6.1. Introduction

When a pulse of standard frequency signal passes through the ionosphere, its group velocity is reduced below the free space velocity and a group path delay is introduced. Uncertainties in this group delay arise from changes in the ionospheric characteristics and lead to timing errors. The delay in the standard signal can, in fact, occur both through the ionosphere and the troposphere. The errors due to the ionosphere are orders of magnitude higher than those due to the troposphere at HF and VLF (Mitra, 1977). The errors are the highest in the HF band and relatively low in LF and VLF bands. The delay in the HF time signal is a function of the propagation path and the parameters of the ionosphere. Tropospheric errors should be included in high accuracy systems specially when microsecond and nanosecond accuracies are involved. The effects depend critically on refractivity gradients and an elevation angle but are independent of frequency (Mitra, 1977).

The diurnal and seasonal variations of the ionospheric parameters such as the electron density (N) and the total electron content (N_p) are the most common feature (Garriott et al., 1965; Yuen and Roeloffs, 1966; Bhar et al., 1976). The variation in these may be related to change in solar XUV flux, solar microwave bursts and also to the variation in
equatorial plasma transport under different geomagnetic conditions (Basu and Dasgupta, 1968; Dasgupta and Basu, 1971). Garriott et al. (1967) have reported during the May, 1967 event that an increase in electron content of $2 \times 10^{16}$ electrons $m^{-2}$ (about 5% of the total ionospheric content) was observed. The outstanding flare event of August 7, 1972 was observed with satellite beacon experiments at 17 stations in North America, Europe and Africa, spanning over ten hours in local time and over 70° in latitudes (Mendillo et al., 1974). The sizes of the individual sudden increases in TEC ranged from $(1.6 \sim 8.6) \times 10^{16}$ electrons $m^{-2}$. The geomagnetic storms can cause appreciable changes in the maximum ionization density ($N_m$) of the E-region. The effect of E-region storms indicates that $N_m$ exhibits strong latitudinal and seasonal dependence (Matshushita, 1959). Mendillo (1971) carried out a comprehensive statistical study of the variation of $N_T$ during geomagnetic storms at Hamilton and observed that the percentage deviation of $N_T$ from its median values is positive in the early phase of the storms but negative during the following phase. Satellite and moon-echo observations show that the TEC decreases during the severe magnetic storms ($K_p > 5$) (Ross, 1960; Taylor, 1961; Lawrence et al., 1963; Hibberd and Ross, 1967).

The feasibility of precise clock synchronization on an intercontinental basis has been demonstrated for time transfer on a global scale (Steel et al., 1964; Jesperson et al., 1968; Easton et al., 1966; Somayajulu, 1977; Somayajulu et al., 1979). The precision of the measurement of the radial velocity of a satellite as indicated by the range rate
depends on the precision of the frequency standard, while the accuracy of satellite tracking is limited by the accuracy of the time standard (Gupta et al., 1977). Also, for successful multiplexing of communication signals, the precision of the standard is important. In time-division multiplexing (TDM), the bit and frame synchronization requires a standard of time, while in frequency division multiplexing (FDM) coherent demodulation of the subcarriers and carriers necessitate a standard of frequency. Usually the desired standards are located at the transmitting end and they are derived at the receiving end by controlling local generators with the information recovered from the received signal. Often the reception of the radio signal involves a standard frequency or phase-stable local oscillator.

From the studies of the phase and frequency fluctuations of radio signals in the LF and VLF bands (Watt and Plush, 1959; Evans and Hagfors, 1968; Sen and Sacha, 1970; Easton et al., 1976) it has been observed that the fluctuations are orders of magnitude lower than that in the HF band. Therefore, the LF-VLF band would be very suitable for the dissemination of standards of time and frequency (Watt, 1967; Bononcini, 1981). The precision of the standard signal received over a certain propagation distance depends on various factors. For example, ionospheric height fluctuations contribute significantly over medium and long ranges (Watt and Plush, 1959). The observed precision is, in practice, limited also by the level of atmospheric noise. All these factors contributing to the fluctuations of phase and frequency are critically examined in this chapter.
and an estimate has been made of the transmitter power required for the L.R.VLF standard transmission for a wide range coverage in a tropical region like India. Besides, the ionospheric and transionospheric effects on the delay of standard frequency transmissions, transionospheric group delay in satellite dissemination and clock synchronization via satellite, determination of the accuracy of epoch in UTC, signal jitter at 10 MHz and 15 MHz ATA signals have been discussed in this chapter.

6.2. Propagational Factors in Time Delay

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 (Watt and Plush, 1959). Had the velocity of propagation of radio waves been constant and equal to the velocity of light in vacuum, it would be a rather simple matter to distribute signals throughout the world with essentially no loss in stability and accuracy (Watt et al., 1961). The constant time delay is then given by

\[ t = \frac{D}{c} \quad \ldots \quad (6.1) \]

where \( D \) = the phase path,
\( c \) = the velocity of light \((3 \times 10^{10} \text{ cm sec}^{-1})\).

Since the velocity of propagation is affected by the random changes in the ionosphere, the actual time delay is given by

\[ t_D(t) = \frac{D}{v_p(t)} \quad \ldots \quad (6.2) \]

where \( v_p(t) \) = the phase velocity.
In fact, the fluctuation in ionospheric characteristics introduces variations in propagation time, which in turn, introduce phase variations of the received signal. The phase delay introduced by the propagational path is given by

\[ \Phi(t) = \frac{2 \pi f}{v_p(t)} \cdot D = \omega t_p(t) \quad \cdots \quad (6.3) \]

where \( f \) is the signal frequency.

Hence, the actual time delay is

\[ t_p(t) = \frac{\Phi(t)}{2 \pi f} \quad \cdots \quad (6.4) \]

Now, the phase of the signal is a function of time, frequency and distance. For a change \( \Delta \Phi \) occurring in time \( \Delta t \), the change in frequency \( \Delta f \) is given by

\[ \Delta f = \frac{\Delta \Phi}{2 \pi \Delta t} \]

Hence, the average departure \( \overline{\Delta f} \) from the transmitted frequency in time interval \( (t_2 - t_1) \) is given by

\[ \overline{\Delta f} = \frac{\Phi_2 - \Phi_1}{2 \pi (t_2 - t_1)} \quad \cdots \quad (6.5) \]

where \( \Phi_1 \) and \( \Phi_2 \) are the actual phase delays at intervals \( t_1 \) and \( t_2 \) respectively.

Basically, uncertainties in the propagation delay originate from the random change in the ionospheric phase path. The ionospheric delay
for a length $s$ of the ray path in the ionosphere is given by

$$
\Delta T = \frac{1}{c} \int_{s} N(s) \, ds \quad \ldots \quad (6.6)
$$

For an evaluation of $\Delta T$, the first step will be to know the ray path trajectory from ray tracing computation. Then, from the known electron density profile one can evaluate the above integral for an estimate of propagation delay. For obtaining an idea of the random changes of $\Delta T$ we must, therefore, have a knowledge of the variability of the electron density profile as well as that of the resulting variability of the ray path. At VLF, the penetration of the signal in the ionosphere is rather small. As a result, the random changes in the delay observed originate mainly from the height fluctuations which is rather small for VLF reflection heights. Also, at VHF, the ionosphere is penetrable and the effect of the ionosphere is small. At HF, the uncertainties introduced by the ionosphere are largest. For, the major length of the ray path involved passes through the most variable part of the ionosphere at the frequency involved. For the short-term variation in propagation delay time, phase instability limits the precision of the received standard frequency signal. This short-term variation in propagation can, however, be assumed to be randomly distributed about an average time delay $\bar{t}_D$ with a rate of change similar to the fade rate (Watt et al., 1961). If the standard deviation of the random time delay is $\sigma t_D$, a single measured value of the delay will, then, range roughly between $\bar{t}_D \pm \sigma t_D$. Generally, both $\bar{t}_D$ and $\sigma t_D$ will have different values for day and night propagation paths.
If we assume a stable oscillator of frequency $f_j$ at the receiving station and compare it with the frequency of the received signal $f_r$, the average observed frequency difference between $f_j$ and $f_r$ will depend upon the type of observation made and on the nature of the phase path fluctuation.

For radio waves having frequencies $f$ substantially higher, the plasma frequency $f_p$ of a region in which the gyromagnetic frequency

$$f_H = \frac{eH}{2\pi m}$$

is much less than

$$f_p = \frac{Ne^2}{\pi m}$$

i.e., $f >> f_p >> f_H$

where $H = \text{intensity of magnetic field}$,

$e = \text{charge of an electron } (1.6 \times 10^{-19} \text{ c.g.s. units})$,

$m = \text{mass of an electron } (9.1 \times 10^{-31} \text{ gm})$,

$N = \text{number of electrons } \text{cm}^{-3}$.

The group velocity of a radio wave

$$u = c \sqrt{1 - \frac{f_p^2}{f^2}}$$

$$= c \sqrt{1 - \frac{Ne^2}{mf^2}} \text{ in c.g.s. units} \quad \text{... (6.7)}$$

The transionospheric group delay $\tau$ at a distance $R$, is given by

$$\tau = \frac{1}{c} \int_0^R \left(1 - \frac{Ne^2}{mf^2}\right)^{-1/2} \text{dn sec.} \quad \text{... (6.8)}$$
In the ionosphere, the electron density rarely exceeds $10^6$ electrons cm$^{-3}$ and for a wave frequency of about 100 MHz, the term \( \frac{N_e^2}{\kappa m_f^2} \approx 10^{-2} \). Thus the increase in the group delay due to the existence of the ionized medium is

\[
\Delta \tau = \frac{1}{2 \pi} \int_0^R \frac{N_e^2}{2 \kappa m_f^2} \, dh \, \sec \, ... \quad (6.9)
\]

\[
= 4.1 \times 10^7 \int_0^R N \, dh \, \sec \, ... \quad (6.10)
\]

where \( h \) = height of the point in the ionosphere,

\( R \) = distance measured along the ray path.

Equation (6.10) shows the increase in the transionospheric group delay \( \Delta \tau \) is proportional to the integrated number of electrons along the ray path.

It has been shown, in general, that when a plane polarized wave is propagated through the ionosphere, it splits into two circularly polarized waves having opposite senses of rotation and different phase velocities. The wave emerges from the ionosphere as a plane polarized wave, which has been rotated relative to the original position. The amount of rotation, \( \Omega \), introduced when the wave traverses the ionosphere has been shown (Brown and Evans, 1958) to be

\[
\Omega = \frac{1}{4 \pi^2} \frac{e^3}{m^2} \int_0^R \frac{N e^2}{2 \lambda m_f^2} \cos \theta \, dr \, \text{rotations} \quad ... \quad (6.11)
\]
The wave suffers the same additional rotation on its return journey. Then for two-way journey, the amount of rotation becomes

\[ \Omega = \frac{1}{2} \frac{3\omega^2}{m^2 \lambda^2} \int_0^R \text{N} \cos \theta \sec i \, dh \, \text{rotations} \quad \ldots \quad (6.11a) \]

where \( \theta \) = the angle between the directions of ray and the field,

\( i \) = the angle between the ray path and the zenith,

\( H \) = earth's magnetic field in gauss at a point \( h \),

and \( N \) is expressed as a function of height \( h \).

The value of \( \cos \theta \) may be computed from

\[ \cos \theta = \left[ -\cos \varphi \sin I - \sin \varphi \cos I \cos (\varphi - \Delta) \right] \quad \ldots \quad (6.12) \]

where

\( I \) = magnetic inclination,

\( \Delta \) = magnetic declination

\( \varphi \) = the geographic azimuth bearing of the observer's locations measured with respect to the subionospheric point

and

\[ \varphi = \sin^{-1} \left[ \frac{r_0}{r_0 + h} \cos E \right] \]

where \( r_0 \) = earth's radius (6370 km),

\( E \) = antenna elevation.

The secant of zenith angle \( i \) is given by

\[ \sec i = \frac{r_0 + h}{\sqrt{(r_0 + h)^2 - (r_0 \cos E)^2}} \quad \ldots \quad (6.13) \]
The magnetic declination and inclination may be assumed to be a first order invariant with height and the intensity $H$ may vary inversely as $(r_0 + h)^3$.

Brown and Evans (1958) and later Bauer and Daniels (1959) have shown that provided there are no more than $10^3$ electrons cm$^{-3}$ in the space beyond the ionosphere, most of the Faraday rotation $\Omega$ occurs within the first 1000 km height. The eqn. (6.11a) can be written as

$$\Omega = \frac{7.55 \times 10^3}{2 f^2} \int_0^{1000 \text{ km}} \frac{H \cos \theta \sec \iota}{1} \, dN \text{ d}h \text{ rotations} \quad \ldots \quad (6.14)$$

The value of the function $H \cos \theta \sec \iota$ is of the order of 0.4 to 0.6 for most latitudes and directions (Little and Lawrence, 1960; Yeh, 1960; Yeh and Gonzales, 1960; Evans and Taylor, 1961). Taking $H \cos \theta \sec \iota = 0.5$ and $f = 140$ MHz, we have from the eqn. (6.10)

$$\Delta \tau \bigg|_{f = 140 \text{ MHz}} \approx 12.67 \times 10^{-9} \Omega \text{ sec.} \quad \ldots \quad (6.15)$$

The total electron content of the ionosphere in cm$^{-2}$ vertical column at lower latitudes varies approximately over the range $5 \sim 6.5 \times 10^{13}$ to $5 \sim 6.5 \times 10^{12}$ electrons between day and night (Bhar et al., 1976). Hence, we can expect that at a frequency of 100 MHz there will be a group delay between about $13 \sim 18 \text{ Sec} \iota$ microseconds and about $1.3 \sim 1.8 \text{ Sec} \iota$ microseconds, depending on the time of the day. These numbers can be scaled inversely by the square of the radiowave frequency relative to 100 MHz to compute approximate values of the delay at other frequencies.
6.2.1. Ionospheric group delay for 10 MHz ATA signal

Table 6.1 shows some examples of group delay for selected paths. The calculations were made on the basis of the appropriate electron density profile over the path under sunspot maximum condition in summer day time (Mitra, 1977).

<table>
<thead>
<tr>
<th>Path</th>
<th>Distance km</th>
<th>Frequency MHz</th>
<th>Hop</th>
<th>Group delay μsec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delhi-Dehradun</td>
<td>215</td>
<td>10</td>
<td>Single</td>
<td>3694</td>
</tr>
<tr>
<td>Delhi-SHAR</td>
<td>1500</td>
<td>10</td>
<td>Double</td>
<td>7436</td>
</tr>
<tr>
<td>Delhi-Bangalore</td>
<td>1720</td>
<td>10</td>
<td>Double</td>
<td>6817</td>
</tr>
<tr>
<td>Delhi-Ooty</td>
<td>1870</td>
<td>10</td>
<td>Double</td>
<td>6351</td>
</tr>
</tbody>
</table>

The variability in time delay can be as large as 2000 μsec, over the large paths.

6.2.2. Transionospheric group delay in satellite dissemination and clock synchronization via satellite relay

Two atomic clocks with a known offset between them may be used to measure the transionospheric delay employing a satellite relay system. Such measurements have been made in various countries. Table 6.2 summarizes the time transfer accuracies of transionospheric signals with satellites. Recently, some measurements have been made in India employing
<table>
<thead>
<tr>
<th>Year</th>
<th>Satellite</th>
<th>Frequency</th>
<th>Remarks</th>
<th>Accuracy µsec.</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1962</td>
<td>Telstar</td>
<td>6390 4170</td>
<td>Two-way</td>
<td>± 1</td>
<td>Steel et al. (1964)</td>
</tr>
<tr>
<td>1965</td>
<td>Relay II</td>
<td>1723 4175</td>
<td>Two-way</td>
<td>± 0.1</td>
<td>Markowitz et al. (1966)</td>
</tr>
<tr>
<td>1967</td>
<td>ATS I</td>
<td>149.2 135.6</td>
<td>One-way</td>
<td>10</td>
<td>Gatterer et al. (1968)</td>
</tr>
<tr>
<td>1968</td>
<td>ATS I</td>
<td>149.2 135.6</td>
<td>One-way</td>
<td>5</td>
<td>Jesperson et al. (1968)</td>
</tr>
<tr>
<td>1968</td>
<td>GEOS II</td>
<td>136</td>
<td>One-way</td>
<td>25</td>
<td>Louis (1972)</td>
</tr>
<tr>
<td>1970</td>
<td>ATS III</td>
<td>6.2 4.1</td>
<td>Two-way</td>
<td>0.5</td>
<td>Hansen et al. (1971)</td>
</tr>
<tr>
<td>1973</td>
<td>Timation II</td>
<td>399.4 149.5</td>
<td>One-way</td>
<td>0.5~0.1</td>
<td>Easton et al. (1973)</td>
</tr>
<tr>
<td>1975</td>
<td>ATS I</td>
<td>Microwave Microwave</td>
<td>Two-way</td>
<td>0.010</td>
<td>Yama et al. (1976)</td>
</tr>
<tr>
<td>-</td>
<td>ATS III</td>
<td>135.6</td>
<td>One-way</td>
<td>25</td>
<td>Easton et al. (1976)</td>
</tr>
<tr>
<td>Year</td>
<td>Satellite</td>
<td>Frequency</td>
<td>Remarks</td>
<td>Accuracy</td>
<td>Reference</td>
</tr>
<tr>
<td>------</td>
<td>-----------</td>
<td>-----------</td>
<td>---------</td>
<td>----------</td>
<td>-----------</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Uplink MHz</td>
<td>Downlink MHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1975</td>
<td>ATS I</td>
<td>6301</td>
<td>4178</td>
<td>Two-way</td>
<td>0.005</td>
</tr>
<tr>
<td></td>
<td>ATS I</td>
<td>6 GHz</td>
<td>4 GHz</td>
<td>Two-way</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td>Symphonie II</td>
<td>6380</td>
<td>4115</td>
<td>Two-way</td>
<td>0.005</td>
</tr>
<tr>
<td></td>
<td>TRRS</td>
<td>2.1 GHz</td>
<td>2.2 GHz</td>
<td>Two-way</td>
<td>10-0.01</td>
</tr>
<tr>
<td></td>
<td>CTS</td>
<td>14.2 GHz</td>
<td>11.88 GHz</td>
<td>Two-way</td>
<td>0.004</td>
</tr>
<tr>
<td>1978</td>
<td>Symphonie II</td>
<td>6347.5</td>
<td>4122.5</td>
<td>Two-way</td>
<td>0.5</td>
</tr>
<tr>
<td>1978</td>
<td>Symphonie</td>
<td>6 GHz</td>
<td>4 GHz</td>
<td>Two-way</td>
<td>0.050</td>
</tr>
<tr>
<td>1978-1979</td>
<td>NTS I</td>
<td>335</td>
<td></td>
<td>One-way</td>
<td>1</td>
</tr>
<tr>
<td>1979</td>
<td>Symphonie I</td>
<td>6 GHz</td>
<td>4 GHz</td>
<td>One-way</td>
<td>1</td>
</tr>
<tr>
<td>1979</td>
<td>Symphonie II</td>
<td>6 GHz</td>
<td>4 GHz</td>
<td>Two-way</td>
<td>0.10-0.01</td>
</tr>
<tr>
<td>1979-1980</td>
<td>BSL</td>
<td>14 GHz</td>
<td>12 GHz</td>
<td>One-way</td>
<td>±0.5</td>
</tr>
</tbody>
</table>
the Symphonie satellite relaying timing signal from atomic clocks stationed at the Delhi and Ahmedabad earth stations (Somayajulu et al., 1979). The accuracy of clock offset measurement or synchronization depends on the total signal delay comprising of the following:

(i) delay introduced by the intervening electronic equipment including the transmitting and receiving systems at the ground station, as well as the satellite transponder,

(ii) delay in the ionosphere,

(iii) delay in the troposphere and

(iv) the free space path delay between the ground stations and the satellite.

The equipment delay is sizeable and is, often, unpredictable, unless special care is taken in the equipment design for a high stability.

The ionospheric delay is inversely proportional to the frequency for frequencies in the VHF band and above as given by eqn. (6.10). The ionospheric error would be small at microwaves. The tropospheric delay is independent of frequency and is negligible for elevation angles greater than 15°, at which most of the measurements are made. The free space delay is subject to minor drifts due to satellite position errors. During the Indian experiments the satellite drift error was less than $1\mu$-second over the one minute interval for which the delay was measured. However, as the drift is systematic it can be taken into account by a least square fit of the piece-wise observations on a computer.
6.3. Signal Jitter and Epoch Determination for ATA Transmissions

The accuracy of ATA epoch in UTC as received at the satellite tracking and ranging station (STARS), Kavalur (12°35' N; 78°50' E) and at New Delhi (28°33' N; 77°16' E) has been evaluated by comparing the data with the other international stations (RID, RWM) for the year 1980. The distribution of errors in epoch of ATA and RID due to jitter in received signals were also recorded at Kavalur and at Calcutta.

Figure 6.1 shows the seasonal variation of the epoch difference between ATA and the reference station RID measured at 1600 hours IST (1030 UT) at Kavalur from October, 1979 to December, 1980 on 10 MHz and 15 MHz. The RMS value of relative epoch accuracy for 10 MHz was found to be 0.8 millisecond and for 15 MHz 0.75 millisecond. In this figure, the monthly average values together with the upper and lower decile points are plotted against the months. It is evident from the figure that the seasonal variations at 10 and 15 MHz signals are remarkably correlated except during June where the epoch differences are anticorrelated.

Figure 6.2 depicts the epoch difference monitored at NPL, New Delhi at 15 MHz between ATA - RID and ATA - RWM from May to September, 1980 which clearly shows that ATA epoch was well maintained with respect to UTC during these months.

The histograms of the distribution of errors in epoch of standard HF signals due to the jitter in the received signal at 10 MHz and 15 MHz recorded at Calcutta between October, 1980 to March, 1981 and at Kavalur
Fig. 6.1 The seasonal variation of the epoch difference between ATA-RID at Kavalur.
g. 6.2 Epoch difference between ATA-RWM and ATA-RID at NPL, New Delhi.
between November, 1979 to October, 1980 are shown in Fig. 6.3. It was noted during the year that the time signal from HFV, Shanghai (31°12'N; 121°26'E) China, dominated over ATA after 1700 hrs IST on both the 10 MHz and 15 MHz signals at Calcutta and at Kavalur (Dixit et al., 1981). However, care has been taken to eliminate this interfering signal while monitoring ATA signals.

6.4. Effect of Geophysical Disturbances on the Radio Signals in the LF-VLF Bands in the Tropical Region and Dissemination of Standard Signals

The orders of precision in time transfer for transmissions at various frequencies over different distances are summarised in Table 6.3. It appears from the table that the precision of time transfer in the LF-VLF bands, in general, is better than that in the HF band. The precision tends to be better at LF than at VLF for distances of the order of 5000 km. For longer distances, however, the signal due to an LF transmission tends to be lost in the background of atmospheric noise. In this situation, the VLF transmission gives better precision than at LF. The precision can be improved greatly by taking the average of the observations of a single transmission received at different locations. Alternatively, the precision can be improved by taking the average of transmissions from different locations received at the same station. In either case, statistical smoothing of the fluctuations, in fact, occur where the same transmission is received simultaneously at different locations (Morgan et al., 1965). The remarkable precision even for distances of the order of 10,000 km is noteworthy (Morgan et al., 1965).
Fig. 6-3 Histograms showing the distribution of error in epoch of ATA and RIO due to jitter in the received signal.
### Table 6.3
The orders of precision in time transfer for ionospheric transmissions at various frequencies over different distances

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Call sign</th>
<th>Distance km</th>
<th>Integration time sec.</th>
<th>Time transfer accuracy μsec.</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>VLF</td>
<td>16 KHz GBR</td>
<td>5200</td>
<td>100</td>
<td>2</td>
<td>Pierce (1957)</td>
</tr>
<tr>
<td>VLF</td>
<td>16 KHz GBR</td>
<td>5600</td>
<td>-</td>
<td>2~3</td>
<td>Sengupta et al. (1981)</td>
</tr>
<tr>
<td>Single station LF</td>
<td>100 KHz LORAN-C</td>
<td>3000</td>
<td>3600</td>
<td>1</td>
<td>Pierce (1957)</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>3600</td>
<td>0.1</td>
<td></td>
<td>Mungall (1974)</td>
</tr>
<tr>
<td></td>
<td>UTC(NEC)</td>
<td>Few to several thousand</td>
<td>3600</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>UTC(BIH)</td>
<td>Few to several thousand</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>60 KHz MSF</td>
<td>5200</td>
<td>100</td>
<td>1</td>
<td>Pierce (1957)</td>
</tr>
<tr>
<td></td>
<td>10 MHz WWV</td>
<td>2000 - 8000</td>
<td>100</td>
<td>10</td>
<td>Watt et al. (1961)</td>
</tr>
<tr>
<td>Multiple station VLF</td>
<td>16 KHz GBR</td>
<td>160 - 5600</td>
<td>-</td>
<td>1~2</td>
<td>Sengupta et al. (1981)</td>
</tr>
</tbody>
</table>
Figure 6.4 shows the nature of variation of the precision of frequency as a function of distance from a single VLF transmission (Morgan et al., 1965). It appears from the figure that the precision is optimum for a propagation distance of the order 5000 km. The existence of an optimum distance arises from two opposing influences in operation. One of these is the increase of fluctuation with distance arising from a larger number of reflecting regions getting involved, coupled with lower effective frequency with increasing distance. The other is the decrease of fluctuation with distance arising from an increase in number of multipath rays tending to combine and smooth the fluctuations.

Figure 6.5 shows how the height fluctuation decrease with increase in frequency (Morgan et al., 1965). From this curve it appears that smoothing effect of multipath rays takes control inspite of the tendency of height fluctuations to decrease with decreasing effective frequencies.

Figure 6.6 shows the typical variation in the LF-VLF bands during a solar flare (Donnelly, 1968d). The corresponding frequency deviations deduced therefrom are also shown here. It shows that while the duration of the phase variation is of the order of 2 hours, the duration of the corresponding frequency deviation is less than half an hour. In most of these cases the precision of frequency is of the order of $10^{-7}$, which is similar to that in the HF band.

Figure 6.7 shows another example (Jones, 1971) of the phase and frequency variation during a flare observed in LF and VLF bands at 12, 16 and 45 KHz. In this case also, we observe that the magnitude and duration
Fig. 6.4 The nature of variation of the precision of frequency as a function of distance from a single VLF transmission received at different locations.
Fig. 6-5 Variation of standard deviation of height fluctuation with frequency.
Fig. 6.6 Typical variations in the phase and frequency fluctuations in the LF-VLF bands during a solar flare of July 7, 1966.
Fig. 6.7 Typical example of the phase and frequency variations during a flare of December 1, 1967 in the LF-VLF bands at 12, 16 and 45 kHz.
of the events is similar to that of the earlier example. From these two examples one can notice that the amplitude of the effect tends to be maximum in the band 16.18 KHz.

We now illustrate some of the effects of the gravity waves on the ionospheric height fluctuations. A few interesting cases of such fluctuations were observed at NPL through the measurement of the frequency deviation of the standard signal at 10 MHz. Figure 6.8 depicts an example of this type as observed at NPL. Figure 6.8 shows the height fluctuations deduced from frequency deviations, while the Fig. 6.9 shows the spectra of fluctuations and reflection height. The spectra indicate the influence of gravity waves with periods of the order of 10-50 minutes (Sastri and Subrahmanyan, 1973). Similar studies have not yet been made at LF and VLF. However, it has been observed that a step change followed by a periodic fluctuation, with a periodicity of the order of 1 hour is often observed in the signal strength recording of LF-VLF bands, presumably due to gravity wave perturbations in the lower ionosphere induced by the thunderstorm activity (Sen, 1967; Sen et al., 1973, 1977; Saha and Sen, 1980). It is expected that the measurement of phase of LF signals at such times would indicate a corresponding height variation.

6.5. Discussion

Comparison of the data obtained from NPL (New Delhi), Calcutta and STARS (Kavalur) conforms to the epoch accuracy of ATA as maintained by NPL during October, 1979 to December, 1980 and that an epoch transfer with an accuracy of 1 millisecond is possible at the receiving station whenever
Fig. 6-8 Fluctuations in reflection height observed during atmospheric gravity waves on 24 Nov, 1971 at 10 MHz = ATA.

Fig. 6-9 Computed weighted mean spectrum of fluctuations in reflection height due to atmospheric gravity wave perturbations.
the ATA signal strength is good. However, it is quite evident that ATA signals are not good for all the days of the year, as well as round the clock, on all the three frequencies and as a result, dependence on the other international standard transmissions at VLF or HF is necessary until some of the existing problems in ATA transmissions are solved. We have tried to monitor 5 MHz ATA signal at Calcutta but could not receive it. The high ionospheric absorption for propagation over the distance is presumed to be the cause of the failure. The result obtained at Kavalur was that the signal strength on 5 MHz was very weak (Dixit et al., 1981).

The general trend of positive correlation of the epoch differences at 10 and 15 MHz suggests that the ionospheric effects on the epoch difference at the two frequencies are of the same order of magnitude. It may be mentioned here that any epoch difference due to drifts in the sources at the two transmitting stations is negligible compared to what is introduced by the ionosphere.

The precision of a standard transmission is limited by the dynamic behaviour of the ionosphere. Ionospheric fluctuations contribute significantly over medium and long range (Watt and Ílush, 1959; Sen and Saha, 1970). The observed precision is, in practice, limited also by the level of atmospheric noise (Dolukhanov, 1971).

The higher stability for VLF comes from the fact that the radio waves are reflected from the bottom of the ionosphere with very little penetration and because the day-to-day variability in this region is relatively small.
But in the case of higher transmission frequency, these waves penetrate more into the ionosphere and the variabilities from the different region add up. From VLF phase measurements obtained at NPL, New Delhi, via 16 KHz CBR has shown the accuracy of the link to be a few parts in $10^{14}$ for frequency and 1-2 µsec for time transfer (Sengupta et al., 1981).

Since the phase and frequency fluctuations are orders of magnitude lower at LF-VLF bands than those in the HF band, the LF-VLF would be very suitable for the dissemination of standard frequency and time.

To estimate the transmitter power required for the LF-VLF standard transmission, we have to investigate the S/N ratio expected at different frequencies in the respective bands (David and Voge, 1969). For this, the level of atmospheric noise at different frequencies have to be considered (Sarkar et al., 1978). Figure 6.10 shows the propagation characteristics of LF and VLF signals together with the level of atmospheric noise at different frequencies. In this figure, the solid line shows the total field variation with distance for different frequencies as derived from Austin-Cohen formula, while the dotted line shows the corresponding variation when only the ground wave is considered (David and Voge, 1969; Dolukhanov, 1971). The thick solid line indicates the total field variation at 20 KHz based on wave guide mode theory; here the dots represent the level of atmospheric noise for 0.01 Hz band width while the crosses represent the level of signal which is 20 dB above the atmospheric noise. It is evident from this figure that for the distance below about 1000 km, ground wave dominates, whereas between 1000 - 2000 km, the
PROPAGATION BY DAY
FIELD STRENGTH FOR $W_r = 1$ KW RADIATED (day)

Fig. 6.10 Long range propagation of LF and VLF signals together with level of atmospheric noise at different frequencies.
The accuracy of time transfer at VHF and microwaves via satellites is, in general, superior to that at VLF. In particular, at microwaves the accuracy may be about an order of magnitude higher than that at L.F. VLF. However, in certain transmission paths such as that passing through the equatorial ionosphere, amplitude and phase scintillation of the transionospheric signal is often observed even at microwaves (Krishnamurthy et al.)
Fig. 6-11 Coverage for standard transmissions for different frequencies.
Fig. 6-12 Typical examples of abnormally high noise level observed during meteorological disturbances at Calcutta.
1976). The space fluctuations would lead to uncertainty in time transfer and may, in fact, degrade the accuracy significantly.

6.6. Conclusion

It may be concluded that the phase and frequency fluctuations are, in general, lower in LF-VLF bands than in the HF band. For the dissemination of standard transmission with a precision greater than $10^{-7}$, we have got to invoke LF-VLF standard transmission. For a range of coverage, of the order of 10,000 km in the LF-VLF band with a S/N ratio 20 dB, the transmitter power required is 1 KW if we assume the CCIR noise values. However, the noise field strength in the tropical regions like India far exceeds the prescribed CCIR values and we have got increase the transmitter power as has already been indicated. It is expected that LF standard transmissions at 100 KHz from a central place will enable an all India coverage with a transmitter power of 100 KW and a precision of $10^{-10}$.

As regards the use of geostationary satellite, time transfer accuracies of 5 - 10 μsec can be achieved with one way VHF transmission and to about 4 - 10 n sec using a two way mode and employing microwave frequencies. The study of the epoch transfer of different standard signals via ionospheric path indicates that the epoch transfer with an accuracy of 1 millisecond is possible at the receiving station whenever the ATA signal strength is good. ATA is transmitting time signals in UTC time scale and it is desirable that NUTI corrections are also transmitted to obtain UTI time scale.