

EVOLUTION OF NON ACOUSTIC DETECTION SYSTEMS

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ABSTRACT

Although, acoustic techniques are currently the in vogue technologies for detection and tracking of submerged bodies like submarine and autonomous underwater vehicles, the advent of silent submarines and the ensuing technologies resulting in the reduction of acoustic signatures is making naval surveillance very difficult, especially in shallow water environments. Although the non-acoustic techniques such as Magnetic Anomaly Detection, LIDAR, bioluminescence detection, etc. were earlier thought to be promising, subsequent research showed their inherent limitations which restrict their use for detection over a wide area and also from a large distance. Of late, detection of physical manifestations such as turbulent wake and internal waves generated due to moving platforms in ocean, have increasingly become popular mechanisms for naval surveillance of moving platforms. Against this backdrop, the paper discusses the general features of turbulent wake and internal waves generated by moving platforms in ocean and describes a novel optoelectronic technique and technology which was designed and developed for naval surveillance.

Index Terms — Photonics, Optoelectronics, Scattering of Light, Sensor, Stratified Fluid, Monitoring, Moving Platforms, Sonar, MAD, SAR, Kelvin Wake, Turbulent Wake, Internal Wave.

1. INTRODUCTION

Naval strategists have long realized that the conventional acoustic surveillance systems have significant constraints imposed both by the technological advances as well as the complexity introduced by the environment, especially in shallow waters. This led to a growing interest as well as demand to look at non acoustic systems for naval surveillance. Although, a number of non-acoustic signatures that can be associated with a moving ship or a submarine – signatures of pressure, surface waves, wake, static electric field (UEP), static magnetic field, extreme low-frequency electromagnetic (ELFE) field, internal waves, changed biological activity, chemical trace metal concentrations and spillages, showed initial promise vis-à-vis the detection and identification of the moving platforms, only the hydrodynamic signatures generated by moving bodies in the ocean have received critical attention from the R&D community. It is now well known that, while the ship itself can be designed to reduce its signatures, it will still leave a trace (wake and wave) in the sea when moving. Current knowledge also indicates that the viscous part of the wake contains different types of perturbations, for example velocity and pressure fluctuations, bubbles, surface and internal waves, temperature fluctuations, biological and chemical changes. However, the complexity of the nature of these phenomena and the perturbations that they generate and their effects on the wake and wave signatures is still poorly understood. Nevertheless, the growing number of publications pertaining to this exciting field, is an indication of the importance and the urgent desire to develop pertinent non-acoustic technologies for surveillance purposes, especially by the western world countries.

2. WAKE GENERATION BY MOVING PLATFORMS AND THEIR CHARACTERISTICS

Researchers have studied wakes behind submerged bodies for many decades. Text books on the fundamentals of turbulence and the associated dynamics (*viz.*, the seminal works on turbulence by

respected authors like Batchelor, Tennekes and Lumley, and Townsend) presented simplified theories for scaling laws of self-similar turbulent wakes. As many of the known analytical theories of turbulent wake dynamics in stratified fluids were intrinsically complex - with no simple solutions, a vast majority of the studies reportedly dealt with numerical simulations and laboratory investigations. Studies reported so far primarily revolved around laboratory investigations on spheres in uniform and steady flows. There were many experimental studies on jets and wakes essentially dealing with simplistic controlled conditions, with no background current shear imposed. Generally, most of the studies pertained to:

- i. Steady state flows
- ii. Disturbances created by 3-D bluff bodies (i.e., spherical bodies or bodies with spherical cross-sections)
- iii. Near wakes
- iv. Non-stratified fluids
- v. Low R_e (Reynolds Number = ratio of inertial to viscous forces) and F_r (Froude number = ratio of inertial to gravitational forces) conditions
- vi. Momentum less wakes generated by self-propelled bodies – i.e., assumption being the thrust produced by the body is compensated by the drag created by the body.
- vii. Far wakes or late wakes (Although though several investigators reported that a three dimensional bluff body towed in stratified fluid leaves behind a highly organized vortex street, there have been very few studies reported on these phenomena).

The studies suggested that for initially turbulent flows the formation of the vortex street occurs at dimensionless times of $\tau = Nt = 50$ to 70 due to periodic shedding of vortices from the surface of the body for different F_r . Here N is the Brunt-Vaisala number or the buoyancy frequency defined as the ratio of buoyant forces to the inertial forces, and t is the time. The typical wake collapse time is $Nt = 2$ to 3 due to the action of stratification. Such vortex streets are rather stable and remain *visible* in stratified flows until very large dimensionless times $Nt = 500$ to 1000 and are observed to be independent of the body R_e . In other words the formation of vortex street occurs at large dimensionless distances, $X/D = Ut / D = (50-70) F_r$, from the body. These studies however, need to be assessed vis-à-vis the real world scenario which comprises of unsteady, stratified geophysical fluid flows which have large R_e and F_r , with significant background current shear present when irregularly shaped bodies are moving unsteadily.

The primary manifestation of a moving platform (body) in stratified fluid is the turbulence and the associated wake and wave generation (Figure 1). Hydrodynamic phenomena like Bernoulli hump, Kelvin wake and internal waves are all related to the initial turbulence generation by moving bodies. Bernoulli hump and Kelvin wake phenomena which move with the moving body are non-propagating components, while the vortex motions and waves are the propagating components of a complex system of hydrodynamic disturbances resulting from the initial turbulence. The propagating components of the complex system are responsible for the spatial and temporal persistence of signatures (Tennekes and Lumley, 1972; Reed *et al.*, 1990; Sarpkaya, 1998; Han *et al.*, 2000; Svennberg, 2001; Rottman *et al.*, 2002; Srikanth *et al.*, 2011; Golbraikh *et al.*, 2013).

For a moving ship there are several sources of turbulence. The shear flow in the boundary layer at the hull is a main contributor to turbulence in the wake. Hull and propeller induced vortices transport and produce turbulence in the interface region between swirling vortex and surrounding fluid. The breaking bow wave is another region of turbulence, but since this turbulence is shallow and positioned along the Kelvin wave system it will be quite isolated from the turbulence in the viscous wake (Hoekstra and Aalbers, 1997). At sea there will not only be the turbulence produced by the ship, but also the background turbulence of the ocean upper layer, originating from breaking of waves and the turbulent energy production of the mean shear flow (Benilov *et al.*, 2001). Though the turbulence in the wake eventually will reach the turbulent level of ocean, these two turbulent fields can for the most part be viewed separately since the wake turbulence significantly exceeds the upper layer turbulence. By diffusion the wake width increases roughly according to a power law of $x^{1/5}$, where x is the distance from the ship (Milgram *et al.*, 1993). The turbulence in the wake is also an important factor when dealing with remote sensors. The physical mechanism allowing the detection of a ship wake on the ocean surface (for example SAR) is basically a result of the diffusion of surface active films and materials in the wake, together with vortex interaction with the free surface and the presence of short wave lengths which essentially affect the backscatter of radar waves, enabling a SAR image of the far wake that looks like a railroad track (Reed *et al.*, 1990; Benilov *et al.*, 2001). In good weather, the far wake can be seen with conventional high altitude photographs as a region of smooth water as far as 100 km behind the ship (Reed *et al.*, 1990). It has been indicated that the change in physical properties (temperature, salinity, density) caused by the wake can persist for an hour or more after the passage of the ship. Also SAR (Synthetic Aperture Radar) imagery can trace the wake up to 100 km aft of the ship. The turbulent kinetic energy in the viscous wake can also be traced for a long time after passage. The distance depends on the sea state, but 2-4 km is not impossible as indicated by Benilov *et al.* (2001).

Benilov *et al.*'s (2001) comprehensive studies covering analytical, numerical and experimental aspects of ship generated wakes in ocean ushered in significant breakthroughs in characterizing the spatial and temporal features of wake - wherein it was demonstrated that the ship wake turbulence is well detectable (*considering a ship length of L , under fair sea conditions the numerical approach predicted a range of $\sim 50L$ while the results from the experiments were more modest, $\sim 10L$*). The turbulent kinetic energy is a good and convenient measure of turbulent activity and the decay of turbulence in the wake can be viewed from the energy perspective (Hoekstra and Aalbers, 1997). Benilov *et al.* [9] relied on decay rate for the turbulent kinetic energy in the wake of ship model and found that the decay could be described by a power law of $x^{-4/5}$. Subsequently Rottman *et al.* (2002) provided another view on the decay of energy in the wake, and observed that the thrust and drag wake dominates and the energy decays as $x^{-3/2}$, while the swirl from the propeller was shown to have less energy but decays as x^{-1} . Thus, with the fast decay of the thrust and drag, the swirl will eventually dominate and the decay of the wake will be slowed down. The stratified case, which probably only is of interest when dealing with submarines, alters the decay of the total energy. It gives higher energy in the far wake than for the non-stratified case. This effect is probably due to the generation of internal waves, which do not decay as rapidly as turbulence, as well as the mixing of water layers of different density.

One of the important insights was provided by Vorapayev *et al.* (2001) who considered the moving bodies to have unsteady motions and a background shear in ocean (*which is consistent with the real world scenario where moving bodies are continuously changing their speed and direction over a*

background shear in ocean). Vorapayev *et al.* (2001) experimentally established that large (compared to the size of the body generating them) coherent vortex structures exist behind a maneuvering self-propelled body in stratified fluids. Spedding (2002) based on digital particle image velocimetry measurements on wakes caused by spherical bodies suggested that the combination of Kelvin-Helmholtz and spiral mode instabilities may account for the observed wavelengths in late wake eddies (*i.e.*, a combination of instabilities and pairing-merging mechanisms are responsible).

Recent studies further demonstrated that large coherent eddies (monopoles, dipoles, and their combinations) are the persistent flow patterns which are easily formed in stratified and rotating fluids. It was also suggested that the planar dipolar eddies possess a linear momentum and can propagate significant distances from the origin. Observations have shown that the flow in the far wake consists of long lasting patches of vertical vorticity of opposite signs (pancake eddies) organized into a vortex street, the vertical length and velocity scales of which are much smaller than those in the horizontal direction. *However, until now there has been no satisfactory theory explaining the mechanism of vortex street formation in the far wake.* In the late wake, coherent vortex structures appear and last for very long durations. Although recent detailed experiments by Spedding (2002); Meunier and Spedding (2006); and others provided information about the physics behind the late wake structures, the experiments provided data only in individual planes, so speculation remained about the vortex geometry and about the roles of dissipation and buoyancy in those structures. Gourlay *et al.*, (2001, 2002) revealing simulations provided volumetric data for wakes (analysis of the fully three-dimensional flow) which complemented the body of previous and ongoing research work. Gourlay *et al.*'s simulations of statistical quantities, such as mean velocity profiles, wake velocity and length scaling and turbulence amplitudes provided precise fully three-dimensional data for every fluid dynamical field. This volumetric data provided vortex geometry data that was earlier unavailable, as it was felt that it is extremely difficult to measure with high sensitivity and accuracy in water tank and wind tunnel experiments. Gourlay and other researchers' simulations further suggested that (i) the fundamental origins of late wake vortices lie in the vortex loop geometry required by Helmholtz' characterization, (ii) that viscous diffusion smoothens initially convoluted loops into smooth rings, and (iii) that the organized configuration of those vortices come from the mean jet flow. Further they have shown that the vortex rings do not require stratification to exist. It is now believed that in stratified fluids, buoyancy suppresses vertical motions, and the vortex lines weave through adjacent vortex rings so that they do not propagate away from each other- which accounts for their more regular organization as compared with the non-stratified case.

In almost all the works related to wakes and waves generated by moving bodies in ocean (stratified fluids) it has been customary to discuss about the wake and wave aft of a moving body but not on the bow side, primarily because a majority of researchers believed that the bow wake (upstream wake) and wave is not significant enough in terms of disturbing the fluid *per se*, although it has been known that shock systems can extend upstream and downstream and appear as unsteady discontinuities. Interestingly, Turner discussed (in his book, *Buoyancy Effects In Fluids*) about the existence of upstream wakes generated by moving bodies in stratified fluids - as only upstream of the body, the vorticity generated by the buoyancy is in the opposite sense to that generated by viscosity, so that a balance between the two becomes possible. However, recent studies in the field of Bioengineering (for example, Peng and Dabiri, 2008) which employed new techniques in fluid mechanics, revealed the

existence of significant coherent structures in the upstream of moving bodies (swimming and flying animals) in fluid environments which have implications to interesting pathways to fluid transport.

Arguing that, the main reason for the inconsistencies between different studies by several researchers and some of the contentious observations vis-à-vis the real world, is an artifact of the failure of the experimental investigations to accurately monitor and simulate the real world scenario; Tataavarti *et al.* (2008) worked on the design and development of a novel opto-electronic system for monitoring the hydrodynamic disturbances in stratified fluids. Their contention was that given the complexity of the theory an appropriately sensitive measurement system should provide insights during field trials, whether the ship and submarine generated hydrodynamic signatures can be suitable candidates for naval surveillance.

3. NON INVASIVE OPTELECTRONIC SYSTEM FOR MONITORING STRATIFIED FLUIDS

The optoelectronic system (after Tataavarti *et al.*, 2008) for real time monitoring of stratified fluids (for example in the ocean) comprises of a continuous wave, coherent, collimated beam of light (or a laser) falling on the surface of a photo detector in such a way that the received light falls partially on the active sensing area of the photo detector and partially on the encapsulation of the photo detector, after passing through the stratified fluid medium (Figure 2). The light intensity falling on the photo detector undergoes changes due to changes in the optical refractive gradient generated as a result of fluid motions in the stratified fluid. The photo detector records the precise time varying light intensity pattern, corresponding to the time varying motions experienced in the stratified fluid due to motions. The output signals from the photo detector are recorded and compared with those obtained from a standard sensor. The efficacy of this method and system for real time monitoring of stratified fluids was demonstrated at sea.

The relationship between the optional refractive index and the temperature (density) of a fluid is given by the Gladstone-Dale Equation, $n = 1 + \kappa\rho$ (the optical refractive index is linearly related to fluid density) where, n is the optical refractive index, ρ the density of the fluid and κ is a constant coefficient which is a function of the laser wavelength and the fluid characteristics. Therefore, the refractive index gradient is linearly related to temperature (density) gradient or the change in refractive index gradient will yield the change in density gradient of a fluid (see Figures 2 and 3). Based on this concept, it can be inferred as follows, as suggested by Tataavarti *et al.* (1995):

$$\begin{aligned} \varepsilon_x &= \int \frac{1}{n} \frac{\partial n}{\partial x} dz; & \delta_x &= \frac{L}{n} \frac{\partial n}{\partial x} \approx \frac{L}{\rho} \frac{\partial \rho}{\partial x} \\ \varepsilon_y &= \int \frac{1}{n} \frac{\partial n}{\partial y} dz; & \delta_y &= \frac{L}{n} \frac{\partial n}{\partial y} \approx \frac{L}{\rho} \frac{\partial \rho}{\partial y} \end{aligned}$$

where, L is the optical path length of the beam in fluid and x and y are horizontal and vertical coordinates. The dimensions δ_y of are $m/(Kg/m^3) \times (Kg/m^3)/m$. Therefore, δ_y will be dimensionless.

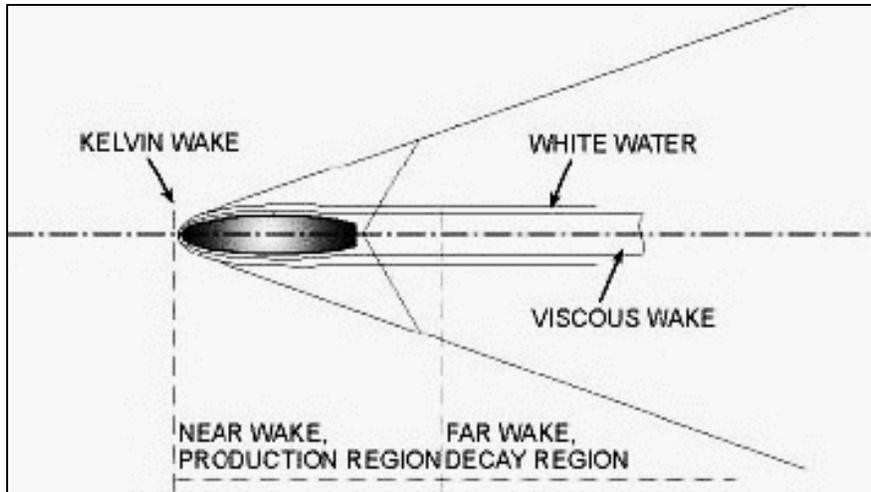


Figure1: The wake of a surface ship.

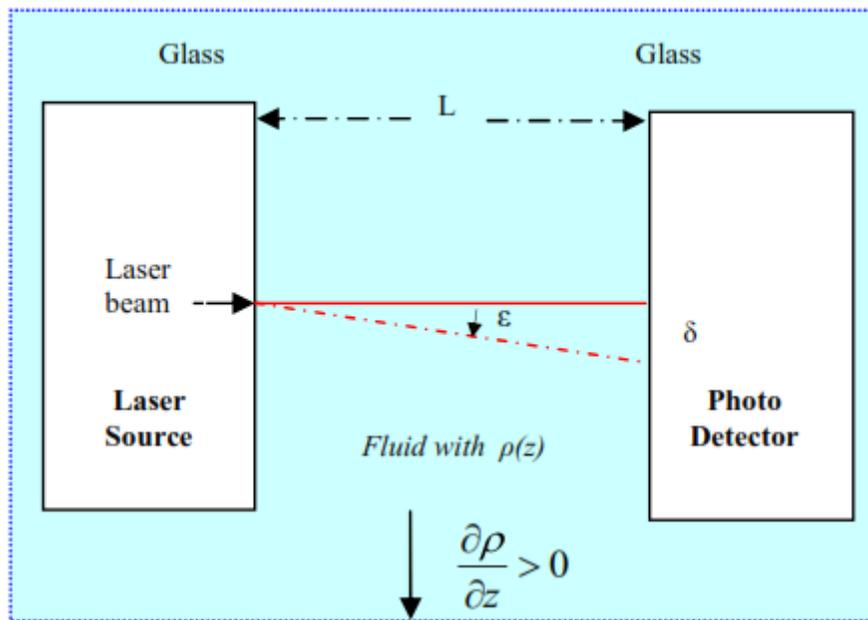


Figure 2: Laser beam deflection in a density stratified fluid.

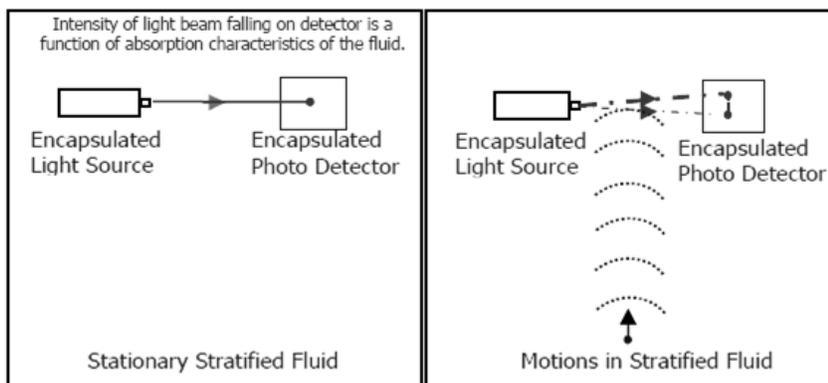


Figure 3: Schematic description of the working principle of photonics system for monitoring stratified fluid motions.

For the optoelectronic systems the minimum resolvable δ (an artefact of the sensitivity of the position sensing detector used), say, $0.1\mu\text{m} = 1 \times 10^{-7}\text{m}$; an optical path length L designed as, say, 0.1m ; $\delta_y = 1\text{m}$; and an average density value of ρ (air) $\approx 1\text{Kg}/\text{m}^3$. For calculating the minimum resolvable $\Delta\rho$ (ΔT) we have

$$\frac{\delta_y \rho}{L} = \frac{\partial \rho}{\partial y}$$

i.e., the minimum resolvable $\Delta\rho$ is, $O(10^{-6})\text{Kg}/\text{m}^3$ (or the minimum resolvable temperature is 0.001°C).

Hence, the sensitivity and accuracy of the optoelectronic sensor system for monitoring fluid parameters using the concept of forward light scattering, are extremely good (orders of magnitude higher) compared to conventional existing technologies, and the same can be realized, with position sensing detectors of sub-micron accuracy and sensitivity. A version of the optoelectronic system developed by Tatavarti *et al.* (2008) for use at sea is shown in the Figure 4.

It is well known that changes in the environment in which a light beam is traversing can be realistically monitored with increased sensitivity (*compared to conventional sensing mechanisms*) if one could study the optical diffraction and interference fringes which are manifest. However, to observe these fringes one needs to make elaborate design involving complex optical configurations and precise optical alignments. Tatavarti and Santhanakrishnan (2010) have patented a simpler method to simultaneously generate and detect the diffraction fringes caused due to changes in the environment, and the same can be used in the study of hydrodynamic disturbances due to moving bodies in stratified fluids. That is, in order to further increase the sensitivity and the dynamic range of sensing we ensure that the laser beam is focused in such a way that forward light falls partially on the active sensing area of the detector, and partially on the outer perimeter of the active sensing area of the photo detector, thus ensuring a spatial intensity pattern on the photo detector.

4. SEA TRIALS FOR PROVING THE NON ACOUSTIC SYSTEM FOR SURVEILLANCE

An elaborate exercise was planned at sea for proving the designed and developed non-acoustic system for surveillance. The optoelectronic system was deployed from a stationary (anchored) Ocean Research Vessel, ORV Sagarnidhi. The target for detection was the naval ship INS Sagardhwani. During sea trials A74 (Sagardhwani was used as a target which was doing different maneuvers as shown. The optoelectronic system (NASA – Non Acoustic Surveillance Accoutrement) was lowered from the stationary platform, Sagarnidhi (shown as a red arrow, anchored at 42m water depth) off Kochi, the details of sea trials is shown in Figure 5. The important results indicated in Figure 6, demonstrate the utility of the non-acoustic system for surveillance. The results indicated that

- There is a marked difference in the time history of laser beam intensity during ambient sea conditions vis-à-vis when a target is present around NASA.
- Results also showed the differences in time series when the target was present at ranges varying from 600m to 20kms.
- The scatter in Laser beam intensity increases with decreasing range of target and vice versa.

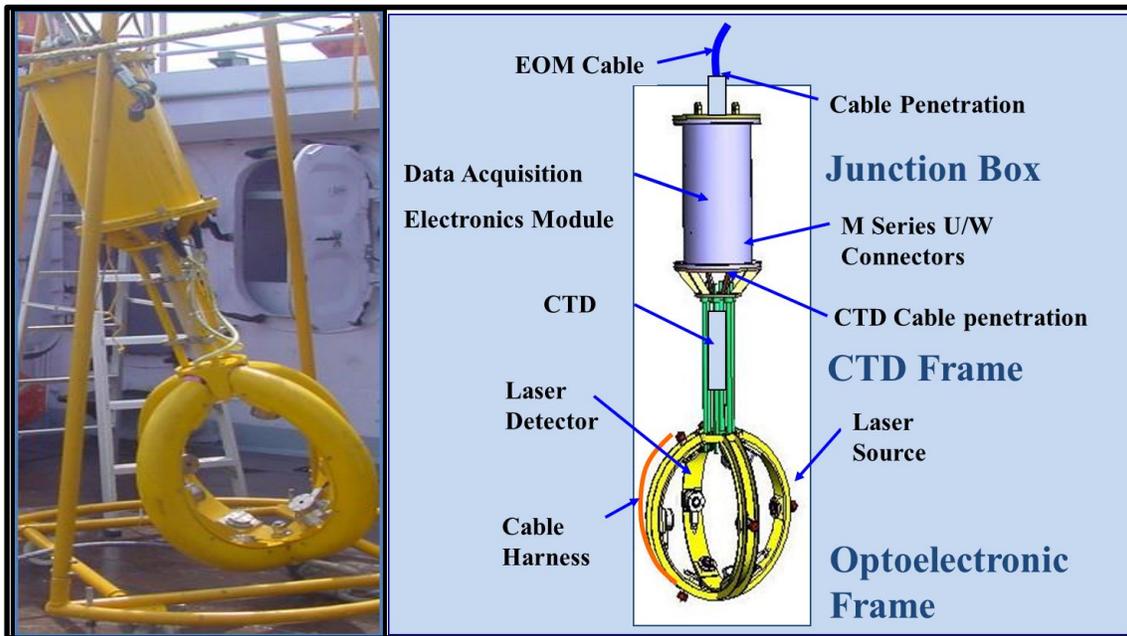


Figure 4: NASA- Non Acoustic Surveillance Accoutrement, used for sea trials. This Optoelectronic System is a self-recording unit with real time display and can either be moored at mid ocean or fixed on the bottom of the seabed.

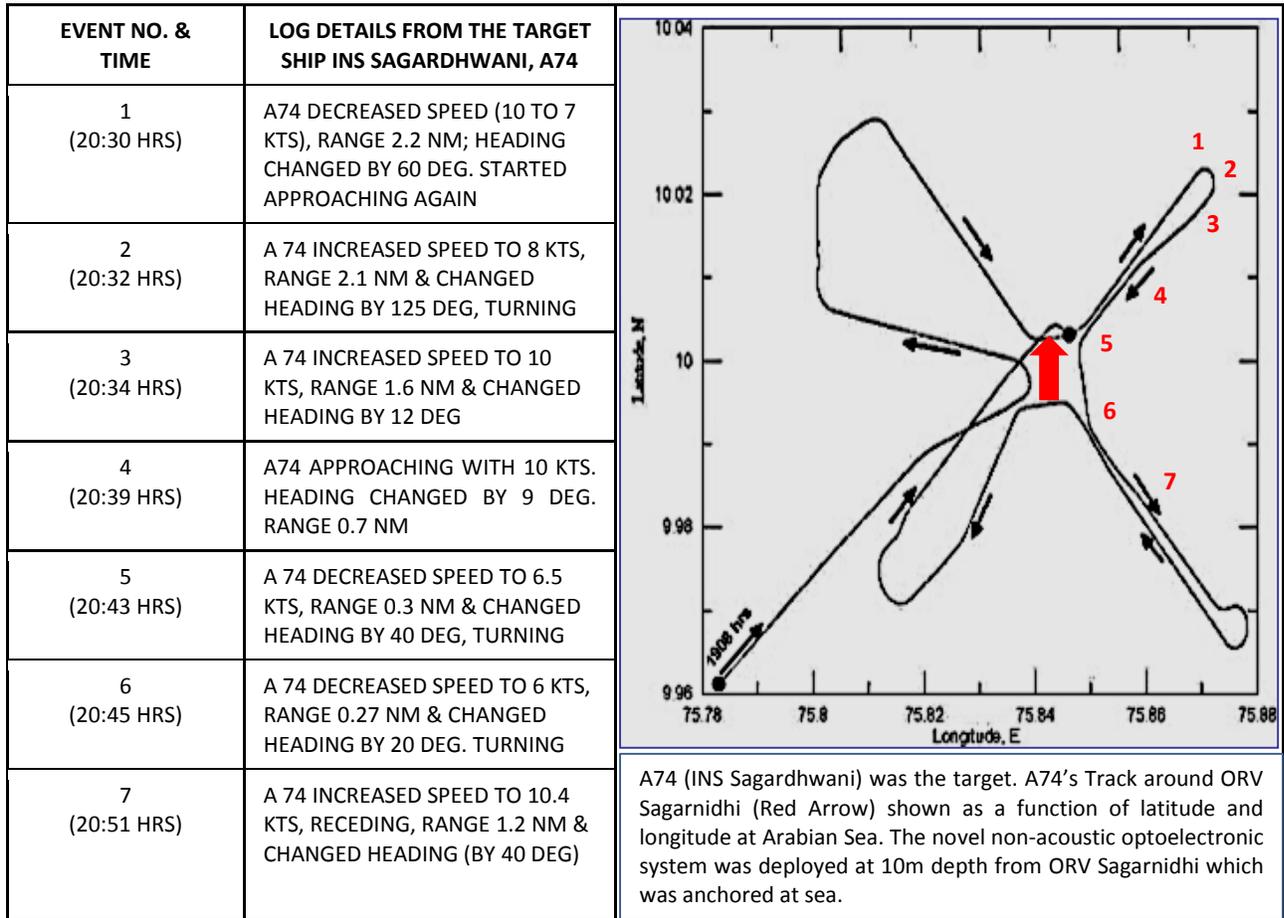


Figure 5: Details of the sea trials conducted in Arabian Sea for proving the non-acoustic system developed at NPOL. In these trials A74 (INS Sagardhwani) was the target and A74's Track around ORV Sagarnidhi (Red Arrow) is indicated with all pertinent details. The non-acoustic optoelectronic system deployed at 10m depth from ORV Sagarnidhi.

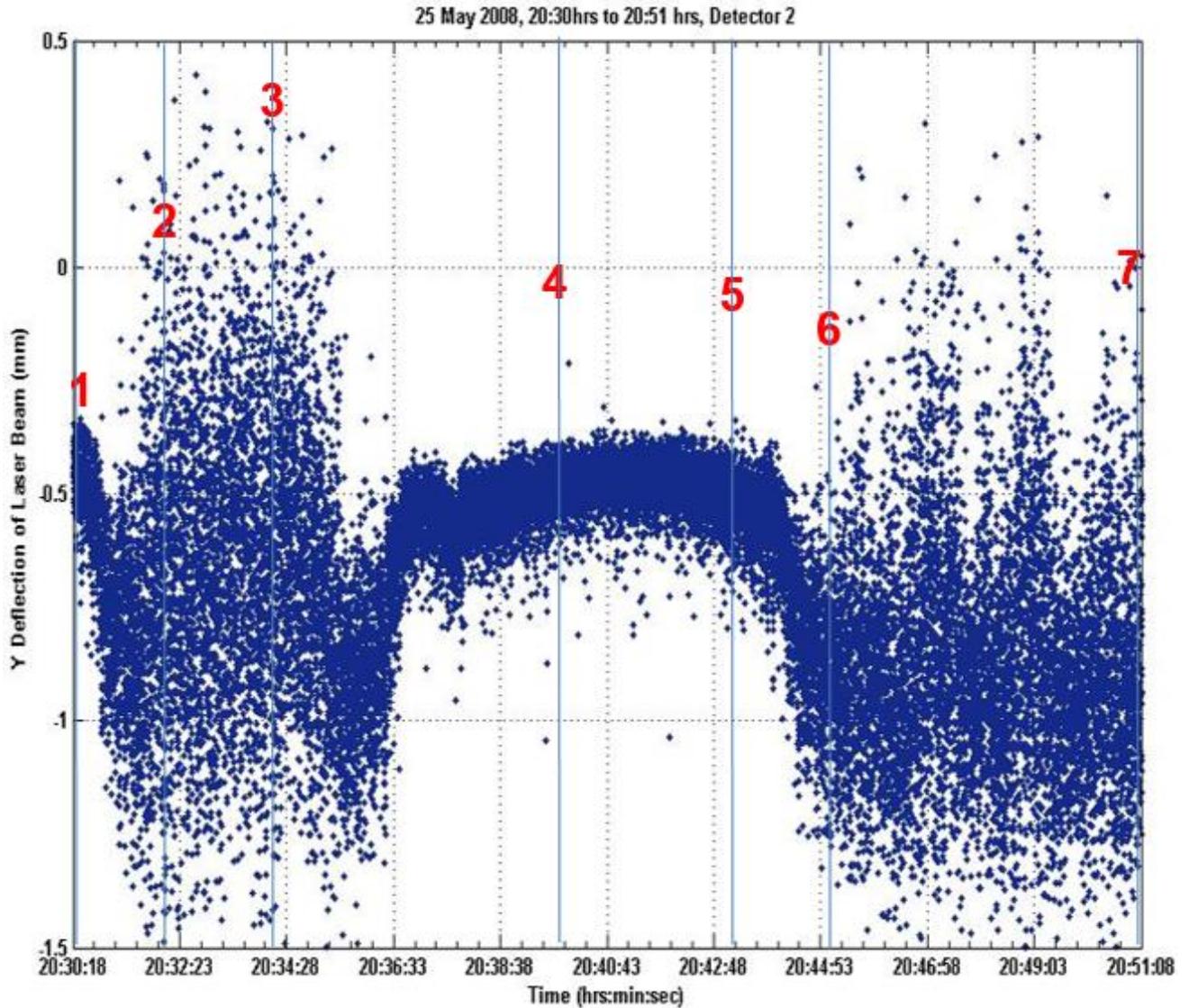


Figure 6: Laser beam deflection in the Y direction (in microns) plotted as a function of real time (sec) during the sea trials held in Arabian Sea during 2008 field experiments. The target was the ship INS Sagardhwani. The display clearly indicates the marked differences in signatures from the detector due to the approaching (events marked as 4 and 5) and receding target vis-à-vis the detector's position. The range of the target can be estimated based on the amplitude of the signature recorded by detector. The propeller frequency is also embedded in the time series signature from the detector (events 6 and 7) when the targets propeller is facing the detector. In this case the propeller's frequency is 30 rpm as can be noticed by the 120s oscillation (events 6 and 7).

- As the target's range increases the mean value of the laser intensity increases (i.e., less dense water is pushed to traverse between the laser source and detector).
- When the target changes course, especially when the propulsion system of the target faces the laser beam the laser intensity scatter increases.
- Detection of targets when they are approaching as well as when they are receding from NASA is possible.
- Even target (bulk carrier) at a range of 20kms detected by NASA – confirmed from Ship's radar.
- Temporal laser beam intensity changes with the changing range and course of target vis-à-vis NASA. NASA could detect passing ship traffic at 20kms and A74 at 8kms as per the trial. The speed of travel of hydrodynamic signatures was confirmed to be more than the known \sqrt{gh} values.

5. CONCLUSIONS

Tatavarti *et al.* (2008) demonstrated that one can discriminate, detect and localize targets, using the novel non-acoustic detection system (which can be easily implemented on board a stationary platform (like a surface or subsurface buoy) or a dynamic platform (like a ship, submarine or even a torpedo) indicating clearly the non-acoustic detection system's use for naval surveillance. The feasibility and scope for implementation of this non acoustic technology on board torpedoes for homing purposes has been the recent research focus at NSTL.

This new science naturally needs critical review, *without any a priori biases* - which is what is lacking in the Indian scenario. The system can be implemented by the Navy for surveillance purposes.

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