Estimation of Vertical Ionosphere From The Oblique Sounding Measurement Using HF Radar System

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Abstract— **Many of radio wave applications require real-time determination of the 2-dimensional structure of the ionospheric electron density along the path, or at least of the mid-path electron density profile. Since it is often impractical to deploy a vertical ionosonde at the point of interest, such as across oceans, the idea of reconstructing an average mid-path profile from oblique incidence measurements is very appealing. In this paper, we present methods for estimate vertical ionosphere profile without vertical ionospheric measurement. This can be achieved by ionogram conversion from the oblique to equivalent vertical at the midpoint between the measurement stations. To get vertical ionogram from the measured oblique ionogram, two steps processing are necessary. The first step is a trace extraction from the ionogram and vector tracking algorithm is used in this phase. Second step is an ionogram conversion from the oblique to equivalent vertical. In order to verify ionogram conversion algorithm, converted vertical ionograms are compared with the measured ionograms. The comparison results show that ionogram conversion methods can be used for the midpoint vertical ionogram estimation without vertical ionospheric measurements.**

Keywords-Ionosphere; Ionogram; Ionosonde; Vertical sounding; Oblique sounding; Trace extraction; Ionobgram conversion; Vector tracking.

I. INTRODUCTION

The ionosphere can be the largest source of error in GPS positioning and navigation. Furthermore, under certain condition, amplitude fading and phase scintillation effects can cause loss of carrier lock and intermittent GPS receiver operation. The ionosphere effects radio propagation especially HF radio communication. The presence of the free electrons in the ionosphere effects radio signals across several bands of radio frequency.

For the ionospheric research, Korean Space Weather Center (KSWC) installed ionosphere measurement radar system, called ionosonde [1], in the place of Jeju and Icheon. Both stations measure vertical ionospheric condition of each sky respectively. The vertical ionosphere measurement can provide the important ionospheric parameters such as critical frequency, virtual height and electron density, for ionoshperic research. Meanwhile oblique ionosphere measurement has the ability to detect the ionosphere over sea and other terrain where it is not practical to deploy vertical ionosonde and provide more information with less transmitting and receiving devices. In a network for ionospheric monitoring, N vertical incident ionosondes can provide the ionospheric information of N locations overhead, but N transmitters and M receives of the oblique incident ionosondes, which are separated from each other, have the potential of characterizing the ionosphere in the vicinity of N×M reflecting points. Therefore, the oblique incident ionosondes still have kept developing by now [2].

This paper describes methods for estimate vertical ionospheric condition without ionosphere measurement. This can be achieved by ionogram conversion from oblique measurement to equivalent vertical at the midpoint between the stations [5], [6]. The conversion algorithm presented in this paper provides not only vertical profile of F layer but also provide information for sporadic E layer occurrence of ionosphere.

In this paper, ionosphere is reviewed first at Section 2. The ionosphere measurement radar system called ionosonde is reviewed at Section 3. Ionosphere measurement status in Korea is reviewed at Section 4. Method for estimate vertical ionospheric condition at midpoint from the oblique sounding measurements at both stations is presented at Section 5. Validation results for estimated vertical ionospheric condition at midpoint is reviewed Section 6. Finally research activities are summarized in Section 7.

II. IONOSPHERE

The ionosphere is a region of the upper atmosphere, from about 85km to 600km altitude. It plays an important part in atmospheric electricity and forms the inner edge of the magnetosphere. It has practical importance because, among other functions, it influences radio propagation to distant places on the Earth.

The ionosphere effects radio propagation from the extremely low frequencies to super high frequencies. Below 30MHz the ionosphere is an essential part of the propagation, whereas above 30MHz the ionosphere is a source of band pollution particularly at night in the LF and MF bands (30kHz to 3MHz) and system disruption for Earth-space communications, such as navigation systems [3].

The D layer is the innermost layer, 60 km to 90 km above the surface of the Earth. The E layer is the middle layer, 90 km to 120 km above the surface of the Earth. The F layer or

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region, also known as the Appleton layer, extends from about 200 km to more than 500 km above the surface of Earth. The Figure 1 shows the structure of ionosphere. At night, the F layer is the only layer of significant ionization present, while the ionization in the E and D layers is extremely low. During the day, the D and E layers become much more heavily ionized, as does the F layer, which develops an additional, weaker region of ionization known as the F1 layer. The F2 layer persists by day and night and is the region mainly responsible for the refraction of radio waves.

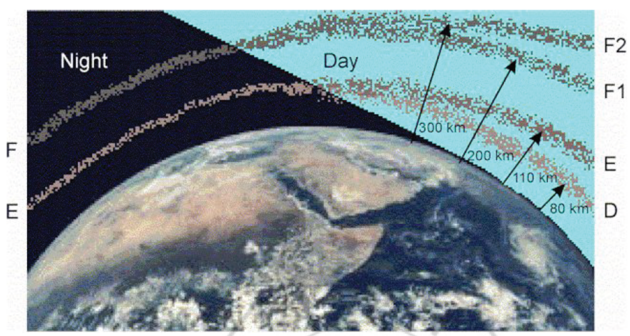


Figure 1. Struectre of ionosphere at day and night

III. IONOSONDES

An ionosonde is a special radar system for the examination of the ionosphere. The changing state of the ionosphere is generally monitored by networks of vertical ionosondes. The transmitter of ionosonde sweeps all or part of the HF frequency range, transmitting short pulses. These pulses are reflected at various layers of the ionosphere, at heights of 100-400 km, and their echo are received by the receiver and analysed by the control system. The result is displayed in the form of an ionogram, a graph of reflection height (actually time between transmission and reception of pulse) versus carrier frequency. An ionosonde consists of;

- A high frequency (HF) transmitter, automatically tuneable over a wide range. Typically the frequency coverage is 0.5-23MHz or 1-40MHz, though normally sweeps are confined to approximately 1.6-12MHz.
- A tracking HF receiver, which can automatically track the frequency of the transmitter.
- An antenna with a suitable radiation pattern, which transmits well vertically upwards and is efficient over the whole frequency range used.
- Digital control and data analysis circuits.

In Korea, model DPS-4D ionosonde are used for ionosphere layer measurements. Figure 2 shows the DPS-4D ionosonde and receive antenna installed in Korea. Table-1 shows the characteristics of DPS-4D ionosonde [1]. The DPS-4D is the latest digital ionosonde that the University of Massachusetts Lowell Centres for Atmospheric Research developed during 2004-2008. The DPS-4D ionosonde uses one simple crossed delta or rhombic antenna for transmission, and an array of four small crossed loops for reception. The DPS-4D system compensates for a low power transmitter (300 W vs. 10 kW for previous systems) by employing intra-pulse phase coding, digital pulse compression and Doppler integration.

Figure 2. DPS-4 ionosonde and receive antenna

TABLE I. MAIN CHARACTERISTICS OF DPS-4D

Parameters	Characteristics
Frequency scan	0.5 ~ 30MHz
Frequency synthesis	Fully digital
Pulse width	533us (16 chips of 33us)
Peak pulse power	2 channels @150W each
Doppler range	±3Hz ~ ±50Hz
Doppler resolution	0.0125 ~ 12.5Hz
TX antenna type	Turnstile Delta or Rhombic
RX antenna type	Active crossed loop

IV. IONOSPHERE MEASUREMENTS IN KOREA

In the past, the vertical incidence ionosonde has been the mainstream for ionospheric detection, due to its ability to accurate measure the echo group range as a function of frequency and to estimate the ionospheric critical frequency, virtual height, and electron density profile so on. However, oblique incidence ionosonde has not been widely applied. The oblique incidence ionosonde can monitor the ionosphere over ocean, marsh, desert and so on, where it is not practical to deploy vertical incidence sounder. Oblique sounding may be used to obtain information about the ionosphere near the mid-point between two ionosonde sites. This makes it useful for recovering ionospheric data at a point where vertical sounding cannot be conducted.

There are two ionosonde stations in Korea, named Jeju station located in 33.4°N, 126.3°E and Icheon station located in 37.1°N, 127.5°E. The ionosondes are operation in the frequency sweep mode, transmitting the phase coded pulse train by the transmit antenna. The GPS receivers are applied in the ionosondes for the time and frequency synchronization between the transmitter and receiver. The output of ionosonde measurements are ionograms. An ionogram is a graph of the virtual height of the ionosphere plotted against frequency. Ionogram is often converted into electron density profiles. Data from ionograms may be used to measure changes in the Earth's ionosphere due to space weather events.

In the ionosonde stations Jeju and Icheon, oblique ionograms 1 to 16MHz operating frequencies with a 25 kHz frequency step are recorded every 30 minutes each. The height bin of vertical ionogram is from 80 to 1280km with 2.5km step. The Figure 3 shows the oblique sounding configuration of two ionosonde stations to get midpoint ionogram information.

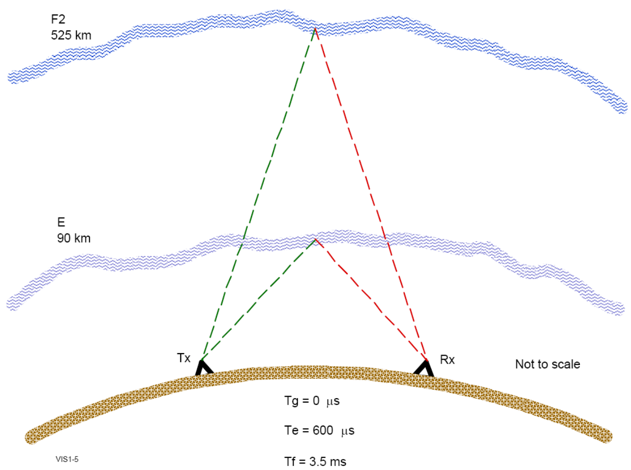


Figure 3. Oblique sounding configuration for the midpoint ionogram measurement

The ground range between Jeju and Icheon stations have is about 430km. The one hop ionospheric reflecting point of oblique propagating path from Jeju to Icheon stations is near the Gochang in Korea. If ionosonde in Jeju station receive pulse signal transmitted from the ionosonde in Icheon station, the strongest receiving signal is a one hop reflected signal at the ionosphere near the Gochang. So oblique sounding ionogram measured at receiving station has information of ionospheric condition at the midpoint between the stations.

The Figure 4 is a map showing the location of Digisonde station Jeju and Icheon and one hop ionospheric reflecting point of oblique propagating path between two stations (midpoint).

Figure 5 shows the oblique ionogram measured at Jeju station. The x axis of ionogram is a frequency with MHz scale and y axis of ionogram is a height with km scale. The color of ionogram shows a direction of signal arrival. When Jeju station receives signal from the Icheon station, arrival azimuth angle is 330 degree and this direction is displayed as a sky blue color in the ionogram. The sweep frequency of ionosonde is from 1 to 16MHz and measurement hight range is from 8 to 1280km. There are two sky blue color signal clusters in the lower part of figure. The left one of the two signal clusters is an Ordinary signal path and right one is an extraordinary signal path. Extraordinary signal is same as Ordinary except polarization was rotated by the geomagnetic field during the ionospheric propagation. The upper signal cluster is a double hop signals.

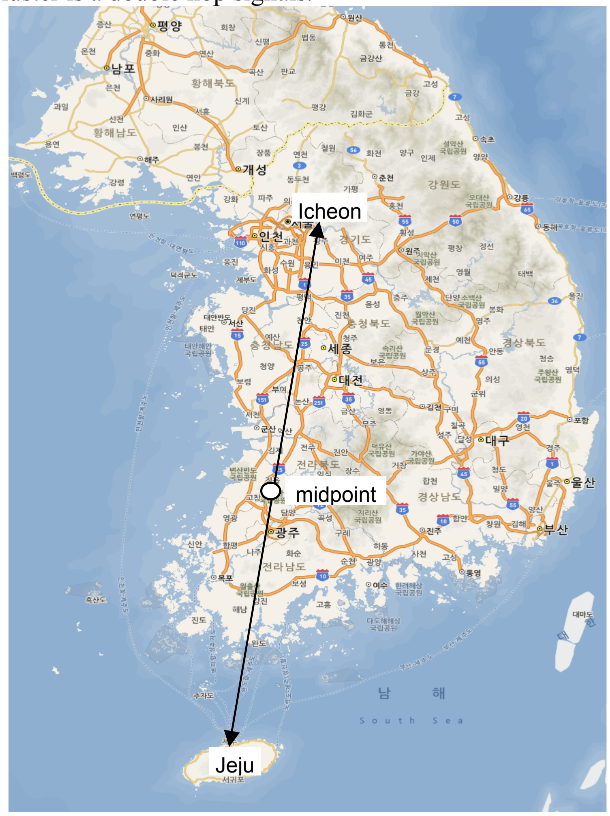


Figure 4. Location of ionosinde stations and midpoint in Korea

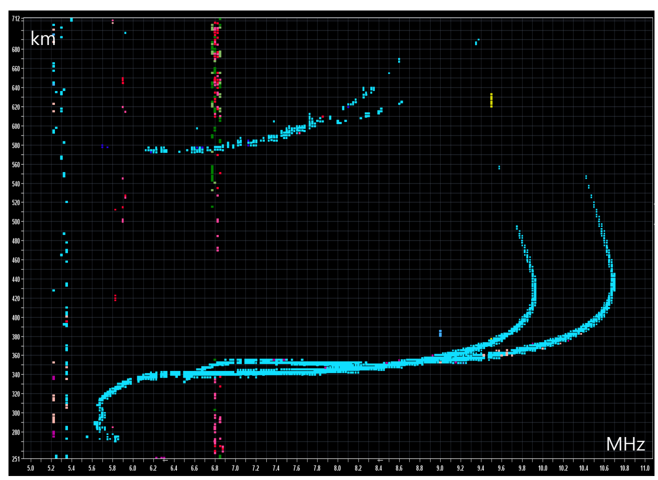


Figure 5. Oblique ionogram measured at Jeju

V. VERTICAL IONOGRAM AT MIDPOINT

As mentioned in section 4, vertical ionogram is more useful than oblique ionogram for the ionospheric research due to its ability to accurate measure the echo group range as a function of frequency and to estimate the ionospheric critical frequency, virtual height, and electron density profile, so on. In this section the idea getting vertical ionogram of the midpoint from the measured oblique ionogram at two ionosonde stations are described. To get vertical ionogram from the measured oblique ionogram, two processing steps are necessary. First step processing is trace extraction from the ionogram and second step processing is ionogram conversion from oblique to vertical.

A. Trace extraction from the ionogram

Before ionogram conversion from oblique to vertical, it needs to extract trace from the oblique ionogram. The trace extraction reduces data size of oblique ionogram and make easy to handle conversion calculation. The problem of reliable trace extraction is a difficult one. Typically only vertical incidence ionograms have been collected regularly because techniques for trace extraction from such have been developed. The variety of trace shapes in oblique sounding due to different ionospheric conditions, bease-lines and ionospheric gradients, adds an order of difficulty to the problem and there seems to be as yet little work published in the open literature on the problem [4].

We developed new algorithm called 'vector tracking' for the trace extraction from the oblique ionogram data. This algorithm can extract ionogram trace well even in week echo signal and noisy environments. The starting point of trace extraction is maximum amplitude point in scattered data of the oblique ionogram. In vector tracking algorithm, amplitude value of eight directions from the maximum amplitude point are compared and maximum amplitude direction is selected as a next trace point. The eight directions are angles of 0, 45, 90, 135, 180, 225, 270, and 315 degree from the selected trace points. Figure 6 shows a trace extraction method in vector tracking algorithm. Four amplitude value of echo signal in eight directions in the ionogram are added and compared each other and direction of maximum amplitude value is selected as a next trace point.

Figure 7 shows example of trace extraction from the ionogram using 'vector tracking' algorithm. Red line in the figure is an extracted trace of ionogram from the starting point in right hand. Blue line in the figure is an extracted trace of ionogram from the starting point in left hand.

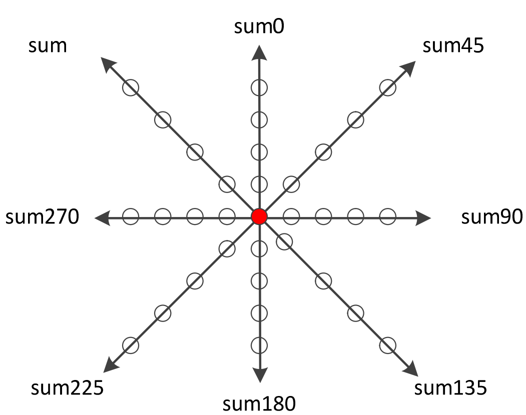


Figure 6. Trace extraction method in vector traking algorithm

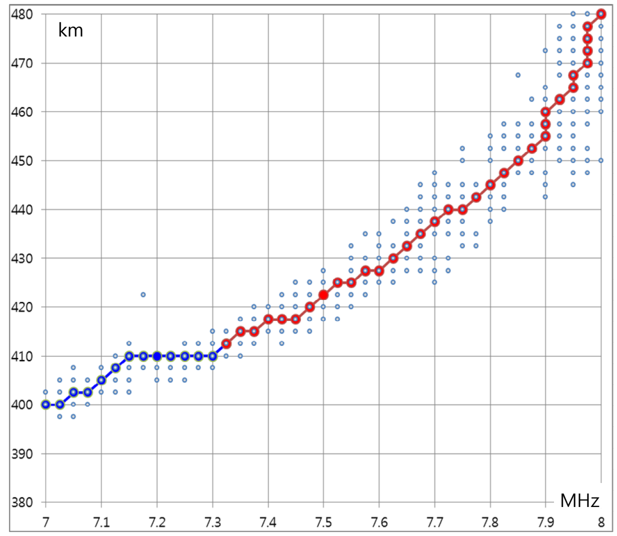
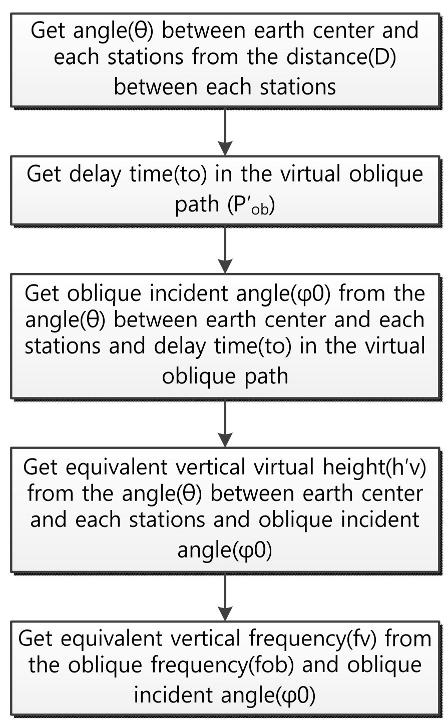


Figure 7. Ionogram trace extraction by vector tracking algorithm

B. Ionogeam conversion from oblique to vertical

The distance between Jeju and Icheon stations is less than 500km. Therefore, it is acceptable to assume ionosphere layers are flat and there are no electron confliction and no geomagnetic disturbance between the stations. In this case, conversion algorithm can be expressed by secant law theory of Berit and Tuve [5] and theory of Martyn's equivalent path [6]. The vertical frequency (f_v) and virtual height (h'_v) can be derived from the oblique frequency (f_{ob}) and virtual path (P'_{ob}). The detailed conversion algorithms can be described in following steps.



From the above steps, we can get equivalent vertical frequency (f_v) and vertical virtual height (h'_v) from the oblique frequency (f_{ob}) and the virtual oblique path (P'_{ob}) between the stations. The equations are as following.

$$f_v = \frac{f_{ob}}{1.002}\cos\left(\sin^{-1}\left(\frac{428.8748}{P'_{ob}}\right)\right) \quad (1)$$

$$h'_v = -3.6097 + \frac{214.4374}{\tan\left(\sin^{-1}\left(\frac{428.8748}{P'_{ob}}\right)\right)} \quad (2)$$

The Figure 8 shows a measured oblique ionogram at both station and converted equivalent vertical ionogram of the midpoint according to the (1) and (2) in above.

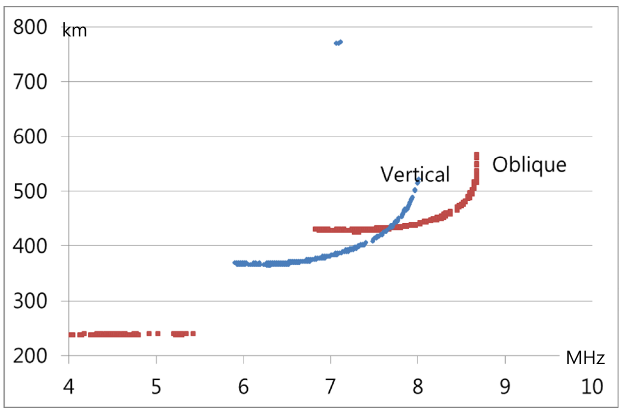


Figure 8. Measured oblique ionogram and converted vertical ionogram

VI. Validation of Algorithm

It needs to validate equivalent vertical ionogram of midpoint between two stations converted from the measured oblique ionogram. The best way is compare converted equivalent vertical ionogram with a measured vertical ionogram at the midpoint. But this method is not practical because it needs new ionosonde installation at the midpoint. The alternative way is compare measured vertical ionogram at both stations. This method seems to be reasonable because distance between the stations is just 430km and measurement interval of each station is short as 8 minutes. So if ionosphere condition is calm, alternative method can be a good choice for the validation.

Figure 9 shows a measured vertical ionograms at Jeju, Icheon stations and equivalent vertical ionogram of midpoint. Equivalent vertical ionogram in the figure is located between the two station ionograms and shape is similar with both ones. This means that ionogram conversion equations (1) and (2) in previous chapter are validated and this conversion can be used for the vertical ionogram estimation without measurement at the midpoint.

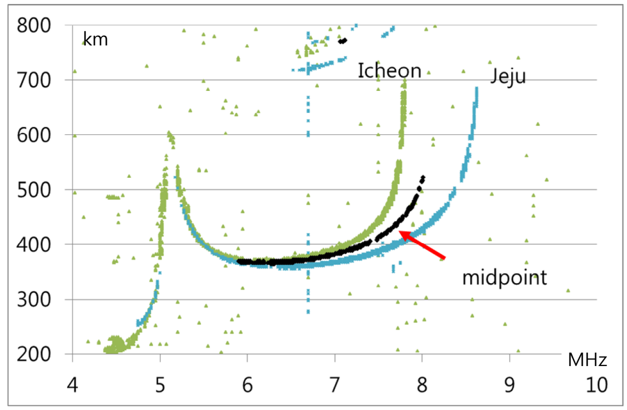


Figure 9. Ionograms of Jeju, Icheon and midpoint

VII. Conclusion and Futher Works

In this paper, we present methods for estimate ionospheric condition without ionosphere measurement. This can be achieved by ionogram conversion from the oblique to equivalent vertical at the midpoint between the measurement stations. First step is a trace extraction from the measured oblique ionogram of the receiving station. The vector tracking algorithm was used in this phase. Second step is an ionogram trace conversion from the oblique to vertical. The equivalent vertical conversion algorithm was used in this phase. In order to verify the conversion algorithm, converted vertical ionogram of midpoint was compared to the measured vertical ionograms of both receiving stations. The result shows that conversion algorithm can be used for the vertical ionogram estimation at the midpoint.

In Korea, we have plans to install new ionosondes in the most east and west points for the full mesh ionosphere measurement network. Then we can get not only 4 stations vertical ionograms, but also midpoints vertical ionogram from the 4 stations measurements using these algorithms. Also we will extend this study to over country sea area. We have plans to cooperate with Japan and China for this research.

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