Polaris: A GPS-Navigated Ocean Acoustic Current Profiler

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ABSTRACT

Results from an initial feasibility study to test whether Global Positioning System (GPS) navigation can be combined with more traditional acoustic methods to measure ocean current profiles are presented. A typical acoustic current profiler such as PEGASUS measures currents by ranging on two acoustic sources (one-way beacons or two-way transponders) as it falls or rises through the water column. These sources must be previously deployed on the bottom, and their positions accurately determined via the attending research vessel. As discussed below, this procedure introduces a number of complications. In particular, any unresolved errors in the source deployment will remain as systematic errors in the resulting velocity data.

The method described here replaces the bottom-mounted sources with hydrophones drifting near the ocean surface. The positions of these hydrophones are computed every few seconds using GPS.

This feasibility test shows that a combined GPS-acoustic system can approach accuracy levels found in the standard method. Furthermore, systematic errors can be significantly reduced. Random errors are estimated to be approximately ± 1–2 cm s^{-1} dependent on station geometry.

1. Introduction

Over approximately the last decade, the PEGASUS ocean acoustic current profiler (Spain et al. 1981) has been deployed by investigators at the University of Miami's Rosenstiel School of Marine and Atmospheric Science to measure vertical profiles of horizontal ocean currents in a wide range of experiments, including studies of the structure, transport, and variability of the Florida Current in the Straits of Florida (Mayer et al. 1984; Leaman and Molinari 1987; Leaman et al. 1987); the evolution of the Gulf Stream as it flows northward to Cape Hatteras (Leaman et al. 1989); the structure of shallow and deep western boundary currents east of the Bahamas (Leaman and Harris 1990) and off South America (K. Leaman and P. Vertes, unpublished manuscript); and the process of deep-water formation in the northwestern Mediterranean (Schott et al. 1988; Leaman and Schott 1991; Schott and Leaman 1991).

In its simplest form, PEGASUS is an acoustic dropsonde (which also measures temperature and pressure), which falls or rises at a rate of 20–70 cm s^{-1} depending on the instrument configuration and emits a 10-kHz acoustic tracking ping at a predetermined rate (usually every 8 s for shallower depths and every 16 s for deeper water). The profiler listens for response pings at two or more of a set of four frequencies: 13.0, 12.5, 12.0, and 11.5 kHz.

Response pings are generated by acoustic transponders, which have previously been deployed in an accurately known configuration on the ocean floor and are programmed to listen for the 10-kHz interrogation pulse and reply on one of the above four frequencies. Although three transponders provide enough information to locate PEGASUS in space, it has been much more common to use only two transponders and rely on pressure to provide the third coordinate.

Velocity-profile accuracy depends on how well we know the depths of the two transponders, the length and orientation of the baseline that connects them, and to some extent the sound speed profile (Leaman and Vertes 1983). It has generally been found that knowledge of a temperature profile in the area from an expendable bathythermograph (XBT) cast or the profiler itself, plus a temperature–salinity curve, is adequate to obtain a sufficiently accurate sound speed profile. Except under extreme conditions, sound speed errors cause only a few millimeters per second errors in computed horizontal water velocity. The other information must be determined from a survey conducted by the research vessel before the profiler is first dropped, and depending on shipboard acoustic and other conditions, this survey can, unfortunately,

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sometimes take several hours to complete. Any errors in determining the above quantities will produce systematic (rather than random) errors in the resulting velocity profiles, as will systematic calibration errors in pressure if this is used as the third coordinate (Leaman and Vertes 1983).

Other "drop-dependent" errors depend on the physical location of the profiler relative to the transponder grid. For example, errors are amplified if the profiler drifts too close to the baseline. It is, therefore, difficult to summarize errors (e.g., in a single table), since through the dependence on geometry they are profile dependent.

Choice of ping repetition interval (8 or 16 s) depends mainly on water depth. Sufficient time must be allowed for multiple echoes to clear out before the next tracking ping is released. Too high a repetition rate in too deep water can hopelessly confuse the instrument. Clearly, for the same vertical resolution, the ping rate is inversely proportional to the fall rate. Thus, to maintain a comparable resolution with a faster descending instrument requires a higher ping rate, which introduces confusion unless a different frequency scheme is used. It is clear that some types of observations are more suited to the above approach than others. Given the effort (often several hours) and cost required to deploy a PEGASUS station, this system is most suited to situations in which 1) a station can be visited numerous times during the lifetime of the transponders (2–3 years usually); 2) enough is known about the currents to be measured so that a reasonable choice of station locations can be made before station deployment; and 3) with limited ship time, a reasonably small number of stations is sufficient for the work. Conversely, it is not well suited to situations in which, for example, exploratory surveys of a region of poorly understood currents are carried out. Nor is it suited for long hydrographic station lines.

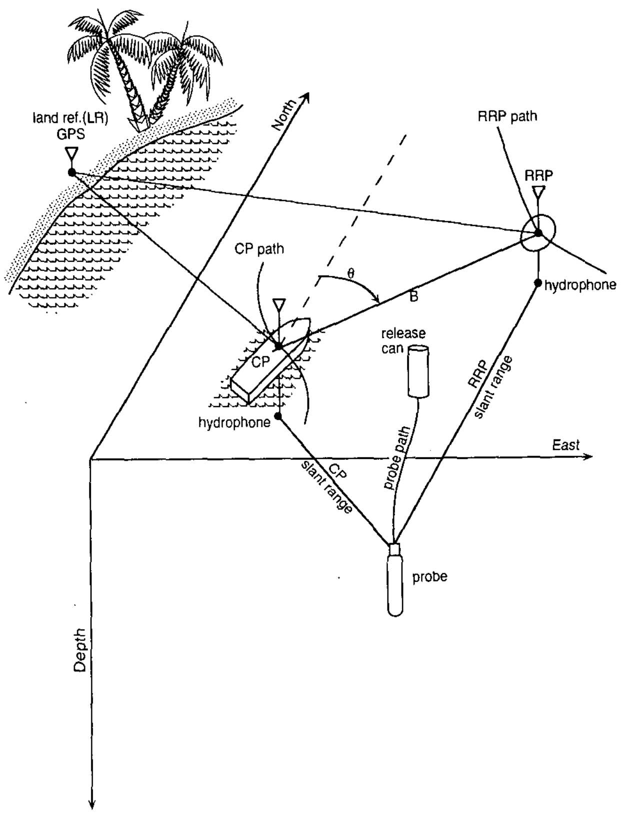


FIG. 1. Schematic of Polaris components.

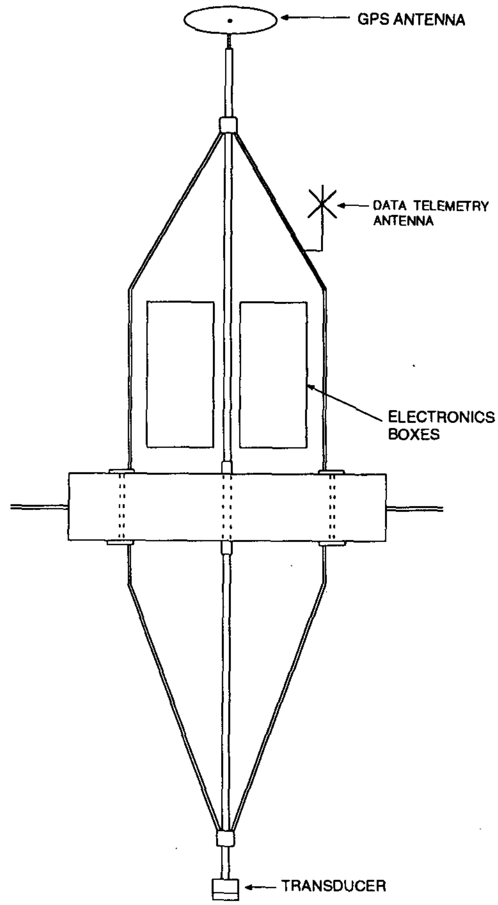


FIG. 2. RRP buoy. The distance from the waterline to the transducer is approximately 2 m.

With the deployment of the Global Positioning System (GPS), it appeared to us several years ago that this system might potentially be accurate enough to navigate an acoustically tracked velocity probe. If this were true, it could produce some significant improvements in the standard "PEGASUS" method. In particular: 1) a relatively simpler, cheaper (possibly even expendable), and faster falling probe could be used; 2) if the navigation transponders or hydrophones could be placed at the surface, then stations could easily be moved; 3) some of the systematic errors inherent in the old approach could be substantially removed. The

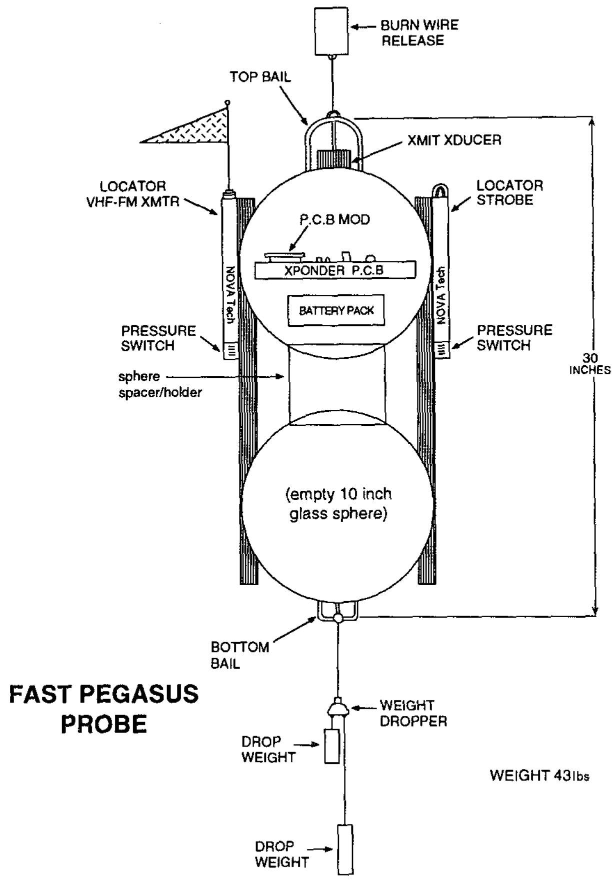


FIG. 3. Side view of the Polaris probe (PP) configuration.

main question was whether the random errors introduced by navigating the transponders or hydrophones at frequent intervals through the course of a drop would be sufficiently small (Leaman 1991). In this paper, we present results of a feasibility study we have conducted over the past two years of this "new-generation" PEGASUS profiler. In section 2 a general system description is provided, along with explanations for some parts of the system that are significantly different from the standard profiler. In this section, GPS navigation requirements are also discussed. More-detailed descriptions of the different system components are given in section 3. Two field tests conducted in 1993 and the methods used to process and analyze the resulting data are described in section 4, and, finally, these results and our next steps are discussed in section 5.

2. General system description

The test configuration used in these feasibility tests (Fig. 1) consists of four components. The Polaris remote range point (RRP) on a stand-off buoy and the command point (CP) on a ship are electronically virtually identical. The two units, each consisting of an acoustic hydrophone and reception unit and an almost collocated differential GPS (DGPS) receiver, have the same role as the bottom transponders in the usual PEGASUS setup. As described below, the DGPS receivers on CP and RRP must be corrected using data from a fixed land reference (LR) station, but the geographical position of LR need not be known exceptionally accurately, nor does LR have to be very close to RRP/CP.

The Polaris active transmitter (the falling probe or PP) consists of a simple beacon-type acoustic transmitter. However, in contrast to the normal mode of PEGASUS operation this beacon is designed to commute through a set of four transmit frequencies (13.0, 12.5, 12.0, and 11.5 kHz) at intervals of 0, 4, 8, and 12 s after the beginning of the basic 16-s transmit window. Prior to deployment, this transmit window is aligned with the corresponding receive windows on CP and RRP using 1-pps (pulse per second) pulses from the GPS receiver clock. This approach is, in fact, similar to a very early mode of PEGASUS measurement when bottom beacons, rather than transponders, were used. Although the acoustic receiver clocks and the probe clock will drift, the effect is negligible over the 1–2-h course of a drop. The purpose in commuting around the four frequencies in the probe is to avoid the inter-

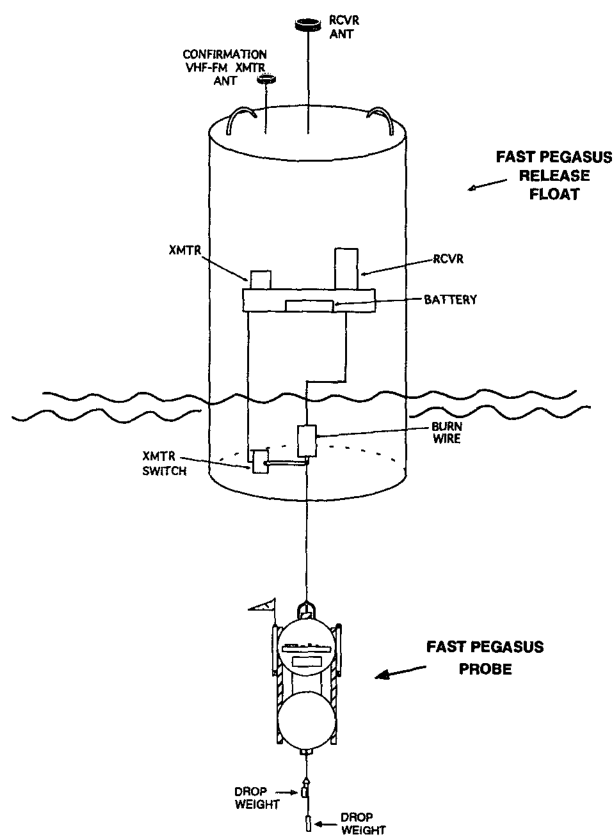
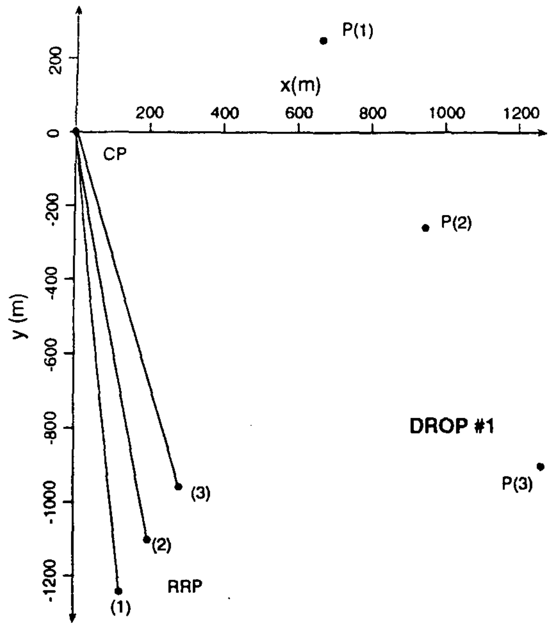


FIG. 4. The surface release "can" used for these feasibility tests.



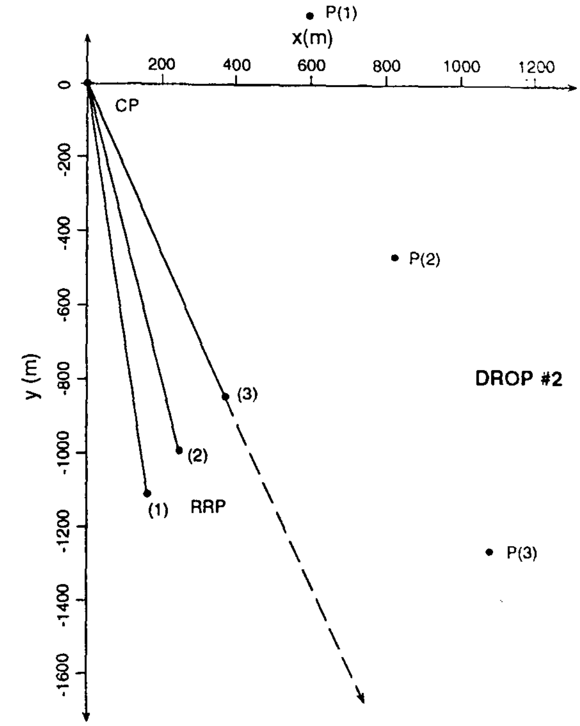


FIG. 5. Surface baselines (CP to RRP) and horizontal positions of the probe (PP) at the start P(1), turnaround P(2), and end P(3) of the drop relative to the CP location for the (a) first and (b) second test drops.

ference problems referred to above, while avoiding any significant loss in vertical resolution with a more rapidly falling probe.

GPS navigation requirements. Previous analyses (Leaman 1991) suggested that to achieve velocity noise levels in this system that would be comparable to (systematic) error levels in a standard PEGASUS, without losing significant vertical resolution through vertical smoothing, would require precision in locating the RRP and CP on the order of 1 m rms. Note that this is precision and not absolute accuracy. We only require that if there are significant systematic errors in position they not change with time over the course of a profile. Our work suggested that this level of precision would be achievable with a high-accuracy dual-frequency GPS receiver. Two GPS frequencies are used for correcting ionospheric delays of the GPS signals, which can introduce significant errors in differential GPS—especially if the land reference and Polaris stations are separated by many hundreds of kilometers.

Security measures, applied by the U.S. Department of Defense (DoD) to the GPS signals result in unacceptable errors in single-receiver navigation. The GPS satellite clocks are dithered under selective availability (S/A). Selective availability can be overcome by differential operation relative to the land reference site (Röcken and Meertens 1991). Because we wanted to use GPS range instead of phase data (range data are much easier and less time consuming to process than phase data), so-called "antispoofing" (A/S) by the DoD poses a potential problem. Under A/S the p-code that is used for very precise GPS ranging to the satellite is encrypted, thus making it unavailable. The Trimble 4000 SSE GPS receivers that we used for this experiment use a cross-correlation technique to measure high-quality, dual-frequency pseudoranges, even when A/S is on. Antispoofing was not on during our experiments and it should not be a problem in the future, if we use dual-frequency receivers capable of operating under A/S.

3. Description of system (RRP, CP, PP, LR) components

Little description need be devoted to the LR. A Trimble 4000 SSE DGPS receiver was operated in the Marine Science Center Building at the Rosenstiel School of Marine and Atmospheric Science, with its antenna mounted on the roof of the building. It was programmed to sample range and phase data every 2 s during the days when the system was tested. Aside from one case where the LR's memory filled up early, no problems were experienced with this unit.

The shipboard (CP) unit had to be "jury-rigged," as funds were not available in the project for its fab-

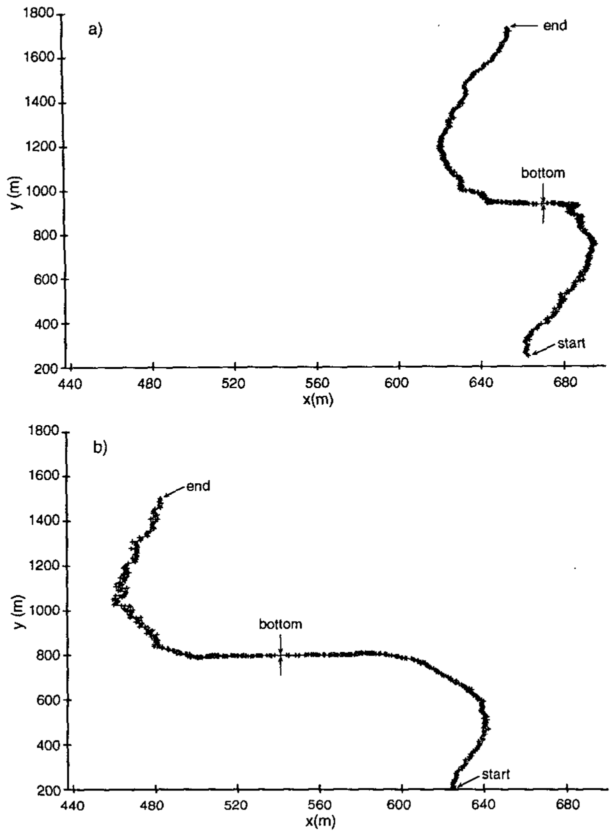


FIG. 6. Absolute x, y probe displacements (down and up) for the (a) first and (b) second test drops.

rication. (Electronically, it is virtually identical to the RRP). To at least approximate the intended complete system, we deployed another 4000 SSE unit in the lab of the research vessel (R/V *Calanus*) used for these tests, with its antenna mounted in an elevated position above the port rail. A standard PEGASUS profiler was then suspended below the same rail so as to be approximately (see below) below the GPS antenna. By synchronizing the clocks in these two devices, we were able to mimic the data that would, in reality, have been provided by the CP.

a. RRP buoy

The RRP buoy (Fig. 2) was designed to allow maximum flexibility in reconfiguring its components rather than for ease of use. This float consists of a flat flotation cylinder with open steel tower frames above and below. Electronics for the GPS and acoustic receivers, telemetry radios, etc. are housed in two watertight boxes on the upper frame. A data-telemetry antenna for real-time GPS data to the ship was mounted on the side of the upper frame, and the GPS antenna was mounted at its topmost point. A watertight cable fed signals from the acoustic transducer at the bottom of the lower frame to the acoustic receiver. Total RRP weight in air (over 400 lb) was far too heavy for operational use; however, as intended, the float was easily modified.

The RRP GPS receiver was programmed to sample and store pseudorange and carrier phase data every 2 s for postprocessing. In addition, the receiver transmitted its position every second to the R/V *Calanus*, where the GPS positions of the ship and of the RRP were displayed in real time on a computer screen.

On the acoustics side, typical PEGASUS-type electronics were used, with separate travel-time counters tracking pulses from PP at sequential frequencies of 13.0, 12.5, 12.0, and 11.5 kHz. These data were stored in a 32-kbyte RAM; however, no telemetry was available for the acoustic data. A time-base reset was present (on CP and PP as well) to synchronize their clocks to be able to compute acoustic travel times.

b. Polaris probe (PP)

For these tests a standard Benthos XT-6000 transponder was modified so as to cycle through a sequence of four output pings (13.0, 12.5, 12.0, and 11.5 kHz) every 16 s with a 4-s separation between each ping. An additional 13″ sphere (Fig. 3) was used to provide increased buoyancy. A standard strobe light and ADF radio were fitted to the transducer end. Although these may have degraded performance somewhat (see below), they were required since this was our only probe. A standard PEGASUS bottom weight release was used to return the probe to the surface; with 15 lb of drop weight, the probe achieved ascent–descent rates of 70–80 cm s^{-1}.

The PP received as input the same clock synchronization pulses as did RRP and CP; however, the probe output was delayed by a known amount (~1.5 s) to avoid a reception blanking interval built into the standard PEGASUS unit.

For the tests in the Florida Current described below, a Polaris station was usually deployed by first launching the RRP buoy. The ship would then proceed at about a 45° angle to the upstream direction for about 70% of the desired baseline length (which is roughly equal to the water depth) and drop the probe in the water. Finally, the ship would proceed directly upstream of RRP and stop at a distance from RRP roughly equal to the water depth to begin the drop. With this method, a means was required to hold PP near the surface until the vessel had stopped on station—thus, the "can" (Fig. 4). The real-time display of the ship and RRP tracks on the water surface were of great help in choosing and executing optimal geometric configurations of the RRP, the ship, and the can. A relatively large (to have reserve buoyancy) metal can was fitted at its bottom end with a release arm actuated by a burn-wire release, to which the probe was attached. A touch-tone pad–encoded command was sent by VHF radio from CP to a pager receiver in the can to fire the burn-wire re-

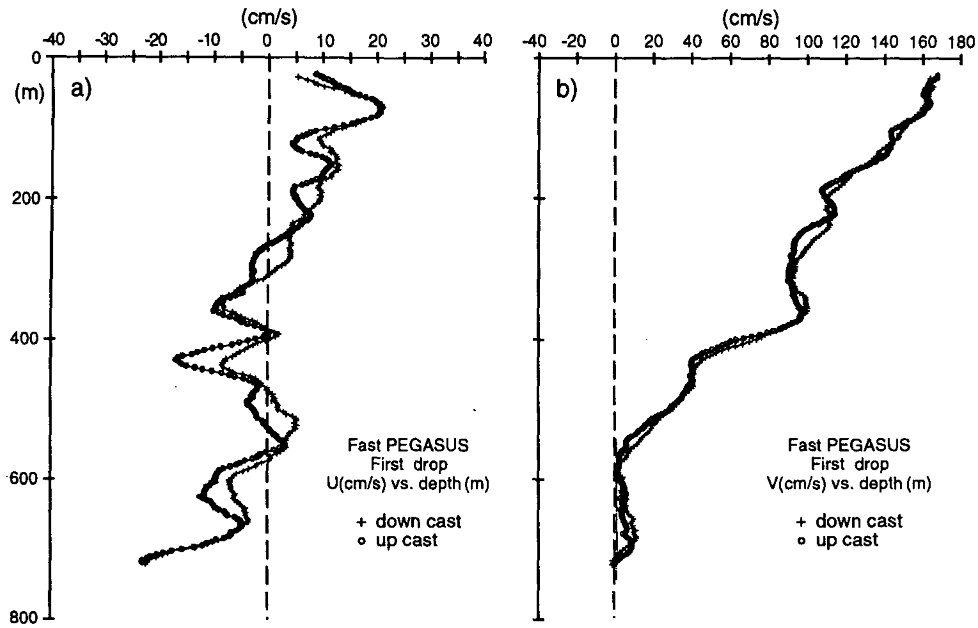


FIG. 7. Absolute Polaris (a) east and (b) north velocity components for the up and down portions of the first test drop. Note the scale change between east and north.

lease. Although the timing was found to be fairly consistent with these releases (25–30 s), this was still inadequate since we wished to know the probe release time to within about 1 s (since probe depth is determined by fall rate and time interval since release). Therefore, a separate magnet, attached by a tether to the PP, was set on the outside of the can. This magnet, upon the probe release, activated a reed switch and thereby turned on a VHF direction-finding radio, which gave us (a) confirmation of probe "departure" to within about 1 s, and (b) a way of finding and recovering the can.

4. Polaris field tests and data processing analysis

a. *Field tests*

In April 1993 a preliminary field test was conducted aboard R/V *Calanus* to test various components of

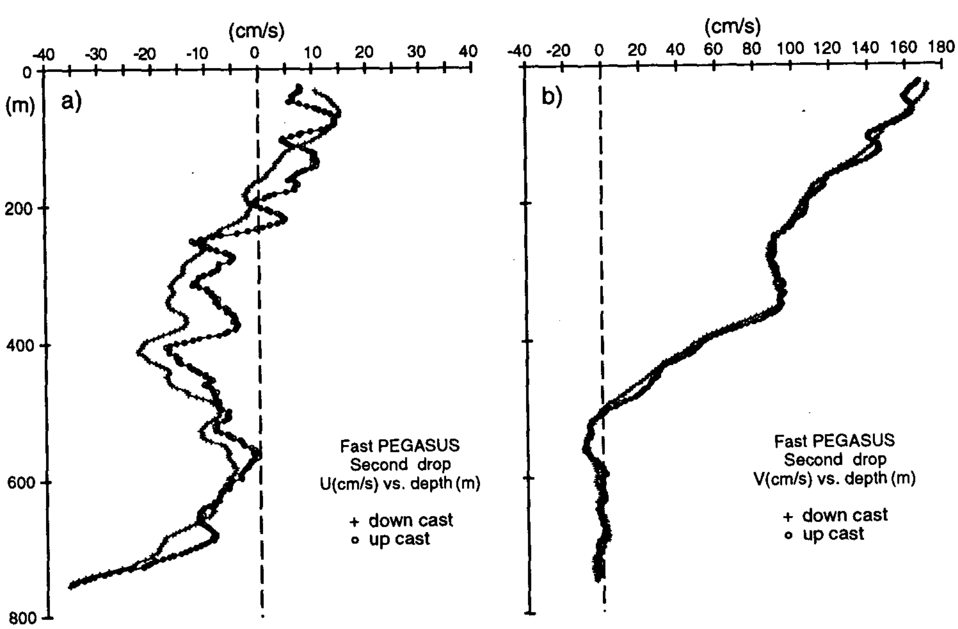


FIG. 8. As with Fig. 7 but for the second test drop.

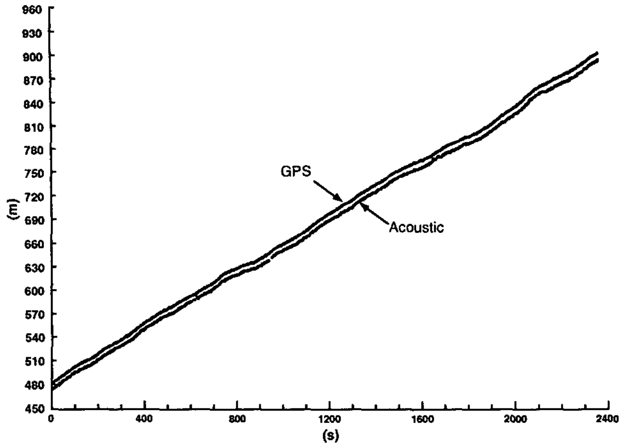


FIG. 9. GPS–acoustic range comparison test.

the Polaris system. RRP was deployed, and the probe was allowed to drift at the surface at increasing ranges from RRP to test acoustic reception.

Due to interference with the DGPS receiver, we could not use a VHF direction-finder radio on RRP. For this reason UNAVCO personnel carried out a series of telemetry range tests by moving CP successively farther from RRP. It was found that significant data telemetry losses began at ranges greater than 8 km. Although this is still adequate for full-depth baselines (5–6 km), it indicates that in deep stations care would have to be exercised so as not to lose real-time RRP tracking and potentially the buoy itself. (However, these data were also stored in onboard memory in the 4000 SSE.) An improved system that we used for the second experiment showed a radio link range of 15 km in tests on land.

In April all attempts to release the probe from the can via radio command failed. This problem was later traced to a newly fabricated batch of burn-wire releases, which had been constructed incorrectly. This problem could not be immediately corrected, and so it was decided to wait for the next planned test cruise (summer, 1993) to deploy the probe. Unfortunately, this cruise had to be delayed until September since all UNAVCO GPS units had become committed to higher-priority geophysics studies in the summer.

During the September 1993 tests, two velocity profiles were obtained successfully in the Florida Current east of Miami in about a 700-m depth. In addition, range tests were carried out to compare acoustic and GPS-derived horizontal ranges. The processing and analysis applied to these data are described below.

The first step was to organize all GPS and acoustic data by time. (GPS data were obtained every 2 s and acoustic data every 4 s.) Acoustic data were adjusted for the initial 1.5-s delay and for the 4-s time shifts between each of the acoustic frequency channels. Then, any potential clock drifts in RRP or CP relative to PP were removed using a least-squares-fit straight line. (At the start and end of the experiment these components were put in close proximity on deck to check for such drifts.) Acoustic range data were then edited for dropouts, etc. Fall rate was computed using the water depth and the time when the probe turned around at the bottom. Once depth was available, geographic x (east), y (north) positions of PP during the drop were computed by creating a "synthetic" CP–RRP baseline based on the arrival times of the acoustic pulses at the two locations. From this, the probe position relative to the baseline was computed as a function of time. Finally, this location was rotated into a geographic coordinate system (using the instantaneous baseline orientation), and these coordinates were added to the CP coordinates (relative to the start of the drop) to determine absolute probe position.

b. Velocity profiles

The primary difference in the two velocity profiles obtained in September 1993 (Figs. 5–8a,b) arises from the fact that the station geometry in the second profile was distorted to cause increased noise levels in the x, y positions (Figs. 5a,b). Note, in particular, that the probe came much closer to the baseline extension (dotted line) in the second profile, and the baseline length decreased over the course of the drop; both of these effects will cause increased errors (Leaman and Vertes 1983). Positions are shown at the start (1), turnaround (2), and end (3) of each drop relative to CP at the origin. In reality of course this surface array was being advected northward by the Florida Current at about 3 kt during this work, thus explaining why PP (due to the subsurface shear of the Florida Current) appears to surface south of where it was deployed—a fact that contributed to some confusion aboard the

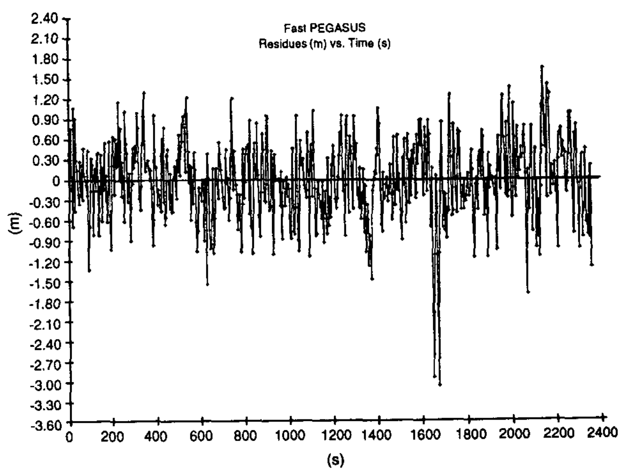


FIG. 10. GPS–acoustic range differences after the offset and trend of the difference (Fig. 9) have been removed.

R/V *Calanus* as well. The RRP remained freely adrift between the two drops.

The absolute *x, y* probe trajectories over the complete range (up and down) for both drops (Figs. 6a,b) clearly show the increased noise in position as the baseline is approached near the end of drop 2. In Fig. 6 the coordinate origin is the geographic location of CP at the start of the drop; thus, PP moves north (increasing *y*) as expected in the Florida Current. Also, it is clear that during the second drop, a region of much larger westward flow was encountered near the bottom. Interestingly, by the time drop 2 was made, the array had advected several nautical miles to a point over the eastern side of a topographic valley opening to the north, which may account for the larger observed westward flow near the bottom.

The absolute east and north velocity components for the first drop, for both up and down portions, are shown in Figs. 7a and 7b. Note the scale change between the two components. Based on numerous other PEGASUS velocity profiles obtained in the Straits of Florida, the comparison between up and down profiles here is quite good. There is some indication of increased "waviness" in the up portion. This may be due to possible "kiting" of the probe during ascent, since the light and radio are pointing forward. However, many of these wavy features are repeated on both up and down portions, suggesting they are in fact real. (Again, the same water was not sampled during the up and down portions.)

Results from the second (worse geometry) profile (Figs. 8a,b) show that regardless of other errors, deploying a station in a good geometrical arrangement is still of major importance. Although the two profiles compare well in many respects (the second profile was made immediately after the first), the increased noise levels, particularly in the east or roughly baseline-perpendicular component (Leaman and Vertes 1983) as the probe neared the surface during the upcast, are evident.

The average descent and ascent rates for PP, as determined from the depth and the times required for PP to travel to the bottom and back, were 0.79 and 0.67 m s^{-1}, respectively. Velocity errors caused by uncertainties in descent and ascent rates (typically less than 1 cm s^{-1} unless the station geometry was very bad) are discussed in Leaman and Vertes (1983). Since the ultimate aim is to develop an expendable free-falling probe, temperature and pressure measurements have not been included on PP. However, we plan to test the probe over a range of water depths to quantify better its fall-rate profile. To determine horizontal velocities least-squares-fit straight lines were fitted to the *x, y* displacements shown in Fig. 6, identical to the procedure used in processing "standard" PEGASUS data. The velocities shown in Figs. 7 and 8 were generated using a 19-point sliding fit. Using the ascent–descent rates above and a 4-s ping repetition interval, the vertical intervals over which velocities were smoothed are 57 m (descent) and 48 m (ascent). This can be compared to a typical PEGASUS profiler with a 16-s ping repetition interval, descent–ascent rates of about 0.45 m s^{-1}, and (typically) seven-point fits, for which the corresponding vertical interval is 43 m.

c. *Range tests*

Over the course of about 1 h, a comparative (GPS–acoustic) range test was conducted. To do this, RRP was launched, and CP then took up position several hundred meters downwind and drifted. The PP was tied to the CP railing using a two-point tie (so as not to swing laterally) so that it was 3–4 m below the surface and roughly 4 m closer to RRP than the GPS antenna on CP. The probe was then allowed to ping at RRP as CP and RRP drifted slowly apart under wind influence, and the CP–RRP acoustic and GPS ranges were simultaneously recorded.

Figure 9 shows the CP–RRP range comparison. In this case, a surface sound speed of 1542 m s^{-1} was assumed. The initial CP-RRP range offset was 7.2 m, increasing to 9.3 m by the end of the experiment. It is interesting to note that if we assume a 4.7-m rather than 4-m tether offset and a 1549 m s^{-1} sound speed, the two curves will coincide. (Although 4.7 m is reasonable—this could not be checked without sending a diver over—the sound speed is about 2 m s^{-1} higher than expected.)

Of greater importance are the differences between these two ranges, since they give us a direct estimate of the (primarily acoustic) GPS–acoustic range errors. These differences (Fig. 10), after a linear offset and trend (Fig. 9) are removed, show an overall variance of approximately 0.36 m^2 ($\sigma = \pm 0.6$ m). This variance level is well within the required limits to obtain velocity profiles with order of 2 cm s^{-1} accuracy (Leaman 1991) or better. We also note that in computing both the velocities as well as the range test, it was found to be unnecessary to resort to the highly accurate (order of 1 cm or better in position) carrier phase data. The estimated noise (rms 30–40 cm) in the L1/L2 pseudorange data was still a relatively minor contributor to the comparative (GPS–acoustic) range noise (Fig. 10).

5. Discussion and summary

In principle, it should be possible to calibrate these results against a separate measurement method, such as a standard PEGASUS station in the area. However, given the complexities in the horizontal and vertical structure of the Florida Current in this area and the differences in these methods, it would in practice be difficult to separate instrumental errors from simple natural variability in the currents.

Nevertheless, these results suggest not only that a combined GPS–acoustic approach to measuring ocean current profiles is feasible but that a level of accuracy comparable to existing acoustic profilers (e.g., PEGASUS) can be achieved. In particular, Polaris is relatively immune to the permanent systematic errors, which can arise due to errors in surveying locations of bottom-mounted acoustic transponders. Remaining errors are random (noise in positions and acoustic range data, noncollocation of transducers and GPS antenna, buoy motion, etc.) and these can be reduced to an acceptable level with sufficient vertical smoothing. It is important to note that in a high-noise environment, such smoothing would reduce the amount of detail seen in the profile; however, the relative absence of systematic errors would reduce any potential bias in other important quantities, such as the vertically averaged current (or transport per unit width).

We are now modifying this system to proceed from the relatively unwieldy test components described above to a system that is more suited to operational use in experiments. This involves a significant redesign of the RRP buoy to make it lighter and easier to launch, streamlining of the existing probe (PP) unit to remove problems such as potential kiting, and design and fabrication of an expendable version of PP.

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