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3aSP1. Matched signals: The beginnings of time reversal

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This paper discusses the original time reversal experiments as conducted by Antares Parvulescu and Clarence Clay. The idea of conducting the first time reversal experiment came about from measurements of the reproducibility of sound transmissions in the ocean in the late 1950's and early 1960's. Then it was believed by many that long range acoustic signal transmissions in the ocean were not reproducible or stable. During a coffee hour in 1960, Parvulescu proposed a simple experiment to create an acoustic matched signal through the use of time reversal, in their coffee room/lab area. This represents the first known record of a time reversal experiment. The paper will then discuss a series of experiments that were conducted underwater to communicate between two ships through the use of this matched signal technique. Details are in the theoretical - experimental monograph of Ivan Tolstoy and Clay [Ocean Acoustics (Mcgraw-Hill 1966 and Acoust. Soc. Am. 1987), Sections 7.4-7.7]. This paper calls attention to these early experiments and theory as the first demonstrations of the now popular technique termed time reversal.

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I. Stories about the First Time Reversal Experiments

In the 1950's most acousticians did not believe that long range acoustic signal transmissions in the ocean were reproducible or stable. A few contrary thinking geophysicists started measuring the stability of wave propagation in the ocean. They knew the basics of ocean currents and internal waves and had studied Chernov, "Wave propagation in a random medium" and learned that fluctuations increase with range.

Measurements of the reproducibility of sound transmissions in the ocean became a major effort of research at the Hudson Laboratories of Columbia University. These researchers knew that the ocean had internal waves and currents. How did these affect sound transmission from a source hundreds of nautical miles away? By today's standards, the equipment was primitive. Data were taken on paper chart recorders and 1 or 2 channel analog magnetic tape recorders. Most computations were done with slide rules, adding machines, and hand wired computers. It was Antares Parvulescu that came up with the idea to use matched signals to measure the stability of wave propagation in the ocean.

A. Coffee Room Experiment

During a coffee hour in 1960 an idea to demonstrate a matched signal experiment was conceived. Antares Parvulescu, Clarence Clay, Ivan Tolstoy, Bob Frosch (lab director), Bill Liang, Peter Rona, and Mel Hinich were present for this experiment. The lab had a collection of reel to reel tape recorders, some with 1 track and some with 2 tracks. Parvulescu tested his idea of time reversed transmissions in the junk filled lab and coffee room that possessed a great deal

of reverberation. A description of one of his demonstrations during a morning coffee hour follows:

A microphone was placed about 20 or 30 feet from a loudspeaker. An analog signal generator sent short impulsive signals to a loudspeaker through an amplifier. The impulses were about a second apart. The room reverberations were received at the microphone and tape recorded. The scope showed a typical reverberation decaying signal. A sequence of these reverberations was recorded on the tape in the forward direction. Next the tape was removed and the reels were reversed so the replay of the tape would give "matched signals" or "time reversed signals". These time reversed signals were amplified and drove the loudspeaker, without moving the microphone or the loudspeaker positions. This second broadcast made a mess of audible noise. Scope displays of the signal at the microphone looked like the auto correlation of the reverberation signal. Instead of sipping coffee, those present took turns listening with their ear next to the microphone. As an ear was moved to the microphone location, the rushing reverberation sound became a click. The spatial extent of the focused position was small. It was then apparent that Parvulescu's "matched signal" idea was a powerful way to measure the reproducibility of signal transmissions between fixed points in the ocean. Figure 1 provides an illustration of the environment in which this experiment was conducted. This experiment was reported on at a meeting of the Acoustical Society of America in 1961.[2]

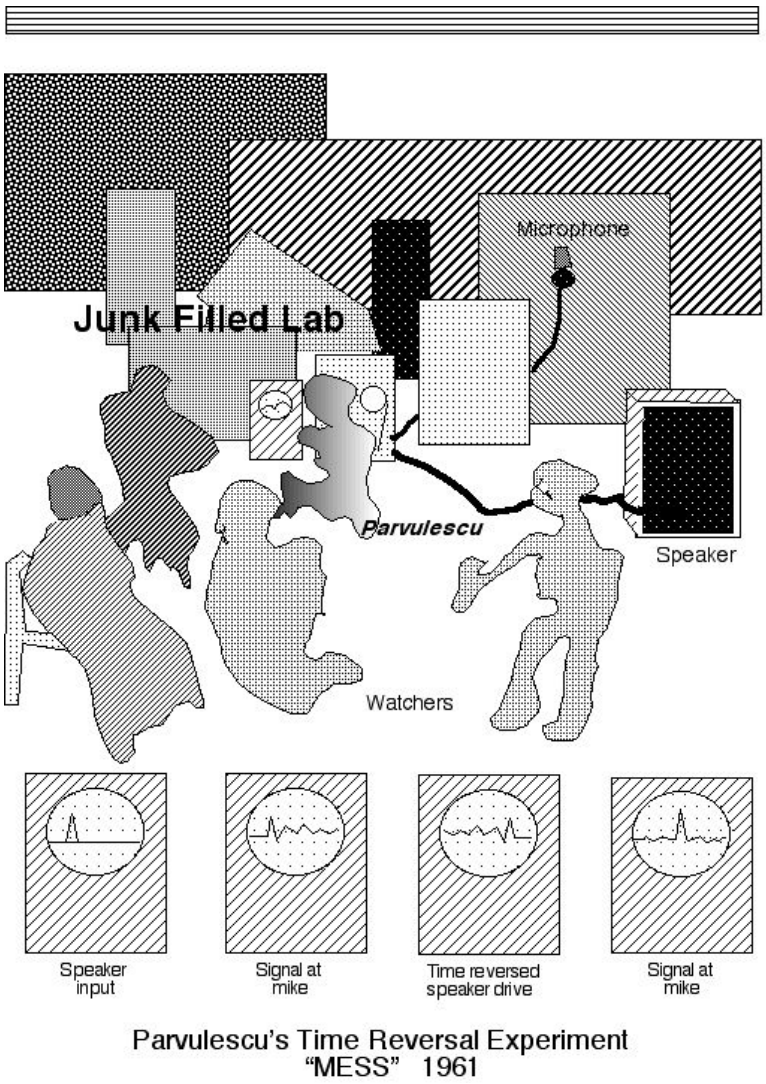

FIG. 1. Illustration of the coffee room environment in which the first time reversal experiment was conducted.

B. Time Reversal at Sea

The next plan was to perform this matched signal experiment in the sea. This experiment had to be planned very carefully. A pair of oceanographic research ships with deep anchoring capability was needed. The source ship, where Clay was stationed, and receiver ship, where Parvulescu was stationed, were to be anchored and the instruments placed on the bottom. The Tongue of the Ocean (located between the Bahamian islands of Andros and New Providence, the

Tongue is a deep oceanic trench) was chosen for the field experiment. The Tongue is 1.8 km deep and about 40 km wide. The idea was to anchor the ships on each side and then place the source and receiver on the sea floor. Communications between Clay and Parvulescu were sent over AM marine radio signals. The transmissions from the bottomed source on Clay's side were poor. So, the source had to be moved to deeper water and hang it from the ship. The source ship was anchored in deep water and the wind the ship roughly stationary. A cross section illustration of the geometry of the Tongue and the positions of the ships is found in Fig. 2 (from Figure 7.6 of Tolstoy and Clay, reference 3). Parvulescu radioed his received signals back to the source ship. These were recorded, the tape was then reversed, and the time reversed signals were played back through the source. Parvulescu radioed back his reception of the matched signal transmissions. A representation of the signals seen during these experiments is shown in Fig. 3 (though what was seen on the scope was a lot better than these reproductions from Figure 7.7 of Tolstoy and Clay, reference 3). Figure 3 shows an expanded scale of the reception of the matched signal. The match failed when the source was dropped from a depth of 40 m to 43 m. Measurements gave the vertical focus region to be about 3 m in height and centered on the matched depth. This work is reported in references 3-4.

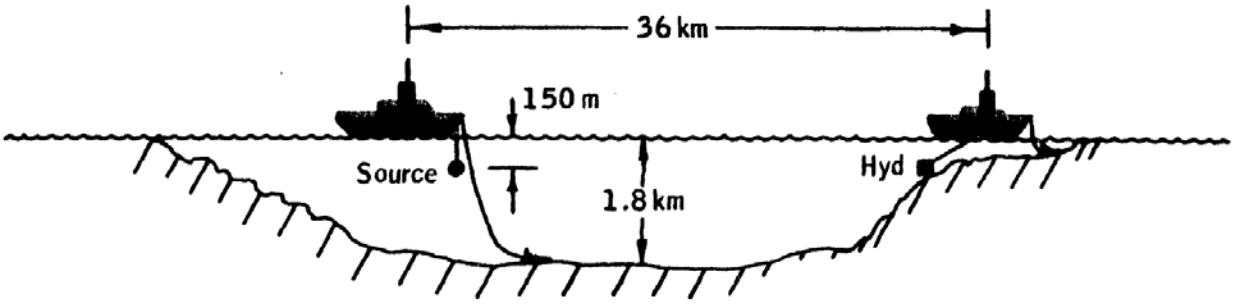

FIG. 2. Illustration of the underwater time reversal experiment conducted in the Tongue of the Ocean.

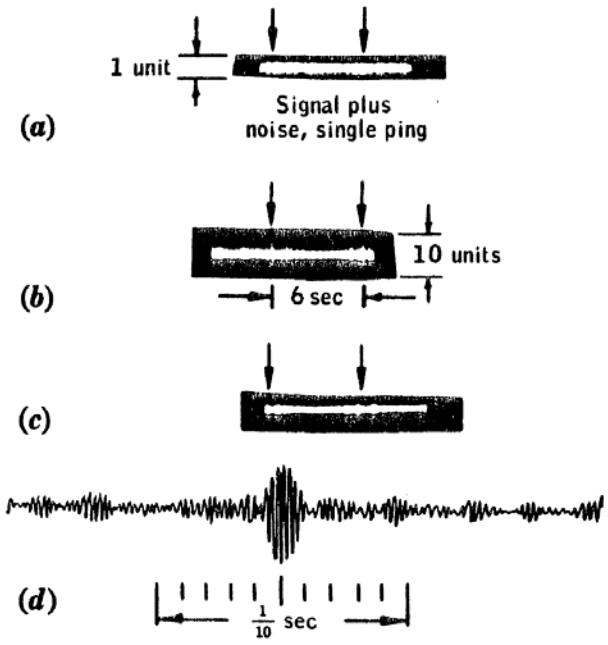

FIG. 3. Photographs of the scope signals made during the Tongue of the Ocean time reversal experiment.

The following description of the experiment results is adapted from reference 3. The source signal was a short 400 Hz pulse which was amplified by a 1.5 kW power amplifier. The signal received by the hydrophone had approximately a signal to noise ratio of 2:1. The recording seemed quite noisy, both from reverberation and from background noise. During the time reversal step, no attempt was made to filter out the background noise so as to provide a true test of the robustness of this matched signal experiment. After broadcast of the time reversed signal, the time reversal focus produced had an approximate signal to noise ratio of 10:1, clearly demonstrating the focusing properties of the time reversal procedure. It was also noted in subsequent experiments that the horizontal extent of the focused signal was much greater than the vertical extent. The amplitude of the focus peak reduced by 40% after moving the ship 150 m (in a direction perpendicular to the direct sound path), and the peak was lost into the noise floor at a distance of 450 m. As noted previously, the amplitude of the focusing was lost into the noise

floor at an increased depth of only 3 m. These results imply that the time reversal experiment created a vertical array of images sources due to the multiple reflections off of the water surface and the sea floor.

The results of the Tongue of the Ocean time reversal experiment proved that, contrary to the beliefs of many acousticians at the time, the transmissions of multi-path signals in the ocean are reproducible as evidenced by the creation of the large amplitude pulse in Fig. 3(c), which represents a focus of energy by the time reversal process.

II. Passing of Clarence S. Clay

Clarence S. Clay, "Clay", passed quickly on April 4th surrounded by family. He is survived by his wife, Jane. He had 4 children, 9 grandchildren, and 5 great grandchildren. Clay played in an orchestral concert the afternoon he passed away. When he got home he felt quite ill and was taken to the hospital where he passed away that evening. **Born:** November 2, 1923 in Kansas City, MO. **Died:** April 4, 2011 in Middleton, WI. **Age:** 87 years old.

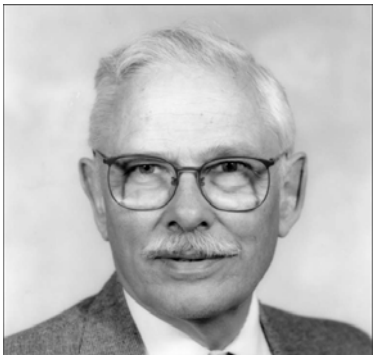

FIG. 4. Photograph of Clarence S. Clay.

He was a WWII Veteran having proudly served his country in the Army Signal Corps. He received his B.S. and his M.S. in Physics from Kansas State University and his PhD in 1951 in Physics from the University of Wisconsin, Madison. He was then an assistant professor at the Univ. of Wyoming, a research geophysicist for Carter Oil Company, a senior research scientist for Columbia University, and finally a professor of Geophysics for the University of Wisconsin, Madison until 1989 and was an active emeritus professor until he passed away.

He specialized in the physics of sound wave propagation in search for oil, structure of the ocean, scatter of sound waves at rough and fractal boundaries, and by marine life. He is the author of 4 books: Tolstoy and Clay, Ocean Acoustics 1967 (ASA 1987), Clay and Medwin, Acoustical Oceanography 1977, Clay, Elementary Exploration Seismology, 1990, Medwin and Clay, Fundamentals of Acoustical Oceanography, 1997. He is an author or coauthor on some 51 JASA articles, and 57 ASA talks. He is a fellow of the ASA and was awarded the ASA Silver Medal in 1993 for Acoustical Oceanography.

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