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Long Delayed Echoes

A Study of Magnetospheric Duct Echoes 1997-2007

INTRODUCTION. On 25th October 1997, at about 19:30 UTC, I was working on 3.5MHz using Hellschreiber, an on-off-keyed facsimile mode in which typed letters are transmitted as patterns of dots which are displayed directly on the screen of a computer. I was experimenting with a 'quick-break' version in which I could listen on the frequency between letters, a technique used by Morse code operators. During this contact, for a period of about 10 minutes, I was aware that I could hear an echo of my own transmission, and therefore see on my screen a double image of the right-hand edges of each of my transmitted letters. The other station in the contact could detect nothing unusual, either on my signal or on his own signal. By saving the screen image and analysing it later, I estimated the echo delay to be about 210ms. This was clearly a much greater delay than could be attributed to normal ionospheric effects. I later reported this incident in *RadCom* **[1]**. This article describes the work I have done to explore this phenomenon in more detail over the last ten years.

THE ECHO SOUNDER IDEA. After this initial experience of a single echo, I realised that it would be possible to construct a 'sounder' that could be used to automate the detection of echoes of this type. With an anticipated echo delay of 210ms, it would be relatively easy to transmit a burst of carrier, switch back to receive and plot the received signal over a few hundred milliseconds, and repeat this process at regular intervals. A long transmitted pulse, say 100ms, in conjunction with a narrow receiver bandwidth, say 20Hz, would give a high sensitivity, but a shorter pulse, say 1ms, and a wider bandwidth of 2kHz would enable accurate measurements of echo delay, but at a reduced sensitivity. That sounds like a trade-off decision is needed, but it is possible to sweep a long pulse over a wide bandwidth and achieve both the sensitivity of the long pulse and the resolution of the wide bandwidth. A 100ms pulse swept over 2kHz could be easily transmitted and received by a conventional 100W SSB transceiver. I have previously described, in a *RadCom* article **[2]** how I used this technique to study the signals from swept-frequency ionospheric sounders (Chirpsounders). By switching back to receive quickly and processing the next 500ms of received signal through a special chirp-filter, it would be possible to capture any echoes within the delay range 100ms-500ms, with a resolution of 1ms, and save the results to disc for later analysis.

INITIAL PROMISING RESULTS. I wrote the software to do this and started sounding in November 1997, initially with little real hope of any result. My patience was rewarded at 2105 UTC on 4 December when another echo was detected and recorded over a 10 minute period on 3.5MHz. The echo signal was some 24dB above the noise and had a round-trip delay of 220 +/-1ms. Another echo was observed the following evening over a 15 minute period at 223ms delay. A quick check on 1.9 and 7MHz showed no sign of an echo on these bands. I repeated the tests at random over the following weeks. No more echoes were detected and I abandoned the tests in February 1998. To do the job properly I would need to be far more methodical and narrow down the search by answering several questions. What were the best times and seasons? What is the best frequency? What is the propagation mechanism? What, if anything, is already known about this phenomenon?

THEORIES. I did no more sounding tests in 1998, but started searching for clues in the literature. It seems that reports of Long Delayed Echoes (LDEs) have been with us since the dawn of the radio age, but with a wide variety of characteristics and few plausible theories. However, Alan Goodacre, VE3HX, **[3]** drew my attention to one pattern of observations which did match mine, which has been the subject of scientific research triggered by a hypothesis first outlined by Pedersen in 1929 **[4]**. Echoes were seen in a study carried out on 13MHz in Washington DC in 1960 **[5]**, although some of these look more like round-the-world echoes at about 135-140ms delay. A more recent study in 1986 in Tasmania **[6]** on 1.9MHz produced many echoes and, within amateur radio circles, echoes like mine, also on 80m, had been heard by amateurs in the Seattle area **[3]**. Other papers I found on this topic describe the propagation mechanism in some detail. In this article I shall use the term Magnetospheric Duct Echo (MDE) to describe this phenomenon.

It is well known that the ionised rare gases in the ionosphere do not respond directly to an imposed magnetic field but, if forced to move by some other means, will be constrained to 'slide' only along the field lines. The earth's magnetic field in the UK is along a line at an angle 70 degrees above the southern horizon. If we follow it out into space beyond the ionosphere, it curves downwards following a circular path, crossing the equatorial plane at a height of about 6000km, continuing to curve until it meets the surface again in the south Atlantic. This is shown as the red line in **Figure 1**. The theory is that irregular blobs of ionised gas, presumably originating in the ionosphere at one or both ends of this arc, are 'drawn out' along the

FIGURE 1

Figure 1: The earth's magnetic field (red line)

field lines into field-aligned columns or strands. This process creates multiple fibre-like structures along the whole arc between the two points where the field lines meet the ionosphere at each end. The level of ionisation is far too weak to reflect a radio wave in the same way as occurs in the ionosphere, but it's enough to cause a radio wave, which is already travelling along a field line, to become trapped so that it follows the curvature of the field-line. This is similar to a microwave duct, in which the ray path follows the curvature of the earth's surface, trapped underneath a layer in which the refractive-index changes with height. However, in these magnetospheric ducts there is no plane surface, just an irregular pattern of ionised strands aligned along the magnetic field. The VLF phenomena known as whistlers follow the same path, although the propagation mechanism is slightly different.

It's tempting to think that the path taken by an echo heard at the transmitter is a there-and-back transit of this path with an intermediate backscatter from the earth's surface at the far end. This can occur, but the signal levels would be very low. Some of the echoes seen in the 13MHz tests done in 1960 with a 100kW transmitter and Yagi antennas may have been of this type. However, it's likely that MDE seen on lower frequencies with far less power involve a much lower loss reflection from the topside of the ionosphere at the far end. This has been confirmed by soundings carried out from satellites above the ionosphere **[7]**. However, for a signal to enter the duct initially, there must also be a path through the ionosphere at the near end. This ties in nicely with the evidence that MDE are generally only heard at night during the winter months, when it is summer at the far end. The observed delay times match, approximately at least, the estimated lengths of the field lines. In particular, the echo delay time is longer as the observer moves away from the magnetic equator.

MORE EXPERIMENTAL WORK. In the winter of 1999 I again started to listen for echoes, but this time on a regular basis, starting on 1 October. Echoes were heard at 2150 UTC on 25 December, 2230 UTC on 29 December, 2220 on 16 January 2000 and at 2100 on 30 January. Nothing more was heard until I stopped at the end of February. In all cases the echo delays were within the range 218 to 223ms, the same as those two years earlier. Although I did try to run the experiment each night, this was not always possible. It was quite difficult to find a clear frequency without the risk of corrupting the trace and/or annoying other band users.

I repeated these tests the following winter 2000/2001, again on 3.5MHz, and logged a further 8 echoes, the earliest being on 16 December and the latest on 12 January. By now it was fairly clear that the peak season was indeed very closely aligned to midwinter, and that echoes could occur at any time between about 2000 and 0100.

Family events prevented me carrying out any more tests during the winter of 2001/2002, but the next phase of the project took shape later that year when the 5MHz experimental channels became available. I saw the opportunity here to propose an experiment that would let me run the sounder all night and every night without having to worry about interference problems. I outlined this proposal to the RSGB 5MHz working group and it was accepted. To minimise interference to other users, I was able to engineer an automatic scheme whereby I monitored the signal from the nearby ionospheric sounder at Inskip, near Preston, and only started the tests when this signal, sweeping past the 5MHz channel in question every 5 minutes, ceased to be received by skywave. This ensured that I never transmitted when my own signals would have been receivable by near-vertical skywave. It also meant that I only transmitted when I expected there to be a clear path up through the ionosphere.

I ran these tests every night from September 2002 to March 2003, but heard no echoes whatsoever. Although the availability of the 5MHz experimental channels was a decided advantage in that I could now transmit all night on a clear frequency, it seemed that I had gone too high in the spectrum and the phenomenon was not present at 5MHz.

That might have been the end of the experiment, but by co-incidence that year I was invited to help a non-amateur organisation with the task of setting up some HF radio links around the UK, and part of that activity gave me permission to transmit on a number of frequencies in the 2-5MHz region. Informal enquiry with the relevant authorities showed that there would be no objection to my use of some of these frequencies at night. This meant that

FIGURE 2

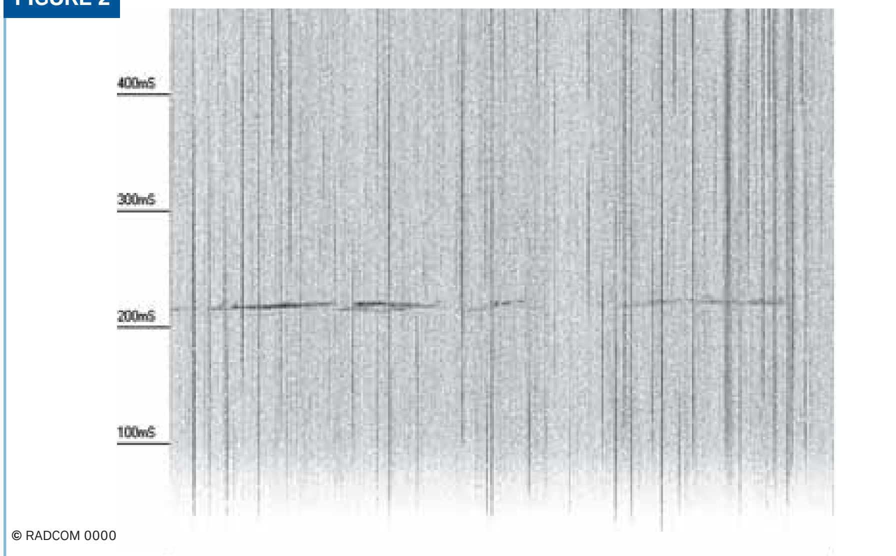

Figure 2: A typical echo trace. Time of day on X axis, reflection time on Y axis.

FIGURE 3

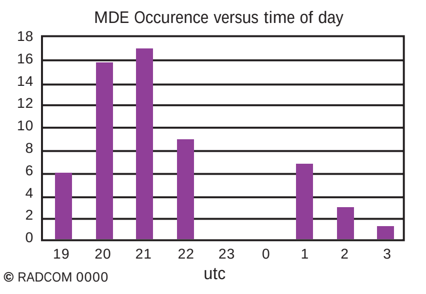

Figure 3: Distribution of MDE occurrence versus time of day

FIGURE 4

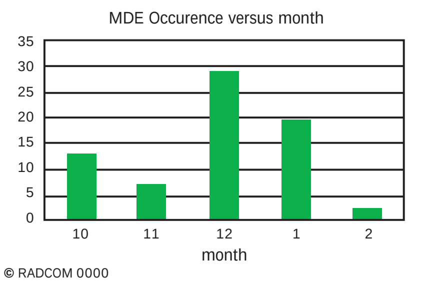

Figure 4: Distribution of MDE occurrence versus month

FIGURE 5

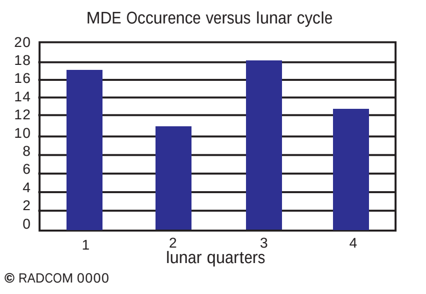

Figure 5: Distribution of MDE occurrence versus phase of the moon

in the winter of 2003/2004 I was able to carry out an intensive set of tests, similar to those I had done on 5MHz, between September and March on a frequency near 3.9MHz. Echoes were seen on December 23, 26, 27 and 29, all within the 2000-2200 UTC period, and at the same echo delay as seen previously. The following year, 2004/2005, I was able to repeat this pattern on a lower frequency (around 2.7MHz). Echoes were seen on 23 November and December 17, 23, 27 and 31, January 1, 3 and 20, and 3 February. Some of these echoes were as late as 0300 UTC.

During the winter of 2005/2006 I ran the sounder again, between November and February, this time on a frequency near 2.4MHz. At this frequency it seemed likely that the ionosphere might reflect late into the night and may block the path up to the magnetosphere, but I chose to stay with the same 1900 UTC start time as on the higher frequencies. A total of 16 echoes were heard between 25 November and 21 January, at times ranging between 1930 and 0130 UTC. It became clear from study of the ionospheric sounder archives from Chilton that some of these echoes were received when the ionosphere was still reflecting. Although I originally reasoned that there would be no point in trying for echoes while the ionosphere was still reflecting, it seemed that the ionosphere, or at least the F-layer, starts to become transparent some time before it ceases to reflect. Much later I was able to confirm that this does occur. There is indeed a condition, known as the Z-mode window, in which a wave polarised in one sense, travelling almost vertically upwards, can 'cross-couple' to the opposite sense and penetrate through the layer.

This brings the experimental phase of this project to the most-recent session, where I ran some tests on 160m, just inside the top end of the band, during the winter of 2006/2007. Here, as with the earliest tests on 3.5MHz, I could only run the experiment while I was in the shack, but it was much easier to find a clear channel at the top end of the band. I heard echoes on a total of 16 occasions, the earliest at 1945 and the latest around 0300.

ANALYSING THE RESULTS. Over the period October 1997 to March 2007, a total of 59 MDE were detected on frequencies between 2 and 3.9MHz. **Figure 2** shows a typical echo trace, seen on 25 November 2005. On this chart the time-of-day is plotted along the X axis, the echo delay in ms up the Y axis, and the signal intensity is shown by the blackness of the image. The blank region around 0-100ms is an effect of the 100ms-long chirp filter and not due to a slow rise in the receiver gain. The vertical scale has been adjusted to make allowance for the time taken for the signal to pass (twice) through the transceiver's SSB filter. The vertical streaks result from un-related interference and can be disregarded. It's interesting to note that single-tone interference only registers as a mild darkening of the trace, and impulse interference shows as a 100ms vertical stripe. Only a signal chirping at the same rate as the transmitted will display a sharp dot with a resolution of 1ms.

FIGURE 6

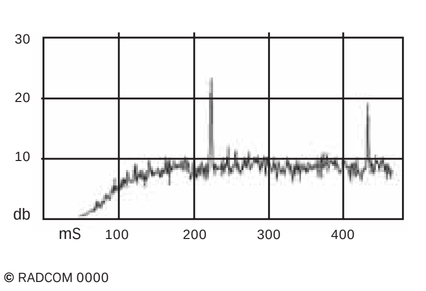

Figure 6: Rare double MDE event of 4 December 2005

The fine structure of the MDE is clearly visible, and shows that there can be more than one path at any time, and some variation in delay over time. It's possible to measure the signal and noise levels from the original data, and this shows a maximum SNR of about 25dB on this particular event. This figure needs some explanation in view of the use of the chirped pulse technique used. When sweeping a 100ms pulse over 2kHz and receiving the echo in a matched filter, a gain of 20dB (100 times power ratio) is achieved. This 25dB figure can therefore either be thought of as measured in a noise bandwidth 100 times narrower than the bandwidth actually used, (effectively about 20Hz), or alternatively as measured in the actual 2kHz bandwidth with an effective power 100 times that actually used. The actual transmitter power was 100W.

Figure 3 is a chart showing the distribution of the times of all the detected echoes over the period of observation, and **Figure 4** shows a similar chart showing the dates. These two charts will give some idea of the best time and best months to listen for an MDE. However, I did restrict my tests to the winter months (October-February) and to the night time (19-03 UTC), so

FIGURE 7

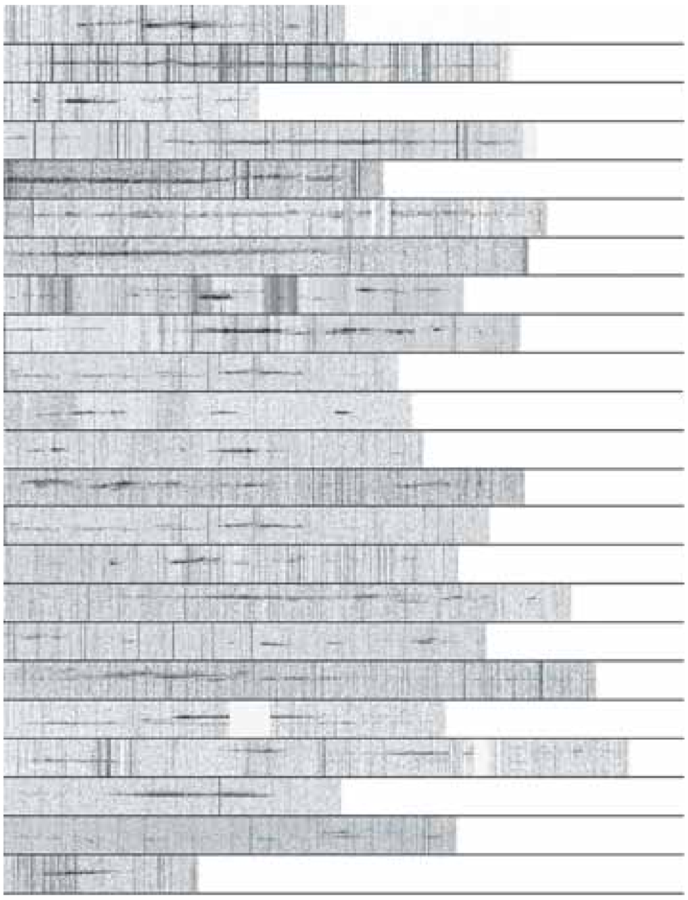

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Figure 7: Compilation of MDE echo traces showing relatively consistent echo time but varying durations

there's a small possibility that I have missed some echoes outside these intervals.

Figure 5 shows the observations shown as a function of the phase of the moon. There has been some suggestion **[5]** that lunar tides affect the mechanism by which free electrons are drawn up into the magnetosphere, and some observations **[4]** show that MDE are more likely in the third quarter of the lunar cycle. I have to say that I see no such trend in Figure 5.

It wasn't possible to automate the recording of the duration of the echo events because of their variable nature, but these ranged from a few tens of seconds up to a few tens of minutes. Several echoes were recorded on magnetic tape in the early tests and as audio WAV files in the later years.

On one single event, on 2.4MHz on 4 December 2005, at 2309 UTC, I saw a 221ms echo followed by a second echo at 438ms which was only 4.2dB lower in level. This is shown in **Figure 6** with the signal level displayed on the Y axis as the average level of about 25 individual chirps received over the 2-minute duration of this event. The fact that the second echo delay is slightly less than twice that of the first echo, and the second echo was so strong, probably means that the intermediate near-end reflection was from the topside of the F-layer. Since the near-end F-layer was also transparent (or I wouldn't have heard anything at all), this represents a remarkably low figure for the duct loss of only 1 or 2 dB.

Figure 7 shows a compilation of a number of echo traces. They have been trimmed to the delay range 200-240ms, since (apart from the double echo just described) nothing of interest occurs outside this range. There isn't space to show them all, and I have omitted many of those with no interesting features, so this is more of a showcase of the variety than a representative selection.

FURTHER EXPERIMENTS? Several interesting possibilities for further study suggest themselves. The length of a magnetospheric duct should vary with the latitude of the observer, so it would be most useful to repeat these observations at other locations to explore this more fully. The duct theory suggests that an MDE may only be audible in a small region around the transmitter, and it would certainly be interesting to know the size and shape of this area, as this would give some insight into the size and shape of the duct. Leaving aside the science for a moment, one wonders if this propagation mode might be useful from an operational point of view. It's interesting to speculate whether a two-way contact could be established between stations at each end of a duct, but study of the earth reveals that there are very few places on the globe where both ends of a magnetic field line lie in populated mid-latitude areas. The Petropavlovsk region of north-east Russia and the Adelaide area of Australia are a possibility, and perhaps Nova Scotia and the South Shetland Islands. I am tempted to suggest that magnetospheric ducts may never be more than a rare scientific curiosity.

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