ROSE: a high performance oblique ionosonde providing new opportunities for ionospheric research

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Abstract
A high quality high frequency (HF) oblique ionosonde has been developed for use in propagation research and associated studies of the ionosphere. The ionosonde is known as ROSE (radio oblique sounding equipment) and requires the connection of a specially designed enhancement to a commercially available chirp sounder receiver (RCS-5) manufactured by the BR Corporation in the U.S.A. Two important features are brought about by the addition of this enhancement. Firstly, an increase in the resolution of an ionogram by a factor of approximately three. This allows the fine structure in the ionospheric returns to be detected. Secondly, colour coding of the ionogram according to the amplitude of the received signal. Detailed mode amplitude information and comparisons of the relative strengths of propagating modes can be achieved through this. Additional features which are provided include display handling, data storage and off-line analytical facilities. This paper describes the system architecture of ROSE, its main features and its application to ionospheric research.

Key words *ionosonde – sounder – ionogram*

1. Introduction

Throughout the world extensive use is made of radio sounding systems to remotely probe the ionosphere (*e.g.* Hunsucker, 1991). One category of remote sensing system is known as the ionosonde, which is essentially a radar emitting pulses, chirp or other waveforms to measure the group delay of the return signal bounced back from the ionosphere. The receiver may be collocated with the transmitter, in which case the ionosonde is a vertical sounder (*e.g.* Reinisch, 1986), or the transmitter and receiver may be separated by distances of up to several thousand kilometres, in which case the ionosonde is known as an oblique sounder (*e.g.* Barry and Fenwick, 1969).

Oblique chirp sounders (*e.g.* Barry and Fenwick, 1969) sweep a phase-continuous signal over the band of interest at rates of up to several hundred kilohertz per second. Due to the method of receiver operation a comparatively narrow receiver bandwidth is used of the order of a few hundred Hertz and this in turn leads to a relatively low transmitter power (10-100 W). One of the main disadvantages of chirp sounders is the relatively complex analysis that must be carried out to determine the ionospheric propagating modes. The advent of specialized digital signal processors (DSPs), together with other technologies, has simplified this task and enabled more extensive development of chirp sounder receivers to be undertaken in recent years.

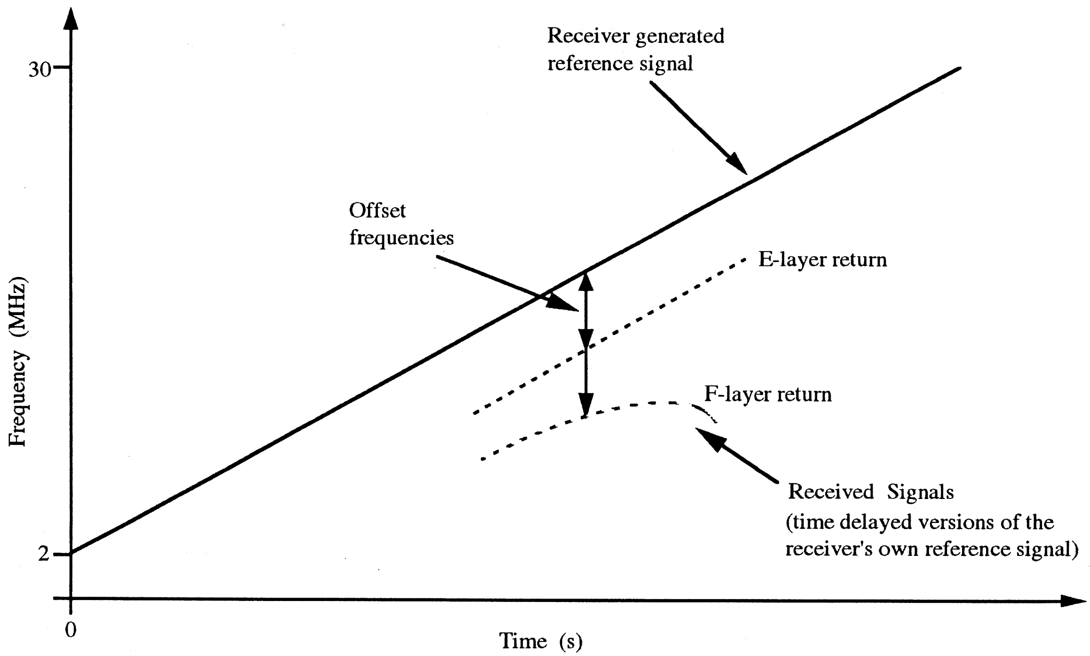

Fig. 1. Frequency analysis in a HF oblique chirp sounder.

2. Chirp sounder receivers

The chirp sounder receiver generates an internal reference signal which is of the same form as that being transmitted at the transmitter site. By carrying out a radio frequency mixing process between this reference signal and the received signal, a baseband signal is obtained which contains a series of frequencies dependant upon the modes of propagation present. The frequencies of the signals are proportional to the time of flight from the transmitter to receiver and, therefore, by carrying out a frequency analysis the relative group delays of the different propagating modes can be calculated (fig. 1). This information is normally displayed as an ionogram – a graph of relative group delay versus radio frequency.

The chirp technique is very attractive because it compresses the integrated energy from a segment (typically 100 kHz) of the total swept bandwidth into a compressed pulse of period t_c. If the bandwidth of the segment is BW_s and this lasts for a time t_s the chirp signal is accentuated in relation to fixed frequency interferers to provide a processing gain given by the ratio t_s/t_c ($= t_s BW_s$).

The absolute time of flight of the transmitted signal is not known unless the transmitter and receiver have some form of accurate time control. Normally, when the receiver is initiated to gather data on a particular path a searching process is employed to synchronise to the transmitted signal. This process involves adjusting the start time of the internal reference signal until the baseband signals are obtained in the correct frequency range.

2.1. *RCS-5 sounder receiver*

The BR Corporation of California, U.S.A. manufacture a chirp sounder receiver (RCS-5) (B.R. Communications, 1985) which is able to receive transmissions from a number of compatible transmitters distributed throughout the world. The RCS-5 is designed to assist the communications operator in selecting the appropriate operating frequency for a particular HF communications link and to this end it displays a simple monochrome ionogram. An indication of either amplitude, automatic gain control (agc) or signal quality is also shown in the form of a simple bar chart, but in each of these cases the displayed value is the integrated value across all the propagating modes at a particular frequency. Therefore, the ionogram cannot show the user whether, for example, the signal amplitude relates to two modes of similar amplitude or one high amplitude mode and one weak mode.

In one operational mode of the BR system the chirp signal from the transmitter is swept linearly from 2 to 30 MHz in 280 s (*i.e.* at 100 kHz/s). In the receiver the signal is segmented into 100 kHz steps, each lasting one second and providing a processing gain of 100 dB. After mixing, the baseband signal lies between 0 and 500 Hz which corresponds to a group delay of 0 to 5 ms. The RCS-5 spectrally analyses this baseband signal with a 2.5 Hz (0.025 ms group delay) resolution in one second intervals and displays the resulting ionogram on its built-in screen with a resolution of 280 points in the horizontal (frequency) direction and 200 points in the vertical (group delay) direction (*i.e.* ionogram resolution is 100 kHz $\times$ 25.0 μs). The agc of the receiver tries to optimise the display to make the propagating modes clear. The main limitation of the monochrome screen is that weak modes are displayed with an equal intensity to strong modes and are therefore indistinguishable.

After an ionogram has been collected the RCS-5 may adjust the sweep start time of its internal reference signal in an attempt to optimise the position of the ionogram on the screen. This adjustment is carried out in 0.5 or 1 ms increments and is known as autoslip. It is possible to disable this feature to avoid, for instance, the complete loss of the ionogram during a night period when the ionospheric returns may be low and the ionogram may be inadvertently slipped out of range.

3. ROSE ionosonde programme

The RCS-5 receiver is primarily designed for the radio communications operator and its use as a research tool to investigate ionospheric propagation is limited by the constraints described above. To meet the requirements of detailed scientific research ROSE (radio oblique sounding equipment) models -100 and -200 have been developed with the aim of enhancing the output from the RCS-5 whilst both avoiding internal modifications and maintaining compatibility with the current world-wide network of chirp transmissions. The priority has been to provide a much higher resolution ionogram which also contains detailed signal strength data to enable the amplitudes of various modes to be compared. Furthermore, archiving and data recall facilities have been developed to enable off-line analysis of ionograms. The more recent development of ROSE-300, which has been prototyped, provides all of the functionality of ROSE-100 and ROSE-200 without the need for the RCS-5 receiver.

4. ROSE-100 architecture

To achieve the improvements described above, and provide scope for future modifications, an enhancement was designed for the RCS-5 which duplicated some of its internal functions whilst further analysing the received signal to improve functionality. The enhancement consisted of a custom designed digital hardware processing and control unit (PCU) which was connected to the ports at the rear of the RCS-5, and an IBM-compatible personal computer (PC) which interfaced to the PCU. The RF front-end of the RCS-5 was utilised to produce a baseband signal. The additional equipment anal-

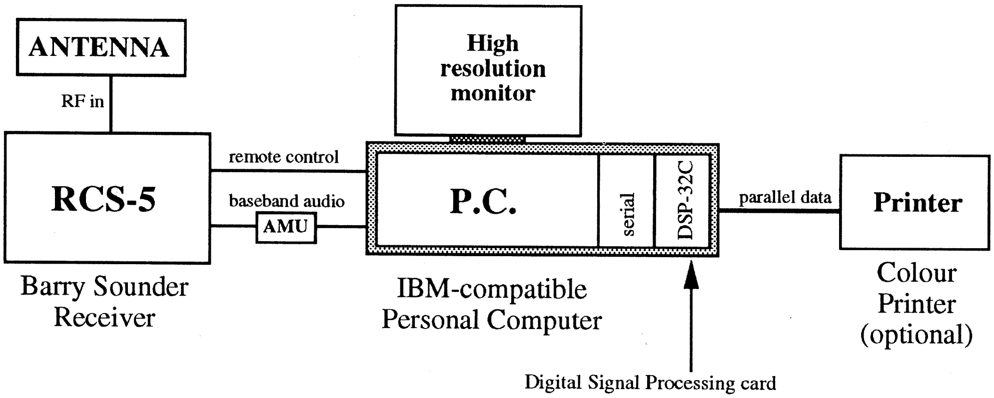

Fig. 2. ROSE-200 block diagram.

ysed this signal and displayed the ionogram. The system was known as ROSE-100 and is described in more detail by Arthur *et al.* (1991).

5. ROSE-200 architecture

During the development of ROSE-100 enhancements to DSP technology occurred which enabled us to dispense with the PCU and utilise a single DSP32C processor board plugged directly into the PC. This latest implementation of ROSE (designated 200) is far more robust and is cheaper to implement than the previous ROSE-100 system whilst retaining the same functionality.

Figure 2 shows a block diagram of ROSE-200. The RS232 remote control interface on the RCS-5 is used by the PC to allow automatic programming of the RCS-5 and the extraction of information regarding the received signal power levels in the form of receiver agc values. The de-chirped baseband (0 to 500 Hz) output signal from the RCS-5 is fed to the DSP32C board through an audio matching unit (AMU) and is analysed for spectral content. The resultant ionogram produced by the PC is colour coded to indicate detailed signal strength information and colour printouts are provided by means of a colour printer. ROSE may be operated with or without the «autoslip» feature offered by the RCS-5.

Table I compares the parameters of ionograms obtained from the standalone RCS-5 against the full resolution ionograms provided by ROSE (100 or 200).

5.1. *DSP functions*

The baseband signal from the RCS-5 is digitally sampled on the DSP32C board and the resultant data stream is arranged into blocks which are weighted using a window function and spectrally analysed using a 2048-point FFT routine to give group delay information. Each block covers a received signal bandwidth of 136 kHz, and lasts 1.36 s as dictated by the transmitter sweep rate. As a result of the wider bandwidth when compared to the RCS-5, processing gain is increased by 5 dB to 105 dB (table I).

The analysis of each block produces 682 values, corresponding to one vertical line on an ionogram with a group delay resolution of 7.3 μs (0.73 Hz). The number of vertical lines which constitute a single ionogram (*i.e.* horizontal resolution) is dictated by the rate at which the blocks are produced and analysed during a sweep. In all cases there is an overlap between the blocks which results in data being shared. Greater overlap pro-

Table I. Comparison of ionogram parameters.

Parameter	RCS-5	ROSE
Frequency axis		
Range	2-30 MHz	2-30 MHz
Resolution	100 kHz	33 kHz*
Total number of points	280 points	836 points*
Group delay axis		
Range	0-5 ms	0-5 ms
Resolution	25.0 μs	7.3 μs
Total number of points	200 points	682 points
Display rate		
Vertical lines per second	1	3*
Processing		
Gain	100 dB	105 dB

* maximum resolution option.

duces more blocks and provides improved display resolution. A choice is available of either one block per second giving 279 lines, two blocks per second giving 418 lines or three blocks per second giving 836 lines. The latter option corresponds to an overlap in the received signal of 103 kHz and produces the highest resolution ionogram of 33 kHz $\times$ 7.3 μs (836 $\times$ 682 points); this marks a substantial improvement over the 100 kHz $\times$ 25.0 μs (280 $\times$ 200 points) of the standalone RCS-5. The former options are of use when data storage space is at a premium or display resolution is limited.

The DSP32C also performs an estimate of the noise floor for each block based upon a filter value selected by the operator. This is useful for removing background clutter from ionograms. The algorithm employed examines each vertical line of the ionogram and determines the differences in the group delay of signals falling within certain pre-defined magnitude ranges. The noise floor is equated to the upper limit of the highest magnitude range containing signals that extend beyond a specified spread in group delay – as determined by the filter value.

Figure 3 summarises the main processes involved in the analysis of the baseband signal.

5.2. *PC functions*

The software for the PC is written in the computer language C and performs the following functions:

a) supports the operator interface;
b) provides overall control of ROSE;
c) processes spectral data supplied from the DSP32C;
d) displays the data in the form of an ionogram;
e) stores ionograms for future use;
f) provides features for recalling and analysing stored ionograms.

As ROSE is primarily a research tool considerable effort has been made to ensure that the software allows control over a large number of system parameters. The operator interface is accessed from a single menu which provides the means for selecting cer-

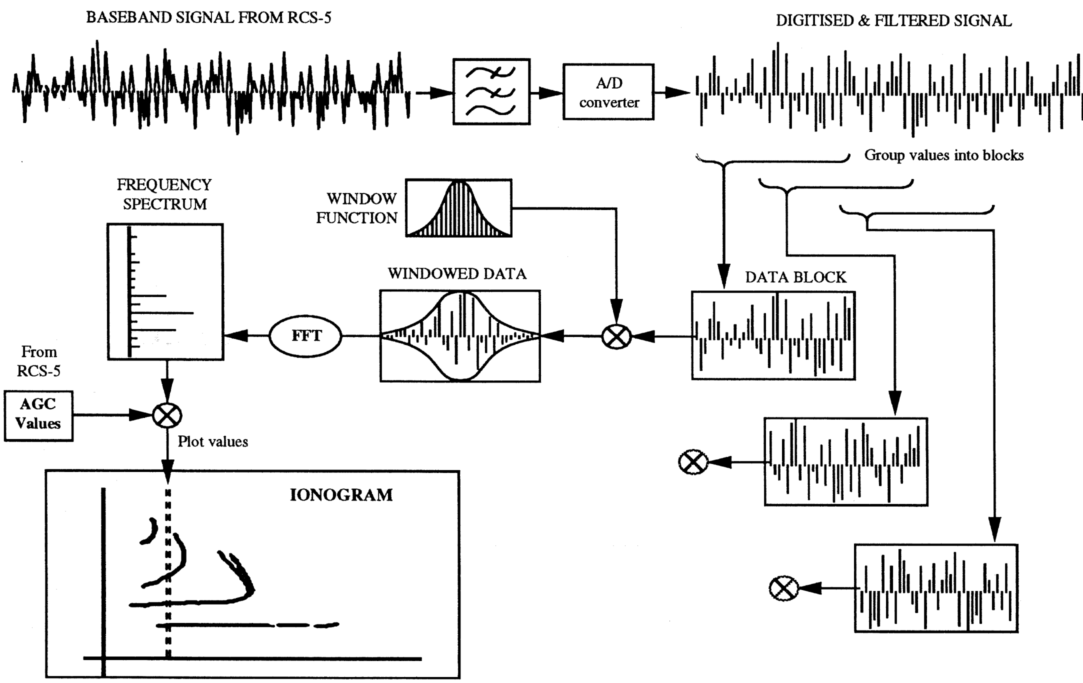

Fig. 3. Analysis of the baseband signal in ROSE.

tain functions or changing parameters using pop-up windows. Operator input is achieved using the PC keyboard or mouse. Three types of operation are allowed. Firstly, the operator may define a sounding schedule with reference to a comprehensive built-in list of transmitter stations. Secondly, the operator may specify certain criteria with regard to the collection and storage of data (*e.g.* signal strength range, filter value, save mode). Thirdly, the operator may select and initiate an operational mode – this may involve the collection of new data or the recall, display and analysis of saved data. The configuration defined in the first two operations may be saved if required to avoid re-specifying for future runs.

The PC provides overall control of the ROSE ionosonde which includes communicating remotely with the RCS-5 and co-ordinating the operation of the DSP32C.

In the data collection mode approximately 700 words of data are passed from the DSP32C to the PC for each vertical line of the ionogram (682 values plus control information). This data must be further processed to determine the position and colour of the display pixels. To achieve this the values are scaled according to agc values derived from the RCS-5 – allowing the frequency dependant power in each propagating mode to be determined. The result may also be filtered, if required, to remove background clutter.

As the RCS-5 sweep progresses the ionogram produced by the PC builds up from left to right. A colour scale of absolute signal strength is displayed along with data collection details and path information. The highest quality ionogram generated by ROSE has a resolution of 836 × 682 points and contains 32 colours. To display this ionogram in full detail, along with its associated labelling, requires a SVGA display monitor with a resolution of 1024 × 768 pixels. However, to maintain compatibility with VGA monitors ROSE is able to automatically display ionograms at a lower resolution and using fewer colours. The full screen ionogram represents the normal display mode. In addition, an alternative mode is available whereby four ionograms are displayed simultaneously at a quarter of the normal resolution and are updated sequentially.

A high resolution ionogram of 836 vertical lines is based upon some 836 × 700 = 585 kwords = 1170 kbytes of data and represents a large amount of information to be stored. Observation of ionograms reveals that only a small proportion of the total display area contains relevant information while the rest is black background. By only recording the colours that appear on the screen file sizes can be reduced to 20 kbytes or less for a single ionogram. The disadvantage of the reduced files is that subsequent off-line processing of ionograms is limited since raw spectral information is sacrificed. ROSE allows ionograms to be saved using either of these formats depending upon whether detailed off-line processing of ionograms or small ionogram files are the priority.

The PC software also provides a number of features for handling ionogram information once it has been stored. In playback mode stored ionograms are displayed sequentially at a high rate to give a movie type of effect. In scaling mode a single ionogram may be recalled and cross-hair cursors used to log certain features of interest. Both of these modes are described in more detail below.

Examples of ionograms collected using ROSE are shown in figs. 4 and 5.

6. Analysis capability

A variety of analysis tools are provided for the display and manipulation of stored ionogram data. They are divided into two categories – those available in playback mode and those available in scaling mode.

Playback mode mimics the real-time data collection display using stored ionogram files. A group of files is selected from a descriptive menu and these are then displayed chronologically. The update rate is much faster than in the collection mode (typically about one second per ionogram) and can be frozen temporarily to allow for evaluation of a particular ionogram. The playback mode of operation is useful for quickly reviewing ionograms prior to a more detailed study and in this role may be used to perform a search within a set of ionograms for those with certain features of interest. Additionally, this mode is very useful for viewing temporal variations in the structure of ionospheric returns. The ionograms may be displayed singly at full screen size, thus allowing the full detail of high resolution ionograms to be realised and short term variations between successive ionograms to be viewed.

Alternatively, the ionograms may be displayed at one quarter screen size allowing four ionograms from one single transmitter or up to four different transmitters to be displayed simultaneously. This is useful for observing ionograms from different paths and for viewing longer term variations between ionograms. All these display options are also available in the data collection mode.

Scaling mode facilitates a more detailed appraisal of ionogram information. Ionograms are displayed singly at full screen size. Two cross-hair cursors are provided for manual scaling and are positioned on each ionogram using the mouse or keyboard. A readout of the centre of the cursors is given in terms of frequency (MHz) and relative group delay (ms) and defines a unique point on an ionogram. Points may be attributed to one of 30 scaling parameters listed on the screen (*e.g.* E LOF, $F2$ MOF (×)) and then saved prior to the selection of the next ionogram. Also provided is a bar chart displaying signal strength for all points along the vertical cursor. This gives a snapshot of the

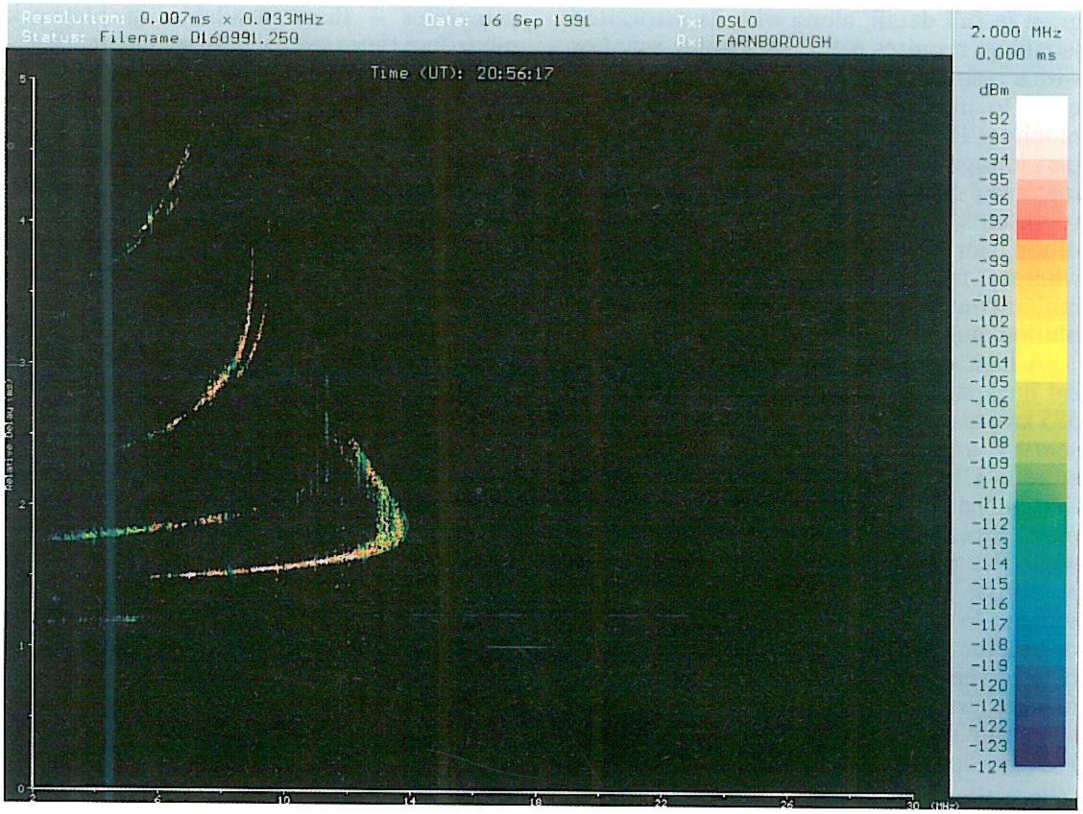

Fig. 4. High resolution colour ionogram collected using ROSE.

ionospheric returns at one particular frequency. Another feature permits the background to an ionogram to be changed from black to grey or white to allow certain colours to be viewed more easily – particularly important for high resolution ionograms. In addition, an ionogram which has been saved with all the raw spectral information preserved may be re-processed to produce an improved image. This involves specifying new values for the range of the magnitude scale and the filter setting. In this way the structure of the ionogram may be examined in close detail or the ionogram may be cleaned up to highlight the most important features.

7. Main features

A summary of the main features which make ROSE a valuable tool for detailed ionospheric research are listed below.

a) Ionograms displayed at high resolution (up to 33 kHz × 7.3 μs, or 836 × 682 points) so that propagating modes are clearly visible and fine structure is discernible.

b) Colour coding of signal power (up to 32 colours) against an absolute scale to enable amplitude comparisons across modes on a single ionogram and also comparisons between ionograms.

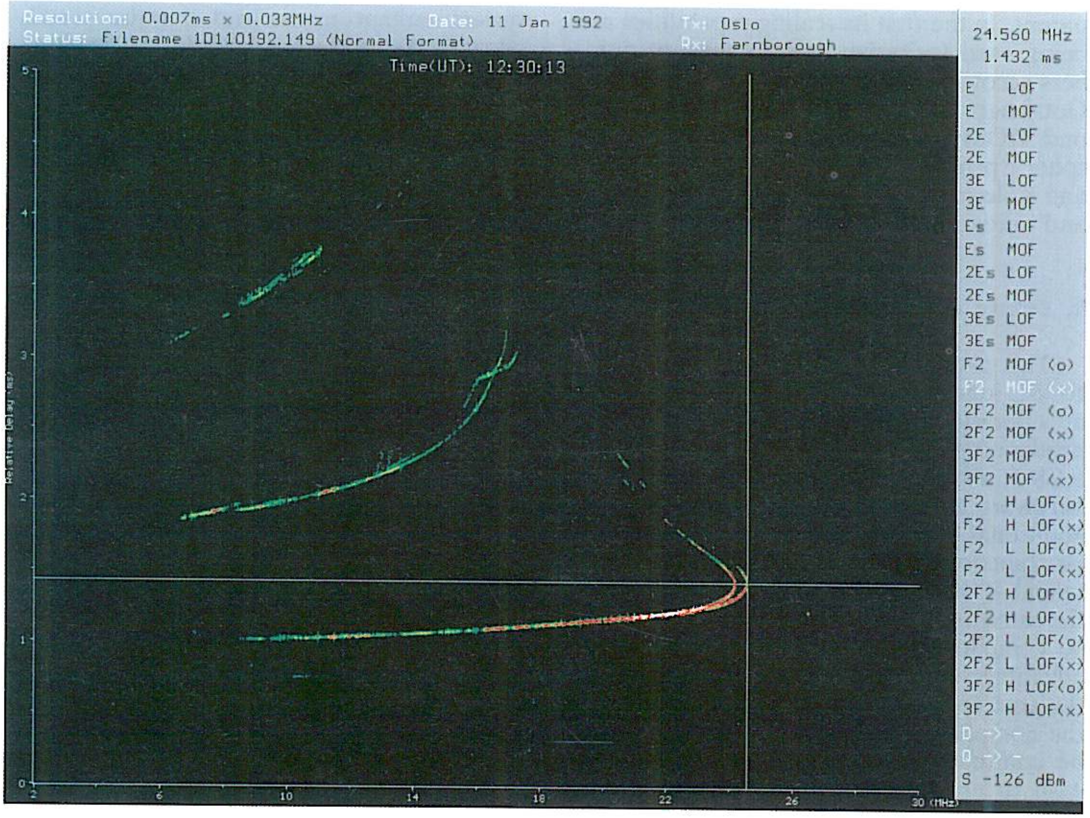

Fig. 5. High resolution colour ionogram collected using ROSE (scaling mode).

c) Full automation allowing ionograms to be collected and saved according to a specified schedule.

d) A choice of display modes to suit applications – based on single or four ionogram layouts.

e) Analytical functions allowing off-line processing of stored ionogram data (including manual scaling of ionograms).

8. Applications

The applications of ROSE are manifold but divide most conveniently into two; those relating directly to HF system operation and those relating to ionospheric measurements. In many cases, indeed very often, the latter are also carried out to support system operation.

An example of the former is the application of ROSE in lieu of the RCS-5 to provide the operator with information on the strongest propagating modes and frequencies, something which is difficult to do with the monochrome display of the RCS-5. ROSE can thus aid the operator to make the best frequency selections for his collocated communication system.

ROSE is currently being used in two fields relating to ionospheric measurements but a number of other applications are apparent. In the first its scaling capabilities are being used to derive pseudo sunspot numbers according to the technique described by Goodman and Daehler (1988). In the second ROSE is being used to derive ionospheric profiles using the technique of Reilly and Kolesar (1989) relating to the derivation and validation of ionospheric maps.

9. Future development

The production of the next generation ROSE ionosonde is currently underway and an operational prototype has already been produced. ROSE-300 will dispense with the RCS-5 sounder receiver, replacing it in hardware terms with an HF receiver and an additional DSP32C board. Again the familiar functionality of ROSE will be maintained – the operator interface will remain the same and the ionogram file structure will be compatible with ROSE-200. One major advantage of ROSE-300 will be in terms of the cost and, accordingly, the availability of the complete system. ROSE will no longer be confined to owners of the RCS-5 who wish to enhance the performance of their existing equipment. The opportunity will present itself for a much wider involvement within the scientific community as ROSE becomes affordable to researchers who currently have no ionospheric probing capability. ROSE-300 will also introduce a flexible architecture which will lend itself to future system enhancements and may be readily adapted to produce a sounder transmitter. This will allow changes in sweep rate and range (including sounding above 30 MHz) to be introduced to cater for particular scientific experiments. Furthermore, accurate signal time-of-flight measurements may be performed with the addition of time keeping by means of Navstar GPS (global positioning system).

It is anticipated that the introduction of ROSE-300 will considerably enhance the scientific value of the ROSE ionosonde.

REFERENCES

ARTHUR, P.C., A.H. DICKSON and P.S. CANNON (1991): ROSE - a high resolution, amplitude coded, high frequency oblique ionosonde, *AGARD EPP, Conference Proceedings*, N. 502, 10.

B.R. COMMUNICATIONS (1985): RCS-5 chirpsounder receiver, *Manual number*, 0040-2540-15001.

BARRY, G.H. and R.B. FENWICK (1969): Oblique chirp sounding, in *Oblique Ionospheric Radiowave Propagation, AGARD Conference Proceedings*, edited by T.B. JONES, N. 13, 487.

GOODMAN, J.M. and M. DAEHLER (1988): Use of oblique-incidence-sounders in HF frequency management, in *IEE 4th International Conference on HF Radio Systems and Techniques*, IEE, 284.

HUNSUCKER, R.D. (1991): *Radio Techniques for Probing the Terrestrial ionosphere* (Springer-Verlag).

REILLY, M.H. and J.D. KOLESAR (1989): A method for real height analysis of oblique ionograms, *Radio Sc.*, **24** (4), 575-583.

REINISCH, B. (1986): The digisonde 256 system and ionospheric research, in *INAG Ionospheric Station Inf. Bull.*, edited by R. HAGGARD, 48.