# Special Research Awards in Ocean Acoustics:
# Postdoctoral Fellowship

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## LONG-TERM GOALS

The long-term goals of this research are to understand the statistics of acoustic fields in deep water ocean environments.

## OBJECTIVES

The primary objective of this work is the development of accurate, and computationally efficient, reduced-physics acoustic propagation models for the prediction of the statistics of ocean acoustic signals in deep-water environments. A significant portion of the work deals with analyzing experimental data for acoustic field statistics and comparing them with theory. Examples of acoustic field statistics of interest are mean intensity, coherence, and intensity variance.

## APPROACH

The focus here is primarily on the Long-range Acoustic Propagation Experiment (LOAPEX) and the Philippine Sea (Phil Sea) experiments to obtain estimates for mode coherence. The experimental estimates are then compared with predictions from transport theory. LOAPEX and Phil Sea datasets were chosen because they are the most recent and up to date deep water experiments. In addition to that, LOAPEX was unique with respect to the other experiments in the aspect that it had acoustic transmissions at multiple ranges (along the same propagation path). Similarly, the Phil Sea experiment had acoustic transmissions and receptions across a wide geographical area. During LOAPEX, broadband signals with a center frequency of 75 Hz were transmitted from a ship suspended source to a mode resolving, 1400-m long vertical receiving array centered on the sound-channel axis. Over a month period, the ship occupied stations at nominal ranges of 50, 250 500, 1000, 1600, 2300, and 3200 km. Acoustic transmissions were carried out from two different depths and different times. Source transmissions at 800-m depth (near axial depth) were carried out at ranges of 50, 250, and 500 km, while all stations transmitted at a depth of 350-m. LOAPEX thus offers a unique opportunity to measure the range dependent internal wave statistics for two complementary source depths. However, there are several challenging aspects of the LOAPEX observations regarding low SNR, corrections for source motion, and small sample sizes. The predictions from transport theory rely on accurate

| 1. REPORT DATE<br>**SEP 2011** | 2. REPORT TYPE | | 3. DATES COVERED<br>**00-00-2011 to 00-00-2011** |
| --- | --- | --- | --- |
| 4. TITLE AND SUBTITLE<br>**Special Research Awards in Ocean Acoustics: Postdoctoral Fellowship** | | | 5a. CONTRACT NUMBER |
| | | | 5b. GRANT NUMBER |
| | | | 5c. PROGRAM ELEMENT NUMBER |
| 6. AUTHOR(S) | | | 5d. PROJECT NUMBER |
| | | | 5e. TASK NUMBER |
| | | | 5f. WORK UNIT NUMBER |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br>**Naval Postgraduate School,Department of Oceanography,Monterey,CA,93943** | | | 8. PERFORMING ORGANIZATION REPORT NUMBER |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) | | | 10. SPONSOR/MONITOR'S ACRONYM(S) |
| | | | 11. SPONSOR/MONITOR'S REPORT NUMBER(S) |
| 12. DISTRIBUTION/AVAILABILITY STATEMENT<br>**Approved for public release; distribution unlimited** | | | |
| 13. SUPPLEMENTARY NOTES | | | |
| 14. ABSTRACT | | | |
| 15. SUBJECT TERMS | | | |

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
| --- | --- | --- | --- | --- | --- |
| a. REPORT<br>**unclassified** | b. ABSTRACT<br>**unclassified** | c. THIS PAGE<br>**unclassified** | **Same as Report (SAR)** | **7** | |

estimates of internal waves and spice for which we used data from temperature, conductivity, and pressure sensors, as well as Acoustic Doppler Current Profilers (ADCPs) that were placed on multiple moorings giving vertical, temporal, as well as geographic information concerning ocean fluctuations.

## WORK COMPLETED

### A. TRANSPORT THEORY COHERENCE

We have worked on validating the transport theory at frequencies of 75 and 250 Hz by performing Monte Carlo simulations with time evolving internal wave sound speed perturbations. The simulations were performed using a deep-water environment typical of the Phil Sea. Due to the demanding computational burden of doing time evolving internal waves and the large number of modes required for the higher frequencies, the calculations were done on the NPS supercomputer Hamming. A manuscript for a special issue of the Journal of the Acoustical society of America (JASA) on this topic is in preparation (Colosi et al, 2011). Details concerning the transport theory approach are in the annual report, `` Analysis and modeling of ocean acoustic fluctuations and moored observations of Philippine Sea sound-speed structure'', award number N00014-11-WR20115.

### B. LOAPEX OBSERVATIONS

We have completed an analysis of the LOAPEX receptions for estimates of mean mode energy, cross-mode coherence, and mode temporal coherence. The estimates were compared to predictions from transport theory. A manuscript for a special issue of the Journal of the Acoustical society of America (JASA) on this topic is in preparation (Chandrayadula et al, 2011).

## RESULTS

### A.TRANSPORT THEORY COHERENCE

So that our transport theory could be confidently applied to the LOAPEX observations, extensive Monte Carlo simulations were carried out at 75 and 250 Hz to test the ability of the theory to predict temporal coherence. The agreement between theory and simulation was found to be excellent for ranges up to the maximum simulation range of 500-km (Colosi et al, 2011). Past 500-km the agreement is also expected to be good, but computational constraints made calculations beyond 500-km prohibitive. Scaling relations from the theory show that the characteristic coherence time (defined as the e-folding time of the coherence function) scales roughly as $R^{-1/2}$ so coherence behavior can be extrapolated out to longer ranges. Examples of results from this analysis are shown in the report, `` Analysis and modeling of ocean acoustic fluctuations and moored observations of Philippine Sea sound-speed structure'', award number N00014-11-WR20115.

### B. LOAPEX OBSERVATIONS

With the mode transport theory well validated for cross mode coherence, as well as temporal coherence the theory was used to interpret the LOAPEX observations. As previously mentioned several complications with the LOAPEX observations made this analysis somewhat difficult. First, the transmissions for a given source depth were made over a relatively short time duration (at most 1 day), and thus the sample sizes in our ensemble averages are somewhat low. Second, the source motion was incompletely known, and corrections had to be figured out and applied.  Third, for the longer ranges,

and particularly for the off axial source, the SNR levels are quite low. The challenges were tackled as follows. For the relatively short intervals of time, a part of the ongoing work is to estimate the error-bars. In order to compensate for the source motion, a combination of acoustic tracking using the ray arrivals and the ship's position estimates via GPS were used. For the low SNR levels, period averaging was implemented for the off-axial receptions. In order to generate accurate predictions using transport theory approach, we used the Garrett-Munk internal wave spectrum, which is consistent with measurements taken during the LOAPEX (Van Uffelen, et al. 2010). Furthermore, the energy level of the internal waves was also derived from observations and was roughly at the nominal GM level.

With these measures, several useful comparisons were made between the observations and the model on the matter of mean mode energy, cross mode coherence, and mode temporal coherence for modes 1 through 10. Figure 1 shows comparisons of mean mode energy for the off-axial source depth at various ranges. Note for the off-axial source the lowest modes are very weakly excited, and thus the degree with which these low mode numbers acquire energy depends on the scattering induced mode coupling. At the longest ranges, 1000, 1600, and 3200-km, Fig 1 shows that the observations and theory are in excellent agreement and that the coupling has transferred significant acoustic energy to the lowest normal modes. Similarly good results are seen for the on axis source.

Figure 2 shows a comparison of cross mode coherence for both the on-and off axial sources. In figure 2 coherences for the on-axis source are relative to mode 1 and for the off axis source they are relative to mode 10. Here the theory is seen to consistently underestimate the observed coherence, though the patterns are quite close. We are presently studying what aspects of the environment could lead to good results on the matter of the mode energies, but poorer results with regards to cross mode coherences. Results similar to Fig 2 are seen for other cross mode coherence combinations.

Lastly, Figure 3 shows the observed and modeled temporal coherence functions for both the on and off axial sources. As in figure 2 results for mode 1 are shown for the on axis case, and results for mode 10 are shown for the off-axis case. For temporal coherence the transport theory model shows reasonable agreement with the observations both for the on and off axial cases. Note for the off axial case, fewer time lags are seen; this is because some time averaging was done to boost the signal to noise level. Results similar to Fig. 3 are seen for modes other than 1 and 10.

## IMPACT/APPLICATIONS

1.  The quality of the comparisons the between the transport theory, and the Monte Carlo simulations as well as the LOAPEX observations suggest that this model could have value as a Navy Acoustic Propagation Code. Some effort should be put forth to examine the value of transitioning this code.

## TRANSITIONS
None

## RELATED PROJECTS

1.  "Analysis and modeling of ocean acoustic fluctuations and moored observations of Philippine Sea sound-speed structure", PI J.A. Colosi, N00014-11-WR20115

## REFERENCES

1. Colosi, J. A., T. Chandrayadula, A. G. Voronovich, and V.E. Ostashev, ``Coupled mode transport theory for sound propagation through an ocean with random sound speed perturbations: Coherence in deep water environments'', J. Acoust. Soc. Am., in prep 2011.

2. Chandrayadula, T., J. A. Colosi, M.A. Dzieciuch, P. Worcester, R.K. Andrew, J.A. Mercer, and B. Howe, ``Observations and transport theory analysis of low frequency, long range mode propagation in the Eastern North Pacific Ocean'', J. Acoust. Soc. Am., in prep 2011.

3. Van Uffelen, L.J., P.F. Worcester, M.A. Dzieciuch, D.L. Rudnick, and J.A. Colosi, ``Effects of upper ocean sound speed structure on deep acoustic shadow zone arrivals at 500- and 1000-km range'', J. Acoust.Soc. Am., 127(4), pp2169-2181.

## RECENT PUBLICATIONS

## PATENTS

None

## HONORS/AWARDS/PRIZES

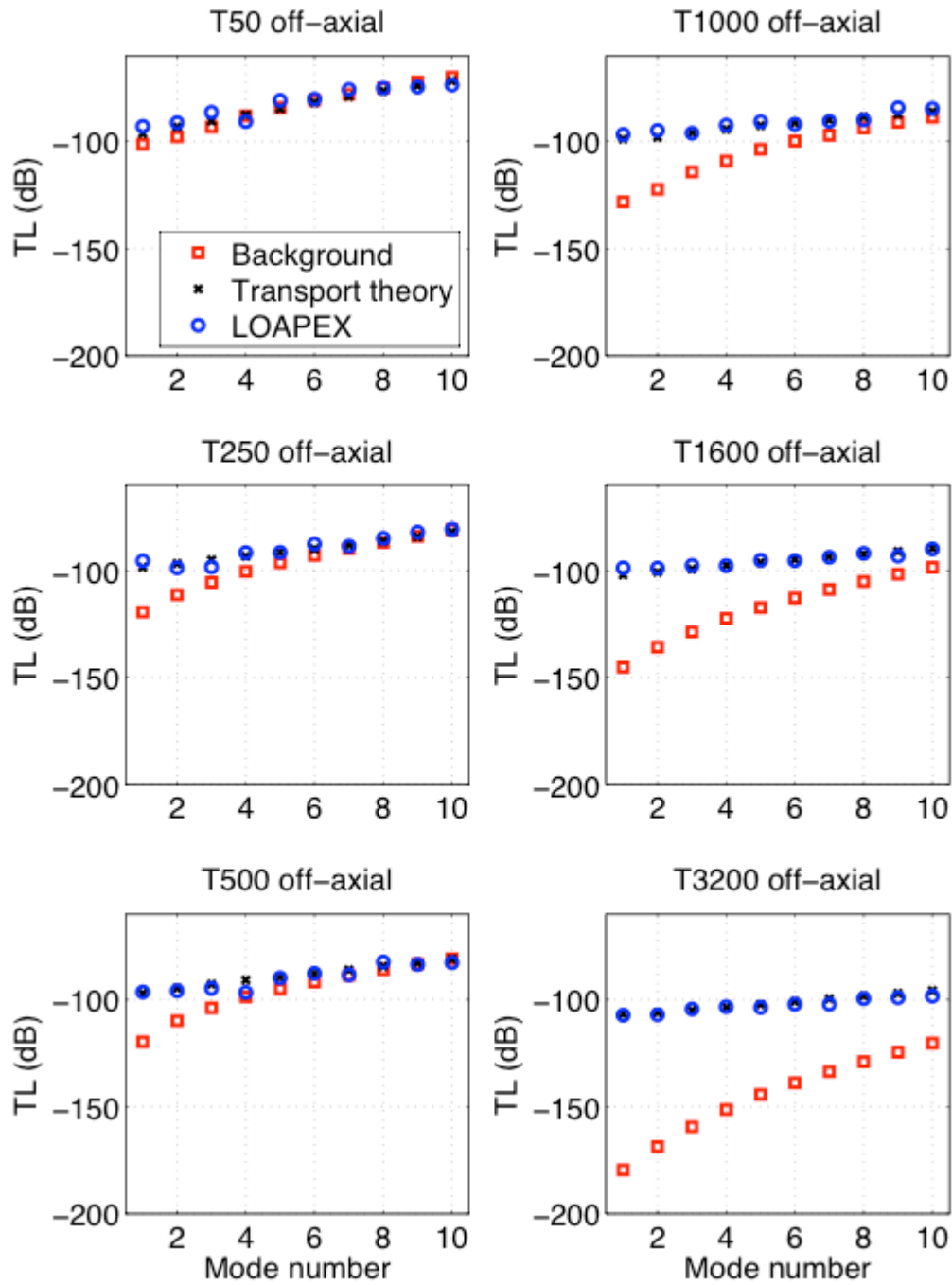ONR Ocean Acoustics Postdoctoral Fellowship Award

**Figures:**



*Figure 1: Observations and transport theory estimates of mean mode energy (transmission loss) for the off-axis LOAPEX transmissions for modes 1 through 10. Both the theory and observations show that the off-axial modes although not initially excited gain a significant amount of energy due to scattering.*
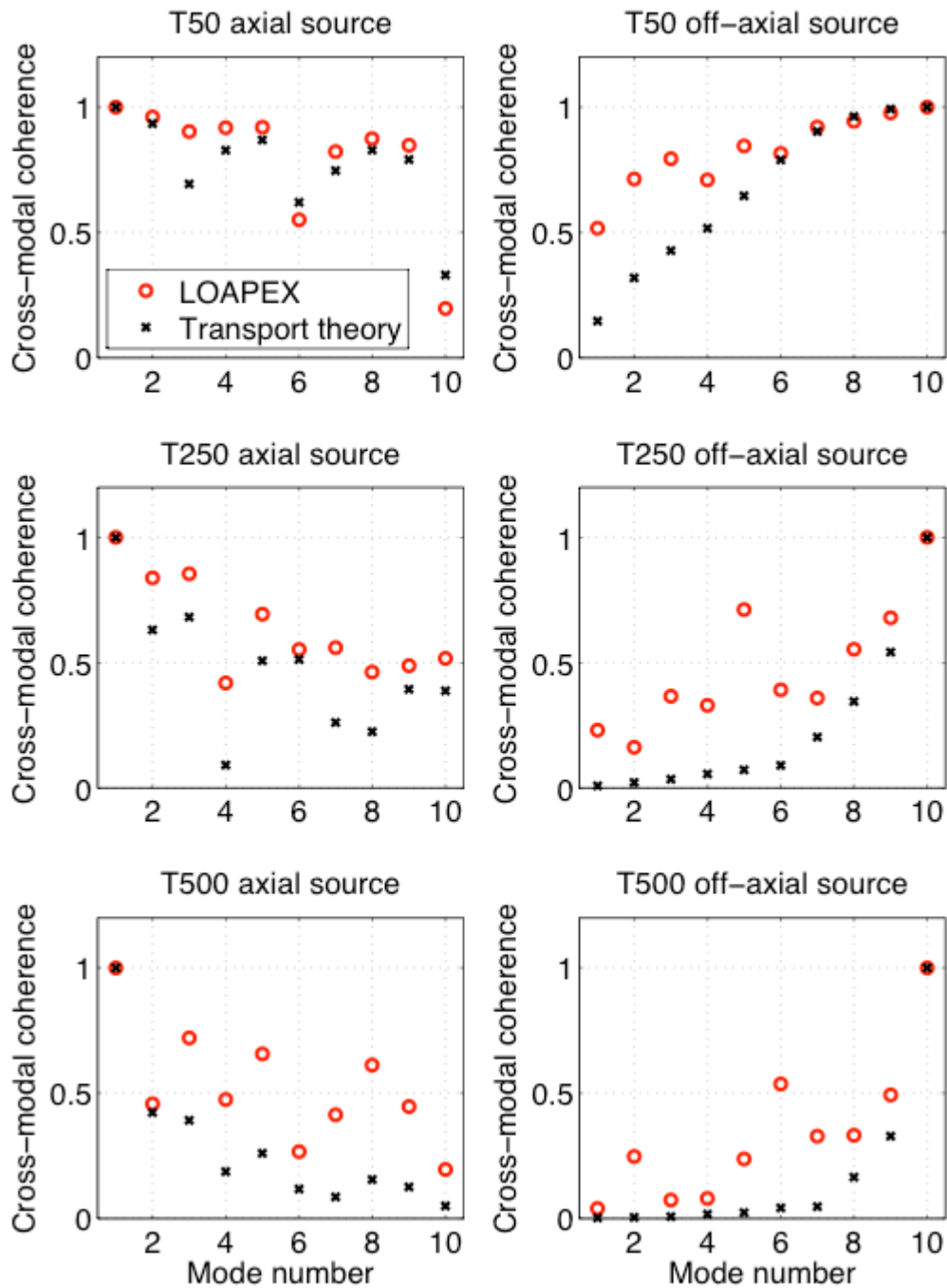
*Figure 2: Cross mode coherence relative to mode 1 for the on axis LOAPEX transmissions (left panels), and cross mode coherence relative to mode 10 for the off axis LOAPEX transmissions (right panels). At T50, there is a significant amount of correlation among modes. The modes are however uncorrelated by the T500 range.*
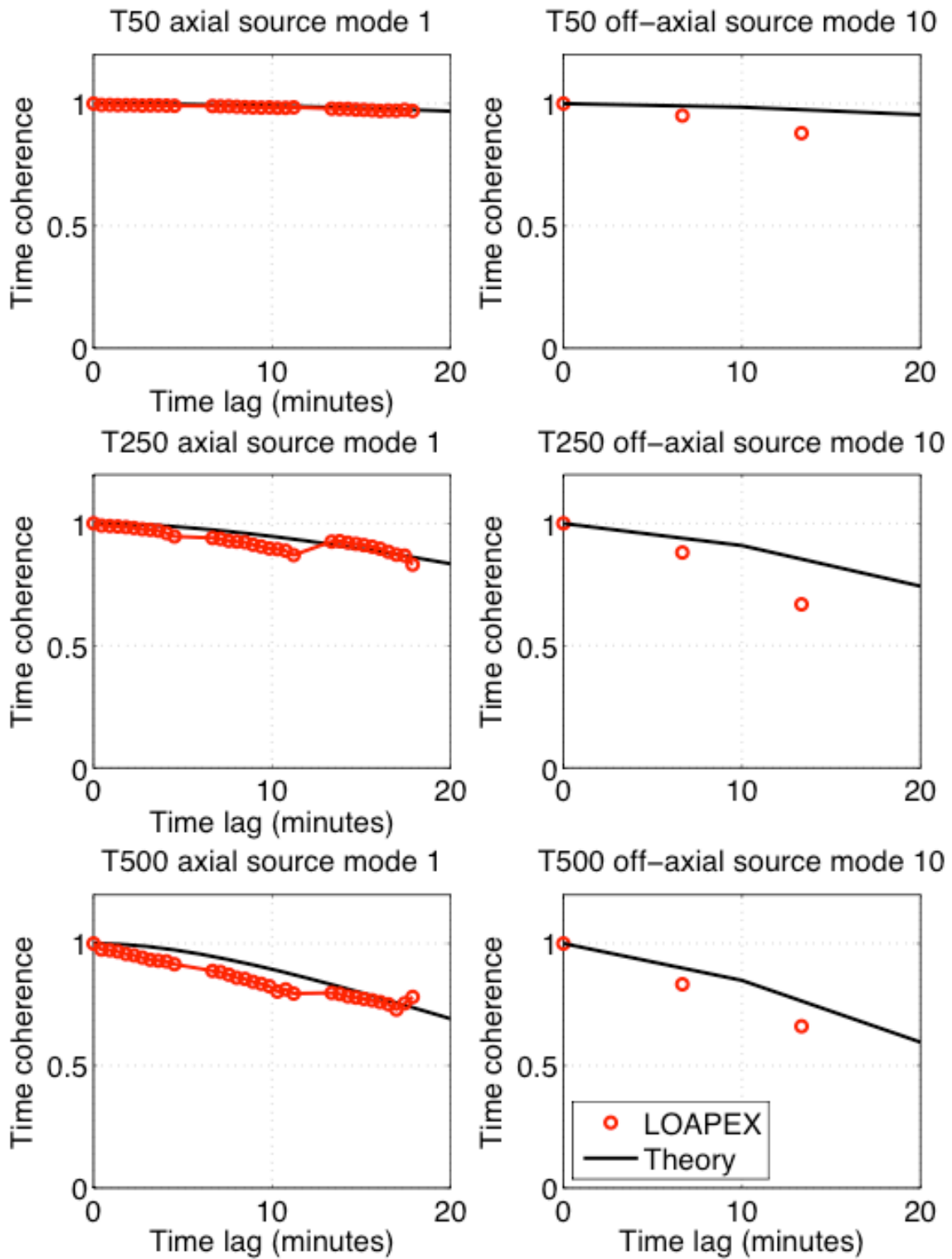*The observations have a higher coherence than the theory.*

***Figure 3: Mode 1 time coherence for the on-axis LOAPEX transmissions and mode 10 time coherence for the off-axis LOAPEX transmissions. The observations are similar to the transport theory predictions. The modes are correlated across time for ranges up to T500.***