Development of Smartphone-embedded Telemetry Drifting Buoy for Tracking Drifting Oil Patches in the Coastal Water and Field Test

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***Abstract*— For accurately tracking drifting oil patches, a new real time telemetry drifting buoy has been developed. The developed buoy, which utilizes Android smart phone as an electronic device for sensing and telecommunication, can provide its position and additional meteorological data such as wind velocity and direction via cellular phone communication network in real time. The developed buoy is very simple, light weight, cost beneficial as well as high performance so as to contribute to improvement of spilt oil tracking. We conducted field tests using the prototype buoys two times. In the first trial in 2012, we verified its basic function and found that our design concept was rational and found some minor modification could give the system practical usage. In the second trial in 2013, improved prototype buoys were deployed to the field test. In the field test, the buoy worked in nearshore area for many hours without human intervention nor network communication errors and supplied good-quality real-time meteorological data. The obtained data were analyzed and found very useful for tracking drifting oil patches on the sea surface since the buoy provides not only water current information but also wind information. They are also contributory to modeling horizontal turbulent diffusivity of oil patches. This paper shows the design of the buoy and the performance in the field tests. As for the application, this paper also presents a new oil tracking method using the buoy as well as discussion about turbulent diffusivity modeling.**

Keywords*— oil spill; buoy; smart phone; tracking; turbulent diffusivity;

I. INTRODUCTION

Location tracking of spilt oil is indispensable to manage oil spill response mission. For this purpose, a drifting buoy is recognized one of the good options. Based on this concept, various types of drifting buoy have been proposed and developed so far. In the early 1970's, cardboard coupons or plywood pieces were used as oil tracking tools, and were followed by more sophisticated devices equipped with radio transmitters and later satellite transmitters. Recently, advanced AUV related technologies have been introduced to a research project for developing an intelligent high-tech buoy such as a spilled oil tracking autonomous buoy (SOTAB) [1] which autonomously detects and chases the spilt oil on the sea surface.

As for the conventional oil tracking buoys which do not have self-propulsion, their drifting response to both the wind and the surface sea current is the most significant factor governing the buoys' performance. Fingas [2] reviewed a lot of field tests to evaluate the performance of various oil tracking buoys. He pointed out that except very few buoys, most buoys or devices did not have the satisfactory performance to track the oil. They move in different manner from the oil under the real sea condition. Especially, as contemporary buoys have to have much volume to have massive electronics devices built-in, they are difficult to realize quick response to the wind. To overcome this difficulty, there are several ideas to be considered. The first idea is to improve the buoy shape so as that the buoy can follow the oil like a discus. The second idea is to have the buoy equipped with propulsion function like SOTAB does. The third idea is our design concept. In it, we give up the perfect tracking but add some alternative function which can compensate the poor tracking performance instead. Fundamentally, the floating oil on the sea surface is driven by the two factors of water current and wind, so real time and on-site data of current and wind, if they can be measured, possibly compensate the poor tracking performance of the buoy by combining an oil drift simulation as shown by Fig. 1.

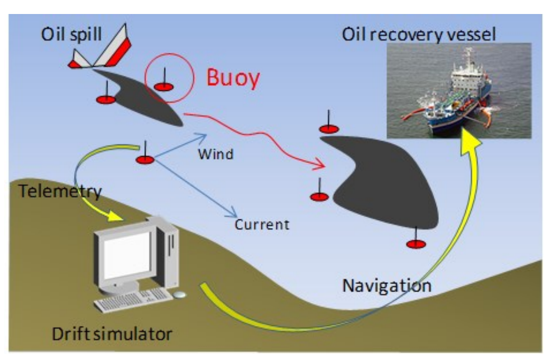

Fig. 1. Concept of real time telemetry buoy for oil tracking

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TABLE 1. MAJOR SPECIFICATION OF THE BUOY

Dimensions	
Diameter	ϕ114
Float	ϕ 480
Height	410(Body)/280(Mast)
Weight	3.6kg(Battery and drogue excluded)
Measurement items	
Location	GPS receiver(*)
Azimuth	Magnetic sensor(*)
Wind velocity	Thermal anemometer 0-15m/s
Components	
Smart phone	Google Nexus 5 (Android 4.4)
Sim	NTT docomo (MVMO)
I/O extension	Sparkfun IOIO DEV-10748
Anemometer	KOA AFS0001
Battery	48(max.) AA

(*)Built-in function of smart phone

To verify whether this concept works well or not, a new oil tracking buoy was produced and tested in this study. Our buoy has the following characteristics:

- Sea truth data acquisition function
- Real time telemetry
- Small size and simple operation
- Low cost

As for the data acquisition function, wind velocity, wind direction as well as GPS position are chosen for the measurement items. The water current is not measured directly, but can be estimated by data processing using GPS and wind vector. Real time telemetry function is implemented by using wireless phone network. An Android smart phone is chosen as the device for this purpose. This choice brought our R&D project much benefit. The smart phone offers various built-in functions such as GPS and magnetic field sensing, a well-organized development environment which leads to easy and short-term development as well as high system reliability. These advantages enabled us to achieve a low cost, small size, easy operation as well as flexibility to various research missions. .

The developed buoy was deployed to field tests to evaluate the performance by comparing to drifting rubber mats and HF radar remote current sensing. It was found that the new buoy system is contributory to spilt oil tracking and also to the relevant academic or engineering studies. This paper presents development and field tests of the buoy, as well as some applications such as oil tracking methodology using the developed buoys and turbulent diffusivity modeling.

II. DEVELOPMENT OF SAMART PHONE EMBEDDED DRIFTING BUOY

A. Overview and Mechanical design of the buoy

Basic design strategy of our buoy is to implement an oil tracking telemetry buoy at a low cost but of high performance

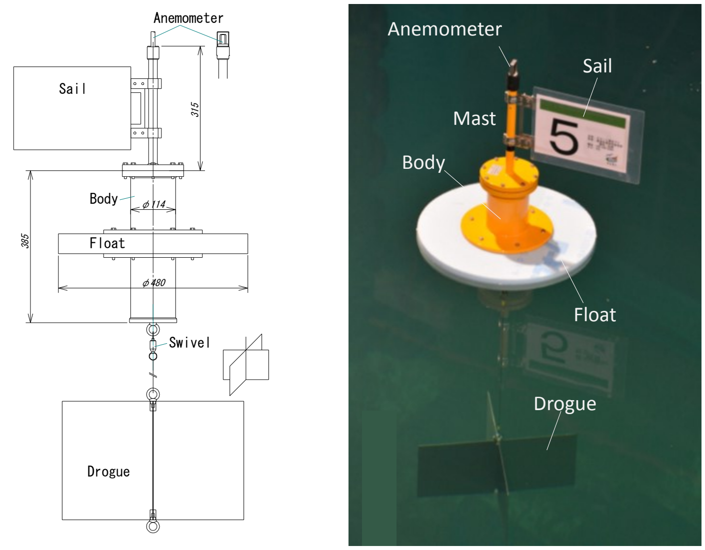


Fig. 2. Buoy exterior

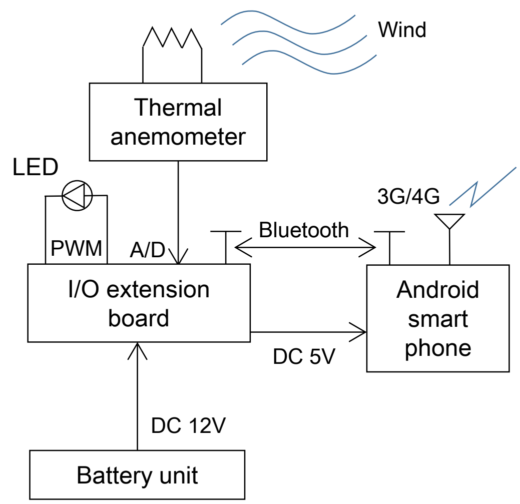


Fig. 3. Block diagram of electronics system

with simple structure and mechanism as much as possible. Specifications of the buoy are listed in Table.1 and its exterior schematic is shown in Fig. 2. The buoy consists of a body, a mast with an anemometer on its top, a sail, a float and a drogue. The body is cylindrical so as to enable the buoy freely rotate around the yaw axis. For pitching or rolling stability, the body is equipped with a toroidal float. The mast has an anemometer on its top and a vertical sail on its side. The sail is blown by the wind and forces the whole buoy face up to the wind. As for the anemometer, a platinum resistance anemometer is adopted after engineering consideration comparing to other types of anemometer such as sonic, cup, laser or pitot, etc.. This device is good for embedded system as it is simple, small as well as low-cost. However, it cannot detect the wind direction by itself. In our buoy, the sail system explained above is introduced to let the buoy face to the wind and its azimuth is detected by a smart phone built-in magnetic field sensor. A cross shape drogue is hung under the body for anchoring the buoy to the water column. A wire connecting the buoy to the

Fig. 4. Buoy interior

Left: circuit side, Right: smart phone side

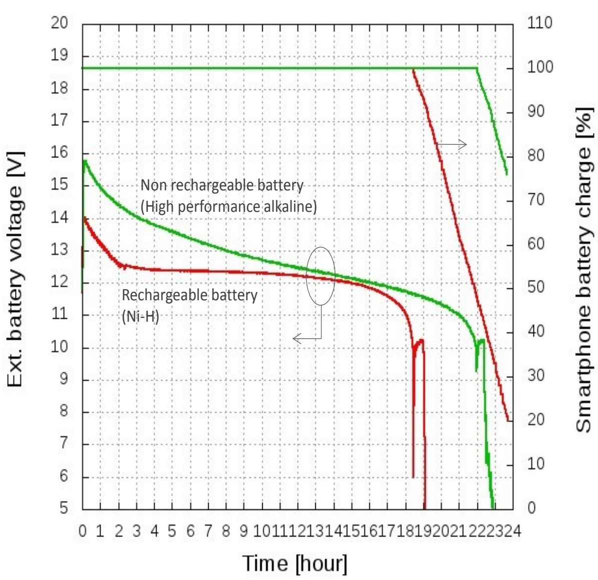


Fig. 5. Battery consumption test

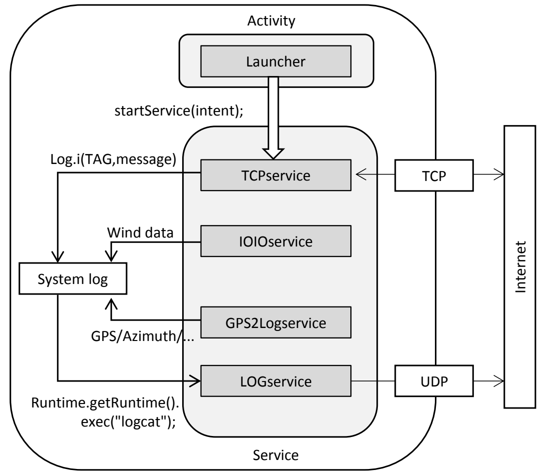


Fig. 6. Block diagram of the operation software

drogue has a swivel joint in the middle to enable the buoy's free rotation. The prototype buoy is so lightweight of 3.6kg (w/o batteries nor drogue) as to be input and recovered by an operator by hand from a boat.

B. *Electronics devices and Software*

A schematic diagram of the electronic system built in the buoy is shown in Fig. 3. As for the core computer system, an Android smart phone was used. The smart phone provides APIs that users can easily access to its internal functions needed for the buoy such as wireless internet communication, GPS signal receiving, orientation measurement as well as a Bluetooth interface which enables data communication to additional peripherals. In our buoy, as A/D conversion was needed for wind data acquisition and battery monitoring, a simple breakout board for an I/O extension of IOIO DEV-10748 SPARKFUN was prepared for this purpose. In addition to the analog input, PWM output function is also used for illuminating a LED on the mast for the night use. As for the power supply for the prototype model, AA batteries were chosen for efficient accumulation in a cylindrical inner space of the body. The interior of the buoy is shown in Fig.4. The number of the batteries is 48 at most, but is adjustable depending on the mission term. Fig. 5 shows an example of battery consumption test using 24 (half the maximum) batteries. The remaining battery capacity can be monitored with the voltage and also the internal battery indicator of the smart phone. If allowable operation time is defined as the time until the smart phone begins to consume its internal battery, 18 hour (36 hour with max. batt.) operation is possible in case of Ni-H rechargeable battery, and 22 hour (44 hour with max. batt.) is

LIST 1 TELEMETRY DATA EXAMPLE

```
12-28 14:54:08.446 I/PARI_BUOY_05( 3219): <GPS>35.31436446,139.36597029,46.0,3.0,0.0,0.0,1388210053000
12-28 14:54:09.226 I/PARI_BUOY_05( 3219): <AUX:WIND>2.0290322 0.04018073                    //Wind velocity data
12-28 14:54:09.226 I/PARI_BUOY_05( 3219): <AUX:EXT.BAT>12.612904                            //External battery voltage
12-28 14:54:09.236 I/PARI_BUOY_05( 3219): <AZIMUTH/MAG>92.996544 -24.601746 -37.265015 1.2878418 //Azimuth information
12-28 14:54:09.246 I/PARI_BUOY_05( 3219): <ACCELERATION>0.08041382 9.823578 0.36094666
12-28 14:54:10.204 I/PARI_BUOY_02( 3206): <PHONE SIGNAL STRENGTH> -83dBm 15 asu             //Radio wave signal strength
12-28 14:54:15.284 I/PARI_BUOY_03( 3231): <GPS>35.31433273,139.36597809,35.0,3.0,0.0,0.0,1388210054000 //GPS information
12-28 14:54:13.422 I/PARI_BUOY_01( 2902): <GPS>35.31434241,139.36598143,37.0,5.0,0.0,0.0,1388210054000
12-28 14:54:09.486 I/PARI_BUOY_05( 3219): <GPS>35.31436445,139.36597028,46.0,3.0,0.0,0.0,1388210054000
```

expected in case of high-performance alkaline non-rechargeable batteries.

Operation software for the smart phone embedded in the buoy is developed using the Eclipse IDE for Android Java on a Linux PC platform. The block diagram of the software is shown in Fig. 6. In the buoy operation, the program should continue to run without physical human interaction such as panel touching, “intent service class”, something like a background job or a daemon process, was used for implementing each component without “Launcher class”.

The acquired data and system status are logged in a system logfile and simultaneously transmitted with UDP to a server machine via the Internet. A data example received by the server is shown in List 1. Each line presents a acquired data which begins with time stamp followed by buoy ID, data tag and data strings which can be easily converted to other formats with a simple shell script or an oneliner including grep, sed or gawk commands.

III. Field Test and Discussions

A. Function verification

To verify whether the developed buoy works as we expected or not, field tests were conducted two times in Yokosuka coastal area (2012) and in Hiratsuka coastal area (2013) as shown in Fig. 7. The test areas were both included in the cellular phone network area on the sea. The first trial using a single buoy, mainly intended to check the basic functions and find points to be improved. The test proved that our basic design concept was reasonable and minor improvements such

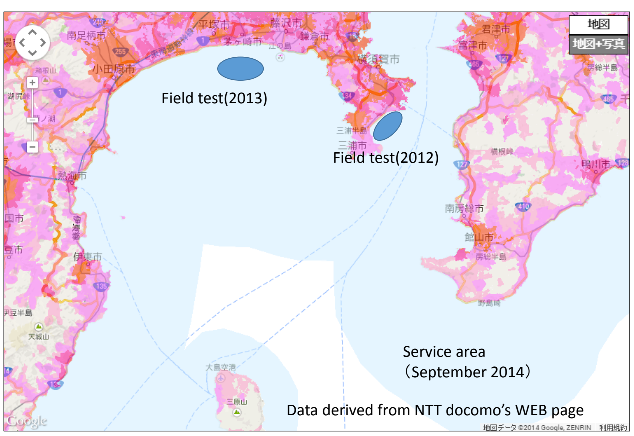


Fig. 7. Field test site and network area for cellular phone on the sea

as float addition to stabilize the buoy motion or software modification would bring practical usage to the buoy. The lessons learned from 2012 test was fed back to the design of the 2013 model.

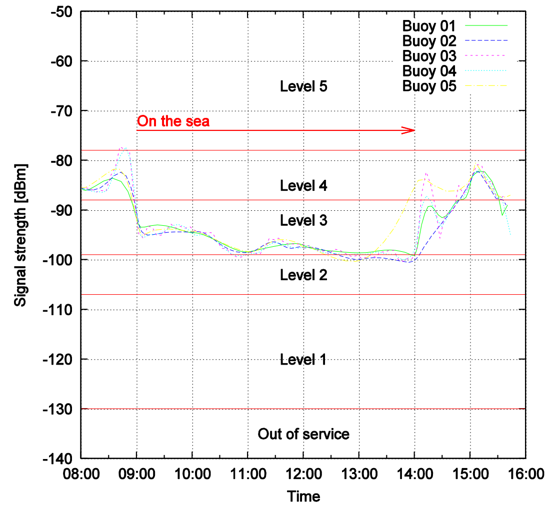
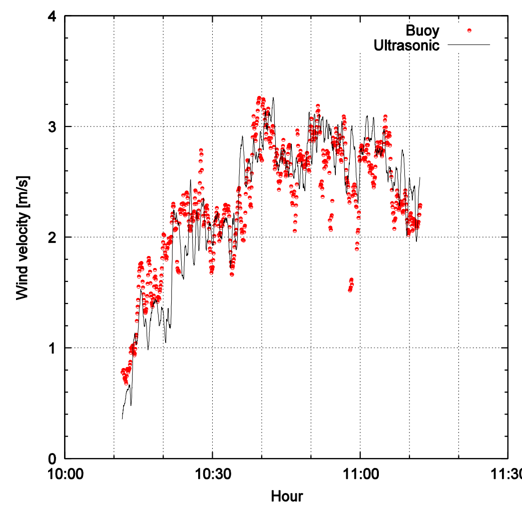
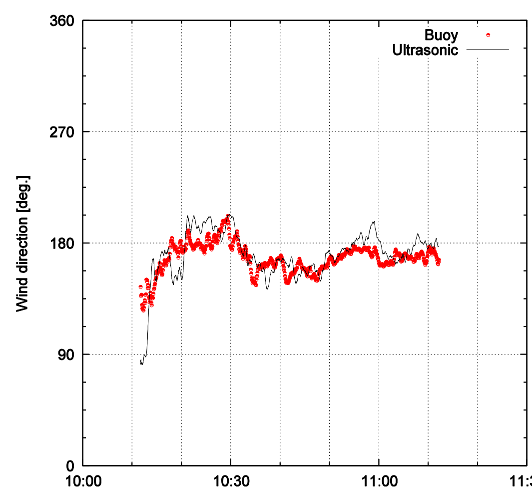


Fig. 8. Wireless telecommunication signal strength on the sea



(a) Velocity



(b) Direction

Fig. 9. Comparison of wind data between the buoy and ultrasonic anemometer.

Elemental evaluation of the 2013 model is given here. Fig. 8 shows a wireless telecommunication signal change while the field test using 5 buoys 1.3-3.5km offshore on Dec. 27th 2013. From 9:00 to 14:00, buoys were on the sea and during the rest of the time, were on the ship. It was found that though the wireless communication signal became weaker when the buoys were on the sea than on the ship, its strength was still kept high above the minimum level needed for the tele-communication (-130dB). It was also confirmed that data transmission successfully continued at the average speed of 400byte/sec and had no long term data loss nor no system halt.

As for the wind measurement, wind measurement comparison between the buoy and ultrasonic anemometer installed on the mother vessel is given. Fig. 9(a) compares their velocities and shows that buoy data was scattered a bit wider but had good agreement to the ultrasonic measurement data. Fig. 9(b) gives the wind direction and shows that correct wind direction was measured by the buoy and the sail-drive rotation mechanism worked successfully.

The developed buoy does not measure the water current directly, however, it can estimate the current vector by combining the GPS data and the wind data. Assuming that the buoy position **X** changes linearly depending on the current and wind, the current vector **W** can be estimated by:

$$\mathbf{W} = \frac{1}{D_{wat}}\left(\frac{d\mathbf{X}}{dt} - D_{win}\mathbf{U}\right) \qquad (1)$$

where, U is the wind vector, D_{wat} and D_{win} are drift factors by the water current and the wind, respectively. D_{wat} is unity (=1.0) and D_{win} depends on the buoy parameters.

The sites of the 2013 test is covered by a HF radar current measurement system operated by Japan Coast Guard whose area and the 2013 test field are given in Fig. 10. Applicability of (1) to the current estimation was tested using the JCG's HF radar data. Correlation coefficient between the current estimation by (1) using buoy data for 6 days and the HF radar measurement was calculated with various D_{win} as a tuning parameter. Fig. 11 shows the correlation coefficient depending on the wind factor. It is found that the highest correlation of 0.76 is obtained when D_{win} is 0.1, which means that the buoy is drifted by the wind at the rate of 0.1 of the wind velocity. Fig. 12 shows a scatter plot of the current velocity measured by HF radar and the buoys, and tells that that wind effect correction defined by (1) can provide a good current estimation to the buoy system.

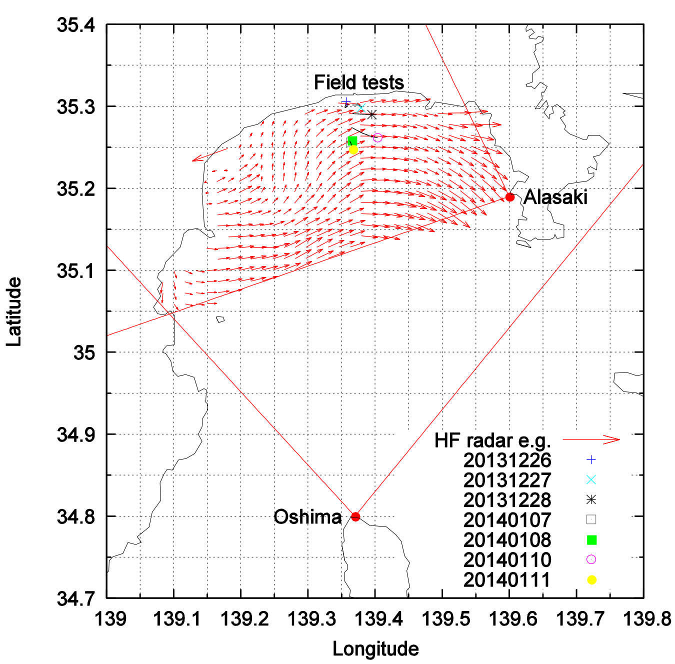


Fig. 10. JCG HF radar system for current measurement in Sagami bay

B. *Oil tracking method*

In this section, oil tracking method using the developed buoys is discussed from the field test results. In the 2013 tests,

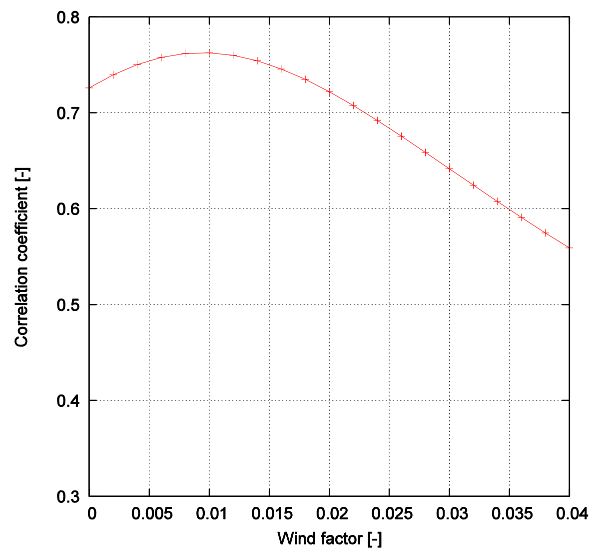


Fig. 11. Relation between correlation coefficient and wind factor

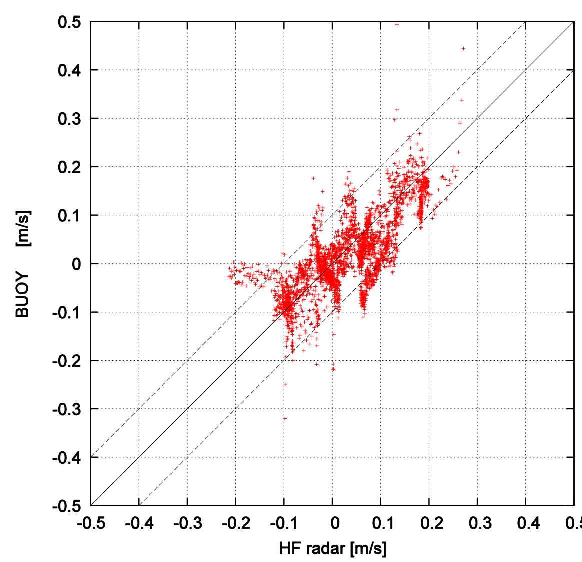


Fig. 12. Scatter plot of wind velocity measured by HF radar and buoy

thin rubber mats equipped with GPS logger as shown in Fig. 13 were deployed as pseudo-oil to simulate floating oil patches and compare their drift movement with the buoy movement. An example of the drift trajectory plot is given in Fig. 14, which observes quite different drift behaviors between the rubber mats and the buoys.

As this discrepancy is caused by the difference of sensitivity to the wind, the rubber mats movement may be possible to be estimated by taking wind drift effect into account. Assuming a situation that the buoy is dispatched on the same position of the oil patch at a certain time, the wind and the current field can be regarded spatially uniform, the oil has the same current drift factor as the buoy has 1.0, the subsequent position of the oil patch $\mathbf{X}_{oil}$ can be estimated using the buoy position $\mathbf{X}_{buoy}$ and the wind vector $\mathbf{U}$ like:

$$\mathbf{X}_{oil} = \mathbf{X}_{buoy} + \Delta D_{win} \int_0^T \mathbf{U} dt \tag{2}$$

$$\Delta D_{win} = D_{win}^{oil} - D_{win}^{buoy} \tag{3}$$

where, ΔD_{win} is the difference of wind drift factor between oil and buoy. This model means that the floating oil is affected by the wind in a very straight forward way without additional factor such as an angular shift due to Coriolis effect, since the Coriolis effect is thought already taken in the current implicitly.

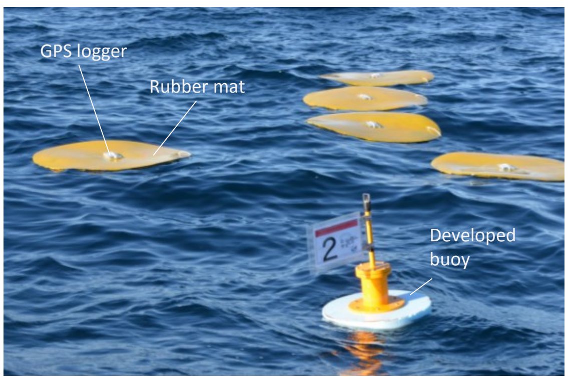


Fig. 13. Pseudo-oil made of rubber and the developed buoy.

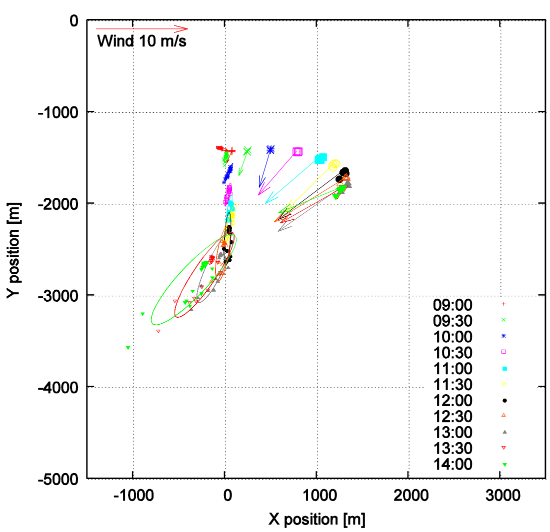
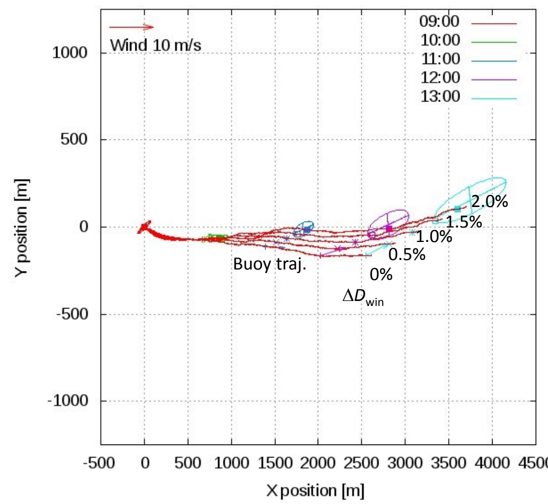
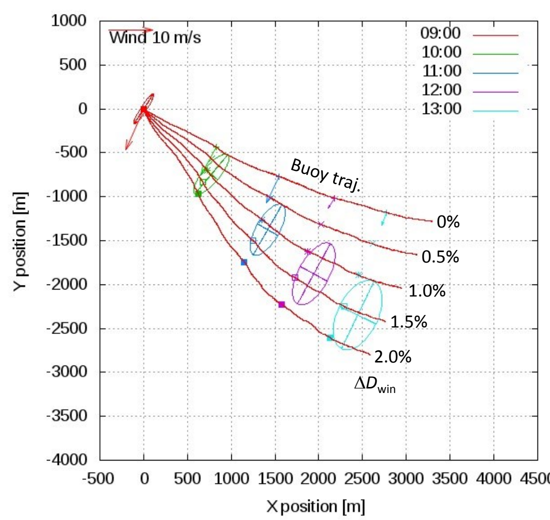


Fig. 14. Drift trajectories of rubber mats and buoys



(a) Case that wind nearly parallel to current



(b) Case that wind nearly perpendicular to current

Fig. 15. Tracking of spilt oil by a single buoy with wind effect correction method.

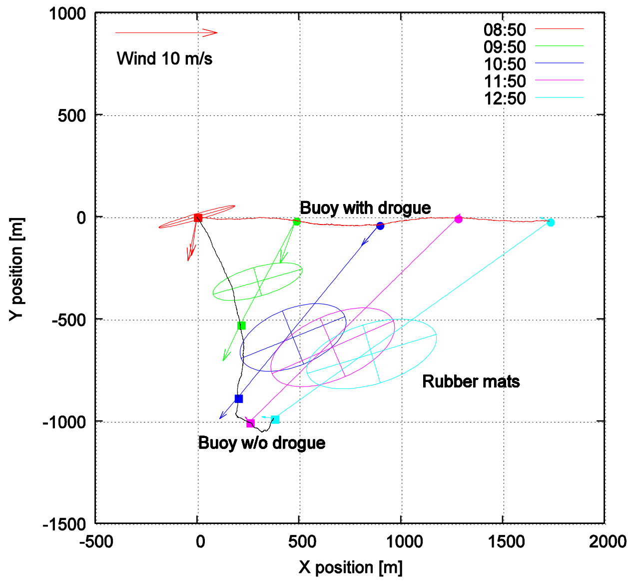


Fig. 16. Oil tracking by two buoy method

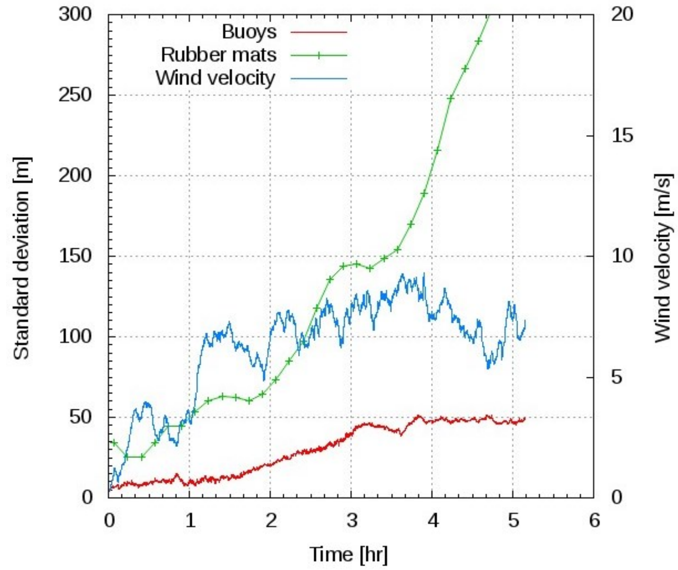


Fig. 17. Scatter of rubber mats and buoys in a field test

Fig. 15 shows two cases that this model is applied to. (a) is the case that the wind is approximately parallel to the current and (b) is the case that the wind is approximately perpendicular to the current. Ellipses in the figures show the area that 20 rubbers mats were distributed at each time, and the percent values means ΔD_{win}. It is found that the ΔD_{win} of 1.5-2.0% provides good guess for the oil drift positon and this ΔD_{win} value is reasonable because our rubber mats has an average wind factor of 3%, which was confirmed by a tank test conducted prior to the field test, and the buoy has 1% as the comparison with the HF radar suggested in the previous section. So the wind effect correction method defined by (2) and (3) works well for better estimation of the oil drift.

The key point of this correction method is an evaluation of the time integrated wind of $\int_0^T \mathbf{U}dt$. In case of oil tracking using a single buoy, this term has to be measured by an anemometer. However, if multiple buoys can be dispatched, this term can be determined from the position difference between buoys having different wind factors instead of direct wind measurement. Now assuming that there are two buoys having wind factors of D_{win}^{buoy1} and D_{win}^{buoy2} , respectively. An analogy with (2) provides the position difference between the two buoys as

$$\Delta\mathbf{X}_{buoy} = \mathbf{X}_{buoy2} - \mathbf{X}_{buoy1} = \Delta D_{win}^{buoy} \int_0^T \mathbf{U}dt \tag{4}$$

$$\Delta D_{win}^{buoy} = D_{win}^{buoy2} - D_{win}^{buoy1} \tag{5}$$

The time integrated wind term is calculated from the position difference as

$$\int_0^T \mathbf{U}dt = \frac{\Delta\mathbf{X}_{buoy}}{\Delta D_{win}^{buoy}} \tag{6}$$

and the targeted oil position can be predicted using the buoys' positions as

$$\mathbf{X}_{oil} = \mathbf{X}_{buoy1} + \frac{\Delta D_{win}^{oil}}{\Delta D_{win}^{buoy}} \Delta\mathbf{X}_{buoy} \tag{7}$$

This very simple relation tells that oil should be detected at an internally or externally dividing point on the line connecting the two buoys.

To verify whether this method is practically applicable to oil tracking, one of the 2013 field trials had two buoys and 20 rubber mats simultaneously drift. The two buoys had different wind factors by attaching a drogue to one buoy and detaching the drogue from the other. As Fig. 16 shows, the buoy without a drogue was more sensitive to the wind than that with drogue and its trajectory was shifted downwind from the buoy with drogue to a considerable extent. In this test case, the oil, actually a group of rubber mats, was found on the line connecting the two buoys at each time. This observation proves that the relation defined by (7) is a good method for estimating the oil position.

C. *Application to turbulent diffusivity modeling*

In addition to the oil tracking tool, the developed buoys were also useful for collecting data needed for oil drift modeling. Oil spread due to the turbulence is one of the difficult factor to determine in oil drift simulation and so far there has been no decisive model yet. Usually it is given empirically as the case may be in the range of 1-100m^2/s [3]. To build a deterministic model giving the turbulent diffusivity for drifting oil, further researches are necessary as well as field tests. In this study, we focused on the fact that the floating oil diffusivity is quite different from the diffusivity of the water column near the surface. In this study, 20 rubber mats and 5 buoys with drogue were introduced to the

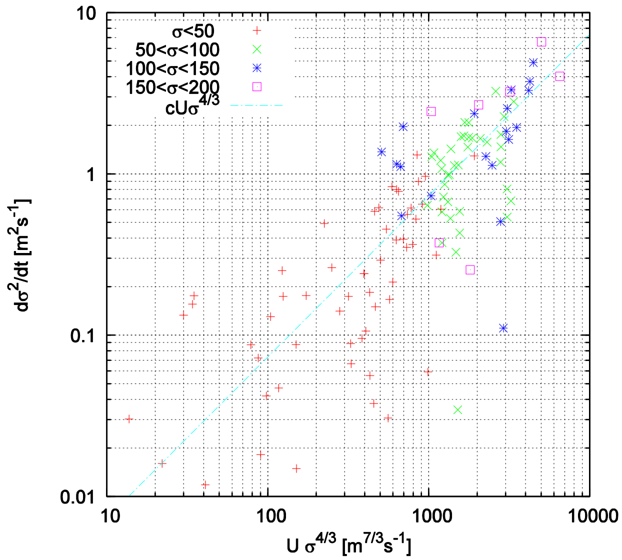


Fig. 18. Turbulent diffusivity correlation

simultaneous drifting test and their standard deviations were calculated. In this case, the buoys provides water column movement and wind information.

Fig. 17 shows an example of change of the standard deviation in a certain trial. It was found that the floating rubber mats scattered more rapidly than the buoys. This observation says that the very thin layer between atmosphere and sea water has much larger turbulent diffusivity than the water column beneath the surface, and also implies that the turbulence in the surface thin layer where the floating oil exist is governed dominantly by the wind than the water current. For a tentative trial, in this study, assuming that the turbulent diffusion of the oil is exclusively caused by the wind, experimental results were arranged to a Richardson-like model [4] with an extension to include the wind effect as

$$\frac{d\sigma^2}{dt} = cU\sigma^{\frac{4}{3}} \tag{8}$$

where σ is a scale length of diffusion which is defined as a standard deviation, which gives relatively good correlation between both sides of the equation as shown in Fig. 18. To complete the model, further data for more various situations are required, and for this purpose, the developed drifting buoy may play a significant role as a real time telemetry measurement tool.

IV. Concluding Remarks

We developed a smart phone embedded drifting buoy which is simple, light-weight, low cost, but provides real time telemetry as well as additional physical measurements.

We deployed the developed prototype to field tests and found that the buoy was very useful for tracking oil and also for physical measurement tool for information required for oil drift modeling.

Acknowledgement

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