TIMING REQUIREMENTS FOR THE SANGUINE ELF COMMUNICATIONS SYSTEM

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SUMMARY

The requirements for transmitter stations clocks are 0.3ms (1σ) ± 1 ms for receiver clocks. It is of interest to note that for Sanguine, as in other coherent systems, the clock requirements are obtained as phase or time rather than as frequency.

1. INTRODUCTION – BRIEF SYSTEM OVERVIEW

The Navy has proposed to build an ELF communications system for communications primarily with submerged submarines. This system has been named Sanguine. The need for Sanguine follows from the following considerations:

In order for a weapon to be an effective deterrent it must be highly survivable. Weapon systems based in the world's ocean waters are the most survivable systems. Consequently, a great deal of emphasis is given to sea-based weapon systems such as the presently operating Polaris/Poseidon weapon system aboard nuclear submarines (SSBNs). The purpose of Sanguine is therefore to provide survivable command and control capability for sea-based and other forces, and in particular, to deliver High Priority Operational Messages.

The basic requirements for a command control and communications (C^3) system are:

- Deliver high priority operational messages, almost worldwide, pre- and post-attack, to SSBNs at speed and depth, and to other U. S. forces
- Survive physical attack (conventional and nuclear)
- Survive the electromagnetic pulse from low and high altitude nuclear bursts
- Be resistant to attack on the propagation path
- Be resistant to electromagnetic attack (jamming)

The C^3 problem has been studied for many years and the only solution which satisfies the above requirements is an ELF system, Sanguine. Sanguine will operate within the frequency band of 30 to 100 Hz; the most likely carrier frequency being 45 or 75 Hz. Figure 1 shows the free-space 45-Hz wavelength compared to the United States. This frequency band has the following characteristics:

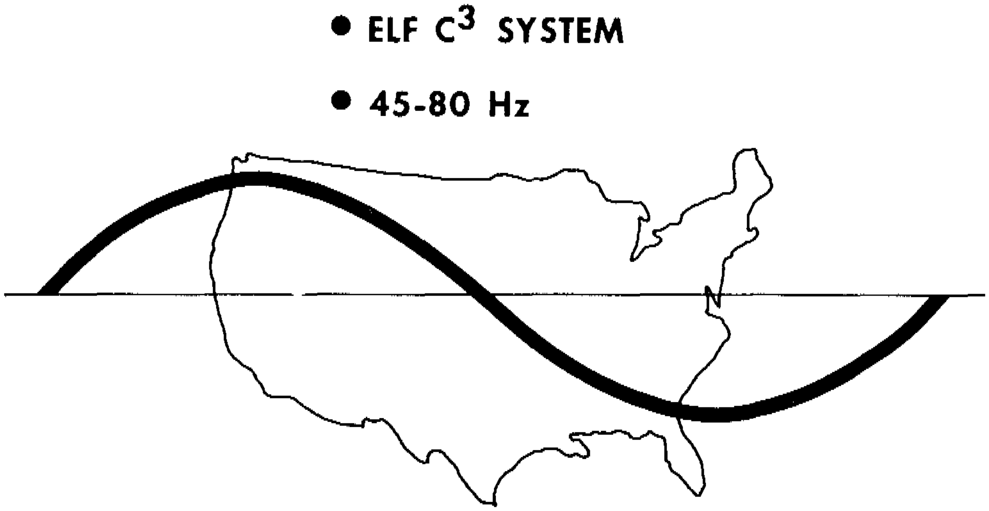

Figure 1. Free-space wavelength at 45 Hz.

Low Atmospheric Attenuation – permits reliable, almost worldwide, communication coverage from a CONUS-based transmitter and denies a jammer the range advantage it would have at higher frequencies

Low Sea Water Attenuation – permits ELF reception at considerable depths

Least Affected by Disturbed Propagation Path – attenuation is not severely increased by nuclear detonations along the propagation path

An illustration of the Sanguine concept is shown in Figure 2.

The transmitting antenna excites electromagnetic waves in the spherical cavity bounded by the ionosphere and the surface of the earth. ELF frequencies are well below the cut-off frequency of the first order mode (≈ 1700 Hz) in the cavity so that only the zero-order mode transverse magnetic waves will propagate.

The general vertical polarized E-field has a small horizontal component which propagates downward through sea water. This component can be sensed by an E-field submarine antenna.

The cost of the Sanguine transmitter will be an order of magnitude higher than the cost of all the receivers. In order to reduce system cost, signal and receiver design have been optimized to allow for the lowest signal-to-noise ratio compatible with C^3 requirements. Coherent detection is therefore used, which imposes timing requirements both on the transmitter and the receivers.

2. THE TRANSMITTER

Transmitter survivability is achieved by a combination of redundancy and hardened antenna and transmitter station design. The basic antenna element is shown in Figure 3; it can be viewed as a loop antenna. One part of the loop is an isolated cable grounded at each end, and the loop is closed by the earth return path. The cable can be buried, so it is very survivable. A power amplifier in a hardened transmitter station drives the current in the loop.

From 1000 to 10,000 of these basic elements will be combined in a transmitter array. Each transmitter station will be unmanned and will operate independently of the other transmitter stations; there will be no communications between stations. Each station must therefore have its own clock.

If each antenna element carries the current ΔI with relative phase as shown in Figure 4, then the resultant current I from N elements is

$$I = \sum_{i}^{N} \Delta I \cos\varphi_i = \Delta I \sum (1 - \tfrac{1}{2}\varphi_i^2 + \cdots)$$

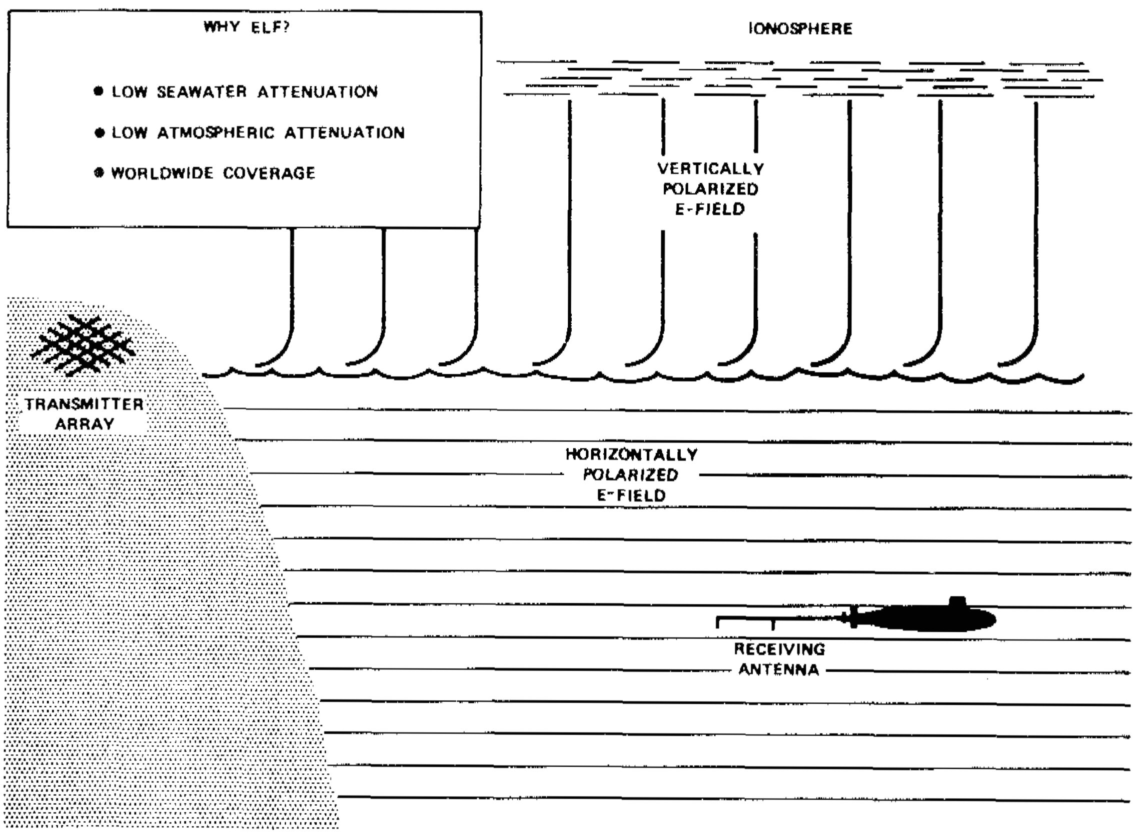

Figure 2. The Sanguine concept.

or $$I = I_0 \cos \sigma_\varphi \quad (1)$$

where $$I_0 = N \Delta I \quad (2)$$

$$\sigma_\varphi^2 = \frac{1}{N} \sum_1^N \varphi_i^2 \quad (3)$$

Thus cos σ_φ is the loss due to phase or timing errors at the transmitter stations. Table 1 shows the time accuracies required for 0.1 and 1 dB loss. Also shown is the required frequency stability obtained from

$$\frac{\Delta f}{f} = \frac{\Delta T}{T} \quad (4)$$

where T = 1 month.

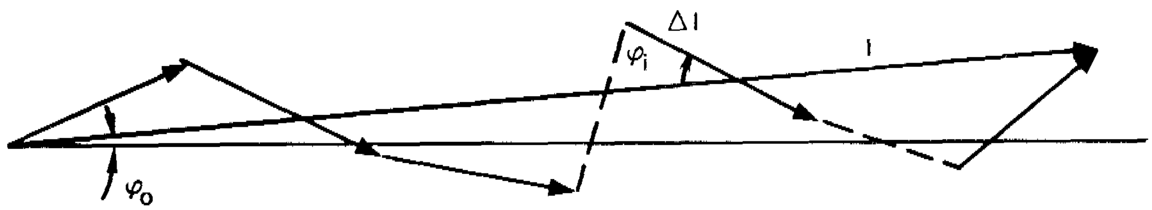

Figure 3. Basic Sanguine antenna element.

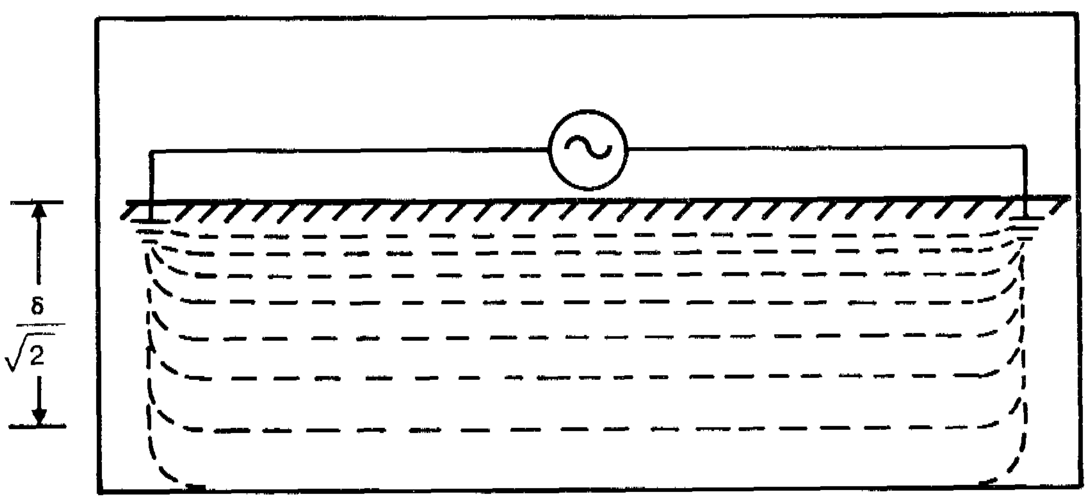

Figure 4. Summation of contributions from each antenna element.

Table 1
Time and Frequency Accuracy Required at Transmitter Stations.

	Phase Error	Time Accuracy		Frequency Accuracy	
Loss	(1σ)	(1σ)		$\Delta f/f$	(1σ)
(dB)	(Radians)	45 Hz	75 Hz	45 Hz	75 Hz
0.1	0.15	0.5 ms	0.3 ms	2.5×10^{-10}	1.5×10^{-10}
1	0.47	1.7 ms	1.0 ms	7.7×10^{-10}	4.6×10^{-10}

For the phase angle φ_0 of the resultant I, we have

$$\tan \varphi_0 = \frac{\sum_1^N \sin \varphi_i}{\sum_1^N \cos \varphi_i} \tag{5}$$

and for small angles

$$\varphi_0 = \frac{1}{N} \sum_1^N \varphi_i \tag{6}$$

and

$$\sigma_{\varphi_0} = \frac{1}{N} \sigma_\varphi \tag{7}$$

σ_{φ_0} is thus small and σ_0 can therefore be tracked by the receiver phase estimator described below.

3. THE RECEIVER

Minimum Shift Keying (MSK) has been selected for Sanguine as the most effective modulation scheme. MSK is a form of frequency-shift keying where the two frequencies f_1 and f_2 are orthogonal over one chip. Or if viewed as phase modulation $\exp\{j(\omega_0 t + \phi(t)\}$, the phase $\phi(t)$ changes linearly $\frac{\pi}{2}$ during one chip. Several chips are combined to one channel symbol.

The phase of f_1 and f_2 will be obtained by a phase estimator in the receiver. The transmitter phase error φ_0 will thus be tracked by the receiver and will not degrade system performance.

For correlation of the chips, time is required. The signal loss due to a timing error is given by the correlation function $R(\tau)$. Following Source 3 we obtain

$$R(\tau) = (1 - \frac{|\tau|}{2T_c}) \cos (\frac{\pi\tau}{2T_c}) - \frac{1}{\pi} \sin (\frac{\pi|\tau|}{2T_c}) \qquad (8)$$

where T_C is the chip time. A plot of Equation (8) is shown in Figure 5.

It is seen that $|\tau|/T_C = 0.1$ only results in 0.1 dB degradation. We thus can allow a total time error.

$$|\tau| = 0.1\ T_C$$

Due to antenna bandwidth limitations T_C will be 40 ms or longer, thus $|\tau| \geq 4$ ms. τ includes propagation path uncertainties and it seems reasonable to allot 1 ms to clock error out of the total 4 ms. The accuracy requirement for the receiver clock is therefore ±1 ms.

SOURCES

1. B. Kruger, "Project Sanguine – FBM Command and Control Communication," Naval Engineers Journal, Vol. 84, No. 3, June 1972. (This unclassified reference gives a SANGUINE System overview.)

2. "Engineering in the Ocean Environment," Record from IEEE International Conference at Newport, Rhode Island, Sept. 1972, IEEE publication 72 CHO 660-1 OCC. (This unclassified reference contains 22 papers on Sanguine.)

3. Sanguine System Design Study (SSDS) (U), Dec 1970. (This Classified report treats the technical aspects of Sanguine in detail.)

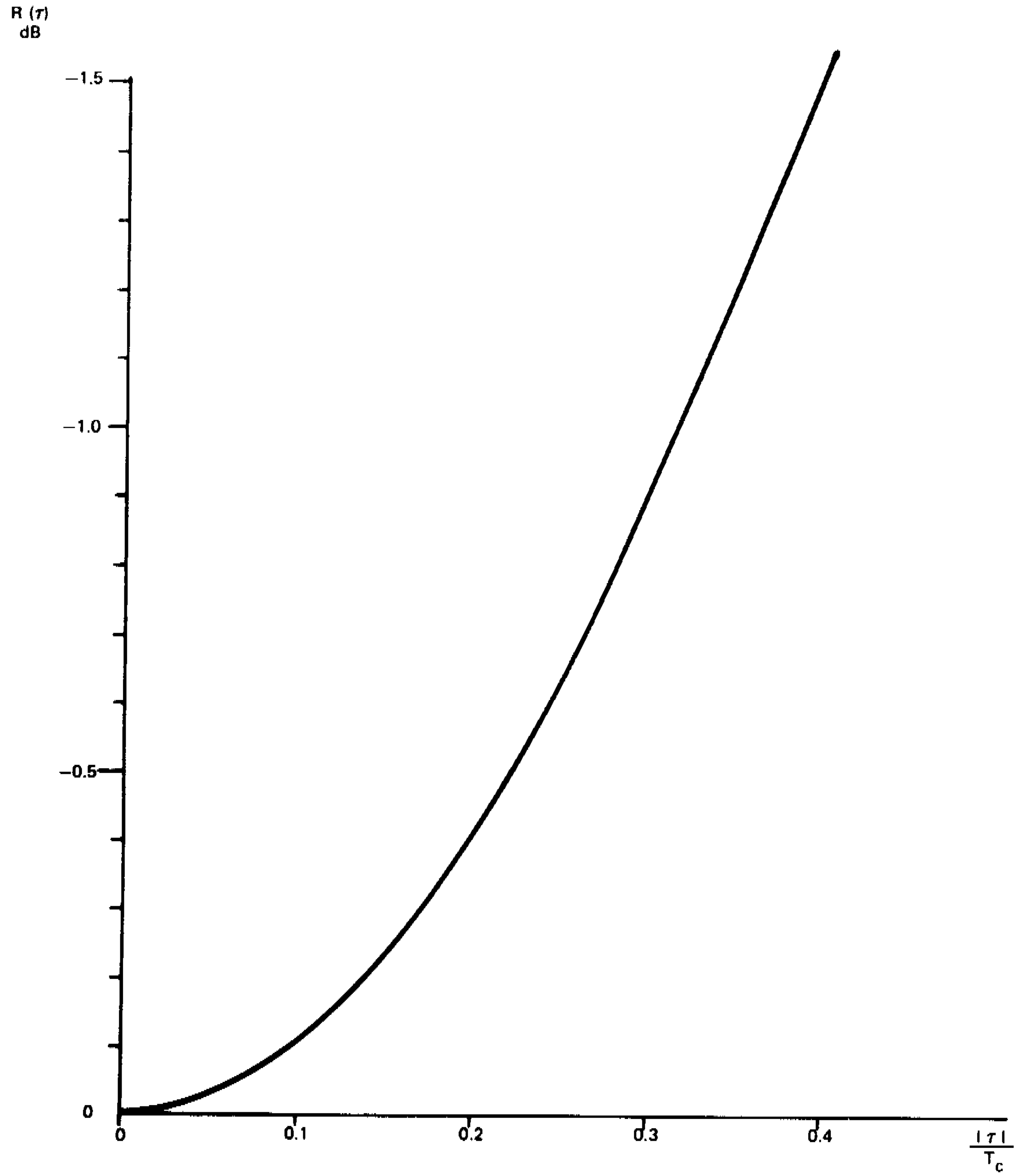

Figure 5. Correlation function R (τ) for chip detection.