Acoustic remote sensing of the sea bed using propeller noise from a light aircraft

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Summary

The main source of sound from a light aircraft is the propeller, which produces a fundamental tone, typically around 80 Hz, with a dozen or so harmonics at multiples of the fundamental. When the aircraft flies over the ocean, some of the propeller sound penetrates the air-sea interface, passes through the water column and enters the seabed. Thus, the aircraft acts as high-speed (50 to 75 m/s), low-frequency (≈ 80 to 800 Hz) sound source, which has potential application in ocean-acoustics experiments. In this chapter, the basic physics of aircraft sound in the ocean is discussed, including the Doppler effect, associated with the high-speed of the source, which introduces a significant shift in the frequencies of the propeller harmonics as the aircraft flies over the receiver station. An inversion technique, currently under development, for obtaining the speed of sound in the sediment from the Doppler-shifted propeller harmonics is described and suggestions for future applications of aircraft sound in ocean-acoustics experiments are offered.

1. Introduction

It may seem that an aircraft would not have much of a rôle to play in underwater acoustics, where most experiments and applications involve submerged sources and receivers. Usually, this underwater instrumentation is deployed from a surface ship or, in near-coastal waters, fixed installations such as towers and piers. In certain circumstances, however, a conventional deployment platform is not practicable, for instance, in remote ice-covered seas, which are often hazardous if not impenetrable to a surface ship. Aircraft offer a solution to this problem and indeed have been used successfully in polar regions to drop acoustic sources and receivers (sonobuoys) into leads of open water between ice floes[1,2]. After deployment, the data from the sonobuoy sensors are relayed back to the aircraft over a radio link, where they are recorded and analysed.

Apart from serving as an airborne instrument-launch platform above hostile seas, an aircraft has potential application as a source of sound in ocean acoustics experiments. Fixed-wing aircraft come in a variety of types, ranging from propeller-driven light aeroplanes powered by a single piston-engine to multi-engine turbo-props and jets, all of which generate sound as they fly. As anyone living near an airport will attest, the sound of an aircraft in flight is clearly audible on the ground.

It is less well-known that a fixed-wing aircraft can also be heard beneath the sea surface. This was confirmed by Urick[3], who used hydrophones (underwater microphones) at various depths in the sea to record the passage of a US Navy P-3C Orion, a four-engine turbo-prop aircraft, flying at 200 knots (≈ 100 m/s) at altitudes between 80 and 330 m. On either side of the sensor station, the sound of the P-3 was detected underwater for just a few seconds, which translates into a horizontal detection range of about 500 m.

Similar observations by Richardson *et al.*[4] have been reported for several types of twin-engine, propeller-driven aircraft. Certain jet aircraft, notably military types and some older commercial jets, are extremely noisy in the atmosphere, although little has been reported on their underwater sound levels. However, during airborne deployments of sonobuoys in the Greenland Sea from a British BAC 1-11 research aircraft[2], the high-pitched whine from the twin jet engines was regularly detected on the underwater sensors as the aircraft circled over the drop site. Helicopters tend to be particularly noisy in the atmosphere, often producing a low-frequency beating sound from the rotors, and, like fixed-wing aircraft, are known to be audible underwater[4,5]. (For a commentary on the transmission of sound through a rough air-sea interface, including data on sub-surface sound levels from a Sikorsky SH-3D helicopter, see the discussion by Professor Medwin in §9.6.1 of this book).

Aircraft-generated sound in the sea is the topic of this chapter. The principal aim of acoustical oceanography is to take received sound signals, which contain information about the source and the environment, and extract that information by performing an appropriate inversion. In this context, we focus on the underwater sound from a fixed-wing, propeller-driven light aircraft powered by a single piston-engine. As we shall discuss, the sound from the aircraft is detectable not only in the atmosphere and the water column but also on a hydrophone buried about 1 m deep in a (fine-sand) sea bed.

At present, the ocean-acoustics research community is interested in characterizing the geoacoustic properties of marine sediments, which typically consist of varying proportions of clay, silt and sand, often with an admixture of shell fragments. The US Office of Naval Research (ONR) is the sponsor of two Sediment Acoustics Experiments[6,7] in the northern Gulf of Mexico, one of which was conducted in 1999 (SAX99) whilst the second is planned for 2004 (SAX04). An important aim of SAX is to relate the wave properties (e.g., sound speed and attenuation) to the mechanical properties (e.g., porosity, density and grain size) of a sediment. In a granular material such as a marine sand, the speed and attenuation of sound both depend on the frequency of the acoustic waves. The sediment sound-wave measurements in SAX are intended to cover as wide a frequency range as practicable; but few techniques are capable of returning reliable information at low frequencies, below 1 kHz. Yet this low-frequency part of the spectrum is critically important to our understanding of the physical mechanisms governing wave propagation in saturated granular materials such as marine sediments.

Fortuitously, the sound from a light aircraft is concentrated at low frequencies, between 50 Hz and 1 kHz. As we shall see, aircraft sound is detectable not only in the water column but also on acoustic sensors buried in the sea bed, making it appealing as a measurement tool for obtaining the low-frequency wave properties of a sediment. Using a simple procedure, the acoustic data from a buried sensor may be inverted to obtain the speed of sound in the sediment, which is arguably the wave property of the sea bed that is of greatest interest.

2. Propeller sound

As a means of aircraft propulsion, the propeller has a long history, dating back to the beginnings of powered flight early in the twentieth century. Propellers consist of a number of blades, usually two or three in the case of light aircraft. A propeller blade is a rotating aerofoil that creates a positive pressure difference between the rear and forward surfaces, which results in thrust.

In addition to thrust, a propeller blade also generates sound[8], the sources of which are categorized as either steady or unsteady. Steady sources would be perceived as constant by an observer rotating with the blade and are the most important in the context of this discussion. An example of a steady source is so-called thickness noise, arising from the displacement (forwards and backwards relative to the plane of the propeller) of air by the finite volume of the rotating blade. To a stationary observer, steady sources are periodic with a fundamental frequency that is given by the rotation rate, R, of the blade. For a propeller with N blades, the fundamental frequency is the rotation rate times the number of blades, NR. Usually in light aircraft, there is a direct drive from the engine to the propeller, in which case the rotation rate, R, is the same as the rotation rate of the engine, which is traditionally expressed in revolutions per minute (rpm). In cycles per second, the frequency, f_1, of the fundamental tone emitted by the propeller is therefore

$$f_1 = \frac{NR}{60} \quad \text{Hz} \ . \tag{1}$$

Although the steady sources are periodic, they are not pure sine waves, which means that, in addition to the fundamental, higher-frequency tones are also emitted. Any periodic signal can be represented as a Fourier sum of sinusoidal terms, each representing a tone, more usually called a harmonic. The frequencies of the harmonics are multiples of the fundamental frequency, a relationship which is expressed by writing the frequency of the n^{th} harmonic as

$$f_n = nf_1 = \frac{nNR}{60} \quad \text{Hz} . \tag{2}$$

Thus, the first harmonic and the fundamental are one and the same.

The harmonic structure of the sound from a two-blade propeller is illustrated in the panel on the right of Fig. 1, which shows a time-frequency plot, or spectrogram, of the signal from a microphone near the port wing tip of a stationary light aircraft with the engine running at 2000 rpm. According to Eq. (2), the harmonics should occur at multiples of approximately 67 Hz, which does indeed match the sequence of prominent tones (bright horizontal lines) in the spectrogram. Between the principal harmonics, and especially noticeable at lower frequencies, below 200 Hz, are additional tones (sub-harmonics) from the engine, which are a result of uneven firing of the cylinders. This lack of uniformity is visible in the pressure time-series data in the panel on the left of Fig. 1, where the four detonation impulses (one from each cylinder) exhibit slightly differing amplitudes. As the sub-harmonics are unimportant in the present context, they are excluded from the following discussion.

When the aircraft is stationary on the ground with the engine running, propeller harmonics are clearly detected with a local microphone up to a frequency well above 1 kHz. This was the situation when the data in Fig. 1 were recorded. With the aircraft in flight, the propagation path to the receiver is much greater, one effect of which is that the higher-frequency harmonics suffer heavy attenuation. Typically, when the aircraft is airborne, the detectable harmonics on a ground-based microphone extend no higher than about 800 Hz. Still, from a practical point of view, with sediment-acoustics applications in mind, this means that the aircraft propeller is a source of sound with highly desirable characteristics: it has a comb of 10 or so discrete tones in the low-frequency band between say 50 and 800 Hz, which is a spectral region of particular interest for sediment acoustics experiments.

3. Doppler frequency shifts

Most sound sources used in underwater-acoustics experiments are essentially stationary, at least compared with a light aircraft, which moves very rapidly, typically in the region from 100 to 150 knots (50 to 75 m/s). As a result of this motion, the harmonics from the propeller will be subject to the Doppler effect[9], a common-place example of which is the change in pitch of an ambulance siren as the vehicle speeds past a stationary observer. (For a general account of sources and receivers in motion, including the Doppler effect, see the discussion by Professor Medwin in §2.6.1 of this book).

Ahead of an aeroplane in flight, the forward motion "compresses" the acoustic wavefronts from the propeller, which raises the frequency of each harmonic, whereas to the rear the wavefronts are "dilated" and the frequencies of the harmonics are reduced. These effects are illustrated in Fig. 2, which shows successive wave crests radiating from the moving source. The wave crests are separated in time by the wave period, Δt, and each is centred on the position of the source at the earlier instant when the wavefront was transmitted. Note that the wave crests are depicted as circular because, in all directions, they propagate away from the point of origin with the same speed, namely the speed of sound, which is governed by the density and compressibility of the medium.

To an observer on the ground, the frequency shifts associated with the compression and dilation of the wave crests will be heard as a down-sweep in pitch as the aircraft flies through the zenith. The *change* in frequency from approach to departure depends on the speed of sound in the transmission medium (air for an observer on the ground) and, as described below, it is this *difference frequency* which will be exploited in measurements of the speed of sound in marine sediments.

The Doppler-shifted frequency of a given harmonic may be derived either by considering the phase of the sound field radiated by the propeller or by making a so-called Galilean transformation from the moving frame of reference of the aircraft to the stationary frame of the observer[9]. Whichever approach is taken, the following expression is found for the Doppler-shifted frequency of the n^{th} harmonic:

$$f_{nD}(\theta) = \frac{f_n}{1 - \dfrac{V}{c_a}\cos\theta} \quad , \tag{3}$$

where V is the horizontal speed of the aircraft, c_a is the speed of sound in air and θ is the angle of elevation, that is the angle between the horizontal and the line of sight to the aircraft. Notice that the Doppler shift depends on the component of velocity, $V\cos\theta$, along the line of sight but is independent of the normal component of velocity, $V\sin\theta$. With the aircraft approaching the observer, the angle of elevation lies in the interval $0 < \theta < \pi/2$, in which case $\cos\theta$ is positive and, from Eq. (3), the frequency is upshifted; on departure, $\pi/2 < \theta < \pi$, $\cos\theta$ is negative and the frequency is downshifted. There is no Doppler shift on the harmonics when the component of velocity along the line of sight is zero, which occurs only when the aircraft is directly overhead (i.e., $\theta = \pi/2$ and $\cos\theta = 0$).

When the aircraft is a long way out, the line of sight is essentially horizontal with an angle of elevation on approach of $\theta \approx 0$ ($\cos\theta \approx 1$) or on departure $\theta \approx \pi$ ($\cos\theta \approx -1$). For these two extreme situations, the Doppler difference frequency is maximal and from Eq. (3) is given by

$$\Delta f_{nD} = f_{nD}(0) - f_{nD}(\pi) \approx \frac{2Vf_n}{c_a} \quad , \tag{4}$$

where we have taken the speed of the aircraft, V, to be much smaller than c_a, the speed of sound in air. According to Eq. (4), the difference frequency scales linearly with the speed of the aircraft, the unshifted frequency of the harmonic, and the reciprocal of the speed of sound in the medium. Conversely, we could re-write Eq. (4) as an expression for the sound speed, c_a:

$$c_a \approx \frac{2Vf_n}{\Delta f_{nD}} \quad . \tag{5}$$

On the right, V, f_n and Δf_{nD} may be assumed known, since all three are fairly easily measured, and hence Eq. (5) provides a simple basis for recovering the speed of sound, c_a, in the medium.

4. Refraction

Of course, in our ocean-acoustics application of propeller sound, the medium in which we are interested is not the atmosphere but the sediment beneath the water column. A sound ray from the aircraft must penetrate the sea surface and the sea floor to reach a sensor buried in the sediment. At both these interfaces the ray will be refracted, or bent, as shown in Fig. 3, because of the difference in sound speed on either side of the boundaries. A familiar example of (optical) refraction is the apparent bending of a stick when one end is placed in water. What effect does refraction have on the Doppler difference frequency of a propeller harmonic in the water column or the sediment?

This question may be answered by returning to Eq. (3), the basic expression for the Doppler shifted frequency. The first point to note is that the angle of elevation governs the Doppler frequency of a ray, the steeper the ray (i.e., the greater the value of θ), the lower the frequency. Secondly, as a ray with elevation angle θ crosses from air into water, its frequency remains unchanged, from which it follows that the term $[\cos\theta]/c_a$ appearing in the denominator of Eq. (3) must be the same on either side of the boundary. A similar argument applies to the interface between the water column and the sediment, allowing us to write

$$\frac{\cos\theta}{c_a} = \frac{\cos\theta_w}{c_w} = \frac{\cos\theta_s}{c_s} \quad , \tag{6}$$

which is well-known as Snell's law for refraction at boundaries between media of differing sound speed.

Now we see that the Doppler difference frequency of the n^{th} harmonic, as observed in air, water or sediment, may be generally expressed as

$$\Delta f_{nDi} \approx \frac{2Vf_n}{c_i} \quad , \tag{7}$$

where the subscript i denotes a, w, or s, according to whether the sensor is in the atmosphere, the water column or buried in the sea bed. Since $c_w > c_a$ and, for sand sediments, $c_s > c_w$, the Doppler difference frequency will be greatest when observed on a sensor in the air and least on a sensor buried in the sediment. Conversely, the sound speed inverted from the difference frequency,

$$c_i \approx \frac{2Vf_n}{\Delta f_{nDi}} \quad , \tag{8}$$

will be least in the air and greatest in the sediment.

5. Aeroplane experiments

Eq. (8) is our essential tool for measuring the speed of sound in the atmosphere, seawater and sediment using sound from the propeller of a light aircraft. Of course, for the Doppler difference-frequency technique to be successful, it is necessary for the aircraft to be detectable by acoustic sensors in the water column and, more importantly, buried in the sediment. Before mid-2002, we did not know whether a single-engine light aircraft would be detectable on a hydrophone in the water column, let alone by a sensor in the sea bed. Although underwater detection of sound from certain types of multi-engine, fixed-wing aircraft had previously been reported, all were relatively large and noisy: a Lockheed P-3C Orion[3] (four-engine turbo-prop), a de Havilland Twin Otter[4] (twin turbo-prop), a Grumman Turbo Goose[4] (twin turbo-prop) and a Britten Norman Islander[4] (twin piston-engine).

As essentially nothing was known about the coupling of the sound of a single-engine, light-aircraft from air-to-water-to-sediment, a series of exploratory flying experiments[10,11] was conducted in the summer of 2002 over the Pacific Ocean, off the coast of southern California about 2 km north of La Jolla. At this near-shore location, the water is about 15 m deep. A four-seat light aircraft, a Tobago TB10 with two-blade propeller and four-cylinder, 180 h.p. Lycoming engine, was flown parallel to the coast at altitudes between 33 and 330 m at a nominally constant air speed of 106 knots (53 m/s). The propeller speed was adjustable and held fixed at 2500 rpm. Accordingly, from Eq. (2), the frequency of the fundamental tone from the propeller was 83.3 Hz, with harmonics at 166.7 Hz, 250 Hz, 333.3 Hz .... .

A sensor station (Fig. 4), with a microphone 1 m above the sea surface, a vertical string of hydrophones in the water column, and an additional hydrophone buried 75 cm deep in the fine-sand sediment, was located 1 km or so off shore. Using a seawater jet, divers buried the sediment phone about one week before the experiments began, allowing time for the sand to settle, providing good coupling to the sensor.

During a single flight, the aircraft flew many tracks back and forth over the sensor station on approximate north-south headings. Flight parameters, including ground speed, lateral position and altitude, were recorded using a GPS satellite navigation system. The duration of a typical flight was 1.8 hours from take-off to touch-down.

Supporting environmental data were collected during the experiments, to help later in interpreting the acoustic measurements. Most importantly, a SeaBird temperature profiler was regularly deployed in the water column, returning the temperature of the seawater as a function of depth. From the temperature profile, the speed of sound as a function of depth was computed from an empirical formula due to Mackenzie[12] [see Eq. (2.3.2) in this book] expressing sound speed in seawater as a function of three variables, temperature, pressure (which scales with depth) and salinity. Since the salinity was not measured as part of our experimental procedure, it was assumed to be constant at 35‰, which is reasonable for the experiment site, where no freshwater inflow is present. (Elsewhere, for instance, near an estuary or in polar regions close to melting ice floes, the salinity may differ significantly from 35‰, which should not be ignored when computing sound speed).

6. Detection of aircraft sound

As the Tobago flew over the sensor station, the sound from the propeller was detected not only in the air but also below the sea surface in the water column and in the sediment. Fig. 5 shows calibrated spectrograms from sensors in the three media from an overflight at an altitude of 66 m on 2 July 2002. Also included in the figure is the sound speed profile in the channel (averaged over several deployments of the SeaBird profiler), superimposed upon which are the positions of the hydrophones in the water column on that particular day.

The propeller harmonics appear in all three spectrograms as bright yellow lines, which are visible for approximately six seconds on either side of the closest point of approach (CPA) to the sensor station. The intensity of the harmonics may be read from the colour bars alongside the spectrograms, which are scaled in dB relative to a standard reference level in underwater acoustics, 1 $\mu Pa^2/Hz$. Notice that the harmonics in the water column and the sediment are an order of magnitude (≈ 10 dB) less intense than those in the atmosphere.

A prominent feature of all the harmonics is a sweep to lower frequency in a brief time interval centred on $t = 0$ as the aeroplane flies over the sensors. The Doppler difference-frequency between approach and departure is easily seen to be greatest on the microphone data, as expected since the speed of sound in air (≈ 340 m/s) is less than that in seawater (≈ 1500 m/s) and fine-sand sediment (≈ 1650 m/s) by a factor of at least 4.4.

Harmonics are visible up to frequencies close to 800 Hz in the microphone data but only to 600 Hz or thereabouts in the water column and the sediment. If anything, the harmonics are a little more stable in the sediment than in the water column because the latter is a somewhat dynamic environment, due to local currents and turbulence.

The least stable harmonics are those from the microphone in air, showing *intensities* which vary noticeably with time and frequency (*i.e.*, harmonic number). This variability in intensity is largely due to the fact that the microphone is about 1 m above the sea surface, which amounts to a significant fraction of a wavelength at frequencies within the band of the propeller harmonics. As discussed by Professor Medwin in § 1.5.5 in this book, this situation gives rise to the Lloyd's mirror effect in which the direct ray from the source to the receiver interferes with the ray reflected from the sea surface. Since the source-receiver geometry of the aircraft experiment is constantly changing, due to the source motion, the interference may be constructive or destructive, with each harmonic exhibiting its own, unique intensity pattern. This accounts for the observed intensity fluctuations in time and harmonic number.

Although the intensities of the airborne harmonics fluctuate, it is important to note that the Doppler-shifted *frequency* of a given harmonic is not significantly affected by the presence of two arrivals, the direct and reflected rays. The frequency is governed by the elevation angle of a ray arrival. For the geometry of the aircraft experiments (*i.e.*, the altitude of the source much greater than that of the receiver), the elevation angles of the direct and reflected arrivals at the microphone are much the same and so too are their frequencies.

Beneath the waves, the frequencies of the harmonics in the water column and in the sediment are stable, which may seem surprising at first sight, given that the sea surface is a rough, moving boundary. When the data in Fig. 5 were recorded, a light breeze was blowing with a wind speed of approximately 5 knots (2.5 m/s), which created a Sea State

1 (small wavelets). In addition, a light swell was running. Although not very rough, the sea surface was far from being a smooth, horizontal plane.

However, sea-surface roughness has little effect on the harmonic structure in either the water-column or the sediment for several reasons, including the fact that surface slopes are small, just a few degrees, and, compared with the speed of the aircraft, surface movement is very slow, introducing negligible Doppler shifts. At the worst, these surface-induced frequency shifts will lead to a very slight broadening of the harmonic lines but should leave the peak frequencies unaffected. The broadening, if present at all, occurs because the aircraft will have flown several tens of metres during the time interval used in computing the component spectra in spectrograms such as those of Fig. 5. Throughout this analysis interval, the acoustic arrival at a sensor in the water column or the sediment may, with equal probability, be randomly up-shifted and down-shifted in frequency by the surface motion. The broadening is so small, however, that the aircraft motion may be considered simply to average out the effects of surface roughness.

7. Sound speed estimates

Perhaps the simplest approach to estimating the local speed of sound from the spectrograms in Fig. 5 would be to take a ruler and read off the frequencies of a given harmonic when the aircraft was far out on the approach, directly over the sensor, and far out on departure. Given that the speed of the aircraft, V, is known from the GPS data, Eq. (8) could then be used to evaluate the speed of sound in air, seawater and sediment.

In fact, a somewhat different procedure was used in which an equation for the spectral shape of the harmonics was fitted to the spectrogram data. This equation contained the required sediment parameters as well as flight parameters such as aircraft speed and altitude, all of which were varied until the best match to the data was obtained. The comparison between the equation and the data was performed by a desk-top computer with a program written in MATLAB.

From the microphone data from twenty or so overflights of the Tobago on 2 July 2002, the average ground speed of the aircraft was estimated to be 54.5 m/s, compared with 54.8 m/s from the GPS. The speed of sound in air, as derived from the acoustic Doppler technique, is 342.3 m/s, which compares favourably with an independent estimate, based on the temperature conditions of the day, of 343.5 m/s. Such close agreement is encouraging, indicating that inversions of the Doppler data yield an accurate estimate of the speed of sound in the atmosphere.

For the same sequence of overflights, Doppler difference-frequency inversions were performed on the data from two of the sub-surface hydrophones, one at a depth of 10 m in the water column and the other buried 75 cm deep in the sediment. The difference-frequency technique returned a mean sound speed of 1529.5 m/s in the water column, which is about 1% higher than the value of 1512.4 m/s obtained from the SeaBird temperature profiler. In the sediment, the Doppler estimate of the speed of sound was 1649 m/s, which cannot be assessed directly against any independent measurement in the sea bed at the experiment site because none exists at the low frequencies produced by the aircraft's propeller. However, at higher frequencies (3.5, 7 and 14 kHz), Hamilton[13] used *in-situ* probes to measure the speed of sound in fine-sand sediments off San Diego, finding values clustering around 1685 m/s.

The slightly higher sediment sound speed measured by Hamilton, as compared with that returned by the Doppler technique, may be largely due to small differences in the geophysical parameters of nominally similar sediments. In particular, the porosity (defined as the volume of pore space between grains per unit total volume) may lie anywhere from 0.4 to 0.45 for fine-sand sediments, corresponding to a spread of sound speeds between 1640 m/s and 1720 m/s, respectively. It is also possible that sediments show weak dispersion, that is, a sound speed that varies slightly with frequency. A recent theory[14] of wave propagation in saturated granular media such as marine sediments predicts dispersion of about 2% per decade of frequency, which is consistent with the difference between the low-frequency measurements of sound speed obtained using propeller harmonics and Hamilton's higher-frequency results.

8. Future developments

Ocean-acoustic inversion techniques based on propeller sound from light aircraft, including those techniques aimed at returning the wave properties of marine sediments, are still in their infancy. Our flights during the summer of 2002 demonstrated that the acoustic signal from the propeller of a Tobago is detectable in the air, the water column and the sediment and that the observed Doppler shift depends on the speed of sound in the medium in which the sensor is located.

Using an elementary argument based on the refraction of acoustic rays, an inversion scheme for obtaining the speed of sound in all three media has been introduced in this chapter. At the low frequencies of the propeller harmonics, however, the water column acts as a waveguide in which the acoustic field is not adequately described in terms of just a single refracted ray. A full solution of the wave equation is required, which will depend on the boundary conditions at the surface and bottom. This wave-theoretic solution contains several new types of wave (Fig. 6), including propagating normal modes, which may be thought of as acoustic resonances between the surface and bottom, evanescent modes, which leak energy from the water column into the bottom, and the lateral wave, sometimes called the head wave, which propagates along the bottom, continually re-radiating energy back into the water column.

Future inversions of aircraft sound to obtain wave speeds will be based on a full wave-theoretic solution for the acoustic field in the atmosphere, the seawater and the sediment. The computation of the full wave field involves all the unknown parameters of the problem, including the wave speed in the sediment, which appears through the boundary conditions that apply at the seawater-sediment interface. To invert for these parameters, a technique adapted from Matched Field Processing[15] (MFP) appears to hold some promise, although has yet to be investigated. As the aircraft approaches towards, overflies and departs from the sensor station, it creates a “synthetic aperture”. At a succession of positions within this aperture, a comparison between the data and the computed field is made for all reasonable combinations of parameter values until an optimal fit is obtained. The set of parameters giving the overall “best fit”, including the speed of sound in the sediment, is taken to be representative of the environment. Although dispersion in the sediment is expected to be weak over the frequency band of the propeller harmonics, it may be detectable with the aid of this optimal fit technique.

As we have seen in this chapter, the Doppler shift observed on the propeller harmonics as the aircraft flies over the sensor station lends itself naturally to a determination of sediment sound speed. A wave property of comparable importance is the attenuation of sound in the sediment and, in particular, the frequency dependence exhibited by the attenuation. In principle, this could be recovered in two ways: by taking the ratio of the intensity of sound from the aircraft, as observed on a hydrophone buried in the sediment at two instants during the approach; or by taking the ratio of the sound intensities on two horizontally separated, buried hydrophones as the aircraft flies towards the sensor station. Future experiments will include two or more buried hydrophones, allowing the two techniques for obtaining the attenuation to be compared.

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Legends to figures

Figure 1 Acoustic data from a stationary Tobago TB10 taken with a microphone at the port wingtip, about 20° behind the plane of the two-blade propeller, which was turning at 2000 rpm. Pressure time-series (left), exhibiting four uneven cylinder-firing impulses, and spectrogram (right), showing the harmonics from the propeller at frequency intervals of approximately 67 Hz.

Figure 2 Ground-based observer listening to an aircraft approaching with horizontal speed V at altitude h. The circles represent wave crests radiated from the moving source at intervals of one wave period, Δt, and travelling through the medium with speed c. At time $t = 0$, the horizontal range to the source is x and the angle of elevation is $\theta = \cos^{-1}(x / \sqrt{x^2 + h^2})$. (Adapted from Pierce[9]).

Figure 3 Refraction of sound rays across the sea surface and the seawater-sediment interface.

Figure 4 Configuration of the flying experiments conducted north of La Jolla, California in July 2002.

Figure 5 a) Average sound speed profile from SeaBird, with small circles depicting depths of hydrophones in water column. b) - d) Calibrated spectrograms from flight of Tobago at altitude of 66 m on 2 July 2002 showing Doppler shifted propeller harmonics (all colour bars: dB re 1 $\mu Pa^2/Hz$): b) microphone 1 m above sea surface; c) hydrophone at depth of 10 m in water column; and d) hydrophone buried 75 cm deep in sediment.

Figure 6 Schematic of different types of waves in the air-sea-sediment environment.

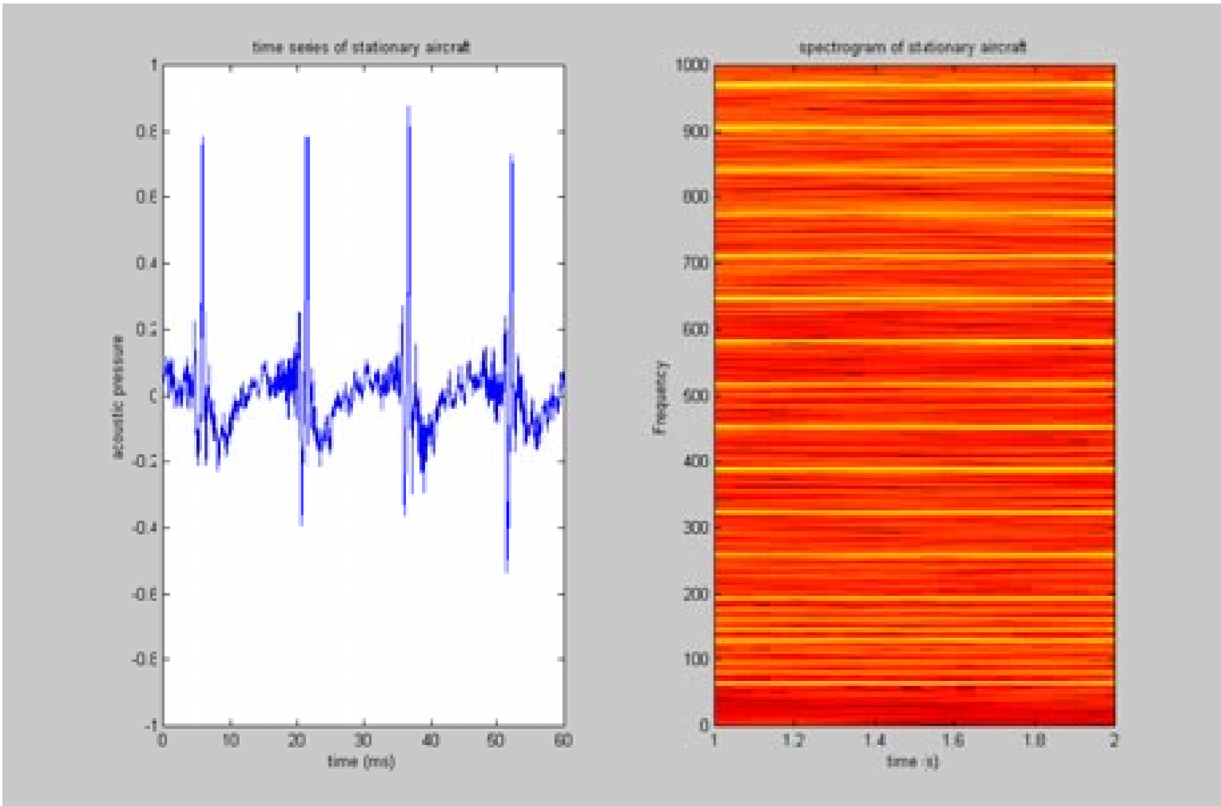

time series of stationary aircraft
acoustic pressure
time (ms)
spectrogram of stationary aircraft
Frequency

Fig. 1

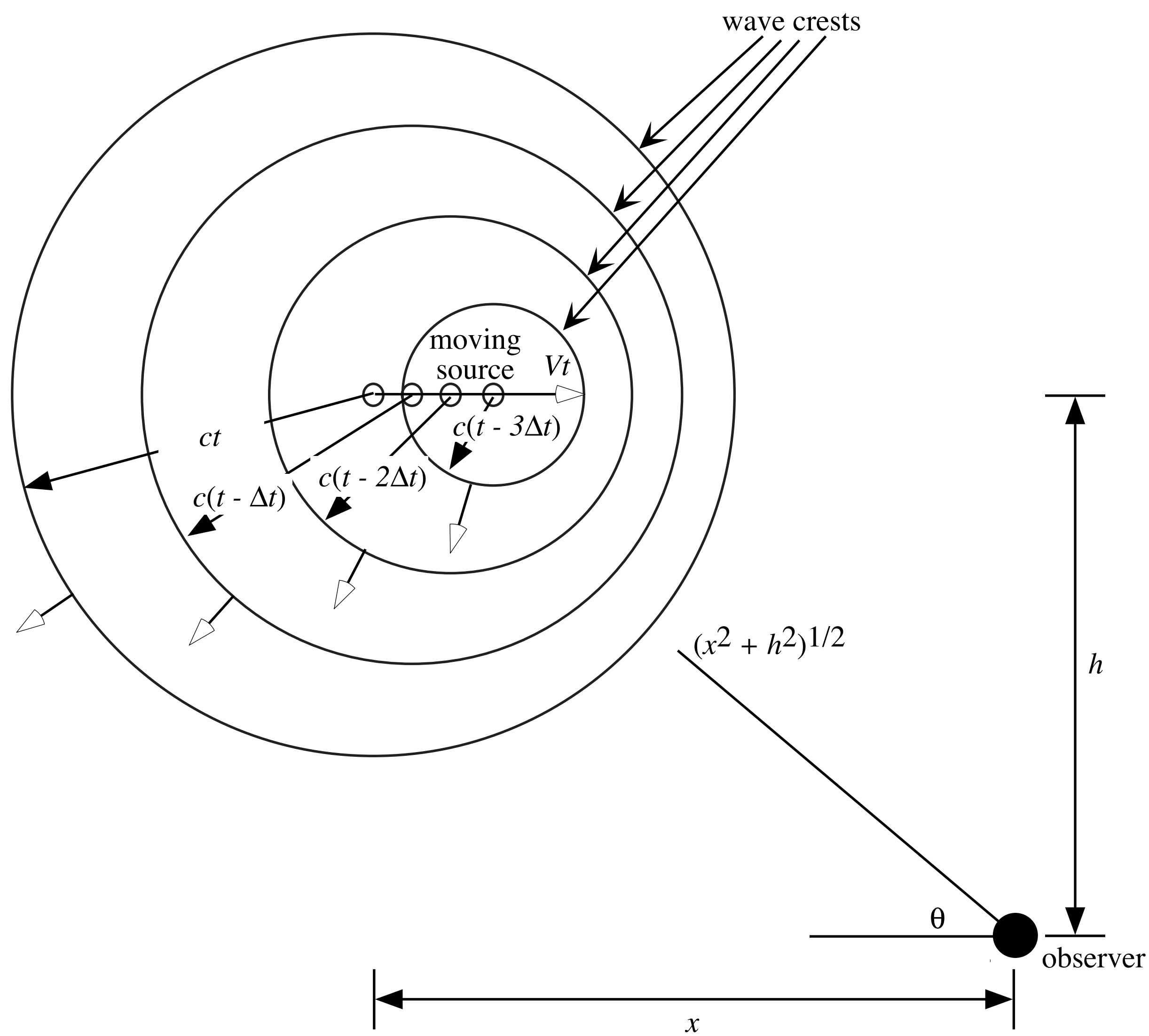
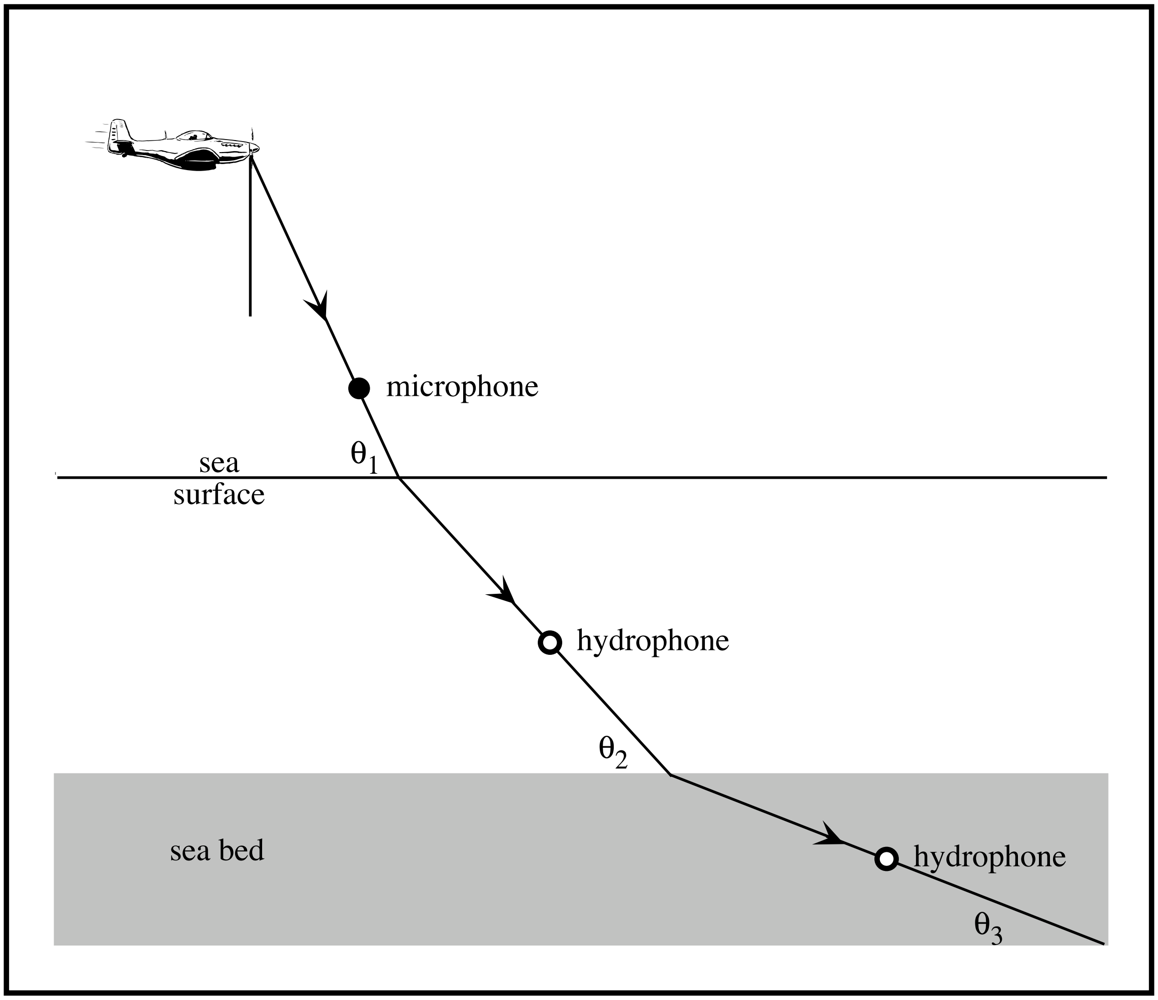

wave crests
moving
source
Vt
ct
c(t - 3Δt)
c(t - Δt)
c(t - 2Δt)
(x2 + h2)1/2
h
θ
observer
x

Fig. 2



microphone
θ1
sea
surface
hydrophone
θ2
sea bed
hydrophone
θ3

Figure 3

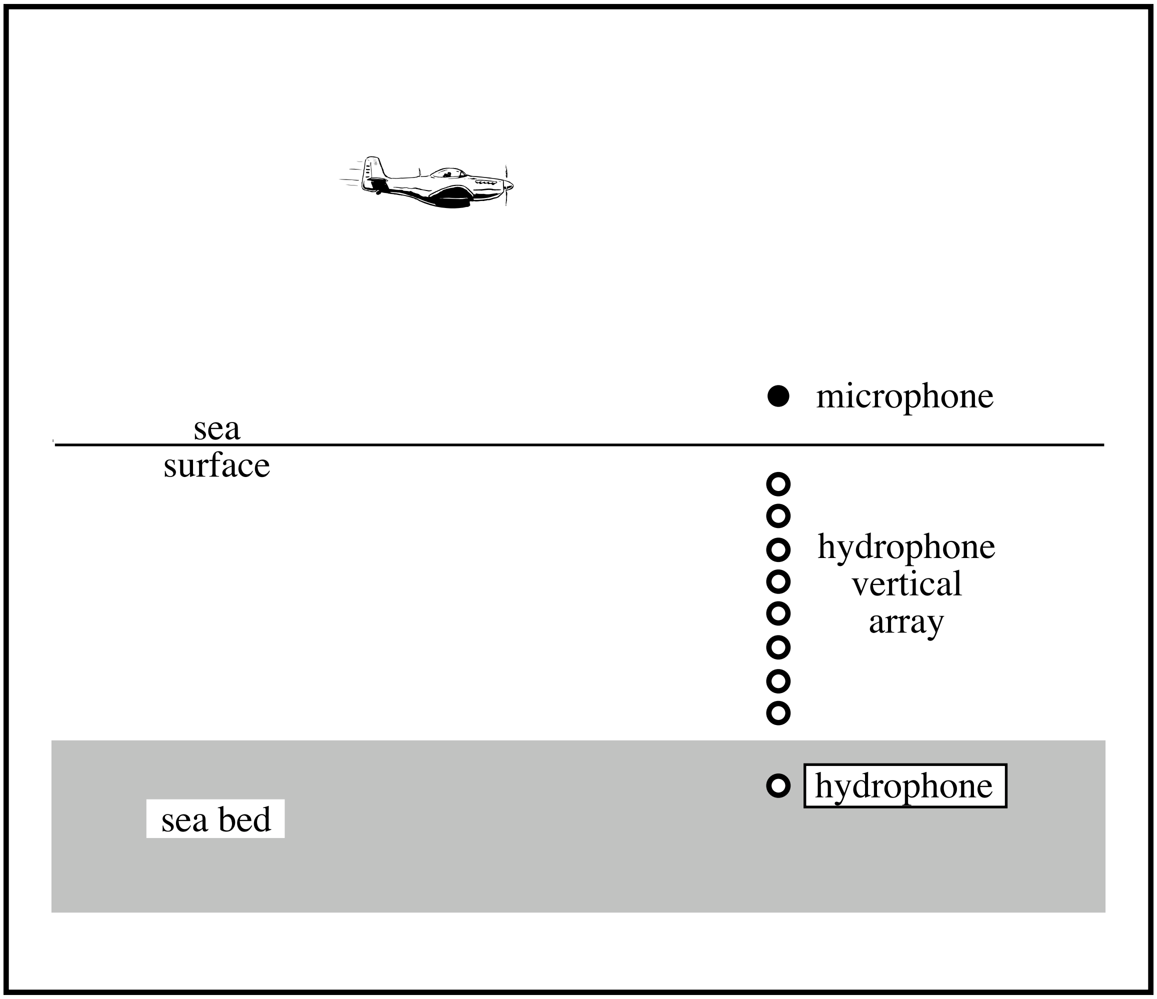

microphone
sea
surface
hydrophone
vertical
array
sea bed
hydrophone

Figure 4

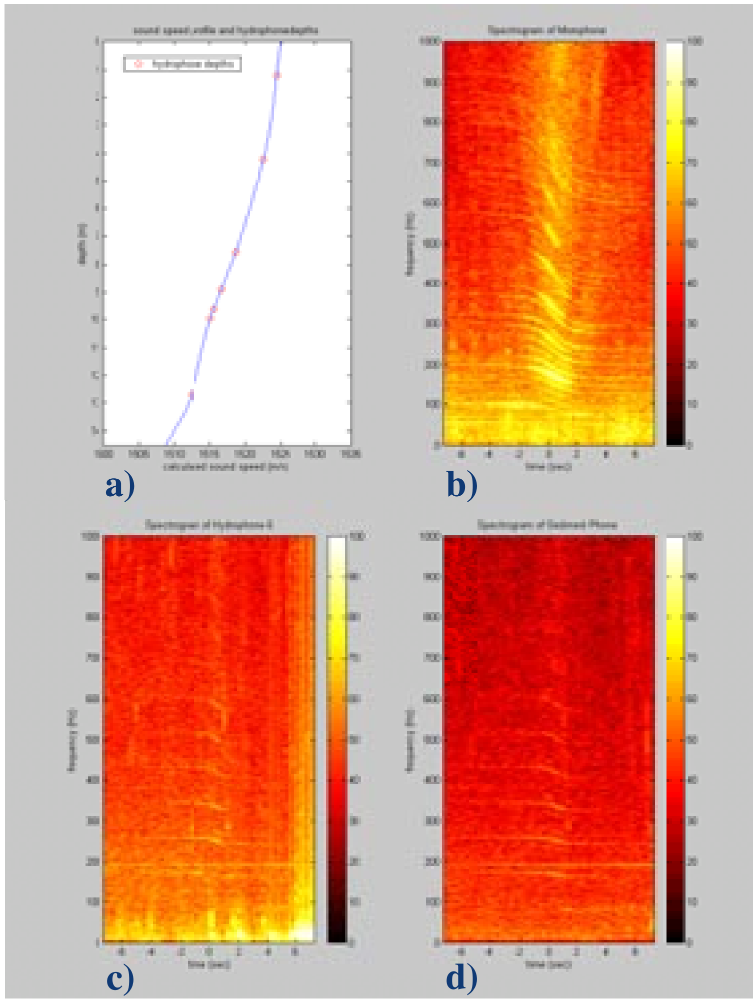


Fig. 5

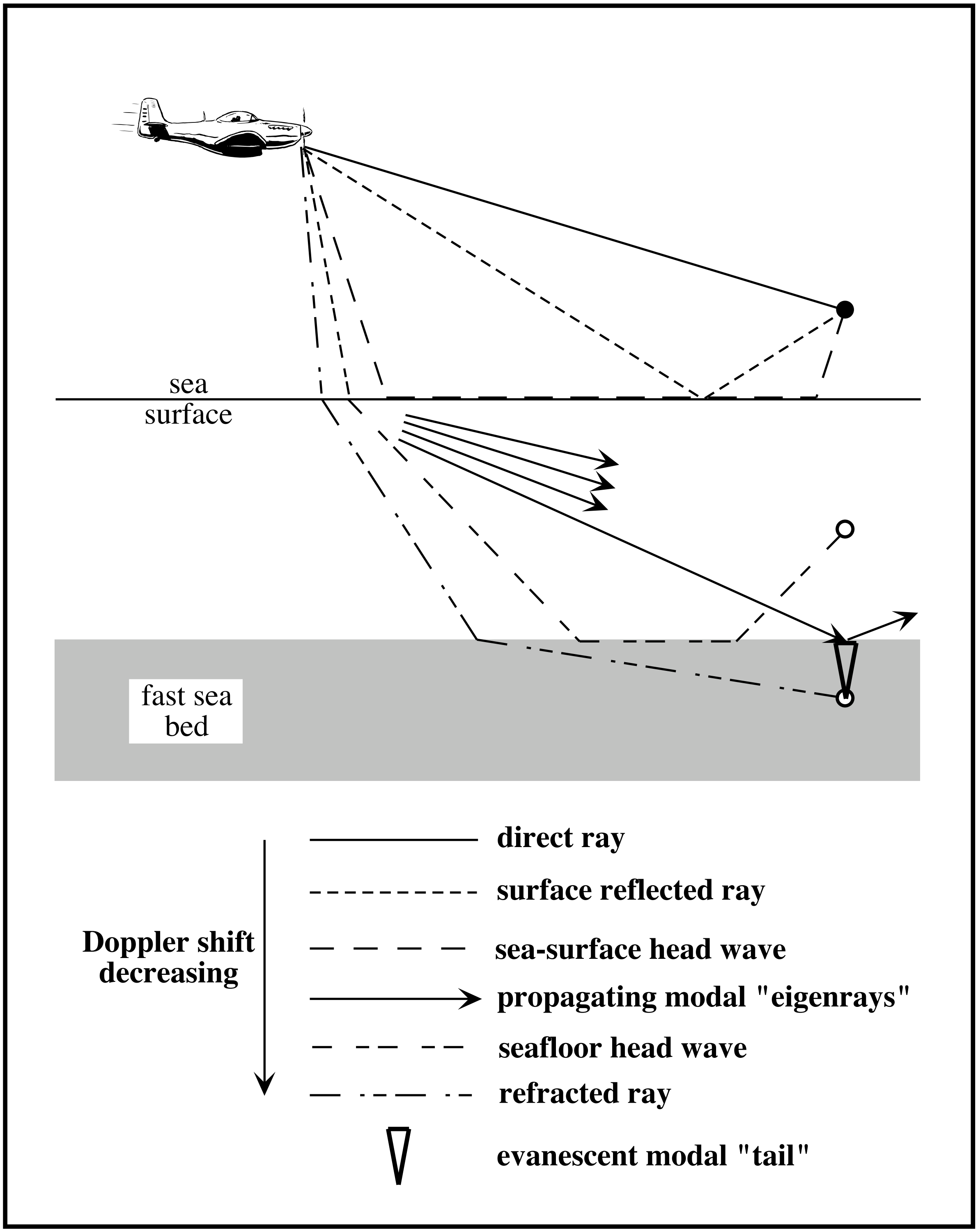

sea
surface
fast sea
bed
Doppler shift
decreasing
direct ray
surface reflected ray
sea-surface head wave
propagating modal "eigenrays"
seafloor head wave
refracted ray
evanescent modal "tail"

Fig. 6