PREDICTION AND MEASUREMENT OF LONG RANGE PROPAGATION OF LF STANDARD FREQUENCY

TSUCHIYA Shigeru
National Institute of Information and Communications Technology
4-2-1 Nukui-kita, Koganei, Tokyo 184-8795 Japan
Phone: +81-42-327-6274
E-mail: *tsuchi@nict.go.jp*

IMAMURA Kuniyasu, ITO Hiroyuki, MAENO Hideo,
NAGATSUMA Tsutomu, KITAUCHI Hideaki
National Institute of Information and Communications Technology
4-2-1 Nukui-kita, Koganei, Tokyo 184-8795 Japan
and
NOZAKI Kenro
Space Engineering Development Co., Ltd.
E-mail: {*kei, hito, tnagatsu, kitauchi, nozaki*}*@nict.go.jp*

Abstract

Wave hop method on LF field strength prediction adopted in the current recommendation of the International Telecommunication Union Radiocommunication Sector (ITU-R) is presented. Measured field strength on Japanese and US standard frequency and time signals (SFTS) is fairly agreed with the prediction in wide range of distance. The wave-hop prediction method is applicable at the lower frequencies than ITU-R recommended.

INTRODUCTION

The standard frequency and time signals (SFTS) of the LF band are widely used for calibrating frequency oscillators and adjusting the time of radio clocks. It is useful to evaluate signal level and interference of LF SFTS for a wide range of distances. The electric field strength of the Japanese SFTS “JJY” at 40 kHz and 60 kHz **[1]** was measured at about 40 points in Japan during the 2004 winter season **[2]**. Based on the domestic measurement, a numerical prediction method for the range of up to 4,000 km was incorporated in the ITU-R recommendation for prediction of field strength below 150 kHz **[3]**. Two predicting methods are presented in the ITU-R recommendation. The wave-hop method is recommended for use above 60 kHz; however, the measured field strength agreed with the wave-hop prediction at 40 kHz.

Mobile measurement far from the transmitting stations has been carried out since 2007. An omnidirectional receiving system with crossed loop antenna was loaded onto a container ship for East-West propagation measurements in June 2007. North-South propagation has been measured by a Japanese Antarctic Research Expedition ship. The prediction method was improved to be applicable up to

16,000 km and the ITU-R recommendation was again revised **[4]**. A brief description on the wave hop method is introduced and the results of the 2007 measurement cruise are discussed in this paper.

PREDICTION METHOD

The wave-hop method treats the radio waves propagating along geometric optical paths and is easy to understand as shown in Figure 1. It is used for the range from short to long distance propagation.

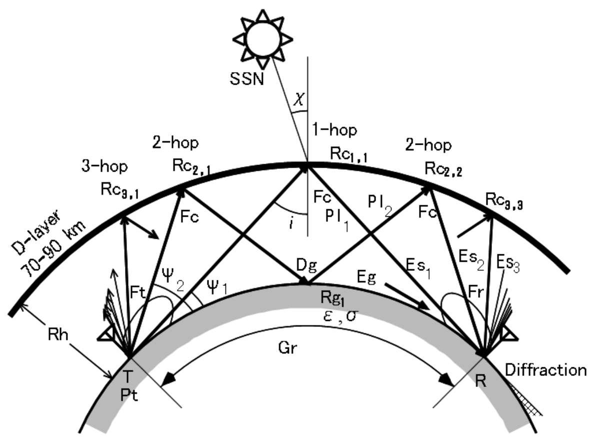

Figure 1. Geometrics of LF propagation in the wave-hop method.

The total field strength *E* of the vertically polarized electric field at the receiving point “R” is the vectorial summation of the ground wave *Eg* and sky waves *Es* reflected between the ground and the ionosphere up to 10 hops.

$$E = |Eg| \exp(-jkd) + \sum_{K=1}^{10} Es_K$$

where

$|Eg|$: field strength of ground wave obtained from Reference **[5]**.

d : great circle distance between transmitting and receiving station.

k : wave number.

The field strength of the sky wave “Es_K” is calculated as follows:

$$Es_K = \frac{600\sqrt{Pt}\cos(\Psi_K)\prod_{L=1}^{K} Rc_{K,L}}{\sum_{L=1}^{K} Pl_{K,L}} Fc_K Rg_K^{K-1} Ft_K Fr_K \exp\left(-jk\sum_{L=1}^{K} Pl_{K,L}\right)$$

where

K : hop number from 1 to 10.

L : apex number from 1 to K.

Pt : radiation power in kW.

Ψ_K : departure and arrival angles of K hop ray.
$Rc_{K,L}$: ionospheric reflection coefficients.
Fc_K : focusing factor.
Rg_K : reflection coefficient of the ground for vertically polarized wave.
Ft_K, Fr_K : transmitting and receiving antenna factors respectively.
$Pl_{K,L}$: propagation length of L^{th} reflection of K hop ray.

$Rc_{K,L}$ and Rg_K are calculated for all the reflection points. $Rc_{K,L}$ is given corresponding to sunspot minimum, medium and maximum periods respectively. It is also a function of solar zenith angle χ, frequency, and ionospheric incidence angle i as shown in Figure 1. $Rc_{K,L}$ varies with location, time of day, and season of year. The resultant field strength shows unstable time variation for long range propagation.

MEASUREMENTS

The three-axis crossed-loop antenna for which the azimuthal deviation of gain is within ±0.5 dB was used for measuring the field strength and the phase as shown in Figure 2. A receiver of 200 Hz bandwidth was switched to each antenna loop and frequencies of 40 and 60 kHz. The noise level of the receiving system is about 29 dBmicroV/m. The field strength is calculated and recorded in the Control PC every 3 minutes, together with the position information of the ship derived from the GPS receiver.

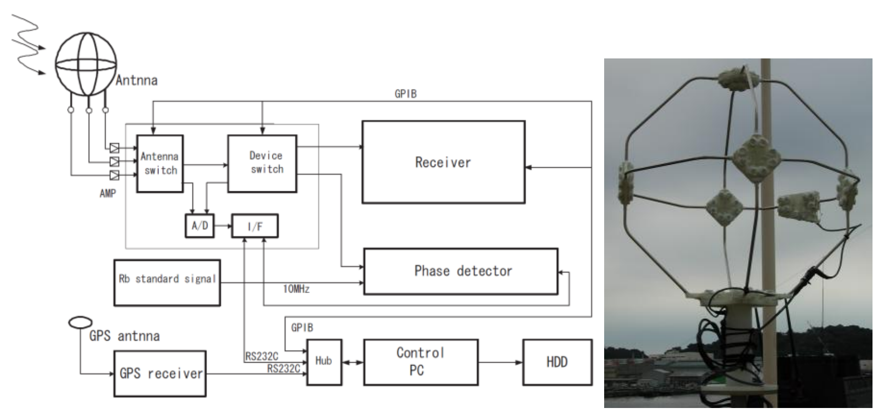

Figure 2. Block diagram of the LF field strength measurement system (left) and the crossed-loop antenna.

A container ship carrying the measurement system left Tokyo on May 13, 2007, for Taiwan, China, and Thailand. After returning from the South-East Asia cruise, she voyaged across the Pacific Ocean along the great circle during June as shown by the blue line in Figure 3. Measured and predicted field strength is plotted on the left column of Figure 4 together with the range from JJY stations and atmospheric noise derived from Reference **[6]**. The SFTS signal is distinguished by calculating the autocorrelation factor (ACF). The ACF of the 40 kHz shows one second repetition at point A of Figure 3 on June 5, as shown in Figure 6(a). Two days after point A, at point C of Figure 3, periodicity in ACF was lost. The JJY signal was considered to be suppressed by the atmospheric noise. The ACF of the 60 kHz showed once no periodicity at the point A; however the periodicity appeared again at the point B of Figure 3, 12 hours after point A. It is considered that JJY 60 kHz was switched by WWVB 60 kHz. The calculated WWVB field strength is plotted in Figure 5 together with measured field strength and distance from WWVB. Measured field strength again agreed with the predicted field strength from WWVB.

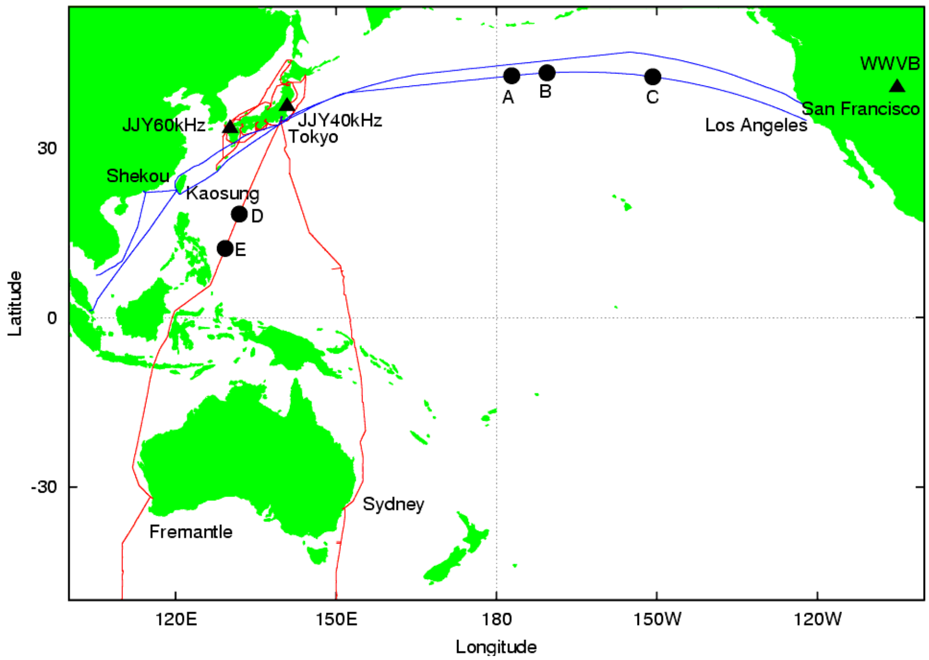

Figure 3. Coastal (red), E-W (blue), and N-S (red) cruise paths in 2007.

After a training cruise around Japan, the Japanese Antarctic Research Expedition ship "Shirase" left Tokyo on November 14, 2007, for Antarctica, stopping by Fremantle, Western Australia. She returned to Tokyo on April 12, 2007, via Sydney as shown by red line in Figure 3. Increased atmospheric noise due to the lightning activity near the equator disturbed the field strength measurement as shown in the right column of Figure 4. The ACF of 40 kHz showed one second periodicity at point D in Figure 3 on November 17, but the periodicity was lost at point E on the next day. The JJY signal was sometimes received beyond Australia; however, continuous measurement was limited up to about 4,000 km.

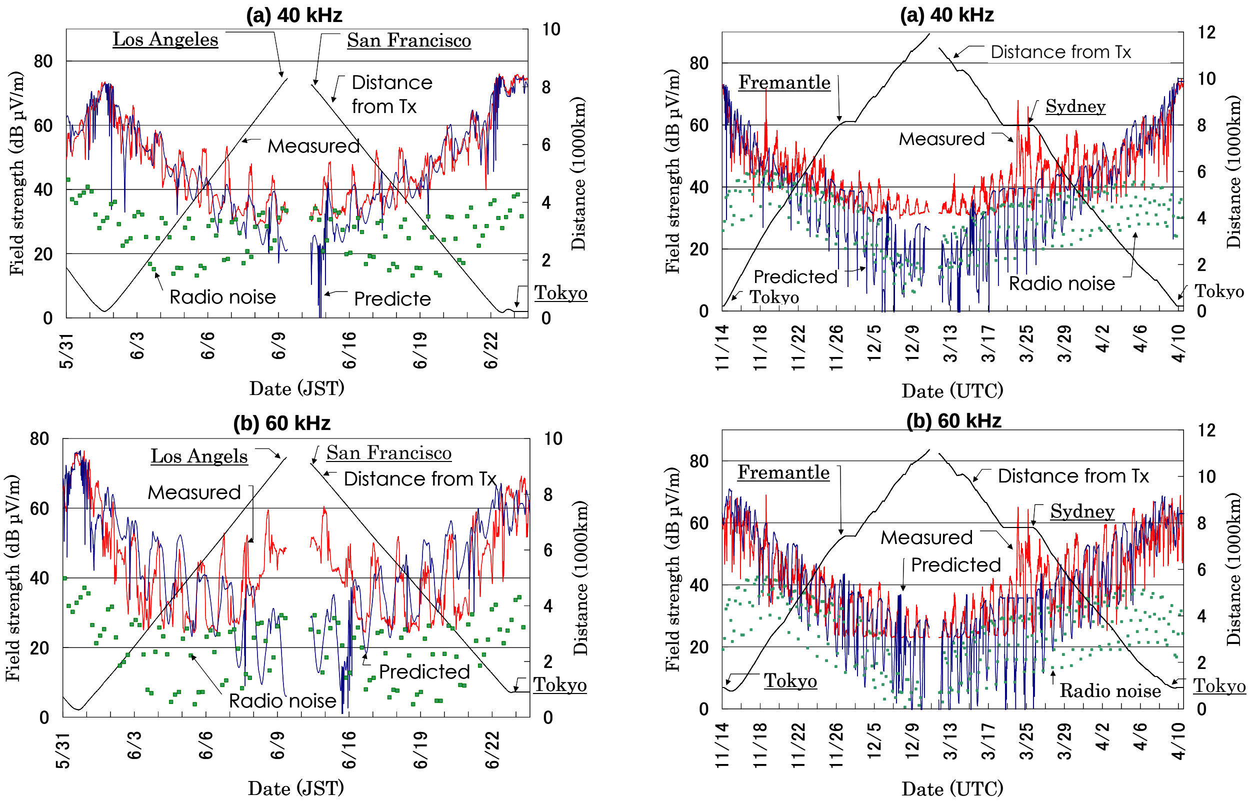

Figure 4. Measured and predicted field strength of JJY.
Left: E-W route
Right: N-S route
Red line: measured field strength
Blue line: predicted field strength
Black Line: Distance from transmitter
Green dots: Atmospheric noise derived from Reference **[5].**

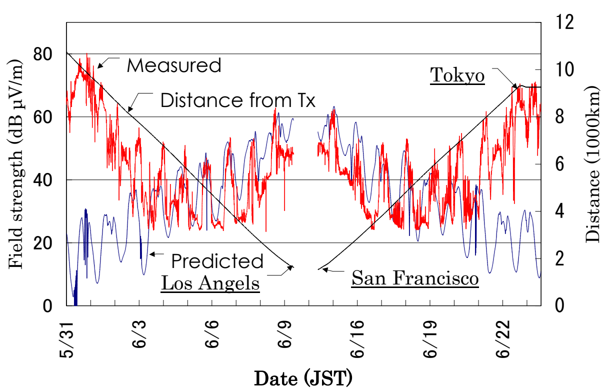

Figure 5. Measured and predicted field strength of WWVB in E-W route.

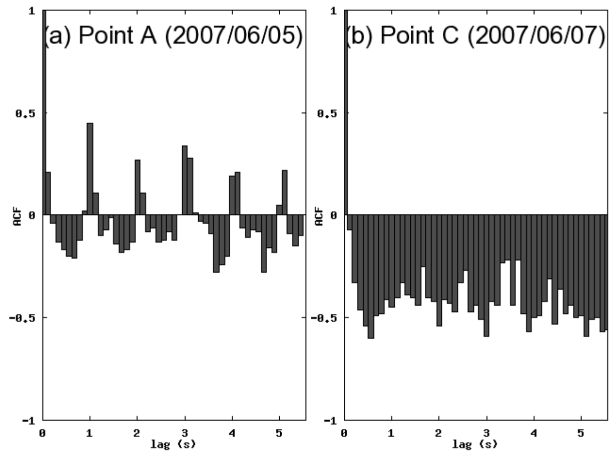

Figure 6. Autocorrelation factor at point A (left panel) and point C (right panel) as shown in Figure 3.

CONCLUDING REMARKS

The predicted field strength by the wave hop method is fairly agreed with the measurement up to several thousands of kilometers. Diurnal and range variation of the field strength is well simulated as low as 40 kHz whereas the ITU-R recommended the use of the waveguide method at such a frequency.

Beyond several thousand kilometers, accurate field strength measurement is difficult because the field strength become comparable to the system noise, atmospheric noise, and man made noise level. The phase variation of the JJY signal was recorded until "Shirase" arrived at the Japanese Antarctic Syowa Station, about 12,000 km from the JJY transmitting station. A narrow band and highly sensitive receiving system is in development for the continuous measurement of long range propagation. The ACF is good to confirm the SFTS radio but another algorithm is studied to distinguish the SFTS signal level from noisy received data.

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