## Contents

# DEVELOPMENT OF THE C-BAND RADIOMETER AND ITS UTILIZATION FOR SEA SURFACE TEMPERATURE RESEARCH IN VIETNAM

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**Abstract.** *The algorithm for sea surface temperature estimation, proposed by specialists from STI, VAST was described and tested with C-band radiometric data obtained during the Do Son Sea experiment carried out in November 2006. The results for sea surface temperature, obtained from the radiometric data, were compared with the results from contact thermometer measurements and MODIS image processing. Good correspondence was observed.*

*Keywords: microwave remote sensing, radiometer, C-band radiometer, sea surface temperature.*

## I. INTRODUCTION

Microwave (MW) remote sensing systems are widely used for investigation of the Earths surface due to their nearly all-weather, day/night capability and relatively large penetration depth. It is well known that all natural objects having temperature larger than absolute zero (T = 0 K = -273.15 C), emit radiation into surrounding space. This phenomenon is known as natural emission. The MW radiometer (RDM) is a passive device for remote measurement of the emission of the objects under investigation and estimation of environmental parameters like soil moisture, sea salinity and sea surface temperature, etc. The satellite SMOS mission of ESA observing soil moisture and ocean salinity and the satellite SMAP mission of NASA are two examples of state of the art in this field.

Under the research project Design and development of a C-band microwave radiometer and its applications for remote sensing of vegetation cover and sea surface environment in Vietnam joint field experiments for passive microwave remote sensing of soil moisture, vegetation and sea surface were carried out in Vietnam by Vietnamese and Bulgarian scientists and specialists in November 2006. The C-band total-power radiometer CRM, developed under this project, was used to measure the emission of the objects under investigation. In this paper, the experimental results obtained during the Do Son Sea experiment are presented. Brief description of CRM is also given.

## II. DESIGN AND DEVELOPMENT OF THE C-BAND RADIOMETER

CRM is a very sensitive receiver designed to measure the brightness temperature of the Earth's surface (soil, agricultural vegetation, trees, water bodies, etc.). The CRM is designed as total-power radiometer (TPR) [1], i.e. the input signal received via the antenna is directly amplified, converted to digital code and presented at the output liquid-crystal display. The simplified scheme of a total-power radiometer is shown in Fig. 1.
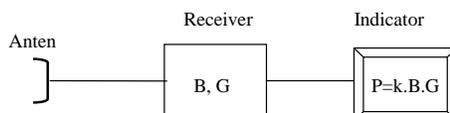


**Fig. 1.** General block digram of Radiometer

The output voltage of the total-power radiometer may be written as follows:

$$U_R = k_B B(T_A + T_N).G, \tag{1}$$

where $k_B = 1.38 \times 10^{-23}$ (J/K) – Boltzmann constant, $B$ – bandwidth of RDM (Hz), $T_A$, $T_N$ - antenna noise temperature and receiver noise temperature (K), $G$ – radiometer gain.

The sensitivity of TPR $\Delta T$ is the highest of all radiometer types [1], and is calculated as follows

$$\Delta T = \frac{T_A + T_N}{\sqrt{B.\tau}} \tag{2}$$

where $\tau$ – integration time ($s$).

### II.1. Block diagram

The block diagram of the radiometer CRM is shown in Fig. 2. The CRM consists of two parts: the high-frequency receiver (Part A) and the processing and power supply unit (part B), which are connected to each other by two cables – the data and power supply cable and the heater cable.

As shown in the block diagram (Fig. 2), the signal from the microstrip antenna (ANT) is fed to the input of CRM by coaxial cable with impedance of 50 Ω. CWT is a transition circuit from coaxial cable to waveguide; WFT is a band-pass filter with bandwidth 300 MHz; LNBC is a low noise block converter. The receiver is mounted in an insulated box with a thermal control system.

The output signal of LNBC is fed to the tuner TUN. For improving the stability of the radiometer CRM two thermostats were used, namely the thermostat of the tuner TMS2 and the thermostat of the microwave unit TMS1. The output signal of the tuner TUN is send to the integrator SUM INT. The output voltage of the integrator is fed into the voltage to frequency converter (VFC) and then fed into the control and processing unit (part B).

To alleviate the noise problems, the signal transmission from part A to part B is performed using electro-optical coupler. The received signal is amplified and converted to digital code in the ANL module and fed into the PIC micro-processing unit. In this unit, the digital codes are processed and the radiometer output signal is displayed on the liquid-crystal display.

On the other hand when working in Remote mode, the radiometer output signal is also sent to a computer through serial interface RS232 or parallel USB. CNTR is the control keyboard, PS is power supply unit.
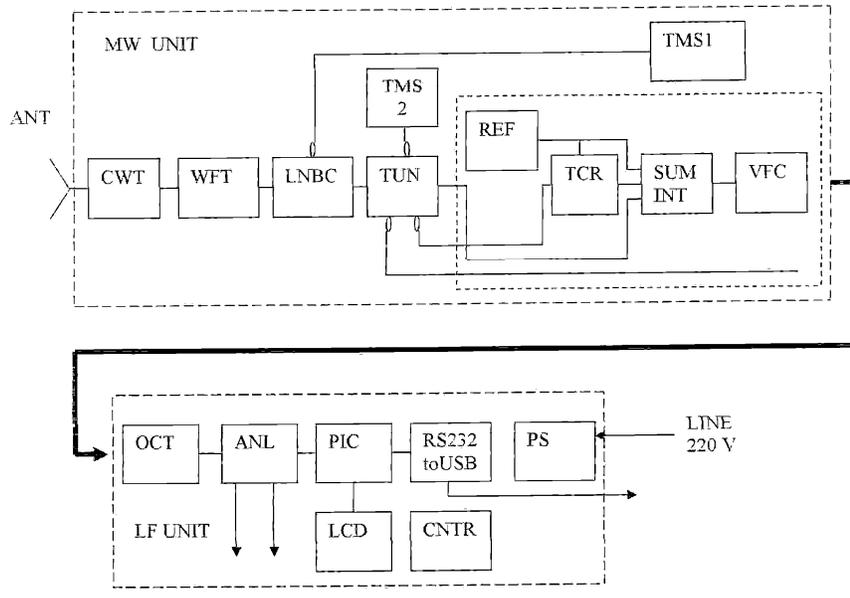


**Fig. 2.** Block diagram of CRM

## II.2. **Characteristics of the C-band radiometer (CRM)**

After CRM was manufactured, a series of tests were carried out in laboratory and field conditions and the following CRM characteristics were obtained:

- Center frequency:               $3.5 \div 3.7$ GHz (8 preselected fixed positions)
- Sensitivity:                    $\leq 0.3$ K
- Integration time:               1 s
- Short-term instability:         $\leq 0.3$ K
- Input signal range:             $0 \div 320$ K
- The width of the antenna beam:  $15^o$
- Power supply:                   220 V(+5%, -10%), 50 Hz
- Power consumption:              70 W during warm up
                                  40 W in measurement mode (LOCAL or REMOTE)
- Type of output signal Analog:   $U_{out} = 0 \div 5$ V DC or digital via RS232 or USB.
- Working temperature:            5 - 40˚C
- Working environment humidity:   35 - 80 %.

The radiometer has two working modes: (1) REMOTE - the measured data is transmitted directly to a computer via RS232 or USB interface; (2) LOCAL - the measured data is processed and displayed on the liquid-crystal display mounted on the front panel of the radiometer and recorded by hand.

## III. THEORETICAL BASICS OF THE PASSIVE MICROWAVE REMOTE SENSING METHOD FOR ENVIRONMENT RESEARCH

Principle of the radiometer's application of research and monitoring of natural resources and environment is based on the measurement of the brightness temperature $T_B$ of the natural objects. The brightness temperature depends on the physical temperature $T_0$ of the object, his dielectric properties and the surface roughness. Empirical and semiempirical models are usually used for estimating environmental parameters such as soil moisture, vegetation biomass, salinity and sea surface temperature, etc. from the measured $T_B$.

In order to measure the brightness temperature of an object, the antenna of the radiometer is directed to this object at incident angle $\theta$. The (radiation intensity/ brightness) $B_f$ can be calculated using the Rayleigh-Jeans formula [2]:

$$B_f = \frac{2k_B T}{\lambda^2}.e \qquad (3)$$

where $B_f$ – radiation intensity (Watt/m$^2$) [2]), $\lambda$ (cm) - the electromagnetic wavelength, $e$ – emissivity of the object.

The antenna noise temperature is represented by the following formula:

$$T_A = \frac{1}{4\pi} \iint_{4\pi} T_B(\theta,\phi).G(\theta,\phi).d\Omega \qquad (4)$$

where, $G(\theta,\phi)$ – the antenna gain, $T_B(\theta,\phi)$ – the angular distribution of the brightness temperature of the object, $\theta$ – angle of incidence, $\phi$ – angle of azimuth.

For a homogeneous medium with uniform temperature $T$ the brightness temperature $T_B$ is usually calculated using the following simple equations:

$$T_{B,p}(\theta) \approx [1 - R_p(\theta)].T \qquad (5)$$

$$e_p(\theta) = 1 - R_p(\theta) \qquad (6)$$

where, $R_p(\theta)$ – reflectivity, $e(\theta)$ – emissivity, $\theta$ – angle of incidence, $p$ – polarization configuration, $p = h$ for horizontal polarization and $p = v$ for vertical polarization.

Reflectivity is calculated using the Fresnel equations for horizontal and vertical polarizations as shown in Refs. [2–4]

$$R_h(\theta) = \left| \frac{\cos\theta - \sqrt{k - \sin^2\theta}}{\cos\theta + \sqrt{k - \sin^2\theta}} \right|^2 \qquad (7)$$

$$R_v(\theta) = \left| \frac{k\cos\theta - \sqrt{k - \sin^2\theta}}{k\cos\theta + \sqrt{k - \sin^2\theta}} \right|^2 \qquad (8)$$

where $k$ – dielectric constant of the natural object.
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## IV. APPLICATION OF THE CRM FOR SEA SURFACE TEMPERATURE RESEARCH

Among sea surface temperature (SST), sea surface salinity (SSS), chlorophyll-a concentration, suspended matter, etc. , the sea surface temperature is the most important parameter governing the energy exchange between sea and atmosphere that depends also on the air temperature and wind speed.

Principle of RDM's application for estimating the sea surface temperature SST [8] is based on the following equation:

$$T = T_{B,p}(\theta)/e_p(\theta), \tag{9}$$

where $T_{B,p}(\theta)$ is the brightness temperature of the sea surface at incidence angle $\theta$ and polarization $p$, $e_p(\theta)$ is the emissivity of the sea surface.

A joint experiment for remote sensing of the sea emission was carried out in November 2006 at Do Son Sea with participation of specialists from STI, VAST, Vietnam, Institute of Marine Environment and Resource (IMER), VAST, Vietnam and Institute of Electronics, BAS, Bulgaria. The radiometer CRM was mounted on a 15 tons ship (Fig. 3) using a mechanical support with antenna angle positioning system. The mechanical support was firmly fixed to the wooden deck of the ship. The brightness temperature of the sea surface was measured by CRM and transferred to a computer. Other parameters like air temperature, wind speed, wave height, sea surface salinity, coordinates of the ship, etc. were measured by traditional methods and GPS receiver.
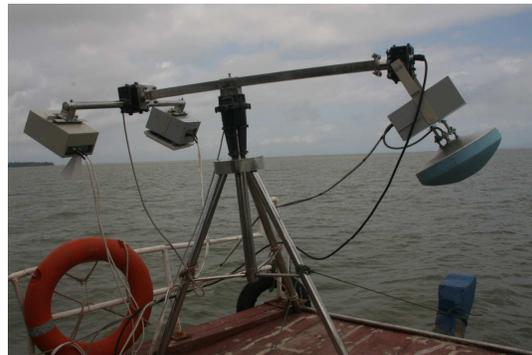


**Fig. 3.** Ship deck and the radiometers LNIR, CRM and XRM

### IV.1. Experimental procedure

The experiments were carried out on November 7, 2006 from 10:29 AM until 13:18 PM at Do Son sea with coordinates 106°51'44.64"E; 20°41'22.56"N (about 12 km from the beach). This time period was chosen to coincide with the MODIS satellite passing Vietnam to take picture at the same time and ship position (first time from $10:29 \div 10:36$ AM; second time from $13:14 \div 13:18$ PM; third time from $13:38 \div 13:42$ PM). Moreover, the air temperature was measured at 3.5 m above the sea surface and the salinity was measured at 5 – 20 cm below the sea surface. The CRM was switched on to warm up. After the preset steady-state  temperature was reached, the CRM was calibrated measuring the emission of the "cold" target clear sky $T_B = 5$ K and the "hot" target absorber $T_B = T_{abs}$ (high-quality microwave absorber with known physical temperature).

The antenna of CRM was directed to the sea surface at incidence angle $\theta$ varying from $0°$ to $60°$ with a step $10°$ and horizontal polarization. At each angle, CRM has measured $T_B$ of the sea surface for about 3 minutes. After that the antenna was automatically rotated to another angle and the next $T_B$ measurement was carried out. The measured data was transferred to PC and later was processed by the program "Radiometer 4.0" developed by specialists from STI.

**Table 1.** Parameters measured by specialists from IMER at Do Son Sea, November 7, 2006

| Time | $T_{sea}$ (°C) Air Temp. | $T_{air}$ (°C) SST | Wave height (cm) | Salinity ‰ (d = 20cm) | Wind speed (m/s) |
|---|---|---|---|---|---|
| 10:30AM | 25.8 | 26.7 | 12 ÷ 17 | 31.5 | 6.4 |
| 13:15PM | 27.6 | 27.5 | 11÷ 16 | 28.5 | 2.3 |
| 13:30PM | 27.8 | 27.5 | 10 ÷15 | 27.5 | 1.8 |

## IV.2. Data processing

### IV.2.1. *Radiometer data processing*

The raw radiometric data were processed [6] and the obtained brightness temperatures $T_{B,h}(\theta)$ were compared with the modeled brightness temperatures $T_{B,mod,h}(\theta)$. Very large differences between the measurements and the model were observed, especially at small incidence angles, because of the emission of the wooden deck of the ship [6]. An original algorithm for correcting the effect of the wooden deck of the ship was proposed in Ref. [6] and was successfully used for calculating $T_{B,est}$ from the measured radiometric data at 3.626 GHz and horizontal polarization. The results for $T_{B,est}$ were also reported in Refs. [7, 8]. Several years later the algorithm was modified for vertical polarization measurements, as shown in Ref. [9], and was used for calculating $T_{B,est}$ from the measured radiometric data at 10.923 GHz and vertical polarization. Klein and Swift dielectric model [3, 5], was used in Ref. [6] for calculating the dielectric constant of sea water from the measured sea water temperature and salinity.

In 2002, in his project report Joel T. Johnson [4] has stated that the dielectric model of Klein and Swift [5] has been found more successful at reproducing water surface observations at L-band Below are the formulas of the Klein and Swift model [3–5]:

$$k = \varepsilon_\infty + \frac{\varepsilon_1 - \varepsilon_0}{1 - 2i\pi f\tau} + \frac{i\sigma}{2\pi f\varepsilon_0} \tag{10}$$

$$\varepsilon_1 = \left(87.134 - 0.1949T - 0.1276T^2 + 0.002491T^3\right)$$
$$\times \left(1 + 1.613 \times 10^{-5}TS - 0.003656S + 3.21 \times 10^{-5}S^2 - 4.232 \times 10^{-7}S^3\right) \tag{11}$$

$$\varepsilon_\infty = 4.9 \tag{12}$$

$$\tau = \left(1.1109 \times 10^{-10} - 3.824 \times 10^{-12}T + 6.398 \times 10^{-14}T^2 - 5.096 \times 10^{-16}T^3\right)$$
$$\times \left(1 + 2.282 \times 10^{-5}TS - 7.638 \times 10^{-4}S - 7.760 \times 10^{-6}S^2 + 1.105 \times 10^{-8}S^3\right) \tag{13}$$

$$\sigma = S\left(0.18252 - 0.0014619S + 2.093 \times 10^{-5}S^2 - 1.282 \times 10^{-7}S^3\right)$$
$$\times \exp\left[(T - 25)\left(0.02033 + 0.0001266(25 - T) + 2.464 \times 10^{-6}(25 - T)^2\right.\right.$$
$$\left.\left. - S\left(1.849 \times 10^{-5}\right) - 2.551 \times 10^{-7}(25 - T) + 2.551 \times 10^{-8}(25 - T)^2\right)\right] \tag{14}$$

where $T$ (°C) – sea surface temperature, $S$ (psu) – sea surface salinity; $\varepsilon_0 = 8.85 \times 10^{-12}$ F/m is the dielectric constant of free space; $\varepsilon_\infty$ – high frequency limit value; $\sigma$ – the ionic conductivity of sea water; $f$ is the frequency of the radiometer in Hertz;

After calculating the dielectric constant of sea water $k$ using equations (10) ÷ (14), the reflection coefficients $R_p$ for smooth sea surface are determined using the Fresnel equations (7)-(8), the emission $e$ is calculated as $e = 1 - R(\theta, k)$. Finally the modeled brightness temperature $T_{B,mod}$ is calculated as:

$$T_{B,mod} = (T + 273.15)e \qquad (15)$$

**IV.2**.2. *Sea surface temperature calculation*
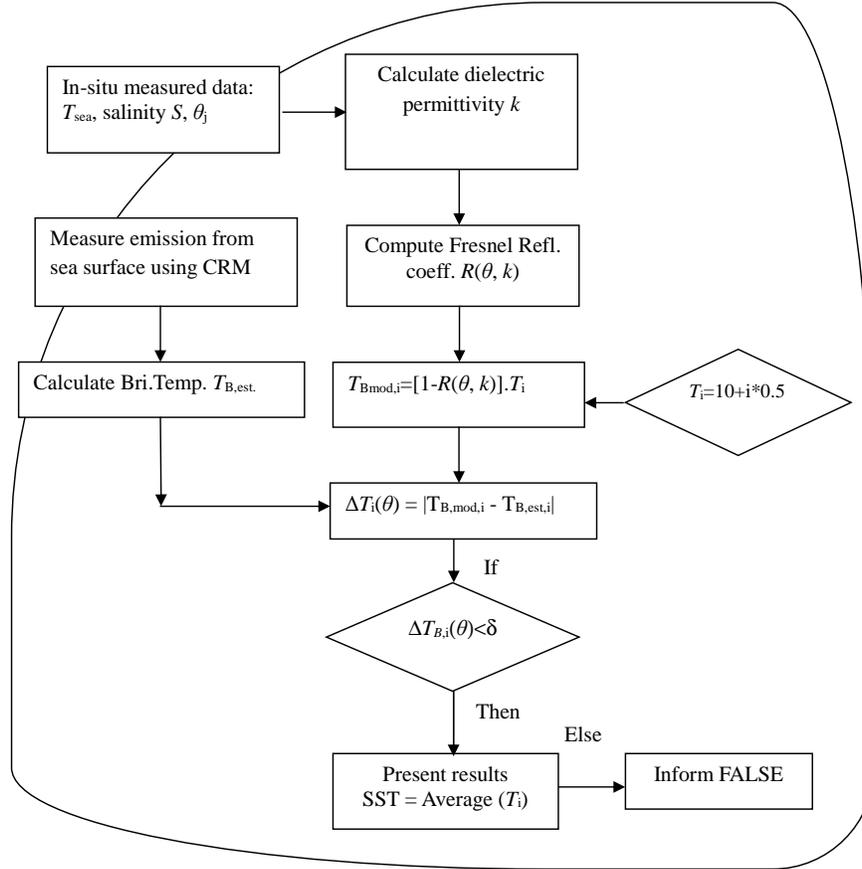


**Fig. 4.** Flowchart for calculation of sea surface temperature SST

The $T_{B,est}$ results were used to calculate the sea surface temperature with the Excel program shown in Fig. 5. The flowchart for calculating the sea surface temperature SST is presented in Fig. 4. The following major steps must be mentioned:

Data input: the data for the measured sea surface temperature $T_{sea}$ (˚C), salinity $S$ (psu), center frequency of CRM, incidence angle, etc. were entered into the Excel program.

Calculations:

- Calculating $T_{B,est}$ for horizontal polarization from the measured radiometric data using the algorithm presented in [6] and [8].

- Calculating $T_{B,mod}$ for horizontal polarization using (5) with temperatures $T_i$ in the range from 10°C to 45°C with a step $\Delta T = 0.5$°C. Klein and Swift dielectric model was used for calculating the dielectric constant of sea water from the measured sea water temperature and salinity. The Fresnel equation at horizontal polarization was used for calculating the reflectivity of a smooth water surface.
- Calculating the difference $\Delta T_{B,i}$ between $T_{B,est,i}$ and $T_{B,mod,i}$;
- Comparing the difference $\Delta T_{B,i}$ against a threshold value $\delta$. If the difference $\Delta T_{B,i}$ is smaller than the threshold value $\delta$, the corresponding $T_i$ value is used to calculate $SST = AVG(T_i)$.

Fig. 5 shows a part of the Excel program for computing the SST according to the flowchart presented in Fig. 4.
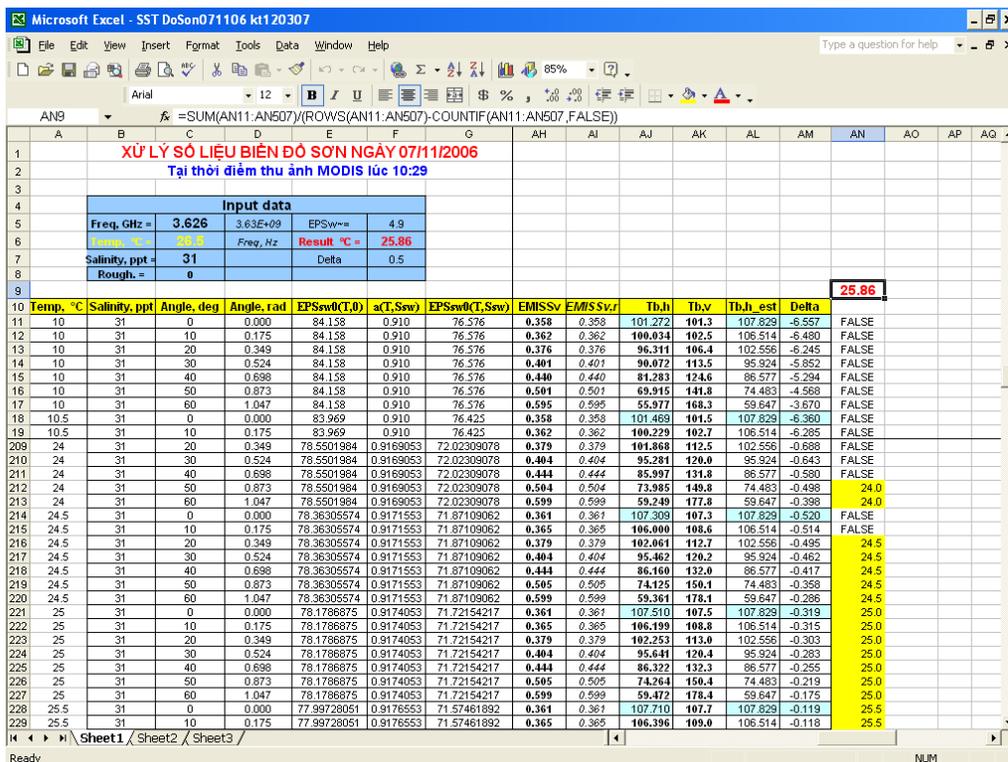


**Fig. 5.** An example of the Excel program for calculating SST

On the other hand, a MODIS image was taken from the Station of the Physics Institute at the same time and position with the CRM. The image was taken on 13:27 PM, 7/11/2006 at the position of the ship carrying the CRM, with coordinates $20^o41'22.56''$E; $106^o51'44.64''$N. The image was processed, the sea surface temperature was calculated and the results are given in the table below.

Table 2 shows results for sea surface temperature SST estimated using three different methods, namely contact thermometer measurements, C-band radiometer measurements and MODIS image processing Good correspondence was observed.

**Table 2.** Results for SST obtained using three different methods

| Time | SST measured by thermometer (°C) | SST estimated from CRM data (°C) | SST estimated from MODIS image (°C) |
|---|---|---|---|
| 10:29AM | 26.5 | 25.9 | 26.3 |
| 13:29PM | 28.0 | 27.5 | 27.8 |

## V. CONCLUSION

Under the research project "Design and development of a C-band microwave radiometer and its applications for remote sensing of vegetation cover and sea surface environment in Vietnam" joint field experiments for passive microwave remote sensing of soil moisture, vegetation and sea surface were carried out in Vietnam by Vietnamese and Bulgarian scientists and specialists in November 2006. The C-band total-power radiometer CRM, developed under this project, was used to measure the emission of the objects under investigation. In this paper, the experimental results obtained during the Do Son Sea experiment were presented. The algorithm for sea surface temperature estimation, proposed by specialists from STI, VAST was described and tested with C-band radiometric data. The results for SST obtained from the CRM data were compared with the results from contact thermometer measurements and MODIS image processing. Good correspondence was observed. The experimental results confirmed that the C-band radiometer CRM is a very reliable instrument for remote sensing research and environmental studies.

## ACKNOWLEDGMENTS

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