A Light Aircraft as a Source of Sound for Performing Geo-Acoustic Inversions of the Sea Bed

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Summary

The two main sources of sound from a light aircraft are the propeller and the engine, both of which produce a fundamental tone and an associated set of harmonics at multiples of the fundamental frequency. Typically, the frequency of the fundamental is in the region of 80 Hz and the harmonics extend perhaps as high as 1 kHz or above. When flying over water, some of the sound is known to penetrate the air-water interface, suggesting that a light aircraft has potential as a low-frequency, broadband source of sound in underwater acoustics experiments. It may even have a useful role in acoustic inversion procedures for obtaining the geo-acoustic and bathymetric properties of the bottom. To explore this idea, a series of experiments using a single-engine light aircraft with a twin-bladed propeller has been performed about 1.5 km off the coast of La Jolla, California. A microphone monitored the sound of the aircraft above the surface and a vertical array of hydrophones received the acoustic signals in the ocean. Some preliminary findings from these experiments are reported and the prospects for light-aircraft involvement in ocean-acoustic inversion techniques are discussed.

1. Introduction

Although sound from fixed- and rotary-wing aircraft is known to penetrate through the atmosphere-ocean interface[1-3], few, if any, of the previously reported underwater measurements of aircraft acoustic signatures relate to fixed-wing light aircraft with a single reciprocating engine driving a propeller. Such aircraft are the backbone of general aviation and are commonly used by flying clubs around the world. The sound from a light aircraft is mainly due to the propeller, with a lesser contribution from the engine, associated with the piston firing rate.

As discussed by Goldstein[4], a theoretical description of the far-field pressure from an aircraft propeller was developed by Gutin[5]; and subsequently the theory was extended to include near-field effects[6]. For the purpose of the present discussion, however, it is sufficient to recognize that the propeller produces a fundamental tone at a frequency given by the expression

$$f_{blade} = \frac{BR}{60} \text{ Hz}, \qquad (1)$$

where B is the number of blades, R is the rpm of the engine, and it is assumed that there is a direct drive from the crankshaft to the propeller, as is the case in the majority of light aircraft. In addition to the fundamental, harmonics appear in the acoustic signature of the propeller at multiples of the fundamental frequency.

According to Eq. (1), the fundamental frequency of the propeller noise from an aircraft with a two-bladed propeller (B = 2) operating at R = 2500 rpm is 83.3 Hz, with harmonics at 166.7 Hz, 250 Hz, and so on.

The harmonic structure may be observed up to 1 kHz or so, depending on propagation conditions in the atmosphere and flight factors such as aircraft altitude.

The low-frequency region of the acoustic spectrum spanned by aircraft propeller noise, say from 50 Hz to 1 kHz, is currently of interest in underwater acoustics in connection with measurements of the geo-acoustic properties of marine sediments[7]. Conventionally, an acoustic inversion for the sea-bed parameters would be performed using a receiving array of hydrophones and a submerged source. A low-frequency acoustic source with a decade or more of bandwidth would be ideal for this type of application; but such sources tend to be in short supply and, even if they were readily available, would be rather costly.

An alternative approach is based on the idea that perhaps a light aircraft could be exploited as a source of low-frequency, broadband sound for use in underwater acoustics applications. Some of the airborne acoustic energy produced by the aircraft will penetrate into the ocean and will arrive at the receiver array via various underwater propagation paths. Since several of these arrivals will have experienced bottom reflections, the potential exists for obtaining the geo-acoustic and bathymetric properties of the sea bed from appropriate inversion procedures.

2. Aircraft Experiments at SIO

A series of experiments is currently being conducted off La Jolla, California, north-west of Scripps pier (32˚ 53.8' N, 117˚ 16.1' W) in which the sound from a Tobago TB10 single-engine, fixed-wing aircraft with a two-bladed, variable pitch propeller is being monitored with a microphone about 1 m above the sea surface and a vertical array of hydrophones suspended below. This particular flying machine has a four-cylinder Lycoming engine that develops 180 hp. Timing and flight parameters (lateral position, altitude, ground speed, climb and descent rates, track) are continuously monitored and recorded using a GPS with a built-in pressure sensor (for accurate altimetry data), which is calibrated before each flight.

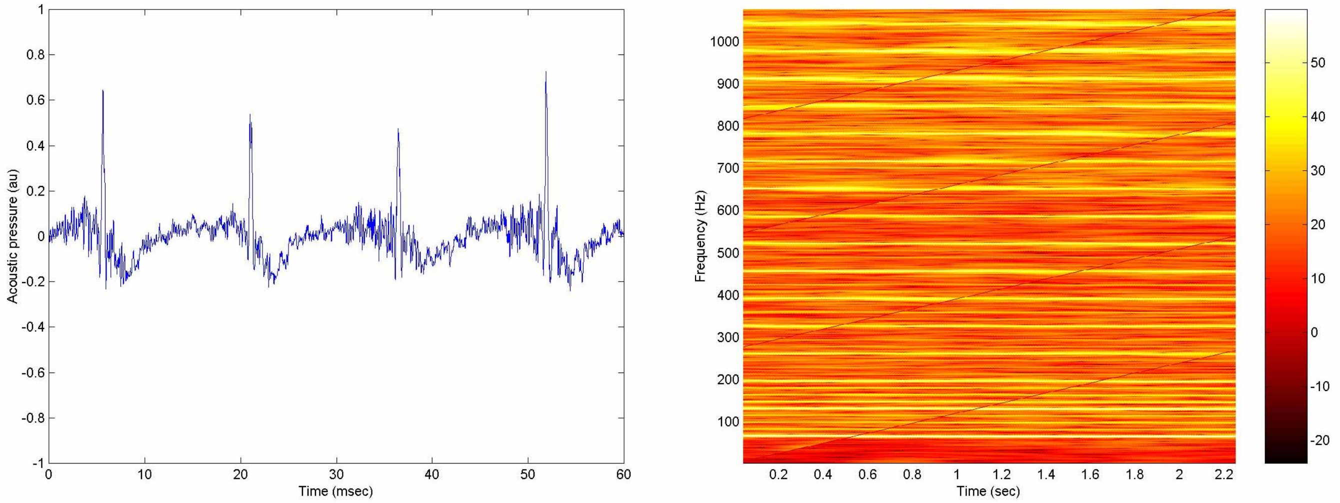
So far, direct overflights of the sensors have been made at a series of altitudes extending from 33 m up to 330 m in uniform increments of 33 m. At a similar set of altitudes, circles centered on the sensor position, as well as linear tracks offset from the sensors by 500 m, have also been flown. Only the flights passing directly over the receiving station are discussed here.

As a reference, the near-field sound from the Tobago on the ground and stationary was recorded with a microphone close to the port wing tip. The sensor was at a distance of approximately 4 m from the spinner, 1 m above the ground and angled about 20˚ behind the plane of the propeller. Fig. 1a shows a sample of the acoustic time series and the corresponding spectrogram, with the engine operating at 2000 rpm. The spectral resolution in the spectrogram is 1.3 Hz. Note the periodically spaced spikes in the time series, which are due to the regular detonations at the piston firing rate.

In the spectrogram of Fig. 1b, the harmonic structure from the propeller is evident in the form of parallel, horizontal lines at multiples of 66.7 Hz. Between each pair of adjacent harmonics, three lower-intensity, equi-spaced lines are visible, the origin of which is not certain but they may be partly due to incomplete cancellation of the odd harmonics from each propeller blade: failure to achieve total destructive interference of these odd harmonics could occur if the two blades were less than perfectly matched. Another contributing factor may be natural resonances of the aircraft structure. Be that as it may, the three lines between adjacent blade-rate harmonics will be referred to as the sub-harmonic structure.

Examples of the airborne and waterborne arrivals from an overflight of the Tobago, as recorded on 22 May 2002, are shown in the spectrograms of Fig. 2. On this occasion, the aircraft was flying over the ocean at a speed of 53 m/s, an altitude of 66 m, and with the engine operating at 2500 rpm. With this set up, the fundamental blade-rate is 83.3 Hz, with associated harmonics at multiples of this frequency. The spectral resolution in both spectrograms is 2.4 Hz.

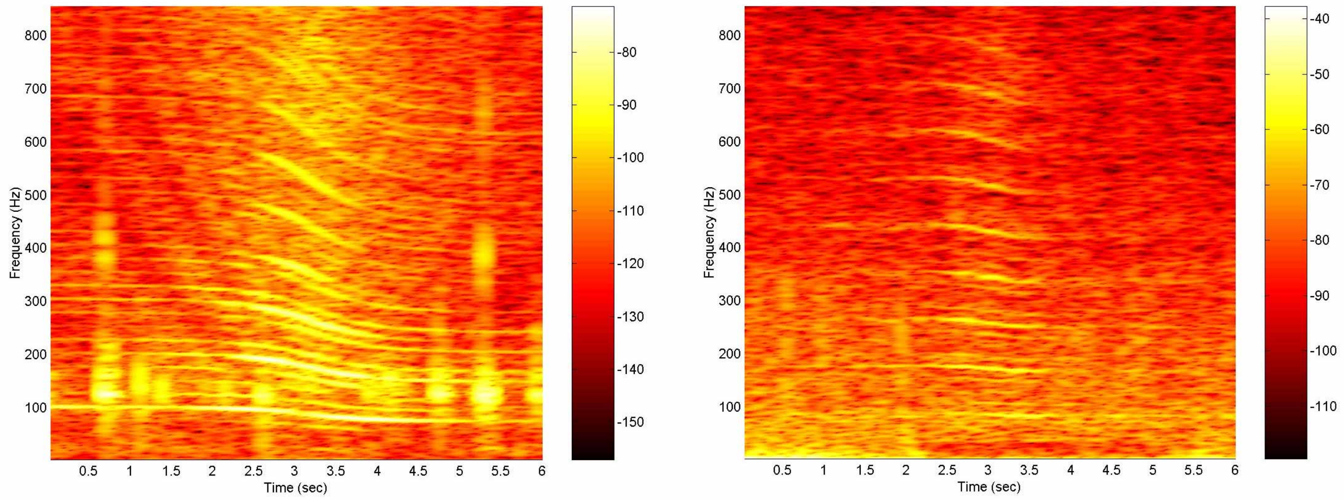
Perhaps the first point to notice in Fig. 2 is that the blade-rate fundamental and its harmonics are clearly discernable underwater



(a)

(b)

Figure 1. Acoustic signature of the Tobago, stationary on the ground with the engine operating at 2000 rpm. (a) Time series and (b) spectrogram. Colour bar is uncalibrated dB scale.



(a)

(b)

Figure 2. Spectrograms from an overflight of the Tobago traveling at a speed of 53 m/s, an altitude of 66 m and with the engine operating at 2500 rpm. (a) Airborne spectrum from microphone approximately 1 m above the sea surface. (b) Underwater spectrum from hydrophone approximately 13 m beneath the sea surface. Colour bars are uncalibrated dB scale.

as well as in the atmosphere. In both cases, the harmonic structure is visible as a series of uniformly spaced lines extending up to about 1 kHz. The sub-harmonic structure present in ground-based acoustic recordings (Fig. 1b) is also visible in the microphone and hydrophone acoustic signatures in Fig. 2.

Above and below the sea surface, a significant Doppler shift is evident in the spectrograms of Fig. 2. On the microphone and hydrophone, a downshift in frequency occurs as the aircraft overflies the receiving station. Notice, however, that for a given harmonic the frequency difference between approach and departure is less underwater than it is in air. This simple observation is interesting because it relates to the physics of acoustic transmission through the air-sea interface.

According to Snell's law, the critical angle for air-to-water sound transmission, assuming a smooth interface, is $\theta_c \approx 13^\circ$. At greater angles of incidence (*i.e.*, shallower grazing angles), total reflection from the surface is expected to occur, in which case no sound will penetrate into the ocean. Referring to the geometry in Fig. 3, it can be seen that a ray arriving at the hydrophone is launched from the aircraft at a steeper angle (*i.e.*, smaller angle of incidence) than a ray arriving at the microphone.

If θ is the angle of incidence of a ray launched from the aircraft, the Doppler shifted frequency is[8]

$$f_D = \frac{f}{1 - \frac{v}{c_a}\sin\theta}\ \text{Hz}, \tag{2}$$

where f is the unshifted frequency, v is the speed of the aircraft and c_a is the speed of sound in air. For the airborne arrivals, θ falls in the range $|\theta| \leq \pi/2$; but for the underwater arrivals, $|\theta| \leq \theta_c$. Thus, from Eq. (2), bearing in mind that $v/c_a \ll 1$, the maximum Doppler shift between approach and departure on the underwater arrivals is

$$\Delta f_{Dw} \approx \Delta f_{Da} \sin\theta_c\ , \tag{3}$$

where $\Delta f_{Da} = 2vf/c_a$ is the maximum Doppler difference between airborne arrivals. According to Eq. (3), with a critical angle for the air-sea interface of 13°, the underwater arrivals should be Doppler shifted by a factor of 0.22 less than those in air. This is consistent with the spectrograms shown in Fig. 2, which may be interpreted as indirect evidence in support of acoustic penetration of the air-sea interface over only a limited range of incident angles, as predicted by Snell's law. The angular width of this penetration regime could exceed the critical angle, θ_c, if surface roughness were significant, as discussed by Lubard and Hurdle [9].

3. Fine Structure in the Underwater Ray Arrivals

In shallow water, each of the harmonics detected by the hydrophone is actually a superposition of multipath arrivals, as illustrated in Fig. 4, which shows just the direct and single bottom-bounce paths. In this particular example, two rays have been selected which have the same Doppler shift (*i.e.*, angle of incidence at the sea surface). From the geometry shown in Fig. 4, it is clear that the bottom-bounce signal is launched well before the direct path, and that these two rays will arrive at the receiver at different times.

Moreover, as the aircraft closes on the receiver station, the bottom-bounce ray will become steeper. Assuming a fast bottom with sound speed greater than that in the water column, the seawater-sediment interface shows a critical angle, which is typically in the region of 30°. When the angle of incidence of the bottom-bounce ray falls below this critical angle, total reflection no longer occurs and the ray will penetrate into the sediment. Based on this argument, it is apparent that as the aircraft approaches the receiver station, the various bottom bounce arrivals are expected to drop out of the hydrophone record, only to re-appear in a symmetrical fashion as the aircraft departs.

Fig. 5 shows an expanded frequency-time plot depicting several ray arrivals associated with the fundamental of the propeller. These curves were computed using the following parameters: aircraft altitude, 66 m; aircraft speed, 53 m/s;

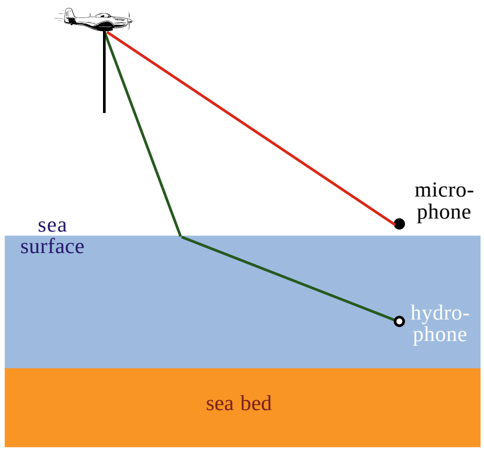


Figure 3. Geometry of direct ray paths to the microphone and hydrophone. The steeper (green) ray from the aircraft shows a smaller Doppler shift.

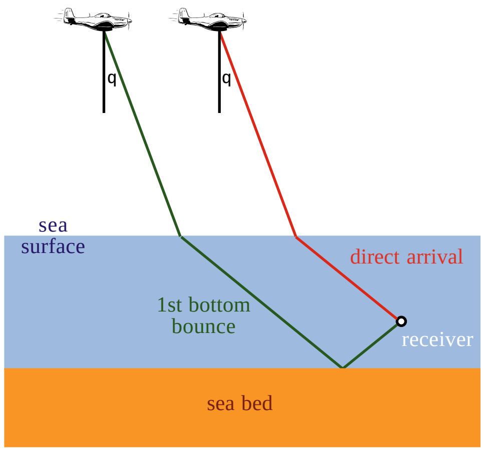


Figure 4. Direct and first bottom-bounce arrival at the hydrophone as the aircraft approaches the receiver station.

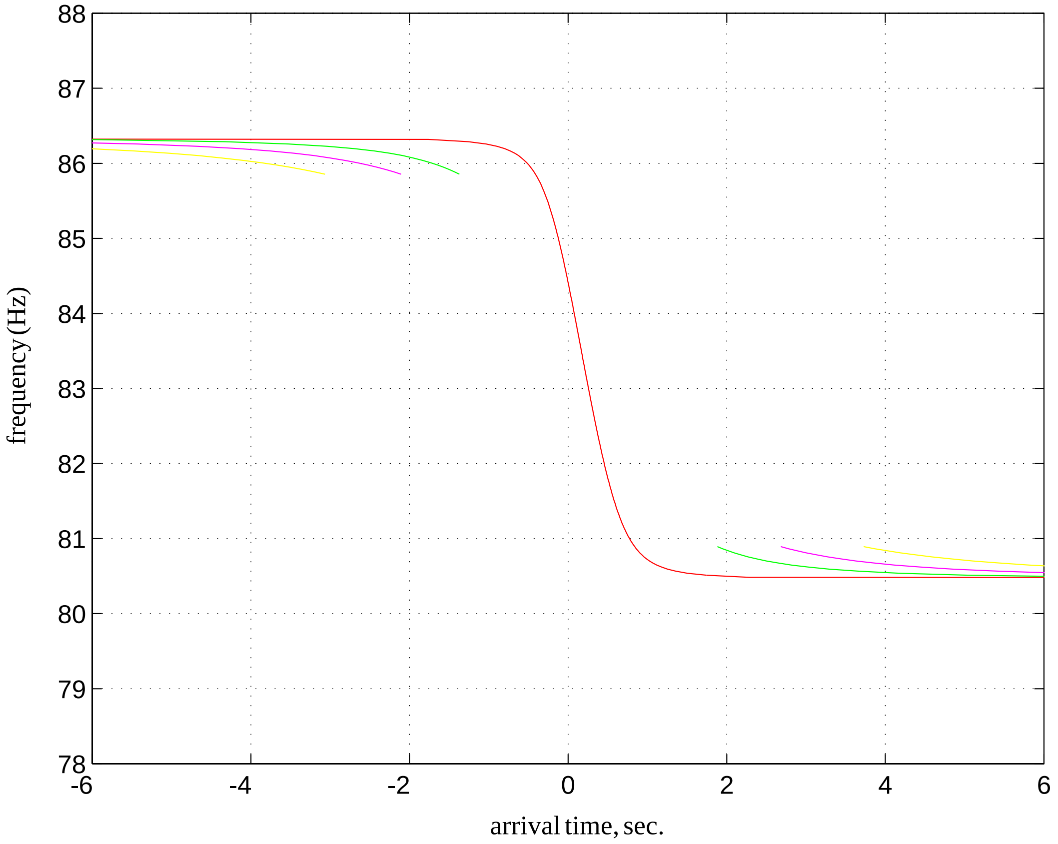


Figure 5. Ray arrivals in the fundamental as a function of time. (See text for details).

hydrophone depth, 13 m; channel depth, 30 m; sound speed in air, 340 m/s, in seawater, 1500 m/s, and in sediment, 1780 m/s; unshifted frequency, 83.3 Hz. The red curve is the direct path from the aircraft to the hydrophone, as in Fig. 4; green is the first bottom-bounce; magenta is one bottom and one surface reflection; and yellow is two bottom and one surface reflection. The gaps in the latter three curves span the times when the associated rays are too steep to reach the hydrophone and instead penetrate into the bottom.

The separation in time of the various array paths illustrated in Fig. 5 could be used to advantage to determine the geo-acoustic and bathymetric properties of the sea bed. This could be achieved in several ways. For instance, with just a pair of vertically aligned hydrophones, the downward-traveling direct and surface-reflected rays could be nulled out, leaving the first bottom-bounce ray as the principal component of each harmonic. The times at which this ray disappears and then re-appears in the acoustic record provide a measure of the critical angle of the bottom. Once the critical angle has been determined, the sound speed of the sediment can be deduced from Snell's law, assuming that the sound speed in the water column is known.

Obviously, more sophisticated inversion procedures, such as matched field processing, could also have application for extracting bottom properties from the acoustic record. If a vertical array of hydrophones were used, and the redundancy of the information contained in the multiple harmonics of the propeller noise were exploited, it may be possible to obtain a very detailed description of the channel parameters. Such an approach could be enhanced by exploiting the correlations that are known to exist between certain sediment parameters, for example, the sound speed and the porosity[10-12].

4. Concluding Remarks

The preliminary experiments conducted recently at SIO using a light aircraft as a source of sound in underwater acoustic applications show considerable promise. Good quality acoustic data have already been collected above and below the sea surface. The latter data sets indicate that it may be possible to perform inversions of the aircraft sound to obtain the geoacoustic and bathymetric properties of the ocean channel.

Acknowledgements

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