INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION

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SMR.380/21

COLLEGE ON THEORETICAL AND EXPERIMENTAL RADIOPROPAGATION SCIENCE

6 - 24 February 1989

LECTURE 5: OBLIQUE AND BACKSCATTER SOUNDING

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2. THEORY OF IONOSPHERIC RADIOPROPAGATION

Lecture 5: Oblique and backscatter sounding

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1. INTRODUCTION

Following from vertical-incidence sweep-frequency sounding two other related sounding techniques have been developed. In oblique-incidence sounding the transmitter and receiver are separated to opposite terminals of a path of interest and swept in synchronism. Backscatter sounding involves use of co-located or nearby transmitter and receiver coupled to antennas with relatively low elevation beams. Signals are received after scattering either directly from the ionosphere or from the ground following ionospheric reflection. Oblique sounding provides information about the state of the ionosphere and the raypaths it can support between the particular terminals considered. Backscatter sounding yields information both about the ionosphere and about ground 'targets' within the surveillance beam. Each can be deployed in real-time, though data interpretation often involves use of ionospheric and propagation prediction models.

2. OBLIQUE-INCIDENCE SOUNDING

2.1 General

A general review of the subject and of developments up to 1970 has been presented by Bradley et al (29). A regularly updated survey text is published by the CCIR (33). Bradley (32) in a recent report to an URSI Working Group examines future needs in oblique-sounding data interpretation and makes proposals for a coordinated measurement and analysis campaign and for the compilation of an extended atlas of ionogram types.

2.2 Historical Development

The development of oblique-incidence sounders had to wait the ability to synchronise the sweep of transmitter and receiver. One of the first sounders was produced at Slough by Wilkins and Kift. This took some 20 minutes to sweep the HF band in 50 kHz steps and involved a mechanical drive of the receiver tuning over a pre-arranged timing sequence. Transmitted pulses were received but often synchronisation was lost. Relative delay of the different modes was displayed as a function of frequency. On very short paths the ground wave was available as a timing reference, but more generally attempts at quantifying signal absolute path propagation times by transmitting in both directions or seeking to link to a station timing reference were rarely successful. Early measurements were made in USA (1, 122, 126, 138), Federal Republic of

Germany (45, 96, 97, 101), Canada (70,80) and Japan (7). With the advent of synthesiser controlled oscillators, chirp sounders became available and data record quality improved considerably. Nowadays commercially manufactured sounder equipments incorporate display facilities that include signal/noise ratio and best assigned channels for communication frequency selection (15, 16). Ship-borne sounders have been deployed operationally (77).

2.3 Data Obtained

Examples of oblique-incidence ionograms are presented. Typically the critical frequency cusp at vertical incidence becomes a 'nose' or 'wedge' which is shallower the longer the propagation path. Each mode has its own trace with particular group delays. The low and high-angle rays merge at the junction frequency. The ordinary and extraordinary waves have separate junction frequencies. The junction frequency is akin to the basic maximum usable frequency (basic MUF) defined by the CCIR as the highest frequency that can propagate between a pair of terminals by refraction alone (34). Nose extensions occur as a result of scattering by ionospheric irregularities, which may involve propagation out of the great circle, or from the effects of ionisation gradients leading to two separate ionospheric reflection regions for the same propagation mode.

Atlases of ionogram types have been published (2, 96). Generally records become more complicated the longer the path (9), particularly at high latitudes (17) where additional propagation effects arise (74) and on paths crossing the equator. The most extensive synoptic data sets of oblique-incidence ionograms are those collected by Moller over the high-latitude path Sodankyla-Lindau (96) and the transequatorial path Tsumeb-Lindau (101). Internationally agreed rules for scaling parameters from oblique-incidence ionograms have been formulated (43, 46). A data base of ionograms and associated scalings from measurements collected by NRL over several paths has been formulated (62).

2.4 Ionogram Interpretation

Oblique-incidence ionograms may be simulated by ray-tracing through model distributions of electron density. General features can be studied with simple ionospheric models and basic ray-tracing procedures. Croft (37) has demonstrated the way ionograms depend on path length, layer height and densities. He has taken single and composite quasi-parabolic layers and generated families of ionograms. On the basis of Snell's law theory and in the absence of horizontal gradients simple analytical expressions for these models yield ground range and group path as a function of raypath launch angle. To model the ordinary and extraordinary wave traces separately, the ray tracing must take account of the Earth's magnetic field, but otherwise this is only necessary at frequencies below 5 MHz. By allowing for horizontal gradients with discrete patches of ionisation at particular ranges, Kopka and Moller (84) have been able to simulate and explain various otherwise anomalous records.

2.5 Comparisons With Propagation Predictions

Many organisations undertake HF radio-circuit propagation predictions and there are a number of standard prediction procedures such as those of the CCIR in worldwide use. Various groups have analysed data sets of oblique soundings and made comparisons with such predictions (eg 92). Analyses are usually concerned with differences between the predicted basic MUF and the measured junction frequency. Even allowing for the fact that the predictions are usually monthly median values requiring adjustment by some statistical day-to-day variability factor, they are commonly some 10-50% too low. This means that propagation often with high signal strengths is possible at frequencies greater than predicted. The operational MUF is defined (34) as the highest frequency providing acceptable performance for a particular radio circuit. Comparisons with maximum observed frequencies on ionograms show that often when intense sporadic-E ionisation is present and not included in the predictions this mode could be used to advantage for communication paths at frequencies considerably above the junction frequency for the regular F-modes.

2.6 Inversion Of Oblique-Incidence Ionograms

As an inverse operation to ionogram simulation (section 2.4) various techniques have been developed to relate ionograms to equivalent midpath electron-density distributions (49, 57, 60, 85, 112, 124). In some cases particular model distributions are assumed (eg 51, 94) and the inversion yields the appropriate values of the model parameters; in others the inversion gives an arbitrary height distribution. Most inversions ignore the effects of ionisation gradients. There has been much past controversy whether more than one ionospheric profile can yield the same oblique ionogram. It is nowadays usually accepted that the inversion gives an equivalent midpath profile. In the absence of a complete ionogram trace this is one of a number of possible solutions.

Clearly electron-density profiles derived from oblique-incidence ionograms complement those determined from vertical soundings and are potentially most valuable in synoptic ionospheric mapping studies where existing vertical sounders are spaced too far apart. Techniques for the automatic inversion to true-height profiles of vertical-incidence ionograms are now in routine use and are being refined (55, 113). These involve advanced signal processing and pattern-recognition algorithms. Proposals for the corresponding automatic identification of weak oblique-incidence ionogram traces in the presence of noise and interference were made some years ago (87). Work is now in progress in the USA (and perhaps also elsewhere) for the full automatic inversion of oblique ionograms.

2.7 Operational Sounding Systems

Clearly an oblique-incidence ionogram is a useful aid to a radiocommunicator in indicating those frequencies with strong signals and least multipath. In the 1960's pulse sounders were sold commercially particularly to military users and there were considerable fears for the spectral pollution the proliferation of these equipments would cause. The common user radio transmission system (CURTS) was set up in the US involving coordinated sounding over a number of paths with a central control point distributing information on best frequencies to use within the area (108). Generally though circuit operators became disillusioned with such systems because: (i) these often used different antennas and powers so that their data were not directly equivalent (ii) difficulties in record interpretation for selection of optimum frequencies (iii) failure for conditions on paths being sounded to apply over adjacent paths and extended time periods and (iv) equipmental difficulties and complexities.

These problems are now understood and a next generation of more portable chirpsounders with more relevant operator displays is in use. There is greater appreciation of spatial correlations of ionospheric changes. Techniques involving ionogram inversions and the up-dating of long-term propagation predictions with near real-time oblique-sounder data are being examined. A group at the Naval Research laboratory USA is very active in this area and has conducted a number of operational trials (61, 67, 132, 133, 134).

2.8 The Future

Commercial sounders continue to be used in support of radio links but on an ad-hoc basis with few permanent ionogram records being taken. Progress in automatic inversion holds promise as the next major breakthrough. There is still scope for improving existing atlases of ionograms and of synthesising abnormal records that occur from time to time.

3. BACK-SCATTER SOUNDING

3.1 General

Besides the standard CCIR texts on this subject (35, 36) the reader is referred particularly to the major treatise by Croft (41) published in 1972. Headrick and Skolnik (71) and Shearman (119) discuss over-the-horizon radars (operational equipments as opposed to experimental facilities) and a recent book by Kolosov (81) reviews design considerations and gives details of current US and USSR systems.

3.2 Historical Development

It was early discovered with high-power pulse transmitters coupled to low beam antennas that detectable echoes were received by ground scattering following ionospheric reflection. The amplitudes of the returns could be interpreted in terms of the so-called radar equation as being inversely proportional to the fourth power of the path length and directly proportional to the effective scattering cross-sectional area. Classical measurements of the relative scattering cross sections of land and sea surfaces were conducted by Ranzi and Dominici (109).

Several groups engaged in oblique point-to-point sounding in the early 1950's also undertook backscatter studies using home-built equipments. First installations examined temporal changes on a single or small number of fixed frequencies (68, 82, 107). These were followed by sweep-frequency systems (90, 117, 123). Skip focusing was evident in the returns and the way the skip position changed with time and frequency was studied.

The mechanism of F-layer propagated ground backscatter echoes was outlined by Peterson (105) and Shearman (116). Separate leading edge echoes were attributable to ionospheric support via the F, E and Es layers. The advantages of the technique for synoptic monitoring ionosphere state have been discussed by a number of workers (115, 135, 139). The relationship to vertical-incidence sounding was examined by Dominici (47). The potential use of backscatter sounding as an aid to communications frequency management has been highlighted (19, 24).

For general ionospheric surveying, physically rotating antenna systems such as stacks of dipoles were deployed in conjunction with PPI displays: these tended to be single-frequency installations. A major problem with early backscatter systems, particularly the rotating types, was that antenna azimuthal beamwidths were too wide, resulting in echoes being received from a range of directions including in some cases the backlobes.

Chirpsounder techniques were introduced to backscatter systems and this led to bistatic installations with transmitter-receiver separations of 50-100 km in order to avoid direct signal breakthrough. Antenna steering was effected electronically through the use of phased arrays. Narrow-sweep chirps and Doppler signal processing permitted the resolution of scatter signals from fixed and moving targets. In 1969 Blair and colleagues demonstrated convincingly the mapping of land-sea boundaries (27, 28). Then followed the realisation that distant ocean waves, ships and aircraft all could be monitored by means of backscatter sounding and so the era of modern over-the-horizon radars was born.

3.3 Ionospheric Structure Inferred From Backscatter Ionograms

Undoubtedly the interpretation of backscatter ionograms is more complex than that of oblique-incidence ionograms. Indeed a backscatter ionogram can be regarded as the composite of a large number of (two-way) oblique-incidence ionograms each to different ground scattering centres. There are complications in that the positions and numbers of such centres are unknown and that echoes can also arise by direct scattering from ionospheric irregularities without hitting the ground. For bistatic systems there can be significant differences for the outwards and return paths.

Ionogram features are discussed by Barclay (10) and a terminology for backscatter modes has been proposed by Bartholomew (18). Early studies were concerned with the incidence of sporadic-E as determined from the characteristics of ground scatter signals (118, 128) and with other aspects of ionospheric structure (20, 50), including ionospheric tilts (95) and motions (127, 130). Controversy centred on the extent to which Doppler frequency shifts imparted to the backscatter signal by ionospheric movements compared with those on a corresponding one-way fixed path (3). Typical ionospheric Doppler shifts and spreads for backscatter are quoted by Earl and Bourne (52) and by Jones et al (79).

It cannot be stressed too strongly that ionogram interpretation is aided considerably by having narrow-beam antenna systems, but these are expensive. Limited use has been made of elevation steering (131) but this has not been widely adopted largely because of cost and complexity, coupled with lack of frequency and azimuth agility. Ray tracing through appropriate ionospheric models has been employed to simulate backscatter records (38, 40, 58, 73, 75, 76, 88, 111). Usually single-hop modes only are considered and emphasis is placed on recording and identifying the leading edge of the backscatter for each of those modes present. Amplitudes can be synthesised with an appropriate propagation loss model (39). In some cases the effects of horizontal ionisation gradients are introduced (99).

Allied to simulation is backscatter ionogram inversion to the corresponding electron-density distributions. Hatfield (69) has shown the

advantages to inversion techniques in having available associated elevation angle measurements, particularly to allow for horizontal gradients. Other inversion approaches have been developed (26, 48, 110). Automatic signal-processing techniques for record identification have been proposed (114).

Bates made a number of studies of direct scattering from sporadic-E irregularities (22) and from F-region irregularities (21). He showed that the scattering is highly aspect sensitive with strongest returns when the radio path is normal to the irregularities which tend to be field aligned (25). Further results have been reported by other workers (8, 56, 63, 83, 106, 129). Direct ionospheric scattering occurs from places where rays are refracted to the condition of perpendicularity and there are irregularities present.

3.4 Remote Sensing

Besides the study of the ionosphere, backscatter techniques also yield information about ground scatter characteristics. This involves discriminating the wanted signal 'target' from the background 'clutter'. Sloping striations seen on swept-frequency backscatter ionograms were interpreted by Moller and Steiwitt (98) and by Muldrew (102) as interference effects arising from scattering by ocean waves. Crombie (42) demonstrated experimentally for HF ground waves that signals are subjected to Bragg scattering from sea waves, with most energy concentrated in a pair of spectral lines Doppler offset by a fraction of a Hertz either side of the carrier frequency. The precise offset depends on the carrier frequency (136); the spectral lines arise from resonant scattering by those components of the ocean wave directional spectrum approaching or receding along the antenna boresight direction. Stewart and Barnum (125) have shown how the relative amplitude of the two lines gives an indication of the strength and direction of the wind generating the waves. A more detailed analysis which takes account of second-order effects has been presented by Lipa and Barrick (86).

Throughout the 1970's groups built installations to monitor sea state using both ground-wave and sky-wave. An important requirement is to have narrow antenna beams that can be steered. Hence ground-wave systems are usually erected near the coast and operate at low VHF; sky-wave systems are limited in upper frequency by ionospheric support. There are also the added complications of ionospheric corruption of the sea spectra. Sky-wave sounders tend to be built several hundred kilometres inland to avoid use of the lower frequencies for which antenna beamwidths are wider and because multiple modes are a major problem at the shorter distances. Research facilities were established in a number of countries using antenna arrays the orders of 300m-2km long with beam steering for different directions of surveillance (4, 6, 23, 64, 65, 137, 140). Data obtained have been described in many papers and the reader is referred to a selection of these (5, 13, 14, 59, 78, 89, 120).

Barnum (12) has demonstrated that ships can be detected against the background sea clutter and tracked by their differing Doppler. Ship Dopplers are a few tenths of a Hertz depending on sounder frequency and ships heading relative to antenna boresight. Coherent integration times of several tens of seconds are needed. Aircraft also can be detected by HF backscatter. Although their effective scattering cross sections are much less than those of ships their speeds are such that they give

Doppler offsets of up to tens of Hertz so that returns are resolved from the sea clutter. For aircraft monitoring integration times of just a few seconds are needed.

3.5 Operational Radar Systems

Probably the first operational radar for detecting aircraft was the British 'Chain Home' link used in World War II (103). Current interest in over-the-horizon radar for military surveillance stems from requirements to provide long-distance coverage for air and sea defence, coupled with a belief that current technology now permits systems to be developed at a fraction the cost of alternative sensors. Any such radar is likely to involve: high transmitter powers for good detection capability of weak targets, narrow antenna beams to aid target location and minimise clutter, frequency agility coupled with spectral monitoring, advanced signal processing including tracker algorithms for rapid analysis of the radar returns and dedicated reliable communication links for data dissemination. Such systems are known to be currently under development in the USA (66) and in Australia(44).

There are many limitations in the use of over-the-horizon radars besides cost. Propagation effects are undoubtedly of over-riding importance (11, 30, 91, 121). Deployment at high latitudes poses further problems. In this case, besides the need to use lower frequencies because of the less dense ionisation, direct ionospheric clutter is more common; also, greater ionospheric frequency spreads must be contended with (31, 100, 104). Plasma instabilities can be generated by high power waves (72) leading to additional clutter, so that the expected improved detection capability with increase of transmitter power is not always achieved.

Radar design has to be given particular attention. A good propagation and system-performance assessment model is a necessary pre-requisite. Frequency management for optimum illumination of wanted targets and ways of transforming from radar to ground coordinates for position finding pose especial problems. Various approaches are currently being considered (53, 54). It seems likely that the adopted solution will incorporate some form of real-time ionospheric channel sounding: a separate mini-radar, an oblique point-to-point sounder, the use of networks of transponders or merely a vertical sounder at the radar site for the up-date of long-term propagation predictions.

3.6 The Future

The promise of the 1960's of backscatter sounding as an aid to point-to-point communications and broadcasting did not materialise, largely because of cost to achieve narrow beamwidths and difficulties of data interpretation. The promise of the 1970's of synoptic sky-wave sea-state sensing over large ocean regions also has not been fulfilled. Systems were built at considerable expense but the difficulties of area surveillance largely without frequency agility, data ambiguities, ionospheric corruptions and signal processing complications have now led to their demise. Over-the-horizon radars have been considered for use in such roles as air traffic control but expense would be great and reliability not guaranteed: there are other preferable options for the turn of the century, based on satellite-monitoring systems.

Radars look like being pursued further solely by the military, though it is a personal view that ultimately they too will become disillusioned with what can be achieved. Radar design should be optimised to meet well-defined objectives. For example, there have to be compromises regarding surveillance area coverage and dwell cycling which affect antenna design, signal processing and Frequency-management strategies. Clutter limits target detectability. Changes in target signatures and amplitudes coupled with variation in background intensities make detection a statistical event. Multimode propagation causes excessive numbers of false detections. So long as operational over-the-horizon radars are seen as extensions of general-purpose research facilities, they too will fail to satisfy.

REFERENCES

1. Agy V and Davies K, 'Ionospheric investigation using the sweep-frequency pulse technique at oblique incidence', J Res NBS, 63D (2), 151-174 (1959).

2. Agy V, Davies K and Salaman R, 'An atlas of oblique-incidence ionograms', Nat. Bur, Stds. Technical Note 31 (1959).

3. Agy V, 'Doppler shifts on high frequency ground backscatter', J Geophys Resch, 74(1), 273-277 (1969).

4. Anderson S J, 'Remote sensing with the JINDALEE skywave radar', IEEE J Ocean Eng, OE-11(2), 158-163 (1986).

5. Anderson S J, 'Advanced techniques for remote sensing of ocean surface conditions with HF sky-wave radar', IEE Conf Proc 607-612 (1987).

6. Anderson S J and Lees M L, 'High resolution synoptic scale measurements of ionospheric motions with the JINDALEE radar', Ionospheric effects symposium, Naval Research Laboratory, 3A-2 (1987).

7. Aono Y, 'Study of radio wave propagation in sweep frequency pulse transmission tests in Japan', J Radio Resch Labs (Japan) 9(42), 127-200 (1962).

8. Baker K B, Greenwald R A and Tsunoda R T 'Very high latitude F region irregularities observed by HF radar backscatter', Geophys Res Lett, 10,904 (1983).

9. Balser M and Smith W B, ' Some statistical properties of pulsed oblique HF ionospheric transmissions', J Res NBS, 66D (6), 721-730 (1962).

10. Barclay L W, 'Some features of HF backscatter ionograms', AGARD Conf Proc, 4-1 (1968).

11. Barnum J R 'Skywave polarisation rotation in swept-frequency sea backscatter', Radio Sci, 8, 411-423 (1973).

12. Barnum J R 'Ship detection with high resolution HF skywave radar', IEEE J Ocean Eng OE-11(2), 196-209 (1986).

13. Barrick D E, Headrick J M, Bogle R W and Crombie D D, 'Sea backscatter at HF: interpretation and utilisation of the echo', Proc IEE, 62, 673-680 (1974).

14. Barrick D E and Snider J B, 'The statistics of HF sea-echo Doppler spectra', IEEE trans AP-25(1), 19-24 (1977).

15. Barry G H and Fenwick R B, 'Oblique chirp sounding', AGARD Conf Proc 13, 487-502 (1969).

16. Barry G H and Fenwick R B 'Techniques for real-time HF channel measurement and optimum data transmission', AGARD Conf Proc 173, 15-1 to 15-10 (1976).

17. Bartholomew R 'Some results of an oblique-incidence pulse-sounding HF (4-to-64 MHz) experiment between Andoya, Norway and College, Alaska', AGARD Conf Proc 13, 451-466 (1969).

18. Bartholomew R 'A proposed terminology for ionospherically propagated backscatter modes', AGARD Conf Proc 13, 467-470 (1969).

19. Bartholomew R R, 'Use of backscatter measurements to improve HF communication predictions' in 'Ionospheric Forecasting' ed V Agy, AGARD Conf Proc 49 14 (1969).

20. Basler R P and Scott T D, 'Ionospheric structure from oblique-backscatter soundings', Radio Sci, 8(5), 425-429 (1973).

21. Bates H F, 'Direct HF backscatter from the F region', J Geophys Res, 65(7), 1993-2002 (1960).

22. Bates H F 'Some effects of dense Es clouds on high-latitude HF backscatter observations', J Geophys Res, 70(23), 5895-5905 (1965).

23. Bates H F 'A proposed polar auroral radar system', J Atmos Terr Phys, 28, 903-907 (1966).

24. Bates H F 'On using direct backscatter to predict communications', Proc IEEE, 54(10), 1457-1458 (1966).

25. Bates HF and Albee P R, 'Aspect sensitivity of F-layer HF backscatter echoes', J Geophys Res, 75, 165 (1970).

26. Bertel L E, Cole D G and Fleury R 'The inversion of backscatter ionograms', Ionospheric Prediction Service Sydney, Technical Report IPS-TR-88-03 (1988).

27. Blair J C, Hunsucker R D and Tveten L H, 'Ionospheric mapping by backscatter', AGARD Conf Proc 49, 17- (1969).

28. Blair J C, Melanson L L and Tveten L H, 'HF ionospheric radar ground-scatter map showing land-sea boundaries by a spectral separation technique', Electron Letters 5(4) (1969).

29. Bradley P A, Eccles D and King J W, 'Ionospheric probing using pulsed radiowaves at oblique incidence', J Atmos Terr Phys, 32, 499-516 (1970).

30. Bradley P A, Bramley E N, Gibson A J and King J W, 'Ionospheric factors affecting the performance of HF sky-wave seastate radars, AGARD Conf Proc 345, 13-1 to 13-10 (1983).

31. Bradley P A, Gibson A J, Schlobolm J C and Westover D E, 'Ionospheric factors affecting the performance of HF sky-wave seastate radars at high latitudes, AGARD Conf Proc 382, 4.1 (1985).

32. Bradley P A, 'Oblique propagation Studies', Advances in Space Research - to be published (1989).

33. CCIR, Report 249, 'Ionospheric sounding at oblique incidence', International Telecommunication Union, Geneva (1986).

34. CCIR, Recommendation 373, 'Definitions of maximum transmission frequencies', International Telecommunication Union, Geneva (1986).

35. CCIR, Report 726, 'Ground and ionospheric side-and-backscatter', International Telecommunication Union, Geneva (1986).

36. CCIR, Report 890, 'The operational use of sidescatter and backscatter', International Telecommunication Union, Geneva (1986).

37. Croft T A, 'The synthesis of oblique ionograms by digital computer', Stanford Electronics laboratories Tech Rept 89 (1964).

38. Croft T A, 'The synthesis of sweep-frequency ground backscatter by digital computer', Stanford Electronics Lab Tech Rept 84 (1965).

39. Croft T A, 'Computation of HF ground backscatter amplitude', Radio Sci, 2, 739 (1967).

40. Croft T A, 'The influence of ionospheric irregularities on sweep-frequency backscatter', J Atmos Terr Phys, 30, 1051-1063 (1968).

41. Croft T A, 'Sky-wave backscatter: a means for observing our environment at great distances', Rev Geophys and Space Phys, 10(1), 73-155 (1972).

42. Crombie D D, 'Doppler spectrum of sea echo at 13.56Mc/s', Nature, 175, (4459), 681-682 (1955).

43. Davies K, 'The description of oblique ionograms' in 'Spread F and its effect on Radio Propagation', AGARD Conf Copenhagen (1964).

44. Desmond S, 'Over the horizon radar in defence of Australia', Electronics Today 8(2), 35-40 (1978).

45. Dieminger W and Moller H G, 'Echo sounding experiments with variable frequency at oblique incidence', Nuova Cimento, Suppl 4, Serie X, 1532-1545 (1956).

46. Dieminger W, 'Oblique incidence soundings of the ionosphere', IQSY Notes 4, 25-33 (1963).

47. Dominici P, 'Confronto tra sondaggi ionosferico per retrodiffusione e sondaggi verticali', Associazione Geofisica Italiana Atti dell' VIII Convegno Annule, Roma: 12-14 febbraia, 159-164 (1959).

48. Du Broff R E, Rao N N and Yeh K C, 'Backscatter inversion in spherically asymmetric ionosphere', Radio Sci, 14(5) (1979).

49. Du Broff R E, Rao N N and Yeh K C, 'Methods of determining ionospheric structure from oblique sounding data', AGARD Conf Proc 263, 13-1 to 13-16 (1979).

50. Dueno B, 'Interpretation of some sweep-frequency backscatter echoes', J Geophys Res 68, 3603-3610 (1963).

51. Dyson P L and Bennett J A, 'A model of the vertical distribution of the electron concentration in the ionosphere and its application to oblique propagation studies', J Atmos Terr Phys, 50(3), 251-262 (1988).

52. Earl G F and Bourne I A, 'Spectral characteristics of HF ground backscatter', J Atmos Terr Phys, 37, 1339-1347 (1975).

53. Earl G F and Ward B D, 'Frequency management support for remote sea-state sensing using the JINDALEE sky-wave radar', IEEE J Ocean Eng, OE-11(2) 164-173 (1986).

54. Earl G F and Ward B D, 'The frequency management of the JINDALEE over-the-horizon backscatter HF radar', Radio Sci, 22(2), 275-291 (1987).

55. Fox M W, 'Automatic ionogram scaling at IPS', Ionospheric Prediction Service Australia, Technical Report IPS-TR-88-04 (1988).

56. From W R and Whitehead J D, 'Es structure using an HF radar', Radio Science, 21(3), 309-312 (1986).

57. George P L, 'True height analysis of oblique incidence HF radio wave data', J Atmos Terr Phys, 32, 905-916 (1970).

58. Georges T M and Stephenson J J, 'HF radar signatures of traveling ionospheric irregularities, 3D ray-tracing simulation', Radio Sci, 4, 679-696 (1969).

59. Georges T M and Maresca J W, 'The effects of space and time resolution on the quality of sea-echo Doppler spectra measured with HF skywave radar', Radio Sci, 14, 455-469 (1979).

60. Gething P J D, 'The calculation of electron density profiles from oblique ionograms', J Atmos Terr Phys, 31, 347-354 (1969).

61. Goodman J M, Daehler M, Reilly M H and Martin A J, 'A commentary on the utilisation of real-time channel evaluation systems in HF spectrum management', NRL Memorandum Report 5454 (1984).

62. Goodman J M and Daehler, 'The NRL data base of oblique-incidence soundings of the ionosphere', NRL Report (1989).

63. Greenwald R A and Baker K B, 'Observations of very high latitude ionospheric irregularities with the Goose Bay HF radar', AGARD Conf Proc 382, 4.5 (1985).

64. Greenwald R A, Baker K B Hutchins R A and Hanuise C, 'An HF phased-array radar for studying small-scale structure in the high-latitude ionosphere', Radio Sci, 20(1), 63-79 (1985).

65. Greenwald R W, Weiss W, Nielsen E and Thomson N R, 'Stare: A new radar auroral backscatter experiment in Northern Scandinavia', Radio Sci, 13, 1021-1039 (1978).

66. G E, 'New radar installations promise 360-degree air defense perimeter', Aviation Week and Space Technology, December 9 (1985).

67. Harnish L O and Hagn G H, 'A comparison of MOF factors and frequency of optimum transmission bands observed using oblique-incidence sounders with sounder-updated PROPHET predictions for a one-month test in the continental United States during the geomagnetically active summer of 1982', Radio Sci, 20(3), 269-279 (1985).

68. Hartsfield W L, Ostrow S M and Silberstein R, 'Back-scatter observations by the Central Radio Propagation Laboratory - August 1947 to March 1948', J Res NBS, 44(2), 199-214 (1950).

69. Hatfield V E, 'Derivation of ionospheric parameters from backscatter data' in 'Ionospheric Forecasting', Ed V Agy, AGARD Conf Proc 49, 16-1 (1969).

70. Hatton W L, 'Oblique sounding and HF radiocommunication', IRE Trans Comm Systems PGCS-9, 275 (1961).

71. Headrick J M and Skolnik M I, 'Over-the-horizon radar in the HF band', Proc IEEE, 62(6), 664-673 (1974).

72. Hedberg A, Derblom H, Thide B, Kopka H and Stubbe P, 'Observations of HF backscatter associated with the heating experiment at Tromso', Radio Sci, 18(6), 840-850 (1983).

73. Hunsucker R D and Iveten L H, 'Large traveling ionospheric disturbances at midlatitudes utilizing the high-resolution HF backscatter technique', J Atmos Terr Phys, 29, 909- (1967).

74. Hunsucker R D and Bates H F, 'Survey of polar and auroral region effects on HF propagation', Radio Sci, 4(4), 347-365 (1969).

75. Hunsucker R D, 'Characteristic signatures of the midlatitude ionosphere observed with a narrow-beam HF backscatter sounder', Radio Sci, 6 535- (1971).

76. Hunsucker R D, 'Analysis of a backscatter signature obtained with a high resolution HF radar system', Radio Sci, 6, 763 (1971).

77. Ichinose M, Kuratani Y and Yamazaki I, 'HF propagation experiments made with chirpsounder aboard a ship', J Radio Resch Labs (Japan) 32, 136, 61-71 (1985).

78. IEEE, Special issue on high frequency radar for ocean and ice mapping and ship location, IEEE Trans Ocean Eng, OE-11(2) (1986).

79. Jones R M, Riley J P and Georges T M, 'Measured ionospheric Doppler spreading of HF ground backscatter', National Oceanic and Atmospheric Administration Technical Memorandum ERL WPL-109 Boulder, Co (1983).

80. Jull G W, Doyle D J and Murray J P, 'Frequency sounding techniques for HF communications over auroral paths', Proc IRE, 50(7), 1676-1682 (1962).

81. Kolosov A A, 'Over-the-horizon radar', Artech, Norwood, MA 02062 (1987).

82. Kono T, 'Experimental study on scattered echoes 1 and 2', Report of Ionospheric Research in Japan, IV(3) 127-135 and (4) 189-199 (1950).

83. Kopka H and Moller H G, 'Backscatter observations from distant field-aligned irregularities', AGARD Conf Proc, 58-1 (1968).

84. Kopka H and Moller H G, 'Interpretation of anomalous oblique sweep-frequency records using ray tracing', Radio Sci, 3(1), 43-51 (1968).

85. Krasheninnikov I V and Liannoy B E, 'Inversion techniques for determining the electron density profile from oblique incidence ionograms', Adv Space Res 8(4), 83 (1988).

86. Lipa B J and Barrick D E, 'Extraction of seastate from HF radar sea echo: mathematical theory and modelling', Radio Sci, 21, 81-100 (1986).

87. Lomax J B, 'Automatic analysis of oblique-incidence sounder data', AGARD Conf Proc 13, 503-524 (1969).

88. Maliphant R G, 'HF ground backscatter analysis with the aid of computer ray tracing', AGARD Conf Proc 37, 7-1 (1968).

89. Maresca J W and Barnum J R, 'Measurement of oceanic wind speed from HF seascatter by sky-wave radar', IEEE Trans AP-25, 132 (1977).

90. McCue C G, 'High frequency backscatter observations at Salisbury, S Australia', Australian J Phys, 9, 454-470 (1956).

91. Millman G H, 'Ionospheric propagation effects on HF backscatter radar measurements', Ionospheric effects symposium, NRL Arlington (1978).

92. Millman G H and Swanson R W, 'Comparison of HF oblique transmissions with ionospheric predictions', Radio Sci 20(3), 315-318 (1985).

93. Millman G H, 'An ionospheric model for HF sky-wave backscatter radar' in 'Ionospheric structure and variability on a global scale and interactions with atmosphere, magnetosphere' AGARD Conf Munich, 16-20 May (1988).

94. Milsom J D, 'Exact ray path calculations in a modified Bradley/Dudeney model ionosphere', Proc IEE, 132H, 33-38 (1985).

95. Mir A, 'Elevation angles of ground backscatter at 16 MHz and large-scale ionospheric tilts', Australian J Phys, 22, 435-441 (1969).

96. Moller H G, 'Variable-frequency pulse transmission tests at oblique incidence over distances between 1000 and 2000 km', Stanford Research Institute, Menlo Park, California (1964).

97. Moller H G, 'Oblique sweep-frequency experiments over a 2000 km north-south subauroral path', Radio Sci 2(1), 77-86 (1967).

98. Moller H G and Steiwitt, 'Phase path differences observed by sweep-frequency backscatter measurements', AGARD Conf Proc 33, 521-533 (1970).

99. Moller H G, 'Backscatter results from Lindau 2. The movement of curtains of intense irregularities in the polar F-layer', J Atmos Terr Phys, 36, 1487-1501 (1974).

100. Moller H G and Taurianen A, 'Observations of intense irregularities in the polar F-region by HF backscatter and satellite scintillation measurements', J Atmos Terr Phys, 37, 161-167 (1975).

101. Moller H G, 'Sweep frequency propagation on a 8000 km transequatorial north-south path', AGARD Conf Proc 173, 13-1 to 13-7 (1976).

102. Muldrew D B, 'Interference patterns in HF signals backscattered from ocean waves', AGARD Conf Proc 37, 8-1 (1968).

103. Neale B T, 'CH-the first operational radar', GEC J of Research, 3, 73-78 (1985).

104. Oksman J, Moller H G and Greenwald R, 'Comparisons between strong HF backscatter and VHF radar aurora', Radio Sci, 14(6), 1121-1133 (1979).

105. Peterson A M, 'The mechanism of F-layer propagated backscatter echoes', J Geophys Res, 56, 221 (1951).

106. Peterson A M, Villard O G and Leadabrand R L, 'Regularly observable aspect-sensitive radio reflections from ionisation aligned with the earth's magnetic field and located within the ionospheric layers at middle latitudes', J Geophys Res, 60, 497-512 (1955).

107. Peterson A M, Egan R D and Pratt D S, 'The IGY three-frequency backscatter sounder', Proc IRE, 47(2), 300 (1959).

108. Probst S E, 'The CURTS concept and current state of development' in 'Ionospheric Radio Communications' Plenum Press, NY, 370-379 (1968).

109. Ranzi I and Dominici P, 'HF backscatter from land and sea', Scientific Note 1, Centro Radioelettrico Sperimentale, 'G Marconi', Roma (1959).

110. Rao N N, 'Inversion of sweep-frequency sky-wave backscatter leading edge for quasi-parabolic ionospheric layer parameters', Radio Sci, 9(10) (1974).

111. Rao N N, 'Analysis of discrete oblique ionogram traces in sweep frequency sky-wave high resolution backscatter', Radio Sci, 10(2) (1975).

112. Reilly M H, 'Ionospheric true height profiles from oblique ionograms', Radio Sci, 20(3), 280-286 (1985).

113. Reinisch B W and Huang X, 'Automatic calculation of electron density profiles from digital ionograms:3, processing of bottomside ionograms', Radio Sci, 18, 1477-1492 (1983).

114. Shaver H N, 'Signal processing techniques for backscatter ionograms' in 'Ionospheric Forecasting' ed V Agy, AGARD Conf Proc 49, 15-1 (1969).

115. Shearman E D R, 'A study of ionospheric propagation by means of ground backscatter', Proc IEE, 103B, 203-209 (1956).

116. Shearman E D R, 'The technique of ionospheric investigation using ground backscatter', Proc IEE 103B, 210-223 (1956).

117. Shearman E D R and Martin L T J, 'Backscatter ionospheric sounder', Wireless Engr, 33, 190 (1956).

118. Shearman E D R and Harwood J, 'Sporadic-E as observed by backscatter techniques in the United Kingdom', J Atmos Terr Phys 18, 29 (1960).

119. Shearman E D R, 'Radar looks over the edge', IEEE Spectrum, 67, 13-15 (1969).

120. Shearman E D R, Sandham W A, Bramley E N, and Bradley P A, 'Ground-wave and sky-wave sea-state sensing experiments in the UK', AGARD Conf Proc 263, 30-1 to 30-10 (1979).

121. Shearman E D R, 'A review of propagation and scattering factors in remote sensing and ship tracking by HF radars', AGARD Conf Proc 345, 12-1 (1983).

122. Silberstein R, 'Oblique incidence propagation work of the CRPL', J Geophys Res, 54, 288 (1949).

123. Silberstein R, 'The use of sweep-frequency backscatter data for determining oblique-incidence ionospheric disturbances', J Geophys Res, 63(2), 335-351 (1958).

124. Smith M S, 'The calculation of ionospheric profiles from data given on oblique incidence ionograms', J Atmos Terr Phys, 32, 1047-1056 (1970).

125. Stewart R H and Barnum J R, 'Radio measurements of oceanic winds at long ranges: an evaluation', Radio Sci 10, 853-857 (1975).

126. Sulzer P G, 'Sweep frequency pulse-transmission measurements over a 2400 km path', J Geophys Res, 60(4), 411-420 (1955).

127. Surtees W J, 'An approximate synthesis of HF backscatter considering ionospheric motions', Radio Sci, 3, 57 (1968).

128. Tanaka T, 'Sky-wave backscatter observations of sporadic-E over Japan', J Atmos Terr Phys, 41 (2), 203-215 (1979).

129. Turunen T and Oksman J, 'On the relative location of the plasmapause and the HF backscatter curtains', J Atmos Terr Phys, 41, 345-350 (1979).

130. Tveten L H, 'Ionospheric motions observed with high-frequency backscatter sounders', J Res NBS, 65D(2), 115-127 (1961).

131. Tveten L H and Hunsucker R D, 'Remote sensing of the terrestrial environment with an HF radio high-resolution azimuth and elevation scan system', Proc IEEE, 57(4) 487 (1969).

132. Uffelman D R, Harnish L O and Goodman J M, 'The application of real-time model update by oblique ionospheric sounders to frequency sharing' in 'Propagation aspects of frequency sharing, interference and system diversity', AGARD Conf Proc 332, 12-1 (1982).

133. Uffelman D R, 'Determination of propagation limitations at HF by real-time update of a computer model from oblique sounder data', AGARD Conf Proc 345, 17-1 to 17-12 (1983).

134. Uffelman D R, Harnish L O and Goodman J M, 'HF frequency management by frequency sharing as assisted by models updated in real time', NRL Memorandum Report 5284, Naval Research Laboratory, Washington DC (1984).

135. Villard O G and Peterson A M, 'Scatter sounding: a technique for study of the ionosphere at a distance', Trans IRE, PGAP-3, 186-201 (1952).

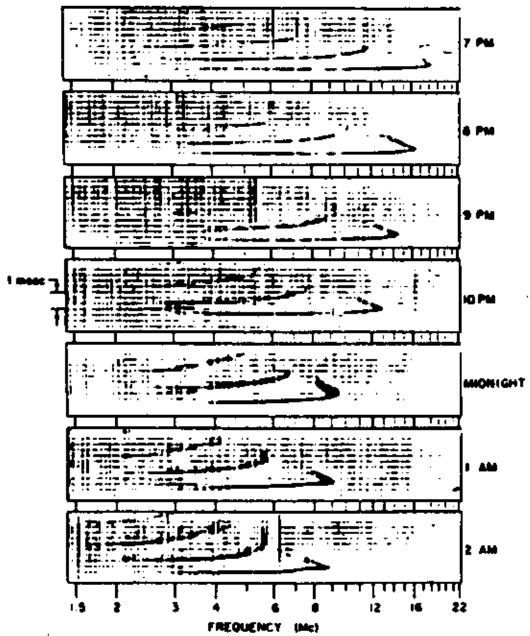
136. Wait J R, 'Theory of HF ground wave backscatter from sea waves', J Geophys Res, 71, 4832-4839 (1966).

137. Washburn T W, Sweeney L E, Barnum J R and Zavoli W B, 'Development of HF skywave radar for remote sensing applications', AGARD Conf Proc 263, 32-1 to 32-16 (1979).

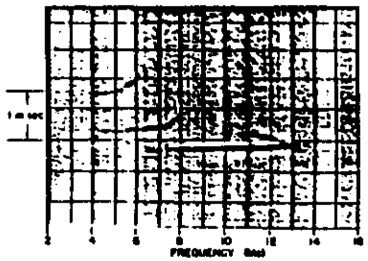
138. Wieder B, 'Some results of a sweep-frequency propagation experiment over a 1150 km east-west path', J Geophys Res, 60(4), 395-409 (1955).

139. Wilkins A F and Shearman E D R, 'Backscatter sounding: an aid to radio propagation studies', J Brit Inst Radio Engrs, 17, 601-616 (1957).

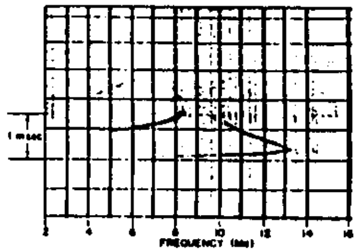
140. Winacott E L Roche C and Chan J Y K, 'The Canadian programme of experimental measurement of sea-state characteristics by sky-wave radar', AGARD Conf Proc 345, 14-1 to 14-17 (1983).



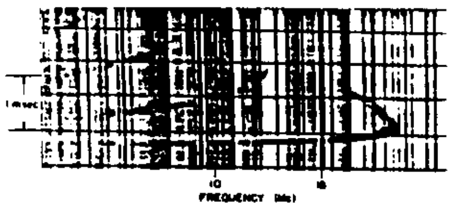
a. From Möller [Ref. 4],



b. From Agy and Davies 1815 record

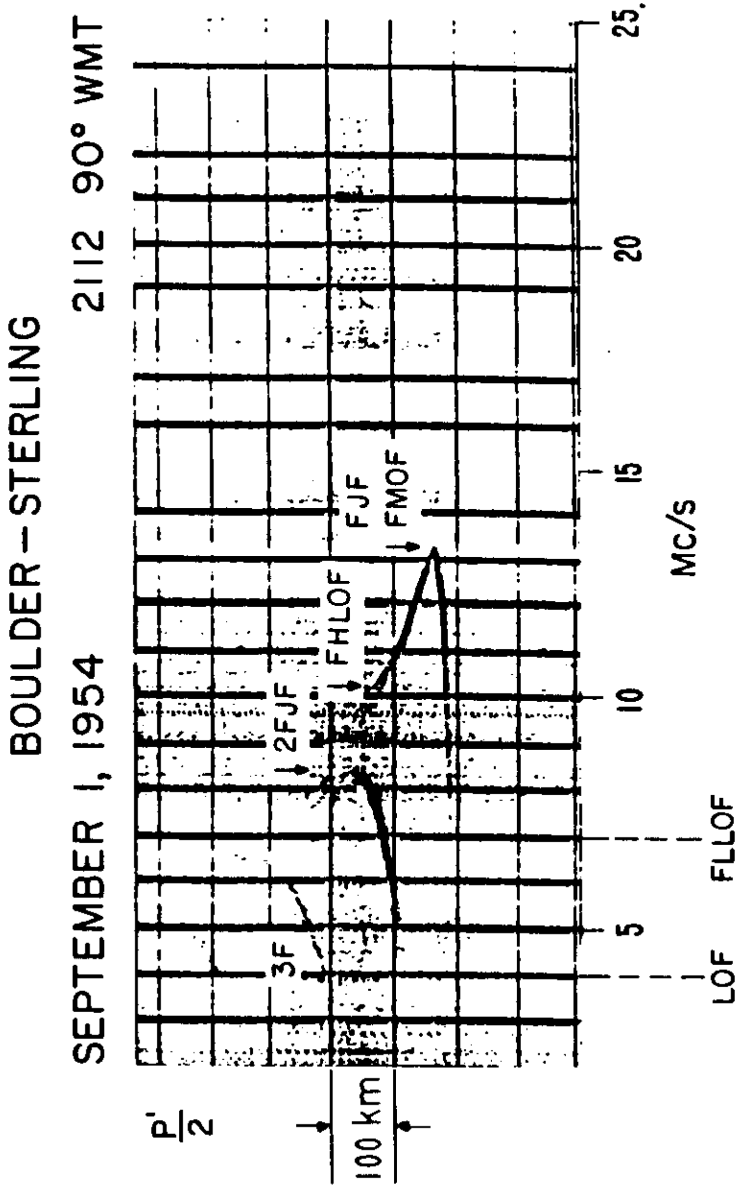


c. From Agy and Davies 2112 record



d. From Agy, Davies, and Salaman 2101 record, April 30, 1957

FIG. 1. EXPERIMENTAL IONOGRAMS



Oblique ionogram for a medium distance of transmission (2400 km) in middle latitudes, showing well-defined echo traces

Figure 2

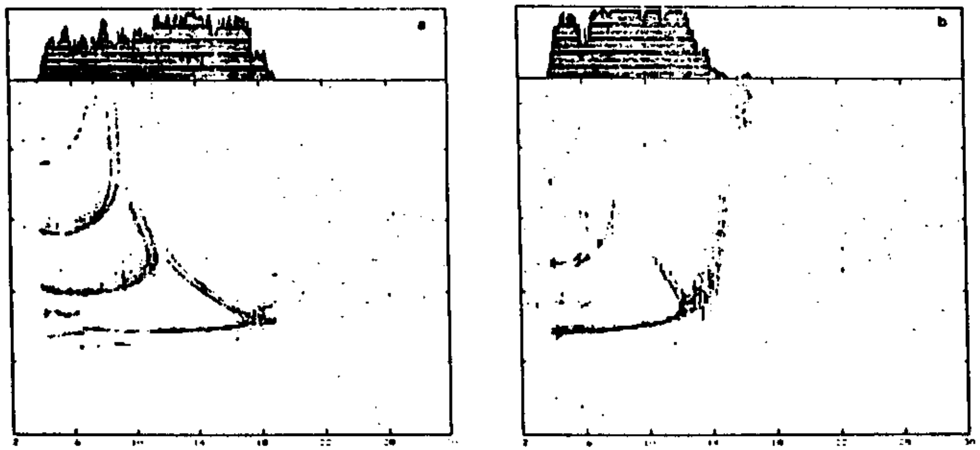


Fig. 3. Swept frequency ionograms for the Iceland - S England path

(a) 3 March 1988 1734h
(b) 21 April 1988 2304h

The ionogram ordinate scale is relative group delay (1ms between marks). The amplitude full scale (upper panel) is approximately 30 dB linear.

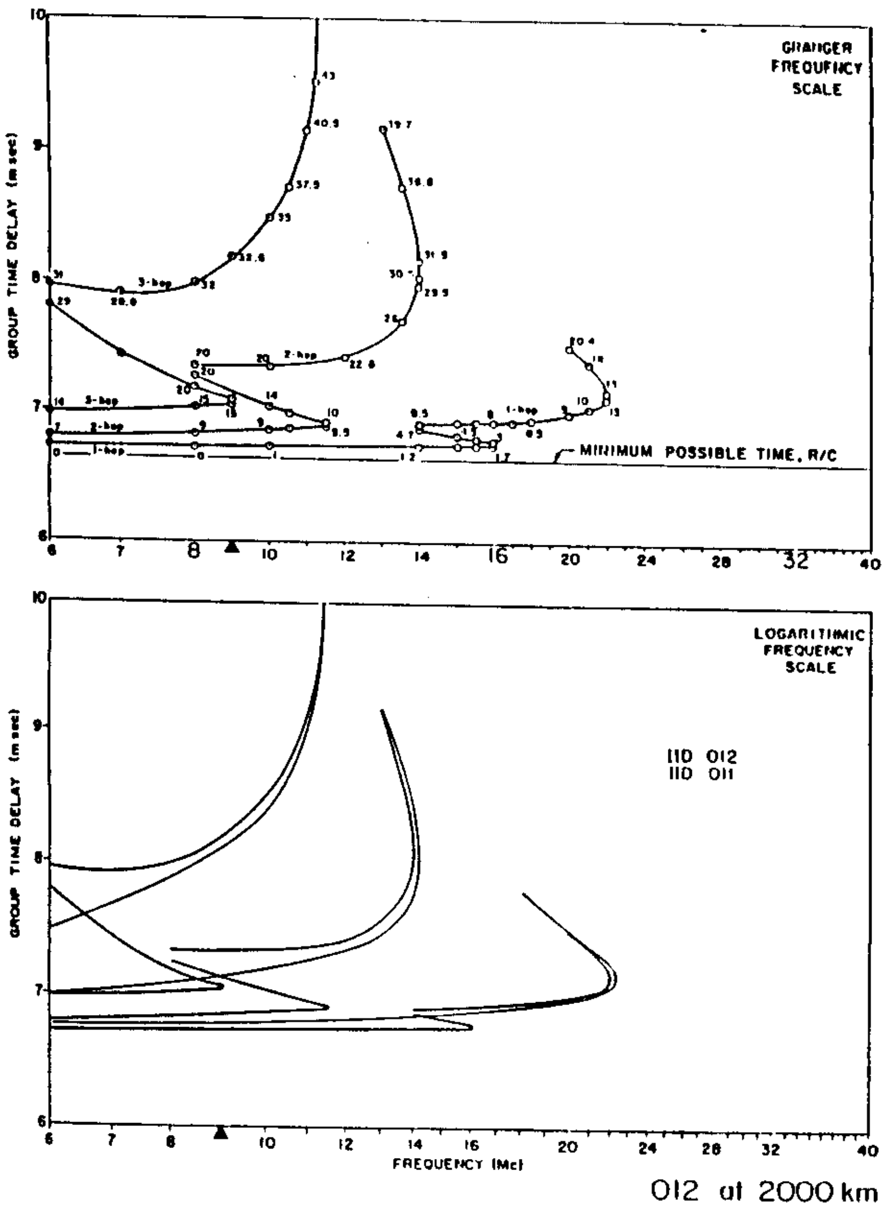


FIG. 4. IONOGRAM FOR IID 012; SEPARATION DISTANCE, 2000 km.

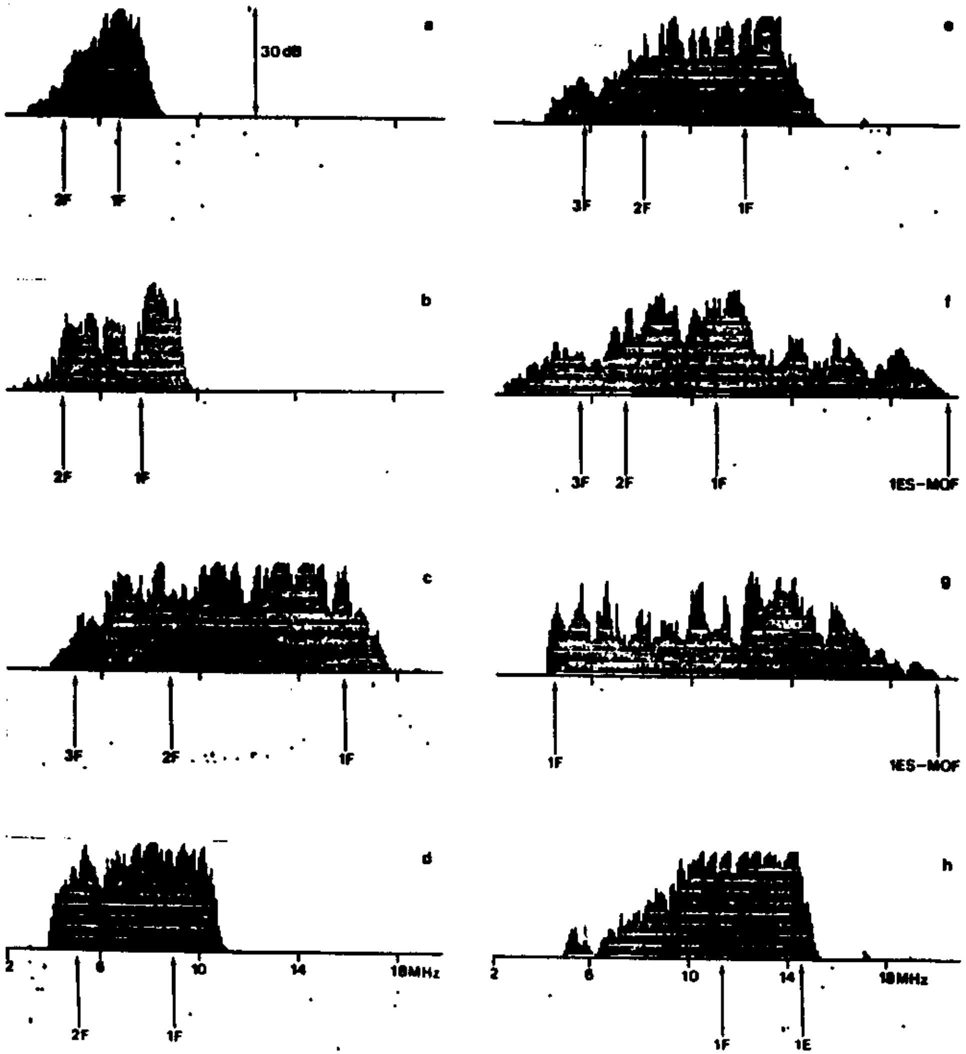


Fig. 5. Measured signal/noise ratio over Iceland - S England path

(a)	8 January 1988	1804h		(e)	8 January 1988	1104h
(b)	20 January 1988	1934h		(f)	13 January 1988	1704h
(c)	13 January 1988	1004h		(g)	13 January 1988	0634h
(d)	24 February 1988	2004h		(h)	30 March 1988	0934h

Arrows indicate ordinary-wave junction frequencies of different modes determined from associated ionograms.

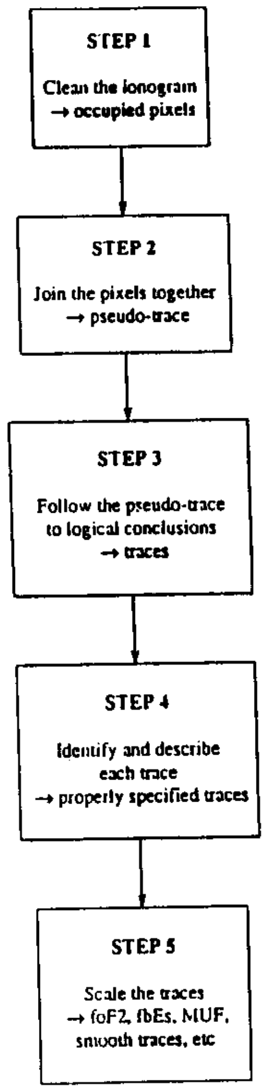
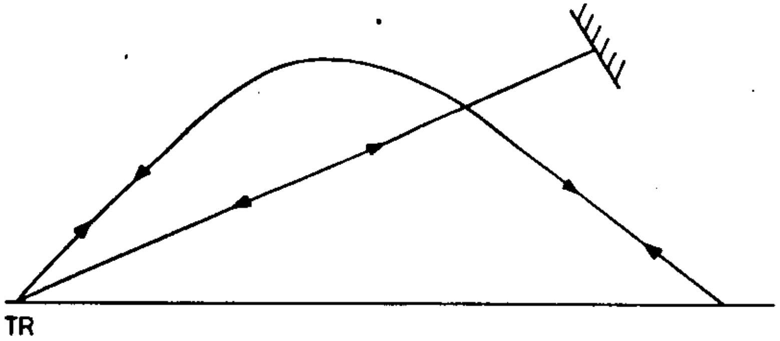
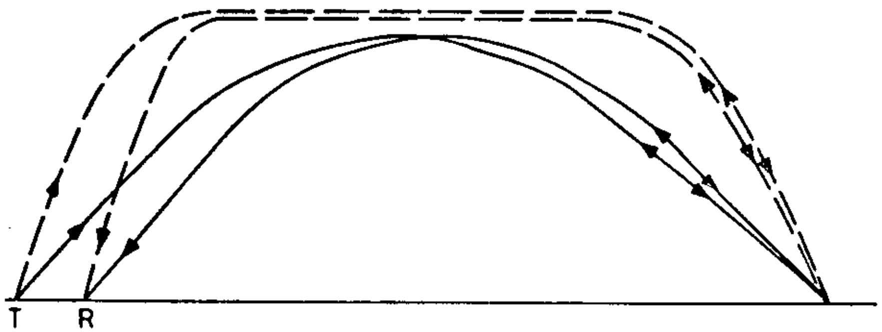


Figure 6 A Schematic of Autoscaling at IPS



GROUND AND AURORAL BACKSCATTER



BISTATIC LOW AND HIGH-ANGLE RAYPATHS

Fig 7

GROUND CLUTTER CROSS-SECTION σ_c

$$\sigma_c = \frac{c}{2W} \cdot R\ \theta\ \sigma_o$$

WHERE:

W = EFFECTIVE RADAR BANDWIDTH

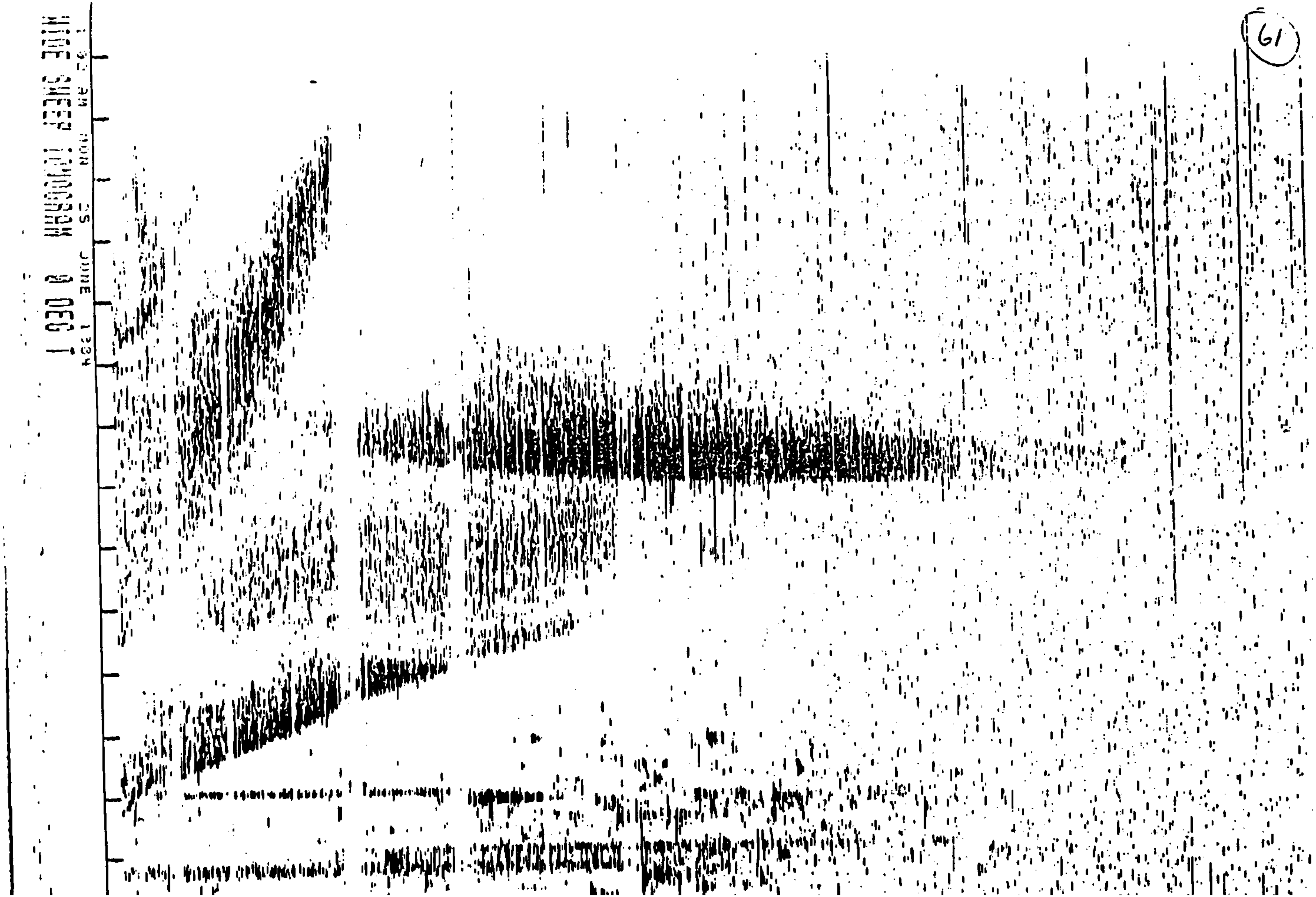
θ = AZIMUTHAL BEAMWIDTH OF RECEIVING ANTENNA

R = GROUND RANGE

c = SPEED OF LIGHT

σ_o = RADAR CROSS=SECTION PER UNIT SURFACE AREA

Fig. 8



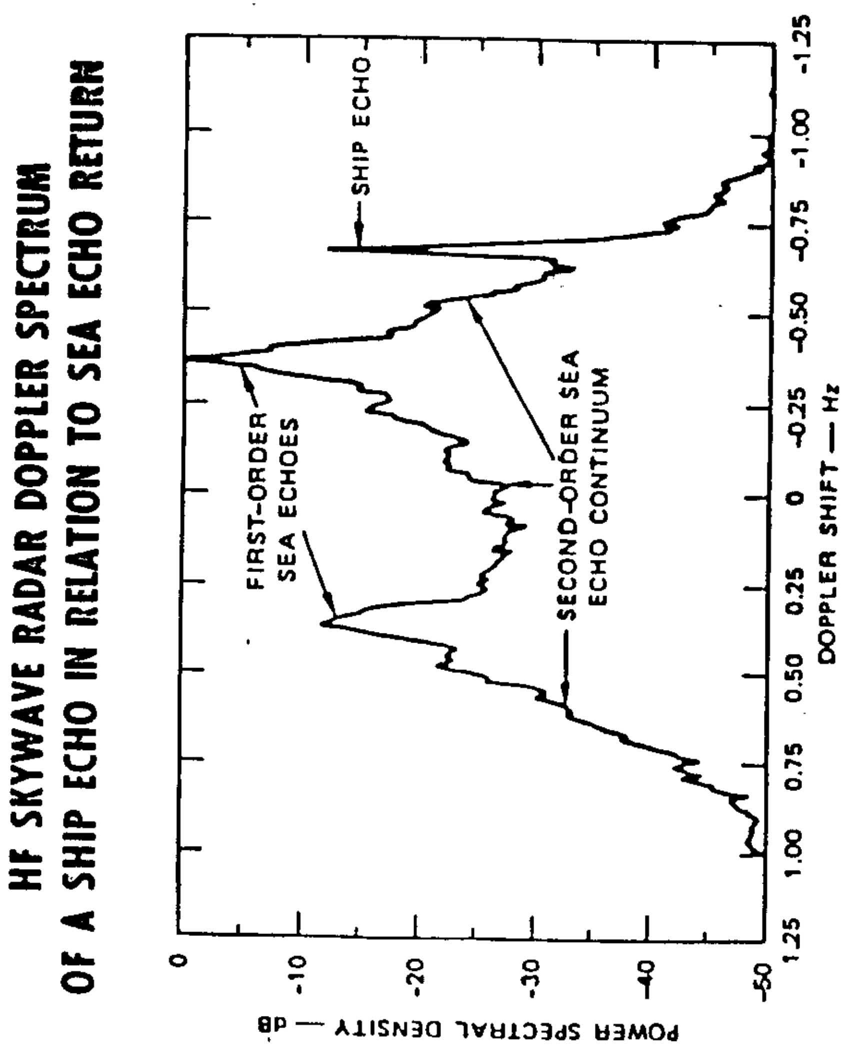


Fig. 10

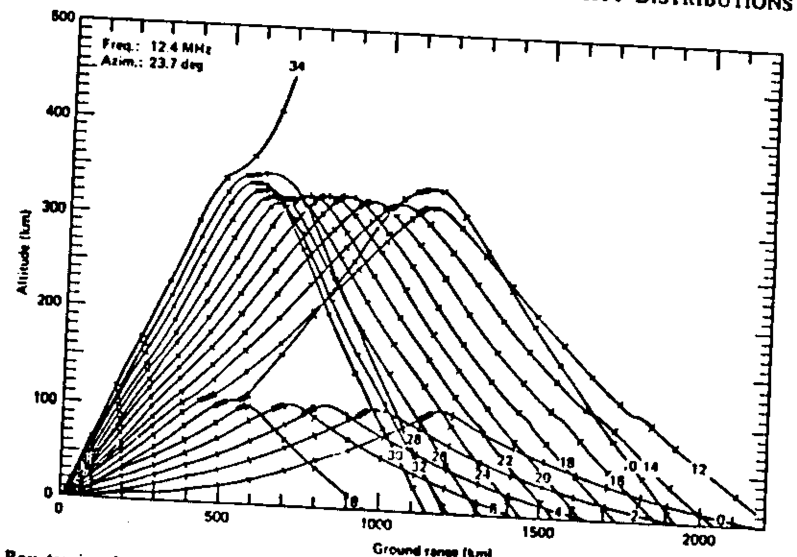


Fig. 11. Ray tracing in a geomagnetic meridian plane for a HF radar located at Anchorage, Alaska, with elevation angle rays from 0° to 34°, in 2° steps. The elevation angle is indicated by the number at the end of the ray. The distance between tick marks on the rays corresponds to a group path of 100 km. The rectangles plotted on the rays indicate that the ray is within 1° of normal to the earth's magnetic field. The electron density distribution used for this ray tracing is described by the set of analytic functions given in the text. The transmitted frequency is 12.4 MHz.