7.1. Introduction

Space communication is a subject concerned with the art of communication between points on the earth and in space, between points in space or between points on the earth through a relay station in space. The success of a space communication system depends largely on the availability of highly accurate and stable standards of frequency and time. With the advent of atomic clock as a primary standard the precision of frequency standards has gone up by a large factor. Portable primary as well as secondary atomic clocks have been developed and flown into space during a wide variety of space ventures (Mungall, 1971). Recently, portable quartz crystal oscillators have been developed that have a stability approaching that of an atomic standard. All these portable units have the frequency stability typically of the order of 1 part in $10^{11}$. With modern ground-based primary standards employing double caesium beam such as the one developed at NRC, Canada (Mungall, 1974; Mungall et al., 1980), a stability as high as 1 part in $10^{13}$ has been attained.

The frequency stability of standard radio signals is governed more by the ionospheric and transionospheric propagation characteristics than by the limitations of the standards (Sen and Saha, 1973). In space communication, where the signal has to pass through the earth's upper
atmosphere, the transionospheric propagational factors degrade the precision and impose a fundamental limitation on the realizable stability which is significantly lower than that of present day standards of frequency and time (Evans and Hagfore, 1968). For a transionospheric path, the phase and frequency deviations of ionospheric origin decrease rapidly with increasing frequency. However, the frequency law of the transionospheric deviation may fail to hold good in the VHF and microwave bands (Sen, 1977), where the effects may not always be negligible for certain transmission paths and are believed to originate from spread-F irregularities in the equatorial ionosphere (Krishnamurthy et al., 1976). Mathur et al. (1970) indicated that the ionospheric effect predominates at frequencies below 1 GHz. The scintillation produced by ionospheric irregularities can become severe and present problems for transmissions from or to satellites in the frequency range 20 MHz through 6 GHz (Aarons, 1978). Although the problem is severe at equatorial and high latitudes, recent observation during high solar activity period (Aarons et al., 1981) revealed that ionospheric irregularities may affect transionospheric signal up to 4 GHz in the anomaly latitudes (15° - 20° dip).

Radio transmissions controlled by atomic standards are now-a-days widely employed for calibration purposes. The precision is lowered by random as well as transient changes in the ionospheric propagation characteristics which can be improved by employing integration (Leiphart, 1962; Sen and Saha, 1973; Sen, 1977; Sen et al., 1977a), diversity reception or by averaging the signals from multiple stations radiating at the same
frequency. In all such measurements, reception of the signal by a 
superheterodyne receiver involves the use of a local oscillator having 
a precision much better than that of the received signal. In cases where 
standard transmission from a station is available at two closely spaced 
frequencies, it may be possible to obtain a standard with a higher 
precision as determined only by the differential ionospheric shift at 
the two frequencies. For certain major frequency deviation effects during 
a solar flare, the differential shift may, in fact, be small.

By employing both the transmissions at 10 and 15 MHz from NPL, 
New Delhi, it may be possible to reduce the error due to ionospheric 
changes and to obtain standards of frequency at 2.5 MHz and 12.5 MHz 
without involving a precision local oscillator in the receiving system. 
A set-up for obtaining a standard with a higher precision without involving 
a precision local oscillator is described in this chapter. The same set-up 
is useful in measuring the precision of an oscillator in cases where the 
ionospheric shift may be neglected. Also a method of measuring the 
differential ionospheric shift without a precision oscillator is indicated 
and a theoretical estimate of the differential shift is made. In addition 
to these, the orders of the error due to the propagational factors have 
been discussed in this chapter.

7.2. Ionospheric and Transionospheric Propagational Effects

The frequency deviations can occur with sudden phase path changes 
induced by enhanced ionization during solar flares. The change of phase
path may be either due to a change in the refractive index in the path below the level of reflection or to a lowering of the height of reflection. Davies et al. (1962) have shown that in the former case, the change in frequency \( \Delta f \) is inversely proportional to the carrier frequency \( f \), whereas in the latter case \( \Delta f \propto f \). Multifrequency observations have shown that for HF, \( \Delta f \) is inversely proportional to the transmitted frequency (Davies, 1962), indicating that the electron density enhancements are predominantly in the non-deviative region. Frequency shift \( \Delta f \) may be related to a time rate of change of phase path \( \Delta P \) (Davies, 1963):

\[
\Delta f = -\frac{f}{c} \frac{d\mu}{dt} \quad \ldots \quad (7.1)
\]

where, \( c = \) velocity of light in vacuum.

If the ionosphere is isotropic, \( \Delta f \) can be expressed as

\[
\Delta f = -\frac{f}{c} \frac{d\mu}{dt} \int \mu \, ds \quad \ldots \quad (7.2)
\]

where \( \mu = \) phase refractive index.

If the ionization changes take place in the non-deviative part of the path for vertical incidence then

\[
\Delta f = \frac{K}{f} \frac{f}{c} \int \frac{dN}{dt} \, dh \quad \ldots \quad (7.3)
\]

where \( K = \frac{f^2}{N} \),

\( f_N = \) plasma frequency,

\( N = \) electron density.
If the magnetic field of the earth is neglected, then for the non-deviative case

$$\Delta f = \frac{K}{f_v \cdot \omega} \int \frac{dN}{dt} \cdot dh$$  \hspace{1cm} (7.4)

where $f_v = f \cos i$ is the equivalent vertical incidence frequency, $i$ = the angle of incidence.

The fluctuation of phase and frequency of radio signals is proportional to the height fluctuation of the reflecting region for the single ray propagation (Watt and Plush, 1959; Sen and Saha, 1970) and is given by

$$\Delta \phi = \frac{2 \pi}{\lambda} \cdot 2 \Delta h \hspace{0.5cm} \text{(vertical incidence)}$$  \hspace{1cm} (7.5)

$$= \frac{2 \pi}{\lambda} \cdot 2 \Delta h \hspace{0.5cm} \text{(oblique incidence)}$$  \hspace{1cm} (7.6)

$$\Delta f = \frac{1}{2 \pi} \cdot \frac{\Delta \phi}{\Delta t}$$  \hspace{1cm} (7.7)

where $\lambda$ = wavelength of the radiowave.

It has been shown from the equation 6.10 that $\Delta \tau$, change of transitionospheric delay, is proportional to the integrated number of electrons along the ray path. The magnitude of the Doppler shift can be estimated by considering the derivative with respect to time of the integrated phase path and is given by

$$\frac{\Delta f}{f} = -\frac{e^2}{2\pi m c f^2} \frac{d}{dt} \int_0^R N dh$$
For an ionospheric ray path one has to start with a ray tracing computation assuming a realistic electron density profile of the ionospheric region involved. For the transionospheric ray path, on the other hand, the frequency being rather high, viz., VHF to microwaves, one may neglect the refraction effects in the ionosphere (Evans and Hagfors, 1968). In that case $\int_0^\infty N \, dh$ can be easily estimated from the ionospheric/exospheric electron density model.

Equation (7.8) shows that if the integrated electron content $\int_0^\infty N \, dh = N_T$ is changing linearly, the received signal would be displaced in frequency by an amount, which, expressed as a percentage of the transmitted frequency $f$, is proportional to $\frac{1}{f^2}$. The actual frequency shift $\Delta f \approx \frac{1}{f}$. Thus, the effect can be serious for frequencies of several hundred MHz.

If we take $H \cos \theta \sec \iota = 0.5$ and $f = 140$ MHz in eqn. (6.14), we have from the eqn. (7.8)

$$\Delta f \bigg|_{140 \text{ MHz}} \approx -1.773 \frac{d\omega}{dt} \text{ Hz} \quad \ldots \quad (7.9)$$

where $\frac{d\omega}{dt}$ = rate of change of Faraday angle in degrees sec.$^{-1}$. 

\[
\Delta f \approx -4.1 \times 10^7 \frac{d}{dt} \int_0^R N \, dh \text{ Hz} \quad \ldots \quad (7.8)
\]
7.3. Orders of Ionospheric and Transionospheric Frequency Shift

Both the ionospheric and transionospheric signals exhibit sudden changes of frequency during various geophysical disturbances such as that induced by a solar flare or during a travelling ionospheric disturbance (TID). Table 7.1 gives the summary of the types and orders of ionospheric and transionospheric effects (Arendt, 1962; Evans and Ingalls, 1962; Porcello and Hughes, 1964; Agy et al., 1965; Evans and Hogfore, 1968; Mithal, 1973; Donnelly and Fritz, 1975; Luthra et al., 1977; Sen et al., 1977a, 1978). It appears from the table that the order of frequency deviations $\Delta f$ in the HF band during the solar flare is a few Hz. In contrast to this, the deviation ($\Delta f$), for a transionospheric signal on 40 MHz is only a few tenths of a Hz. This is an order of magnitude less compared to that for an ionospheric signals at HF. It also appears that the orders of shifts are similar during different geophysical disturbances. However, the random shift due to moving irregularities can be smoothed out by statistical averaging. 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 (Krishnamurthy et al., 1976). Figure 7.1 depicts some examples of solar flare effect (Donnelly and Fritz, 1975) referred to as SFD and TID (Davies et al., 1975a). A TID, which could raise the total electron content by 2% in 10 minutes, would give rise to frequency deviations of the order of 0.03 Hz at 100 MHz (Evans and Hogfore, 1968). Davies et al. (1975a) found the unusual sudden increase in Faraday rotation (Fig. 7.1c) at the three Colorado stations at 140 MHz, which occurred at
Table 7.1

Orders of the ionospheric and transionospheric frequency shifts of various types

<table>
<thead>
<tr>
<th>Type of the shift</th>
<th>Geophysical shift</th>
<th>Random shift</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Solar flare</td>
<td>TID</td>
</tr>
<tr>
<td>Doppler shift (Δf)</td>
<td>5 Hz at 10 MHz</td>
<td>4 Hz at 10 MHz</td>
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<tr>
<td></td>
<td>3.5 Hz at 15 MHz</td>
<td>2.5 Hz at 15 MHz</td>
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<tr>
<td></td>
<td>2.5 Hz at 20 MHz</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.04 Hz at 100 MHz</td>
<td>0.03 Hz at 100 MHz</td>
</tr>
<tr>
<td>Relative shift (Δf/ f)</td>
<td>0.5 x 10⁻⁶ at 6 MHz</td>
<td>10⁻⁸ at 140 MHz</td>
</tr>
<tr>
<td></td>
<td>10⁻⁷ at 20 MHz</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10⁻⁸ - 10⁻⁹ at 40 MHz</td>
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</table>
Fig. 7.1 Typical transitionospheric SFDs and TID.
Night with distinct time shift between the onsets and have explained these in terms of increases in spread-F ionization and scintillation zone. The change in timing of the events is due to TID and was accompanied by an increase in amplitude and phase scintillations and marked increase in spread-F (Davies et al., 1975b; Donnelly and Fritz, 1975).

Using eqn. (7.9) it has been found that the Doppler shift for a transionospheric path at 140 MHz due to irregular changes of TEC along the ray path is of the order of one cycle, five cycles and two cycles for the stations Ft. Morgan, Table Mtn, and Elbert respectively while the respective shifts in the relative frequency are $0.7 \times 10^{-8}$, $3.5 \times 10^{-8}$ and $1.4 \times 10^{-8}$ approximately.

7.4. Typical Set-up for Reducing the Ionospheric Effects

A typical set-up for obtaining a standard of frequency at 2.5 MHz and 12.5 MHz by employing both the ATA transmissions at 10 MHz and 15 MHz from the National Physical Laboratory, New Delhi is shown in Fig. 7.2. The local oscillator frequency

$$f_0 = \frac{f_a(1) + f_a(2)}{2} = \frac{15 + 10}{2} = 12.5 \text{ MHz} \quad \ldots \ (7.10)$$

where $10 \text{ MHz} < f_0 < 15 \text{ MHz}$ and the subscript (1) and (2) refer to reception of signal at 15 and 10 MHz respectively.

The 2.5 MHz IF output due to the signal at 15 MHz is given by
Fig. 7-2 Typical set up for obtaining standards of frequency at 2.5 MHz and 12.5 MHz by employing both the ATA transmissions at 10 MHz and 15 MHz from NPL New Delhi (Arrows 1, 2, 3, 4 indicate 2.5 MHz, 12.5 MHz, 10 MHz, and 15 MHz respectively).
\[ f_1 = f_s(1) + \Delta f_s(1) \pm \Delta f_r(1) - (f_0 + \Delta f_0) \]
\[ = \{f_s(1) - f_0\} + \Delta f_s(1) \pm \Delta f_r(1) - \Delta f_0 \]
\[ = 2.5 + \Delta f_s(1) \pm \Delta f_r(1) - \Delta f_0 \quad \ldots \quad (7.11) \]

where \( f_s(1) \) = the signal frequency 15 MHz at the source,
\( \Delta f_s \) = the frequency shift introduced by ionospheric
disturbance due to a solar flare (SFD) or a TID,
\( \Delta f_r \) = the random ionospheric shift due to drifting
irregularities in the ionosphere,
\( f_0 \) = the local oscillator frequency 12.5 MHz,
\( \Delta f_0 \) = the drift of the local oscillator frequency.

Similarly, the IF output due to the signal at 10 MHz is given by
\[ f_2 = (f_0 + \Delta f_0) - f_s(2) - \Delta f_s(2) \pm \Delta f_r(2) \]
\[ = \{f_0 - f_s(2)\} - \Delta f_s(2) \pm \Delta f_r(2) + \Delta f_0 \]
\[ = 2.5 - \Delta f_s(2) \pm \Delta f_r(2) + \Delta f_0 \quad \ldots \quad (7.12) \]

It may be noted that the random shift \( \pm \Delta f_r(1) \) or \( \pm \Delta f_r(2) \) will not be affected by change of sign in so far as they are not additive or subtractive over a period large compared to the quasi-periods involved. However, if the frequency \( f_s(1) \) and \( f_s(2) \) are close to each other, \( \Delta f_r(1) \) and \( \Delta f_r(2) \) may be partly correlated and the spacing for which correlation is 0.5, is the so-called correlation spacing of frequency or correlation bandwidth. For the case considered, correlation is expected to be nil. Therefore, \( \Delta f_r(1) \) and \( \Delta f_r(2) \) are statistically
The amplitudes of the two IF outputs are made equal by the action of the limiters. The resultant frequency at the output of the adder will then be the mean of the frequencies at the two IF outputs. Accordingly, we have the resultant frequency

\[
f_A = \frac{f_1 + f_2}{2}
\]

\[
= 2.5 + \frac{\{\triangle f_1(1) - \triangle f_1(2)\}}{2} \pm \frac{\{\triangle f_1(1) + \triangle f_1(2)\}}{2}
\]

Here, again, the subtraction of random shifts \(\pm \triangle f_1(1)\) and \(\pm \triangle f_1(2)\) results in an increased peak shift due to the lack of correlation of the two shifts. In practice, such an increased shift would not be harmful. For, the quasi-frequency of the random shifts would be increased, when the two independent shifts are either added or subtracted. As a result, the integrated frequency shift for a given observing time will be effectively lowered by an addition or subtraction. Also the differential ionospheric shift

\[
\frac{\triangle f_1(1) - \triangle f_1(2)}{2}
\]

is much less than the shift \(\triangle f_1(1)\) and \(\triangle f_1(2)\) expected for an individual signal. The resultant output frequency \(f_A\) at 2.5 MHz could, therefore, be employed as a standard after passing through a tuned amplifier. An unknown frequency near 2.5 MHz input can be compared with the amplified output at 2.5 MHz by a beat detector (no. 1) in Fig. 7.2.
The equation for the ionospheric shift is given in article 7.2. Experimental data to establish the frequency law is too meagre. The orders of the ionospheric shifts of various types are shown in Table 7.1.

Assuming an inverse frequency law for the shifts, the geophysical shifts at 10 MHz and 15 MHz will be reduced drastically by the set-up. The differential shift would be less than 2 Hz, while the random shift would be within ± 20 Hz. The precision is thus limited only by the random shift. Again, since the time variations of the random shifts at 10 MHz and 15 MHz are statistically independent, the shift after integration would be reduced by a factor of 2 even though the peak of shift without integration is more.

A theoretical study of the differential and random ionospheric shifts indicated an inverse frequency law for both types of shifts as indicated by the eqn. (7.8). From the Table 7.1, it appears that the precision of the standard at 2.5 MHz derived from the 10 to 15 MHz signals is better than that expected from an individual signal at 10 MHz or 15 MHz, particularly at the times of geophysical disturbances producing coherent ionospheric shifts. Further, the local oscillator drift is cancelled and is thus without effect on the precision of the standard derived. The set-up shown in Fig. (7.2) would also provide a standard at 12.5 MHz. For this, the calculated output frequency $f_p$ of the product device (3) will be

$$f_p = f_1 - f_2$$

$$= \left\{ \Delta f_1(1) + \Delta f_1(2) \right\} \pm \left\{ \Delta f_r(1) + \Delta f_r(2) \right\} - 2\Delta f_0$$

$$= 2 \left[ \frac{\left\{ \Delta f_1(1) + \Delta f_1(2) \right\}}{2} \pm \frac{\left\{ \Delta f_r(1) + \Delta f_r(2) \right\}}{2} - \Delta f_0 \right]$$

... (7.14)
In case where $\Delta f_0$ is much greater than the ionospheric shifts, the drift of the oscillator $\Delta f_0$ can be measured from $f_0$ as indicated by the beat detector 2. Further, an unknown frequency near 12.5 MHz may be calibrated by using it as the local oscillator fed at input 2. The unknown frequency will be varied till a zero is indicated in the beat detector 2. The precision of the calibration would then be governed by means of the ionospheric shifts at 10 MHz and 15 MHz. Thus, the set-up can also serve as a reference standard at 12.5 MHz. Besides these, the set-up can also provide with the standards at 10 MHz and 15 MHz in the conventional way. Thus zeroes in the beat detectors (3) and (4) would indicate that the unknown frequencies are 10 MHz and 15 MHz respectively.

A theoretical estimate of the differential shift is given by

$$\Delta f = -\frac{2}{2\pi mc^2} \frac{d}{dt} \left[ \int_0^R N \, dh \right]$$

for a one-way travel

$$\approx \frac{4.1 \times 10^7}{c f} \frac{d}{dt} \left[ \int_0^R N \, dh \right]$$

If we assume the total electron content (TEC) along an ionospheric ray path to be independent of frequency, then the shifts at 10 MHz and 15 MHz are in the ratio:

$$\frac{\Delta f_{10}}{\Delta f_{15}} = \frac{15}{10} = 1.5$$

$$\Delta f_{10} - \Delta f_{15} = (1.5 - 1) \Delta f_{15} = 0.5 \Delta f_{15} \quad \ldots \quad (7.15)$$
Comparing the shift for direct observation at 2.5 MHz and 15 MHz,
\[
\frac{\Delta f_{2.5}}{\Delta f_{15}} = \frac{15}{2.5} = 6,
\]
\[
\therefore \Delta f_{2.5} = 6 \Delta f_{15} \quad \ldots \quad (7.16)
\]
From eqn. (7.15) and (7.16)
\[
\frac{\Delta f_{10} - \Delta f_{15}}{\Delta f_{2.5}} = \frac{0.5 \Delta f_{15}}{6 \Delta f_{15}} = \frac{1}{12} \quad \ldots \quad (7.17)
\]
Thus the differential shift is reduced by a factor of 12 over that expected by direct transmission at 2.5 MHz. In practice, the direct transmission at 2.5 MHz would be received via the E-region, while each of the 10 MHz and 15 MHz transmission is reflected from the F-region. As a result, the assumption that \( \int N \, dh \) along the ray path is independent of frequency is not fully justified. Nevertheless, eqn. (7.17) gives us a rough idea about the improvement expected.

The fact that the precision of the derived standard at 2.5 MHz is limited mainly by the differential ionospheric shift during geophysical disturbances prompted us to think of studying the shift. For this, the 2.5 MHz output from the 2.5 MHz tuned amplifier is fed to the mixer 5 which in conjunction with the loop filter and the VCO essentially constitute a phase-lock loop. The frequency of the VCO will track that of the input (2.5 MHz) of mixer 5. The input to the VCO gives an indication of the instantaneous frequency (2.5 MHz) of the derived standard. This is recorded on the pen recorder for the study of the differential shift.
A similar set-up for transionospheric signals would be useful in obtaining precision standards from satellite broadcast of standard signals. In cases where more than one station broadcasts standard signals at the same frequency, a ray diversity technique may improve the frequency stability of the received signal. For instance if the stations are equidistant from the reception centre and located sufficiently apart from one another, so that the random ionospheric shifts for the different propagation paths may be assumed statistically independent then for \( n \) stations radiating at the same frequency, the ionospheric shift would be reduced by a factor of \( \sqrt{n} \).

### 7.5. Conclusion

It may be concluded that the precision of a radio transmission controlled by an atomic clock of high accuracy, is governed more by the ionospheric and transionospheric propagation characteristics than by the limitations of the standards. The transionospheric propagation path is more stable than the ionospheric one, although the frequency law of the transionospheric Doppler shift may fail to hold in the UHF and microwave bands, where the effects may not always be negligible. The standard time broadcasts can be more effectively utilized directly by employing relatively simple experimental set-up if a careful study of the differential ionospheric shift is made. The theoretical estimate of the differential shift in the resultant output frequency at 2.5 MHz showed that it would be reduced by a factor of 12 over that expected by direct transmission at 2.5 MHz. After passing through the tuned amplifier the resultant output frequency \( f_A \) at 2.5 MHz could, therefore, be employed as a standard.