TARUN CHANDRAYADULA

9176001526/044-22574808
109 B Ocean Engineering, IIT Madras
tkchandr@iitm.ac.in
Adyar, Chennai, India 600036

EDUCATION

- **George Mason University, January 2010** Fairfax, VA
  Ph.D., Electrical Engineering
  Thesis: Mode tomography using signals from the Long Range Ocean Acoustic Propagation Experiment
  Advisor: Dr. Kathleen E. Wage
- **George Mason University, May 2003** Fairfax, VA
  M.S., Electrical Engineering
- **University of Madras, May 2001** Chennai, India
  B.E., Electronics and Communication Engineering

WORK HISTORY

- **Associate Professor** November 2022 - Present
  Department of Ocean Engineering, Indian Institute of Technology Madras, Chennai
- **Assistant Professor** September 2014 - October 2022
  Department of Ocean Engineering, Indian Institute of Technology Madras, Chennai
- **Assistant Professor** April 2014 - August 2014
  Department of Electrical Engineering, Indian Institute of Technology Delhi, New Delhi
- **National Research Council Research Associate** April 2010 - October 2013
  Naval Postgraduate School, California
- **Graduate Research Assistant** May 2002 - March 2010
  School of Information Technology and Engineering, George Mason University, VA
- **Graduate Information Technology Assistant** January 2002 - July 2002
  School of Information Technology and Engineering, George Mason University, VA
- **Graduate Teaching Assistant** August 2001 - December 2002
  School of Information Technology and Engineering, George Mason University, VA

RESEARCH INTERESTS

- Random matrix theory, Signal processing, propagation modeling, wave propagation through random media, array processing, acoustic communications.

SPONSORED PROJECTS

- Localization of Ships using their Acoustic Signature in the Deep Ocean (2021-2023, National Technical Research Organization, New Delhi)
- Acoustic mode variability during the Philippine Sea Experiments (2018-2021, Naval Research Board, India, and Office of Naval Research Global, London)
- Investigation of Acoustic Propagation in the Presence of Internal Waves across Shallow Waters of Northern Bay of Bengal (2016-2018, National Institute of Ocean Technology, Chennai)
- Design of a conformal array for strategic purposes (2016-2017, Naval Physical Oceanographic Lab, Kochi)
- Wave-theoretic approaches to acoustic inversion (2015, Naval Physical Oceanographic Lab, Kochi)

STUDENT GUIDANCE

- Gaja Chandrasekar (Ph.D. student)
- P. Sivaselvi (Ph.D. student), Graduated December 2022

- Nikita R. Pinto (M.S. Student), Graduated July 2022
- R. P. Raju and Sameer Babu (Part-time Ph.D. students currently at NPOL, Kochi)

JOURNAL PUBLICATIONS

- Sivaselvi Periyasamy and Tarun K. Chandrayadula, "A model for deep water acoustic timefronts using transport theory" J. Acoust. Soc. Am. **153**, 895-908 (2023).
  There are currently no models to fully predict the effects of internal-wave-induced scattering on acoustic pulses. Existing models, which predict time domain statistics either use the ray-based path integral method or Monte-Carlo type simulations. The path integral method fails to accurately predict all the effects of scattering. The Monte-Carlo methods base the statistics on ensemble averages, and are not physics based models. This paper overcomes these limitations by using the modes of the waveguide in a transport theory application. The transport theory equations have so far been only used to explain diffusion of mode intensities and decorrelation due to internal waves, at individual frequencies. This paper extends the current narrowband application to predict mode correlations across different frequencies, and from that the broadband time-front, time wander, travel-time bias, and the amount of spread in intensity across time and depth. To validate these predictions, this paper uses separate Parabolic Equation (PE) simulations. The comparisons between the two are good, suggesting a success for the mode-based transport theory approach.

- Nikita R. Pinto and Tarun K. Chandrayadula, "Long-term frequency changes of a potential great whale call from the central Indian Ocean during 2002-2019" JASA Express Letters, February 2021.

  This paper uses observations from hydrophones in the central Indian Ocean to track long-term changes (2002-2019) in calls by an unidentified whale. These calls around 20-45 Hz consist of a set of tones which form a comb, followed by a downsweep. This paper builds detectors to isolate the calls to show that while the average comb frequencies steadily increase across the years to fade away, the downsweep however decreases, and branches into higher frequencies. The estimated changes are unlike those observed for species in the Indian and Southern Oceans.

- Tarun K. Chandrayadula, P. Sivaselvi, John A. Colosi, Peter F. Worcester, Matthew A. Dzieciuch, James A. Mercer, Rex K. Andrew,"Observations of low frequency, long range propagation in the Philippine Sea and comparisons to mode transport theory" J. Acoust. Soc. Am. **147(2)**, 877-897 (2020).

  The year-long Philippine Sea (2010–2011) experiment (PhilSea) was an extensive deep water acoustic propagation experiment in which there were six different sources transmitting to a water column spanning a vertical line array. The six sources were placed in an array with a radius of 330 km and transmitted at frequencies in the 200–300 Hz and 140–205 Hz bands. The PhilSea frequencies are higher than previous deep water experiments in the North Pacific for which modal analyses were performed. Further, the acoustic paths sample a two-dimensional area that is rich in internal tides, waves, and eddies. The PhilSea observations are, thus, a new opportunity to observe acoustic modal variability at higher frequencies than before and in an oceanographically dynamic region. This paper focuses on mode observations around the mid-water depths. The mode observations are used to compute narrowband statistics such as transmission loss and broadband statistics such as peak pulse intensity, travel time wander, time spreads, and scintillation indices. The observations are then compared with a new hybrid broadband transport theory. The model-data comparisons show excellent agreement for modes 1–10 and minor deviations for the rest. The discrepancies in the comparisons are related to the limitations of the hybrid model and oceanographic fluctuations other than internal waves.

- John A. Colosi, Bruce D. Cornuelle, Peter F. Worcester, Matthew A. Dzieciuch, Tarun K. Chandrayadula,"Observations of phase and intensity fluctuations for low-frequency, long-range transmissions in the Philippine Sea and comparisons to path-integral theory," J. Acoust. Soc. Am. **146(1)**, 567-585 (2019).

  In the Philippine Sea, from April 2010 to March 2011, a 330-km radius pentagonal acoustic transceiver array with a sixth transceiver in the center transmitted broadband signals with center frequencies between 172 and 275 Hz and 100 Hz bandwidth eight times a day every other day. The signals were recorded on a large-aperture vertical-line array located near the center of the pentagon at ranges of 129, 210, 224, 379, 396, and 450 km. The acoustic arrival structures are interpretable in terms of ray paths. Depth and time variability of the acoustic observations are analyzed for six ray paths (one from each transceiver) with similar vertical sampling properties in the main thermocline. Acoustic-field statistics treated include: (1) variances of phase and intensity, (2) vertical coherence and intensity covariance, (3) glinting and fadeout rates, and (4) intensity probability density functions.Several observed statistics are compared to predictions using Feynman path-integral theory assuming the Garrett-Munk internal-wave spectrum. In situ oceanographic observations support this assumption and are used to estimate spectral parameters. Data and theory differ at most by a factor of two and reveal the wave propagation regimes of unsaturated, partially saturated, and fully saturated. Improvements to the evaluation of path-integral quantities are discussed.

- Tarun K. Chandrayadula, Kathleen E. Wage, Peter F. Worcester, Matthew A. Dzieciuch, James A. Mercer, Rex K. Andrew, and Bruce M. Howe,"Reduced rank models for travel time estimation of low mode signals measured during the Long Range Ocean Acoustic Propagation EXperiment," J. Acoust. Soc. Am. **134(4)**, 3332-3346 (2013).

  Mode travel time estimation in the presence of internal waves (IWs) is a challenging problem. IWs perturb the sound speed, which results in travel time wander and mode scattering. A standard approach to travel time estimation is to pulse compress the broadband signal, pick the peak of the compressed time series, and average the peak time over multiple receptions to reduce variance. The peak-picking approach implicitly assumes there is a single strong arrival and does not perform well when there are multiple arrivals due to scattering. This article presents a statistical model for the scattered mode arrivals and uses the model to design improved travel time estimators. The model is based on an Empirical Orthogonal Function (EOF) analysis of the mode time series. Range-dependent simulations and data from the Long-range Ocean Acoustic Propagation EXperiment (LOAPEX) indicate that the modes are represented by a small number of EOFs. The reduced-rank EOF model is used to construct a travel time estimator based on the Matched Subspace Detector (MSD). Analysis of simulation and experimental data show that the MSDs are more robust to IW scattering than peak picking. The simulation analysis also highlights how IWs affect the mode excitation by the source.

- Tarun K. Chandrayadula, John A. Colosi, Peter F. Worcester, Matthew A. Dzieciuch, James A. Mercer, Rex K. Andrew, and Bruce M. Howe,"Observations and transport theory analysis of low frequency, long range acoustic mode propagation in the Eastern North Pacific Ocean," J. Acoust. Soc.Am. **134(4)**, 3144-3160 (2013).

  Second order mode statistics as a function of range and source depth are presented from the Long Range Ocean Acoustic Propagation EXperiment (LOAPEX). During LOAPEX, low frequency broadband signals were transmitted from a ship-suspended source to a mode-resolving vertical line array. Over a one-month period, the ship occupied seven stations from 50 km to 3200 km distant from the receiver. At each station broadband transmissions were performed at a near-axial depth of

800 m and an off-axial depth of 350 m. Center frequencies at these two depths were 75 Hz and 68 Hz respectively. Estimates of observed mean mode energy, cross mode coherence, and temporal coherence are compared with predictions from modal transport theory, utilizing the Garrett-Munk internal wave spectrum. In estimating the acoustic observables there were challenges including low signal to noise ratio, corrections for source motion and small sample sizes. The experimental observations agree with theoretical predictions within experimental uncertainty.

- John A. Colosi, Tarun K. Chandrayadula, Alexander G. Voronovich, and Vladmir E. Ostashev, “Coupled mode transport theory for sound transmission through an ocean with random sound speed perturbations: Coherence in deep water environments,” J. Acoust. Soc.Am. **134(4)**, 3119-3133 (2013).

  Second moments of mode amplitudes at fixed frequency as a function of separations in mode number, time, and horizontal distance are investigated using mode based transport equations and Monte Carlo simulation. These second moments are used to study the acoustic observable of full field acoustic coherence, including depth separations. Calculations for low order modes between 50 and 250 Hz are presented using a deep water environment typical of the Philippine Sea. Comparisons between Monte Carlo simulations and transport theory for time and depth coherence at frequencies of 75 and 250 Hz and for ranges up to 500 km show good agreement, thus validating the theory. The theory is used to examine the accuracy of the adiabatic approximation, the quadratic lag approximation, and the range and frequency scaling of coherence. It is found that while temporal coherence has a dominant adiabatic component, horizontal and vertical coherence have more equal contributions from coupling and adiabatic effects. In addition the quadratic lag approximation, common to much of the theoretical work to date on coherence, is shown to be most accurate at higher frequencies and longer ranges. Lastly the range and frequency scalings are found to be sensitive to the functional form of the exponential decay of coherence with lag, but temporal and horizontal coherence show scalings that fall quite close to the well known inverse frequency and inverse square root range laws from path integral and ray theories.

CONFERENCE PUBLICATIONS

- S. Periyasamy, T. K. Chandrayadula and J. A. Colosi, ”Broadband scattering models for acoustic time-fronts in deep water,” OCEANS 2022 - Chennai, 2022, pp. 1-7,

  Acoustic time-fronts that propagate in the deep ocean undergo scattering due to internal waves. Sound-speed perturbations induced by internal waves cause changes in the mean intensity of the time-front and also scatter energy into the shadow zone. This paper presents a mode-based broadband scattering model to predict the intensities of the time-front. The model uses transport theory equations that combine the physics of acoustic mode propagation and scattering due to internal waves. Complementary to this model, this paper also considers a low complexity version, which uses the adiabatic phase approximation, and thus offers savings in computations. This paper compares both the models predictions against the observations from the Philippine Sea (2010-2011) deep water experiment (PhilSea10). The comparisons show that while both the transport theory models predict the statistics of mode pulses, the low complexity version fails to predict the intensities of the time-front. The full transport theory further suggests a mode-based explanation for energy scattering into the shadow zone. This paper also presents some limitations of the transport theory in predicting the mean arrival time of mode pulses.

- John A. Colosi, Tarun K. Channdrayadula, Jacob Fisher, Weston Coby, Brian Dushaw, Matthew A. Dzieciuch, and Peter F. Worcester, “The effects of internal tides on acoustic phase and amplitude statistics in the Philippine Sea,” Proceedings of Meetings on Acoustics, Montreal., June 2013.

Moored oceanographic sensors and satellite altimetry has revealed energetic diurnal and semi-diurnal internal tides in the Western Philippine Sea. Because the internal tides have a complex spatio-temporal pattern and large vertical displacements, these waves have the potential for causing strong acoustic variability. This talk will present a tidal analysis of signal fluctuations from the PhilSea09 experiment in which broadband signals with a center frequency of 275Hz and a bandwidth of 50 Hz were transmitted at the sound channel axis to a large aperture vertical array 185-km distant. Signal phase and amplitude statistics along distinct branches of the observed wavefronts will be analyzed and compared to ray-based model predictions using internal tide information obtained from moored oceanographic instruments at the source and receiver. Key issues are the acoustic effects of the internal tide nonlinearity, temporal stability, high mode structure, and complex horizontal interference patterns.

- Tarun K. Chandrayadula, John E. Joseph and, Chris W. Miller, "Monterey Bay Ambient Noise Profiles using Underwater Gliders," Proceedings of Meetings on Acoustics, Montreal., June 2013.

  In 2012, during two separate week-long deployments, underwater gliders outfitted with external hydrophones profiled the upper 100 m of Monterey Bay. The environment contains various noises made by marine mammals, ships, winds, and earthquakes. Unlike hydrophone receivers moored to a fixed location, moving gliders measure noise variability across a wide terrain. However, underwater mobile systems have limitations such as instrument and flow noise, that are undesired. In order to estimate the system noise level, the hydrophones on the gliders had different gain settings on each deployment. The first deployment used a 0 dB gain during which the ambient noise recordings were dominated by the glider. The second used two hydrophones, one with a 0 dB gain and the other with 20 dB. Apart from system sounds, the higher-gain hydrophone also recorded far-away sources such as whales and ships. The noise recordings are used to estimate the spectrograms across depth and record time. The spectrograms are integrated with the glider engineering data to estimate histograms of noise power as a function of depth and glider velocity. The statistics from the two different deployments are compared to discuss the value of gliders with external hydrophones in ambient noise studies.

- Tarun K. Chandrayadula and Kathleen E. Wage, "Interpolation methods for vertical linear array element localization," Proceedings of the 2008 IEEE/MTS Oceans Conference, Quebec City., September 2008.

  Array element localization is crucial for applications such as ocean acoustic tomography. Loss of navigation data makes it difficult to compensate for array motion when implementing operations such as mode filtering or beamforming. This paper presents a method for estimating missing array navigation data using an empirical orthogonal function (EOF) model. The method can be applied to estimate the location of some vertical array elements based on the location of the other elements. It assumes that second order statistics can be estimated from a set of navigation measurements for the full array. The paper applies the EOF-based method to estimate missing navigation data for the long range ocean acoustic propagation experiment (LOAPEX). The results are evaluated by examining how the errors in mooring motion estimation affect mode processing. In particular the paper analyzes the degradation in array gain and the errors in time of arrival for the low order modes. The error statistics indicate that use of the EOF method has a negligible effect on mode processing.

- Tarun K. Chandrayadula and Kathleen E. Wage, "Mode Equalization at Megameter Ranges," Proceedings of the 2005 IEEE/MTS Oceans Conference, Washington D.C., September 2005.

  Low frequency underwater sound propagation over ranges of 3.5 megameters or more has a complicated multipath arrival structure with early steep angle-arrivals, followed by an energetic finale composed of the lower order acoustic modes. Internal waves produce time-varying multipath and induce frequency-selective fading in the received signals. The low mode arrivals are strongly affected by internal waves, making it difficult to obtain precise travel time measurements for these signals. An equalizer along with suitable spatial filters, mitigates the multipath of the lower order modes. The signal to noise ratio (SNR) measured at the output of the equalizer is used as an observable to localize modes, make time of arrival (TOA) measurements and measure the multipath spread of the modes. Results for the new mode equalizer on a simulated channel are presented. The mode equalizer is also tested on one of the North Pacific Acoustic Laboratory (NPAL) receptions.

RECENT CONFERENCE PRESENTATIONS

- Nikita Pinto and Tarun K. Chandrayadula "Long-term variations in calls produced by a potential blue whale species from the central Indian Ocean." CTBTO Science and Technology Conference, Vienna, Austria, June 2021.
- Nikita Pinto and Tarun K. Chandrayadula "Distributed detection framework and three-dimensional propagation model for acoustic detection of baleen whales." CTBTO Science and Technology Conference, Vienna, Austria, June 2019.
- Sivaselvi P, Tarun K. Chandrayadula, and John A. Colosi "Cross-frequency cross-mode coherence using transport theory." 164th Meeting of the Acoustical Society of America, New Orleans, Louisiana, December 2017.
- Tarun K. Chandrayadula, John A. Colosi, Peter F. Worcester, and Matthew A. Dzieciuch "Acoustic mode based internal tide tomography from the PhilSea 2009 experiment." 163rd Meeting of the Acoustical Society of America, Boston, Massachusetts, June 2017.
- Tarun K. Chandrayadula, John A. Colosi, Peter F. Worcester, and Matthew A. Dzieciuch "Acoustic mode travel time variability in the Philippine Sea." 162nd Meeting of the Acoustical Society of America, Honolulu, Hawaii, December 2016.

HONORS

- Invited talk at the Acoustical Society of America meeting (June 2021)
- Recipient of a 2010 National Research Council (NRC) fellowship based on a research proposal and academic achievements
- ONR Special Research Award (January 2006 - Fall 2009)
- Recipient of the George Mason University, Information Technology and Engineering doctoral student fellowship (Fall 2004, Fall 2005)