Air Force Research Laboratories

PNT and GPS Space Segment
Investment Portfolio and
Science & Technology
Investments

30 October 2014

Colonel David Goldstein
Director
Space Vehicles Directorate
Air Force Research Laboratory
Space Vehicles Directorate
Vision and Mission

Our Vision
Be indispensable to our nation in improving AF and DoD space capabilities

Our Mission
Stay One Step Ahead in Space

Distribution A: Approved for Public Release
Heritage  
Providing Mission-Critical Capabilities

Impact to Major Systems

- Balloon Program
- Minute Man I
- Rad-hard Electronics 1959-60
- DSP-1
- Detectors 1960-70
- GPS Block I
- Nuclear/Hardening 1970-80
- MILSTAR
- Rad-Hard Processor 1980-90
- Wx Sensors 1960-2000
- STSS Demo System
- Detector/Read out & Processor 1990-2010
- STSS Demo System
- Detector/Processor 1990-2010
- DMSP

Enabling Technologies

- Space Environmental Impacts
- Spacecraft Charging Detection/Mitigation
- High-Efficiency Cryocoolers 1985 - Present
- Payload Adapter 1998 - Present
- Advanced Solar Cells & Arrays 1991 - Present
- DETECTOR/PROCESSOR 1990-2010
- DMSP
- GPS Block I
- Rad-Hard Processor 1980-90
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Heritage
Employing Innovative Concepts & Ops

Missile Warning Sensors
MSTI-1 168 kg
MSTI-2 170 kg
MSTI-3 210 kg

Spacecraft Technology
MightySat-1 64 kg
MightySat-2 120 kg

Hyper Spectral
Launch Failure
Inspectors GN&C

MightySat-3 210 kg

DoD Space Test Program sponsorship for Launch, Spacecraft and/or Ops

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AFRL at a Glance

Employees
- Total: 5,827
- Civilian: 4,610
- Military: 1,217

S&Es
- Total: 3,455
- Civilian: 2,778
- Military: 677

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World Class Facilities
AFRL/Space Vehicles Directorate

Existing Facilities – 55 Bldgs
- 402,000 Sq Ft – Kirtland AFB, NM
- 36,000 Sq Ft - Holloman AFB, NM
- 31,000 Sq Ft - HAARP, Alaska
- 24,000 Sq Ft - Sunspot

Comprehensive integration & test facilities for small, experimental satellites or spacecraft components

Distribution A: Approved for Public Release
AFRL is investigating science and technology options for future GPS spacecraft
• Increasing flexibility
• Reducing spacecraft cost
• Exploring new signal options
• Developing components for reduced payload cost, size, weight, and power
• Manufacturable atomic clocks

AFRL is developing inertial components for GPS-denied navigation
• Cold atom inertial navigation systems
Science and Technology for GPS Spacecraft

- AFRL has funded a portfolio of projects supporting next generation GPS spacecraft

<table>
<thead>
<tr>
<th>Technologies</th>
<th>Capabilities</th>
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<tbody>
<tr>
<td>High efficiency GaN amplifiers</td>
<td>Lower-SWaP spacecraft OR higher power signals</td>
</tr>
<tr>
<td>On-orbit Reprogrammable Digital</td>
<td>Increased signal flexibility after launch</td>
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<tr>
<td>Waveform Generators</td>
<td>Lower cost OR increased capability payload</td>
</tr>
<tr>
<td>New antenna concepts</td>
<td>Increased signal strength</td>
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<tr>
<td>Supporting electronics</td>
<td>Information assurance designed-in from the start</td>
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<tr>
<td>Algorithms and new signal combining</td>
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<tr>
<td>methods</td>
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<tr>
<td>Satellite bus technologies for lower</td>
<td></td>
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<tr>
<td>SWaP/ increased resiliency</td>
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<tr>
<td>Advanced cyber technology</td>
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*SWaP = Size, Weight, and Power*
Objective:
- Design, fabricate, and characterize performance of advanced L-band power amplifier engineering development units - Space qualifiable/suitable for GPS

<table>
<thead>
<tr>
<th></th>
<th>Threshold</th>
<th>Objective</th>
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<tbody>
<tr>
<td>Increased $\eta$ (%)</td>
<td>45%</td>
<td>60%</td>
</tr>
<tr>
<td>Increased Power (W RF$_{\text{out}}$)</td>
<td>250</td>
<td>400</td>
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</tbody>
</table>

Payoff:
- Lower S/C power required for same signal strength
  - Less mass/cost for power system
- Reduces waste heat for same signal strength
  - Enables denser layout, decreases thermal subsystem requirement
- Increased signal strength for anti-jam
- Decrease part count in boxes

Acquisition Status:
- Three, 36-month contracts awarded in June 2014
  - Ball, $2.1M
  - Boeing, $4.5M
  - Northrop Grumman, $1M
On-Orbit Reprogrammable Digital Waveform Generator Project

Develop & Demonstrate TRL 5+ technology to digitally produce GPS Signals

Payoff / Benefits
• Reprogrammable on orbit
  – Enables on-orbit up-dates/additions to waveforms
  – Enables shifting of power between modulations.
  – Enables pre-correction of signals
• Improves performance
  – Increased position/time accuracy
• Reduces part count, complexity, & expense
• Reduces mass & power consumption
• Reduces payload integration risk and schedule

Status & Projected Schedule:
• ~$31M over 3 years
• BAA release expected December 2014
• Expect multiple contract awards
Advanced Clock Technologies for GPS Spacecraft

Goal: Develop manufacturable, highly-stable timing for GPS satellites

• **Cold atom atomic clock (cesium)**
  – Leverage clocks used by NIST & USNO – develop low SWAP, space-compatible version
  – Addressing manufacturability and reliability
  – Expect 5X performance headroom over GPS III clocks
  – Status:
    • Built/ tested more-manufacturable microwave cavity
    • Laser system build – in progress

• **Vapor cell optical clock (rubidium)**
  – Similar to current GPS clocks, except lamp and OCXO are replaced with manufacturable telecom lasers & Rb vapor cell
  – Effort began in 2013:
    • Demonstrated 3X performance over GPS III clocks for times less than a few seconds
    • Working to extend useful time and developing packaging options

OCXO = Oven-Controlled Crystal Oscillator
### 59 Small Business Innovative Research Contracts Awarded in 2014

<table>
<thead>
<tr>
<th>Topic</th>
<th>Group</th>
<th>Title</th>
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<tbody>
<tr>
<td>AF141-099</td>
<td>Power Aware GPS User Equipment</td>
<td></td>
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<tr>
<td>AF141-100</td>
<td>Secure Time Delivery Military GPS receivers in Challenged RF Environments Using Existing Wireless Infrastructure</td>
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<tr>
<td>AF141-102</td>
<td>M-Code External Augmentation System</td>
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<tr>
<td>AF141-111</td>
<td>GPS Receiver Cryptography Key Delivery Leveraging NSA’s Key Management Infrastructure (KMI)</td>
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<tr>
<td>AF141-113</td>
<td>Selective Availability Anti-Spoofing Module (SAASM) Compliant GPS Receiver for GEO</td>
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<tr>
<td>AF141-125</td>
<td>GaN Technology for GPS L-Band Power Amplification</td>
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<tr>
<td>AF141-243</td>
<td>Advanced Space Antenna for GPS</td>
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<tr>
<td>AF141-245</td>
<td>L-Band Wide Bandwidth High Performance Diplexer, Triplexer, &amp; Quadruplexer</td>
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<tr>
<td>AF141-250</td>
<td>64MB+ Radiation-Hardened, Non-Volatile Memory for Space</td>
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<tr>
<td>AF141-251</td>
<td>On-Orbit Reprogrammable Digital Waveform Generator for GPS</td>
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<tr>
<td>AF141-110</td>
<td>Compact Precision Atomic Clock</td>
<td></td>
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<tr>
<td>AF141-126</td>
<td>Optical System for Precision Atomic Clocks and Stable Oscillators</td>
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<tr>
<td>AF141-122</td>
<td>GPS PNT Flexible Satellite</td>
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<tr>
<td>AF141-252</td>
<td>Positioning, Navigating, Timing, Communications, Architecture, Mission Design</td>
<td></td>
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<tr>
<td>AF141-253</td>
<td>Disruptive Military Navigation Architectures</td>
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Research Projects
Prof. Mark L. Psiaki, NRC Senior Research Associate*

*on sabbatical leave from Cornell University’s Sibley School of Mech. & Aero. Engr. during 2014-2015 academic year

A. FFT-based direct acquisition of GPS M-code

- \( N/2\log_2(N) \) acceleration of search, speed-up factor 300-1000 with practical \( N \)
- Respect practical \( N \) limit without limiting coherent accumulation interval
- Target TTFF \( \sim 100 \) sec with 2 sec warm-start timing uncertainty, significant J/S
- Test offline & on MITRE GNSSTA SWRX

B. GPS spoofing/meaconing detection & recovery

- Exploit unique spoofed signal features (e.g., identical directions of arrival, code distortion/multiple peaks)
- Develop/analyze precise detection statistics
- Re-acquire true signals using long coherent integration

Raw RF data to correlate w/M code

M code subintervals w/zero-padding for FFT-based cross-correlation

M code of full coherent integ. interval

Initial Attack

Drag-Off

Code

Fractional Part-of-Cycle (s)
Developing a Concept for an AFRL Space Flight Experiment

GPS technology ideas under consideration:

**Test advanced payload technologies**
- Advanced Amplifiers
- ORDWG (Digital Waveform Generator)
- Active array
- Advanced clocks
- High power, directional signals

**Crosslink experiments**

**Experiments with alternate signals**
- Binary coded signals
- Composite BPSK
- Sinusoidal offset carrier
- Multilevel coded spreading symbols
- Prolate spheroidal wave functions

**Ground segment experiments**
- Uplink ranging
- Control of hosted payloads

**Other potential experiments**
- LEO to MEO via electric propulsion
- Alternative orbits

**Also:**
- Quantify how well advanced signal generation and transmission meets
  - Current GPS requirements
  - Future needs
- Measure ground systems’ performance

**Goal:** Solidify a GPS experiment concept for consideration as AFRL’s next space flight experiment (~2016-2020)
Cold Atom Inertial Navigation Systems (INS)

• Developing Cold Atom INS for GPS-denied navigation
  – Chip Based Cold-Atom INS
    • Chip used to control atoms from outside vacuum system
    • Very high accuracy
    • Small form factor
  – Free-space cold atom INS (with AOSense)
    • Operation in 0-1 g environment
• Improving laser systems for cold atom devices
  • Develop robust, maintenance-free laser system
  • Develop laser diodes and optics into small form factor
  • Package into monolithic integrated structure

• Basic research effort on continuously replenished Bose-Einstein Condensate (BEC)
  – Distill thermal atoms into BEC using quantum stimulated scattering
  – Use atom-chip structures to transport atoms continuously to BEC
Summary

• AFRL has funded a portfolio of science and technology efforts to provide options for future GPS spacecraft

• The goal of these efforts is to provide options for:
  • Flexibility in future spacecraft
  • Smaller, less costly space vehicles
  • Performance improvements at affordable cost

• Cold atom technologies show promise for GPS-denied navigation