zunicalc, Inc.

- Phase 1A Proposal Title: "Cyclostationary Signal Processing for Enhanced HF Signal Separation and Geolocation by Extraction of Temporal Signatures"
- ‘Cyclostationary Signal Processing’ (CSP)
- Exploit the statistical structure of communication and radar signals
- PSK31, AM-DSB, LFMCW radar, and many others have exploitable CS
- Main benefits are noise and cochannel-interference tolerance
- 'Signal Separation’
- Separation of modes belonging to a single transmitted signal
- Separation of multiple cochannel signals each with multiple modes
- DF and copy for each mode of each signal is desired
- 'Temporal Signatures’
- Time-of-arrival differences for the modes of a single signal
- Use together with DOA for each mode to enhance emitter geolocation using high-fidelity ionospheric model


## NWRA Cyclostationary Signals: The Core Concepts

Since 1984


The cycle frequencies (CFs) $\alpha$ are the key.

CFs are simple functions of modulation parameters like bit, symbol, chip, and hop rates, and doubled carriers.

Also mixtures of doubledcarriers and harmonics of modulation rates.

Normalizing spectral correlation by the geometric mean of the variances of the two involved waveforms results in the spectral coherence function.

Since 1984


Simulation Example to Illustrate Expected Performance Benefits Compared to Conventional Processing

Three vector sensors (18 elements) SINAD for Two Simulated Skywave AM Signals


- Bandwidths of $\sim 3 \mathrm{kHz}$
- X-O component delays $\sim 0.5 \mathrm{~ms}$
- One-hop propagation
- Detection probabilities, angle statistics, SINADs averaged over several minutes
- Block length of 655 ms
- 'CSP' = MUSIC, Cyclic MUSIC, SCORE, and simple non-blind BF used ("Data-Free Weight Vector" (DFWV) beamformer)
- 'No CSP' = MUSIC and non-blind BF only


## CSP vs. No CSP: Detection

## Two Simulated Skywave AM Signals

Detection of All Four Signal Components ( 2 X and 2 OModes )



## CSP vs. No CSP: Signal Separation/SINAD Two Simulated Skywave AM Signals

Average Output SINAD Over All Four Signal Components ( 2 X and 20 Modes)


Average SINAD Improvement of 35 dB with DFWV Beamforming
Negligible Degradation for Miscalibrated Arrays, But Must use CSP

## Collected-Data Examples to Illustrate Nominal Operation

## Radar Scenario Processing Results

 (March 3, 2012 19:22 Radar)Scenario 1, Azimuth Angle Estimates

## Azimuth



Block $=0.33 \mathrm{sec}$
MUSIC Only

Elevation


## TDOA



Random angle estimate perturbations not yet fully explained

## USB Scenario Processing Results

(March 4, 2012 18:23 UTC USB)


## NWRA

## Signal Processing Phase-1A Assessment

- Complete end-to-end signal processing solution written in MATLAB
- Performance on IARPA HF-GEO data inconclusive
- Array calibration error not quantified
- Final Phase 1A EMVS data sets had unexpected very low SNRs
- Directed to focus only on ionospheric modeling before final testing of Phase 1A algorithms
- Algorithms degrade for small X-O relative delays and small signal bandwidths
- Suggest using well-calibrated array to separate $X$ and $O$ via polarization first, when possible, then apply CSP-based algorithm - The cochannel situation will still exist and will still benefit from CSP


# Phase 1B Principal Results 

NorthWest Research Associates
Zunicalc, Inc.
ASTRA

## Assimilative Ionospheric Modeling

- Extended and applied NWRA's ionospheric data assimilation algorithm
- GPS Ionospheric Inversion (GPSII; pronounced "gypsy")
- GPSII assimilates GPS L1/L2 beacon signals, ionograms, and a host of other ionospheric-related data types
- In Phase 1B, GPSII was extended to assimilate delay-Doppler from known HF links
- Motivated by ASTRA TIDDBIT Doppler sounder

Fridman, Sergey V., L. J. Nickisch, Mark Aiello, and Mark A. Hausman "Real time reconstruction of the three-dimensional ionosphere using data from a network of GPS receivers" Radio Science, 41, RS5S12, doi:10.1029/2005RS003341, 2006

Fridman, Sergey V., L. J. Nickisch, and Mark Hausman, "Personal-computer-based system for real-time reconstruction of the three-dimensional ionosphere using data from diverse sources," Radio Science, 44, RS3008, doi:10.1029/2008RS004040, 2009

Crowley G., and F. S. Rodrigues, "Characteristics of Traveling Ionospheric Disturbances Observed by the TIDDBIT Sounder," Radio Sci., doi:10.1029/2011RS004959, 2012.

## The Ionospheric Reconstruction Problem: Tikhonov Method

$$
\begin{aligned}
& N(\mathbf{r}, t)=N_{0}(\mathbf{r}, t) e^{u(\mathbf{r}, t)} \\
& U=\{\{u(\mathbf{r}, t)\}, \text { Biases }\} \\
& Y \approx M[U]
\end{aligned}
$$

$Y$ is the set of measured absolute/relative TEC values and data points from other types of ionospheric measurements.

| The solution must fit the data within <br> errors of measurements. |  |
| :--- | :---: |
|  |  |
| There are infinitely many such solutions: | $(Y-M[U])^{T} S^{-1}(Y-M[U]) / \operatorname{dim}(Y) \leq 1$ |
| The smoothest solution is selected by <br> minimizing the stabilizing functional |  |

-The pseudo-covariance $P$ matrix is defined in such a way that the stabilizing functional tends to take on larger values for unreasonably behaving solutions ("reasonable" $\Leftrightarrow$ "smooth").
-The nonlinear optimization problem is solved iteratively (NewtonKontorovich).

## NWRA Assimilation of Doppler data into GPSII

- GPSII encodes the Ray Path Response operator
- Describes how ray quantities change with electron density changes
- Doppler shift is time derivative of phase path

$$
D=-\frac{f}{c} \frac{\partial P}{\partial t} \approx-\frac{f}{c} \frac{\left(P_{i}-P_{i-1}\right)}{\left(t_{i}-t_{i-1}\right)}
$$

so the functional derivative is

- NWRA developed a ray tracing services package called IonoSynth
- Based on Jones-Stephenson 3D magnetoionic ray tracing
- Incorporates ray homing for specified links
- Generates vertical and oblique ionograms
- Generates time series of AoA
- Generates channel scattering function figures of merit
> Time series of delay, Doppler shift, signal strength for propagation modes on specified links (through 3 hops)
- Output in both flat file and XML formats
- Uses GPSII output ionosphere model
- IonoSynth is fully documented in an ICD


# GPSII/IonoSynth results for 19 January 2014 WSMR data 

Generated 08/08/2014

## GPSII/IonoSynth Test Case

- The following set of slides show summary plots for tests of the GPSII/IonoSynth analysis of Government-provided data for 19 January 2014
- Angle-of-Arrival (AoA) results are presented for assimilation of Doppler sounding data alone (1 minute cadence)
> 7 links assimilated
- 7 Links Assimilated
- January 19 th, 2014
- Range/Doppler vs time used as input to GPSII



Doppler (Rob to G10): O-mode


Since 1984


Since 1984

## 01/19/2014 Doppler sounding only



Since 1984


## 01/19/2014 Doppler sounding only

Since 1984


## 01/19/2014 Doppler sounding only

Since 1984


Since 1984


Since 1984

## 01/19/2014 Doppler sounding only



Since 1984


Since 1984


## Conclusions

- Successful HF Geolocation requires two integrated factors
- 1. Good signal discrimination and angle estimation
- 2. Good ionospheric modeling and HF propagation algorithms
- Understanding HF propagation and corresponding signal effects is necessary for accomplishing 1.
- For example, polarization separation is necessary before good AoAs can be determined if OIX are not separated in range or Doppler
- In Phase 2, a unified approach integrating 1. and 2. should be addressed
- NorthWest Research Associates
- Lead Investigator: Dr. L. J. Nickisch (NWRA)
- Current Team Members:

Dr. Sergey Fridman (NWRA)
Dr. Mark Hausman (NWRA)
Dr. Shawn Kraut (NWRA)
Dr. Chad Spooner (NWRA)
Dr. Dennis Knepp (NWRA)
Dr. Greg Bullock (NWRA)
Dr. George Zunich (Zunicalc)
Dr. Geoff Crowley (ASTRA)

- Research areas of interest
- Ionospheric modeling
- HF radiowave propagation
- Cyclostationary signal processing
- Unique qualifications and capabilities
- Ionospheric data assimilation
> HFGeo Phase 1B performer - Demonstrated mediumscale TID mitigation by assimilation of Doppler sounding data
- HF radiowave propagation
> HFGeo Phase 1B performer - Developed IonoSynth tool that utilizes 3D magnetoionic ray tracing to generate HFGeo performance metrics (vertical/oblique ionograms, channel scattering function modal delay/Doppler, angles-of-arrival)
- Cyclostationary signal processing
> HFGeo Phase 1a performer - Developed signal isolation, angle estimation, and time-difference-ofarrival estimation algorithms
- Type of research group we seek to join:
- We would like to team with a prime contractor who will develop the overall HFGeo Phase 2 system architecture, hardware and software. NWRA, together with Zunicalc and ASTRA will advance the ionospheric modeling, propagation algorithms, and signal processing algorithms initiated under our Phase 1A and 1B efforts and assist in integrating these capabilities into the prototype Phase 2 system.


## Contact Information

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