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Stability of Standard Transmissions Propagated through Transionospheric Paths*

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In space communication systems, the stability of the standards of time and frequency play a vital role in determining the performance. The frequency stability of standard transmissions is limited by transionospheric perturbations. A knowledge of the nature of the transionospheric effects under the normal as well as the disturbed conditions of the ionosphere, would help in taking steps to mitigate the effects. The various steps involved in this process are critically examined and the scope for further investigations is indicated.

1. Introduction

The success of a space communication system depends largely on the availability of highly accurate and stable standards of frequency and time. Although the advent of atomic clocks have made it possible to realize precise standards of frequency and time,[1] certain problems still remain unresolved for space applications. Recently, portable primary as well as secondary atomic clocks have been developed and flown into space during a wide variety of space ventures.[2] Recently, portable quartz oscillators have been developed that have got a stability approaching that of an atomic standard. All these portable units have got the frequency stability that is typically 1 part in 10^{11}, while modern ground-based primary standards employing double Cs beam, such as that developed at NRC, Ottawa,[3] Canada, have got a stability as high as 1 part in 10^{13}. Whatever might be the stability of the standard, in space communication, where the signal has got to pass through the earth's upper atmosphere, the transionospheric propagational factors degrade the precision and imposes a fundamental limitation on the realizable stability,[4] which is significantly lower than that of present day standards of frequency and time. The orders of the errors due to the propagational factors and the methods of reducing the errors are critically examined in this paper. Also, a method involving round trip delayed feedback is suggested and scope for further investigations indicated.

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2. Transionospheric Propagational Effects

A radiowave suffers a delay in passing through the ionosphere. Changes in this propagation delay lead to a change in the phase of the received signal.[5] The rate at which the phase changes indicates the Doppler shift arising from an apparent radial motion of the sources of signal caused by the changes in the ionosphere. At vhf, the change in frequency Δf of a transionospheric signal can be looked upon as the Doppler shift introduced when the integrated electron content along the ray path in the ionosphere changes.[4]

The magnitude of the shift can accordingly be expressed as

$$\Delta f = -\frac{e^2}{2\pi mcf}\frac{d}{dt}\int_0^R N dh$$

$$\approx -\frac{4{\cdot}1 \times 10^7}{cf}\frac{d}{dt}\int_0^R N dh \quad \text{(in Hz)} \quad \ldots(1)$$

where

- $\int_0^R N dh$ Total electron content along the ray path
- R Distance measured along the ray path
- h Height of the point in the ionosphere
- N Electron density
- e Charge of an electron
- m Mass of an electron ($9{\cdot}1 \times 10^{-28}$ g)
- c Velocity of light (3×10^{10} cm/sec)
- f Radio wave frequency in Hz/sec

To evaluate Δf from this relation, the total electron content along the ray path can be obtained directly from propagation type experiments such as those involving Faraday concept of integrated electron content.[6,7]

The rate of change of the total electron content and hence Doppler shift become sizable during various geophysical disturbances[8,9] such as that induced by a solar flare or TIDs. Fig. 1 depicts some examples of the solar flare effect[10] referred to as SFD (sudden frequency deviation) and TID effect.[11] Thus, besides random frequency deviations due to moving irregularities in the ionosphere, transionospheric signals exhibit sudden changes of frequency during SIDs and TIDs, although changes which occur during sunrise may also have a significant effect. Table 1 gives the summary of the types and orders of transionospheric effects.[8,9,12] It may be noted that under unusual conditions a TID may cause a shift, while in the equatorial regions in the presence of spread-F irregularities usually high frequency shifts are expected.[13]

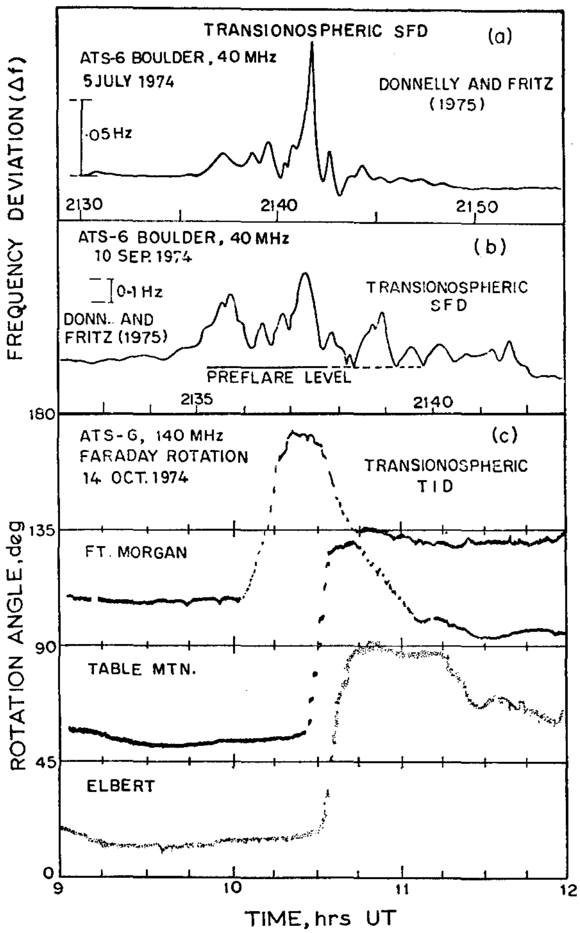

Fig. 1 — Typical transionospheric SFDs and TID

The results of clock synchronization experiments by various research workers have demonstrated that using a geostationary satellite, time transfer accuracies of 10 μsec can be achieved with one-way vhf transionospheric transmission to 50 nsec using a two-way mode and employing microwave frequencies.[14] Table 2 summarizes the resume of clock synchronization experiments and time transfer accuracies of transionospheric signals with satellites.

Table 1 — Types and Orders of Transionospheric Propagational Effects

Type of the shift (Origin of the shift)	Geophysical shift: Solar flare	Geophysical shift: TID	Random shift (oving irregularities in the ionosphere)
Doppler shift (Δf)	0·04 Hz at 100 MHz	0·03 Hz at 100 MHz	±0·1 Hz at 100 MHz
Relative shift	0·5 × 10^{-8} at 6 MHz	10^{-8} at 140 MHz	10^{-9} at 100 MHz
$\left(\frac{\Delta f}{f}\right)$	10^{-7} at 20 MHz		10^{-11} at 1000 MHz
	10^{-8}-10^{-9} at 40 MHz		10^{-13} at 10,000 MHz

Table 2 — Time Transfer Accuracies of Transionospheric Timing Signals Relayed by Artificial Satellites[14]

Satellite used	Year	Location (agency)	Frequency	Remarks	Accuracy
Telstar	1962	USA, UK	micro-wave	two-way	± 1 μsec
Relay II	1965	Mofave, Calif., USA and Kashima, Japan	micro-wave	two-way	± 0·1 μsec
ATS-1	1967	Colo., Calif., Alaska, USA	vhf	one-way	10 μsec
ATS-1	1968	Colo., Calif., Hawaii, USA	vhf	two-way	5 μsec
ATS-1	1973-75	Calif., USA N.C., USA	4-6 GHz	two-way	50 nsec
ATS-1	1975	N.C., USA Japan, USNO, USA Japan	micro-wave	two-way	10 nsec
SMS/ GEOS	1974	—	uhf (468·825 MHz)	—	100 μsec
ATS-3	1974	RGO, Australia & USNO, USA	—	—	0·2 μsec

3. Reducing Transionospheric Propagational Effects

There are five methods of mitigating the influence of transionospheric propagational effects. They are discussed below.

3.1 Choice of Optimum Frequency

The fact that the changes in the phase and frequency in the transionospheric propagation during various geophysical disturbances decrease rapidly with increasing frequency, suggests that raising the operating frequency sufficiently would reduce the transionospheric shifts to negligible values. However, the frequency cannot be raised beyond 10,000 MHz where absorption by the terrestrial atmosphere as well as the thermal noise generated by it would impose limitations on the stability of phase and frequency of the standard signals. For space communication, as depicted in Fig. 2, the minimum radio noise background occurs around 5 GHz, at which a standard signal can be propagated to the longest distance.[15] On the other hand when the signal is not marginal the stability of phase and frequency will be greater at higher frequencies. The optimum frequency for standard transmission would, in practice, lie between 5 and 12 GHz. The results of the clock synchronization experiment indicate that the optimum would be near 10 GHz.[14]

3.2 Two-frequency Observation

Equally accurate measurements made simultaneously at two frequencies may be employed to deduce the plasma effect. For instance, if simultaneous measurements of the transionospheric shifts be made at f_1 and f_2 then we have by utilizing Eq. (1)

$$\Delta f_1 = \left(\frac{f_2}{f_1}\right) \Delta f_2 \qquad \ldots(2)$$

From Eq. (2) it is clear that if we know the shift at any one frequency, then the shift at any other frequency can be calculated without involving the term of TEC or the effect of ionospheric plasma can be deduced.

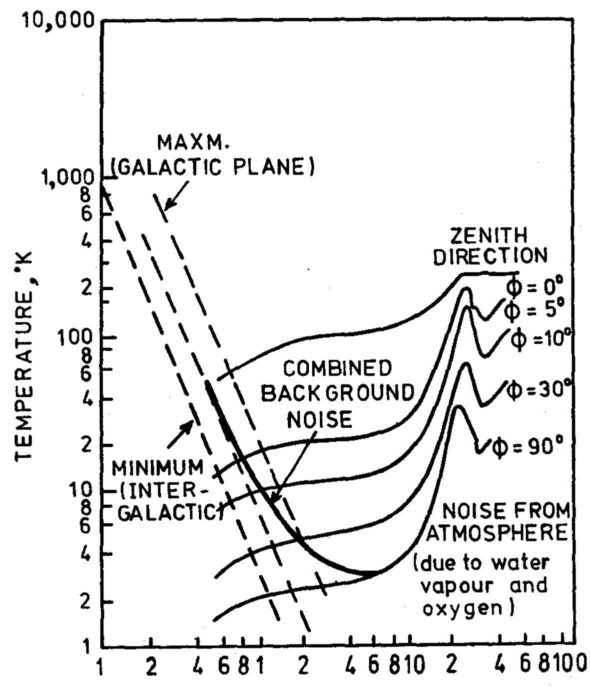

Fig. 2 — Combined background noise for space communication

3.3 Diversity System

If a satellite receives the standard signal from n intersynchronized ground stations simultaneously then the resultant received signal will be $\sqrt{n}$ times more stable. The spacing between different ground stations in this case should be such that the transionospheric shifts in the individual ray paths are statistically independent. The spacing depends on the size of the inequalities and its motions. For a typical scale size of TIDs of $\sim$ 200-400 km in quasi-wavelength, horizontal speed is 100-350 m/sec with direction chiefly from north to south. Fluctuations in $\int N dh$ are approximately $\pm$ 2% due to TIDs. For small scale irregularities of scale size approximately 4 km with tendency for irregularities to be elongated along the lines of magnetic field, apparent wind speed lies in the range 50-300 m/sec with quasi-periods of 1-0·1 min (Ref. 4). During SFDs, however, since the effect is always over the entire sunlit hemisphere, such a diversity would not be fruitful.

3.4 Independent Standards at Ground and Space

If perfectly stable standards were realizable then the two independent standards initially intercompared may be located at the ground and space. In the absence of any ionospheric shift such idealized standards would, in principle, be allright for space communications. Presence of the transionospheric shift, however, still imposes a fundamental limitation on the precision for a transionospheric wave.

3.5 Round-trip Feedback Method

The information of transionospheric shift may be suitably fed back to a ground-based standard frequency source to reduce the error as shown in Fig. 3. In this case, the correction is delayed by T, the round-trip delay, which is about 0·25 sec for a geostationary satellite relay. However, in view of the fact, that the time scale transionospheric shift is greater than a minute, particularly during geophysical disturbances like SFD and TID, the round-trip

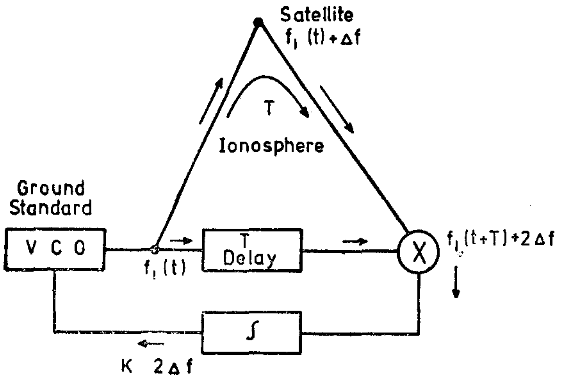

Fig. 3 — Round-trip feedback method of mitigating the influence of transionospheric propagation

delay is negligible and the feedback would be quite effective. The system effectively acts as a phase-lock loop with the transmission medium included in the input channel of the loop. With this system if the feedback is very large, the input to the product detector will be stable at f_1 which means that the stability of the standard at the satellite will be poor, being shifted in the opposite direction by $k\,2\,\Delta f - \Delta f$, i.e. $(2k-1)\,\Delta f$. If k be made 1/2, the received signal at the satellite will be free from transionospheric shifts, while that received at the ground station will contain the shift. If $k = 1$, the signal at the ground would be drift-free while that at the satellite will be shifted in the opposite direction. It may be noted that the matching of the round-trip delay by the local delay network ensures that the inherent random drift of frequency of VCO would be reproduced at the second ground station since the drift pattern of the returned signal would then be 90° out of phase by action of the phase-lock loop.

In practice to receive the standard signal at the satellite, a stable local oscillator would be necessary. Such oscillators, may be a stable secondary standard such as that involving temperature-controlled lens shaped, 5th overtone crystal oscillator, or a rubidium standard. Alternatively, it may be an ordinary oscillator, which need not, however, be highly stable. For any change in the frequency of the on-board oscillator, it tends to be corrected by the round-trip phase lock loop and we still expect a stable frequeney f_1 at the ground for $k = 1$ and a stable frequency at the satellite for $k = 1/2$.

4. Conclusions

It can be stated that the stabilities of atomic frequency standards have reached a stage where the precision of a standard transmission is governed more by the propagational characteristics than by the limitations of the standards. In the presence of the sizeable geophysical disturbances of various types, the stability expected would be much less. So a detailed study of the nature of the transionospheric effects under the normal as well as the disturbed conditions of the ionosphere is required, which would help in taking steps to mitigate the effects of transionospheric origin. However, a stable frequency at the ground can be obtained with $k = 1$ and at the satellite with $k = 1/2$ with round-trip delayed feedback method. Such studies of the transionospheric propagation might prove to be useful not only in revealing the true nature of the source of frequency shift of ionospheric origin but will eventually help in the dissemination of the standards of time and frequency on a worldwide basis. Such worldwide standards may have useful applications in long range navigation for maritime and aviation purposes, for precision moving target indication, very long baseline interferrometry (VLBI) as well as the determination of velocity of propagation of radio waves.

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