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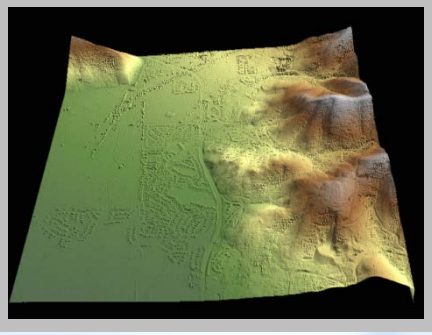

Emerging Applications for Radar Intelligence, Surveillance, and Reconnaissance

Armin W. Doerry

U.S. DEPARTMENT OF ENERGY | NNSA National Nuclear Security Administration

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Emerging Applications for Radar Intelligence, Surveillance, and Reconnaissance

Armin W. Doerry

Sandia National Laboratories

SIAM Conference on Imaging Science

Albuquerque, NM, USA

25 May 2016

ABSTRACT

From the first experiments in the late 19th century to today, radar has continually evolved and become an indispensable tool in the area of Intelligence, Surveillance, and Reconnaissance (ISR). Today's applications include military, intelligence, homeland security, resource management, and scientific missions. As new needs arise, radar offers the possibility of further evolution to meet those needs. We discuss in this presentation some of the emerging applications for ISR to which radar imaging might offer utility.

The task is to "**Exploit Phenomena**" to gain situational awareness.

To design and build such a system:

First, we have to *characterize* the phenomena.

Then we have to employ/develop mathematics to maximize the separation of "information" from "noise."

Using term "noise" very loosely

Only then can we decide the correct hardware/algorithms to build and field operationally.

An "image" is just a map of useful information to meaningful coordinates, usually spatial.

We will discuss

- **Foliage Penetration (FOPEN)**
- **Maritime ISR**
- **Arctic ISR**
- **Spectrum Access**

ISR = Intelligence, Surveillance, and Reconnaissance

Threats

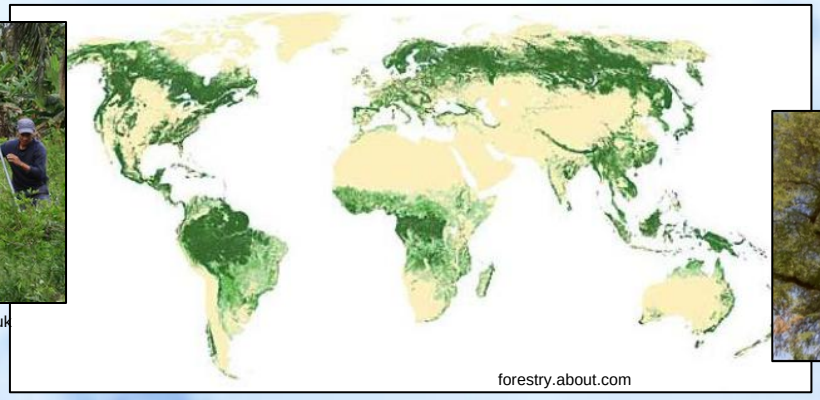
- **South America (US SOUTHCOM)**
  - **illicit trafficking of drugs and other material**
  - **growing problem even with Islamic terrorists**
- **Sub-Saharan Africa (US AFRICOM)**
  - **growing problem of terrorist sanctuaries in failed and failing African states**
- **Many problematic regions exhibit fairly heavy foliage that hinders more traditional ISR assets.**

Lord's Resistance Army

www.theguardian.com

Farc Rebels

www.bbc.co.uk



forestry.about.com

america.aljazeera.com

Boko Haram

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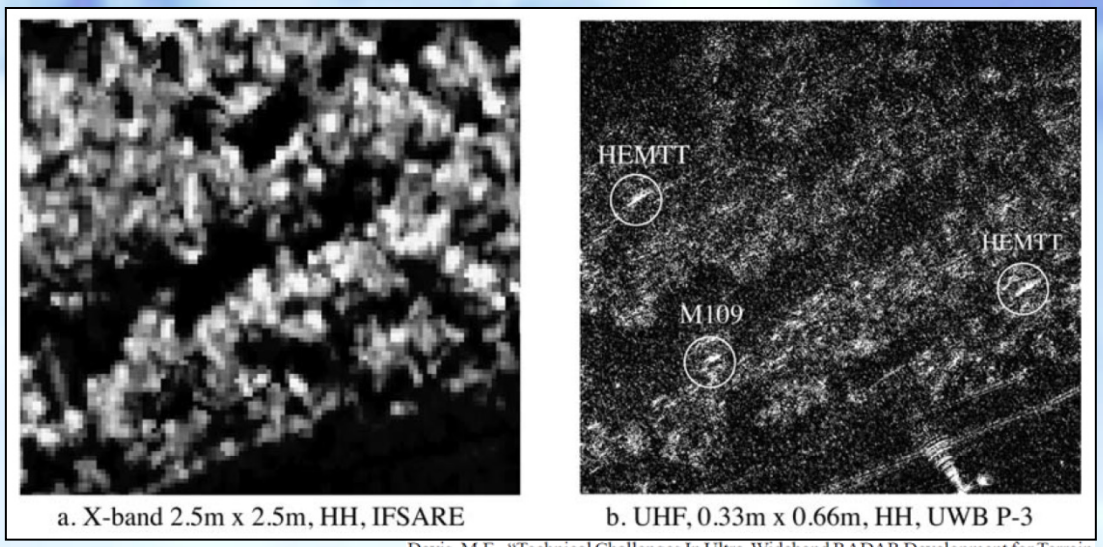
Foliage Penetration - Issues

- **Penetrating long-wavelength (VHF/UHF) FOPEN radar fairly well established**

SAR images of foliage-obscured targets



a. X-band 2.5m x 2.5m, HH, IFSARE

b. UHF, 0.33m x 0.66m, HH, UWB P-3

Davis, M.E., "Technical Challenges In Ultra-Wideband RADAR Development for Terrain Mapping," *Proc*", Presented at *IGARSS*, Seattle, WA, April 1998.

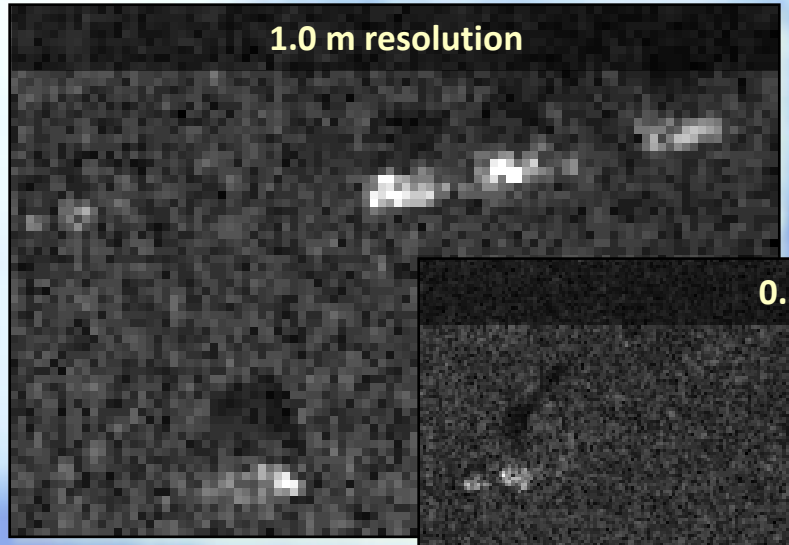
But

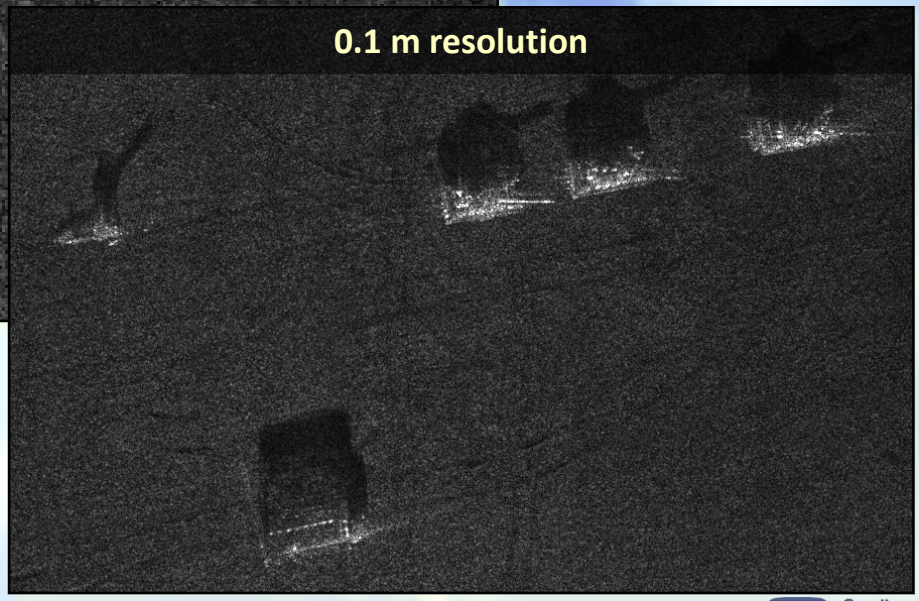
Signal bandwidth is accordingly very limited in several respects

- **Limited resolution for target characterization/identification**
- **Spectrum sharing issues, i.e. interference**

SAR = Synthetic Aperture Radar

Value of Resolution





Finer resolution clearly offers more detail

- **but at the expense of greater required bandwidth**

Foliage Penetration - Needs

www.satnews.com

- **Technologies that need to be explored include the following.**
  - **FOPEN Phenomenology, including target resonance characteristics**
  - **Interference-tolerant image formation and signal processing techniques**
  - **Low interference waveforms**
  - **Multi-band radar systems and exploitation techniques**
  - **VHF/UHF Polarimetric Exploitation**
  - **FOPEN Moving Target detection and tracking**

www.srcinc.com

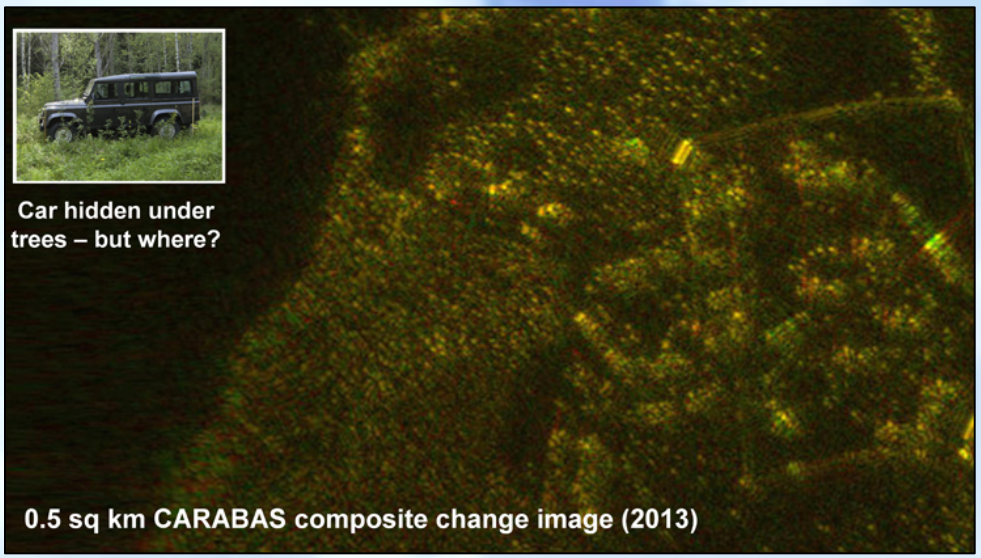
  - **New meta-material antennas**
  - **Ultra-wideband sub-GHz radar hardware**

Behavior Analytics/Filters

- **An individual image is just a snapshot in time**
- **A sequence of images allows us to observe the time dimension**
  - **Allows us to observe behavior**

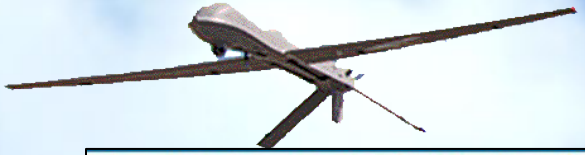
www.saab.com

- **Question**
  - **How can we exploit observed versus expected behavior to help us with FOPEN information extraction?**



www.saab.com

Threats – Maritime Domain



- **The US Asia 'pivot' means inherently dealing with islands and coasts of the Pacific rim,**
  - **defined by areas claimed as a state's Economic Exclusion Zone (EEZ),**
    - **stretching from the seaward edge of the state's territorial sea out to 200 nautical miles from its coast.**

www.worldbulletin.net

www.huffingtonpost.com

- **An increasingly belligerent Iran continues to threaten closing the Strait of Hormuz.**
  - **This will likely include the use of mines, swarms of speedboats, and Iran's submarine fleet.**

www.reuters.com

- **Illicit Trafficking (drugs, etc.) via maritime routes**

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Island Building

News › World › Asia

South China Sea dispute: Beijing is 'not afraid of war' with the US - but just what would they be fighting over?

War of rhetoric reaches new levels after US guided missile destroyer sails past the Subi Reef - a 5.7km strip of sand that isn't even above sea level during low tide

Adam Withnall | @adamwithnall | Wednesday 28 October 2015 09:28 BST |

A handout photo released by the US Navy dated 25 May 2015 of the guided-missile destroyer USS Lassen (front) conducting a naval exercise off South Korea *EPA*

The battle of rhetoric between the US and China continues to escalate over the disputed South China Sea, with state-linked newspapers claiming Beijing is "not frightened to fight a war in the region".

The threat in an editorial of the Global Times comes after the US said it did sail a Navy ship near to China's artificial islands in the Spratly archipelago – and that it will do it again.

But just what is it that has led the two nations, who are otherwise

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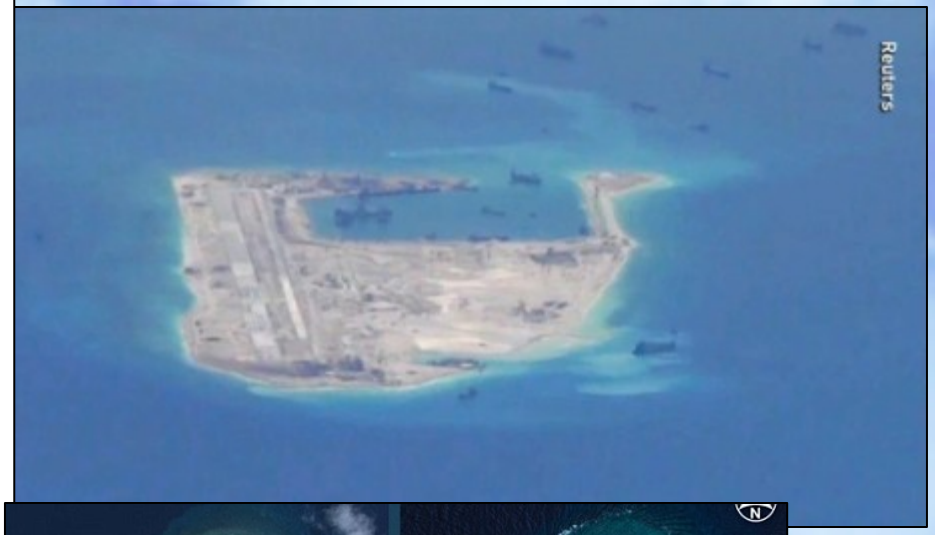

www.cnn.com

www.dailymail.co.uk

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Threats – Submarine Vessels

- **Modern diesel-electric coastal submarines are increasingly ‘quiet’ and difficult to detect.**
- **Illicit trafficking (e.g. drugs, etc.) via the use of both semi-submersible (low-freeboard) water-craft, and true fully-submersible submarines.**

www.globalsecurity.org

www.jeffhead.com

Submarine Detection – Issues

- **Typical radar frequencies are unable to penetrate seawater**
  - **Limited to detecting surface scattering**
- **Seas are in constant motion**
- **Sea “clutter” not nicely behaved**
  - **Great variability**

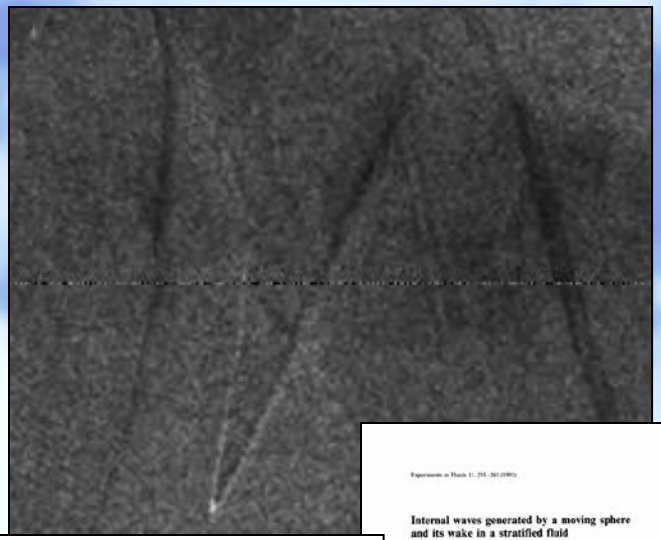
www.esrl.noaa.gov

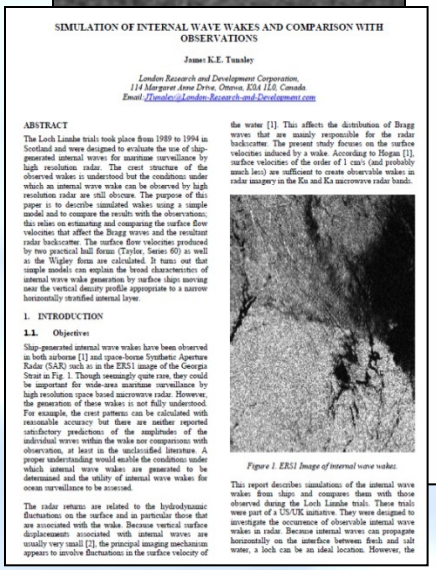
www.antiguaatlanticrowers.com

Submarine Detection - Needs

- **Exploration of variety of techniques to detect threat submerged craft**
  - **Direct detection techniques**
    - **e.g. periscope detection**
      - **Small targets difficult to separate from sea clutter**
  - **Indirect detection techniques**
    - **e.g. wake detection**
      - **Internal wakes**
        - » **Loch Linnhe tests in the 1980's and 1990's**
  - **Utility of Doppler processing**
    - **e.g. MTI processing**

Courtesy EAS, 1999





SIMULATION OF INTERNAL WAVE WAKES AND COMPARISON WITH OBSERVATIONS

James K.E. Tunaley

London Research and Development Corporation, 114 Margaret Anne Drive, Ottawa, K0A 1L0, Canada. Email: JTunaley@London-Research-and-Development.com

ABSTRACT

The Loch Linnhe trials took place from 1989 to 1994 in Scotland and were designed to evaluate the use of ship-generated internal waves for maritime surveillance by high resolution radar. The crest structure of the observed wakes is understood but the conditions under which an internal wave wake can be observed by high resolution radar are still obscure. The purpose of this paper is to describe simulated wakes using a simple model and to compare the results with the observations; this relies on estimating and comparing the surface flow velocities that affect the Bragg waves and the resultant radar backscatter. The surface flow velocities produced by two practical hull forms (Taylor, Series 60) as well as the Wigley form are calculated. It turns out that simple models can explain the broad characteristics of internal wave wake generation by surface ships moving near the vertical density profile appropriate to a narrow horizontally stratified internal layer.

1. INTRODUCTION

1.1. Objectives

Ship-generated internal wave wakes have been observed in both airborne [1] and space-borne Synthetic Aperture Radar (SAR) such as in the ERS1 image of the Georgia Strait in Fig. 1. Though seemingly quite rare, they could be important for wide-area maritime surveillance by high resolution space based microwave radar. However, the generation of these wakes is not fully understood. For example, the crest patterns can be calculated with reasonable accuracy but there are neither reported satisfactory predictions of the amplitudes of the individual waves within the wake nor comparisons with observation, at least in the unclassified literature. A proper understanding would enable the conditions under which internal wave wakes are generated to be determined and the utility of internal wave wakes for ocean surveillance to be assessed.

The radar returns are related to the hydrodynamic fluctuations on the surface and in particular those that are associated with the wake. Because vertical surface displacements associated with internal waves are usually very small [2], the principal imaging mechanism appears to involve fluctuations in the surface velocity of the water [1]. This affects the distribution of Bragg waves that are mainly responsible for the radar backscatter. The present study focuses on the surface velocities induced by a wake. According to Hogan [1], surface velocities of the order of 1 cm/s (and probably much less) are sufficient to create observable wakes in radar imagery in the Ku and Ka microwave radar bands.

Figure 1. ERS1 Image of internal wave wakes.

This report describes simulations of the internal wave wakes from ships and compares them with those observed during the Loch Linnhe trials. These trials were part of a US/UK initiative. They were designed to investigate the occurrence of observable internal wave wakes in radar. Because internal waves can propagate horizontally on the interface between fresh and salt water, a loch can be an ideal location. However, the

Experiments in Fluids

Internal waves generated by a moving sphere and its wake in a stratified fluid

E. J. Hopfinger and J.-B. Flor*

Institut de Mécanique de Grenoble, B.P. 53, F-38041 Grenoble, France

J.-M. Chomaz and P. Bonneton

Météorologie Nationale, CNRM Toulouse, 42 Ave. Coriolis, F-31057 Toulouse, France

1 Introduction

2 Experiments

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Maritime Modes - Needs

- **Robust, Reliable Mine and Mine-like object detection**

- **Robust, Reliable Small vessel detection**
  - **Life-raft detection**

www.yachtingmonthly.com

http://www.rivercityvibe.com

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Threats – Maritime Vessel ID

- **vessel characterization, classification, identification**
  - **Uncooperative target vessels**
  - **In spite of deception techniques**
  - **In spite of unknown target motion**

ASIA PACIFIC

U.S. Said to Turn Back North Korea Missile Shipment

By DAVID E. SANGER JUNE 12, 2011

SEOUL, South Korea — The United States Navy intercepted a North Korean ship it suspected of carrying missile technology to Myanmar two weeks ago and, after a standoff at sea and several days of diplomatic pressure from Washington and Asia nations, forced the vessel to return home, according to several senior American officials.

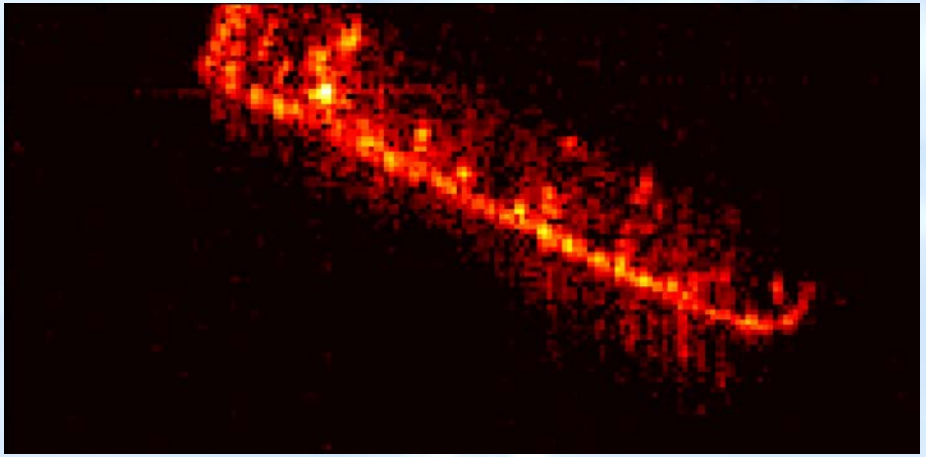
Washington made no announcement about the operation, which paralleled a similar, far more public confrontation with North Korea two years ago. But in response to questions about what appears to be a growing trade in missiles and missile parts between North Korea and Myanmar — two of the world's most isolated governments — American officials have described the episode as an example of how they can use a combination of naval power and diplomatic pressure to enforce United Nations sanctions imposed after the North's last nuclear test, in 2009.

It was a rare victory: a similar shipment of suspected missile parts made it to Myanmar last year before American officials could act. Despite the Obama administration's efforts to squeeze North Korea with both economic and trade sanctions, there are continuing reports of sophisticated missile technology exchanges, some of it by air, between North Korea and Iran,

New York Times

www.apfn.net

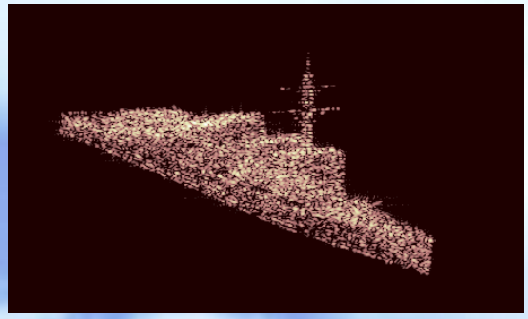
Typical ISAR image of vessel in open ocean

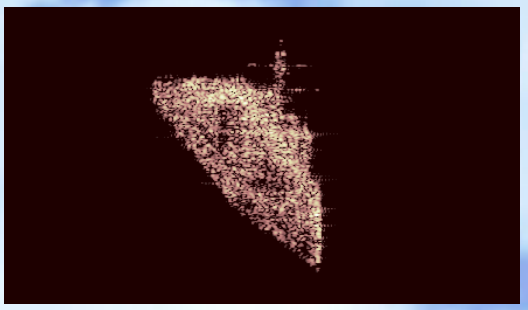


ISAR = Inverse SAR

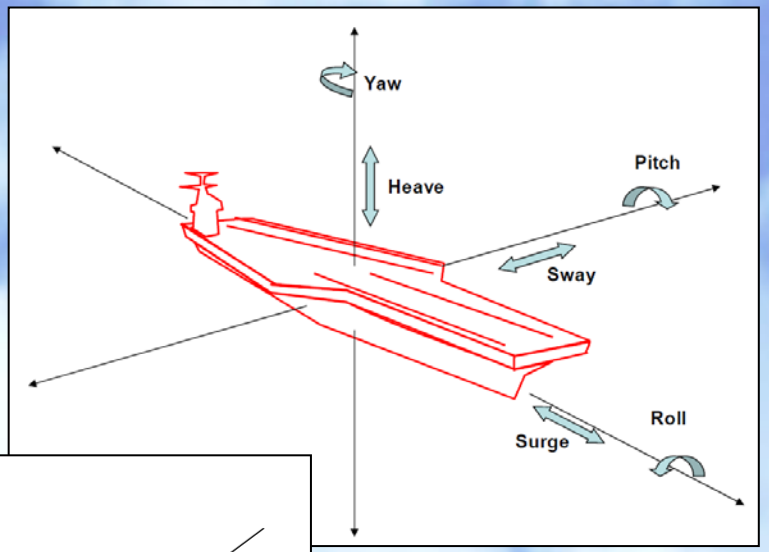
Maritime Vessel Imaging - Needs

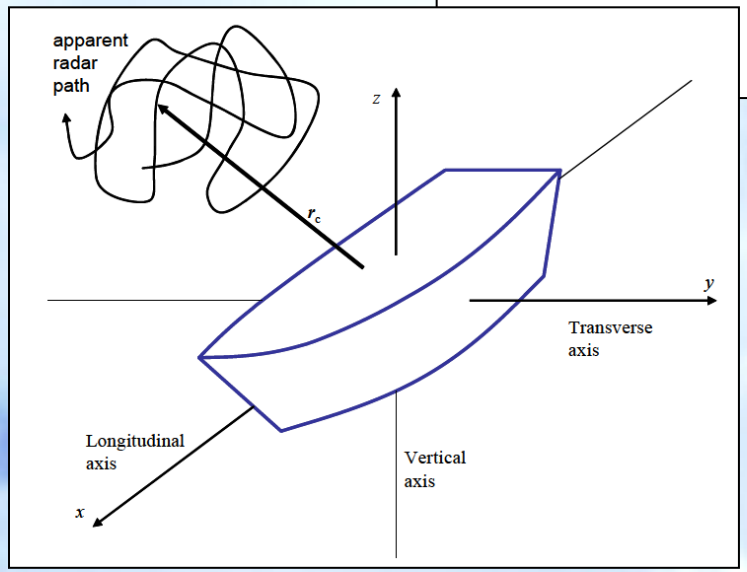
- **Robust & reliable high-fidelity Inverse-SAR imaging**
  - **3D imaging**
  - **Fine-resolution imaging**
  - **Multi-aperture techniques**





Maritime ISAR imaging with airborne radar
Master of Science Thesis
VERONICA BÄCKSTRÖM
ANTON SKÄRBRATT
Department of Radio and Space science
Radar Remote Sensing Group
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden, 2010





Vessel motion should allow creating a 3-D image

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Threats – Arctic

- **Control of a treasure chest of resources**
  - **experts estimate that more than 20 percent of the world's oil and gas reserves are in the Arctic**
- **Navigation through new arctic shipping routes**
  - **Northwest Passage across the arctic coast of Canada**
  - **Northern Sea Route across arctic coast of Russia**

Wikimedia Commons

Bloomberg

Rosneft Says Exxon Arctic Well Strikes Oil

By Ilya Arkhipov, Stephen Bierman and Ryan Chilcote - Sep 27, 2014

Russia, viewed by the Obama administration as hostile to U.S. interests, has discovered what may prove to be a vast pool of oil in one of the world's most remote places with the help of America's largest energy company.

Russia's state-run OAO Rosneft (ROSN) said a well drilled in the Kara Sea region of the Arctic Ocean with Exxon Mobil Corp. (XOM) struck oil, showing the region has the potential to become one of the world's most important crude-producing areas.

(PA photo via *IHS Maritime 360*)

www.geology.com

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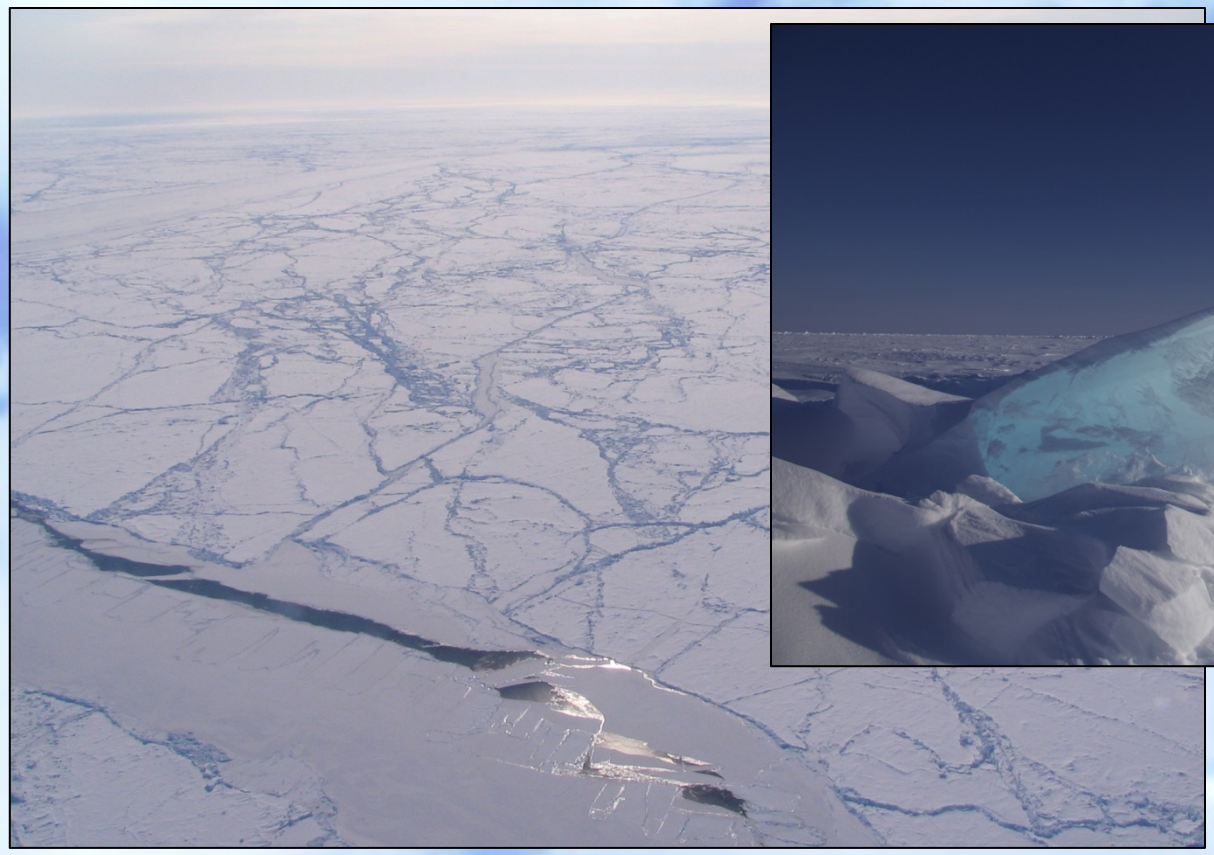
Arctic ISR - Issues

- **All same issues of non-arctic maritime ISR**
- **Added environmental factors**
  - **Sea Ice**



www.nasa.gov

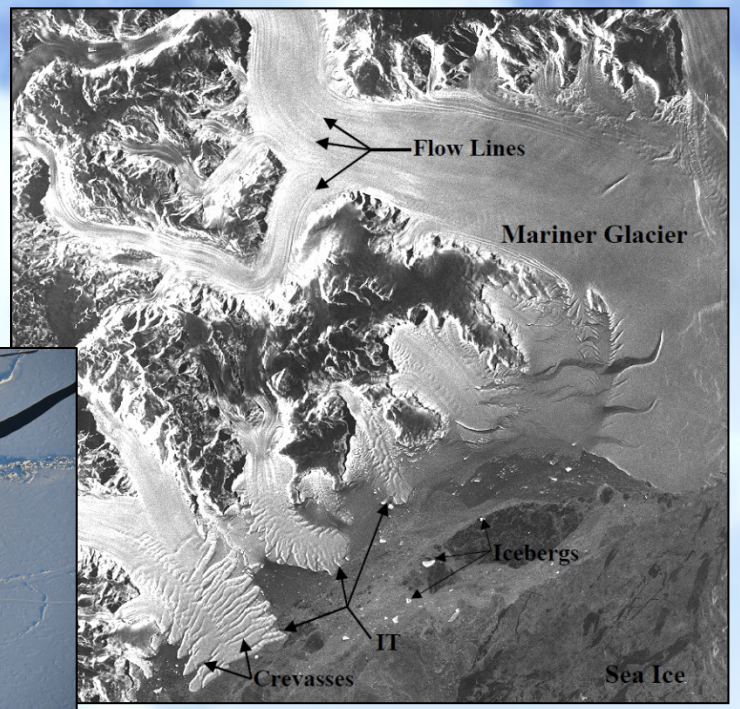
www.nasa.gov

Arctic ISR - Needs

- **Reliable ISR of the arctic will be critical**
  - **monitoring environmental conditions**
    - **Sea ice thickness maps**
  - **Persistent human activities detection and monitoring**
    - **Shipping**
    - **Resource management**

www.way-up-north.com

wall.alphacoders.com



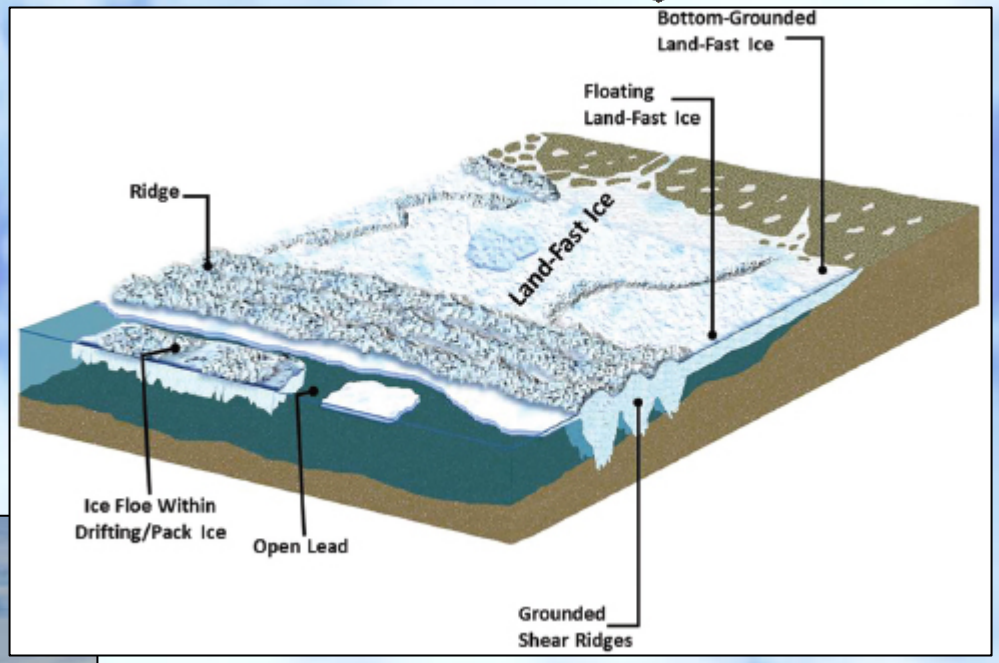
CSA 1997

Ice-breakers have limits to sea-ice thicknesses through which they can break.

Sea Ice Thickness - Challenges

Sea ice may

- contain ridges on top and bottom
- have several layers
- be topped with snow
- contain puddles of water
- change with time
  - move
  - alter form



University of Alaska Fairbanks, Geophysical Institute

blog.helenglazer.com

web.vims.edu

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Threats – Spectrum Access

- **Near-peer adversaries offer the potential to subject ISR radar systems to jamming and spoofing**
  - **Falls under the larger banner of Anti-Access / Area-Denial (A2/AD)**
- **Fratricidal jamming**
  - **Too many systems want to use same spectrum**

SAR image with interference

www.rrsg.uct.ac.za

North Korean GPS Jammers

www.ubergizmo.com

Spectrum Access - Issues

- **Radar potentially vulnerable in multiple areas**
  - **Direct radar waveforms**
  - **GPS navigation**
  - **Command & Control**

The question is

1. **How do we avoid these vulnerabilities?**
2. **How do we ensure adequate performance in spite of these vulnerabilities?**

See discussion in:

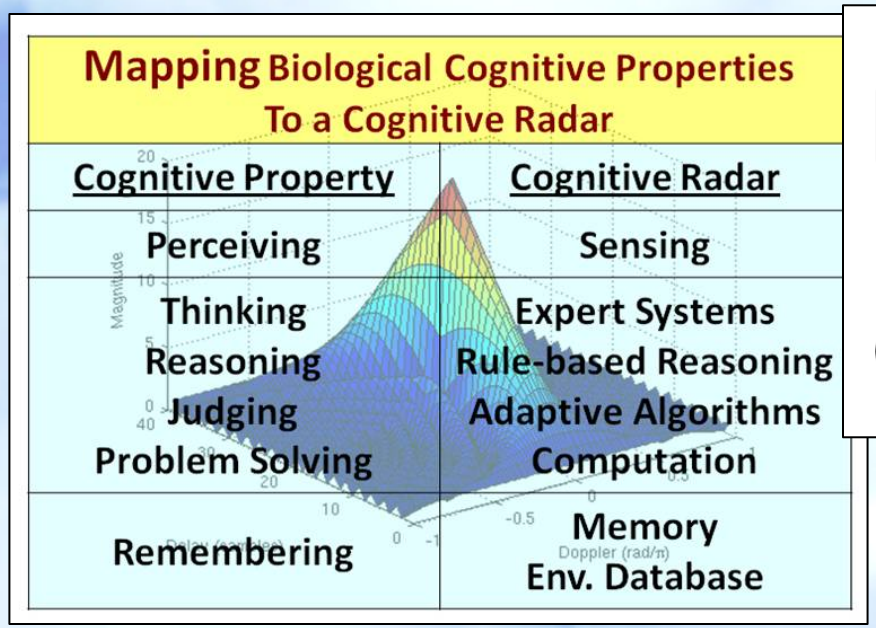
Armin W. Doerry, “Comments on radar interference sources and mitigation techniques,” SPIE 2015 Defense & Security Symposium, Radar Sensor Technology XIX, Vol. 9461, Baltimore, MD, 20-24 April 2015.

Spectrum Access - Needs

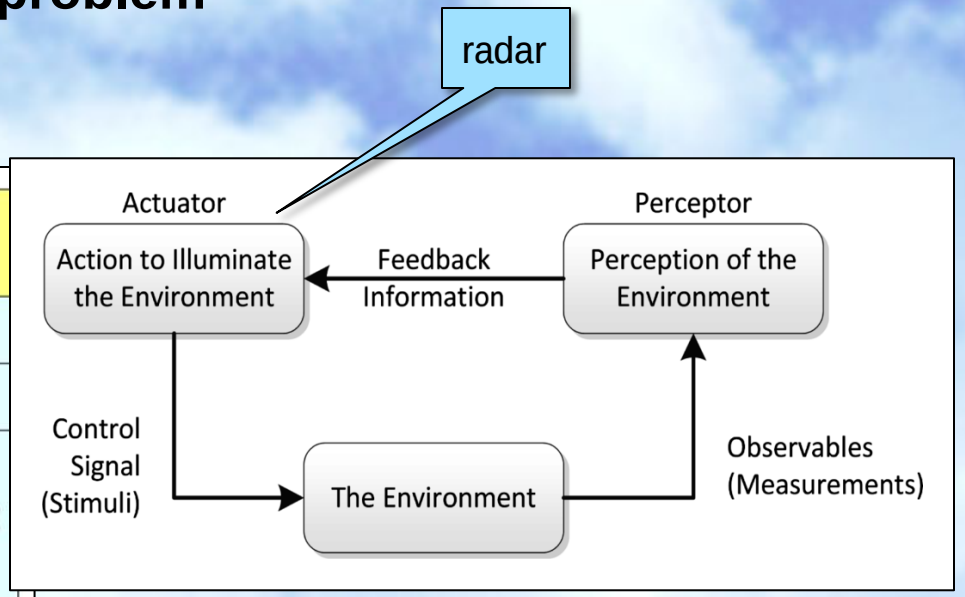
- **Radar Waveforms**
  - **Low Probability of Intercept (LPI) waveforms**
  - **Low Probability of Detection (LPD) waveforms**
  - **Optimized waveforms (Cognition)**
- **Radar Signal Processing**
  - **Null-steering array antennas.**
  - **Interference mitigating signal processing techniques.**
  - **Radar operation in the absence of GPS-aiding, in a GPS-denied environment.**
- **Reduced dependence on GPS**
  - **External navigation aiding techniques.**
  - **SAR-image (or other radar data) aiding of the navigator.**
- **More Autonomy**
  - **Cognition**

Cognition & Optimization

- **If we know (or can measure) the spectral environment, then we can adapt radar operation accordingly**
  - **Becomes an optimization problem**

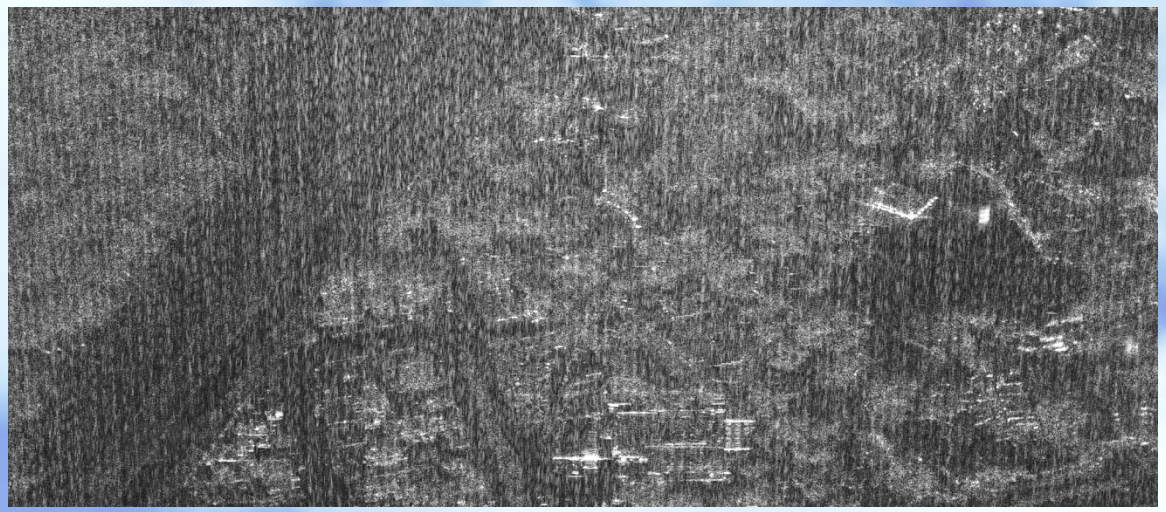


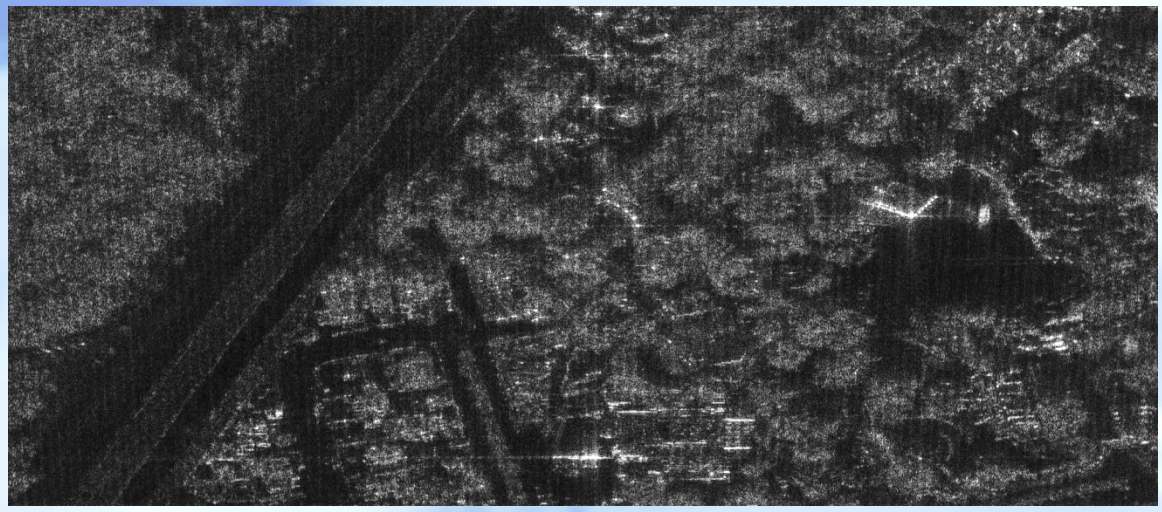
www.defenseiq.com



Khashayar Kotobi, Philip B. Mainwaring, Conrad S. Tucker, Sven G. Bilén, "Data-Throughput Enhancement Using Data Mining-Informed Cognitive Radio," www.mdpi.com

Interference Mitigation





If the radar receiver remains linear, then even rudimentary signal processing techniques can often be employed to noticeably clean up a SAR image,

<u>but</u>

More sophisticated interference (e.g. intentional jamming or spoofing) will require more sophisticated processing.

Takeaways

- **There are many ISR problems that still need to be solved**
  - **Radar seems to be a good candidate for many of them**
- **We need to first understand the nature of the problem**
  - **Phenomenology**
  - **This is a hard problem all by itself**
- **Only then can we develop the right algorithms to extract and map the information we need**
  - **And build the right sensor system**

The End

Miscellaneous Needs

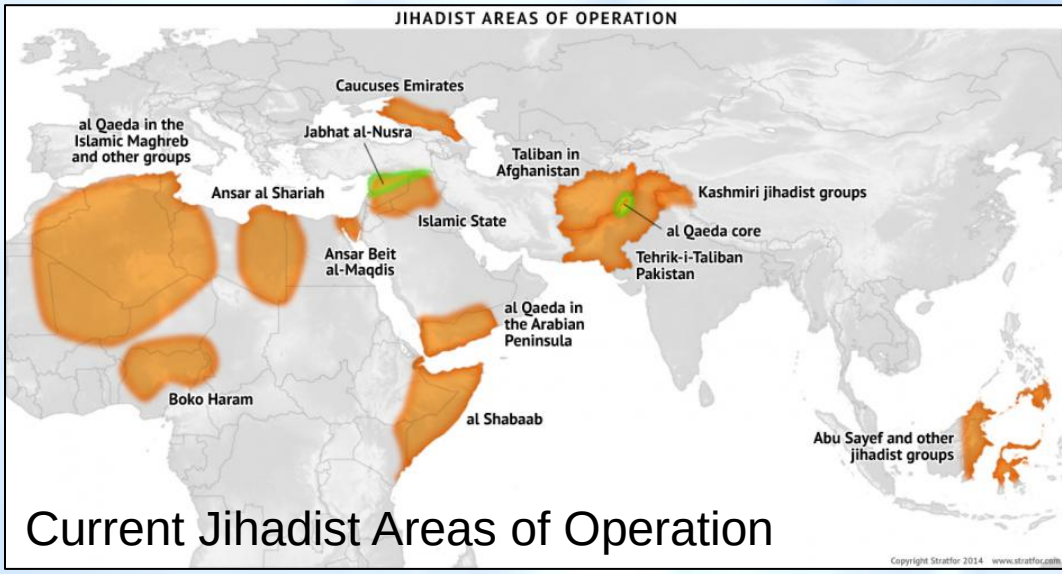
- **Tunnel Detection**
- **Fine Resolution Moving Target Imaging (ISAR)**
  - **with the goal of target discrimination, and perhaps even identification**
- **Adjustable aperture antennas**
  - **to facilitate both near-range wide-angle radar modes, and long range high-gain modes**
- **Multi-user, multi-mode scheduling algorithms**
  - **Think about how a mainframe computer's operating systems handles multi-tasking, or jobs from multiple users.**
- **Behavior Discrimination**
  - **Not just where they are, but also what they are doing**
- **Windmill Effects Mitigation**

Background

- **The US is emerging from 14 years of Counter-Insurgency (COIN) operations in Iraq and Afghanistan**
  - **Asymmetrical warfare against technologically unsophisticated adversary**
  - **US history suggests that this kind of conflict will nevertheless continue to be much more common than larger conflicts**
- **In 2011, President Obama announced his "pivot" to the Pacific**
  - **Prepare for dealing with a technology "near-peer"**
  - **Both China and Russia are becoming increasingly aggressive**
    - **It's all about controlling economic resources**
- **The US Military is an Expeditionary Force**
  - **Operates with small forward-deployed footprint**
    - **Drives "Doing more with less."**
      - **Favors remote operation**
      - **Favors automation**
      - **Favors multi-mission, multi-mode radar systems**

Truisms to Guide us

- **There will always be future wars and armed conflicts**
  - **More likely COIN operations than major conflicts**
- **The DoD will generally drive needs more than DHS**
  - **mainly because they will typically have larger funding**
- **Our military is expeditionary in nature**
  - **We fight wars "over there" and not "over here"**
- **Commitment to minimize collateral damage**
  - **which means "precision strike"**
  - **which requires "precision ISR"**
    - **including high-confidence target identification**



Current Jihadist Areas of Operation

Truisms to Guide us

- **ISR and strike missions are merging**
  - **effort to "shorten the decision cycle"**
  - **Decision cycles will keep getting shorter**
    - **Information latency will become less and less tolerable**
- **Bad guys include some smart people**
  - **who will always figure out a way to nullify a current advantage of yours**
  - **Urgent needs and quick-reaction needs will always manifest to counter bad guys' evolving strategies and tactics**
    - **JUONS and QRC needs**
- **In the end, it's about the information, not the data**
- **The easier an instrument is to use, the more it will get used**

What that means for us

- **Will require ever more capability**
  - **Better performance**
    - **Range, resolution, modes, utility**
- **Will require ever smaller packages**
  - **Size, weight, and power**
    - **Part of larger sensor suites**
- **Will need to be ever easier to use**
  - **Automated data analysis and tactical decision making**
- **Will need to be adaptable**
  - **Quick mitigation of surprises**
    - **JUONS, etc.**

The End (for real)