Institute for Software Integrated Systems
Vanderbilt University

Accuracy Enhancements for TDOA Estimation on Highly Resource Constrained Mobile Platforms

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WASP

Overview

- Introduction
- Motivation
- Challenges
- Solutions
- Results
- Demo

- Supported by DARPA / IXO

Introduction

- Increase in location aware systems and services, E911
- Need for close range monitoring
  - urban and hostile environments
- Need for intelligence in hazardous areas
- Availability of enabling technology
  - Low-cost, low-power DSP
  - RF networks
  - Positioning services (GPS)

Existing systems

- Large form factors
- Large stand off / fixed locations
- High cost
  - Cell phone base station ~$10,000
  - Military units (~$50,000-100,000)
- High precision, networked systems
- Urban clutter
- “Theater” level vs. field level

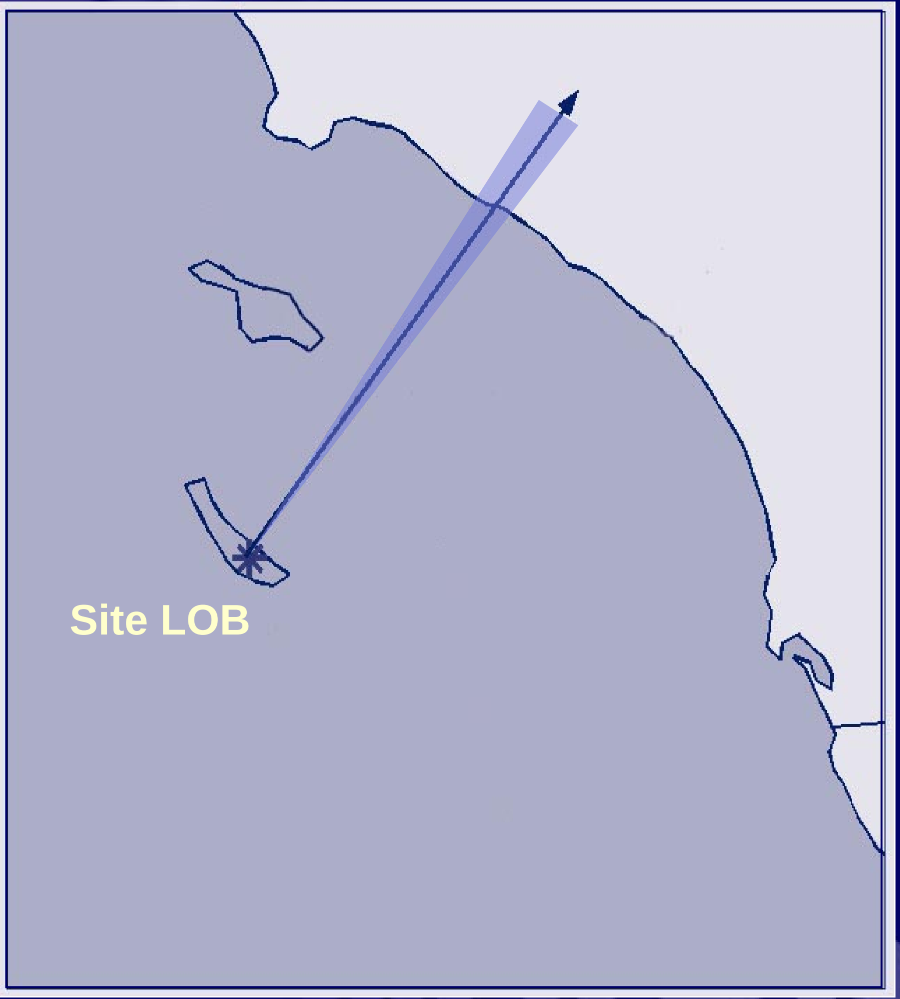
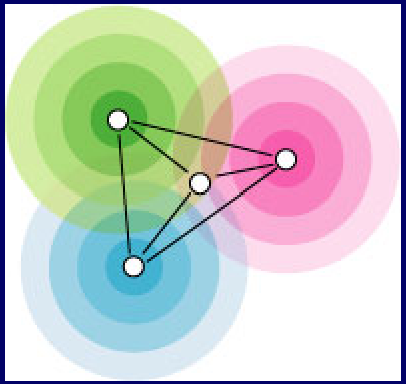
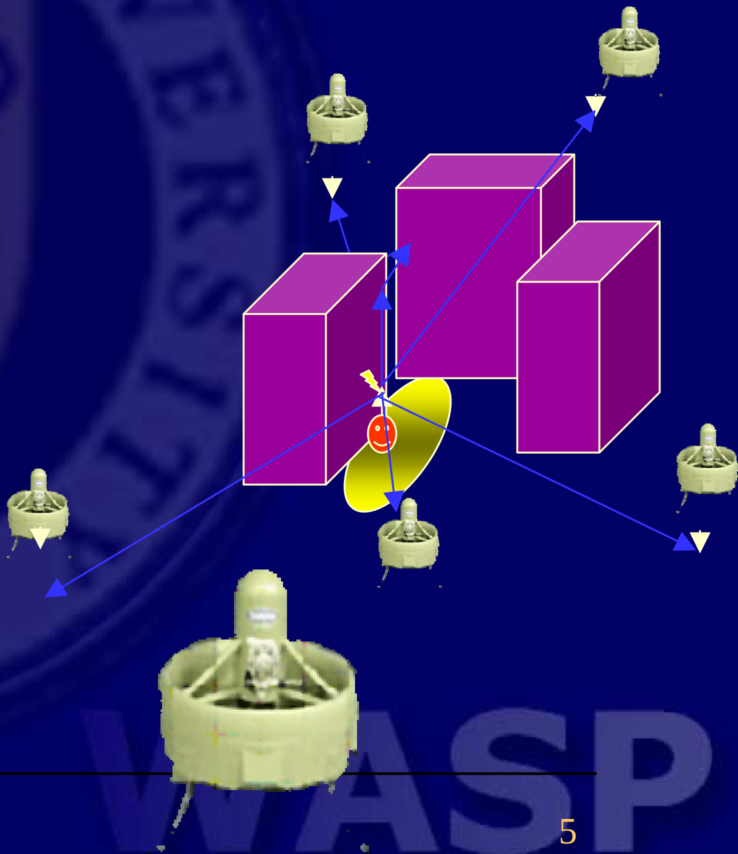


Image: courtesy Southwest Research Institute (SwRI ®)

Challenges

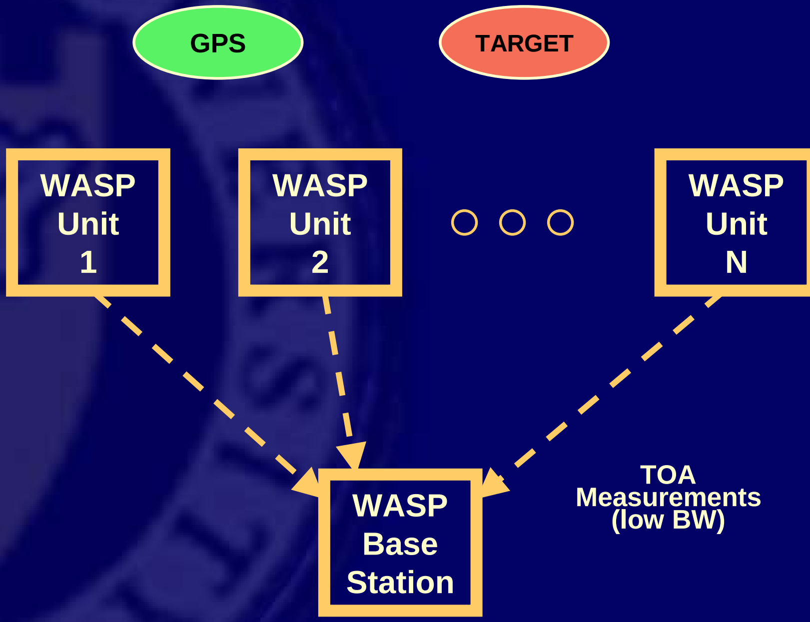


- Effective in urban areas
  - Uniform high precision in all scenarios
- Mobile = Small and low weight
- Longevity = low power
- Stealth = limited bandwidth
- Spatially separated = No global clock
- Low cost = No high precision sampling clock
- Varying environmental conditions
  - Differing radio characteristics

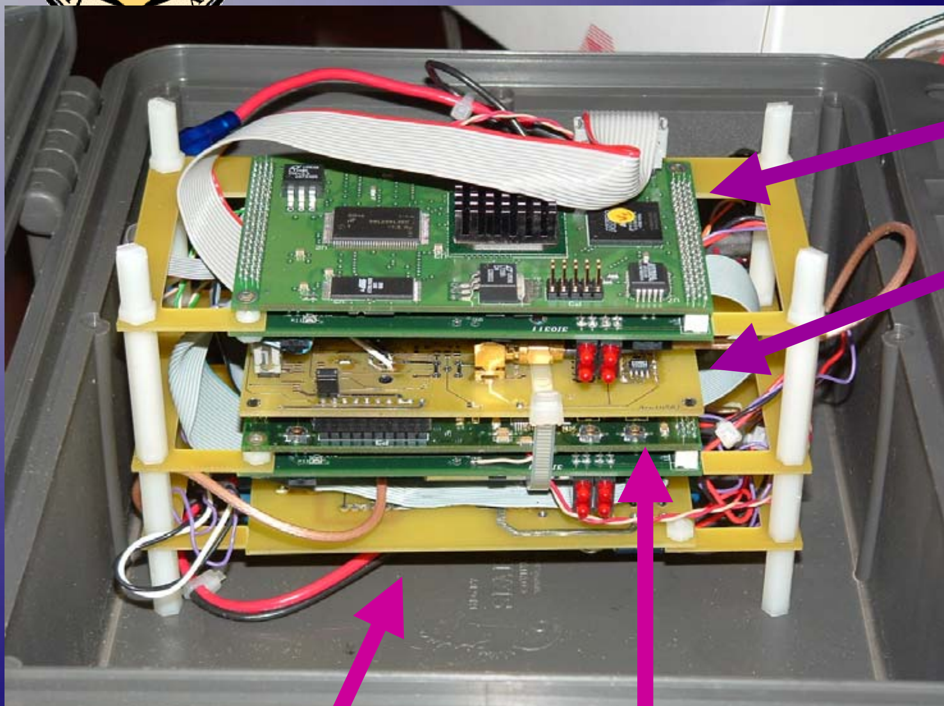


Solutions

- Local processing
  - Matched filtering with template
  - Stealth, low power, Low bandwidth
- GPS for global clock
  - Jitter correction, introspection
  - Lack of common global clock
- Doppler and time-shift correction
  - Using GPS clock for local clock calibration
  - Varying sample rates
  - Low precision clock



TOA electronics package

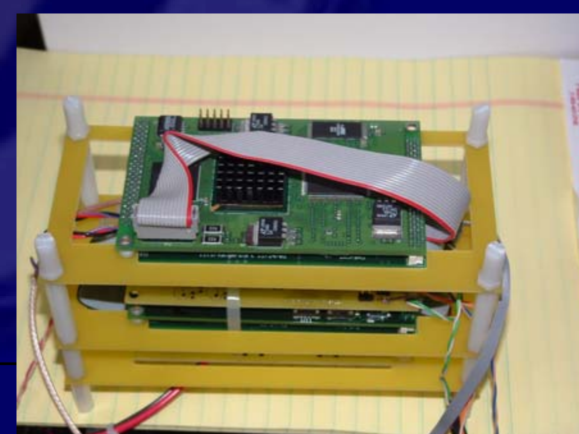


DSP Module

Analog Front-End

A/D Converter
(2MHz)

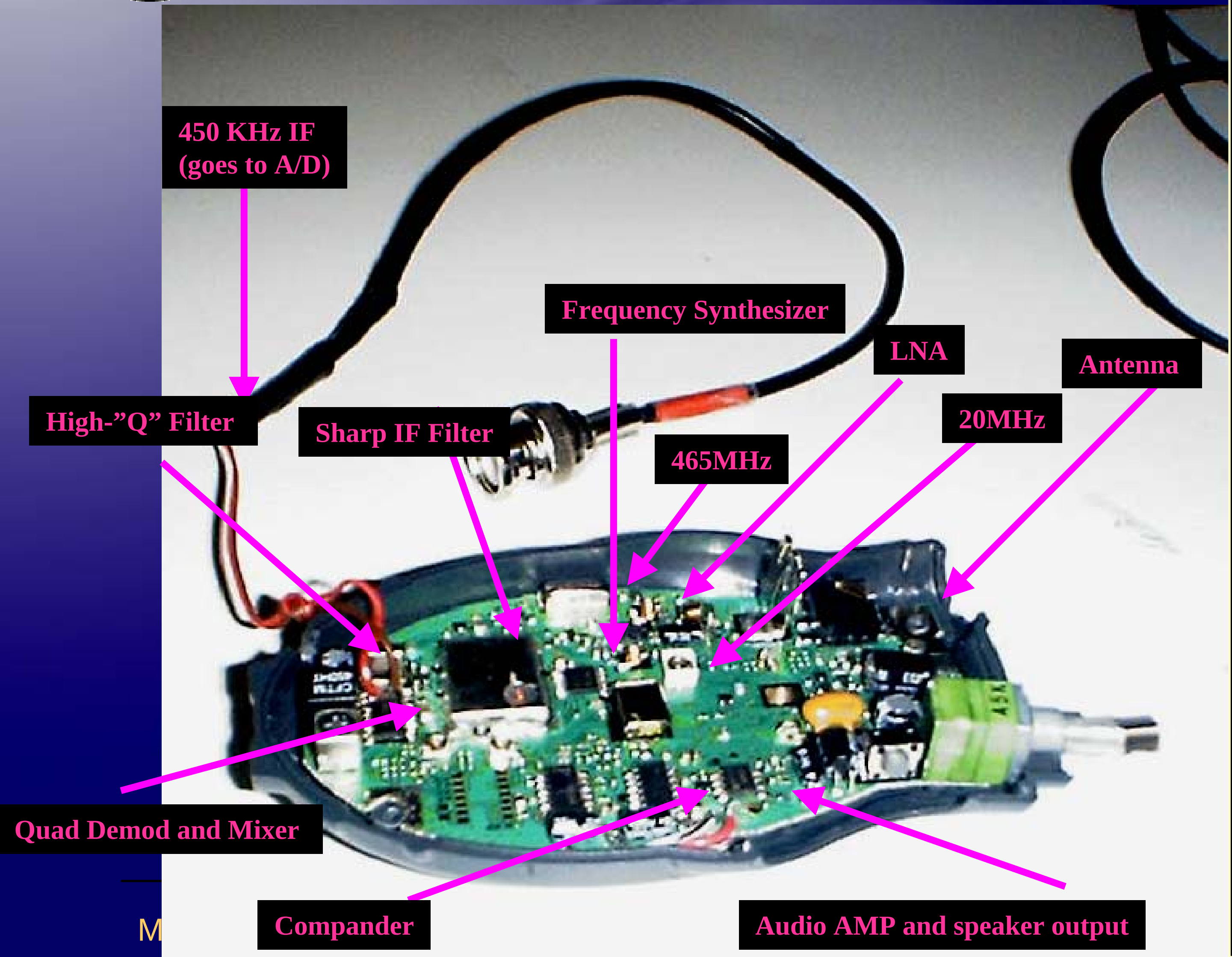
Power Supply
GPS, RF Modem



Weight : under 1 lb

4”x5”x6”

FRS Radio Modifications for IF



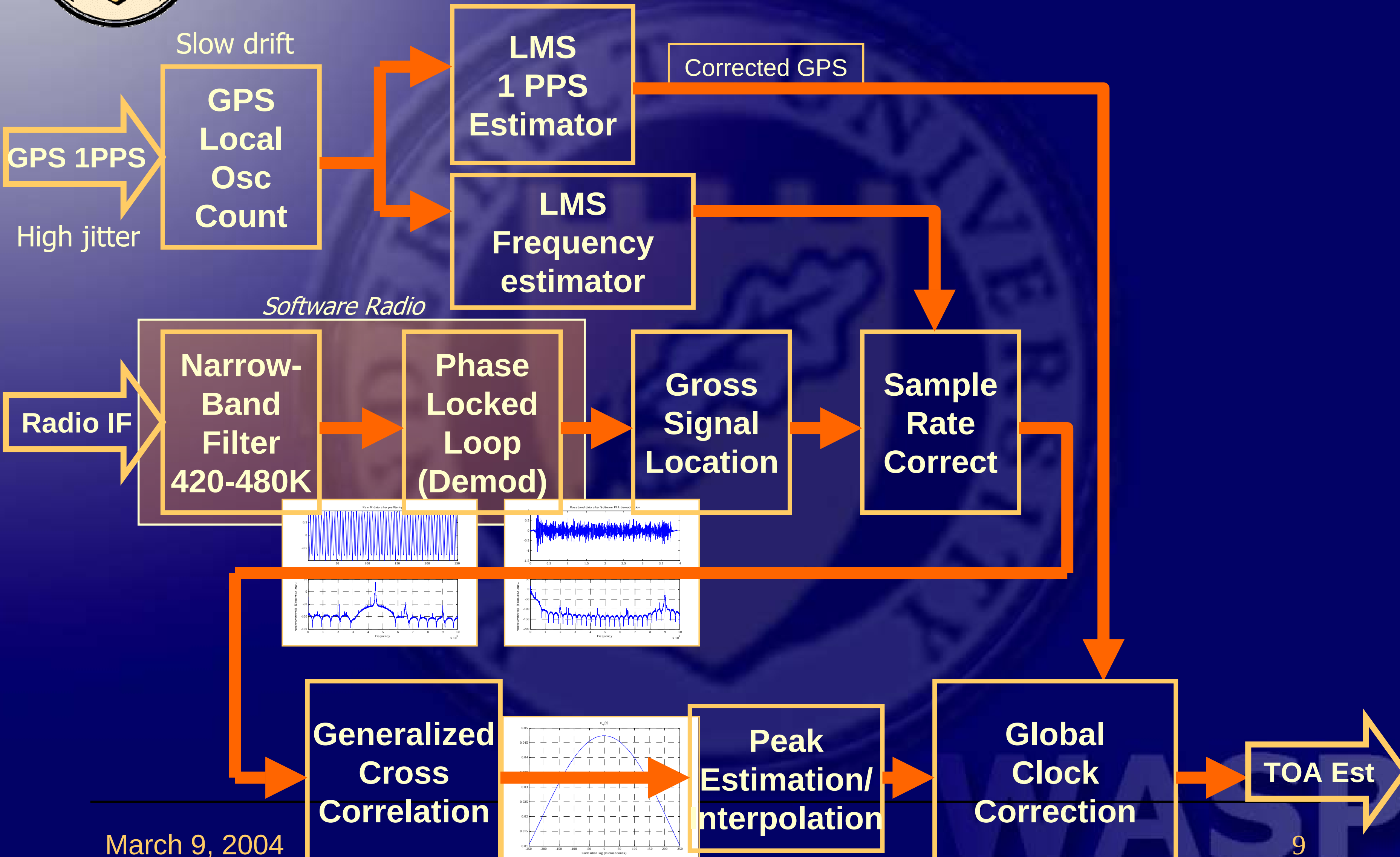
Benefits:

-Ability to use any radio
-Cheap
-Flexible

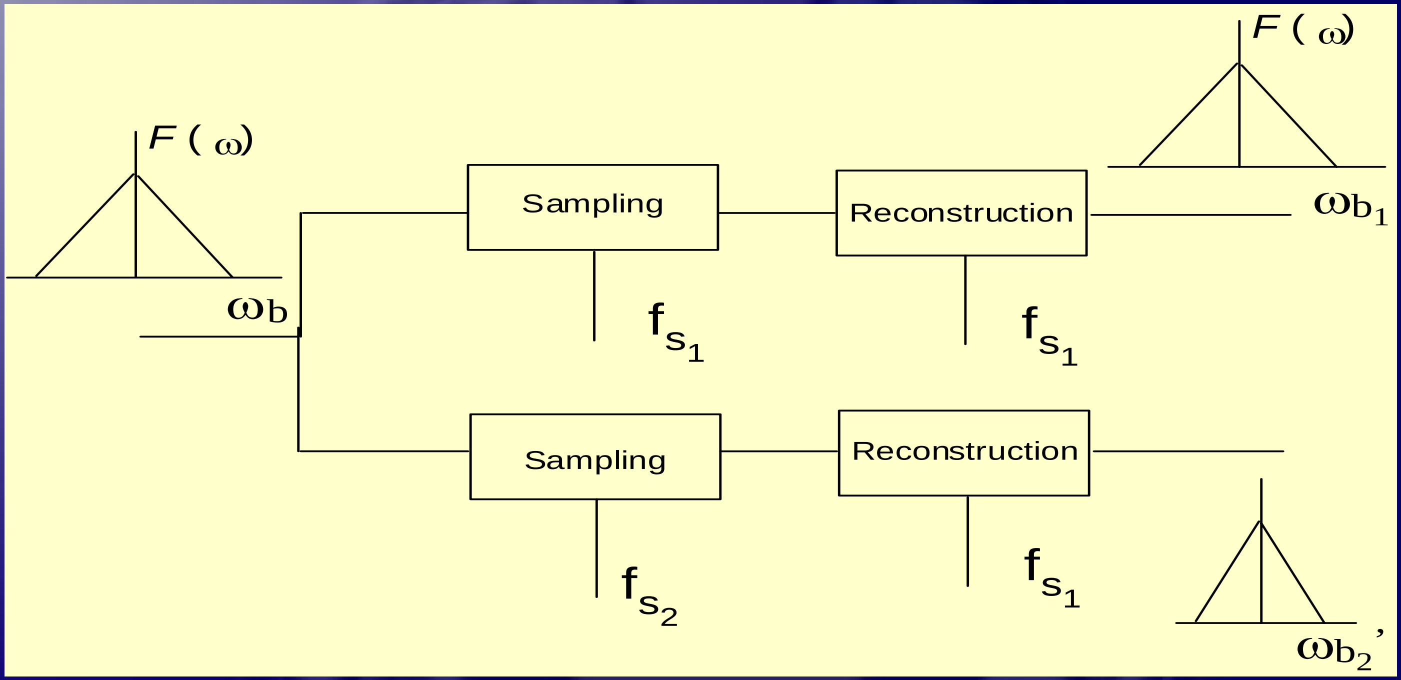
Challenges:

- Phase Linearity
- Poor Demod Perf.
- Poor Baseband Perf.
- Near Field Effects
- Limited Range

Signal processing system architecture



Effect of different sampling frequencies



$$g(t) = f(s(t-\tau))$$

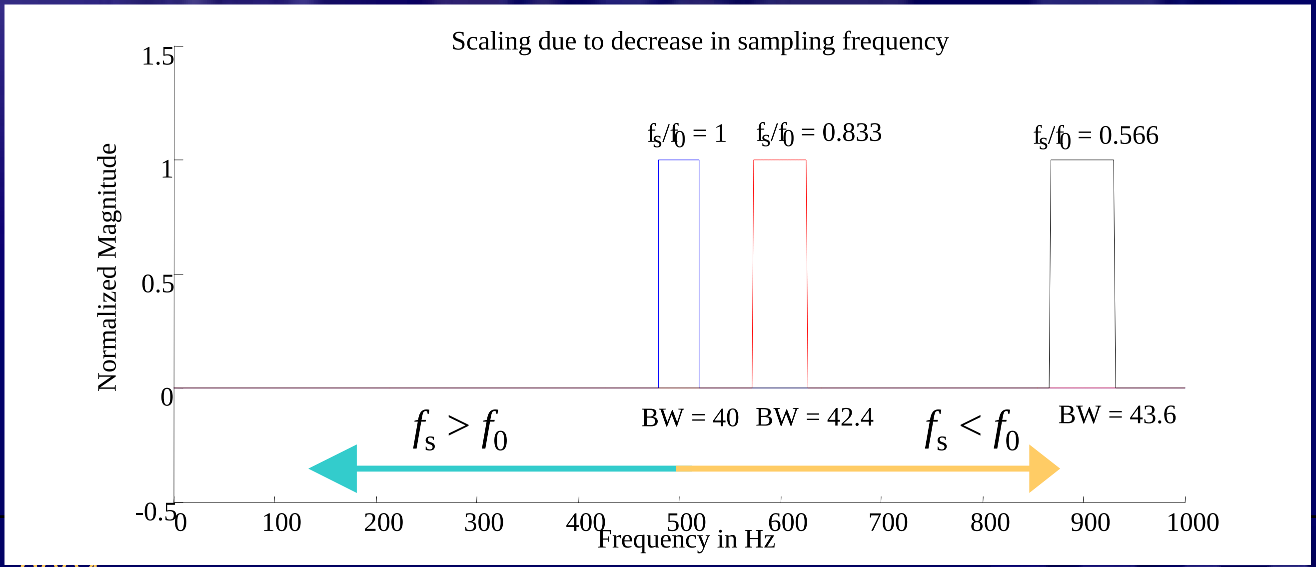
$$G(\omega) = s^{-1}F(\omega / s)e^{-j\omega s\tau}$$

Approximating frequency scaling as shifting

- Doppler shift explanation
  - Taylor series approximation
- Let $s = 1 - a$, then $G(\omega) = 1/(1-a)F(\omega/(1-a))e^{-j\omega(1-a)\tau}$

if $a << 1$, we have $G(\omega) = (1+a)F(\omega(1+a))e^{-j\omega(1-a)\tau}$

(Typically, a = 20-200 ppm)



Doppler approximation

- For narrow band signals,

$$F(\omega_0 + \delta\omega) = 0, |\delta\omega| > \frac{\omega_b}{2}$$

$$F(s\omega) = F(s\omega_0 + \delta\omega) = 0, \delta\omega = \omega - \omega_0$$

$$G(\omega) \approx (1+a)F(\omega + a\omega_0))e^{-j\omega\tau}$$

$$g(t) \approx f(t-\tau)e^{-j\omega_d(t-\tau)}$$

- where *ωd = aω*o *= (1-s) ω*o

Disadvantages of Doppler shifting

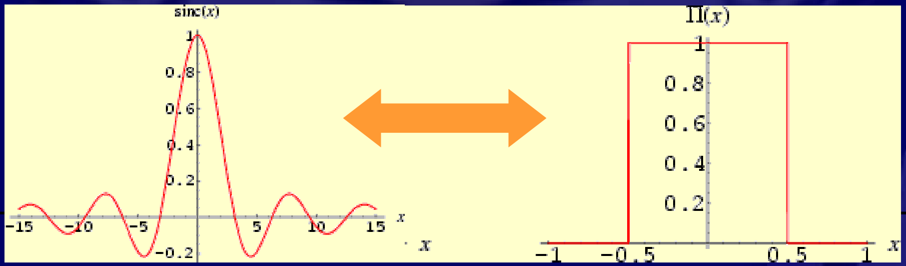
- Input signals modulated by complex exponential before Fourier domain correlation

$$\tau = \arg\max \left| \int_{-\infty}^{\infty} f(u) g^{*}(u+t) e^{-j\omega_d t} du \right|$$

- Input signals become complex
- Memory requirement doubles
  - Greater memory access times
  - Lower through put
  - More power consumption
  - More memory / faster memory = greater cost

Alternative correction

- Can we shift in time instead of frequency?
  - Accomplished by multiplication by complex exponential in frequency domain
  - Performed during frequency domain correlation operations
- Time and frequency are duals
- Shifting and approximating in time = shifting and approximating in freq

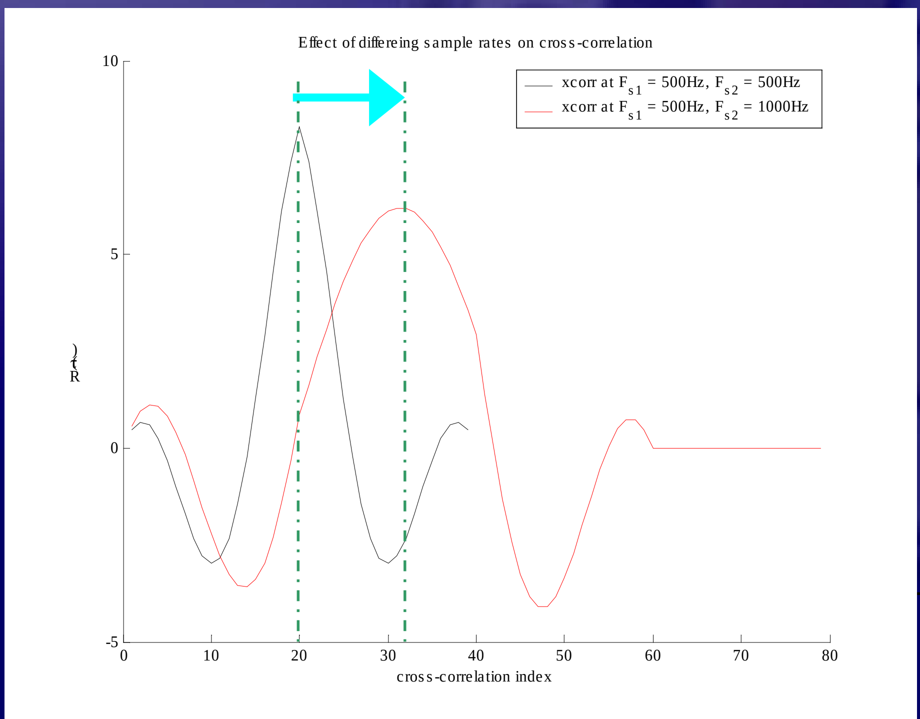


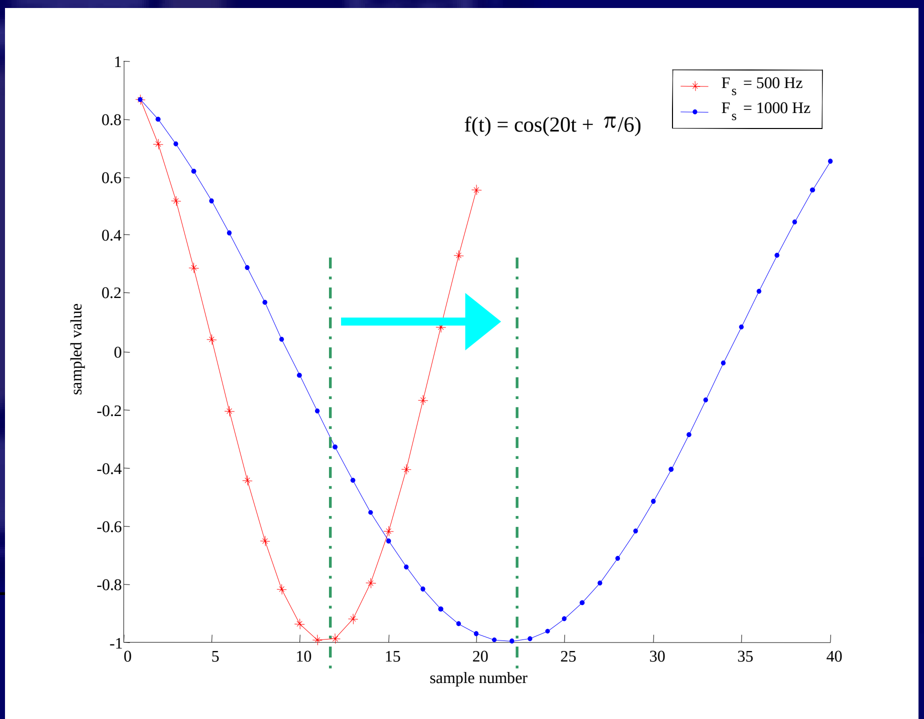
Time domain effects of different sampling rates

- Faster sampling rate “delays” features in the sampled domain
- Compensate by advancing delayed signal

$$\tilde{F}(\omega) = F(\omega)e^{j\tau_d\omega}$$

$$\tilde{f}(t) = f(t + \tau_d{}^o) = f(t + (s-1)\frac{T_2 - T_1}{2} - s\tau)$$





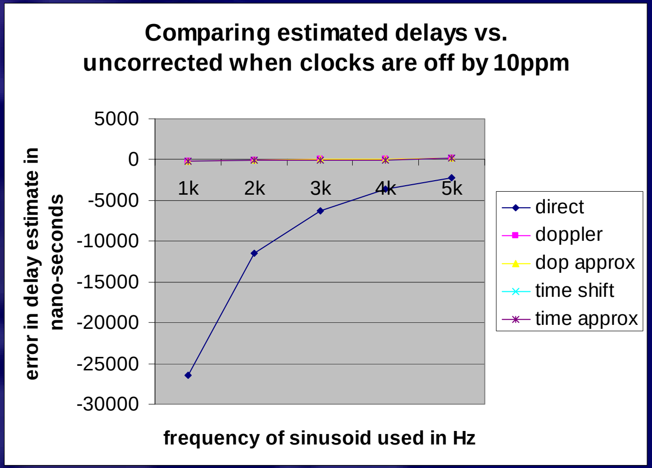
Comparing the two

- Trade-off between accuracy and performance
  - Doppler
    - Affords greater accuracy
    - Requires more memory / computation
    - Modulates entire signal with complex cosine before xcorr
  - Time-shifting
    - Provides acceptable accuracy
    - Uses lesser memory (input signal stays real)
    - Applies only to few significant frequency bins
    - Faster throughput
- Approximations are easy to apply

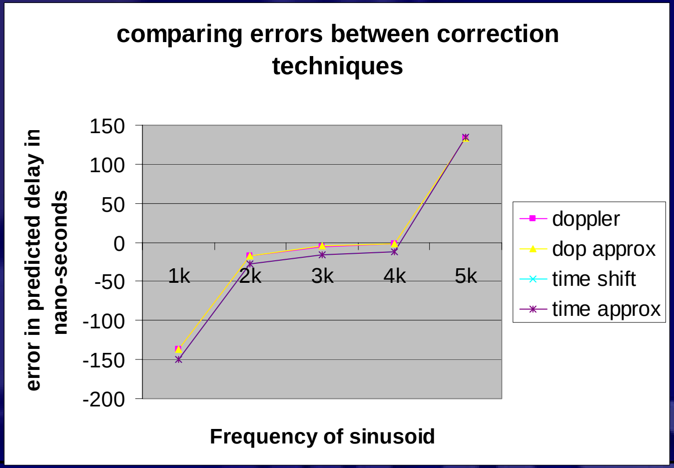
$$\exp(j\omega_d t) = 1 + j(\omega_d t)$$

Results – Evaluating correction techniques

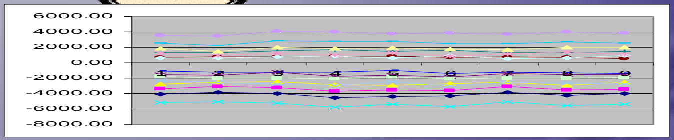
- Corrected error is within allocated error budget for the signals of interest

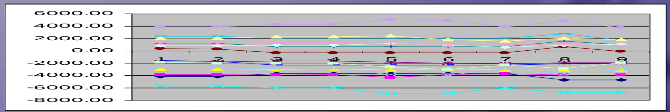


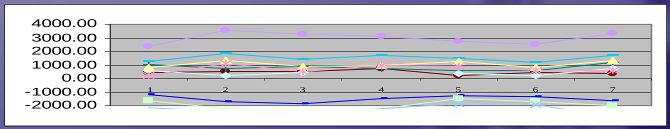
- Signal of interest (1Khz – 3kHz) PRN
- Oscillator clock drift: ±100 ppm
- Delay in uncompensated case: ~1-10 μ-sec
- Duration of signal of interest (template) : 0.2 sec
- Nominal sampling freq: 2 MHz

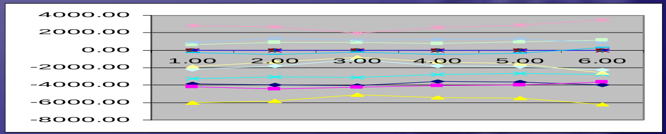


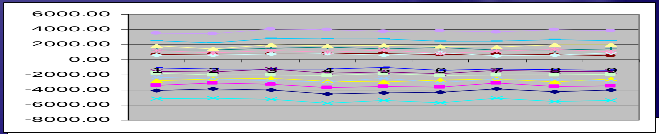
Testing Results
Time-of-arrival Consistency

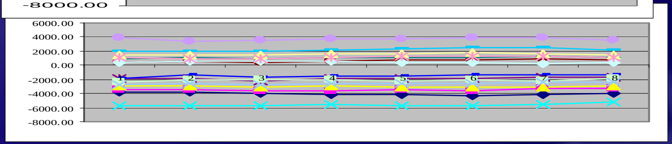






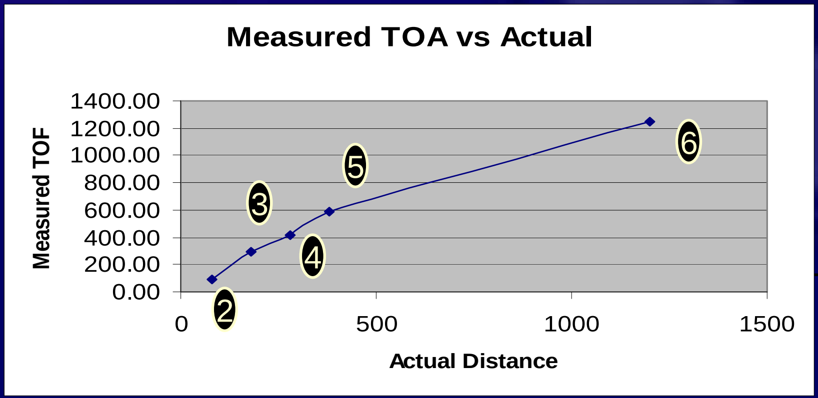




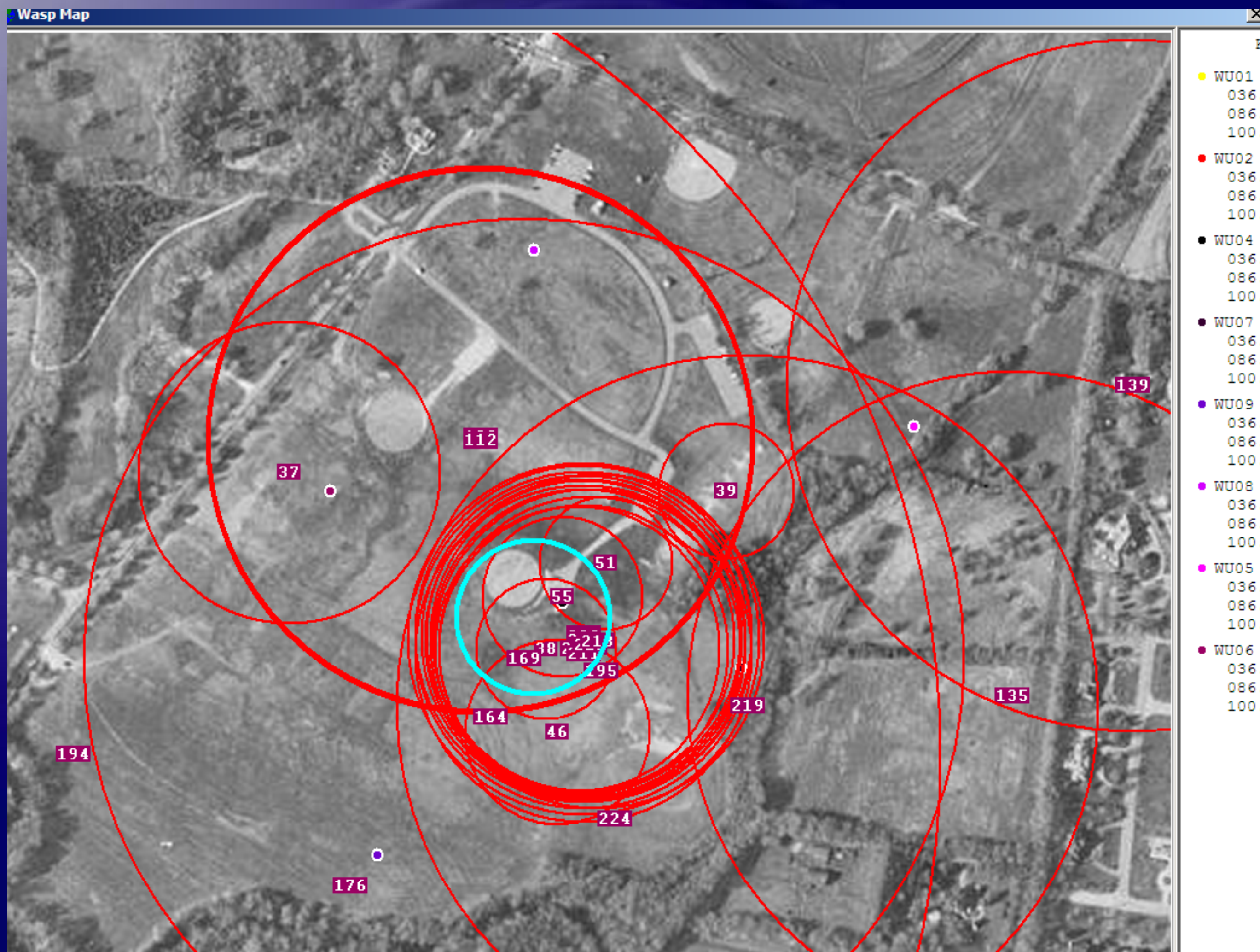


Delta

- 2m
- 103m
- 190m
- 127m
- 170m
- 1243m



Demo


Wasp Map
112
37
39
51
55
169
164
46
195
219
224
194
176
139
135
WU01
WU02
WU04
WU07
WU09
WU08
WU05
WU06

Conclusion

- Developed a new TDOA system
  - Highly constrained
  - Solved several problems due to distributed clocks
  - Developed algos
  - Tested in field

Questions/ Applause?

Road Map

- Overview
  - Present all the different topics we are going to talk about
- Introduction
  - Increase in location aware systems and services, E911
  - Need for close range monitoring – urban and hostile environments
  - Need for intelligence in hazardous areas
- Motivation
  - Cost – compare cell phone/ E911
  - Large stand off
  - Urban clutter
  - Theater level vs. field level
- Challenges
  - Saptially separated - Lack of global clock
  - Stealth + low-power - Lack of bandwidth for communication
  - Cost - No high precision common sampling clock
  - Varying environmental conditions – changing sample rates

- Solutions
  - Local processing – matched filtering with template
  - GPS for global clock – jitter correction, introspection
  - Doppler and time-shift correction – varying sample rates
- Signal processing system architecture
  - Insert picture here
- Effect of different sampling frequencies
  - Show picture of how things scale with changing sampling freq
  - Show equation
- Approximating scaling with frequency shifts
  - Doppler shift explanation – Taylor series approximation
  - Include figure from Sonar signal analysis
- Disadvantages of Doppler shifting
  - Input signals modulated by complex exponential
  - Input signals become complex
  - memory requirement doubles -> greater memory access times

- Alternative correction
  - Time shifting
  - Time and frequency are duals
    - Insert picture for gate function and sinc function
  - Shifting and approximating in time = shifting and approximating in freq
  - Include relevant equations here
- Advantages
  - Reduces memory requirements
  - Reduces access times
  - Approximation is easy to apply
    - Add equation for 1 + jw
  - Trade-off between accuracy and performance
- Results
  - Simulation results
  - Field results
- Demo