

Technology of Water Flow Measurement Represented by Thirty Years of CMTC

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Abstract- The Current Measurement Technology Committee or CMTC joined the IEEE Oceanic Engineering Society in the 10th year of that society and CMTC workshops have continued through its 9th workshop held in 2008. These workshops have documented with their published proceedings the rise of acoustic Doppler profiling, the appearance and later development of HF radar techniques for observing surface current, electromagnetic profiling, and laser Doppler and ultrasonic point measurements of current. Workshop proceedings document the applications of the various measurement techniques to estuaries, rivers, and ports. And direct and indirect measurements of waves and turbulence have been increasingly reported. A division of practitioners of current measurement into Wizards and High Priests, Cognoscenti, and Happy Go-Lucky Users has continued at each workshop. Typically at one workshop a new technology is described, at the next workshop four or five years later, instruments resulting from the new technology have been compared to trusted older techniques, and, at the workshop after that, use of the technique in oceanographic studies is reported. Although some instruments first brought to the attention of the observational community at a CMTC workshop have now become commodities, there remain intriguing problems and solutions that are presented at every gathering. The CMTC Proceedings are a valuable record of these developments, tests, and applications.

I. INTRODUCTION

When Quebec City was founded in 1608, ship speed was measured with a chip log and sand glass and tidal currents and trade wind currents were estimated from times of ship passages. The Gulf Stream was known in the 18th century and a route to England utilizing its assist was recommended to packet boats. Surface flow into the Mediterranean at the Straits of Gibraltar had been known since antiquity but a proposal to the Royal Society to study a purported reverse flow at depth was rejected in the 18th century on the basis that it was nonsense to think that flow would go into the Mediterranean only to go back out. This attitude towards experimental science was disappearing in the 19th century and early in the 20th century direct measurement of current from a lowered instrument by Ekman obtained flow direction and force with a kind of current rose made by dropping balls into a segmented dish. Mechanical current meters with recording strip charts were state of the art in the 1960s. These were Savonius rotors and vanes or propeller and vane but concern with aliasing gave rise to the Vector Averaging Current Meter in 1969. As improvements in recording from photographic film to magnetic tape became

available, arrays of such VACMs were deployed in the 1970s. The misbehavior of the Savonius rotor to oscillatory flow was overcome for near-surface moored measurements with the Vector Measuring Current Meter, which used orthogonal sets of fan blades instead of rotor and vane. This development in 1977 and reported at the 1st CMTC workshop in 1978 was the last major thrust for mechanical current meters. After that, acoustic, electromagnetic, and Lagrangian techniques were more generally used for current measurement.

The First 400 Years:

There is no doubt that observations of sea surface currents for the purpose of survival in fishing and navigation go back in oral history to be lost in the mists of time. The first records of observations appearing in literature available to us are about the unexpected and awesome, like Lescarbot's report about the Gulf Stream, made with a thermometer:

I have found something remarkable upon which a natural philosopher should meditate. On the 18th of June, 1606, in latitude 45° at a distance of six times twenty leagues east of the Newfoundland Banks, we found ourselves in the midst of very warm water despite the fact that the air was cold. But on the 21st of June all of a sudden we were in so cold a fog that it seemed like January and the sea was very cold too [1].

Lescarbot had recorded the Gulf Stream. By the late 1700s the Gulf Stream was being documented and used to get commercial advantages in ship routing. In response to a report that mail ships were taking two weeks longer than merchant ships to go from England to New England, the Postmaster General, Benjamin Franklin, had Timothy Folger, a Nantucket Sea Captain, plot the course of the Gulf Stream, and a chart was printed by the General Post Office [2].

In 1770 James Cook was mapping the east coast of Australia near 28°S, and as was the custom, laid over for the night off the place he named Point Danger with Mount Warning in the distance behind:

"Wednesday 16th May 1770 - Winds Southerly, a fresh Gale...until 10 o'clock (ship time), when, having increased our Soundings to 78 fathoms, we wore and lay with her head in shore until 5 o'clock a.m., when we made Sail. At daylight we were surprized by finding ourselves farther to the Southward than we were in the evening, and yet it had blown strong all night Southerly" [3].

Cook had recorded the East Australian Current, which is the western boundary current that controls the climate of Eastern Australia.

One can find many such references to observations from the poop deck of a clipper ship, or from the bow of a sea-going Polynesian canoe, but it is the measurement technology that we are interested in here.

As with most oceanography, current measurement could not progress without the ability to chart longitude positions, and the invention of the marine chronometer by John Harrison was a significant step forward for the technology. There was another significant development at about the same time. Stommel (1995) notes that Laplace had written down the hydrodynamical equations for a perfect fluid on a rotating sphere in 1775 and it took more than 100 years to introduce the idea of the Coriolis Effect on ocean currents [2]. Stommel credits William Ferrel (1882) as being the first to understand the role of the Coriolis Effect on the distribution of currents caused by wind coupling [4]. In retrospect, one can see the development of associated technology, and understanding of the problem, getting ready for a period of rapid development at the end of the 19th century.

The earliest current meter that we can discover is one designed by John Elliott Pillsbury (1848 - 1919) [5]. Pillsbury was the commander of the US Coast and Geodetic Steamer, *Blake*, from 1884 - 1889 with a commission to record temperature and vector currents at various depths across the Gulf Stream at a range of transects from the Florida Straits to Cape Hatteras. In the introduction of his report, Pillsbury records his motivation:

In a vessel floating on the Gulf Stream one sees nothing of the current and knows nothing but what experience tells him; but to be anchored in its depths far out of the sight of land, and to see the mighty torrent rushing past at a speed of miles per hour, day after day and day after day, one begins to think that all the wonders of the earth combined can not equal this one river in the ocean [5].

A picture of the Pillsbury Current Meter is shown in Fig. 1. He anchored the ship at each observation station and lowered an instrument to a predetermined depth to measure the vector current and the temperature.

Four rotating cones were the basis of the current speed measurement, and the shaft drove a worm gear, whose rotation recorded the total rotation in a set period. Rotation was prevented while the instrument had vertical speed, so that the instrument could be lowered at a steady rate to the pre-determined level without rotating, and then retrieved without further rotation after the set period. The direction was determined by a vertical vane which rotated with the current, and a compass mounted on a gimbal, both of which were locked when there was vertical movement of the instrument. On retrieving the instrument, the positions of the locked compass and vane showed the current direction at the pre-determined depth.

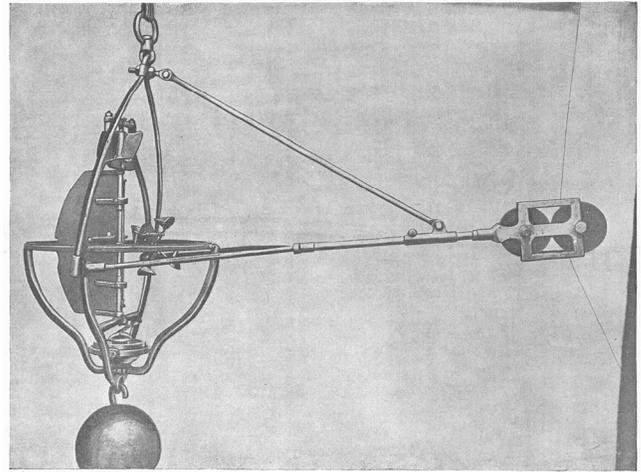


Fig. 1. The Pillsbury Current Meter (from Pillsbury, 1891) [5].

One disadvantage of the Pillsbury current meter was that the direction was measured only at the very end of the recording period: effectively at an instant. Ekman, working from Bergen, developed a current meter with rotating cups and a vane which produced a kind of current rose by dropping small metal balls at equal time intervals into a sectorized dish [6]. The distribution of the balls across the sectors gave a direct representation of the histogram of current directions.

II. CMTC WORKSHOPS

Oceans Conferences were yearly events until 2005 when we started to hold two Oceans conferences each year. But Current Measurement Technology workshops have been held less frequently: nine times in the last 30 years with a total of 347 papers and talks on current measurement technology. The growth in numbers of papers over the last 30 years at the CMTC workshops is shown in Fig. 2. These offer snapshots of the field over this period, exhibiting the initial presentation of a new technology, a difficult problem, or a new application of a technology and later the deployment in a more routine way of what had been presented earlier. Some of the most valuable contributions from the workshops have been intercomparisons of instruments, sensors, and techniques. CMTC workshops have been held every four or five years except that the 8th workshop was inserted halfway between two workshops at the normal five year interval as an experiment. The intent was to try a European rather than North American venue. The number of papers at each the 8th and 9th workshops was substantially below average. In the analyses that follow, a combination of the 8th and 9th is also presented with the assumption that the contributions were divided into the two workshops in the interval where there would normally have been only one.

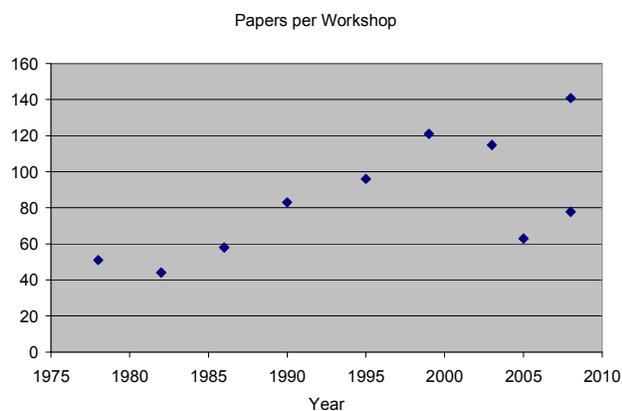


Fig. 2. The count of CMTC workshop papers has generally increased except for the last three workshops, which were closer together than the average. If the last two are lumped into a single count the trend is generally supported throughout. The sum of the 8th and 9th is also plotted at 2008 along with the 9th.

In an effort to trace and document the developments from the CMTC workshops, we have grouped papers into 46 topics. These in turn have been grouped into broad areas that share characteristics. For example, under the broad area of Quality the topics Problems, Intercomparison, Standards, and Quality Assurance have been grouped. The six broad areas are Applications, Instruments, Platforms, Quality, Remote Sensing, and Techniques, with total paper counts in each broad area of 88, 87, 41, 65, 36, and 30 respectively as indicated in Table I. Fractional numbers are assigned for those papers that span two or more topics so that each paper

summed over all topics contributes 1 to the total count. These data have been examined for trends. It must be admitted that the clientele of these workshops do not include every practitioner of current measurement technology in the world so there are inherent biases when viewed as representing the entire field.

Tabulation of Papers

In the broad area of Applications we have grouped the topics of Turbulence, Large Scale, Survey Application, Survey, Application, Tomography, Waves, Internal Waves, Rivers, Surf Zone, and Long Range. These terms are somewhat arbitrary and the distinction between Survey and Application with the mixed term Survey Application may seem a quibble but there is a distinction intended such that Survey covers the mapping of currents in a region, not as a test of a technique but rather to obtain information about the currents over that region. Application does not intend to obtain such general current information but rather fills the need of a current measurement for some other purpose such as a measure of erosional stress on sediment. Survey Application, the mixed term, is used when a measurement supporting an application is extended in space or time in the sense of a survey but not a survey of current. Distinctions of Large Scale and Long Range refer to topics stressing the measurements of current over basin scales in the former case and over full ocean depth in the latter case. The rest of the topics should be less ambiguous.

TABLE I
TOPICS AND BROAD AREAS IN CMTC WORKSHOPS

	1 st 1978	2 nd 1982	3 rd 1986	4 th 1990	5 th 1995	6 th 1999	7 th 2003	8 th 2005	9 th 2008	8 th +9 th 2008	Sum
Applications											
Turbulence	1				1	4	2	0.5		0.5	8.5
Large Scale	1	1		2	0.5						4.5
Survey Application	3	3	1		1.5		1	4.3	0.5	4.8	14.3
Survey	3		0.5	1	6.5	6	2.3		3.5	3.5	22.8
Application	4										4
Tomography		1	1	1							3
Waves				1	0.5	3.5	4.5	1.3	2	3.3	12.8
Internal waves					2	4					6
Rivers				0.5		2	5.8	1	1.5	2.5	10.8
Surf Zone								0.5	0.5	1	1
Long Range							0.5				0.5
Subtotal	12	5	2.5	5.5	12	19.5	16.1	7.6	8	15.6	88.2
Instruments											
ACM	1					1		0.5		0.5	2.5
VMCM	1										1
EMVP	0.5	1	1					0.5		0.5	3

Development	0.5		3.5	3	9	6	1	0.3	3.5	3.8	26.8
ADP		2	8.5	2.5	3.5	2	6.1	2.3	2.8	5.1	29.7
Electric Field		1		4.5	1.5						7
LDV		1									1
ADCP				2				0.3		0.3	2.3
Recorder				1							1
Correlation Sonar				1.5							1.5
Horizontal ADP						3	1				4
Ancillary Measurements						3	1	0.5	1	1.5	5.5
Wind							0.5				0.5
Acoustic Doppler							0.8				0.8
Subtotal	3	5	13	14.5	14	15	10.4	4.4	7.3	11.7	86.6
Platforms											
Profiler	2	0.5					2				4.5
Drifter		1		1	4	4	2	0.5	0.5	1	13
Volunteer Ship			0.5								0.5
Platforms				2	3	3	4.1	2.5	2	4.5	16.6
Ship							0.5				0.5
Observatory							0.5	2	2.5	4.5	5
Ice								1		1	1
Subtotal	2	1.5	0.5	3	7	7	9.1	6	5	11	41.1
Quality											
Problems	3	0.5		3	4	1	1.8	1	2	3	16.3
Intercomparison	2	1.5	6	2.5	1	4	5.8	2.8	1.8	4.6	27.4
Standards	1		1								2
Quality Assurance		4	2.5	3	3	1	1.3		4.5	4.5	19.3
Subtotal	6	6	9.5	8.5	8	6	8.9	3.8	8.3	12.1	65
Remote Sensing											
HF	1	1	0.5	3.5	5	6.5	6.6	3.3	3.8	7.1	31.2
Satellite		1							1.5	1.5	2.5
Microwave Radar		0.5							1.5	1.5	2
Subtotal	1	2.5	0.5	3.5	5	6.5	6.6	3.3	6.8	10.1	35.7
Techniques											
Data Processing	1	1		1	1	4	3.3	2	1.5	3.5	14.8
Real Time			1	3.5	0.5	1	2.5	3.3		3.3	11.8
Acoustic Telemetry				0.5	0.5			0.3		0.3	1.3
Sensor Integration						1					1
Optical								0.3	1	1.3	1.3
Subtotal	1	1	1	5	2	6	5.8	5.9	2.5	8.4	30.2
Review	1	2	4	3		1	1	1	2	3	15
Total	51	44	58	83	96	121	115	63	78	141	347

Trends over 30 Years

The original CMTC workshop addressed "...concern within the marine community about the ability of existing current measurement systems to provide accurate and reliable flow velocity information when subjected to the full range of marine environmental conditions" [7]. NOAA's Office of Ocean Engineering (OOE) sponsored this first workshop with the University of Delaware Sea Grant

College Program. Not surprisingly, Applications papers were most represented followed by Quality. Techniques, Platforms, and Instruments were much less in evidence as shown graphically in Fig. 3. The breakdown from Table I indicates that under Applications, at that first workshop, all but two of the 12 papers so grouped were on Survey, Applications, and Survey Applications; uses of existing current meters for conventional tasks like monitoring of

environmental conditions, support of offshore engineering on oil rigs and pipelines, and surveys of ocean currents for Navy needs and circulation studies. At this workshop, one new current meter and two older current measurement techniques were presented. However, there was considerable concern with Quality represented as Problems (3), Intercomparison (2), and Standards (1 instance, and only raised again as a concern once after the first workshop). Intercomparison is an essential stage in validation of quality and has had a consistent record of presentations (albeit there is some variability from workshop to workshop) while total count of papers addressing current meter quality has been consistently above 6 (almost without a defect).

The 1st workshop also introduced high frequency radar to the ocean engineering community as a technique for measuring surface current. This topic has grown steadily over the succeeding workshops from 1 paper at the 1st to a total of 7 between the 8th and 9th workshops. In addition, Microwave Radar although presented at the 2nd workshop [8], has reappeared at the 9th in two papers. Satellite Remote Sensing as applied to ocean currents has had a similar count of papers as Microwave Radar.

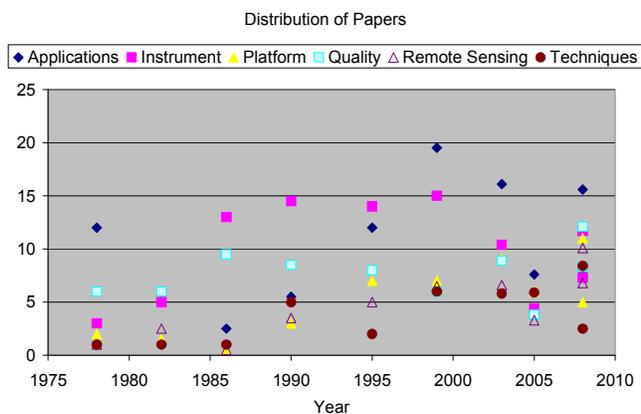


Fig. 3. The distribution of papers shows variations between workshops with Applications preeminent at the 1st symposium followed by Quality. Instruments became dominant in the 3rd through 5th, only dropping below Applications after the 5th. The 9th as well as the aggregate of the 8th and 9th are both plotted for 2008.

Instruments and Acoustic Doppler Profilers

Instruments became the dominant subject in the 3rd workshop [9] and were only surpassed again by Applications in the 6th. Instrument papers reached a total of 15 in the 4th workshop [10]. This was only in part due to the worries about performance and reliability expressed at the 1st workshop. It resulted from new technologies enabled by advances in electronics and micro processors that permitted acoustic Doppler techniques to be incorporated into stand-alone current meters. The count of papers on Acoustic Doppler instruments is shown in Fig. 4. This figure under represents the role of ADCP (Acoustic Doppler Current Profilers) as developed and marketed by RDI Inc. since these have become a standard of comparison and appear in many Intercomparison papers as either the instrument being

investigated or the standard against which another sensor, such as HF Radar, is being compared. As listed under Instruments, the ADCP, as presented in a paper about the instrument itself, is less dominant while Acoustic Doppler Profilers have appeared more often. Platforms upon which ADPs have been mounted reached a peak of 4 reports at the 5th workshop [11]. Horizontal ADPs appeared for the first time in the 6th workshop [12] but then became important for River applications so that the direct appearance under Instruments is offset in part by their presentation in papers about Rivers. This is a nice example of the transition of an instrument from presentation as a development to a use and finally to an application. In fact, if the ADP and ADCP papers are lumped and a plot is made of where the papers presenting these instruments might be grouped, Fig. 5 shows this transition.

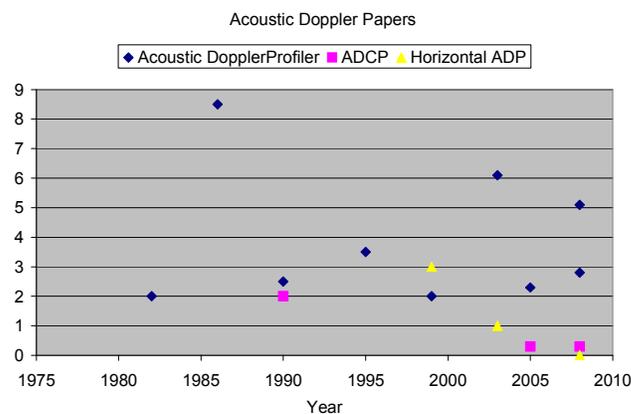


Fig. 4. The distribution of Acoustic Doppler Profiler papers among three topics shows an apparent decline in ADCP papers relative to ADP papers.

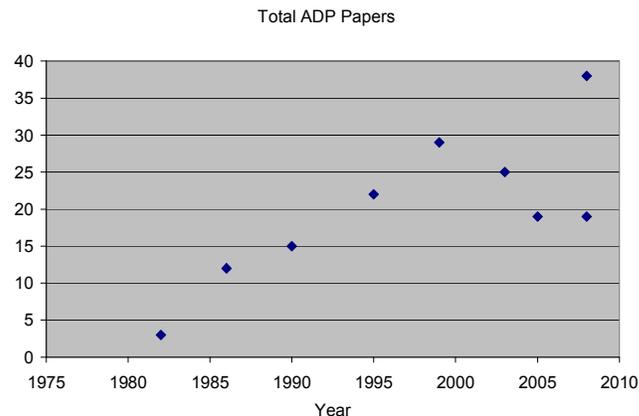


Fig. 5. The total count of Acoustic Doppler Profiler papers has increased nearly steadily since the 2nd CMTC workshop. The 8th and 9th are also plotted as a sum at 2008.

The distribution of ADP papers making up the total count is shown in Fig. 6. There is an increase in the count of papers describing Applications throughout. This is a measure of how well these developing technologies have been accepted and used in surveys and other studies. There is also a steady trickle of new instrument reports with a total of 10 instruments described in papers over the last 30 years.

Instruments papers on ADP, ADCP, and Horizontal ADP were not presented until the 3rd workshop in 1986. Techniques have the greatest single year paper count at 11 papers at the 6th workshop and this is an indication that data processing and other technique enhancements have continued after the emergence of a new instrument that adds to its capability.

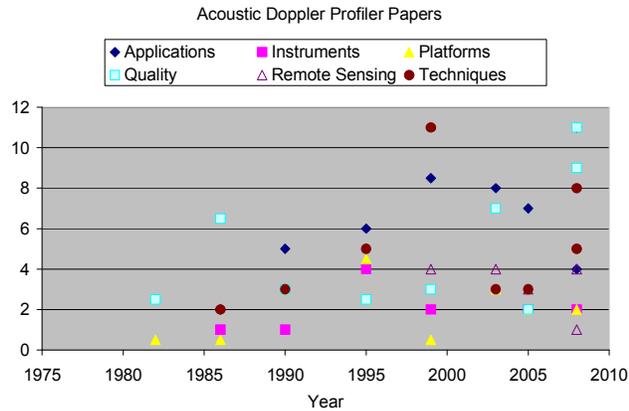


Fig. 6. The distribution of ADP papers among topic areas shows a concentration of papers in the Intercomparison and Quality topics indicated with the blue squares. Applications are next in number followed by Techniques.

The emergence of the RDI Acoustic Doppler Current Profiler as a viable tool for oceanography is an interesting story that deserves a brief history, more than can be adequately recounted here. Acoustic backscatter of sound from particles or acoustic inhomogeneities in water is Doppler shifted in frequency by the relative velocity between the acoustic transducer or transducers and the scatterer. In fact, it is the component of velocity along the angle bisector of the acoustic beams if there are two transducers or along the line to the transducer if there is only one. It has long been known that a measure of the Doppler frequency shift can reveal the scatterer velocity. What made the ADCP valuable for ocean scientists was that by ranging the transmission and reception of the sound, a velocity profile could be obtained. During the Coastal Ocean Dynamics Experiment of 1981-1982, Jim Irish and Neal Pettigrew from University of New Hampshire, asked Fran Rowe and Kent Deines to develop a self contained acoustic Doppler current profiler for upward looking current measurements and based upon the initial purchase order for this instrument, RDI, Inc. was formed. The success of this instrument known as the ADCP led to others being ordered and later versions were mounted on ships for downward measurement, a less unique application since there had been shipboard mounted Doppler speed logs by Ametek Straza before RDI. However, the profile from the RDI shipboard mounted instruments was so valuable that RDI did well and spawned other instrument manufacturing companies based upon the understanding of the technique and the expertise of the engineers from the mother company. Sontek was spun

off, initially making a fine scale single point acoustic Doppler current probe, then Nortek spun off from Sontek and they made both a single depth acoustic Doppler current meter and a Doppler current profiler. Aanderaa, long famous as the company making the greatest number of current meters ever, mechanical Savonius rotor type instruments, also developed an acoustic Doppler point current meter. These four companies have dominated the acoustic Doppler current measurement field.

Innovation in ADPs continues as higher and lower frequencies are explored, data processing extends the capabilities, and applications previously unidentified are discovered. One such is the horizontal profiling of current, useful on rivers and in harbors. The relatively narrow acoustic channel in a river or harbor is an issue since an acoustic beam hitting the surface of the water or the bottom makes the interpretation of the Doppler return ambiguous or worthless. But transducer geometries have been optimized for these tasks and they have been used successfully by many clients. Wave measurements are another frontier that has been exploited by novel transducer geometries and data processing algorithms. There have also been regular presentations on trawler proof ADCP bottom mounts over the years. In Fig. 6 these appear under Platforms along with those ADPs that have novel shipboard mounts.

Other Current Measuring Instruments

Other current measuring instruments have been reported and their developments are regularly seen at CMTC workshops. At the 1st workshop, the most recent and possibly one of the last mechanical current meters was presented, the Vector Measuring Current Meter. This was a significant improvement in many ways over the Vector Averaging Current Meter. Where the VACM had a rotor and vane with response issues to rapidly varying flow, the VMCM had pairs of fans that were little affected by such near surface waves and oscillations. One other paper on the Price mechanical current meter retrofit completed the inventory of papers on mechanical current meters.

But acoustic travel-time current meters by Falmouth Scientific and by Nobska Development have seen multiple papers, in fact the MAVS current meter by Nobska has been represented by at least one paper at every workshop since 1990. Other instruments such as the Laser Doppler Velocimeter, Electro-Magnetic Current Meter and Electro-Magnetic Velocity Profiler (EMVP) with bottom tracking sonar have been introduced. In addition to the EMVP, other profiling instruments have been presented as have drifters both surface and subsurface. A Lagrangian instrument reported upon most recently was a glider, combining drift type behavior with control and providing a platform for other sensors.

Quality has had a resurgence of interest beginning at the 7th workshop with 7 papers [13]. This was not as significant at the 8th workshop [14] but reached an all time high of 9 papers at the 9th workshop [15] for a combined 8th and 9th

sum of 13 papers, reminiscent of the worry at the 1st workshop over problems and reliability. Unlike the 1st workshop, however, at the 9th workshop the instruments were quite reliable and the worry was more about how far the measurements could be taken. Issues like power required to obtain signal when there were few scatterers, how to process data to reject spurious signals, and rejection of other noise were Quality factors under consideration.

HF Radars

HF ocean radar technology emerged in the last part of the 20th century and brought a new spatial dimension to current measurement. Instead of single-point measurements (at one geographic coordinate) we now have the technology to create maps of surface current vectors on a fine scale of grid points and with a time scale that allows us to resolve tidal effects.

The underlying physics for the use of HF radar to map surface currents was given by Crombie who was working in New Zealand on ionospheric sounding and found coherence in the clutter coming from a sea echo into his antenna side-lobes [16]. Crombie found the characteristic spectral lines at ± 0.376 Hz from the transmitted radar signal, produced by Bragg scatter from the surface gravity waves on the ocean. When the water is more than a couple of metres deep, these resonant waves follow the deep water dispersion relation and the Doppler shifts are set by their phase velocities. Any underlying current which has a component in the direction of the radar beam will impose an extra Doppler shift, and it is this offset which is used to produce surface current vectors from two radar beams acting in triangulation at the target zone.

After Crombie's work in 1955, there was a latency period before this current measuring technology was taken up in several laboratories around the world. The on-site computational load to do the A/D sampling and cope with the data volume was beyond the capability of computational equipment available then, and we had to wait until the 1970s before we had single-board computers that we could take in a trailer or van to the sea side. Through the late 70s and the 80s there was rapid growth in the applications research, and by the mid 90s commercial systems were emerging.

There are two main genres of ground-wave OF ocean radar. One uses a phased array receive antenna and offers measurements of wave directional spectra at the grid points; and the other uses a more compact direction-finding antenna system on the receiver. A more comprehensive review of the different types is given by Heron [17]. Both genres produce maps of surface currents, and a typical map taken over a ten-minute period in Great Barrier Reef waters, using a phased array system, is shown in Fig. 7. This product has no gap-filling and no smoothing in time or space dimensions.

The present trend is for data like that shown in Fig. 7 to be archived in GEOSS-compatible data archives for wider access by researchers and managers.

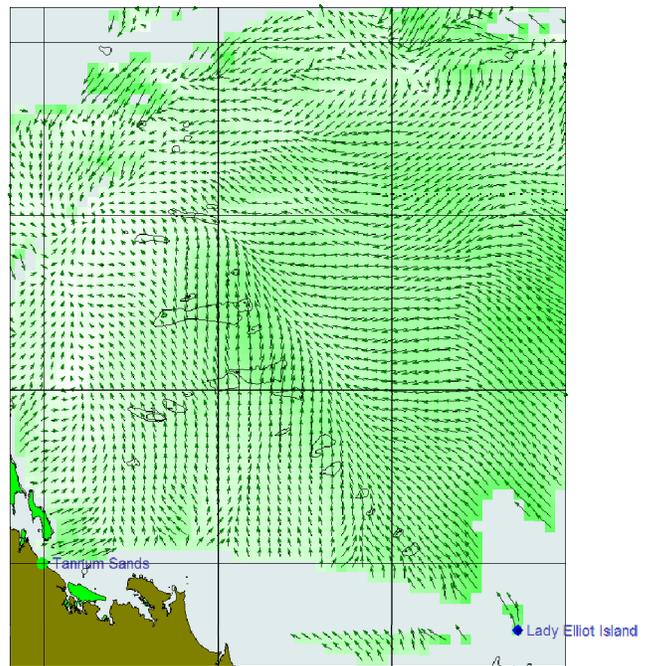


Fig. 7. A 10-minute grab of data from the WERA phased-array HF radar System operating in the southern Great Barrier Reef. The wide grid lines are at 0.5° latitude and longitude, and the grid scale for mapping is 4 km. Reefs are shown at the 10m bathymetry level. Surface currents are typically 20-30 cm/s.

III. CONCLUSIONS

CMTC workshops have provided a forum for technologists to exchange information about current measurement and to vent technology concerns over the past 30 years. These workshops with their single track format and close association between delegates and exhibitors in the second half of this period facilitate development and use of current measuring technology. However, CMTC workshops are not the only venue for these interactions. Oceans conferences also have regular sessions on current measurement technology. CMTC sessions at Oceans conferences have not been tabulated and analyzed here for lack of space and time but represent a similar but not identical set of topics. Responsibility for CMTC workshops and CMTC sessions at Oceans rests with the Current Measurement Technology Committee, one of 18 Technology Committees of the Oceanic Engineering Society of IEEE. Members of CMTC include volunteers with interest in the technology who are willing and able to solicit papers in the field, review abstracts, present papers at Oceans and CMTC workshops, and chair sessions at these and other conferences and symposia.

ACKNOWLEDGMENT

Data for Figure 7 were obtained from the Australian Coastal Ocean Radar Network archive at NCRIS/IMOS. We are grateful to the NOAA Rare Books Library for permission to reproduce the picture of the Pillsbury Current Meter.

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