Location and Recovery of Lost Instruments Using Acoustic Targets

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Abstract - **Despite the increasingly reliable techniques and technologies developed by the oceanographic community, the all too frequent failures of instruments and moorings to surface on command remains a problem. The loss of both equipment and data is costly to the community. In our experience, the effort to locate and recover lost equipment, even in shallow water, has often been futile and costly. In this paper we describe a low-tech, approach that we have developed and used to recover two lost instruments. Our approach utilizes passive acoustic targets, side scan sonar, and divers. A large research vessel is not required, the targets can be readily manufactured from stock material, and, in deeper waters, ROVs can replace the divers.**

I. BACKGROUND

In 1994 we were involved in several overlapping research programs taking place off the Outer Banks of North Carolina. We had deployed a large (6m), instrumented BASS (Benthic Acoustic Stress Sensor) tripod in 20m of water approximately 5km offshore of the Army Corps of Engineers Research Facility in Duck, NC. Colleagues had deployed a bottom mounted ADCP (Acoustic Doppler Current Profiler) in a 3mx2mx1m trawl resistant frame a further l0km offshore in 25m of water. The ADCP system was a one of a kind prototype. The cost to replace either instrument was approximately $100,000 (US).

The BASS tripod was equipped with two independent recovery systems. Each system employed a bum wire to release a rigid float string on receipt of a coded acoustic command. The floats carried lift lines to the surface that could be used to recover the tripod. The ADCP frame included compressed air cylinders and inflatable lift bags that could raise the entire platform to the surface for recovery. Bag inflation was triggered acoustically by sending a signal to a commercial release. Triggering the release freed a heavy spring, mounted in a plastic tube, to open a valve and inflate the bag.

During the first of several recovery cruises for the tripod, both recovery systems were triggered multiple times. Neither float string appeared on the surface. This may be a familiar scenario to more than one reader. The authors dove on the known GPS position of the instrument and swept out a portion of a 30m (radius) circle around an anchor pivot before dwindling air supplies forced the abandonment of the search.

On a subsequent cruise, several hours after multiple acoustic triggers were sent, one float reached the surface at dusk. Recovery was postponed until morning because of deteriorating visibility. By morning the float had vanished and one of us (Morrison) and a colleague again dove on the GPS position, sweeping out another circular search pattern with a rope. Dwindling air supplies again forced the abandonment of the search.

Attempts to improve on the GPS position by triggering the release mechanism's transponder with a pinger on the ship's inflatable, while triangulating on the response at the research vessel, failed because of uncontrolled ship drift. Detection with the vessel's depth sounder was similarly unsuccessful. We chose to forego the use of a grapple, because of the difficulty involved and the risk of damage to the equipment.

The ADCP suffered a similar, if somewhat less dramatic, fate. While the acoustic release was responsive to the deck unit, the platform did not return to the surface after multiple attempts. No divers were present on the cruise and no immediate search or follow-up recovery cruises were conducted.

II. UNDERSTANDING THE PROBLEM

After the frustrating failed attempts to recover the tripod in 20m of water we came to the realization that the problem was not so much the localization of the equipment nor its physical recovery, but the link between those operations. Put another way, we were unable to translate the information we had at the surface to information useful to divers on the bottom. Bottom time is limited and can easily be exhausted if it is necessary to search even a small area.

Consider that the GPS position of the tripod was fairly well established, optical visibility while diving was as high as 3m to 4m, the bottom was sand and mud, free of growth and rocks, and the depth was well inside diver limits. We dove several times from ships of opportunity and searched large circles, pivoting around an anchor with a sweep line. The anchor was placed from the ship based on the GPS position. Yet, although

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we knew almost precisely where the tripod lay (localization), we were unable to attach a lift line (recovery).

At face value the situation seemed absurdly simple, thus our frustration. The tripod was only 20m down and we had a GPS fix from the deployment. Recovery should have been a straightforward exercise, yet we were unable to even find the equipment. Of course, those readers with long experience will recognize and appreciate the actual difficulty of this seemingly simple task.

More realistically, the actual accuracy of the original differential GPS fix, acquired when the tripod was deployed, was inherently no better than 10m; the reference station for the differential signal was more than 30km away. The error was probably larger given the distance and variable bearing from the GPS antenna to the launch point on the starboard side of the vessel. Further error was introduced by the time difference between the GPS fix logged on the bridge and the actual release of the tripod from the crane. Similar errors are associated with the placement of the pivot anchor.

Diver disorientation and drift, ship's drift, and the finite time between location fixes and diver actions, while trying to carry the imprecise surface information to the bottom, also contribute, particularly if the divers place the pivot. For example, during one brief dive in these waters one of us (Morrison) and a diving safety officer entered 20m of water directly from the starboard side of a moderately large research vessel. They descended straight 'to the bottom to compare some gauges with the ship's depth sounder. They ascended "straight" to the surface less than five minutes later, approximately 500m from the port side of the vessel. The larger the area that has to be searched, the more unlikely it is that divers with limited-bottom time will be able to complete the search. The reliability and repeatability of such a search is also in question.

The critical points to be made here are, first, that surface information is probably not as precise as we would like to believe. Second, and more importantly, even with precise surface knowledge, the problem of transferring that knowledge to a bottom system that could then reliably attach a lift line remains. The search burden placed on the bottom system has to be reduced to some realistic level. Note that all of these problems exist, in varying degrees, if GPS is replaced by ship mounted or towed sonar or if the divers are replaced by ROVs or grapples.

Obviously both problems could be avoided by using a 'high-tech" search system such as an ROV or manned submersible with its own sonar and possibly an acoustic navigation network on the bottom. However, the cost of such a system, particularly compared to the cost of the lost instrument, is often prohibitive. This was certainly so in our case. After the first recovery attempt failed we were essentially dependent on ships of opportunity to pursue our recovery efforts.

We needed a system based on inexpensive and readily available or easily manufactured components that could realistically address the localization and linkage problems as outlined above.

A portable, towed, side scan system was available, at nominal cost, from a pool of instruments maintained by the Coastal Research Center (CRL) of the Woods Hole Oceanographic Institution (WHOI). The side scan could almost certainly locate the instrument, but that position information was relative to the tow fish. The position of the fish relative to the ship at any given moment would not be well known. Side scan alone would provide little or no improvement over the GPS information, which we already knew to be inadequate.

However, by using acoustic targets in conjunction with the side scan we were able to solve both problems.

III. LOCALIZATION AND LINKAGE WITH ACOUSTIC TARGETS

Our method uses a pair of sonar reflecting anchors, each attached to a surface float by a light line sized for minimal scope. The anchors were fabricated in the WHOI welding shop from 3/8" mild steel plate. One of the anchors is shown on the deck of the recovery vessel in Fig. 1. The anchors are the acoustic equivalent of the comer-cube radar reflectors found on most small and large vessels. Geometrically they are simply the top half of such a reflector.

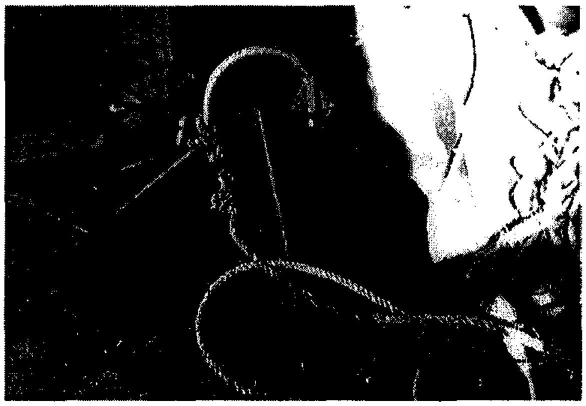

Fig. 1: SONAR REFLECTING ANCHOR - The material is 3/8" mild steel plate. The anchors are approximately 40cm along each side and 21cm tall at the peak below the lift point. Each one weighs 48lbs (22kg). The dimensions reflect a balance between signal return strength and directionality.

We chose the dimensions with attention to several competing factors. Maximizing the strength of the return echo makes the anchors easier to image and is therefore desirable. Increasing the size of the reflector increases the echo strength, but it also increases the directionality or focus of the echo beam. This is simply a result of the antenna equation, which says main lobe width decreases with increasing aperture [l]. The practical consideration here is manufacturing tolerance; if the focus is narrow and the planes of the reflector are not orthogonal, the return echo will miss or only graze the transducer on the tow fish. This would reduce the strength of the return echo and make it difficult to detect at any distance, just as the wide, weak return of a small target would be difficult to detect. The anchor also needs to be sized for handling.

The sonar could be operated at either 100KHz or 500KHz, acoustic wavelengths of 1.5cm and 0.3cm. Patently only a reflector that was "many" wavelengths wide would provide sufficient signal return strength to stand out clearly on the sonar record. Therefore the angles between the planes of the anchor would have to be fairly precise. The WHOI welding shop was able to manufacture both anchors in the space of a few hours to an angular precision better than 1^0. In practice we found that the anchors were clearly visible at both 100KHz and 500KHz. However, they were easier to distinguish from natural objects (e.g., rocks) at 500KHz. At the higher frequency the return echo was more focused and produced a clear hyperbola on the side scan record, a characteristic of a strong point source [1]. (As the tow fish travels in a straight line past a point target, the finite angular width of the main lobe, oriented at a right angle to the line of travel, passes over the target. The slant range from the transducer is largest when the edge of the main lobe first encounters the target. The range decreases to a minimum as the center of the main lobe paints the target and then increases again. The geometry is such that the range curve is a hyperbola. Distributed targets, such as our tripod, do not generally exhibit an obvious curve because of the interference of returns from several different parts of the structure.)

Using the anchors to locate and recover a lost instrument is an iterative process. An initial side scan tow past the site images the lost equipment and produces a rough GPS position. That position is obtained by estimating (guessing) the location of the tow fish relative to the ship's antenna. That offset is combined with the measured side scan range offset and applied to the GPS fix obtained as the instrument was imaged. Accuracy of a few tens of meters is sufficient, although increased accuracy will shorten the process. If desired, the GPS to tow fish offset can be measured by making side scan passes in opposite directions and differencing. In practice, we did not find this to be necessary. In either case, estimation is easier if the side scan passes are made along north-south or east-west tracks.

Proceed to the estimated GPS position and deploy one of the anchors. A second side scan pass will now show both the instrument and the first anchor. The location of the instrument is now known relative to the anchor and the divers can reach the anchor simply by following the line from the surface float. Significantly, this relative error is completely independent of all the previous localization errors. In fact, the absolute and relative locations of the ship, the GPS antenna, the tow fish, and the instrument are no longer relevant.

Now use the offset between the first anchor and the instrument, as measured by the side scan, to make a relative placement of the second anchor. The placement is simply done by hand and eye relative to the first surface float. Recall that the scope of the line has been kept small. The anchor can be placed from the research vessel, but the process will be faster if the ship's boat can be used.

A further side scan pass will show the instrument and both anchors. The second anchor will presumably be much closer to the instrument. An iterative cycle of leapfrogging anchor movements and side scan passes is then followed until the acoustic images of the instrument and one of the anchors converge. Again, note that the errors making localization difficult have all been rendered harmless. They affected only the "initial guess" that started the iterative process and were irrelevant thereafter.

Finally, divers with a lift line descend to the anchor along the float line, a physical link carrying the now precise surface information provided by the side scan to the divers in a form that is useful at the bottom.

IV. YES, BUT DOES IT WORK?

We applied this approach to the location and recovery of the BASS tripod and the trawl resistant ADCP in early November of 1994. On November 2 we departed Norfolk, VA on board the R/V Cape Hatteras for the transit to the 20m site where the tripod lay. The ship's schedule would allow us only one day on site. We arrived on station at 0400 on November 3 and began operations. Given our inexperience operating side scan sonars, we made several initial passes along both north-south and east-west tracks, imaging the tripod on each pass and estimating the position from the ship's GPS. The positions varied, but all fell inside a circle of radius 50m. We were very fortunate in having a flat, nearly featureless bottom with no other strong targets in the vicinity of the tripod. The multiple passes also allowed us to refine our communication procedures with the bridge as we waited for first light. The refinements improved the timing, and therefore the accuracy, of the GPS fix. Fig. 2 is a copy of the hand annotated side scan record from one of these passes. At dawn we placed the first anchor at 36°11.875'N 75°42.40'W from the deck of the R/V Cape Hatteras. We then made another set of side scan passes, trying to image both the tripod and the anchor. These passes were made operating the side scan at 100KHz with a cross track range of 100m to either side. The results were somewhat ambiguous with several false returns. We attribute this entirely to our inexperience. We assumed, incorrectly, that one of these was the anchor. The eastbound pass is shown in Fig. 3.

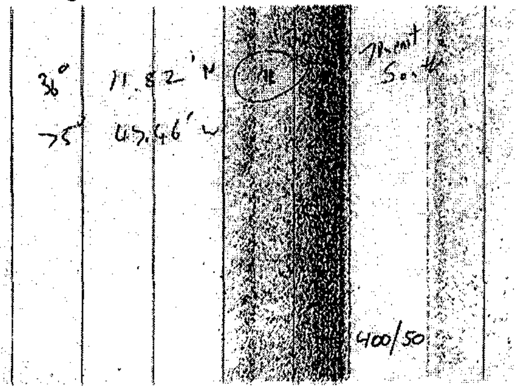

Fig. 2: SIDE SCAN PASS IMAGING THE TRIPOD - This is a copy of the hand annotated side scan record (thermal paper strip chart) of one of the initial imaging passes. The ship was on a southward track (towards the top of the figure). The ship track is centered on the vertical white strip with the "400/50" notation. Sonar returns appear to both the left (port, east) and right (starboard, west) of the track. The 400/50 notation indicates the full-scale range to either side was set to 400m and the distance between range lines was 50m. The range lines are the equally spaced vertical lines to either side of the track. The full extent of the record to left and right is not shown and the cropping was done asymmetrically. The tow fish cable was positioned off the starboard side of the fantail with the crane. Bubbles and turbulence in the wake of the RN Cape Hatteras cause the strong (dark) return on the port side. The tripod is circled and lies ~70m to the east of the ship's track. The GPS position is marked. The strong returns may be from the air filled pressure housings. There were no other strong targets near the tripod.

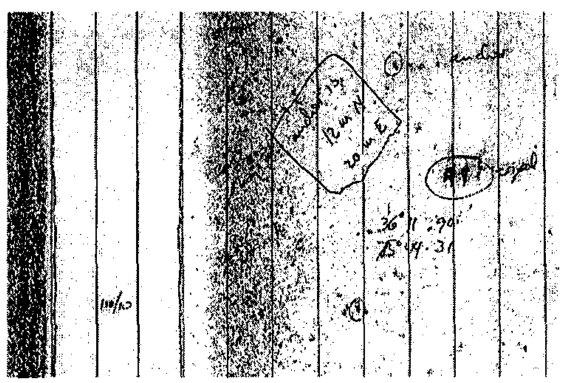

Fig. 3: IMAGING THE TRIPOD AND THE FIRST ANCHOR - The ship is on an eastward track and the range lines are spaced 10m apart. The tripod is circled and labeled. Two false anchor returns are also circled. The one we assumed was the real anchor, 23m ENE of the tripod, is also labeled.

We later determined that the ambiguity arose because the ship track was too far from the targets. Only the tripod was within the 100m range for which the side scan had been set; none of the returns was the anchor, which was actually about 30m WSW of the tripod.

We placed the second anchor about 20m WSW of the first, judging the distance and direction essentially by eye. This placement was made from the inflatable launch of the RN Cape Hatteras with some assistance from a spotter on the bridge of the larger vessel.

The next side scan pass was made eastbound and closer to the targets. The acoustic frequency was still set at 100KHz, but we had extended the range to 150m on each side of the track line. This pass is shown in Fig. 4.

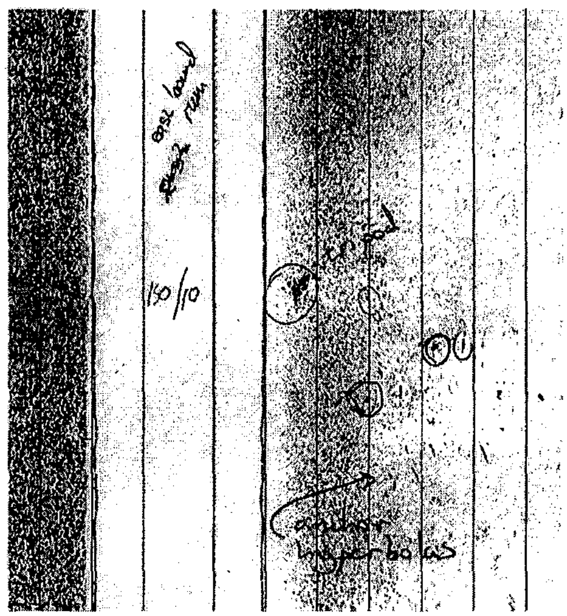

Fig. 4: TRIPOD AND BOTH ANCHORS AT 100KHz - The ship is on an eastward track and the range lines are spaced 10m apart. The tripod is circled and labeled. The anchors are visible SW of the tripod. Note the faintly visible hyperbolas. This time there was no ambiguity about the location.

This time there was no ambiguity about the anchors. Although faint, each anchor produced a clear hyperbola in the side scan record. The anchors were actually SW of the tripod. We changed the side scan frequency to 500KHz, hoping for a clearer picture, and were rewarded on the next pass. The westbound track is shown in Fig. 5. While the anchors are more apparent at this frequency, the tripod is somewhat fainter. There are benefits to having more than one frequency available.

The misplacement of the second anchor was now clear and also easily correctable. It was also apparent that we were learning and improving with practice. Using the inflatable, we moved the second anchor, which was somewhat further from the tripod, using the surface float of the first anchor as a reference. The second anchor was moved to a position approximately 25m NE of the first anchor. Again, this was done by eye from the launch with assistance from a spotter on the R/V Cape Hatteras. The side scan pass that followed is shown in Fig. 6.

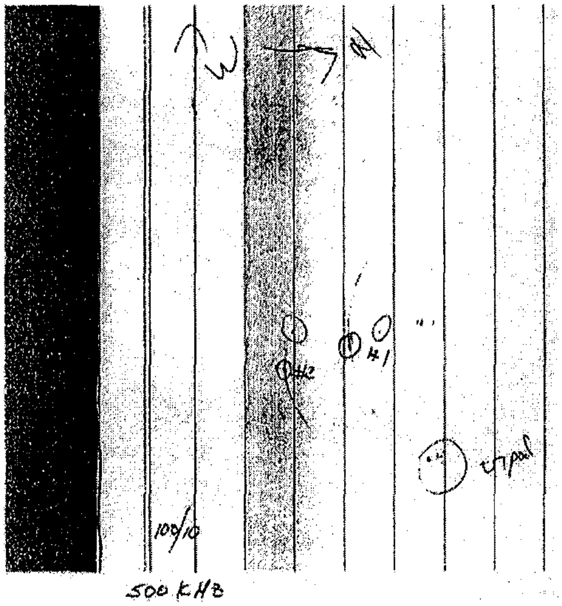

Fig. 5: TRIPOD AND BOTH ANCHORS AT 500KHz - The ship is on a westward track and the range lines are spaced 10m apart. The tripod and anchors are circled and labeled. Note the clear, unambiguous, hyperbolas produced by the echoes from the anchors. Note also that the tripod is fainter at this frequency and that the bubbles in the wake of the ship are brighter.

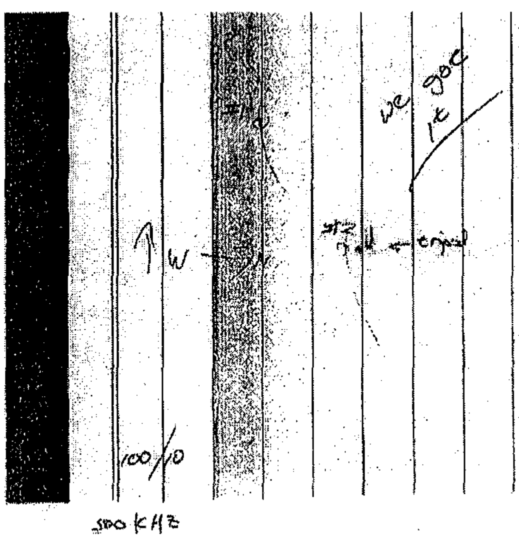

Fig. 6: CONVERGENCE - The ship is on a westward track and the range lines are spaced 10m apart. Both anchors are clearly identified by hyperbolas. The second anchor appears to have converged with the tripod. The notation to the upper right says it all.

The echoes of the second anchor and the tripod had converged, essentially on the first iteration (the first iteration after we figured out what we were doing).

The authors dove from the inflatable, following the line from the surface float down to the second anchor. We trailed a lift line and carried a shackle and a wrench with us. At the bottom the lifting bail of the tripod was easily located only 40cm from the anchor. We attached the lift line and proceeded to inspect the instrument.

The tripod was lying on its side, trapping one of the recovery floats against the bottom. The line from the float that had been seen on the surface during the earlier cruise was present right up to the eyebolt that attached it to the float. The bolt had been sheared cleanly off. We assume the propeller of one of the research vessels then in the area struck it during the night or early in the morning. The float might have been below the surface at that time, pulled under by the drag of the flood tide on the lift line. The cradle from which the float had released was at an angle that might have trapped the float even after the bum wire released it. This was due to the resting position of the fallen tripod. From other angles it could have released cleanly. The right combination of currents, perhaps during a particular direction of tidal flood, could have subsequently freed it. This would explain sighting the float on the surface some hours after the release signals were sent. From other damage to the frame it was apparent that a fishing trawler, or something similar, had struck the tripod and tipped it over.

We ascended the lift line to the inflatable, recovered the anchors, and returned to the R/V Cape Hatteras. From there we recovered the tripod without further difficulty. It was now mid morning on November 3, less than six hours after our early morning arrival on station.

The transit to the 25m site, 10km distant, occupied the next hour. The recovery of the ADCP can only be described as a text book example of this approach. We located the instrument on the first pass, based on the GPS position from the deployment cruise. We used the 100KHz acoustic frequency and a large cross-track range. The ADCP, like the tripod, was a stronger target at the longer wavelength. The extended range improved the chance of imaging the target. We placed the first anchor and achieved convergence in two iterative steps. The divers located the ADCP about 1m from the anchor and attached a lift line. The instrument was recovered without farther difficulty.

Examination showed that several fittings in the inflation lines had pinhole leaks due to localized corrosion. This may have been due to spot impurities in the brass. By the time the release was triggered there was no air left in the system. The release itself had fired, but bivalve larvae and a considerable sediment load had settled inside the spring tube. The larvae had grown larger and had developed hard shells over the months of the deployment, jamming the spring and preventing it from turning the inflation valve.

With both instruments secured on deck we headed towards Beaufort, NC, the R/V Cape Hatteras' home port, and broke for lunch. It was 1300 on November 3. We had trained ourselves in the technique, located the targets at sites l0km apart, attached lift lines, and recovered both instruments in less than nine hours.

V. OBSERVATIONS AND LESSONS LEARNED

Several caveats and observations are in order here. We were more than a little fortunate to have lost the tripod and the ADCP in such uncluttered terrain. The nearly complete absence of strong false returns aided us significantly and we freely concede that the recovery cruise would probably not have been as smooth or as successful if the bottom morphology had been more complex. However, that does not mean this method is inappropriate over more complex terrain, only that a more experienced side scan operator may be required to separate the true targets from the false in the record.

It should be noted that, while we were working in favorable terrain, we had no prior experience operating side scan sonars or interpreting their output. Further, we had no prior experience applying the new approach. We were still completely successful. Note as well that there are a number of active, shallow water experimental programs intentionally located in uncomplicated terrain. There will be lost instruments to recover from similar circumstances in the future.

The addition of a passive reflector to an instrument package would greatly improve its visibility at minimal cost. The reflector would be particularly helpful in cluttered terrain because the target, like the anchors, would stand out from other targets by exhibiting a hyperbola in the sonar return.

This approach would probably be difficult to apply in continental slope and deeper waters. In those cases remedies involving more costly, sonar equipped ROVs or manned submersibles may be necessary. However, we think our approach will suffice for continental shelf waters, with low-cost, video-only ROVs replacing divers below 40m depth. Placing anchors on either side of a target instrument might also facilitate grappling since the surface floats could provide some terminal guidance to the vessel.

Lost instrument recovery is not an inexpensive operation and those costs need to be weighed against the potential benefits. One obvious cost associated with our approach is the side scan sonar. Side scan systems are readily available today. Some portable units can be purchased for as little as $10,000 (US). Units are also available for rent. Even the fairly advanced unit we had access to could be operated successfully, at least at a basic level, with relatively little training and experience.

Another obvious cost is ship time, which varies depending on the situation and requirements of the recovery. Our approach reduces search time, making much more efficient use of the research vessel. It is also quite easy to operate the side scan system from a small boat. We were able to run it successfully from a 25' dive boat charter at one point. All of the work of locating the target and attaching a lift line and marker could be accomplished from such a craft very inexpensively. A large research vessel would only be required for the actual recovery, a relatively fast operation when lift lines are already in place.

There are several important benefits to recovering a lost instrument. First there is the instrument itself, which is generally expensive and often irreplaceable. Then there is the data set, which can be enormously valuable and can never be replaced if lost.

A more subtle benefit, one with long term ramifications for future instruments, is the knowledge gained about the mode of failure. In the case of the ADCP, a prototype, our colleagues were able to identify the weaknesses in their recovery system and improve their design. This will prevent multiple expensive losses in the future. We have added greater redundancy to our recovery system, with an improved float system that is generally not dragged under water by currents and that can release cleanly from the tripod over a much greater range of angles [2]. This approach has already saved us from undertaking several search and recovery cruises.

Finally, we do not wish to claim that our method is the only answer or even the best answer in all situations. We think it is a good answer and one that we feel confident recommending. The approach falls into the broad category we call "nickel knowledge". Nickel knowledge is the sort of information that is derived from experience and shared among practitioners, often simply by word of mouth. It is seldom codified in a textbook, but once learned it can make a job easier or more likely to be successful. Oceanographic engineering is a field particularly rife with nickel knowledge. This is just one more piece.

ACKNOWLEDGMENTS

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