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The Impact of Sea State on HF Surface-Wave Radar Ship Detection and Tracking Performances

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***Abstract*—Nowadays, we face an ever increasing interest in new technologies and solutions for the maritime surveillance (MS) domain. In such a context, oceanographic high-frequency surface-wave (HFSW) radars have started to get significant attention. In fact, they are operated to provide remote sensing information of wide open-sea areas, but they may also contribute with useful cost-effective track-based information to current operational MS systems. In this paper, specific interest is devoted to the analysis of the system detection and tracking capabilities under different meteo-oceanographic (METOC) conditions. Experimental data are acquired by three HFSW radars operated by the Helmholtz Zentrum Geesthacht (HZG) at the German Bight, North Sea, within the Coastal Observing System for Northern and Arctic Seas (COSYNA). Here, they operationally retrieve continuous sea state and currents. In this work, ship reports from the Automatic Identication System (AIS) are the ground truth information used for evaluating HFSW radar system capabilities, while METOC data are directly acquired from COSYNA. Preliminary results are presented and discussed, together with outlines for future research.**

Keywords*—*HFSW radar, maritime surveillance, METOC information, AIS navigation data, system performance.

I. INTRODUCTION

Maritime surveillance (MS) represents one of the most active research fields for many national and international institutions. Hence, in order to provide accurate pictures of wide open-sea areas, new technologies and algorithms need to be investigated. In such a context, HFSW radars could be valid tools for long-range monitoring applications [1], [2]. These sensors operate along the coasts for ocean remote sensing but, in addition, they provide a low-cost source of ship detection data that may contribute with useful track-based information to current operational MS systems.

In this paper, three Wellen Radar (WERA) systems deployed in the German Bight are considered [3]. They are operated by the Helmholtz-Zentrum Geesthacht (HZG) within the Coastal Observing System for Northern and Arctic Seas (COSYNA). Their task is to retrieve continuous sea state and currents on operational basis. As described in [4], and emphasized for the WERA system in [5], the METOC conditions can affect the HFSW radar coverage. However, at the best of our knowledge, with respect to ship detection and tracking applications, little work has been performed so far [6]. The aim of this study is to outline a possible dependency of the radar coverage, and thus its ability to detect and track targets, under consideration of the sea and weather conditions.

The processing chain implemented for the network of HFSW radars is as follows. Target detection is performed by the ordered statistics constant false alarm rate (OS-CFAR) algorithm, which operates in the range-azimuth-Doppler domain [1]. For the radar measured range, the dependency on radial speed for continuous-wave (CW) signals is considered, as outlined in [7]. The multi-target tracking (MTT) strategy is based on the Joint Probabilistic Data Association (JPDA) rule for detection-to-track association and the unscented Kalman filter (UKF) for track update [2]. Finally, in order to take advantage of the different installation geometries, a track-to-track association and fusion (T2T-A/F) paradigm is used, as described in [2], [8].

Ship reports from the AIS navigation system, recorded from several land-based stations and from external providers, are exploited as ground truth information. The methodology proposed in [2] is applied to classify detections, single- and multi-sensor tracks. Both single-sensor and multi-sensor performance are evaluated. However, only preliminary results are shown and discussed. A full statistical characterization, which could be provided in terms of time-on-target (ToT), false alarm rate (FAR), track fragmentation (TF) and accuracy as described in [2], is currently object of further investigations. Finally, the METOC information used for comparisons are provided by the COSYNA system.

The rest of the paper is organized as follows. The HFSW radar sensor network operated by HZG in the German Bight is introduced in Section II. Section III outlines the impact of sea on the measured backscatter signal, while Section IV describes the METOC information. Results are presented and discussed in V. Concluding remarks and directions for future work are given in Section VI.

II. THE HFSW RADAR SENSOR NETWORK IN THE GERMAN BIGHT

In the South-Eastern part of the North Sea, known as the German Bight, HZG is currently operating the experimental COSYNA network. Among the operated sensors, which can collect in situ or remote data, we have a network of HFSW radar systems. This network consists of three WERA radars is installed on the islands of Wangerooge ($53°47'25''N$, $7°55'8''E$) and Sylt ($54°47'19''N$, $8°16'59''E$), and close to Büsum ($54°7'10''N$, $8°51'28''E$). The WERA systems were made operative full-time in 2010, but STO-CMRE started the acquisition of data only on June 2013. The locations of the HFSW radars and their areas of coverage, nominally extending over an area of 150 km $\times 120°$, are depicted in Fig. 1. Offshore research platforms, wave-rider buoys, coastal and off-shore sensor installations are represented by full cyan dots. These

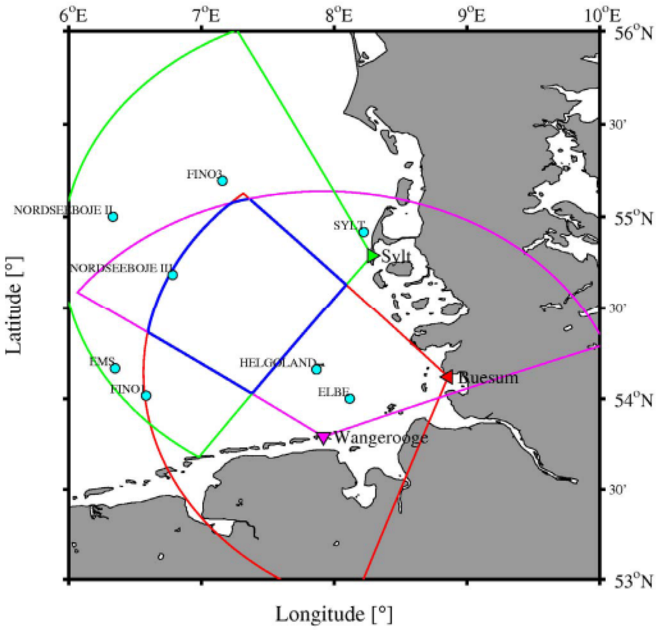

Fig. 1: Setup of the HFSW radar sensor network in the German Bight: Sylt (green), Büsum (red), and Wangerooge (magenta) sites. Colored triangles define sensor positions, while perimeters the areas nominally covered by radars. The blue perimeter depicts the region in which the three sensors fields of view overlap. Cyan dots represent off-shore platforms and sensors deployed within COSYNA.

represent a part of all the sensors and platforms deployed within COSYNA.

A. *The WERA system*

WERA was developed by the University of Hamburg in the late nineties, for remote sensing applications. A commercial version is available since 2000 [3], [5]. The main benefits are in the long-range coverage and low-power requirements. In fact, using linear frequency modulated continuous-wave (LFMCW) chirps, a single station can operate at 50 W on average, with a negligible impact on the electromagnetic pollution.

WERA can be considered a quasi-monostatic HFSW system. In fact, separate locations are used for the transmitter (Tx) and the receiver (Rx), which are made up of $\lambda_0/4$ monopole arrays, where λ_0 is the carrier wavelength. The distance between Tx and Rx is approximately 300 m on a straight line. For each system, the Tx has a rectangular antenna arrangement, while the Rx's are made by 12 (for Sylt and Büsum) and 16 (for Wangerooge) elements linear antenna arrays. The angles w.r.t. North of the three array installations are 97°, 5° and 349°, for Wangerooge, Sylt and Büsum respectively. The azimuth information is extracted via beamforming (Hamming window), with a nominal field of view of 120° around the broadside direction.

Sylt and Büsum transmit on the same carrier frequency and sharing the same bandwidth (i.e. $f_0 = 10.8$ MHz), but with orthogonal modulating waveforms (i.e. the first dowsweep, the second upsweep). Wangerooge operates in the $12.2 - 13.5$ MHz interval, with upsweep chirps. For all radars, the chirp repetition interval is $T_c = 0.26$ s. The chirp bandwidth is $B = 100$ kHz for all the systems, meaning that range resolution is $\Delta R = 1.5$ km.

B. *The processing chain*

Radar observations undergo on-site a quality control and radio frequency interference (RFI) removal. As already described, target detection is performed in the fast Fourier transform (FFT) domain by a 3-D (range-azimuth-Doppler) ordered statistics constant false alarm rate (OS-CFAR) algorithm. The coherent processing interval (CPI) is made of 512 samples (i.e. chirps with duration T_c). Two consecutive CPIs overlap of 75%, meaning that a detection occurs every 33.28 s. A range correction for compensating the Doppler effect is then applied, considering all these factors, as presented in [7]. An MTT strategy was presented in [3] based on the Joint Probabilistic Data Association (JPDA) rule followed by the unscented Kalman filter (UKF) [9]. Then, to exploit the aspect diversity due to the system geometries, a data fusion (DF) paradigm was described in [10], while a full statistical characterization of the detection, tracking, and DF performances of the proposed system was presented and discussed in [2].

III. SIGNAL PROPAGATION AND SEA CLUTTER

At the best of our knowledge, all the analyses conducted so far have not taken into account the possible implications of the sea state (and other environmental parameters) on the HFSW radar detection and tracking performance. It is known that the working range of a generic radar system is determined by the signal-to-noise ratio (SNR), which in turn depends on the propagation loss and scattering strength of the rough sea surface [4]. The peculiarity of HFSW radars resides in the fact that the signal can propagate also along the sea surface. For this reason, these electromagnetic waves are called ***surface-waves*** and can propagate at distances well beyond the optical horizon (e.g. up to $100 - 200$ km, depending on the specific radar setup).

It is known that the electromagnetic waves are affected by some relevant parameters of both the sea and the atmosphere. These parameters sum up into the complex relative dielectric constant ϵ. The attenuation of HF propagation depends strongly on the imaginary part of ϵ, i.e. it depends on frequency and conductivity, where the conductivity is a function of salinity and temperature.

Resonant Bragg scattering is the dominant process which generates the HF radar backscatter signal. The weak nonlinear interaction between the incident electromagnetic waves and the gravity sea surface-wave field generates scattered electromagnetic waves, which only partially return to the radar site. The magnitude of the radar echo from the open sea, affected by the scattering coefficient, tends to vary slowly with range and azimuth. However, much more important than the average magnitude of the sea echo is the doppler spectrum. The waves of the sea surface introduce a complex modulation on the reflected radar signal. A model which accounts for the observed properties of sea clutter, under the assumption that the sea is not too rough, is the one proposed by Barrick and Rice, described in [4] and in the references therein.

IV. THE METOC INFORMATION

As pointed out in [4], [5], the backscattered signal is strongly affected by the sea state. One of the most important parameters that characterize the sea state is the significant wave height. It is usually denoted as $H_{1/3}$, because it is defined as the mean wave height, trough to crest, of the highest one third of the waves. As expected, at near-range and for high sea states, the backscattered power is larger than for smaller sea states. Conversely, at middle and far ranges other issues occur, like shadowing effects (e.g. due to wave-breaking) or absorption by foam. The analysis presented in [5] was made using the WERA system in oceanographic parameter estimation mode, i.e. with carrier frequency in the range $27.5-30$ MHz. Other parameters affecting the signal propagation are the radar operating frequency, the sea salinity and the temperature which jointly affect the conductivity, and thus the imaginary part of the dielectric constant. The more saline is the sea, the better for the propagation, while the conductivity increases as well with increasing sea temperature [4], [5].

Also ocean surface currents can negatively affect the radar detection capabilities, by shifting the first-order Bragg peaks and, thus, the blind regions of the CFAR detector. Currents could also be responsible of significant variations of the average water conductivity and temperature values, especially at the estuaries of the rivers (e.g. Elbe and Weser). In this region currents are induced by the strong daily tides ($2-3$ m difference in height in a semi-period). Moreover, in shallow waters, these tides could make the seabed emerge and limit the coupling of the electromagnetic waves with the sea, especially close to the sand banks all around the coast of the Wadden Sea. However, it is no easy task to exhaustively describe all these aspects and, thus, only average behaviors and trends will be analyzed.

It is also important to note that in the German Bight region, a number of wind farms is currently operating or under construction. These farms could degrade the tracking performance of HFSW radars. Unfortunately, their impact has not been quantified yet. However, further research is ongoing in this sense.

V. PRELIMINARY ANALYSIS OF THE RESULTS

The effectiveness of the multi-sensor MTT (MS-MTT) system is investigated and both single sensor and multi-sensor performance are evaluated. Preliminary qualitative results are presented in Fig. 2. The estimated tracks agree with most of the AIS trajectories, except those along the Wadden Sea estuaries, for which we do not have radar coverage, see also Fig. 1. Moreover, other tracks appear showing a good coherency, but with no corresponding AIS (e.g. those going towards and away from Helgoland).

In this Section, the JPDA-UKF trackers at Büsum, Sylt and Wangerooge are analyzed, as well as the T2T-A/F system. The HFSW radar tracks are validated using the AIS reports as ground truth information. The procedure for validating the radar tracks can be found in [2]. It is important to remark the fact that the available AIS were sparser in the Northern region, thus it was impossible for us to compare also the results at the Sylt WERA station. For this reason, the next step will be to acquire more ground-truth information in order to have a clearer maritime picture of the cooperative vessel traffic.

Table I summarizes some preliminary experimental results for 39 days recorded during March, April, August and October 2013 at Büsum (B) and Wangerooge (W). The second column of the Table describes the mean and the standard deviation values of the significant wave height $H_{1/3}$. In the third column, the average water temperature is recorded by a ferry-box along the Cuxhaven-Helgoland route. Columns $4-6$ define the ToT values, averaged over the whole illuminated areas, for the JPDA-UKF trackers at Büsum and Wangerooge and the T2T-A/F system respectively. Unfortunately, data from Wangerooge were not always availabe in the choosen days (see column 5).

As we can observe from the analysis of the results shown in Table I, the average ToT estimated at Büsum varied between 4.50% and 22.58%, while at Wangerooge varied between 3.55% and 20.19%. The ToT at the T2T-A/F system varied instead between 4.50% (when only Büsum was available) and 37.39% (when both sensors were available). From the results, the ToT trend tends to decrease with increasing sea state (see for instance 25 and 28 October). Moreover, this dependency is most likely related to the average size of the vessels in the specific season. For instance, during March and April we suppose that the percentage of commercial traffic (e.g. cargos, tankers) is larger than the percentage of private vessels or small fishing boats, which instead should be more numerous during the hot months.

The water temperature is an important factor as well. For completeness it has been reported in the Table, but its implications have been only qualitatively addressed. As we can observe, the final ToT value for the T2T-A/F system (column 6) is almost coincident with the sum of the ToT from the two sensors (columns 4 and 5). This fact could be explained by the relative ship-sensor geometries Büsum and Wangerooge. This result suggests that the DF system coverage is almost maximized. On the other hand, we will have probably no gain in terms of RMSE and track fragmentation, as instead shown in [2]. However, the results shown in Table I do not take into account the size of the vessels and are averaged over the whole illuminated area. In the following, the outputs are color-coded as follows. The JPDA-UKF outputs at Wangerooge and Büsum are shown in magenta and red respectively, while the T2T-A/F output is in blue. Output track contacts are validated constructing a 3-D (range-azimuth-radial speed) performance validation region (PVR) for each AIS contact, following the procedure described in [2] and references therein.

Fig. 3 depicts the ToT for a range of different ship lengths and for given average sea state conditions, represented by four different mean $H_{1/3}$ intervals and averaged for simplicity over the whole area between March and October 2013. Unsurprisingly, tracking is better at lower sea states, with detection and tracking capabilities worsening with increasing sea states. For instance, the mean ToT decrease is about 10% for all the classes of ships when $H_{1/3}$ increases by just 1 m on average.

In conclusion, the system performances degrade mainly for the instability of the propagation medium at high sea states, as stated also in [5], [6]. The height of the waves can affect the sea-backscattered signal, and in addition to the direction, have a negative impact on the propagation ranges. We can

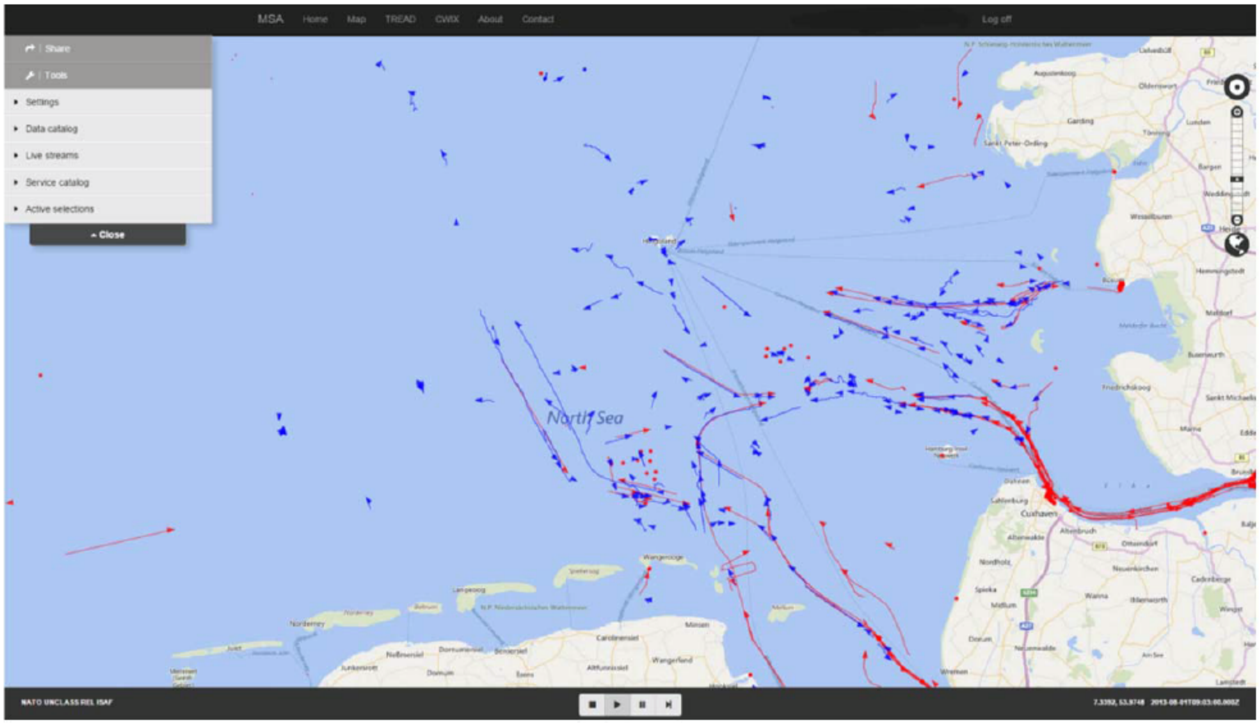

Fig. 2: AIS ship routes (red arrows) and HFSW fused tracks (blue arrows) recorded on August 1, 2013 from 8 : 00 to 9 : 00 UTC. Tracks are displayed via the Maritime Situational Awareness (MSA) viewer developed at STO-CMRE.

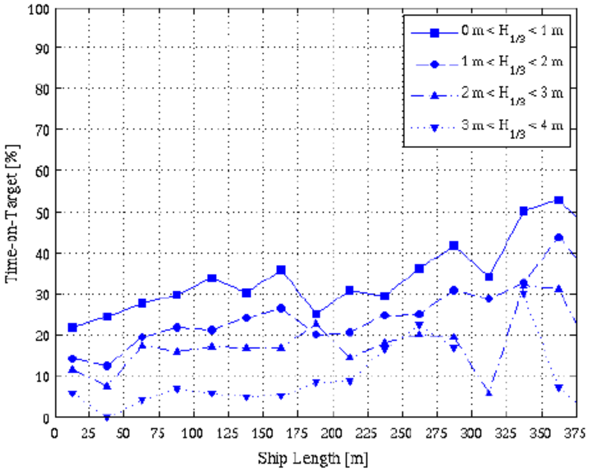

Fig. 3: Time-on-Target of the T2T-A/F system versus ship length, under different sea state conditions summarized by the significant wave height ($H_{1/3}$): (a) case $0 < H_{1/3} < 1$ (squares with continuous line); (b) case $1 < H_{1/3} < 2$ (circles with dashed line); (c) case $2 < H_{1/3} < 3$ (up-triangles with dash-dotted line); (d) case $3 < H_{1/3} < 4$ (down-triangles with dotted line).

conclude that there is a dependency of the sensor capabilities from the sea state conditions, but further studies are mandatory to provide a more accurate analysis of the problem. For this reason, currently our research is driven to jointly analyze in more depth the relevant performance statistics, such as the estimated ToT, the TF and the FAR [2].

VI. CONCLUSIONS

In this study, a maritime surveillance system based on a network of simultaneously operating low-power HFSW radars has been presented and its performance evaluated by means of experimental data recorded in the German Bight. Different issues have an impact on system performance, e.g. different sea state and salinity conditions affecting the signal propagation, different coastline profiles, but also high vessel traffic. A first analysis of the single-sensor and multi-sensor tracking capabilities has been conducted and preliminary results have been discussed w.r.t. different METOC conditions. Results have demonstrated a dependency of the system ToT on the significant wave height. When the sea state is low (i.e. $0 < H_{1/3} < 1$), the final ToT can reach also $35 - 40\%$ on average for all vessel sizes. However, an increase of just 1 m can reduce the ToT of about 10% on average for all the ship categories. Moreover, the results have shown that the radar installations at Büsum and Wangerooge are such that the final system ToT is maximized, i.e. is the sum of the ToTs from the two sensors. Despite these promising results, our analysis is still far from being complete. For this reason, future research efforts could be effectively directed to solve the aforementioned problems.

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Date	$H_{1/3}$ **(avg, std) [m]**	**Temp. avg [°C]**	**ToT**$_B$ **[%]**	**ToT**$_W$ **[%]**	**ToT**$_{T2T-A/F}$ **[%]**
1-Mar	$(1.60, 0.66)$	4	14.78	–	14.78
2-Mar	$(1.31, 0.48)$	4	15.09	–	15.09
3-Mar	$(1.40, 0.54)$	4	15.22	–	15.22
4-Mar	$(0.81, 0.32)$	4	18.48	–	18.48
6-Mar	$(0.40, 0.15)$	4	21.61	–	21.61
7-Mar	$(1.71, 0.71)$	4	12.00	–	12.00
8-Mar	$(2.17, 0.96)$	4	4.50	–	4.50
9-Mar	$(2.22, 0.94)$	4	6.31	–	6.31
11-Mar	$(1.52, 0.60)$	4	12.76	–	12.76
12-Mar	$(0.62, 0.22)$	4	18.64	–	18.64
12-Apr	$(0.46, 0.20)$	4	21.56	8.42	29.33
13-Apr	$(0.50, 0.19)$	4	20.11	17.82	36.07
14-Apr	$(0.92, 0.42)$	4	20.25	18.71	36.00
15-Apr	$(0.67, 0.31)$	4	20.15	16.65	34.97
16-Apr	$(0.84, 0.38)$	4	16.53	9.12	24.64
23-Apr	$(1.34, 0.47)$	6	19.35	3.55	23.21
24-Apr	$(1.31, 0.50)$	6	22.58	8.84	31.05
25-Apr	$(0.90, 0.36)$	6	19.76	7.67	27.07
26-Apr	$(0.72, 0.25)$	6	18.60	9.20	28.13
27-Apr	$(0.66, 0.20)$	6	17.68	9.51	29.62
28-Apr	$(0.93, 0.44)$	7.5	17.93	8.31	27.23
29-Apr	$(0.93, 0.44)$	7.5	17.93	8.31	27.23
1-Aug	$(0.54, 0.19)$	20	18.98	20.19	34.24
2-Aug	$(0.48, 0.19)$	21	14.73	19.87	35.35
3-Aug	$(1.04, 0.35)$	20.5	12.36	17.52	32.83
4-Aug	$(0.71, 0.28)$	21	13.61	15.82	31.81
5-Aug	$(0.53, 0.18)$	21	14.34	15.78	30.10
6-Aug	$(1.00, 0.29)$	21	12.97	12.40	25.12
8-Aug	$(1.32, 0.39)$	19.5	11.25	10.60	23.61
12-Aug	$(1.44, 0.45)$	18.5	12.51	6.82	19.21
16-Aug	$(1.00, 0.40)$	19	23.52	19.00	36.39
17-Oct	$(2.00, 0.67)$	15	11.36	–	11.36
18-Oct	$(1.34, 0.46)$	14	17.91	–	17.91
24-Oct	$(2.21, 0.84)$	14	14.27	12.23	27.88
25-Oct	$(1.40, 0.54)$	13.5	20.40	18.29	37.39
26-Oct	$(2.09, 0.85)$	13.5	16.78	19.73	34.50
28-Oct	$(3.96, 1.43)$	13.5	7.07	–	7.07
29-Oct	$(2.49, 0.83)$	13.5	7.80	–	7.80
30-Oct	$(1.94, 0.65)$	13.5	13.14	–	13.14

TABLE I: METOC information and estimated ToT from 2013 dataset.

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Abstract

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Keywords

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