An Effective and Efficient Long-time Coherent Integration Method for Highly Maneuvering Radar Target in Sparse Domain

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Abstract

Robust and effective detection of “high-speed and highly maneuvering” target is one of the fundamental and difficult problems in both military and civil fields. Long-time coherent integration (LTCI) is proved to be an effective way to strengthen the weak signal and improve signal-to-clutter ratio. Recently, we have extended the concept of LTCI and proposed several methods for maneuvering target detection and estimation, i.e., Radon-fractional Fourier transform (RFRFT), Radon-linear canonical transform (RLCT), Radon-fractional ambiguity function (RFRAF), Radon-linear canonical ambiguity function (RLCAF), and phase differentiation-Radon-Lv’s distribution (PD-RLVD). They can compensate the range and Doppler migrations simultaneously while the computational burden is the biggest problem for real applications. In this paper, the concept of sparse time-frequency analysis is introduced. Then we tried to establish the concept of LTCI in sparse domain, which is called sparse LTCI (SLTCI). The SLTCI combines the merits of LTCI and compressive sensing (CS), which is effective for maneuvering target detection and efficient for computation. Finally, we give an example of marine target detection using CSIR data, which indicates that the proposed method can achieve higher integration gain, better clutter suppression ability, and less computational burden.

1. Introduction

- Detection and recognition of sea surface target are important for both civilian and military applications. It is rather difficult to detect weak marine targets, such as low attitude, slow moving, small size, and highly maneuvering targets. Their radar returns have a common characteristic, i.e., low signal-to-clutter ratio (SCR).

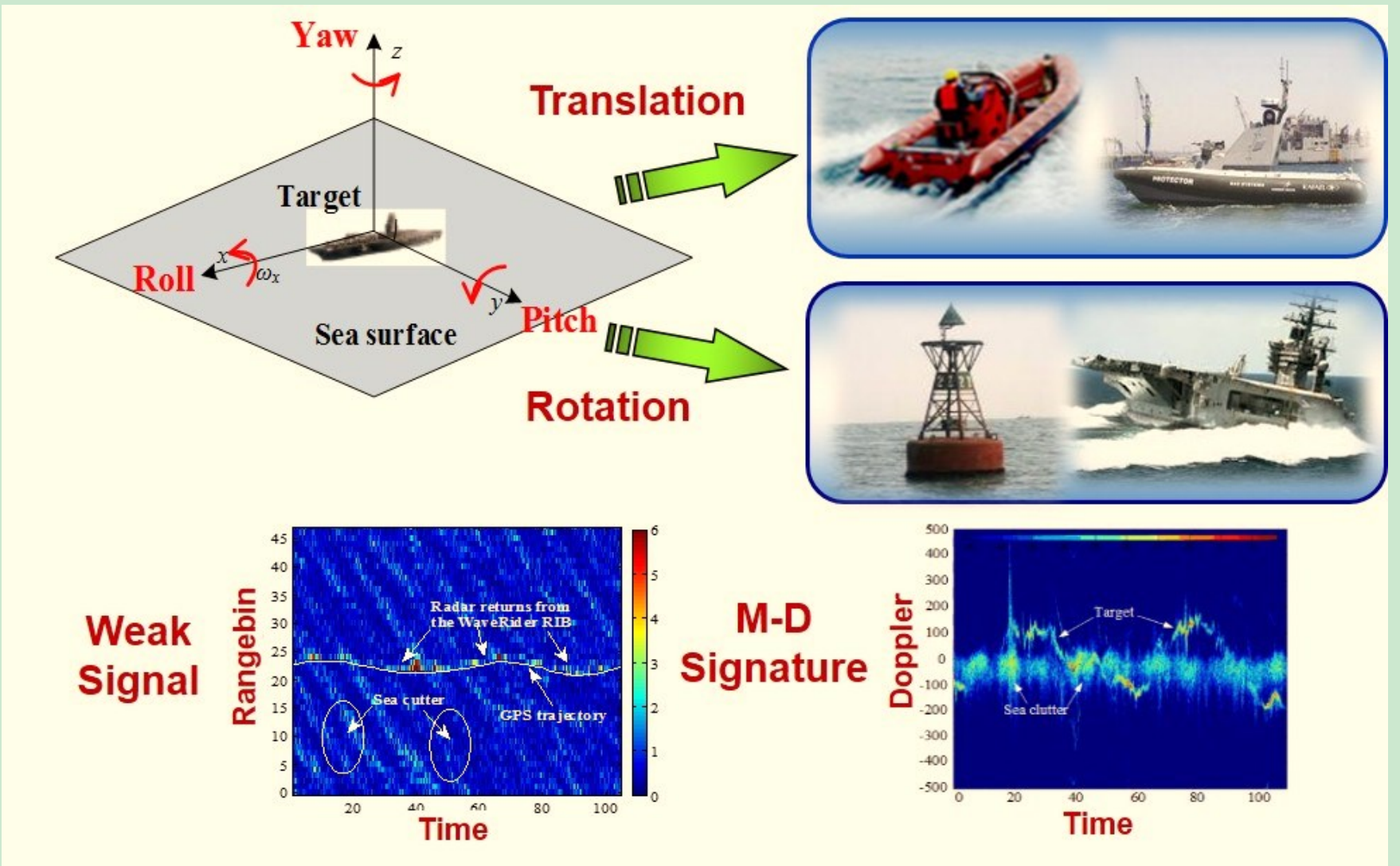

Fig. 1. M-D characteristic of a sea surface target.

- Recently, m-D characteristics have been employed for target detection and recognition as they can provide more detailed information. It is noted in the special issue of m-D published in IET RSN that the sea surface targets may also exhibit micromotions especially for high sea state and high mobility. (See Fig. 1)
- In this paper, the m-D properties of sea surface target are studied systematically. Experiments using real radar datasets are carried out to demonstrate the m-D signatures and its promising applications for radar detection and recognition.

2. Principle of Sparse Time-frequency Analysis

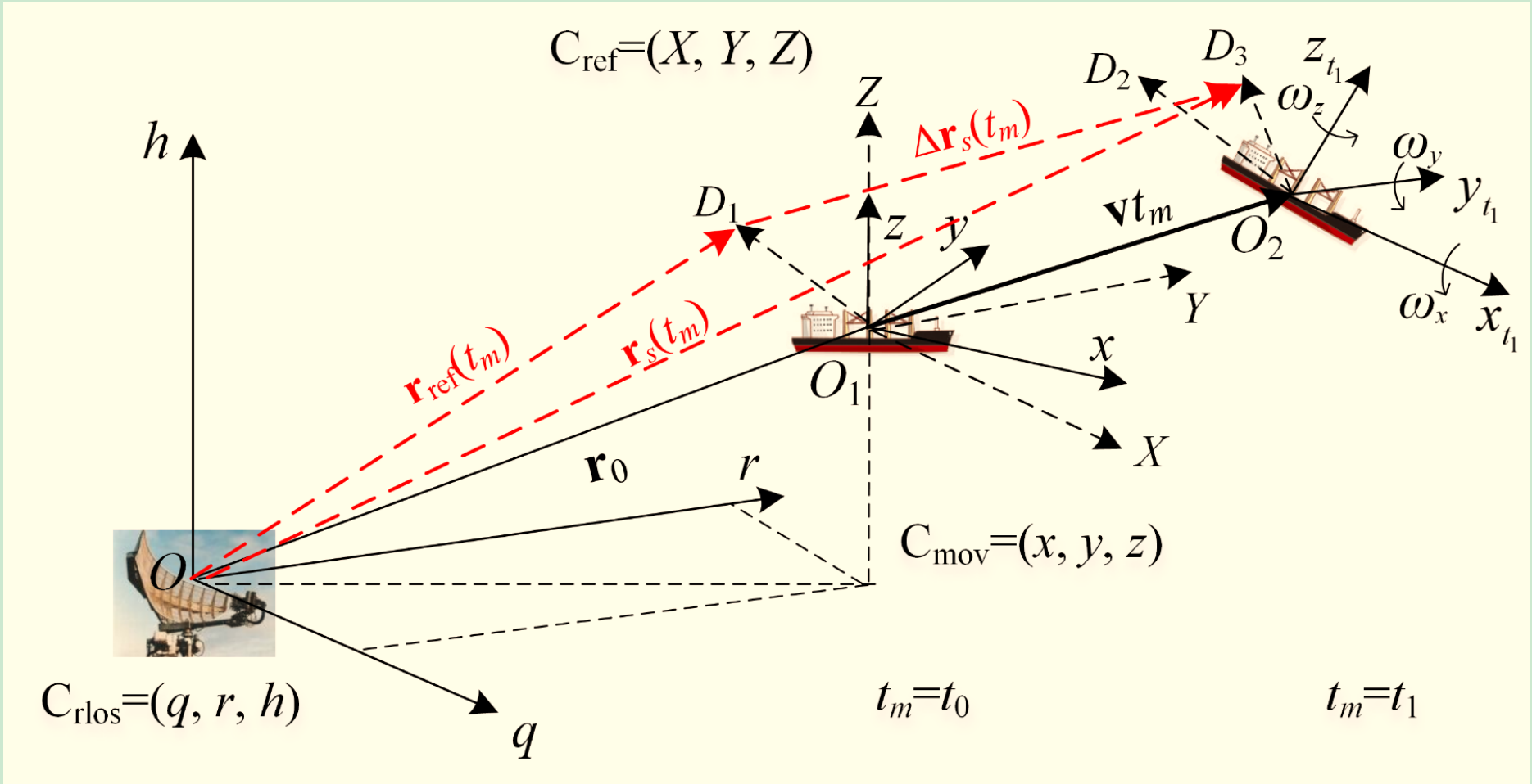

Fig. 2. Observation geometry of a marine target with micromotion.

☐ The observation geometry of a sea surface target with micromotion (See Fig. 2) shows the RLOS range vector is $\mathbf{R}_s(t_m) = \mathbf{r}_0 + \mathbf{v}t_m + \mathbf{R}_t\mathbf{R}_0$, where $\mathbf{v}$ denotes the velocity due to the translational movement, $\mathbf{R}_t$ is the rotation matrix, and $\mathbf{R}_0=(X_0, Y_0, Z_0)^T$. The m-D is composed of two parts, i.e., $f_t(t_m)$ and $f_r(t_m)$, the Doppler of translational and rotational motions.

[redacted] (1)

☐ **Signal model for Short-time Observation**

In case of short-time observation, the nonuniform translation and rotation movements can be modeled as sum of linear FM (LFM) signals.

$$x(t) = \sum_i A_i(t)\exp\left(\mathrm{j}2\pi f_i t + \mathrm{j}\pi\mu_i t^2\right) + c(t), \quad |t| \le T \tag{2}$$

where $f=2v_0/\lambda$, $\mu=2a_s/\lambda$ is the chirp rate.

☐ **Signal Model for Long-time Observation**

The m-D is usually time-varying and can be expressed as the second order approximation a high-order phase signal, i.e., the quadric FM (QFM) signal.

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3. Detection Method via LTCI in Sparse Domain

a) Parameters initialization for long-time coherent integration, such as the searching scopes of different parameters according to the prior information. The target’s returns are extracted according to the preset searching trajectory.

b) Choose the proper dictionary according to the prior information of target to satisfy the sparsity condition.

c) Solve the CS optimization problem to obtain the coefficients of sparse representation.

d) Target detection in sparse domain with a constant false alarm rate (CFAR) detector.

e) Estimate the motion parameters according to the peak coordinates in the sparse domain.

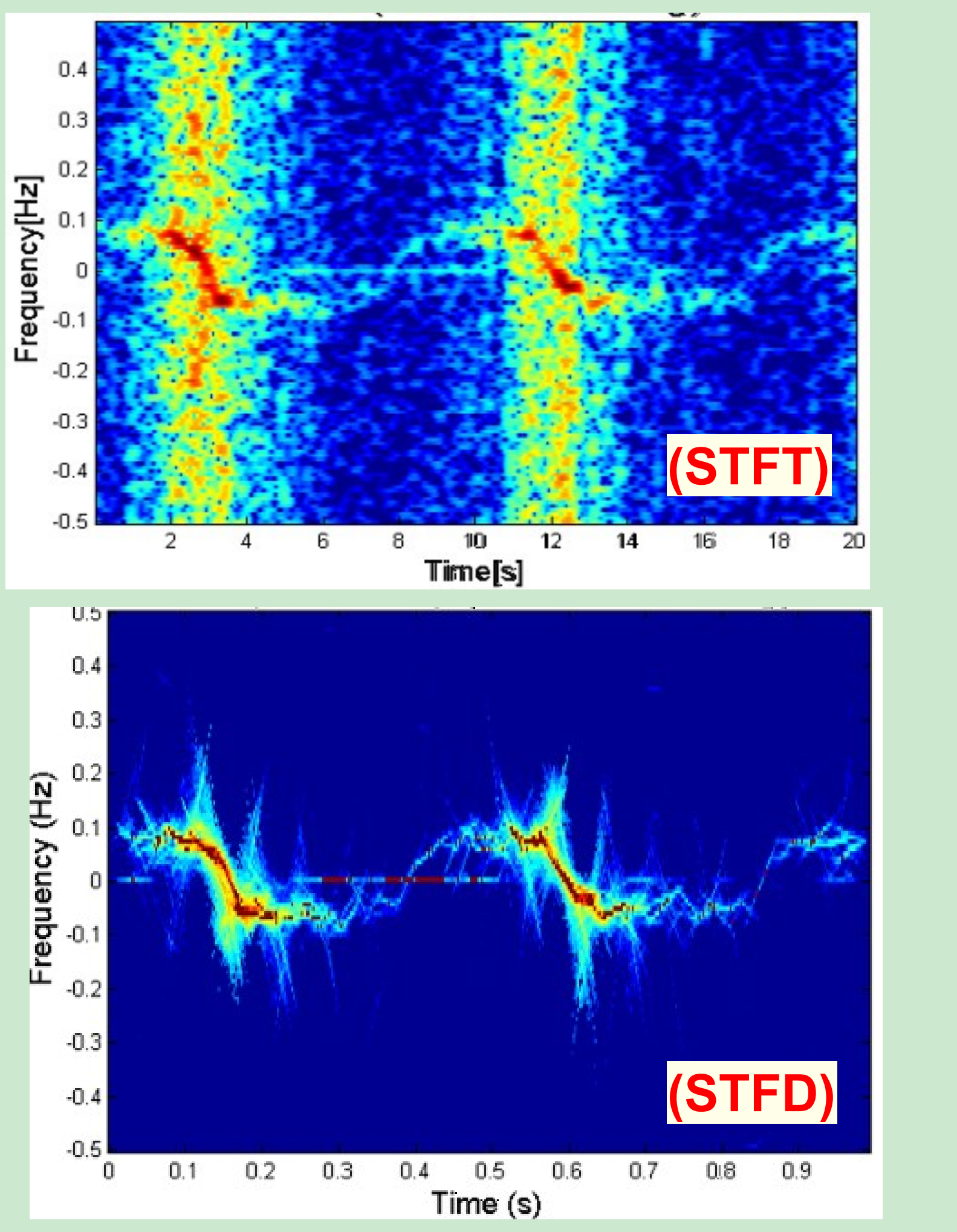

Fig. 4 Comparison between STFT and sparse time-frequency distribution (STFD). [Tutorial given by Prof. Amin]

4. Experimental Results for Detection of Marine Target with Micromotion

➢ **Description of X-band CSIR Data**

The measurement was conducted with the Fynmeet dynamic RCS measurement facility at the Over-berg Test Range (OTB) in 2006. Fig. 1 shows the descriptions of TFA17_014 dataset. During the observation time, the target moves across several range bins and its Doppler changes with time. It is difficult to separate the WaveRider RIB from strong sea clutter in range and Doppler directions.

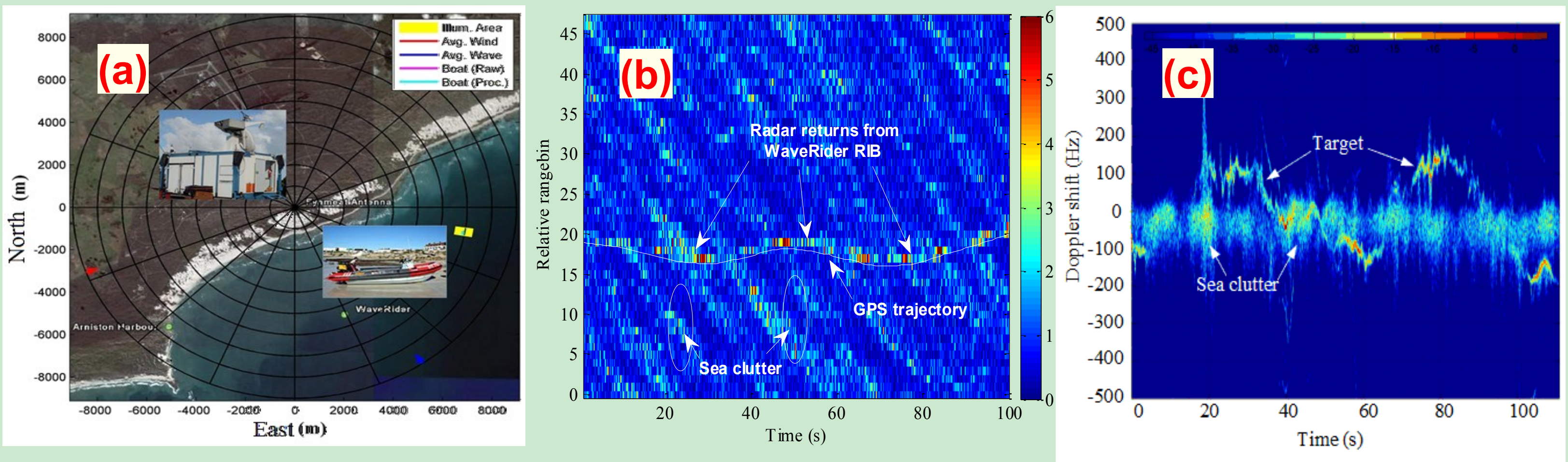

Fig. 4 Descriptions of the CSIR dataset (TFA17_014 dataset).
(a) Plan overview of radar deployment. (b): Range profiles of radar returns.
(c) High Doppler resolution spectrogram of target range bin.

➢ **Integration and detection results**

We carry out the SLTCI and compare the detection results of different methods (Fig. 2). The proposed method (SRFRAF) can greatly increase both the integration gain and estimation accuracy. Due to the sparse representation, the signal is concentrated in the sparse domain with less sea clutter. Moreover, the computation time reduces greatly using SRFRAF.

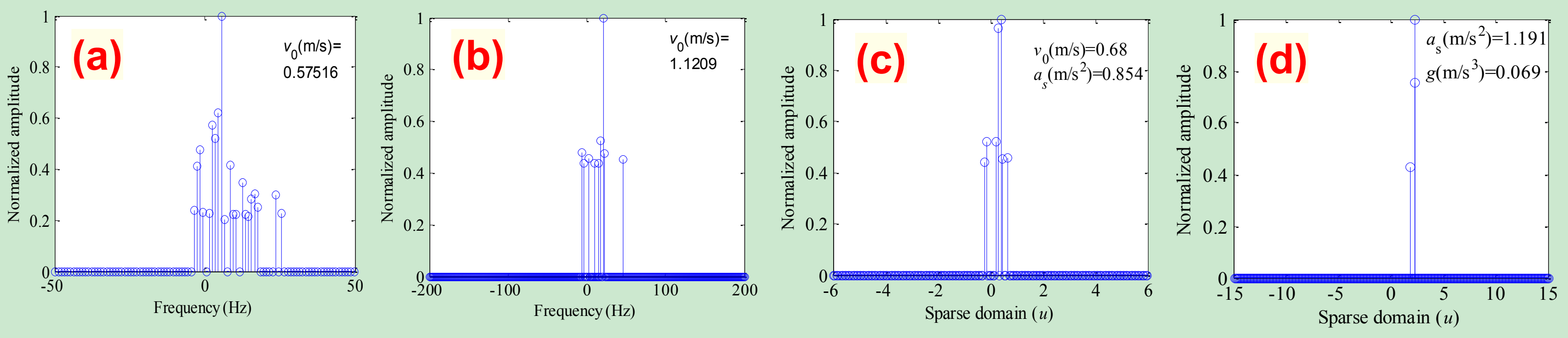

Fig.2. Detection results comparison via coherent integration in sparse domain (t_0=75s)
(a) Sparse MTD (SMTD); (b) Sparse RFT (SRFT); (c) Sparse FRFT (SFRFT); (d) Sparse RFRAF (SRFRAF)
(The integration time of (a) and (c) is 1.5 s; the integration time of (b) and (d) is 7.5 s).

Detection methods	SMTD	SFRFT	SRFT	RFRAF	SRFRAF
Sampling number	256	256	1024	1024	1024
Sparse signal components	25	10	13	None	2
P_d (SCR=-5dB)	36.55%	70.21%	68.35%	81.27%	89.35%
Computing time (ms)	5.7	8.9	15.6	38.2	20.4

Table 1 Comparisons of detection and computational burden performances (P_{fa}=10^{-4})

Conclusions

- We established the concept of LTCI in sparse domain (SLTCI), which combines the merits of LTCI and sparse representation.
- Higher integration gain and estimation accuracy, less computational burden can be obtained compared with other common methods.
- Future work will focus on the detailed analysis of SLTCIs for different motions.