Voxnet: a Rapidly Deployable Distributed Acoustic Sensor Network

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6.S062

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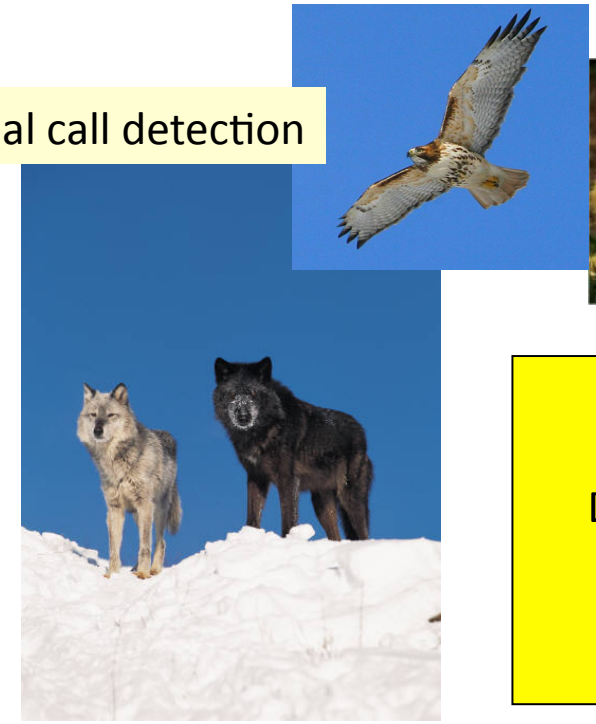
Distributed Acoustic Sensing Applications

Animal call detection

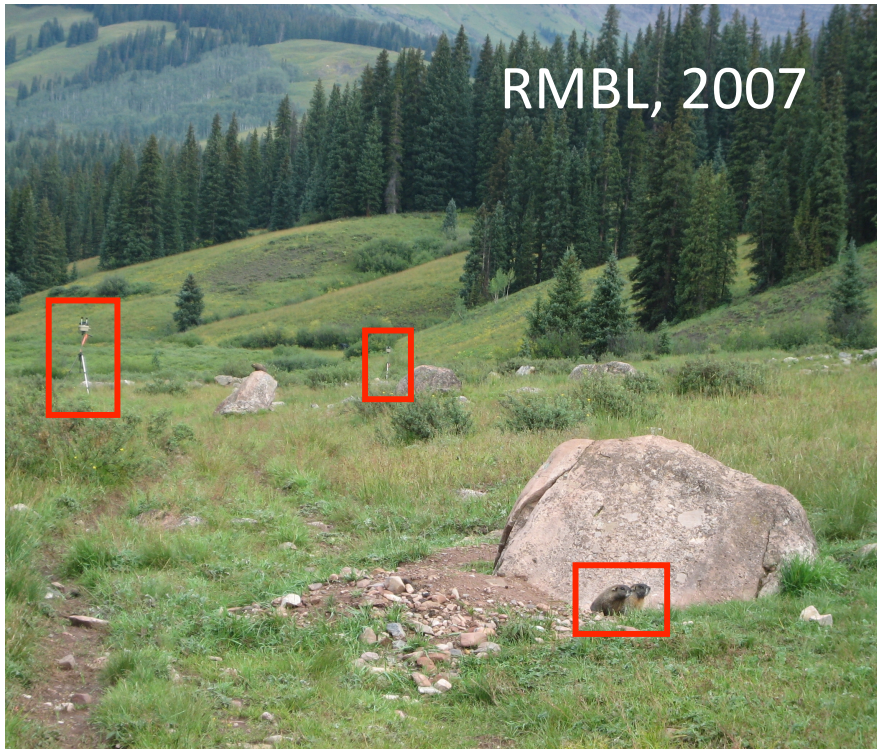


Condition-based maintenance

Goal:
Develop a *platform* to support distributed acoustic sensing

Perimeter security, Vehicle tracking

VoxNet



Terrestrial bio-acoustics, e.g.,

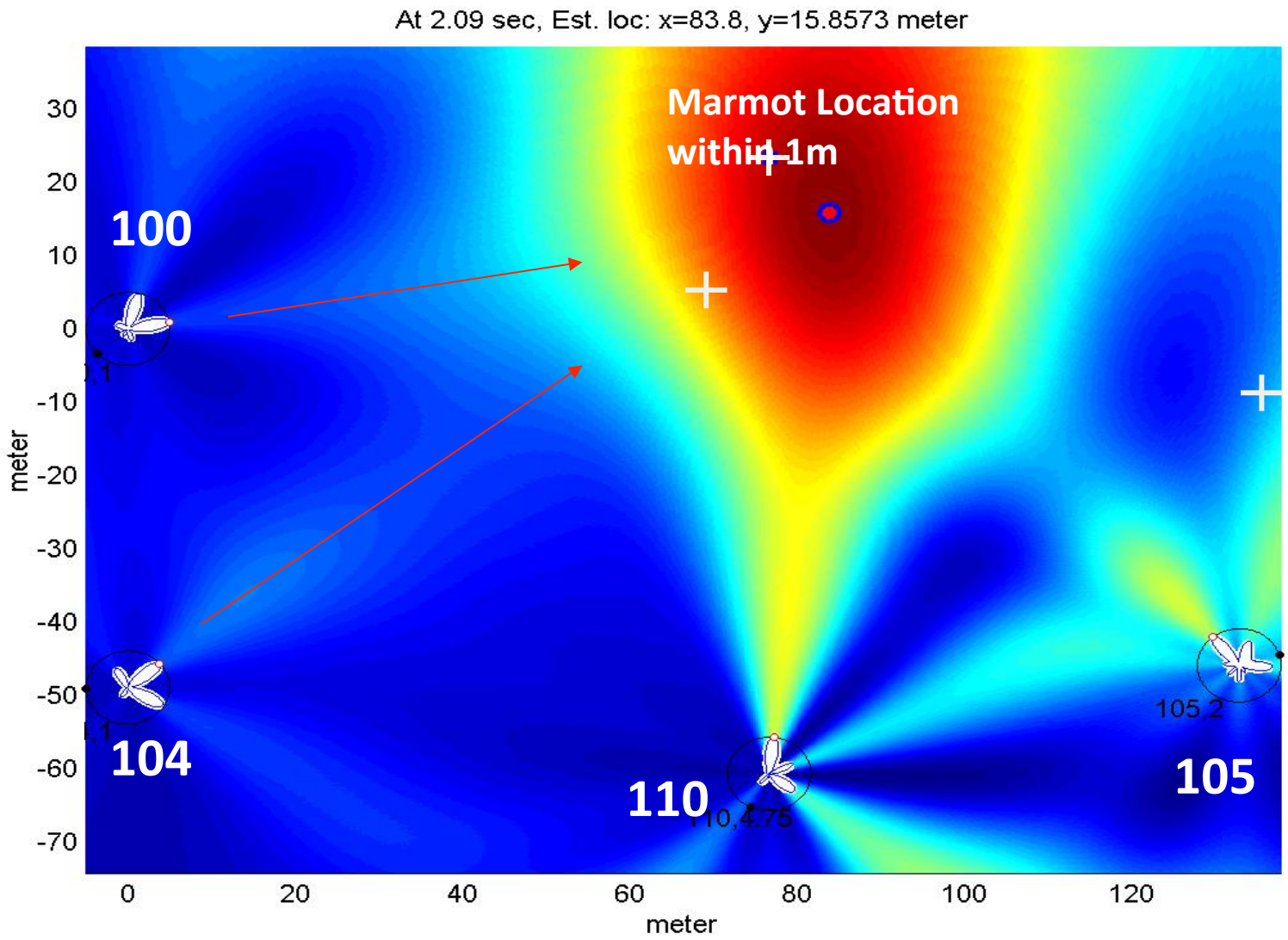
- marmot alarm calls
- bird calls
- wolves
- human encroachment

Allen, et al., VoxNet: An Interactive, Rapidly-Deployable Acoustic Monitoring Platform, IPSN 2008

Initial Applications and Deployments

- Rocky Mountain Biological Lab
  Gothic, CO
  - Marmot localization study
  - 2 weeks in 2006
  - 3 months in 2007
- Chajul Biological Station
  Chiapas, MX
  - Bird localization and classification
  - 2 weeks in 2007

Call localization application



Ali, et. al., An Empirical Study of Collaborative Acoustic Source Localization, IPSN 2007.

Key Challenges in Terrestrial Acoustics

- "Free space" is rare
  - Blocked LOS: foliage, earth
  - Reverb, multi-path, attenuation
- Spectrum cluttered with noise
  - Wind, rivers, rain
  - Other animals
- Wireless performance
  - GPS often blocked by foliage
  - 2.4 GHz absorption

Design Implications

Difficult environment →

- Need many vantage points
- Need sensors closer to sources

→ Distributed →

- Greater complexity – more parts
- More ways to be mis-configured

→ Deployable →

- Wireless, self-contained, resilient
- Self-configuring, easy to maintain

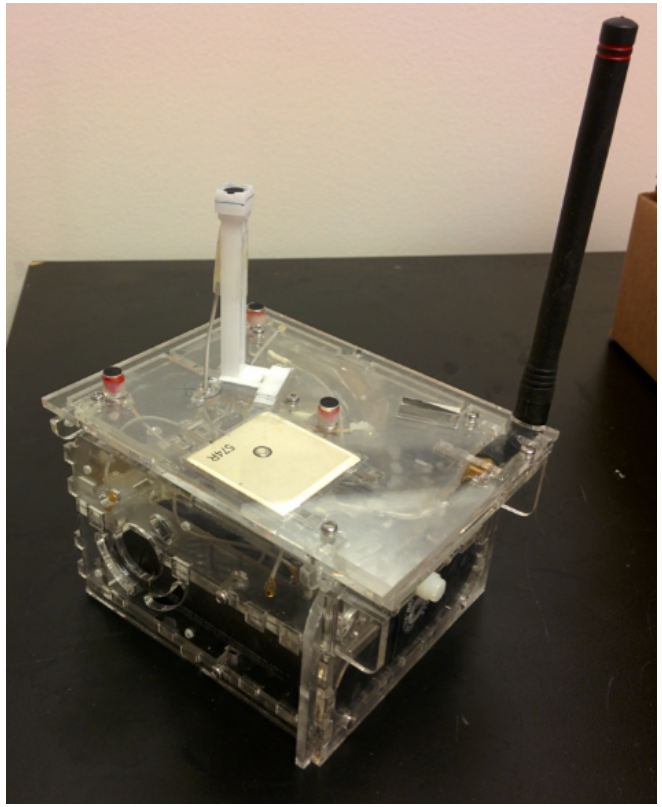
VoxNet Platform

Hardware:

OMAP3
256MB RAM
SD Card
BT/802.11B
433 Mhz
Supervisor uC
Li+ battery
Charge controller

Sensors:

4x48KHz audio
GPS
Internal temp/RH



Key Features:

Rapid deployment
- Small / light
- Self-contained

Self calibration
- Absolute location
- Precise relative location
- Precise orientation
- Time synchronization

App environment
- Field programmable
- Real time responses
- Spill to disk

Hardware Platform Evolution

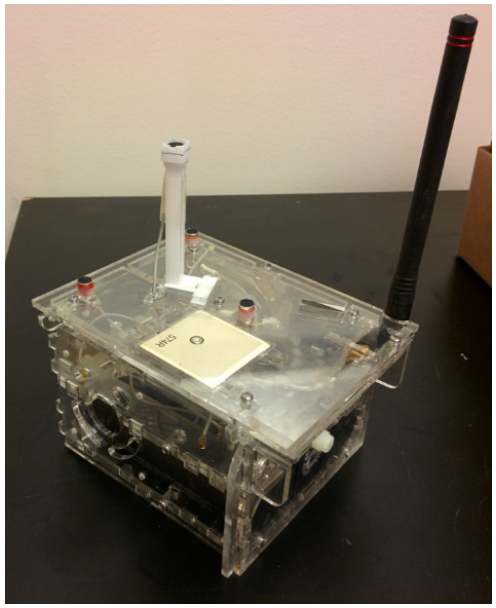
Version 1 (2005)

Large pelican box (16x10”)
External gel cell battery
Separate mic head

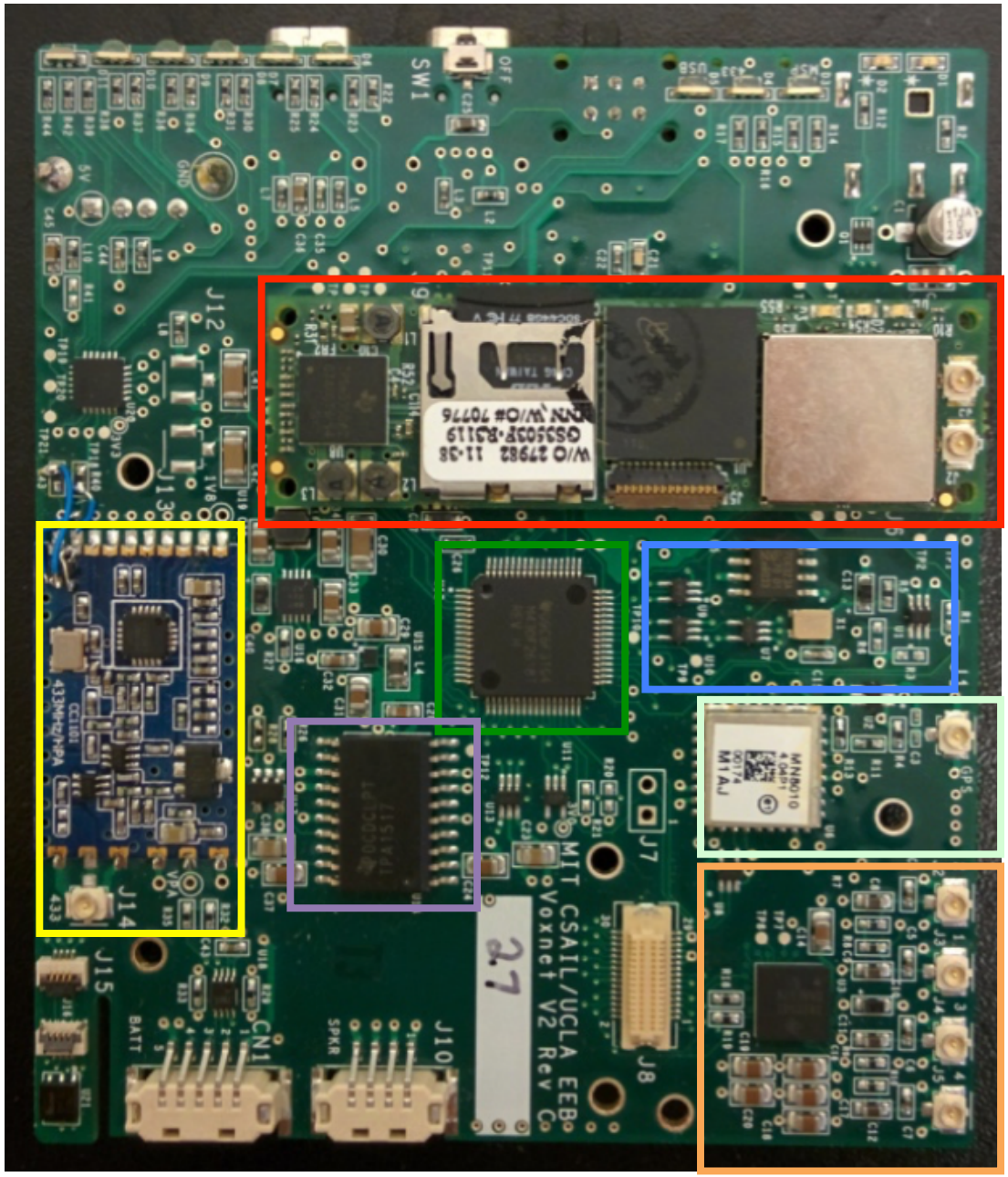
Version 2 (2007)

Small pelican box (8x6”)
Internal Li+ battery
Detachable mics and speaker cube.

Version 3 (2009)



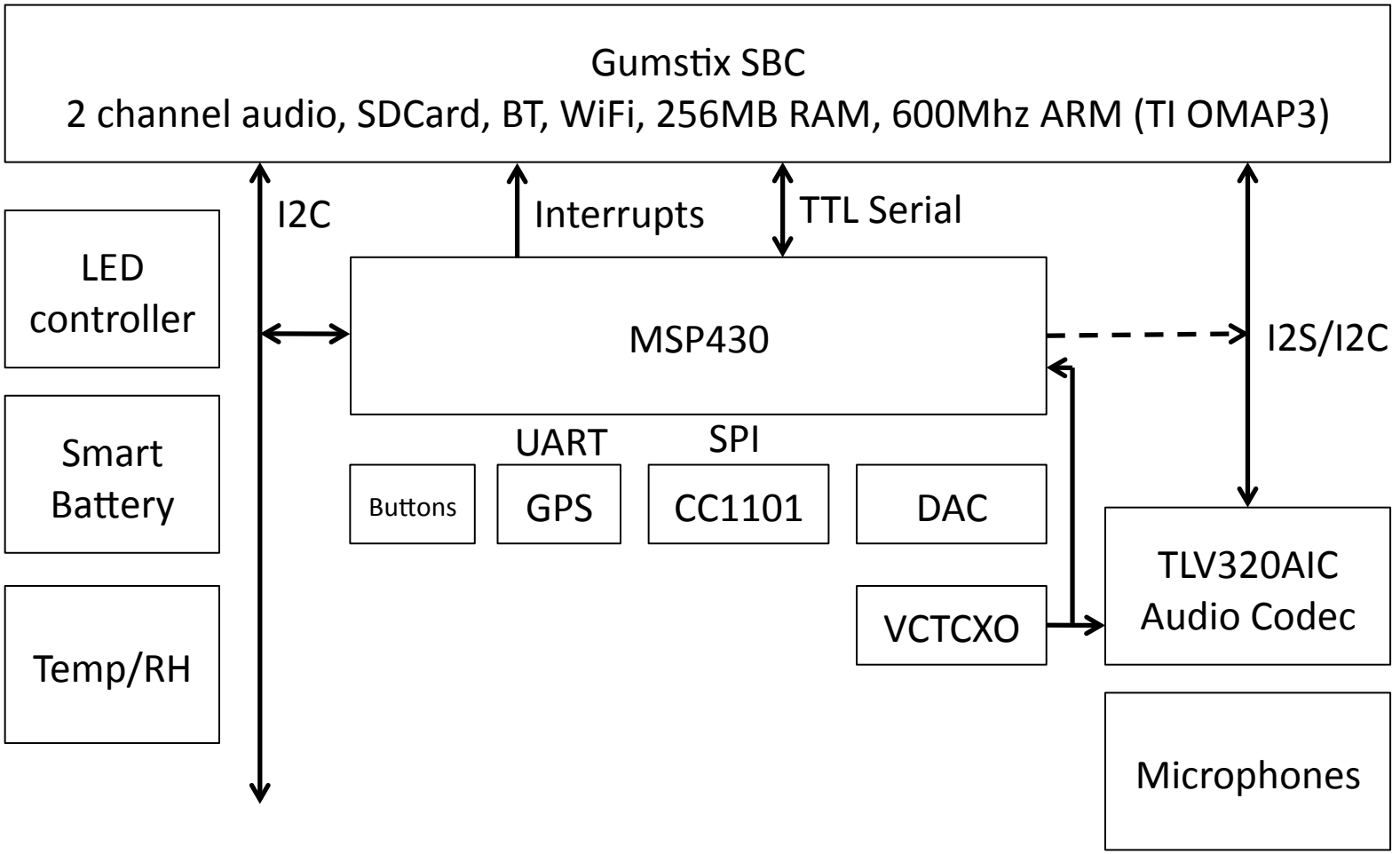
Laser-cut case (5x4”)
Internal Li+ battery
Integrated mics and speakers. Designed as a peripheral board for an off the shelf SBC.



Hardware

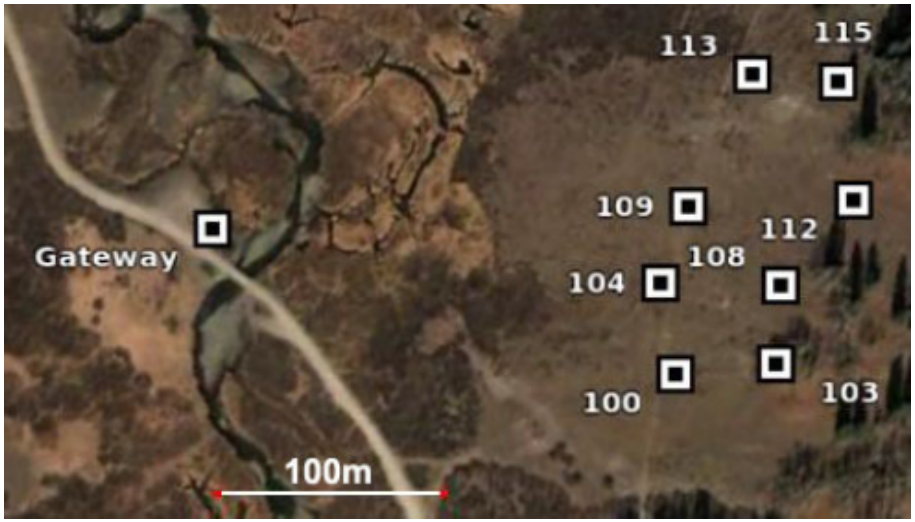
- Gumstix SBC
- CC1101 module and P/A
- MSP430 controller
- Frequency locked audio clock
- Audio P/A
- GPS
- 4 Channel codec
- Not visible: Power supplies, battery charger, LED controller

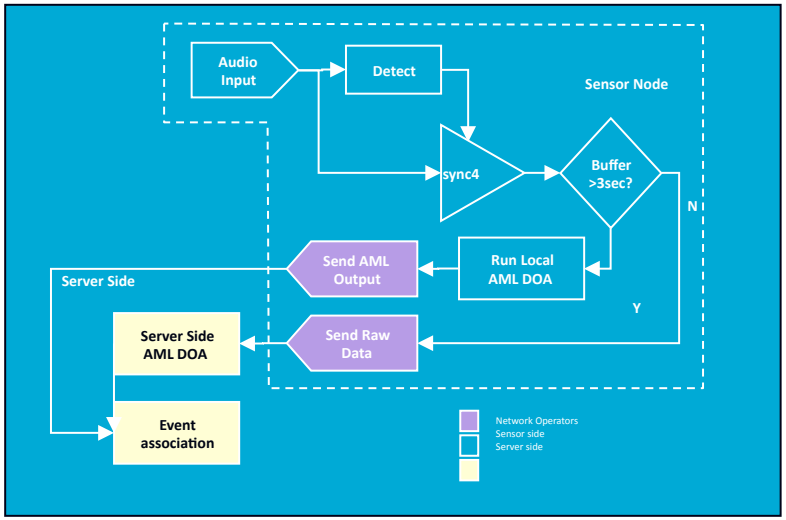
Hardware Block Diagram



VoxNet Software Platform

- Maintains a multi-hop wireless network
- Time synchronization between nodes
- Precise relative location and orientation
  - Does not rely on GPS
  - Much higher accuracy than GPS
- Voxnet programming interface

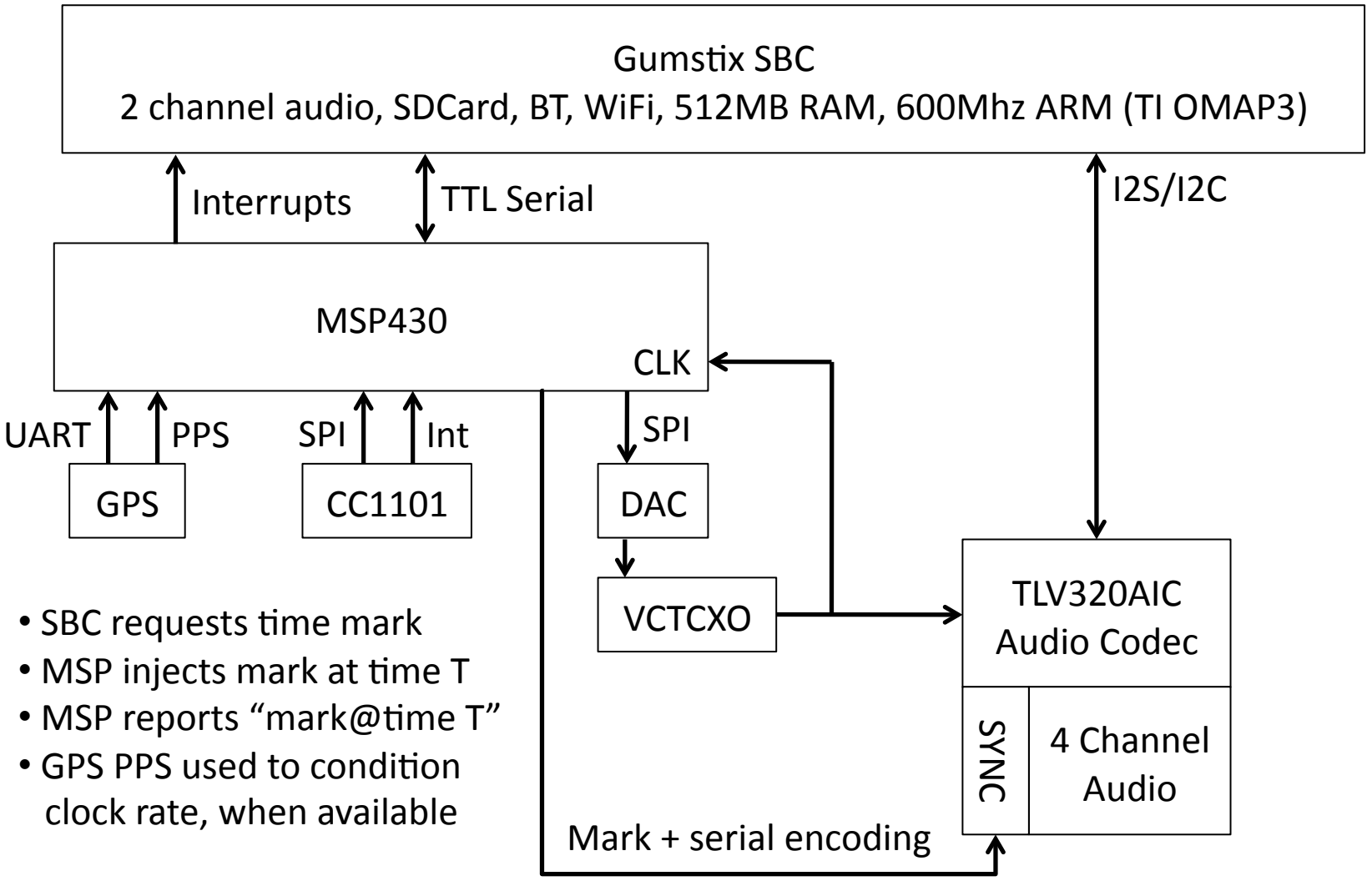




Time Synchronized Sampling

- Why?
  - Substantially reduces error in distributed TDOA
    - E.g. time of flight audio range estimation
  - Post-facto analysis of long-running distributed recordings
- Implementations requires multi-layer support
  - Hardware, Software, Network
- Principle of free-running clock
  - Let clock run, rather than jumping it
  - Maintain and record mapping/conversion data

Hardware support for time-synchronized audio sampling

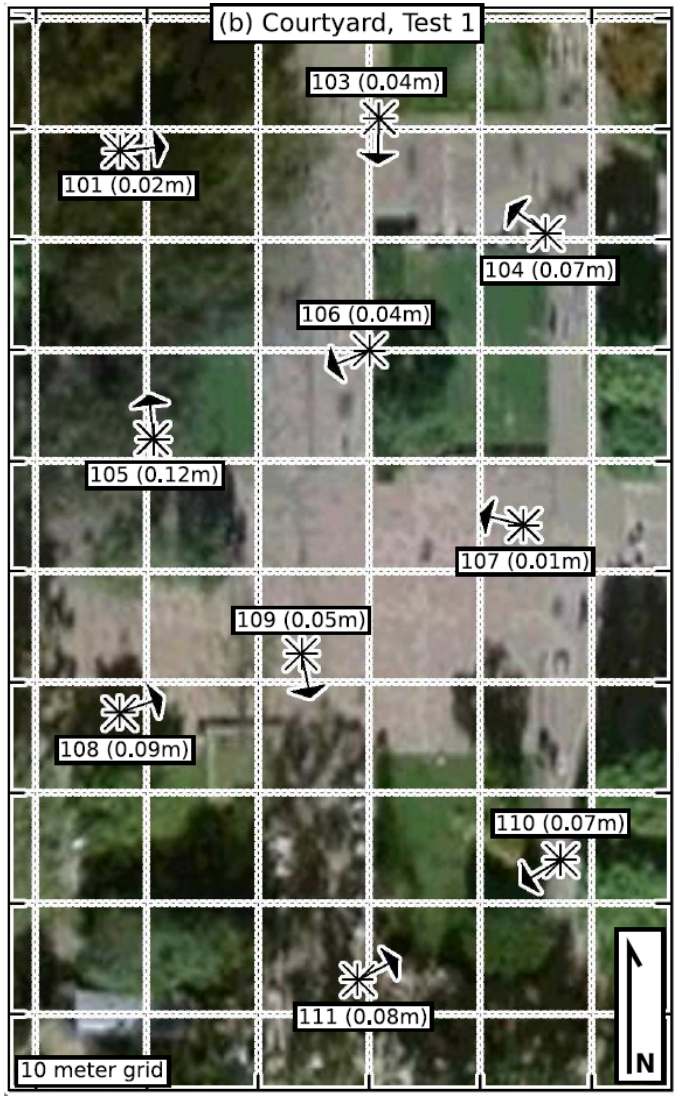


Software/Network support for TS

- At least one node with access to GPS
  - Declares itself ‘level 0’ and propagates GPS time in sync packet
- Each node maintains an up-to-date mapping between its internal clock and GPS time
  - Non level-0 nodes transmit best mapping as level n+1
- Live analysis uses current mapping
- Historical mapping recorded for use with recorded data

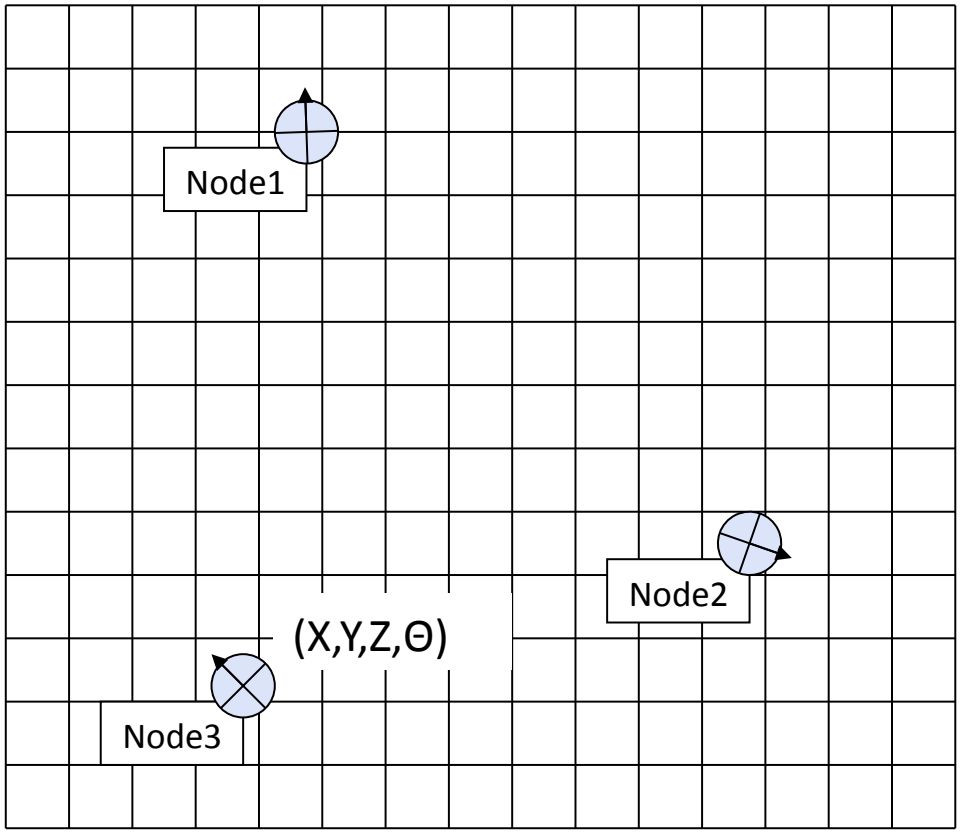
Precise location and orientation

- Based on audio TOF, TDOA
  - Over-constrained system of non-linear constraints
- Highly accurate
  - 5-10 cm position error in 200 m (0.05%)
  - 1 degree orientation error
- Works well in foliage
  - Redundant measurements ensure accuracy



Girod, et. al., The Design and Implementation of a Self-calibrating Acoustic Sensing Platform, SenSys 2006

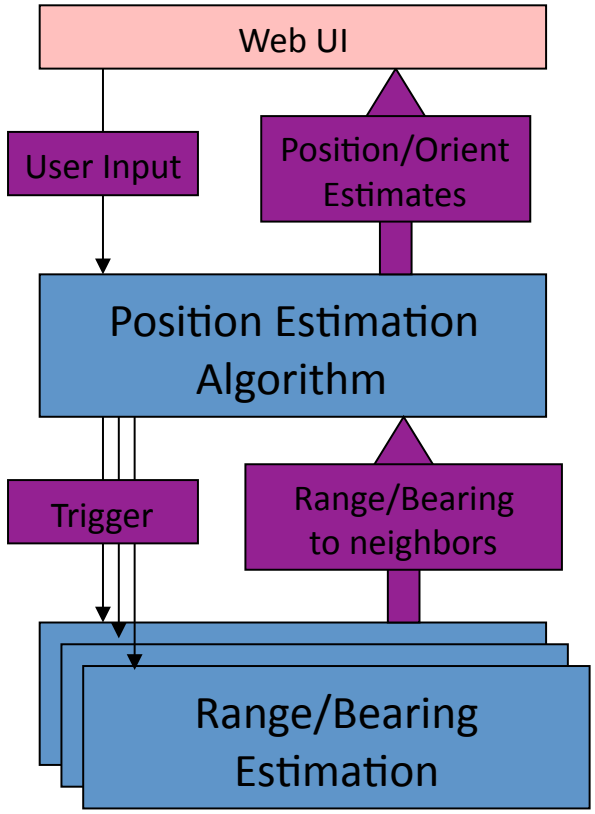
Self-calibration:
Precise location and orientation



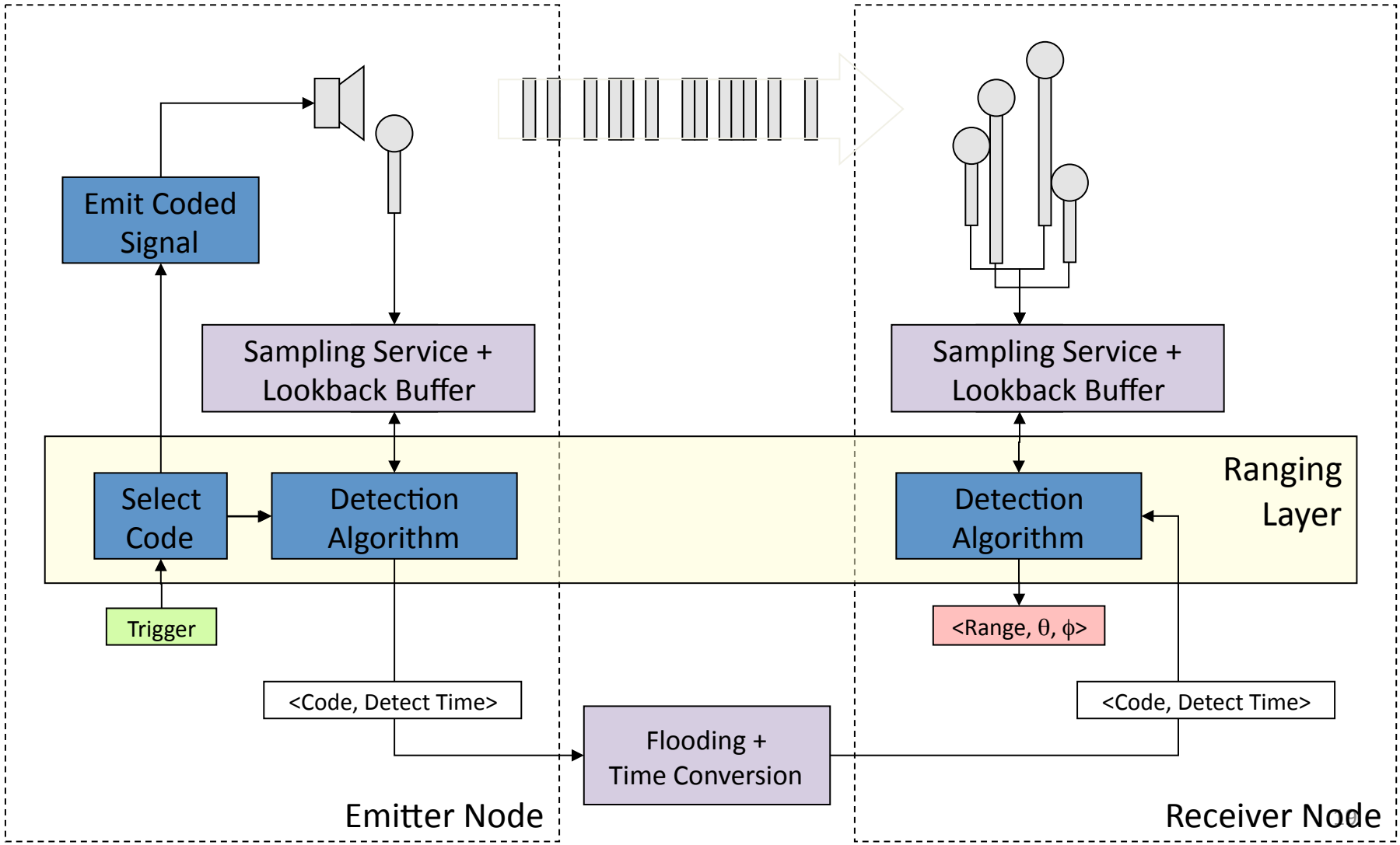
- For each node, estimate:
  - 3D position (X,Y,Z)
  - Array orientation Θ
- Fit relative coordinates to survey and/or selective GPS availability
- Assume all arrays are level
- Metric (given ground truth):
  - Avg 2D, 3D position error
  - Avg orientation error

System Overview

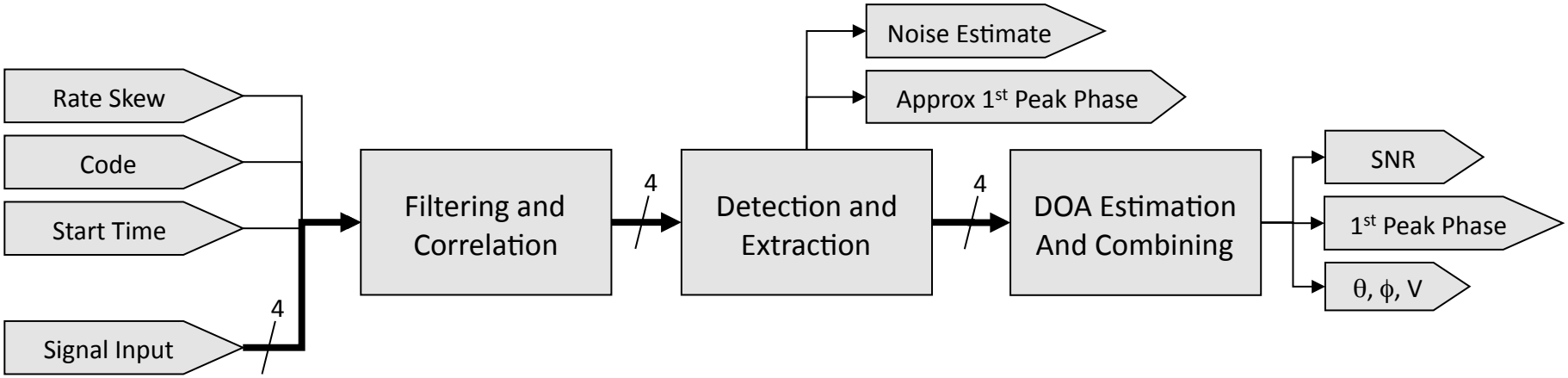
- Range/Bearing Estimation
  - Distributed through network
  - Emitter chirps, other nodes detect phase of chirp via correlation
  - Estimate AOA using local TDOA
  - Report (R,θ) data to position layer
- Position Estimation
  - Centralized algorithm
  - Triggers each node to chirp in turn, receives (R,θ) estimates
  - Least squares algorithm to compute relative map (X,Y,Z,Θ)
  - Fit map to surveyed locations



Range and Bearing Estimation System Overview



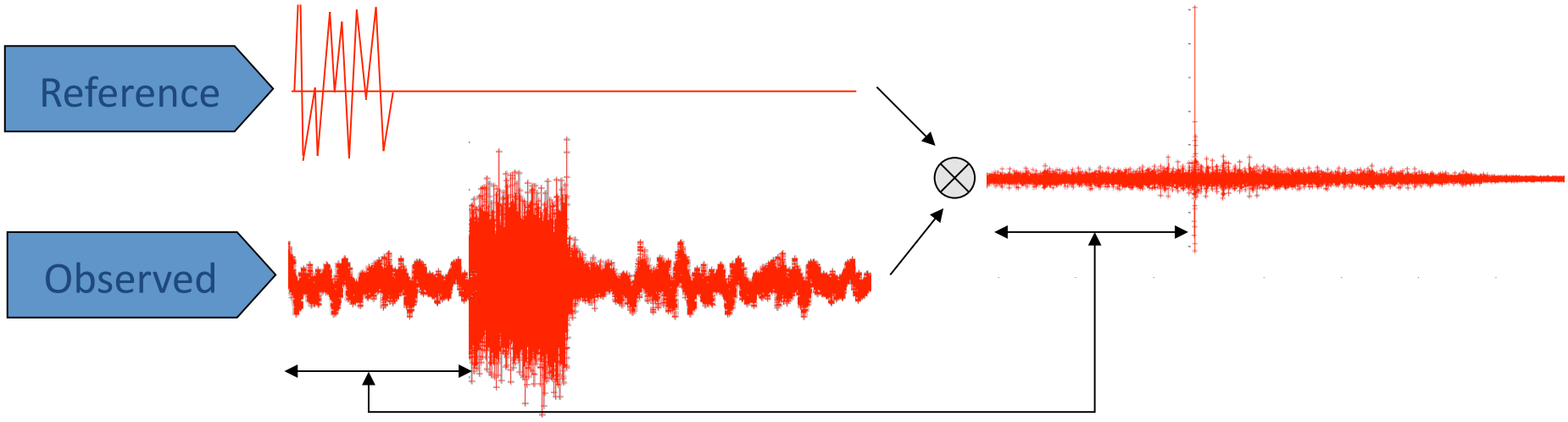
Range and Bearing Estimation Algorithm



- Inputs:
  - The input signals from the microphones
  - The time the signal was emitted (used to select from input signal)
  - The PN code index used
- Outputs
  - Peak phase (i.e. range): R
  - The 3-D direction of arrival: θ, ϕ
  - Signal to Noise Ratio (SNR)

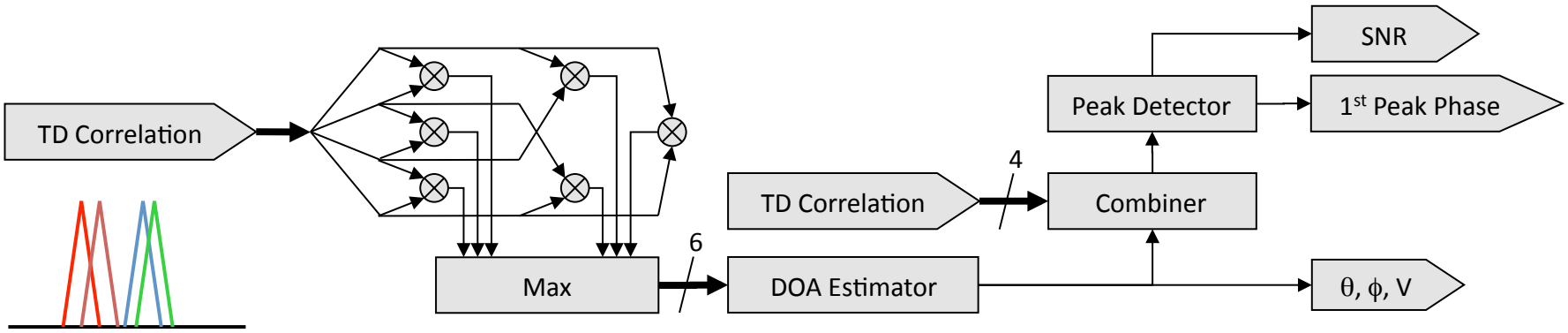
Correlation

- Signal detection via “matched filter” constructed from PN code
  - Observed signal S is convolved with the reference signal
  - Peaks in resulting “correlation function” correspond to arrivals
  - Earliest peak is most direct path



Lag = Time of Flight

DOA Estimation and Combining Stage

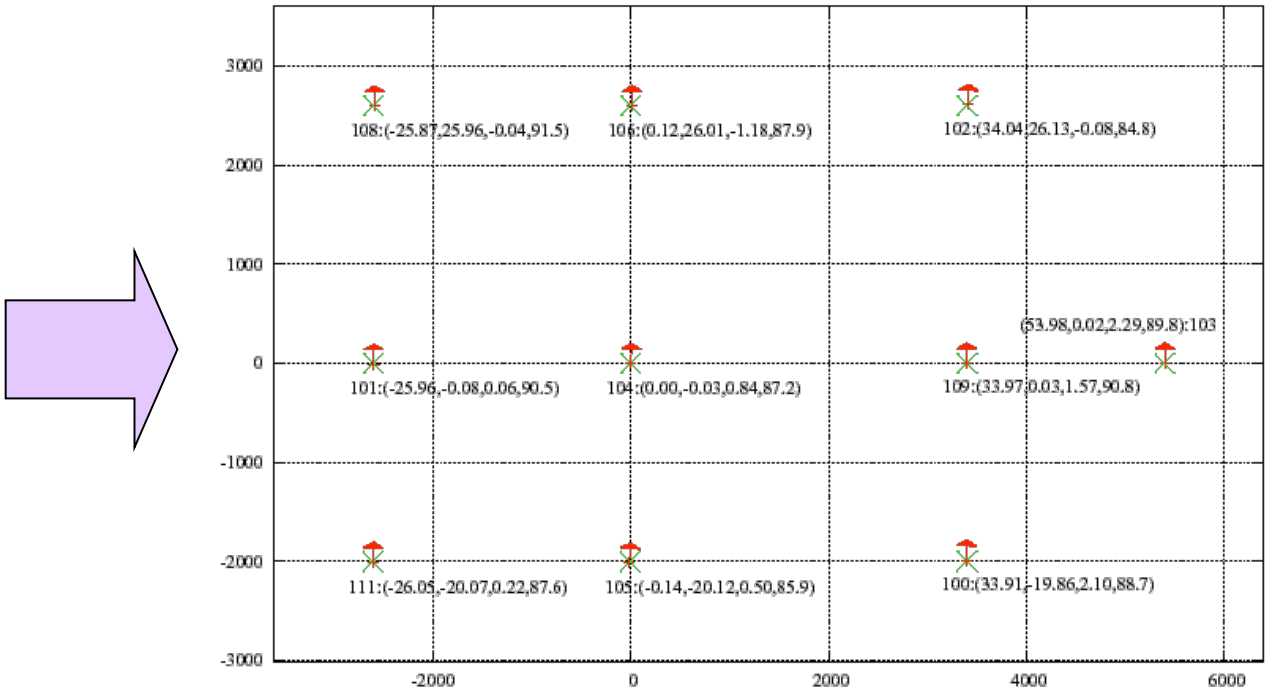


- 6-way cross-correlation of "peak region" → DOA Estimator
  - DOA Estimator: non-linear least squares fit of phase offsets to array geometry, determine most likely DOA
  - Resilient to perturbations in microphone placement
- DOA estimate used to recombine signals to improve SNR
- Final peak detection yields final range estimate R

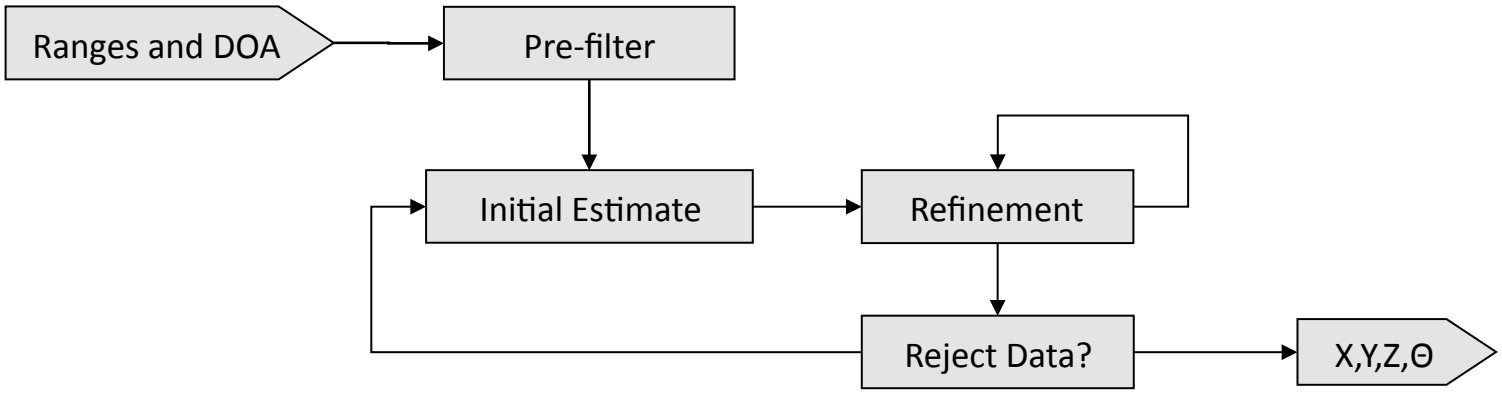
Position Estimation

- Problem:
  - Given pair-wise range and DOA estimates
  - Estimate X,Y,Z locations and orientation Θ for each node

R,θ,ϕ

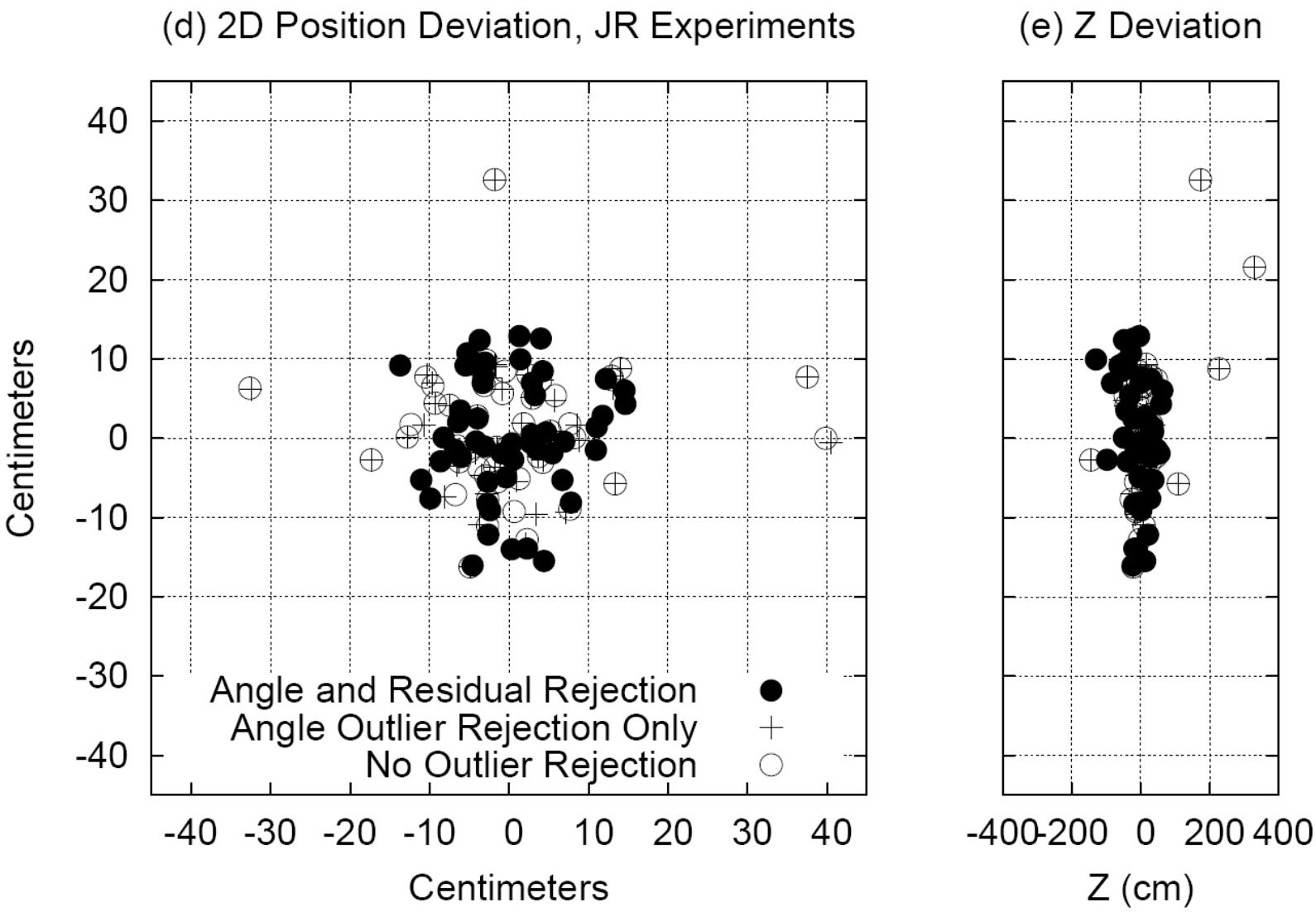


Position Estimation Solution



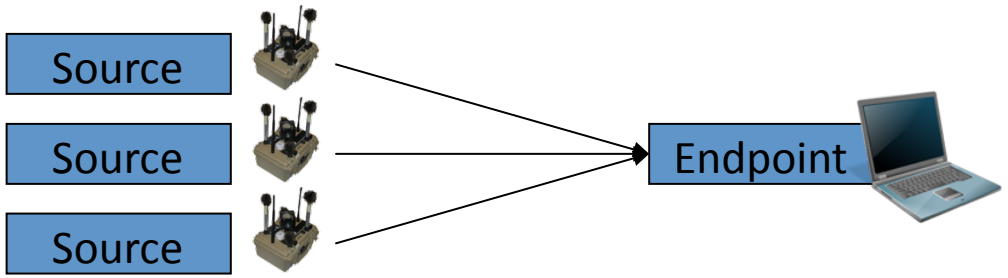
- Iterative refinement
  - Non-linear least squares position estimation
  - Interleaved orientation estimation
- Filtering out bad data is key to good results
  - Pre-filtering step
  - Over-constrained system → reject inconsistent data

Self localization accuracy



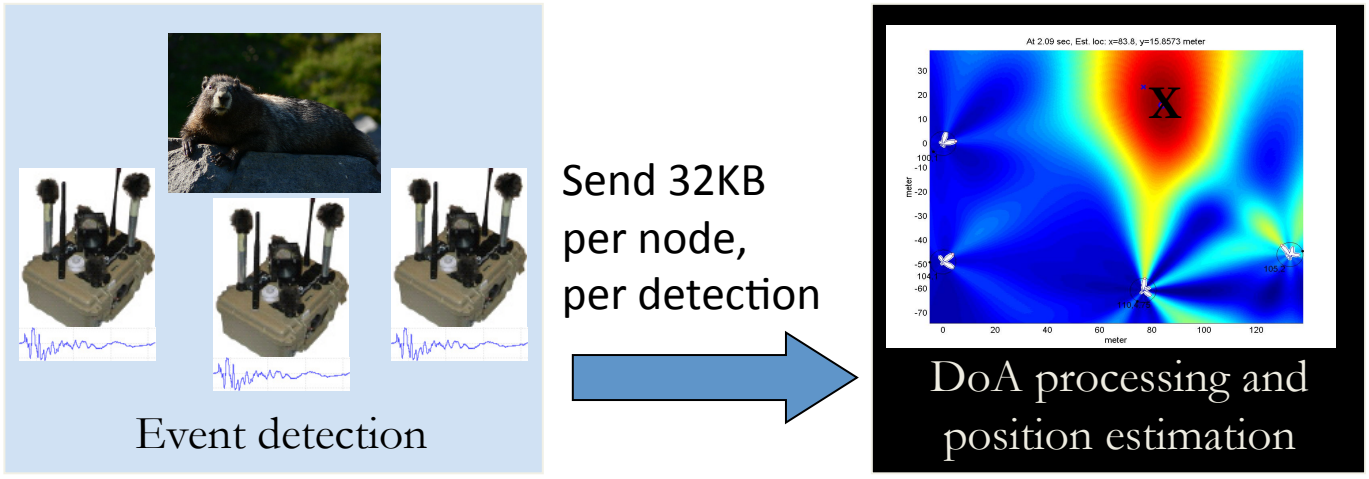
VoxNet Applications

- Programming language: Wavescript
  - High level, stream-oriented macroprogramming language
  - Compiles down to a directed graph of communicating 'stream operators' which data flow through (source to endpoint)
  - Operates on stored OR streaming data
- User writes a script connecting operators
  - Writes both node side + sink side separately
- User decides where processing occurs (node, sink)
  - Explicit, not automated processing partitioning



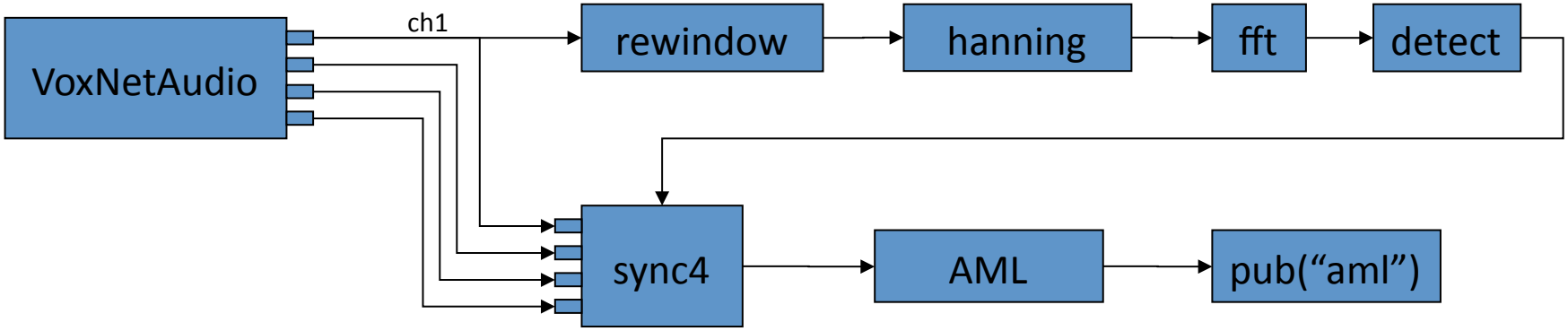
Example VoxNet application

- Detect and determine location of marmots
  - Combine DoA estimates from surrounding nodes
  - Obtain results on-line



NODES SINK

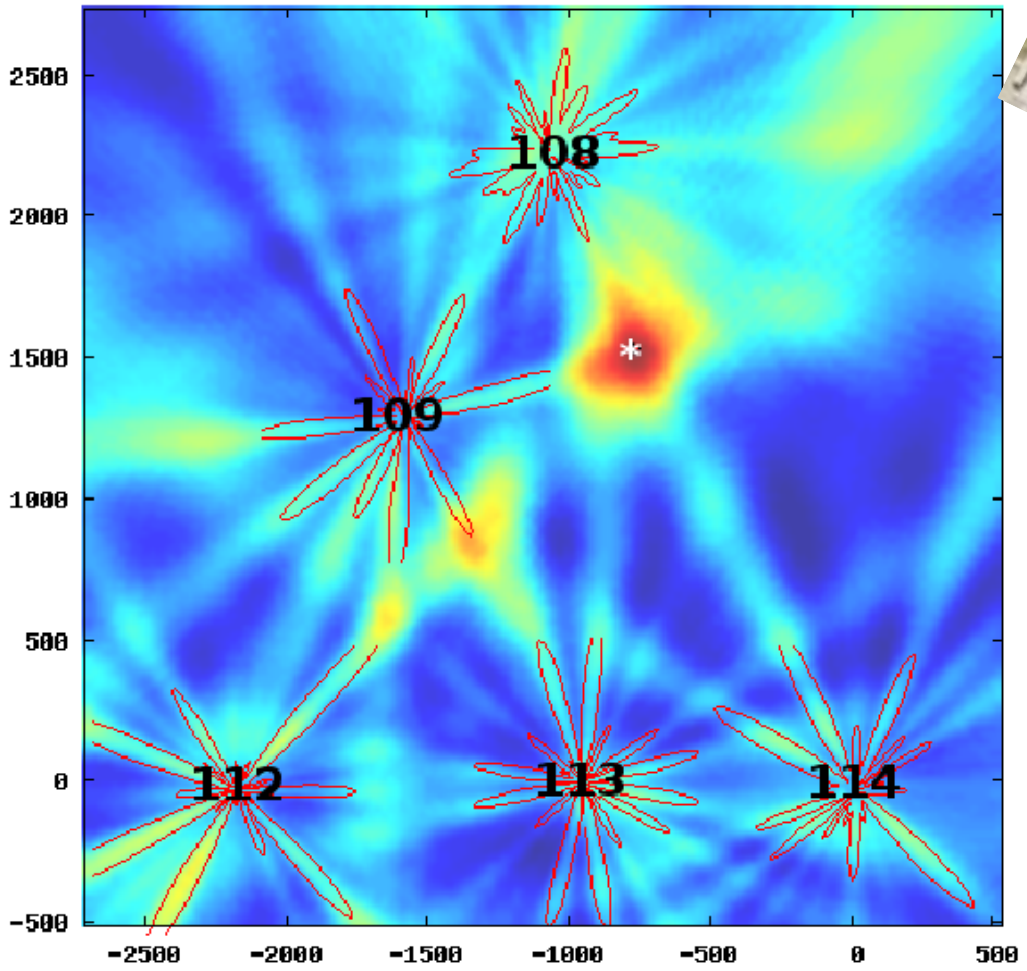
Demo Application: Streaming data plus AML direction finding



VoxNet Node

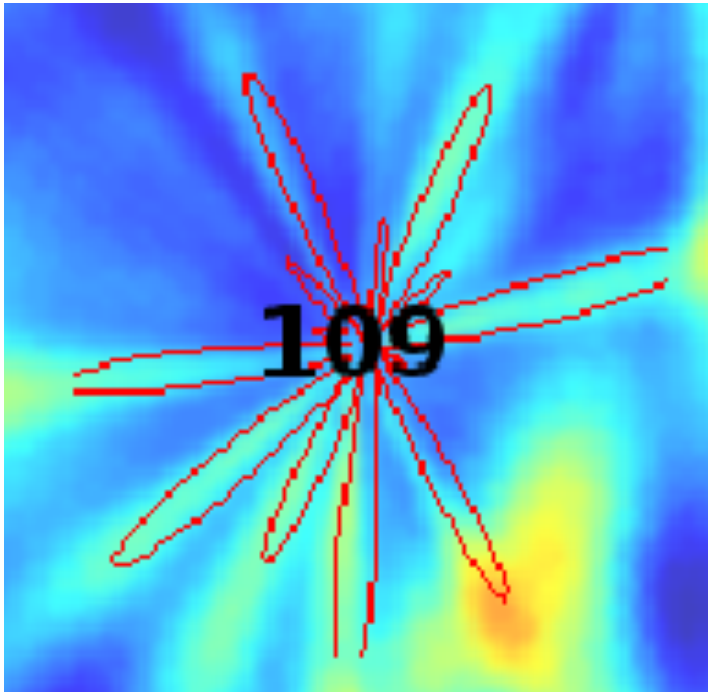
Laptop

IPSN Demo Video

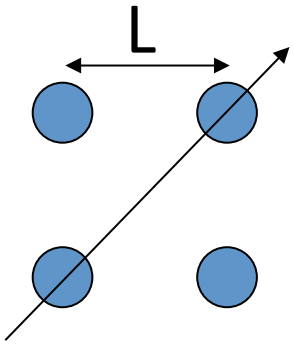


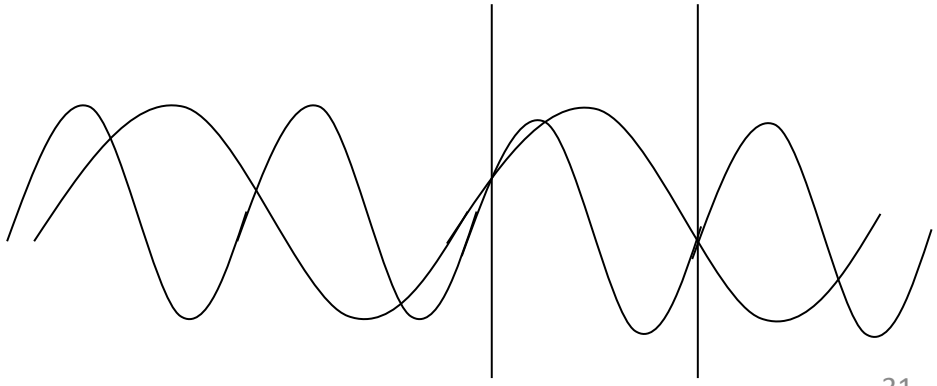
- Outdoor demo, behind Media Lab
- System deployed and auto-calibrated
- Human in field blows dog whistle
- System detects whiste, localizes source in real time

Spatial Aliasing



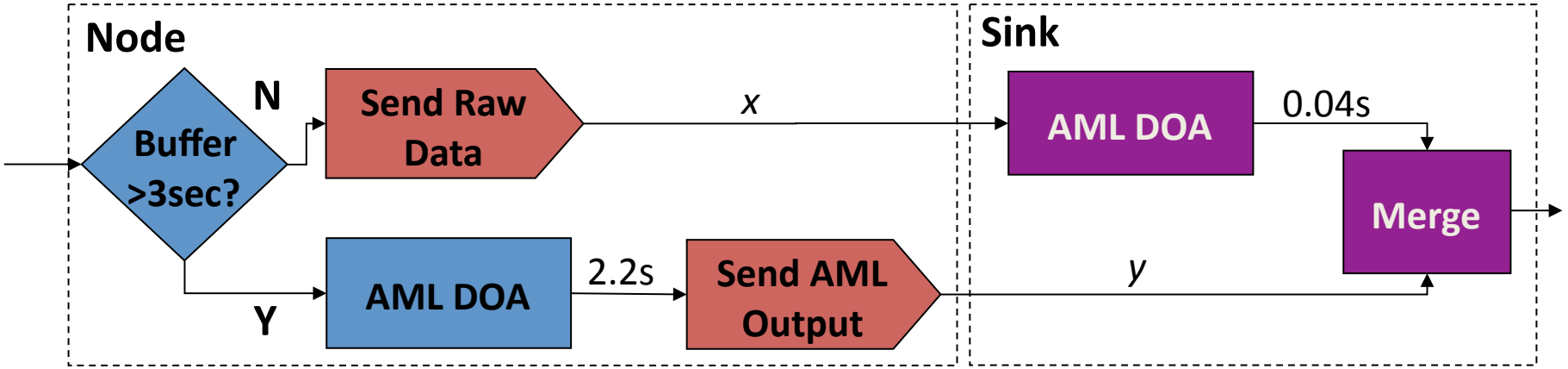
- Ambiguities in direction can occur if signal $\lambda < L/2$
- Spurious "Grating lobes"
- Filter using multiple nodes





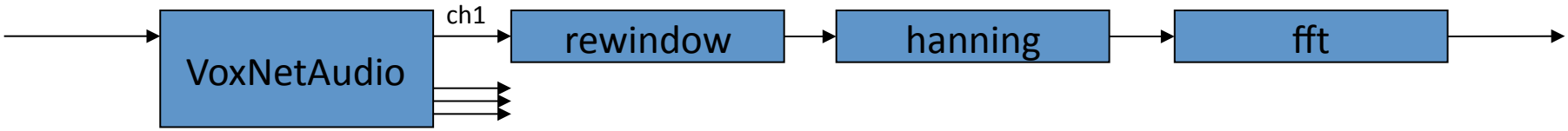
Applying the trade-off at run-time

- Aim: process raw data locally when possible
  - Node has limited buffer space for data samples
  - Event detection can happen faster than real-time, so can catch up



- Wavescript makes this easy to implement
  - Trivial, natural to split and merge multiple streams
  - Same on-node and sink DoA implementations

Example – energy calculation



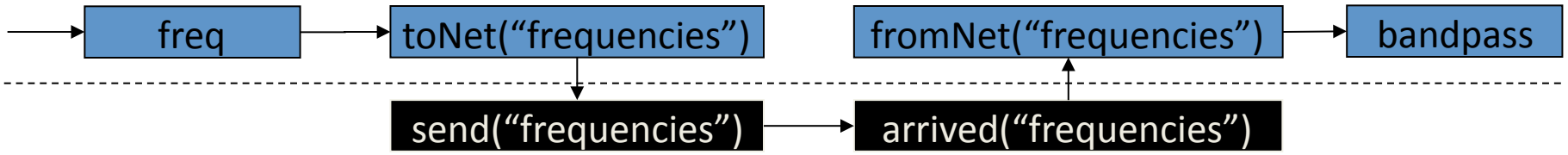

```
// acquire data from source, assign to four streams
(ch1, ch2 ch3, ch4) = VoxNetAudio(44100)

// window ch1 data stream into 32 sample chunks,
// passing through hanning then fft operators
freq = fft(hanning(rewindow(ch1, 32)))

// apply bandpass filter to freq
bpfiltered = bandpass(freq, 2500, 4500)

// calculate energy in bandpassed data
energy = calcEnergy(bpfiltered)
```

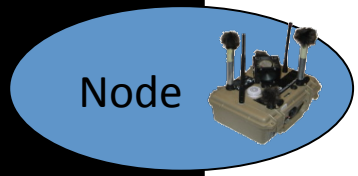
Splitting up a logical program




```
// acquire data from source, assign to four streams
(ch1, ch2 ch3, ch4) = VoxNetAudio(44100)

freq = fft(hanning(rewindow(ch1, 32)))

//send data to sink
toNet("frequencies",freq)
```

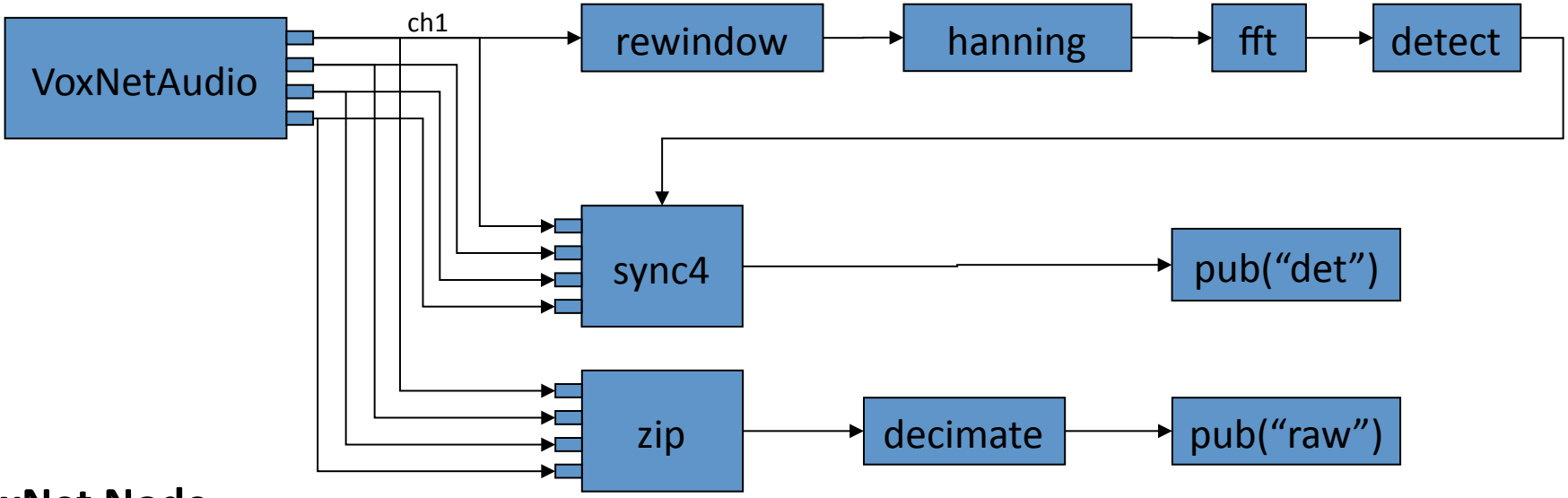



```
// receive data from node stream
freq2 = fromNet("frequencies")

// apply bandpass filter to freq
bpfiltered = bandpass(freq2, 2500, 4500)

// calculate energy in bandpassed data
energy = calcEnergy(bpfiltered)
```

Demo Application: Streaming data plus AML direction finding



VoxNet Node

Laptop