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Christian Doppler
Life and Work • Principle and Applications

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The Doppler Effect in Physical Oceanography: Measurements in the Strait of Messina

Abstract

After a short discussion on the technical characteristics of Acoustic Doppler Current Profilers (ADCP), which use the Doppler effect to retrieve oceanic current velocities, as well as of Synthetic Aperture Radars (SAR), which use the Doppler effect to detect surface signatures of oceanic phenomena, I will illustrate the performance achieved by in-situ and remote sensing “Doppler measurements” in Physical Oceanography through the analysis of data referring to the hydrodynamics of the Strait of Messina, in the Mediterranean Sea.

Introduction

The development of oceanic as well as atmospheric sciences of the last few decades has been significantly influenced by the advent of devices based on the Doppler effect. Wind speed is retrieved on a routine basis by means of meteorological Doppler radars. These systems are able to accurately measure wind velocities at different levels because of the frequency shift experienced by the reflected signal, which depends on the velocity of the reflectors with respect to the emitting source. In oceanography, in-situ as well as remote sensing measurement strategies based on the Doppler effect allow, e.g., for the measurement of current velocities in the ocean interior (by means of vessel-mounted or lowered Acoustic Doppler Current Profilers (ADCP)) as well as features of the surface and of the ocean’s interior, having signatures at the sea surface (by means of Synthetic Aperture Radars (SAR)). ADCP measurements have significantly contributed to the knowledge of the oceanic velocity fields and their variability, as they considerably extend the possibility of oceanic velocity measurements, once very limited by the complexity of using conventional current meters. SAR measurements have significantly contributed to extend our knowledge of the dynamics of mesoscale and small-scale oceanic phenomena: among others, fronts, vortices, surface and internal waves, filaments, oil films as well as ice coverage have been largely investigated using this “Doppler device” (see, e.g., Alpers 1985; Brandt et al. 1997; Hessner et al. 2001; Rubino et al. 2001).

I will briefly describe the functioning of ADCP and SAR and discuss their capabilities specifically referring to the hydrodynamics of the Strait of Messina in the Mediterranean Sea.
ADCP and SAR Measurements

Acoustic Doppler Current Profilers (ADCP) are devices designed to measure water velocity through the water column. An ADCP can be used in different ways: it can be mounted on the bottom of the vessel to perform current measurements while the ship moves; it can be fixed on the seabed to measure the velocity near the bottom and toward the surface; it can be lowered on a cable from the surface to measure the water speed throughout the water column. The ADCP emits pings of sound at a constant frequency in the water. As the sound waves travel, they are reflected back to the instrument (which is then configured as a receiver) when they encounter particles located in their path. Due to the Doppler effect, sound waves reflected by particles moving away from the emitter experience a frequency decrease, whilst sound waves reflected by particles moving toward the emitter experience a frequency increase. The frequency difference between emitted and received waves constitutes the Doppler shift. By using the Doppler shift, an ADCP can calculate the velocity of the reflecting particle, and hence of the water. At a constant pressure, given a certain water temperature and salinity, the time needed for a sound wave to go and come back depends on the distance travelled only. By measuring the time between emission and reception, an ADCP is also able to measure current speed at different depths with each series of pings.

In order to provide very high resolution images, an SAR uses the propagation characteristics of radar pulses as well as the capability of modern electronics to process the large dataset. The obtained data represent a very useful complement to optical remote sensing data as they are virtually independent of the time of day and weather conditions. In order to explain the functioning of SAR systems, let us consider a spaceborne SAR imaging perpendicular to the satellite velocity. The imaging procedure can be analysed in the range as well as in the azimuthal dimensions. Range (or cross track) is the “line-of-sight” distance from the radar to the object to be imaged (target). In the range measurement, an SAR does not differ significantly from conventional radar devices. Indeed, range is determined by measuring the time needed from the transmission of a pulse to the reception of its echo from the target. Azimuth (or along track) is a distance perpendicular to range. SAR devices differ from conventional radars because of their capability to produce images having a very high azimuthal resolution. Conventionally, this could be achieved using a very long antenna, which focuses transmitted and received signals into a very sharp beam. In a similar way, optical devices need large apertures (mirrors or lenses in the case of telescopes, which can be considered as the analogous to the radar antenna) to produce high resolution images. However, in order to obtain such a large resolution, radars would require longer physical antennae (many hundreds of meters) as technically feasible. A spaceborne radar, however, could collect data during its flight and then process the dataset as if they were received by means of a physically long antenna. The distance the aircraft flies in synthesizing the antenna is named the synthetic aperture. Let us illustrate the process by which a high azimuthal resolution is achieved in terms of the Doppler shift: Targets ahead of the aircraft produce a positive Doppler shift, whilst targets behind the aircraft yield a negative one. As the aircraft flies the synthetic aperture, echoes are resolved into a number of Doppler frequencies. The azimuthal position of a target is thus determined by its Doppler frequency.

The Strait of Messina

In order to illustrate aspects of the capability of ADCP and SAR devices in physical oceanography, I will refer to measurements carried out in the Strait of Messina (see, e.g., Brandt et al. 1997; 1999;
Rubino et al. 2001). This is a narrow channel which separates the island of Sicily from the Italian Peninsula and thus connects the Tyrrhenian and the Ionian Seas.

Fig. 1 shows an SAR image depicting part of the island of Sicily, part of the Calabrian peninsula, and part of the southern Tyrrhenian as well as of the northern Ionian basins. As typical for SAR images acquired over the ocean, different signatures of oceanic as well as atmospheric phenomena can be delineated as coherent patches of enhanced/reduced backscatter regions (visible as different grey tones). Phenomena which are often detected in SAR images are, among others, wind waves (swell), atmospheric and oceanic fronts, regions of different wind activity, katabatic winds, internal atmospheric and oceanic waves, oceanic eddies and filaments, river discharges, oil spills, ship wakes, etc. (see e.g. the project “The tropical and subtropical ocean viewed by ERS SAR” at “earth.esa.int/applications/ERS-SARtropical” for an accurate description of these phenomena and their SAR signatures). In particular, north and south of the Strait, due to the interaction of the predominantly semi-diurnal tide with the local bathymetry, internal solitary waves are generated, which propagate northward, toward the Tyrrhenian Sea, as well as southward, toward the Ionian Sea.

Their surface manifestations have been often observed (see, e.g., Brandt et al. 1997; Rubino et al. 2001) using the SAR aboard the First and Second European Remote Sensing Satellites (ERS1 and ERS2) as bands of reduced and increased radar backscatter (see Fig. 2).

Fig. 1. ERS 1 SAR image of the Strait of Messina. The image shows strong sea surface manifestations of trains of internal solitary waves propagating southward into the Ionian Sea as well as northward, into the Tyrrhenian Sea (adopted from Brandt et al. 1997)
Fig. 2. ERS 1 SAR image of the Strait of Messina. The image shows strong sea surface manifestations of a train of internal solitary waves propagating northward into the Tyrrhenian Sea (adopted from Brandt et al. 1997)

Fig. 3. Density distribution measured by the CTD chain (a) and distribution of the horizontal velocity field measured by the ADCP (b) between the positions A and B marked in (c). In (a) the colours represent the different water densities. In (b) they represent the different directions of the horizontal velocity, while their brightness represents the velocity strength. The density field (a) is characterized by the presence of a northward propagating internal undular bore, the horizontal velocity field (b) by the presence of a surface jet (adopted from Brandt et al. 1999)
While southward propagating internal solitary waves are observed very frequently, observations of northern propagating internal solitary waves are much rarer. This asymmetry is connected to the vertical stratification north and south of the Strait: usually, the near-surface water south of the Strait is denser than the near-surface water north of the Strait. As a consequence, while, during southward tidal flow, lighter Tyrrenhian water from the north flows as a surface layer into the Ionian Sea and generates strong internal solitary waves, during northward tidal flow denser Ionian water intrudes in the Tyrrenhian Sea as a subsurface jet and generates weaker internal solitary waves.

On October 24 and 25, 1995, high-resolution oceanographic measurements were carried out in the Strait of Messina using a towed CTD (Conductivity, Temperature, Depth) chain and a vessel-mounted ADCP. The analysis of the water masses demonstrates that, during the observation period, the climatological vertical distribution described above was reversed. As a consequence, a strong surface jet bringing Ionian water into the Tyrrenhian Sea (Fig. 3) and a less intense subsurface jet bringing Tyrrenhian Water into the Ionian Sea (Fig. 4) were observed (Brandt et al. 1999).

**Fig. 4.** Density distribution measured by the CTD chain (a) and distribution of the horizontal velocity field measured by the ADCP (b) between the positions A and B marked in (c). In (a) the colours represent the different water densities. In (b) they represent the different directions of the horizontal velocity, while their brightness represents the velocity strength. The density field (a) is characterized by the presence of a southward propagating internal undular bore, the horizontal velocity field (b) by the presence of a subsurface jet (adopted from Brandt et al. 1999).
The observed stratification and the corresponding dynamics are related to the mesoscale dynamics in the central Mediterranean Basin. As ADCP measurements indicate, during the period of investigation the Atlantic Ionian Stream (AIS), which transports Modified Atlantic Water toward the Eastern Mediterranean Basin, occupied the southern part of the Strait of Messina (Fig. 5). This caused a reversal of the climatological density distribution in the upper layers of the approaches to the Strait of Messina.

Fig. 5. Two paths of the AIS. The one marked by the light grey line is adopted from Malanotte-Rizzoli et al. (1998), the other, marked by the dark grey line, is inferred from the horizontal velocity data acquired by the vessel mounted ADCP during AIS'95 in a near-surface layer between 20 and 40 m depth (black arrows). The length of the arrows gives the strength of the velocity (adopted from Brandt et al. 1999).

Conclusions

The in-situ as well as remote sensing measurements (ADCP and SAR) presented above have been chosen to illustrate the capability of devices based on the Doppler effect in Physical Oceanography. Using ADCP, for the first time very high resolution observations related to the structure and variabil-
The study of surface and subsurface oceanic, strong nonlinear and non-hydrostatic water jets of tidal origin have been performed (Brandt et al. 1999). Measurements carried out by means of a spaceborne SAR were used to obtain a detailed description of different characteristics of the internal wave field in the area of the Strait of Messina. Again, ADCP measurements were used to explain the observed anomalous tidal phenomena in the Strait of Messina and thus to connect small-scale and mesoscale phenomena occurring there with larger scale circulation patterns of the central Mediterranean Sea. Investigations like the one presented here would not have been feasible without the advent of devices based on the ideas of Christian Doppler.

References

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