ALMA 2014: OBSERVATIONS OF MULTIPLE SOUND SCATTERING FROM RANDOM INHOMOGENEITIES TRANSPORTED BY A MEAN FLOW

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Abstract: *The very first sea trial of DGA TN's modular ALMA system (Acoustic Laboratory for Marine Applications) occurred in October 2014, over the Eastern Corsican shelf (water depth about 85m). The almost motionless system consisted in a source located at about 7km of a 2D array of 64 receivers (about 2m x 2m). The summer configuration involved a strong thermocline emphasizing contributions of bottom reflections of sound, combined with an exceptionally flat sea surface. There was no other significant ensemble movement than a littoral current oriented from the source toward the receiving array. Despite this stationary configuration, interesting Doppler shifts were observed when analyzing transmitted long continuous sinusoidal waves (20 s length), simultaneously at several frequencies (2, 5, 7, 11 kHz). We did not only witness an intuitively predicable, even if very fast spectral broadening of the signals, but also measured constant frequency shifts, depending on the transmitted frequency and stable over two hour and a half. Explanations to these two mechanisms may be searched in scattering by random medium fluctuations transported by a current or in an occurrence of Wolf effect.*

Keywords: *Random media, Moving media, Acoustic scattering, Internal Waves, Doppler shift, Wolf effect.*

1. THE FIRST SEA TRIAL OF *ALMA* SYSTEM: OCTOBER 19-20 2014

As a tool for a better understanding and modeling of underwater acoustic phenomena, *DGA Naval Services* has conceived a deployable modular system called *ALMA* (Acoustic Laboratory for Marine Applications); this system was realized and delivered in October 2014 and is currently in service with the collaboration of *ALSEAMAR* and *COMEX* companies. *ALMA* consists in a SX05-01 dual barrel steve projector source (*Sensortech*) and a set of short linear "legs", i.e. 2.25m-long arrays with 16 equally spaced SQ *Sensortech* sensors, which can be connected in arbitrary 1D, 2D or 3D configurations; the system can be deployed down to 200m depth. We summarized in this article some interesting observations collected during the very first sea trial of the ALMA system.

Compared with the many published descriptions of acoustic experiments, the *ALMA 2014* campaign features some rare or maybe unique characters for investigating scattering effects arising from movements in the water column. We not only have almost motionless source and receivers, but meteorological and oceanological circumstances were also extraordinary favorable: the sound speed profile associated with the strong summer thermocline (Figure 3) is bottom refracting and almost no contribution from the sea surface connects source to array; moreover the sea surface was exceptionally flat (sea state 0). All these circumstances converge to the eradication of any significant contribution of sea surface scattering and fluctuations from sea surface waves; the *ALMA 2014* campaign appears as ideal for investigating the stochastic fluctuations of acoustic signals due to volume effects, including internal waves, currents and/or turbulence.

The *ALMA 2014* campaign was conducted on October 19-20 2014, over the Eastern Corsican continental shelf, at about 5km off Alistro, near Bastia. The sea bed, at about 85m depth between source and receiver, is a quite flat sandy bottom, quite hard and acoustically a good reflector. The source was anchored at a depth of about 50 m below surface. The legs of the receiving system were connected in a "square" configuration, consisting in 4 columns of 16 sensors; the array was located at 60 m below surface (upper line of sensors), at about 7.6 km from the source. Figure 1 displays a picture of the "square" receiving array configuration, and Figure 2 provides a schematic representation of the experimental configuration.

On October 20th 2014, the source transmitted 19 times a combo sequence every 8 minutes during about 2 hours and a half. This combo consisted in short 1s-long CW chirps at 2, 5, 7 and 11 kHz, a 2s-long LFM pulse ranging from 4 up to 6 kHz, a long 20s-long comb of 4 spectral peaks at 2, 5, 7 and 11 kHz, and a 10s-long white pseudo-random noise; CW chirps and LFM were repeated twice in the combo with a delay 30 s.

Several probes of temperature were immersed during the 2 days of the campaign, giving elements for calculations of ray paths. Figure 3 displays sets of temperature profiles collected on October 20th; the hydographical configuration features a typical end-of-summer type, with a sharp thermocline (quick vertical fall of temperature) from 20m to 60m, below a narrow mixing layer below surface. Undulations of temperature can be observed in the thermocline over the two days; these oscillations most probably betray the presence of internal waves, frequent in such unstable configurations with strong vertical gradient of density.

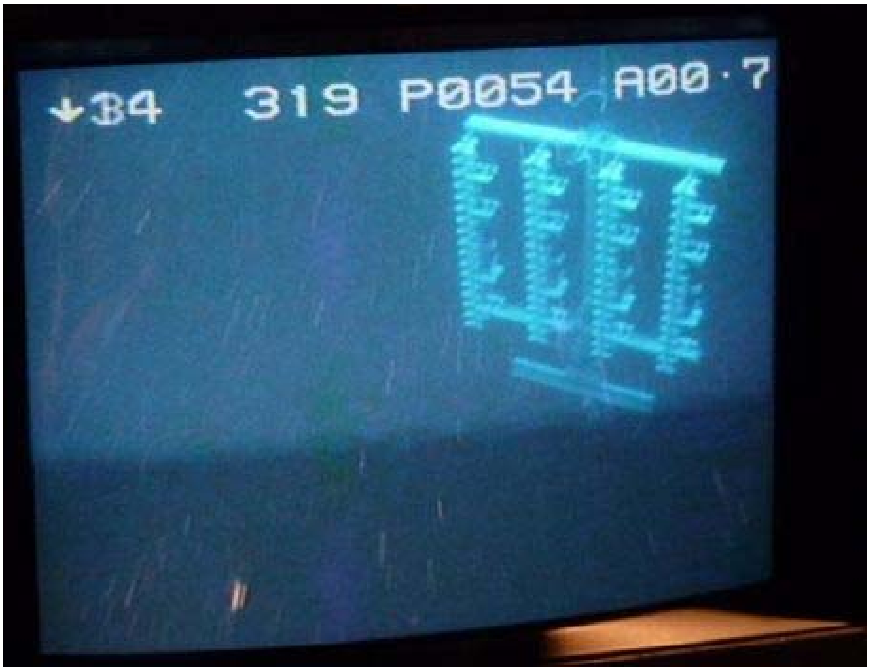

Fig.1: A picture of the underwater array ALMA in the square 2014 configuration.

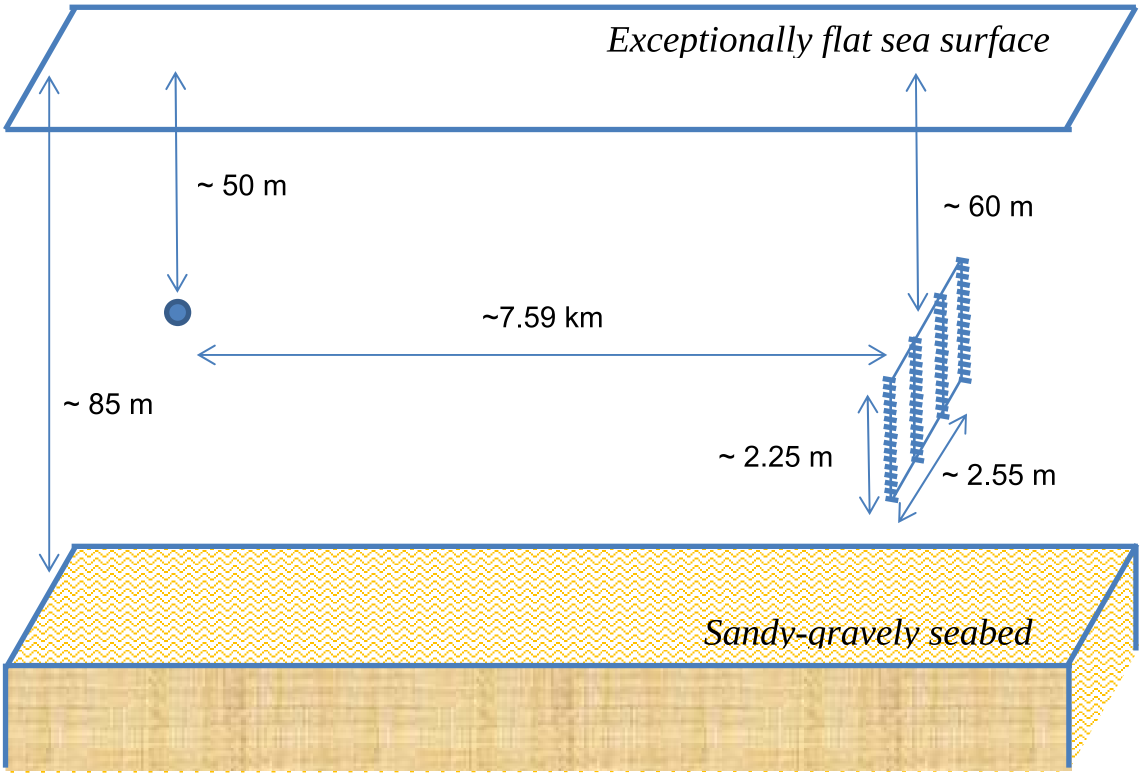

Fig.2: A schematic display of the ALMA 2014 experimental configuration.

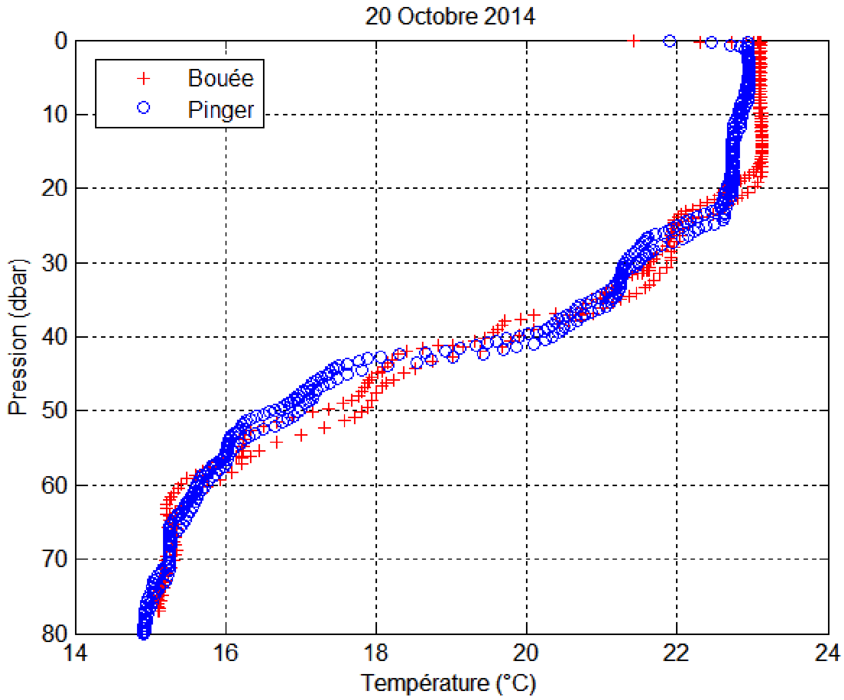

Fig.3: Four measurements of sea water temperature profiles for the day of observations near the source (blue) and near the receiving array (red).

2. ON SOME OBSERVATIONS FROM ANALYSIS OF RECEIVED SIGNALS

The analysis of the different components of the 19 transmitted combos provided observations of many different kinds of phenomena:

- The examination of the 10s-long random noise demonstrated a sharp resonant absorption peak at about 5 kHz, which may be attributed to small swimbladder fishes (probably juvenile anchovies).
- The short CW chirps gave way to investigations of the spatial coherence of the acoustic field over the array, particularly the excellent horizontal correlation along horizontal lines and inversely a poor vertical correlation; this probably illustrates the effects of sound speed fluctuations associated with internal waves with quite long horizontal correlation scales and shorter vertical correlation lengths.
- The wide-band of the LFM pulse made possible investigations of the properties of the Impulse Response (IR), of its spatial correlation and of its temporal variability; apart from conclusions similar to those obtained from CW chirps for spatial correlation, we otherwise observed good correlations between IR transmitted at intervals of 30s and radical changes (no correlation) after 8 minutes. Again this is probably the signature of the relatively slow oscillations of internal waves.
- The long 20s comb of spectral peaks made possible the examination of the detailed variations of amplitude and phase of signals for all transmissions, simultaneously over all receivers; spectral broadening was unsurprisingly observed, but furthermore we witness more striking a mean Doppler shift extremely constant over the full 2.5 hour sequence. We interpreted this feature as arising from the transport of random sound speed fluctuations by a mean current.

We focus now on this last puzzling phenomenon, arising from the analysis of the components of the 20s long CW comb at 2, 5 and 7 kHz; the 11 kHz component was far too corrupted by ambient noise for giving significant results. For each transmission and sensor, the following procedure was applied. The combs were first band-passed around the nominal frequencies over narrow windows for reducing ambient noise effects. Then the amplitudes and phases of resulting complex signals are extracted: a linear regression of the phase variations over the 20 s sequence is performed, demonstrating the presence of a shift from the nominal transmitted frequencies (Figure 4). This unexpected shift is an increasing function of transmitted frequency only; except for some rare bursts (maybe due to destructive interferences), this shift is very stable and constant on all sensors and over the full 2.5 hour sequence. Last steps are subtracting the mean frequency shift and displaying the resulting complex signals in the complex plane ("phasor" representation); this graphical representation gives insights on the structure of random fluctuations of the acoustic field.

The observed mean frequency shifts are about 0.1 Hz, 0.23 Hz and 0.26 Hz for the spectral peaks at 2, 5 and 7 kHz respectively; the resolution in frequency for a 20 s long harmonic signal is of the order of 0.05 Hz, so that these observations of shift are significant, at least for the 5 and 7 kHz components. The shifts are close to proportional to frequency, and are equivalent to shifts from approaching objects travelling at velocities about 0.07 m/s, 0.07 m/s and 0.06 m/s (±0.01 m/s).

Once this mean Dopplerization subtracted, the remaining complex signals still displays random relatively fast fluctuations; they betray changes in the medium over the 20 s. These fluctuations can be represented in the complex plane. The shape of the resulting graphical display information on the inner structure of the signal fluctuations, in terms of the classification and unsaturated *vs*. saturated terminology proposed by Flatté (Chap.XX, in ref.[1]). This way, different regimes can be differentiated, as displayed by the examples of the graphs of Figure 5:

- At 2kHz: the complex signal remains on quite a narrow ring, meaning that its amplitude remains almost constant, and that only the phase undergoes random fluctuations during the 20 s sequence. We are in presence of the « unsaturated » regime, where the « ray paths » connecting source and receiver remain approximately stable; the phase fluctuations simply are the integrations along these rays of the wave slowness fluctuations.

- At 5kHz: the ring is fattened and crossings of its central zone are frequent. We enter the « saturation » regime: each ray path associated with the mean environment may split into several multi-paths, which interfere and produce zero crossings. The relatively scarceness of these zero-crossings at 5kHz is typical of "partial saturation".

- At 7kHz: the ring is filled, meaning that amplitude and phase violently fluctuate because of sharp interferences between multiple unstable micro-paths. We witness the signature of a strong speckle configuration, "fully saturated" in Flatté's terminology.

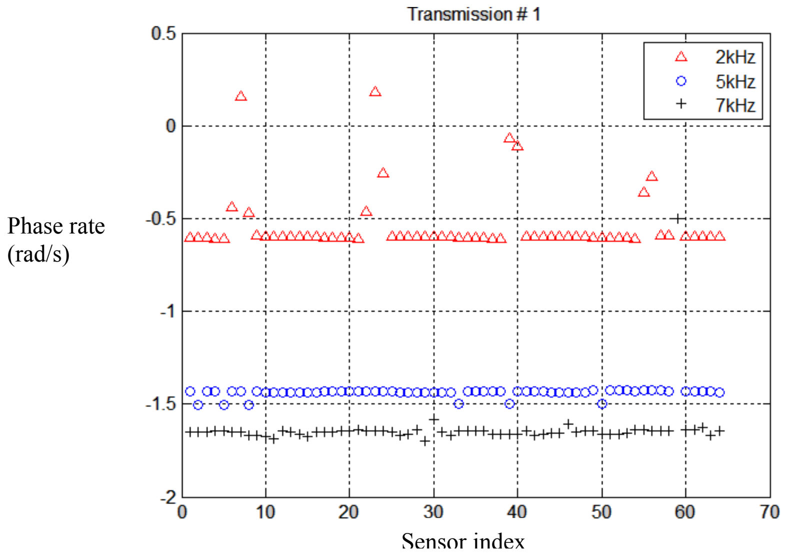

Fig.4: Phase shift rate (-2π x frequency shift) of the three CW components of the comb along array (sensors 1 to 64) (horizontal axis) for transmission #1.

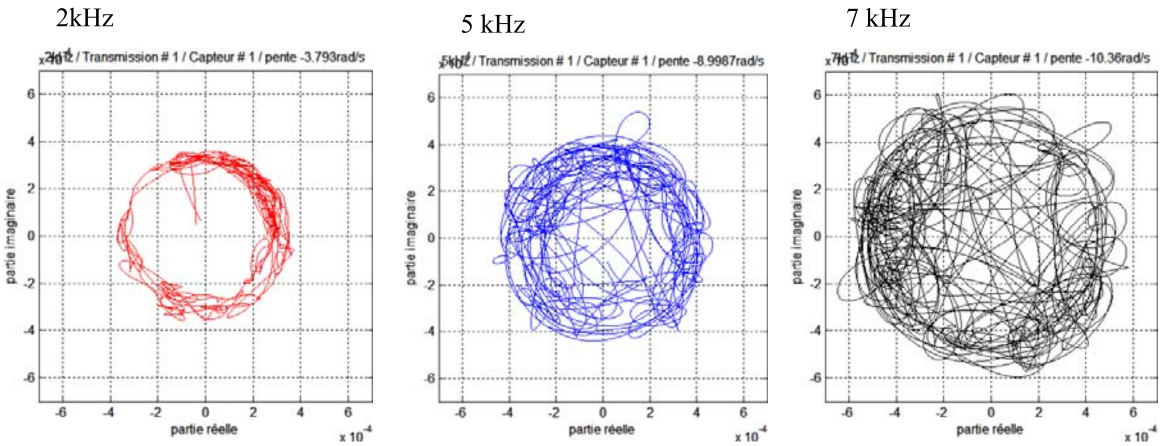

Fig.5: Rotations of perturbed signal in the complex plane after subtraction of the mean frequency shift of Figure 4 (transition from unsaturated to saturated behaviors) for transmission # 1, at receiver# 1

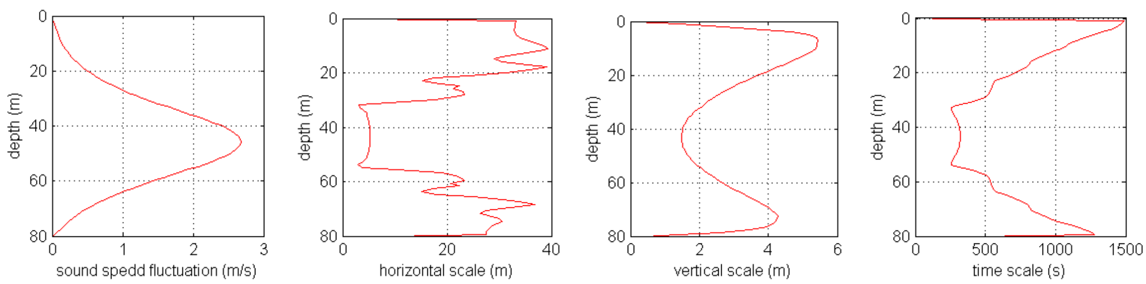

Fig.6: Characteristic of an internal wave field as predicted by TUS model ONDIN: from left to right, r.m.s. amplitude of sound speed fluctuations, horizontal Taylor scale, vertical Taylor scale, time scale

3. INTERPRETATION OF FREQUENCY SHIFTS AND FAST PHASE FLUCTUATIONS

The problem is now to find an explanation to the puzzling problem of the observed mean Dopplerization and of the fast fluctuations over times of 20s. The phenomenon cannot be attributed to movements of the instruments: source and array are anchored, and the only type of movement which we could detect by cross-correlating the short LFM pulses between the four columns of the array was a slow weak rotation of the array around its vertical central axis. One could otherwise suspect some instrumental artifact, like distortions of the signals by the transmitting source or the recording system: this fear was dissipated by the analysis of signals collected during the later *ALMA-2015* campaign in another place, and involving exactly the same instruments and signals: this time, no significant mean frequency shift was observed.

The explanation must be searched in movements of the experiment's environment itself, which features two dynamic phenomena:

- Internal Waves (IW) and turbulence: their presence is demonstrated by the undulations of the measured temperature profiles (Figure 3). They are otherwise predicable in an intrinsically unstable end-of-summer thermocline configuration. Using a *Thales Underwater System* model relying on Garrett-Munk spectrum, we may await internal waves resulting in fluctuations of sound speed up to more than ±2 m/s in mid waters (Figure 6), with spatial scales of a few meters and minimum time scales of about 4 minutes.

- Strong mean current: a fast current is visible on the picture of Figure 1, displayed as short white lines corresponding to transported grains. The presence of such a current, flowing from South to North (i.e. almost exactly from source to array), was otherwise observed during the *MELBA* oceanographical campaign, conducted by *IFREMER* during Spring 2011 (ref.[2]). By mere coincidence, a leg of *MELBA* campaign is very close to the *ALMA 2014* zone, where water velocities of about 0.1 m/s were observed.

A first good candidate for explaining the observed acoustic variability could be the scattering by "cells" of sound speed fluctuations associated with IW. Nevertheless, the predicted shortest time scale of the IW is of about 4 minutes, *i.e.* quite larger than the 20 s over which the phase of the observed signals undergo fast intense fluctuations of phase. The time variations of the IW alone can explain neither the phase fluctuations, nor the mean Doppler shift. An explanation can be found in a combination of IW with the current, which could produce both effects (Doppler and phase fluctuations).

A second explanation could be looked for in short fast fluctuations of turbulence, which may feature significant variability at short time scales. Acoustic scattering from temperature microstructure induced by turbulence seems a reasonable candidate for fast variations in a strongly stratified channel (see e.g. ref.[3]). The combined spectral broadening due to time variations of the medium, combined with the filtering due to spatial scattering, may result in a translation of the broadened signal spectrum, *i.e.* of the mean frequency. This is the Wolf effect (ref.[4]), which results in "fake" Doppler shifts.

The two mechanisms are not mutually exclusive, and may play simultaneously.

4. CONCLUSION

As a tool for investigating the complexity of acoustic propagation in shallow waters, for providing elements of validation of models, and for giving orders of magnitude of relevant oceanic phenomena, the *ALMA* system fulfilled its objectives as early as for its very first sea trial, in October 2014. The acoustical signature of many different marine mechanisms were observed, ranging from absorption peaks from resonant fishes to random scattering by sound speed heterogeneities resulting in losses of spatial and temporal coherence. The most puzzling phenomenon was the presence of rapid phase fluctuations, faster than the fluctuations associated with Internal Waves, combined with a mean frequency shift. Explanations to these two observations can be found in scattering from random IW or temperature microstructure induced by turbulence transported by a fast current, or maybe in Wolf effect due to turbulence; as far as we know, this could be (if validated) the first reported occurrence of Wolf effect in the field of underwater acoustics.

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