4-12 Development of Long-Range Ocean Radar System

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Communications Research Laboratory developed a new high-frequency ocean surface radar system named Long-Range Ocean Radar (LROR) that is composed of two radars located on two of the Ryukyu Islands in the southwest part of Japan. LROR is designed to observe surface currents up to 200 km from the radar sites with range resolution of 7 km and will be used for the experimental observation of upper region of the Kuroshio Current in the southern part of the East China Sea. We started performance evaluations and experimental observations in July, 2001.

Keywords
HF radar, Surface current, Kuroshio current, Remote sensing

1 Introduction

The high-frequency (HF) ocean surface radar is a kind of a Doppler radar that can monitor ocean-surface condition, such as surface current vectors, ocean surface winds, and ocean waves, by making a frequency analysis of backscattered echoes from the ocean surface. The HF ocean surface radar can continuously observe over a large area from land, while the conventional methods using ships and mooring buoys can measure only at some particular points on the ocean. Therefore, the importance of HF ocean surface radar is increasing in various subjects such as oceanography, coastal engineering, and fishery.

HF ocean surface radar has been developed in many countries since the late 1970s and its effectiveness for the current field observation has been rated highly. The Communications Research Laboratory (CRL) began to develop the HF ocean surface radar with frequency of 24.5 MHz in 1986, and the first HF ocean surface radar in Japan was completed in 1988. Since then, a lot of experimental observations have been conducted in Japan in collaboration with various institutes and universities and improvement of the observation system and data analyzing processes have been performed. The 24.5 MHz HF ocean surface radar is useful in measuring small-scale oceanographic phenomena. However, it is not suitable for large-scale phenomena such as the Kuroshio current because maximum current observation range of the 24.5 MHz HF ocean surface radar is not long enough. Therefore, the development of new HF ocean surface radar capable of long-range observations using the 9.2 MHz frequency was launched in 1999 and the system was completed in July 2001.

2 The Principles of HF Ocean Surface Radar

The ocean surface measurement by HF ocean surface radar is based on the scattering theory of radio waves by ocean surface waves[1]~[4]. Fig.1 shows a schematic diagram of observation using HF ocean surface radar. The shore-based radar transmits HF radio waves toward the sea surface, and the radio waves are strongly backscattered by ocean surface waves with half the radio wavelength (Bragg resonant scattering). Frequency

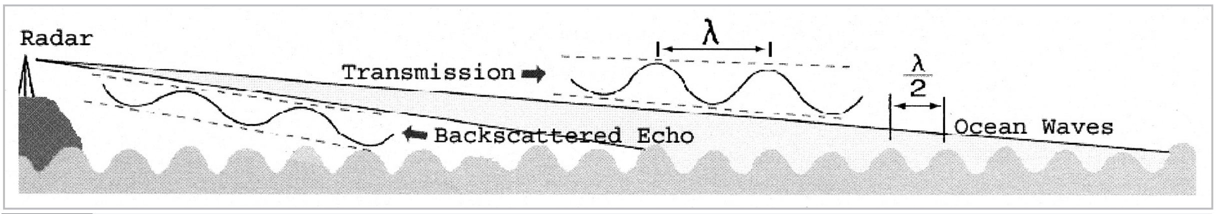

Fig.1 Schematic diagram of the HF ocean surface radar observation

analyzing this backscattered signal, there are typically two prominent peaks called "first-order echoes" near the Bragg frequency, which is the frequency corresponding to the phase speed of the ocean wave contributing to the Bragg resonant scattering. Fig.2 shows a typical scheme of a Doppler spectrum measured with the HF ocean surface radar. Peak with positive Doppler frequency is corresponding to approaching waves toward the radar, and that with negative frequency is corresponding to receding waves from the radar. In Fig.2, f_B represents the Bragg frequency, which can be expressed as:

$$f_B = \pm \frac{2C_0}{\lambda}$$

Here, C_0 is the phase speed of the ocean wave contributing to the Bragg resonant scattering and λ is wavelength of the transmitted radio wave. From the linear dispersion relationship of ocean surface waves, C_0 can be uniquely determined as:

$$C_0 = \sqrt{\frac{g\lambda}{4\pi}}$$

Here, g represents the gravitational acceleration. The actually measured Doppler velocity corresponding to the peak frequency of the first-order echo is the sum of the phase speed of the ocean wave of a stationary sea surface and the radial current component along the radar beam direction. Therefore, the radial current component can be obtained by subtracting the phase speed of the ocean wave from the Doppler velocity corresponding to the first-order echo. However, since it is only the radial current component that can be measured for a single radar in order to calculate two-dimensional current vectors it must be necessary to combine two radial current components at a point measured from different direction. Therefore, in general, two or more radars must be needed for current vectors observation using HF ocean surface radar. The root-mean-square (RMS) error of the combined current vector is dependent on the crossing angle α of the two radar beams. If we assume that both the radial current components and errors are independent and that RMS values of the measuring errors of the radial current components are equal between two radars, the RMS error of the combined current vector is $1/|\sin(\alpha)|$ times the RMS error of the radial current component[5].

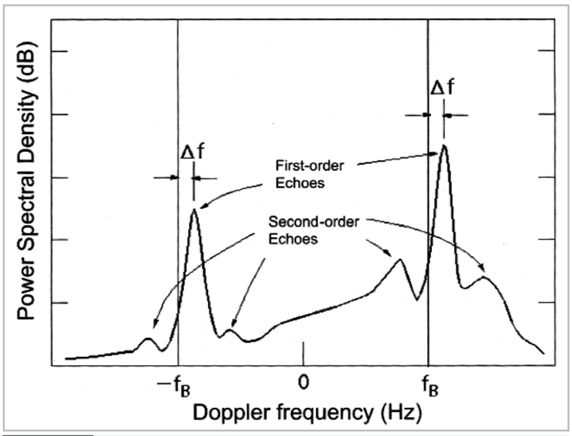

Fig.2 A typical scheme of the observed Doppler spectrum

According to the analysis of the motion of water particles in the vertical plane accompanying ocean surface waves, it is shown that the current velocity measured by HF ocean surface radar corresponds to that at depth of $\lambda/8\pi$ from the surface[4].

An ocean wave with a wavelength of several meters observed by the HF ocean surface radar is mainly induced by ocean surface wind near the observation point, and so the direction of the ocean surface wind and the direction of maximum growth of the ocean wave usually coincide. The positive and negative first-order echoes observed by HF ocean surface radar correspond to ocean waves approaching and receding from the radar, respectively, and the peak intensity of the first-order echo is dependent on the growth of the ocean wave contributing to the Bragg scattering. Thus, it is possible to estimate the direction of the ocean surface wind based on the peak intensity ratio between the two first-order echoes. Furthermore, the ocean wave spectrum can be estimated by analyzing the shape of "the second-order echoes", a shape which is a secondary continuum that appears around the first-order echoes. However, since the intensity of the second-order echoes are significantly lower than that of the first-order echoes, Doppler spectrum with extremely good signal-to-noise ratio is required for ocean wave spectrum estimation. Therefore, the areas for which ocean wave spectrum can be estimated is extremely restricted compared to that of the current vectors.

3 The Long-Range Ocean Radar (LROR)

Characteristics of the long-range ocean radar (LROR) system are summarized in Table 1. The maximum observable range of the LROR depends on various factors such as sea conditions, background noise level, receiver sensitivity, and electromagnetic conditions surrounding the radar site, but the most dominant factor is the propagation loss of ground waves. Fig.3 shows ground wave propagation curves for various frequencies on the sea surface taken from a CCIR (ITU-R) report[6]. When compared at the same distance, it can be seen that the ground-wave propagation loss is smaller at lower frequencies. For example, the propagation loss of a 9.2 MHz is smaller by about 30 dB at 200 km compared to a 24.5 MHz, which is the transmission frequency of the HF ocean surface radar already developed by CRL. With the LROR, current measurement up to 200 km offshore has been made possible by transmitting radio waves at frequency of 9.2 MHz with maximum transmission power of 1 kW. In Japan, it is almost impossible to secure a sufficiently wide and continuous frequency bandwidth in the HF band, so the LROR adopts a frequency modulated interrupted continuous wave (FMICW) type radar that is able to use frequencies resources more efficiently than the short-pulse type radar. The sweep bandwidth is 22 kHz, which corresponds to the range resolution of about 7 km. The current velocity resolution, which is determined by the incoherent integration time of received signal, is 2.5 cm/s.

Table 1 *Characteristics of the LROR system*

Radar Type	FMICW
Frequency	9.2 MHz
Sweep Bandwidth	22 kHz
Transmission Power	1 kW (Max.), 500 W (Average)
Range Resolution	7.0 km
Current Velocity Resolution	2.5 cm/s
Beam Width	8˚
Transmission Antenna	3-element Yagi antenna
Receiving Antenna	16-elements linear array of 2-element Yagi antenna DBF (Digital Beam Forming)

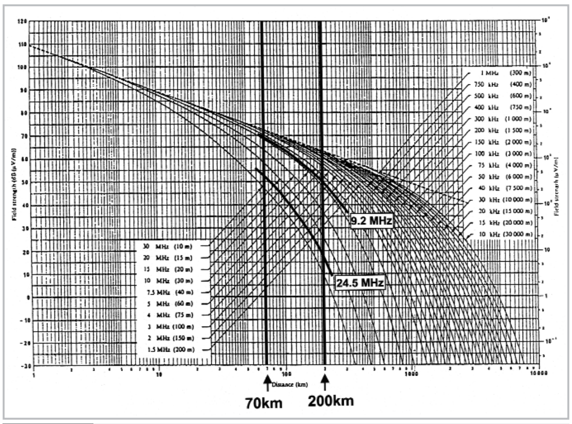

Fig.3 *Ground wave propagation curves on the sea surface[6]*

Fig.4 shows the antenna system of the LROR. The LROR adopts a digital beam forming (DBF) technique in which the signals simultaneously received by multiple-elements antenna are digitally processed to obtain angular information. The transmission antenna is a 3-elements Yagi antenna that transmits a fan beam with horizontal beam width of 120˚

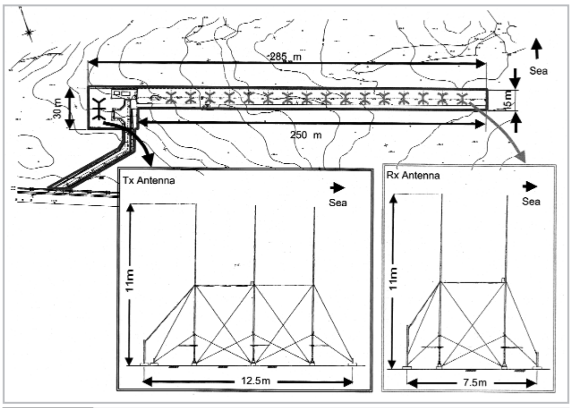

Fig.4 *The antenna system of the LROR*

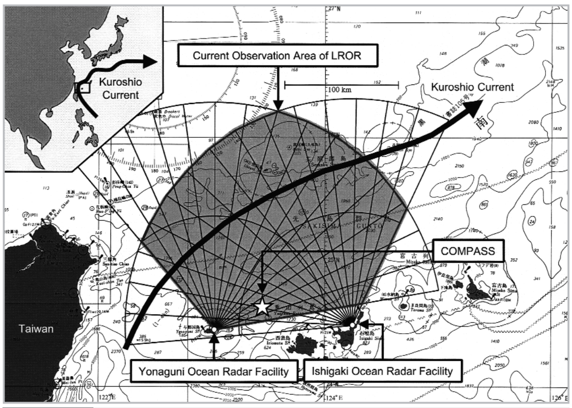

Fig.5 *Surface current observation area of the LROR*

toward the sea surface. The receiving antenna is a 16-elements linear array antenna with an aperture of 208.2 m, consisting of 2-elements Yagi antennas, which are individually equipped with both a receiver and an A/D converter. The signals received by each element antenna are digitally processed to form a virtual beam in an arbitrary direction within a ±60˚ to antenna front direction. The horizontal beam width is about 8˚ in antenna front direction. The CRL 24.5 MHz HF ocean surface radar adopts a narrow-beam scanning type, and so it takes 2 hours to scan the whole observation area (90˚ width), resulting in a maximum lag time of 2 hours among the observation points. With the LROR, which uses the DBF technique, data can be acquired simultaneously at all observation points. Therefore, it is now possible to detect phenomena with extremely short-term variations and to obtain the information that requires simultaneous data acquisition in whole observation area, both of them can not be observed with the CRL 24.5 MHz HF ocean surface radar.

Fig.5 shows the observation area of surface current vector by the LROR. In general, to obtain current vectors with HF ocean surface radars, a multiple-radars observation is necessary, and so the LROR system is consisting of two radars at Ishigaki Island and Yonaguni Island. Both radars can measure the radial current component along the radar beam direction within a fan-shaped area with a radius of 200 km and a central angle of 120˚. The current vector can be calculated in the overlapping area of the two fan-shaped areas. In this area, the main flow axis of the Kuroshio current exists approximately 100 km away from the Ryukyu Islands, and so the LROR has a sufficient ability to observe the current field of the Kuroshio current. The error factor 1/|sin (α)|, which represents the RMS value of the error induced in combining the current vector, was equal to or less than 2.0 in the whole observation area except for some small part on its eastern, western, and southern edges.

Fig.6 is a simple block diagram of the LROR system. Each of the LROR sites at Ishigaki Ocean Radar Facility (Fig.7) and the Yonaguni Ocean Radar Facility (Fig.8) is connected to the Okinawa Subtropical Environment Remote-Sensing Center (CRL Okinawa) by dedicated lines, and each radars can be controlled from the CRL Okinawa. In the normal operation mode, the raw data obtained by each radar are converted at the radar site into

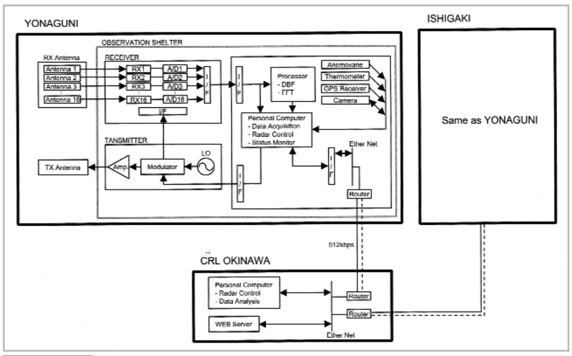

Fig.6 *A simple block diagram of the LROR system*

Fig.7 *Ishigaki Ocean Radar Facility*

Fig.8 *Yonaguni Ocean Radar Facility*

16 Doppler spectral data sets for every 8° in beam direction. The total of 32 Doppler spectral data sets produced at the two sites are sent automatically to the CRL Okinawa and the radial current components and current vectors are automatically calculated in pseudo real-time. The observation times and points of the LROR on Ishigaki and Yonaguni islands do not necessarily coincide. Therefore, when calculating the current vector, it is necessary to prepare a set of radial-current components of both the same observation time and the same observation point by performing some temporal and spatial interpolations. First, we make a temporal interpolation to obtain two data set whose observation time are the same. A data set consisting of radial current components at a particular observation time is produced for each radar by linear interpolation using two data sets of radial current components derived directly from the Doppler spectra acquired most close to the required time. Next, we make a spatial interpolation to obtain a pair of radial current components at an observation point. For one of the components, we directly use the value belonging to the data set calculated in the previous step. The other value at the same observation point is calculated by linear interpolation using 4 values, which are selected from the other data set obtained in the previous step, at the nearest to the point in every one point. Then, the paired components are combined to obtain current vector at each observation point. Finally, the current vectors may be converted into that on grid points at 7-km intervals if it is necessary for convenience in actual application. In normal operation mode, radars at Ishigaki site and at Yonaguni site are operated alternately every 30 minutes to avoid interference between them, and so the current vectors are calculated once an hour.

Fig.9 shows an offshore-observation buoy (COMPASS: CRL Ocean Monitoring Platform in Sakishima) moored in March 2001 at the point indicated by a star in Fig.5 (123°26'54"

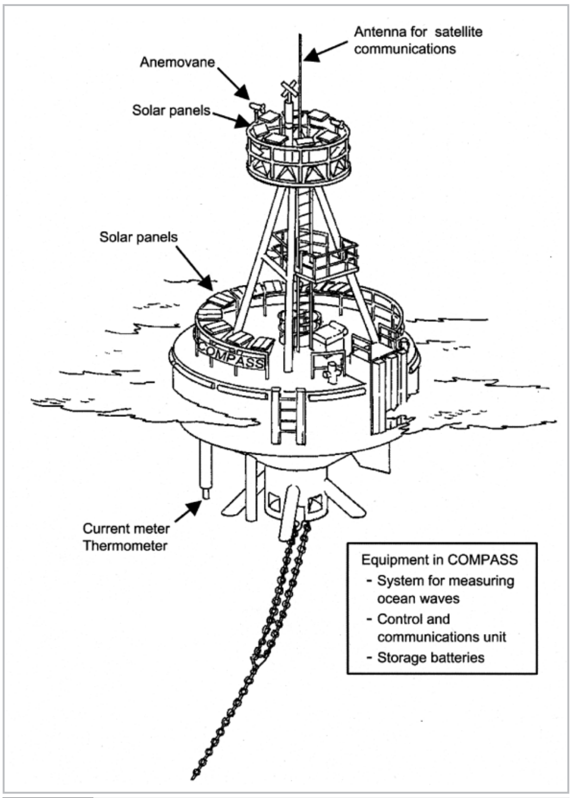

Fig.9 *Bird's eye view of COMPASS*

E, 24°37'55"N). The buoy has a diameter of about 9 m, displacement of about 100 t, and the height above the sea surface is about 10 m. Ocean surface wind is observed with the anemovane (Kona System KDC-S4) attached to the top of the buoy, and the water temperature and current direction and velocity at a depth of 4 m are measured with the acoustic Doppler current meter with thermometer (Sontek ARGONAUT-MD). Ocean wave measurement is taken using the motion sensor (Seatex MRU) installed inside the buoy. The measured data is automatically transferred to the CRL Okinawa via the Orbcomm satellite communication service and Satellite Marine Phone. The COMPASS measurement data will be used to verify the performance of the LROR. The error factor 1/|sin (α)| of LROR at the COMPASS is 1.8.

4 Preliminary Observation Results of Current Vectors

Fig.10 shows current vectors observed at 12:00 on July 24, 2001. It is clearly shown that the Kuroshio current flowing into the observation area from the southwest turns east near the continental shelf. The maximum measured current velocity exceeds 200 cm/s. As in this example, the first-order echoes from more than 200 km away can be detected by both radars in the daytime, and so the current vectors can be measured at sufficiently long ranges. However, during the night it is difficult to constantly detect the echoes at long range and, in some cases, the detectable range may decrease to below 100 km. This characteristic decrease of the detectable range in the nighttime seems to be due to ionospheric behavior, and further research must be necessary.

Fig.11 shows the current vectors observed at 09:30 on Sept.16, 2001. It is the very time when typhoon Nari (#16) of 2001 was passing through the observation area of the LROR. Typhoon Nari generated near Miyako Island and took an extremely irregular course. It had been staying for a record period in a region

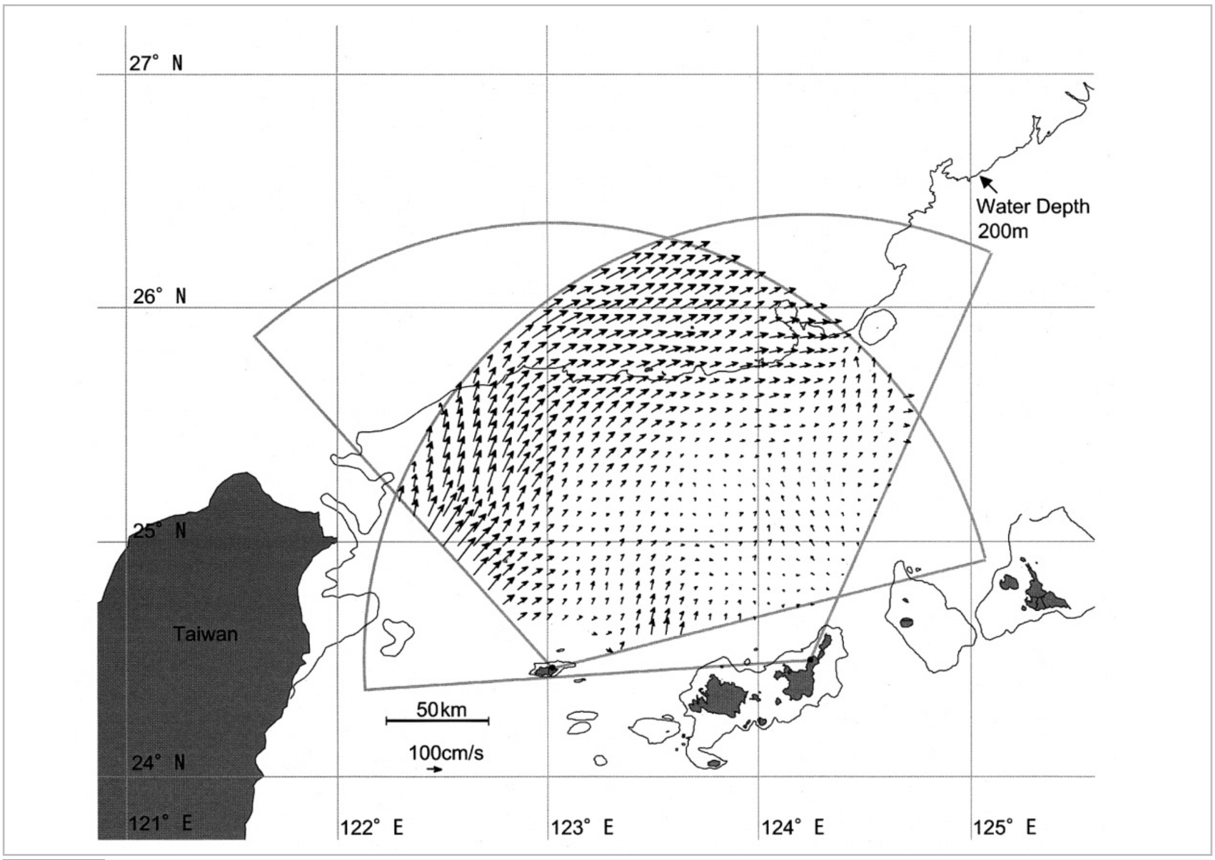

Fig.10 *Observed current vectors for 07/24/2001 1200JST*

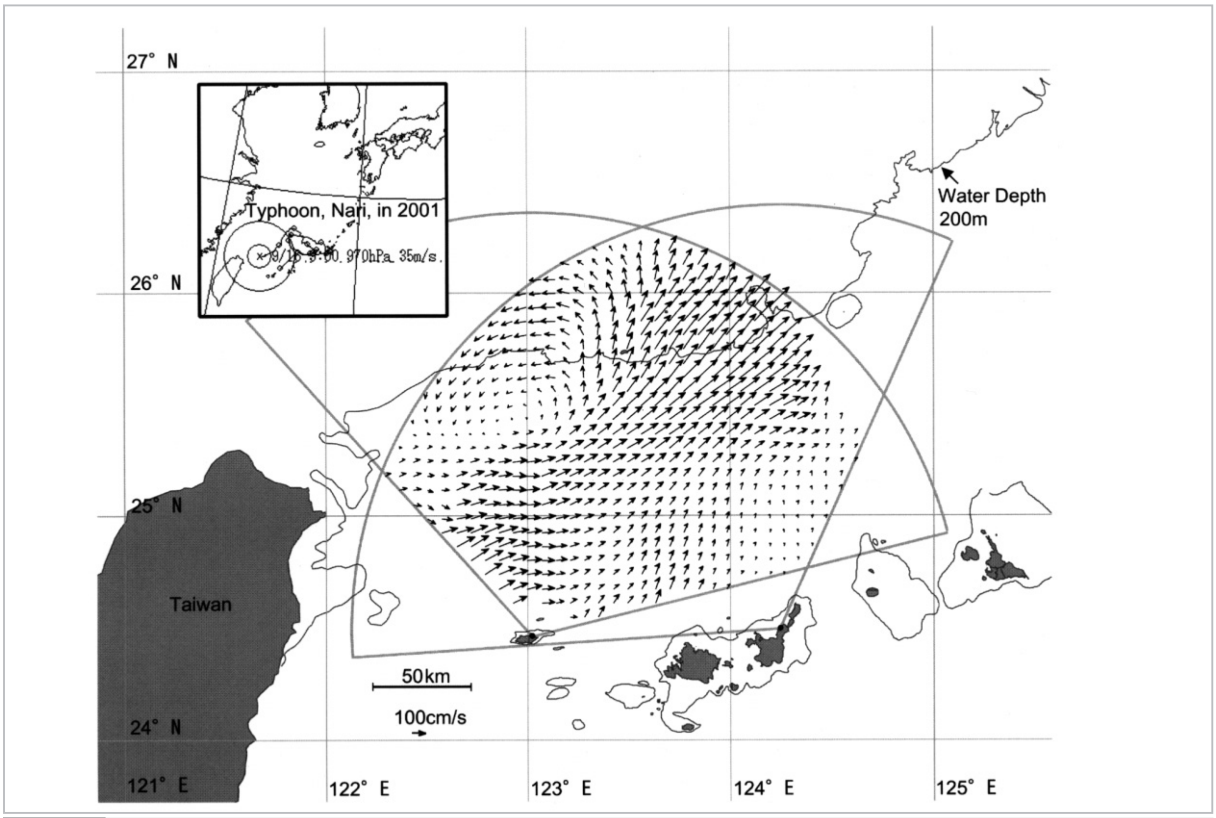

Fig.11 *Observed current vectors for 09/16/2001 0930JST*

west of Okinawa Island, causing great damage to the Okinawa Island and the surrounding islands. Then, it turned south and passed through the observation area of the LROR from the northeast to the southwest from the night of Sept.15 to the evening of Sept.16. The position of the eye of the typhoon at 09:00 on Sept.16 is indicated by an × in the upper-left flame of Fig.11. According to the Japan Meteorological Agency, the pressure at this time was 970 hPa and the maximum wind velocity was 35 m/s. In the northwestern part of the observation area, there was a very fast eddy-like current seemed to be induced by the strong winds of the typhoon. Considering the current field of this area in a calm sea state, the net velocity of the eddy-like current was approximately 100-150 cm/s, which is 2.8-4.3% of the maximum wind velocity of the typhoon. This value is considered to be reasonable because, in general, the maximum current velocity induced by ocean surface wind is thought to be about 3% of the wind velocity. The LROR observation indicated that this eddy-like current was moving to southwest between 07:00 and 16:00 on Sept.16.

5 Summary

The Communications Research Laboratory (CRL) has developed a long-range ocean radar (LROR) system, which can measure surface currents up to 200 km offshore, and experimental observations of the upper region of Kuroshio current in the southern part of the East China Sea has been performed since July 2001.

In the future, radar performance evaluations of the LROR will be done using the observation data from the offshore-observation buoy COMPASS moored in the East China Sea as well as a long-term continuous observation of the current field of the Kuroshio current.

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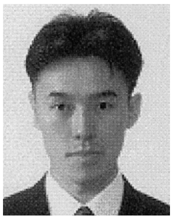
Radar Remote Sensing



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Radar Signal Processing