19th Annual Center for Advanced Signal and Imaging Sciences (CASIS)
Signal and Imaging Sciences Workshop, May 13, 2015
Lawrence Livermore National Laboratory

Clock Synchronization Through Underwater Acoustic Communication Channels

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Retired October 2013 from:
Lawrence Livermore National Laboratory
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Grace Clark, Ph.D., IEEE Fellow, has a consulting business, Grace A. Clark, Ph.D., Consulting. From 2010-2012, she was a Visiting Research Professor in the Center for Cyber Warfare at the Naval Postgraduate School (NPS), Monterey, CA, on Professional Research and Teaching Leave from the Lawrence Livermore National Laboratory (LLNL), Livermore, CA. After more than 30 years at LLNL, she retired from LLNL in 2013 to run her consulting business. She earned BSEE and MSEE degrees from the Purdue University EE Honors Program and the Ph.D. ECE degree from the U. of California Santa Barbara. Her technical expertise is in statistical signal/image processing, estimation/detection, pattern recognition/machine learning, sensor fusion, communication and control. Dr. Clark has contributed more than 220 publications in the application areas of acoustics, electro-magnetics and particle physics. Dr. Clark is a member of the ASA Technical Council on Signal Processing in Acoustics, as well as the IEEE, SEG (Society of Exploration Geophysicists), Eta Kappa Nu and Sigma Xi.

My Current Research is Focused on *Nonlinear, Non-Gaussian* Signal Processing Problems

- **Mobility Modeling and Estimation for Ad Hoc Networks of Unmanned Ground Vehicles**
  - Estimate position, velocity and acceleration, given only measurements of Received Signal Strength Indicator (RSSI) signals from fixed or mobile base stations
  - with Prof. Preetha Thulasiraman, NPS

- **Illumination Waveform Design for Non-Gaussian Multi-Hypothesis Target Classification in Cognitive Radar**
  - with a student at NPS

- **Statistical Feature Selection for Non-Gaussian Target Classes**
  - with a student at NPS

- **Clock Synchronization Through Time-Variant Underwater Acoustic Channels**
  - with Prof. Joe Rice, NPS

Research Team

- **Pascal Gagnon,** *LCdr, Royal Canadian Navy*
  Former MSEE Student at Naval Postgraduate School

- **Joseph A. Rice,** *Research Professor, Naval Postgraduate School*

- **Grace Clark,** *Ph.D., IEEE Fellow, Grace Clark Signal Sciences,*
  Former Visiting Research Professor, Naval Postgraduate School

Grace Clark
&
Pascal Gagnon

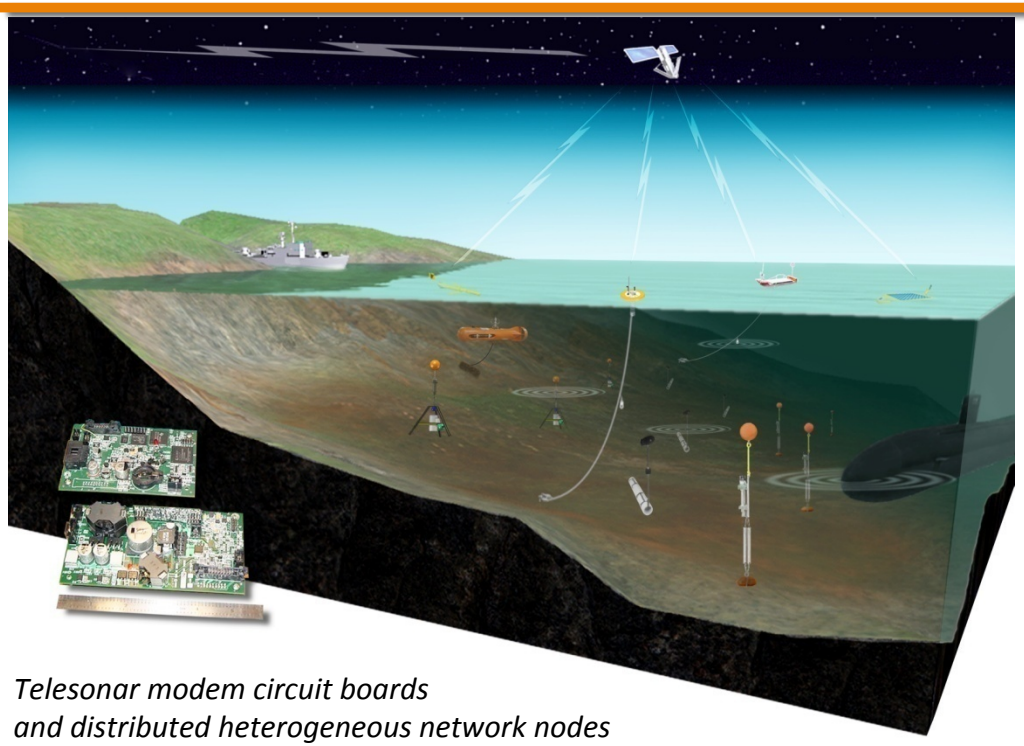
Joe Rice

Agenda

- **Introduction**
  - ***The Seaweb Network***
  - ***The Underwater Acoustics Clock Synchronization Problem***
  - ***The Through-Water Challenge***
  - ***Existing Protocol***
- **The Proposed Clock Synchronization Protocol**
- **Simulation Studies**
- **Real-World Experiments in Del Monte Lake at NPS**
- **Conclusions and Discussion**

The World of Acoustics Before Signal Processing

Seaweb maritime sensor networks



Telesonar modem circuit boards and distributed heterogeneous network nodes

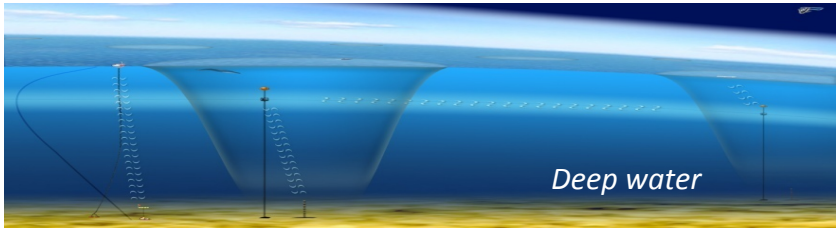
Applications
- ASW—SPSS detection—ISR
- Port security—Sea-base defense
- Ocean environmental monitoring
- Submarine comms—RECO—C2

Principal investigator
- Research Professor Joseph Rice
- jarice@nps.edu, +1 831 524 4488

Sponsors
- ONR 32, CRUSER, NIWO, OSD

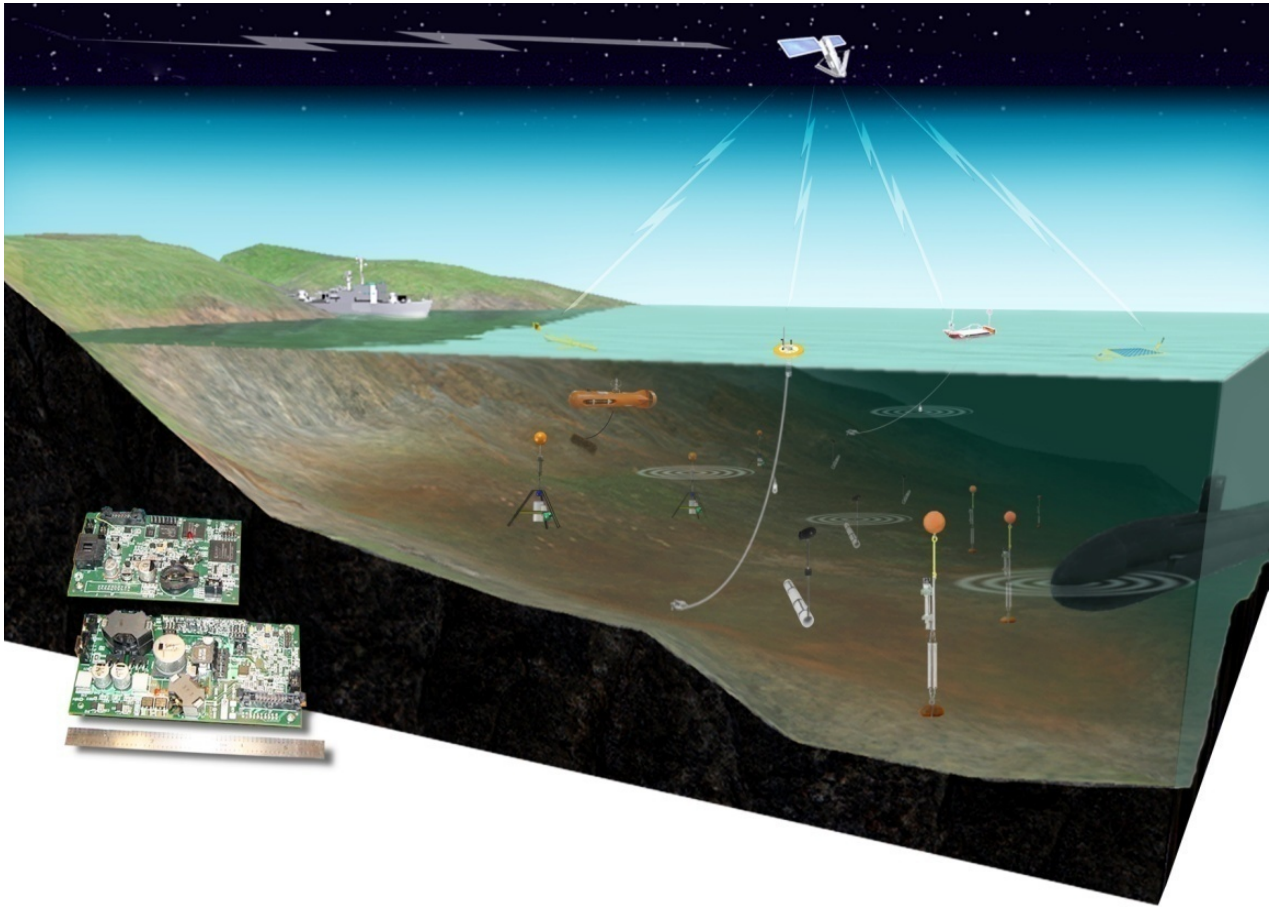
Goal: Advance through-water acoustic networking and undersea wide-area surveillance.

Approach: Physics-based research—interdisciplinary development—collaboration—frequent sea tests.



Seaweb Maritime Sensor Networks (Joe Rice, NPS)

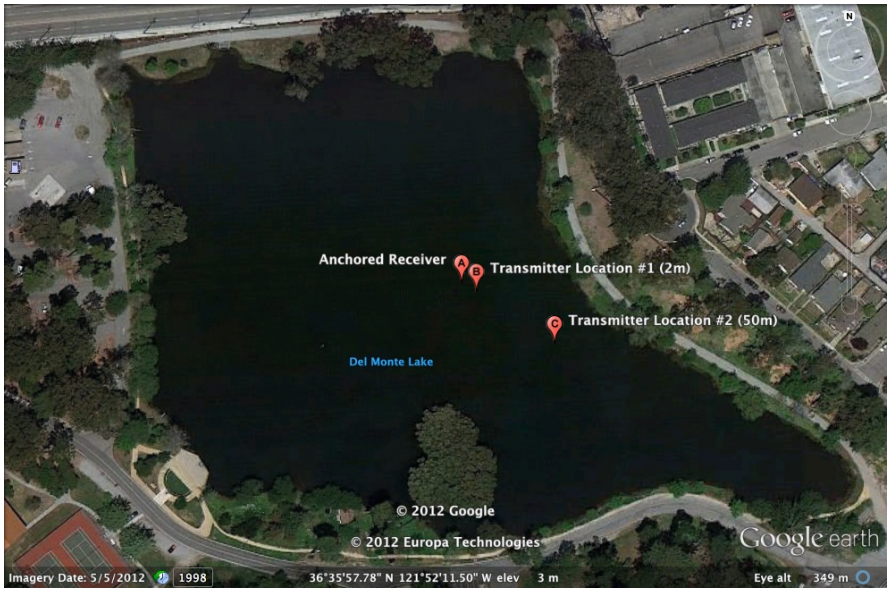
- Underwater wireless network (acoustic)
- Telesonar digital acoustic modems from Teledyne Benthos, Inc.
- 9-14 kHz acoustic signaling
- Data packets up to 4 kbytes at 800 bit/s
- Sensor nodes and repeater nodes with wide-area network routing



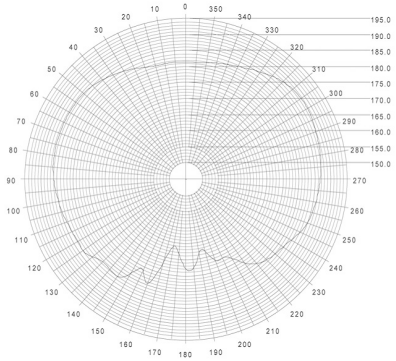
Typical Transmitter and Receiver Nodes

(Teledyne Benthos)

- Deck box capable of transmitting arbitrary waveforms (wav files)
- SM-75 Node with high fidelity data acquisition and SD-card recorders
- Series of 30 chirps, 9-14 KHz
- Various chirp lengths



Transmitter Node



Receiver Node

Clock Synchronization is Important for Seaweb

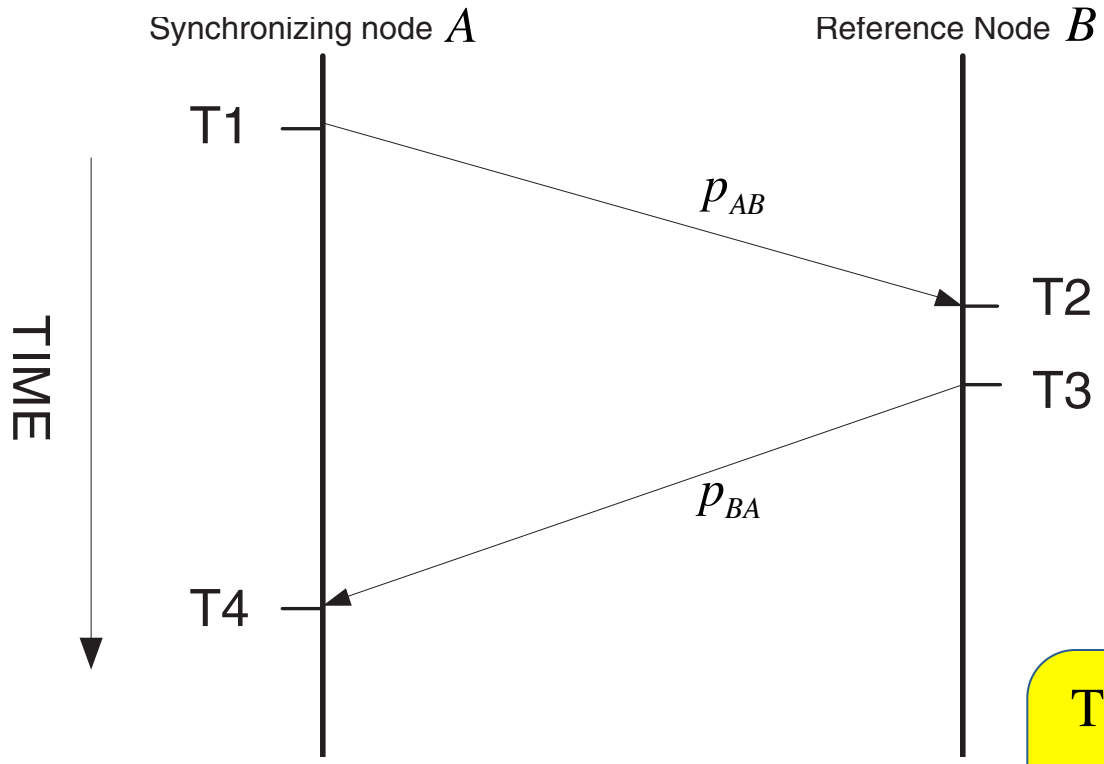
- **Clock-synchronization = Time-Synchronization**

- **Each node has its own internal clock**

- **Clocks are quartz crystal based – they are affected by:**
  - ***Temperature***
  - ***Pressure***
  - ***Voltage changes***
  - ***Hardware aging***

- **Important for:**
  - ***Data Fusion***
  - ***Power Management***
  - ***Transmission Scheduling (TDMA)***

Model for Time-Stamped Message Exchange Between Two Nodes: *We Cannot Assume Channel Reciprocity*



p_{BA} = Propagation Delay from B to A

p_{AB} = Propagation Delay from A to B

Total Propagation Delay:

$$P = (T2 - T1) + (T4 - T3)$$

$$= p_{AB} + p_{BA}$$

The Literature Assumes Reciprocity:

$$p_{AB} = p_{BA}$$

A. Syed, and J. Heidemann, "Time Synchronization for High Latency Acoustic Networks", *Proceedings IEEE Infocom*, Barcelona, Spain, 2006.

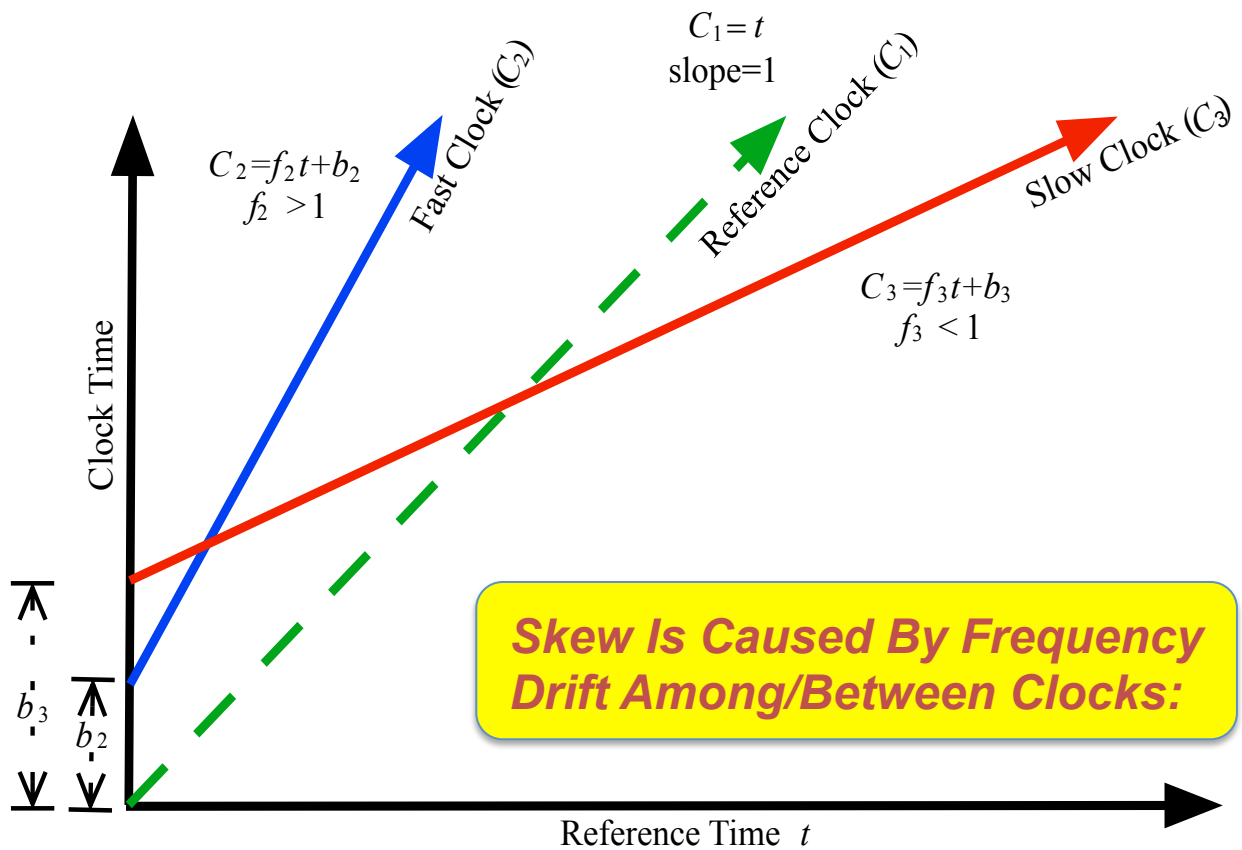
The Clock Model is Linear: We Define Skew (Slope) and Offset (y- Intercept)

$C_i(t) = f_i t + b_i$ = Clock Time for Clock i

$i = 1, 2, \ldots, N_{clocks}$

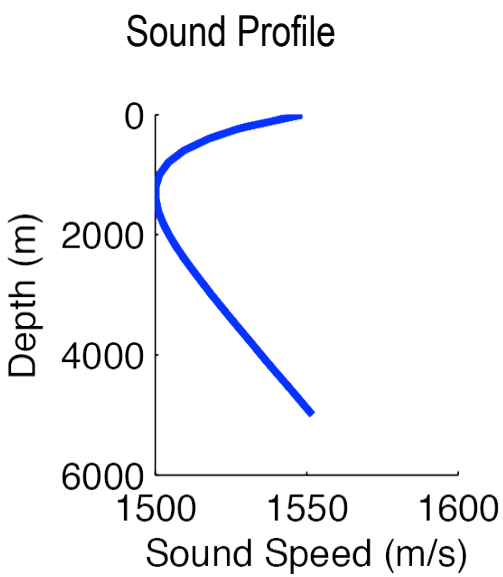
f_i = Skew (slope)

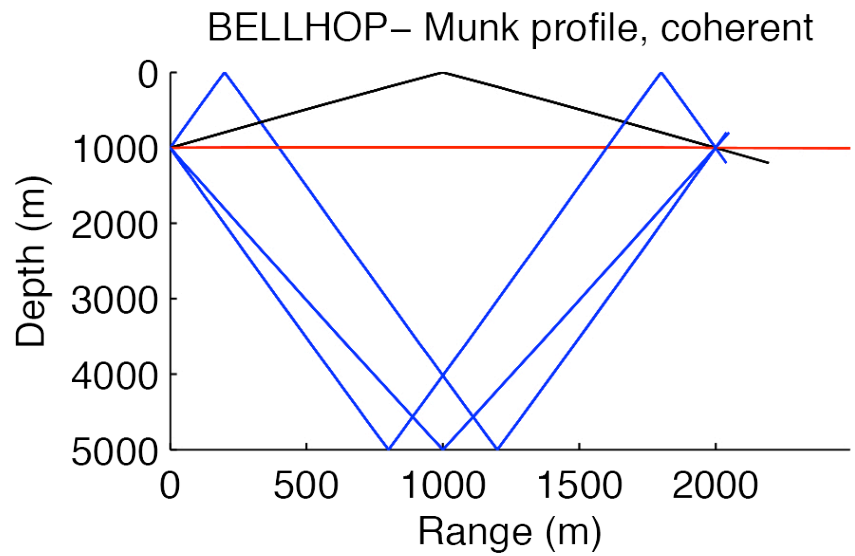
b_i = Offset

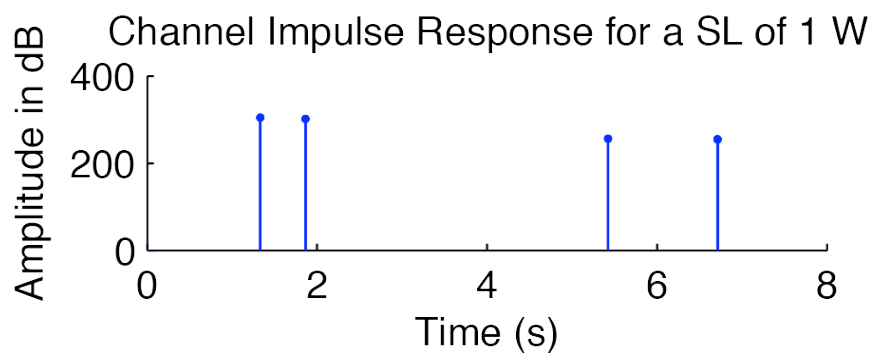


The Obvious Idea is to Synchronize on the First (Stongest) Arrival: *But Multipath Obviates This Idea*

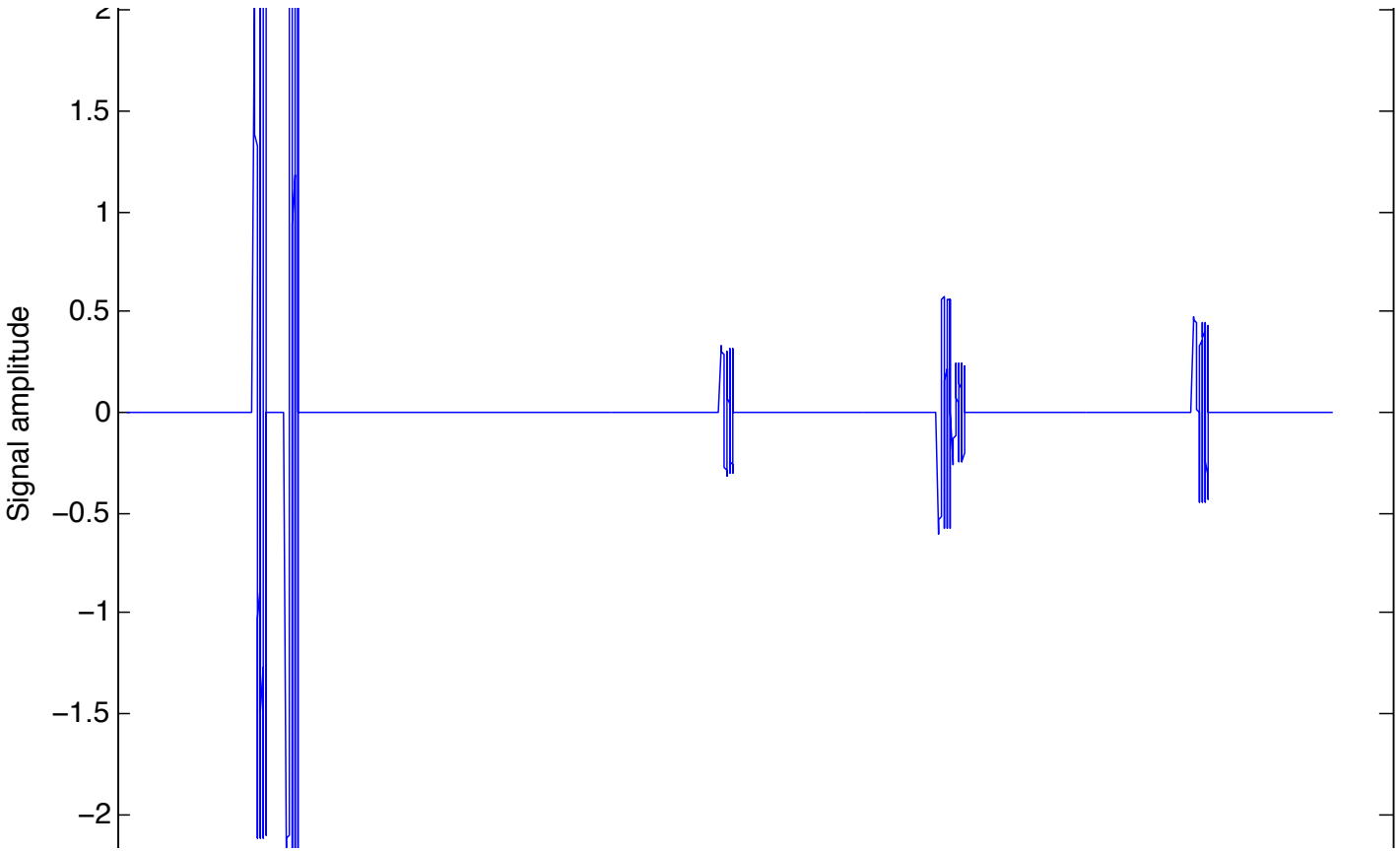
We use the Bellhop software package to simulate underwater acoustic wave propagation



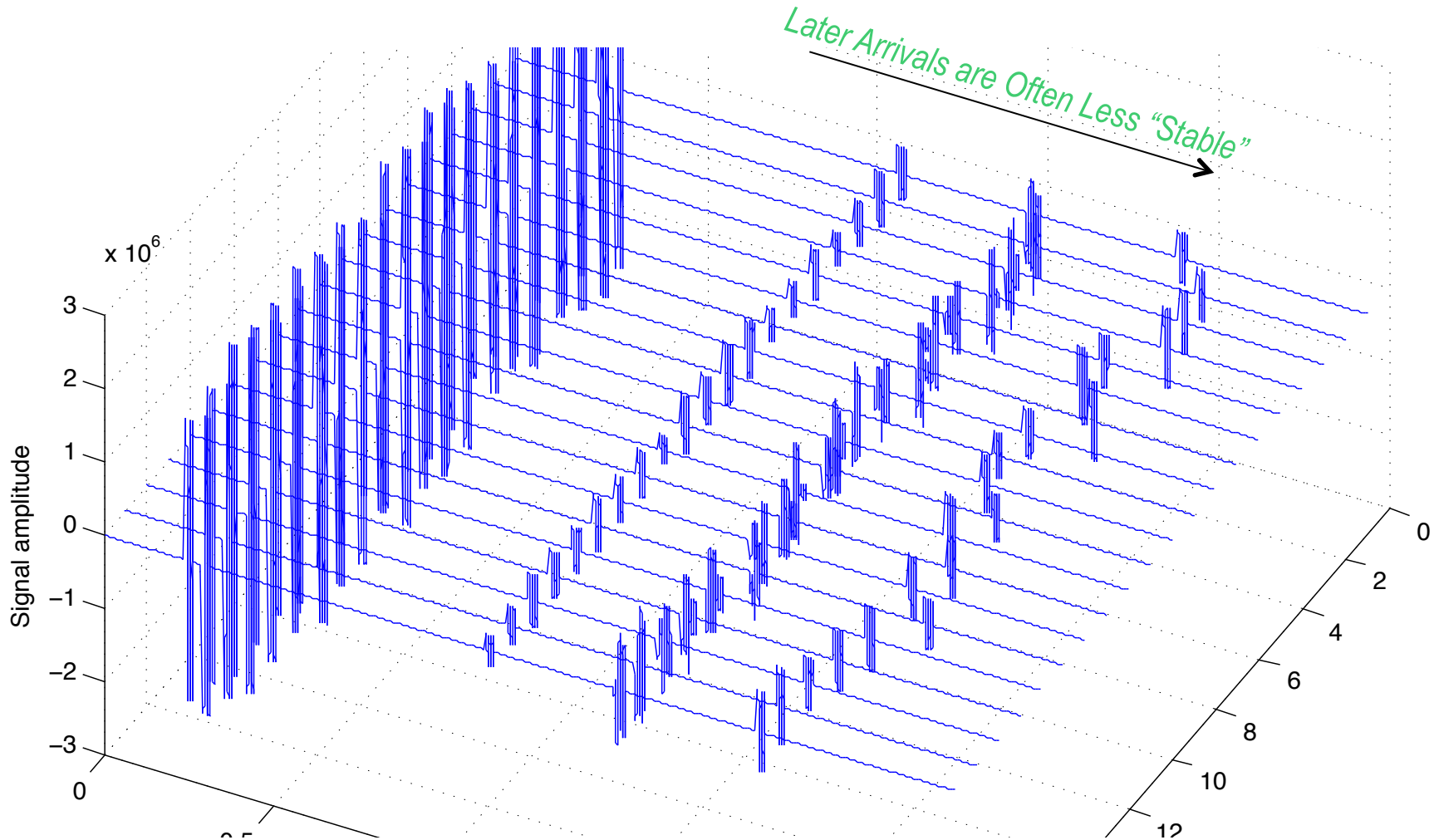




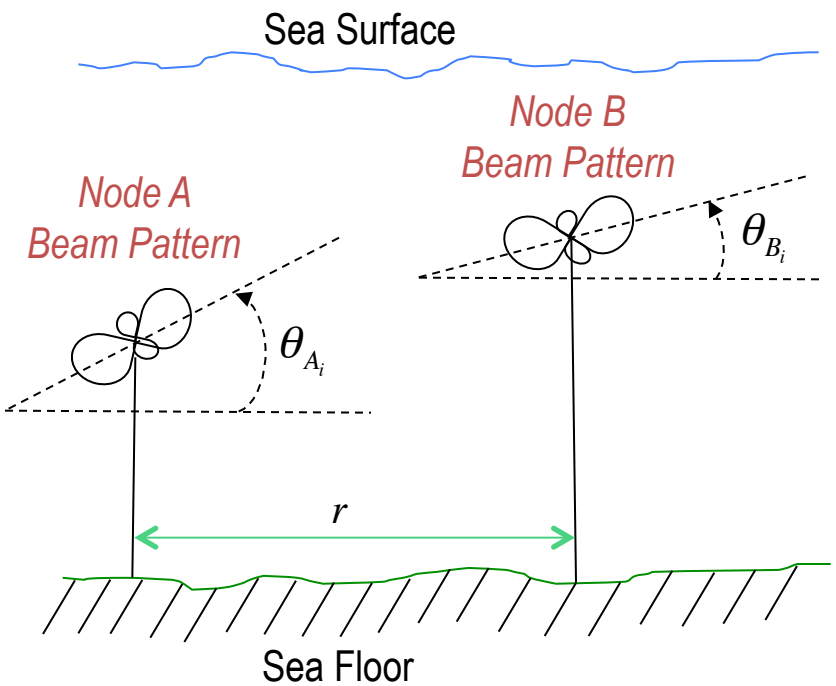
Plot a Single LFM (Linear Frequency Modulated) Chirp Response Measurement Signal y(t) Received at node B



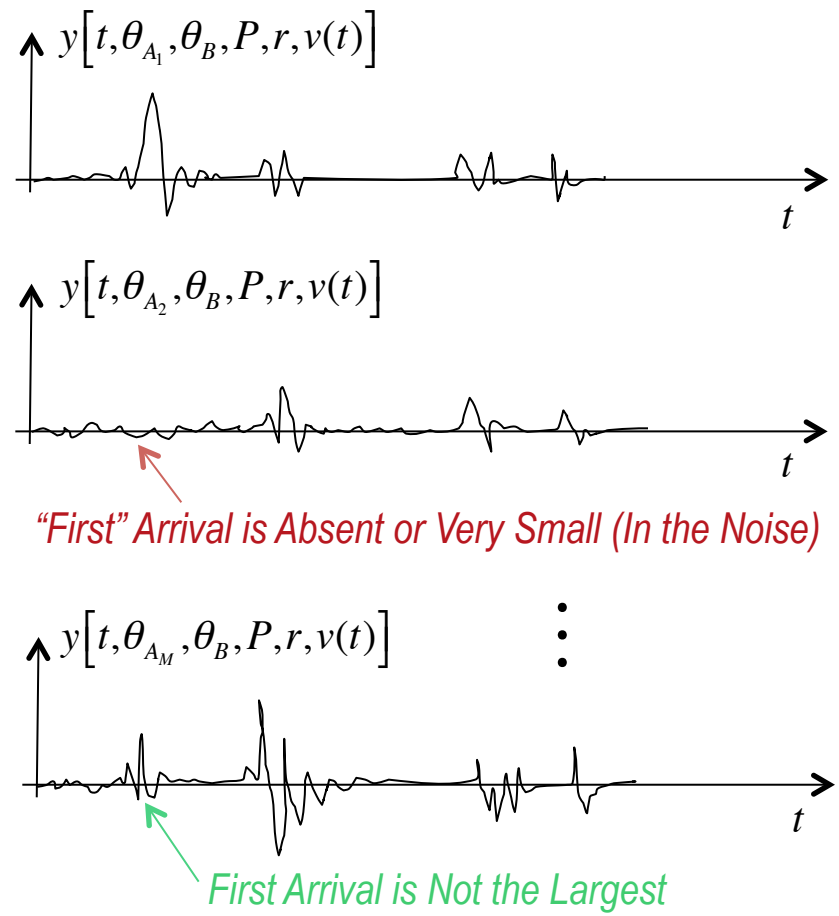
Ensemble of 20 Received Chirp Response Signals:
Note the Variation in Multipath Arrival Times ("Instability")



Consider an Ensemble of *M* Signals Received at Node B: The Largest Reflection is Not Always the First Received



- *Fix the angle of Node A.*
- *Let the angle of Node B angle vary, i = 1,2, …, M*



$y\left[t,\theta_{Ai},\theta_{Bi},P,r,v(t)\right]$ = Signal Measured at Node B

t = Time

P = Sound Profile

r = Range

$v(t)$ = Measurement Noise

Clock Synchronization is an Active Research Area for Every Type of Communication Channel

- **Clock synchronization is particularly challenging for Underwater Acoustic Comm.**
  - *Latency is large (slow speeds, large delays)*
  - *Multipath is problematic*

- **Techniques in the literature assume:**

  (1) The channel has the reciprocity property

  ➔ *Forward and Backward propagation properties are the same*

  ➔ *Forward and Backward propagation delays are the same*

$$p_{AB} = p_{BA}$$

  (2) The channel is time-invariant

- ***Good News for Us → Real-world experiments demonstrate that:***
  - *The first multipath arrival is always present and strong*
  - *Later multipath arrivals are less "stable" as they interact with channel boundaries (we will show how to exploit this later)*

We Modify and Extend the "TSHL Protocol" by Relaxing Incorrect Assumptions and Exploiting Ensembles of Multipath Arrivals

TSHL Protocol ("Time Synchronization for High Latency")	**Our New Protocol**
• **Assumptions:** (1) Channel Reciprocity ➔ Constant Propagation Delays $p_{AB} = p_{BA}$ (2) Channel Time-Invariance (3) We can synchronize on the Strongest multipath arrival ➔ Does not really deal with multipath	• **Assumptions:** (1) No Channel Reciprocity ➔ $p_{AB} \neq p_{BA}$ (2) Channel is Time-Variant ➔ Adapt to variations by estimating channel impulse responses periodically, adjust skew and offset (3) We can synchronize on the Most Stable arrival (Not necessarily the strongest). We don't have to get all arrivals right, just most stable
• **Uses Two Stages:** (1) Skew Correction (One-Way Messaging) - Use linear regression on the SPI (measured Synch. Pulse Interval) = Delay between received pulses = Assumed to be Constant (2) Offset Correction (2-Way Messaging) - Calculation is simple due to assumptions	• **Uses Two Modified and Extended Stages:** (1) Skew Correction (One-Way Messaging) - Matched filter, Estimate Arrival Times + pdf's - Regression on Arrival Times, Skew Calc. (2) Offset Correction (2-Way Messaging) - Matched filter, Estimate Impulse Responses - Correlate the Impulse Responses, Offset Calc.

Technical Approach: Exploit Statistical Properties of an Ensemble of Measured Arrivals (Stochastic Processes)

- Each measured signal is a single realization of a stochastic process

$$y\left[t,\theta_{Ai},\theta_{Bi},P,r,v(t)\right] = \text{Signal Measured at Node B}$$
$$t = \text{Time}$$
$$P = \text{Sound Profile}$$
$$r = \text{Range}$$
$$v(t) = \text{Measurement Noise}$$

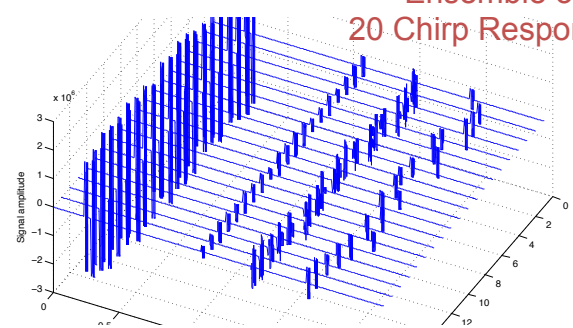
- By fixing the angle of Node B, P and r, we can represent the stochastic process by:

$$y\left[t,\theta_{Ai}\right] = x[t,\theta_{Ai}] + v(t)$$

- We can represent an ensemble of M realizations of the stochastic process over the angle of Node A as follows:

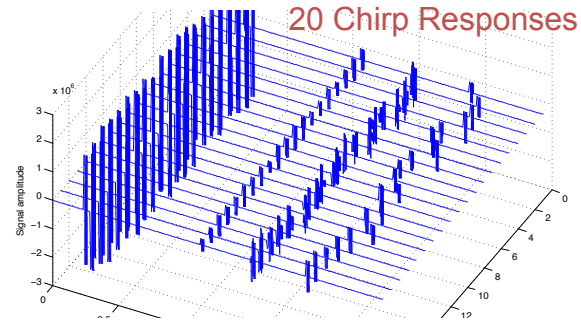
$$\left\{y\left[t,\theta_{Ai}\right]\right\}_{i=1}^{M} = \left\{x[t,\theta_{Ai}] + v(t)\right\}_{i=1}^{M}$$

Ensemble of 20 Chirp Responses



Using an Ensemble of Measured Signals,
Estimate the Arrival Times of the Multipath Arrivals

Ensemble of
20 Chirp Responses



Given:

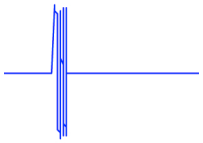
- An ensemble of measurements $\{y[t,\theta_{Ai}]\}_{i=1}^{M}$

Let the angle of Node B vary over a range values

$$\theta_{Min} \le \theta_{B_i} \le \theta_{Max}, \; i = 1, 2, \ldots, M$$

For Simulations, We Let the Range of Node B Angles = $[0^0, 30^0]$

- A Reference Wavelet representing the reflection from one interface



Example of a reference linear frequency-modulated chirp

Estimate: The arrival times of the various multipath arrivals

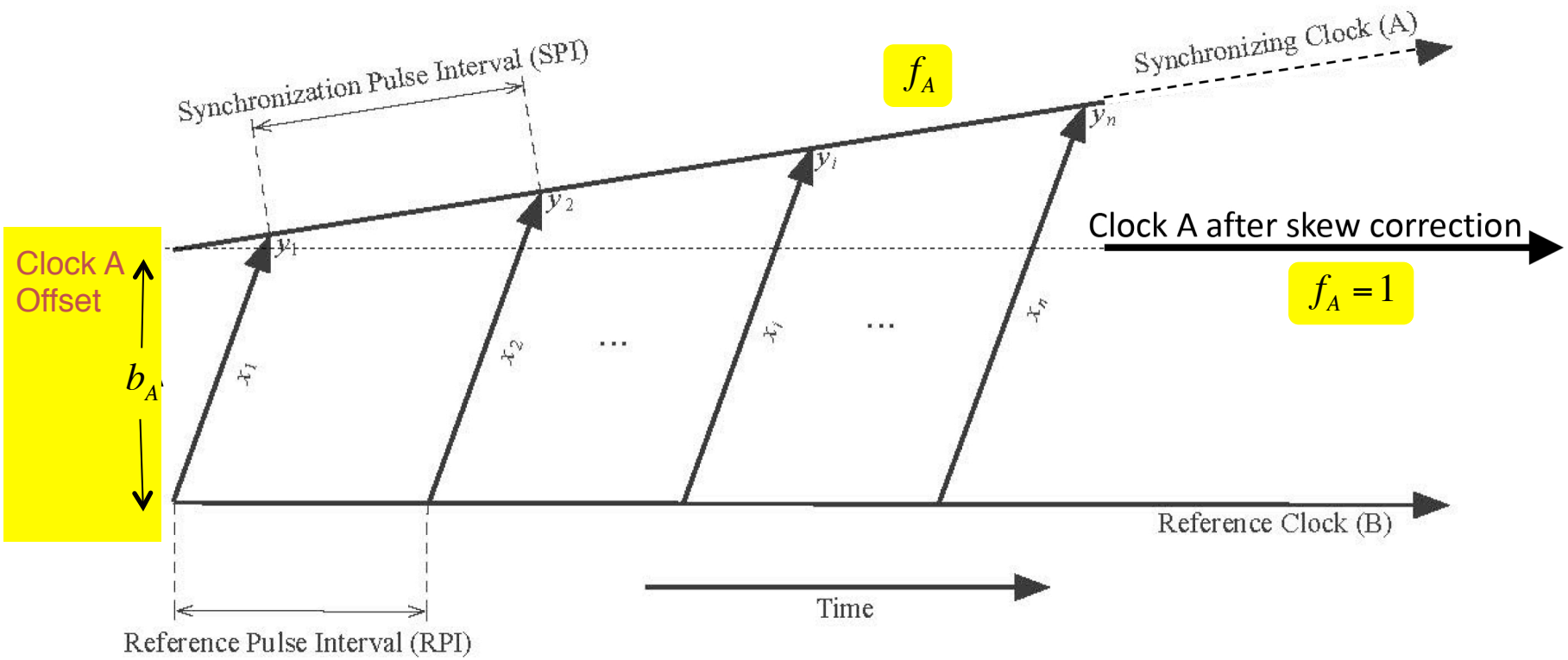
N_A = No. of Arrivals You Expect (You Choose This)

$$\underline{a}^* = \begin{bmatrix} a_1^* \\ a_2^* \\ \vdots \\ a_{N_A}^* \end{bmatrix}$$

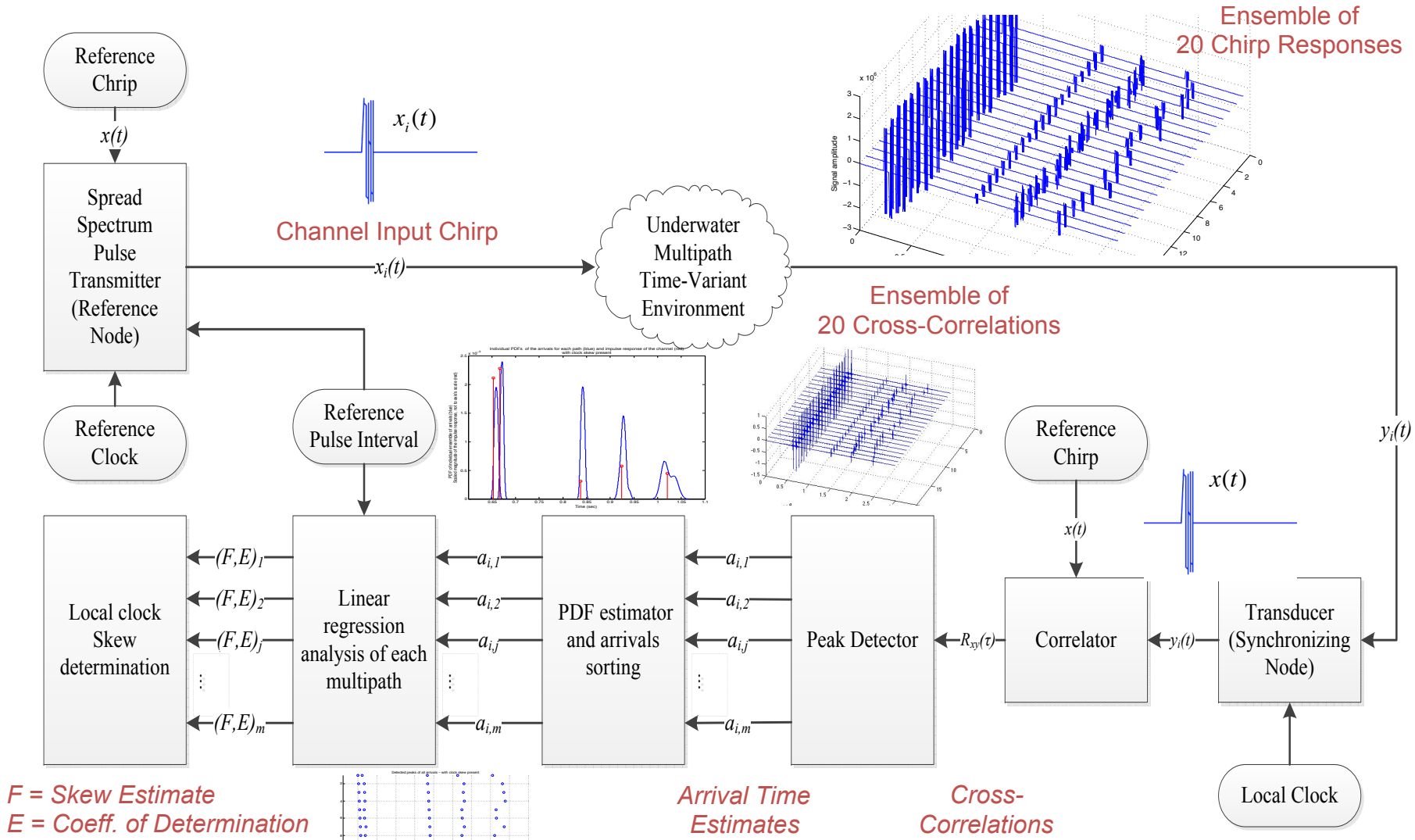
Stage 1: One-Way Message Dissemination for Skew Correction

The Goal is to Synchronize Clock A to Reference Clock B

- Reference Clock B is slaved to a reference time (e.g. GPS or atomic clock)
- Clock B transmits a series of chirp pulses $x_1, x_2, \ldots, x_n$ with known RPI, transmit times
- Estimate arrival times $y_1, y_2, \ldots y_n$ and estimate the skew f_A
- Knowing RPI, Clock A adjusts its clock frequency and corrects its skew f_A



Stage 1: One-Way Messaging to Estimate Clock Skew:
Exploit Estimates of the Multipath Arrival Times



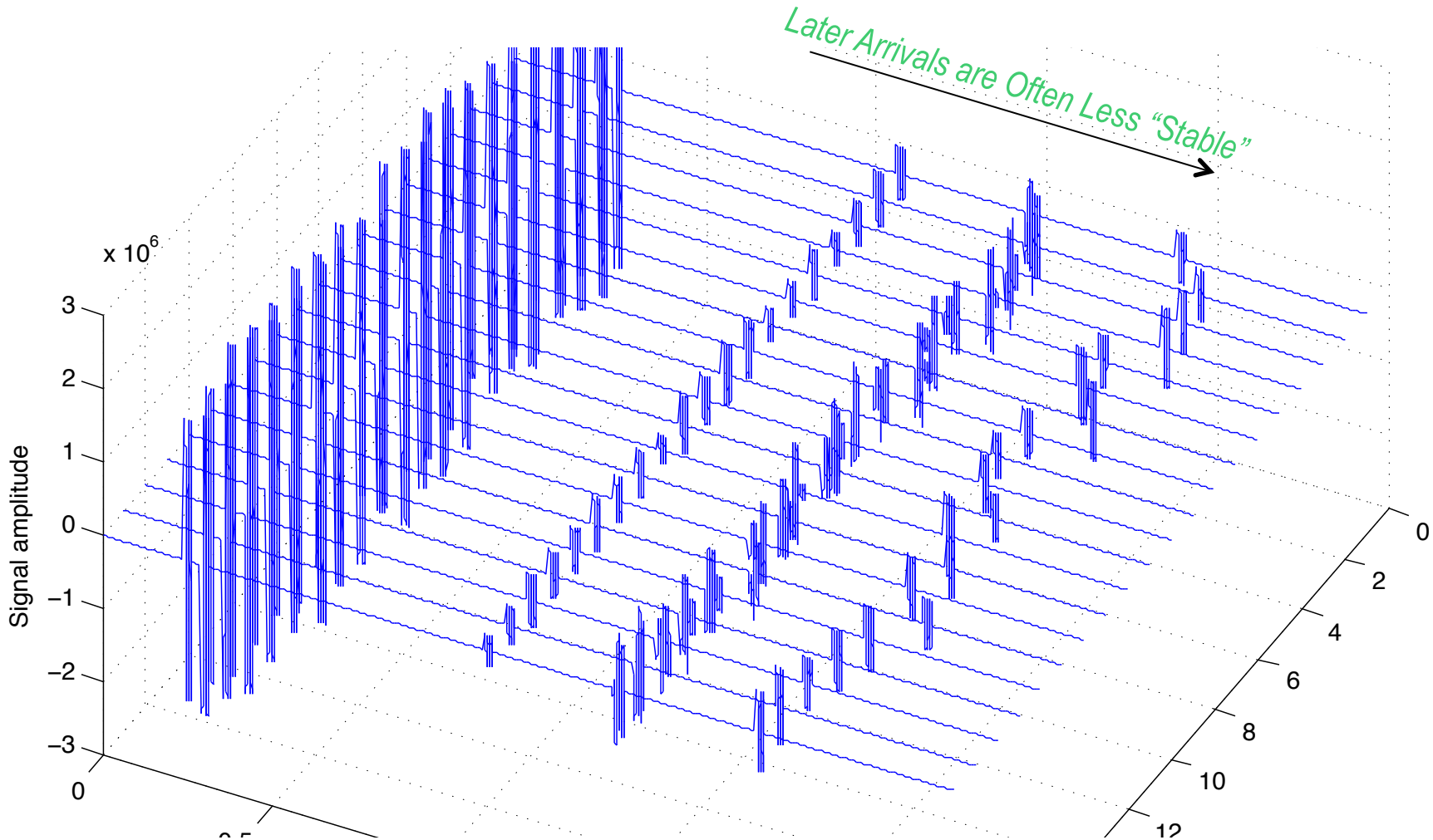
F = Skew Estimate
E = Coeff. of Determination

Arrival Time Estimates

Cross-Correlations

Pick Arrival with Largest E as the Most Stable

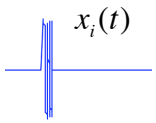
Ensemble of 20 Received Chirp Response Signals:
Note the Variation in Multipath Arrival Times ("Instability")

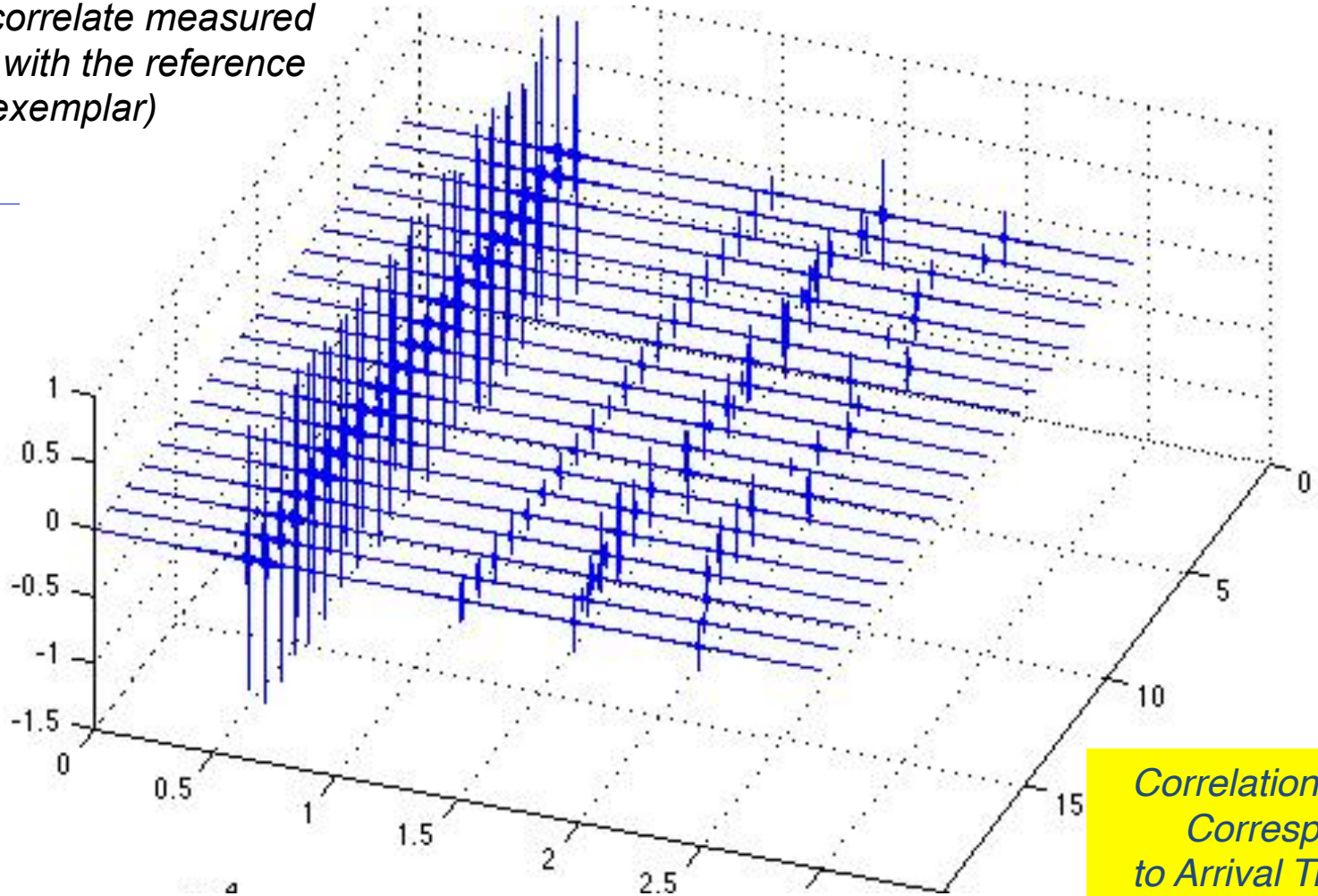


Ensemble of 20 Matched-Filtered Chirp Response Signals

The Plot Shows Cross-Correlation vs. Lag Time

Cross-correlate measured signals with the reference pulse (exemplar)



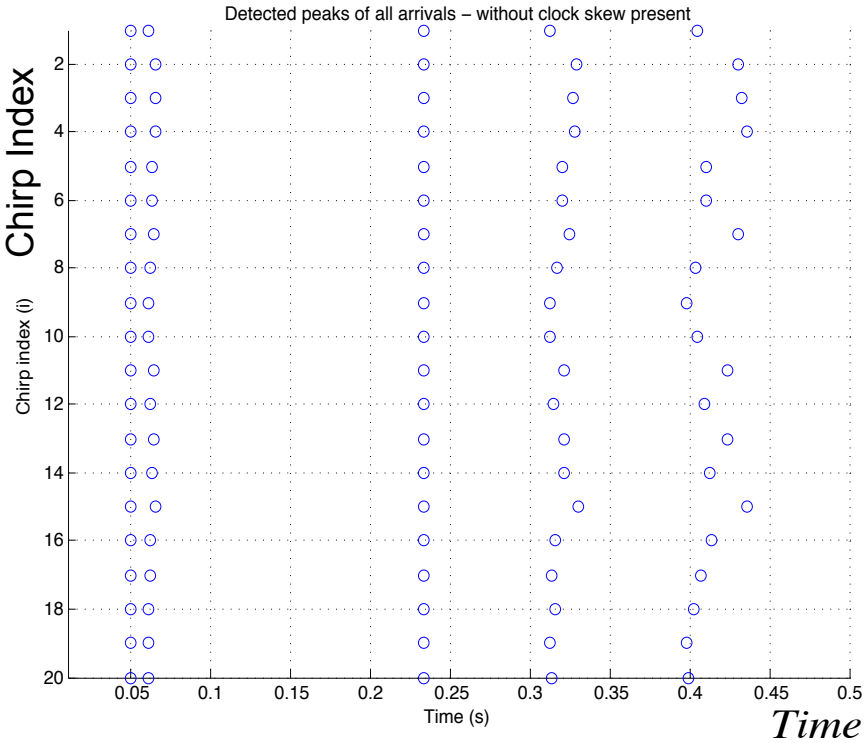


Correlation Peaks Correspond to Arrival Times of the Multipath Arrivals

Apply a Peak Detector to the Cross-Correlations to Estimate Multipath Arrival Times Over the Ensemble (20)

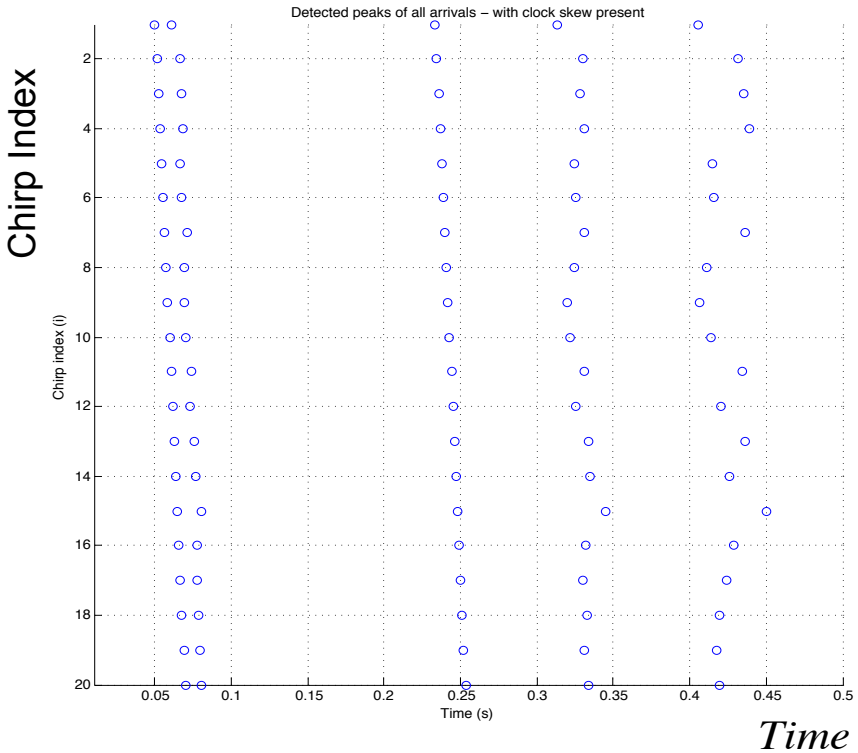
Detected Peaks for All Arrivals for a Clock

With Zero Skew Present



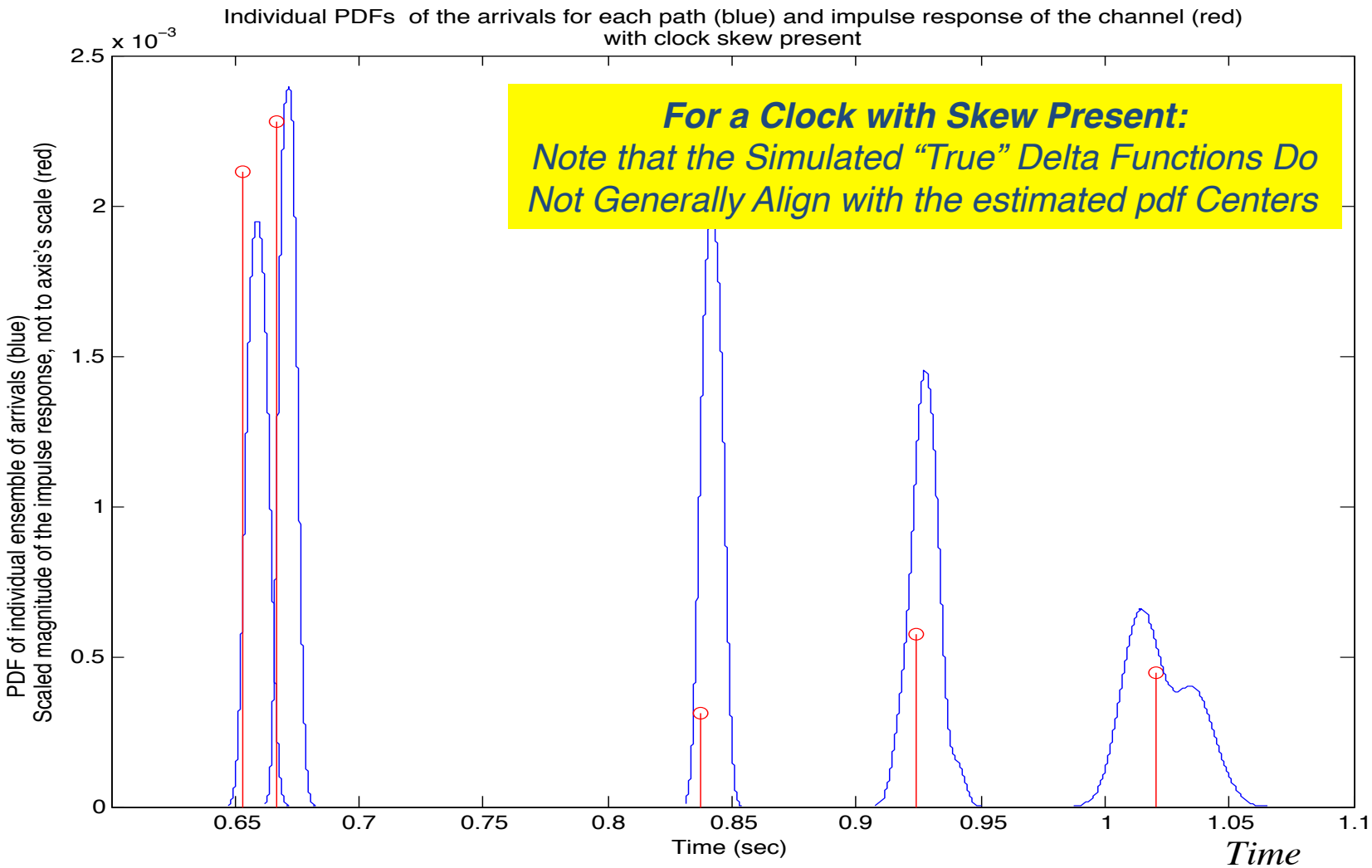
Detected Peaks for All Arrivals for a Clock

With Skew Present



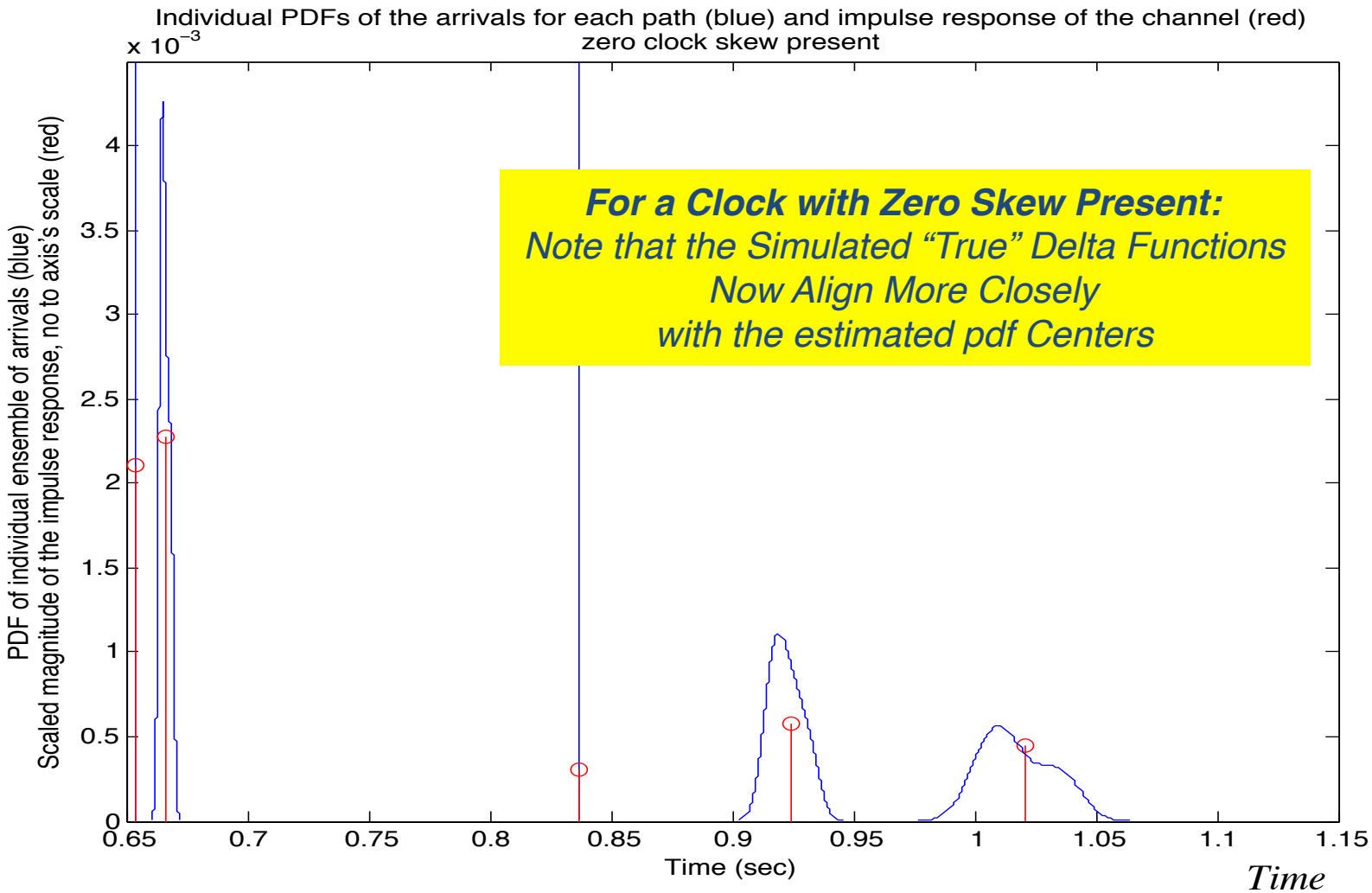
Note the Variation in Arrival Times for a Single Multipath Arrival

Blue: Individual Arrival Time pdf Estimates $\{p(a_j)\}_{j=1}^{M}$
Red: Simulated Impulse Response for the Channel



For a Clock with Skew Present:
Note that the Simulated "True" Delta Functions Do Not Generally Align with the estimated pdf Centers

Blue: Individual Arrival Time pdf Estimates $\{p(a_j)\}_{j=1}^{M}$
Red: Simulated Impulse Response for the Channel



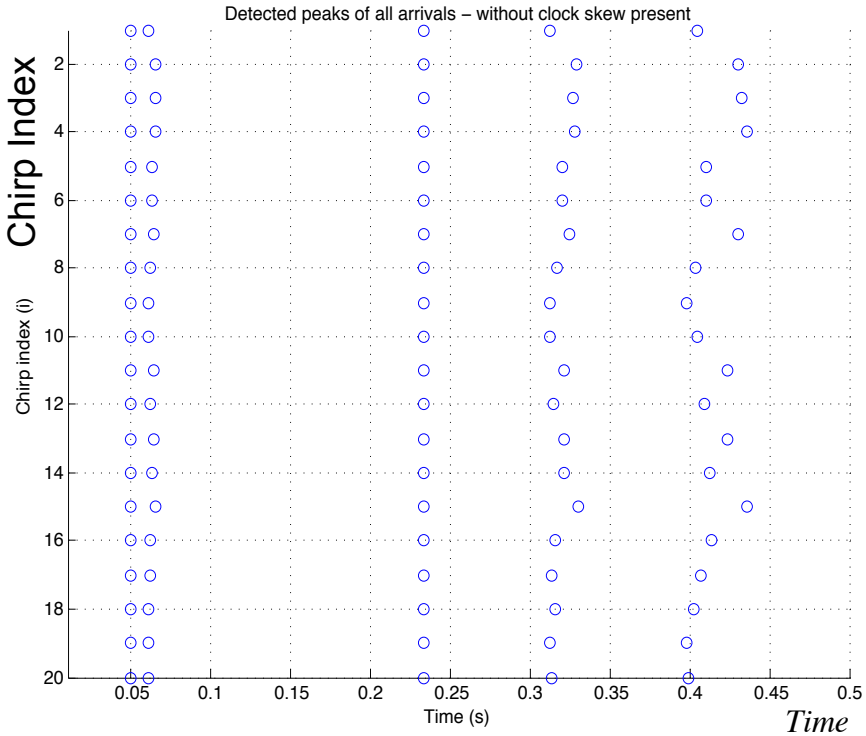
For a Clock with Zero Skew Present:
Note that the Simulated "True" Delta Functions Now Align More Closely with the estimated pdf Centers

Fit a Line to the Arrival Times for Each Multipath Arrival (Linear Regression)

For Illustration Purposes, I Drew the Lines Manually on the Plot Below

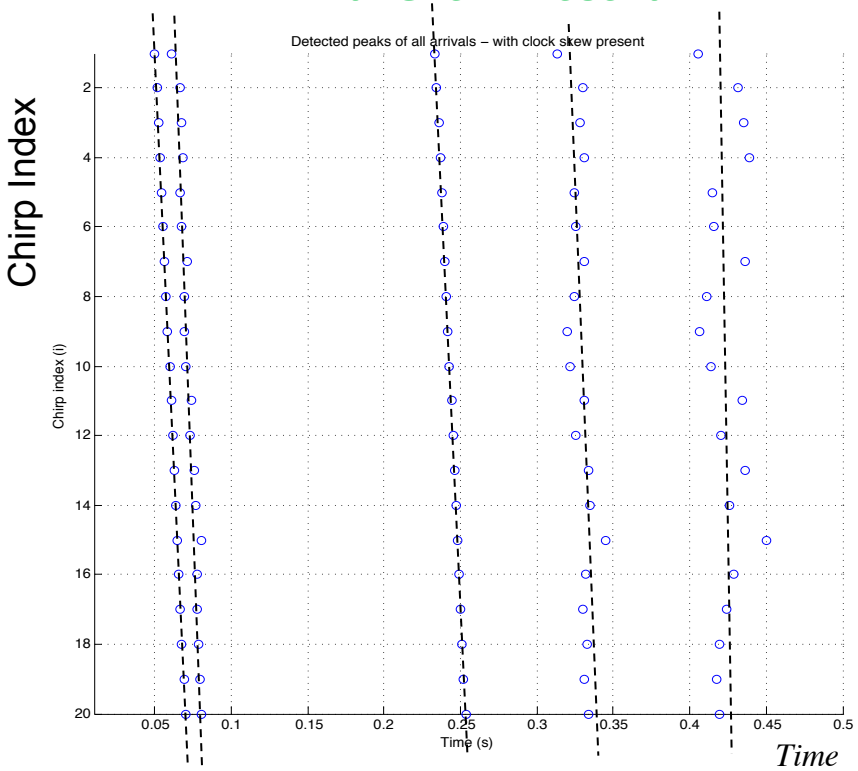
Detected Peaks for All Arrivals for a Clock

With Zero Skew Present



Detected Peaks for All Arrivals for a Clock

With Skew Present



Note the Variation in Arrival Times for a Single Multipath Arrival

Use Linear Regression to Fit a Line to the Arrival Times for Each Multipath Arrival, Determine the Most Stable One

Correlation Peak Arrival Times for All Multipath Arrivals

Times at which chirps were transmitted

Linear Regression

$\hat{\underline{F}}$ = Vector of Skew (Slope) Estimates for All Multipath Arrivals

E = Coeff. of Determination = 1 – Normalized Squared Error = (a measure of estimation quality)

$\underline{E} = \{E_j\}_{j=1}^{J}$ Vector of Coefficients of Determination for All Arrivals. Note: $E_j \in [0,1]$

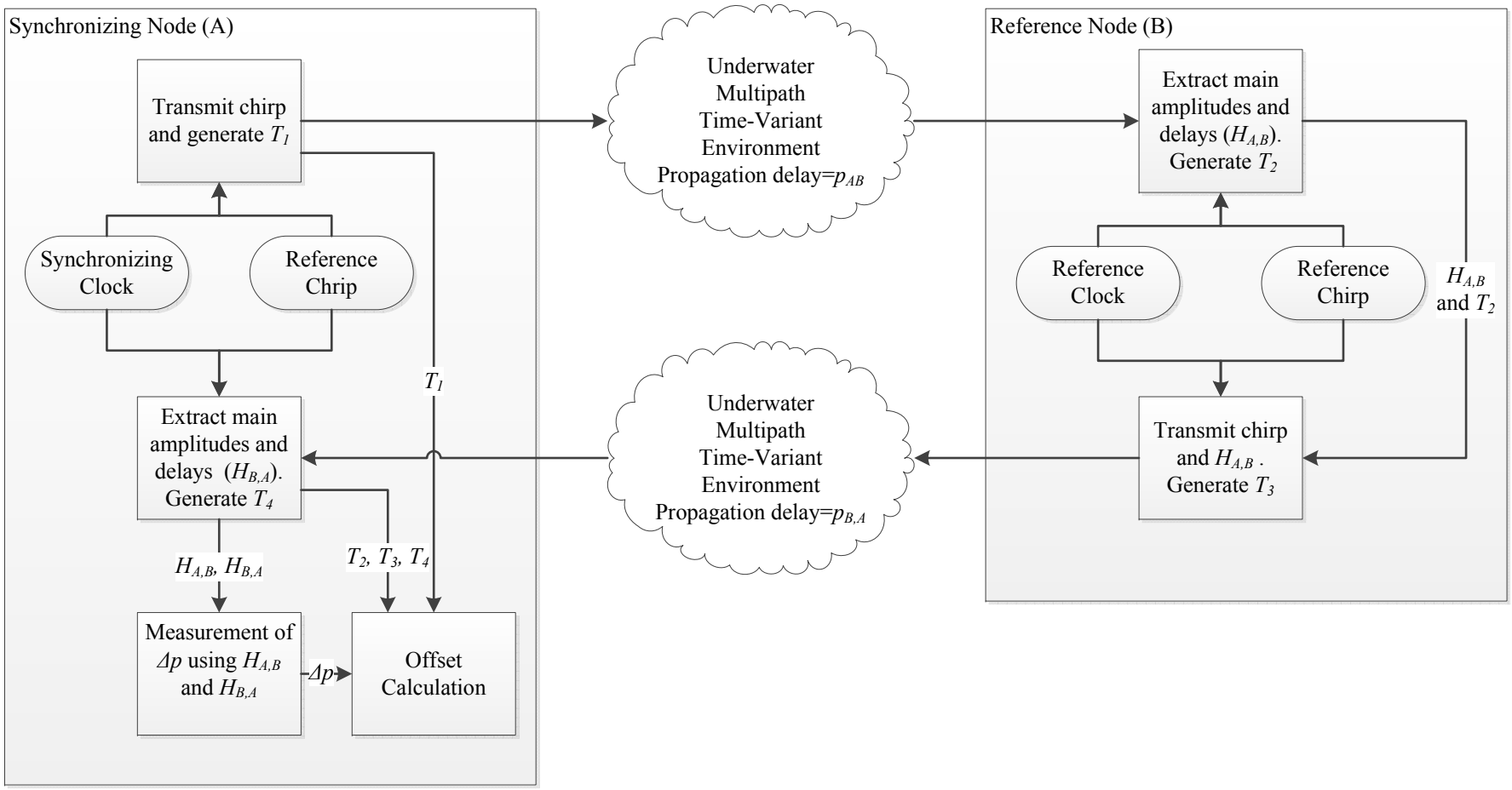
Sort, Take Max

$\{E_j\}_{j=1}^{J}$

- Choose the Multiplath Arrival Corresponding to the Largest Value of $\{E_j\}_{j=1}^{J}$ as the most stable
- Also consider the number of correlation peaks: If too few (set a threshold), assume the arrival is not a real arrival

- Declare this to be the Most Stable Multipath Arrival
  - Use the Estimated Skew $\hat{f}_A$ Corresponding to this Arrival

Stage 2: *Summary of the Two-Way Message Exchange Used for Clock Offset Correction*

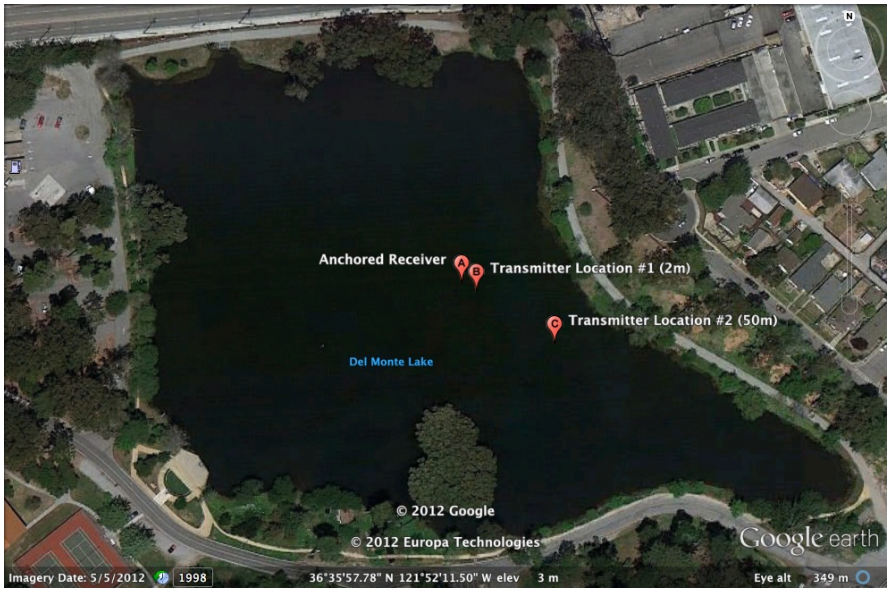


Del Monte Lake at the Naval Postgraduate School (Only about 2 meters deep)
Chosen for Accessibility and Low Noise – Not a Realistic Network Location

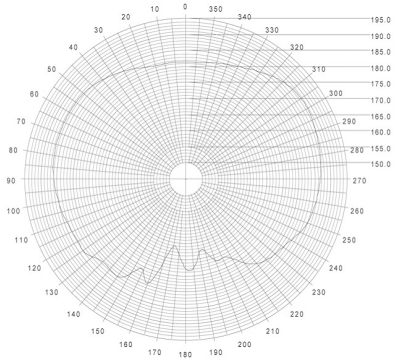
Del Monte lake Experiment

2m and 50m Ranges between Transmitter and Receiver

- Deck box capable of transmitting arbitrary waveforms (wav files)
- SM-75 Node with high fidelity data acquisition and SD-card recorders
- Series of 30 chirps, 9-14 KHz
- Various chirp lengths
- No ground truth



Transmitter Node



Receiver Node

Conclusions

- We propose a new clock synchronization protocol that copes with *multipath arrivals, time variant channels and lack of channel reciprocity*
  - *We exploit **ensembles** of measurement signals*
  - *Simulation studies validate the approach in theory*
  - *Limited studies in a lake validated the skew correction stage, but experiments in offset correction were not possible*

- **Future Work:**
  - *Direct comparisons with algorithms in the literature*
  - *More realistic experiments (deeper water, ground truth)*
  - *Real-World Test of the Offset Estimation part of the protocol*
  - *Tests using various Reference Pulse Intervals (RPI)*
  - *Develop improved arrival sorting algorithms (current method is vulnerable to noise and superimposed arrivals)*
  - *Use our protocol to improve range estimation between two nodes*

The World of Acoustics Before Signal Processing

Publications

- ***"Clock Synchronization Through Time-Variant Underwater Acoustic Channels,"***

Thesis, MSEE/MSEngineering Acoustics Student: LCdr Pascal Gagnon, Royal Canadian Navy, Co-Advisor: Prof. J. Rice, Co-Advisor: Prof. G. A. Clark, Co-Advisor: Prof. Roberto Cristi. (Graduated: August 2012). *Graduated with Distinction, Received the Outstanding Thesis Award.*

- P. Gagnon, G. A. Clark and J. Rice, ***"Channel Modeling and Time Delay Estimation for Clock Synchronization Among Seaweb Nodes,"*** Lawrence Livermore National Laboratory Report LLNL-IM-634713, UComms Conference, Session on Underwater Communications: Channel Modeling and Validation, NATO Undersea Research Centre, secretariat.ucomms.net, La Spezia, Italy, September 12-14, 2012.

P. Gagnon, G. A. Clark and J. Rice, ***"Channel Modeling and Time Delay Estimation for Clock Synchronization Among Seaweb Nodes,"*** Tenth International Mine Warfare Technology Symposium, Cruser Technology Continuum, Sponsored by the Mine Warfare Association, Lawrence Livermore National Laboratory report IM626565, LLNL-CONF-563994, Embassy Suites, Monterey, CA, May 7-10, 2012.