

Supplementary Information for

An Updating of the IONORT Tool to Perform a High-Frequency Ionospheric Ray Tracing

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This PDF file includes:

Supplementary text
Figures S1–S8

- Figure S1 shows the ray tracing results for the epoch 28 November 2022 at 12:00 UT, for the O propagation mode, simulating a transmitter positioned in Kuala Lumpur (3.0° N, 101.0° E; Malaysia), and setting the loop cycles in frequency from 2 to 12 MHz (with a step of 2 MHz), and in elevation angle from 2.5° to 12.5° (with a step of 5°). Two values of the azimuth angle equal to 120° and 150° were chosen. For $\alpha = 120^\circ$ the minimum length path (≈ 1651 km, group delay ≈ 5.5072 ms) occurs for $f = 2$ MHz and $\Delta = 12.5^\circ$, while the maximum length path (≈ 2888 km, group delay ≈ 9.6357 ms) occurs for $f = 12$ MHz and $\Delta = 2.5^\circ$. For $\alpha = 150^\circ$ the minimum length path (≈ 1662 km, group delay ≈ 5.5470 ms) occurs for $f = 2$ MHz and $\Delta = 12.5^\circ$, while the maximum length path (≈ 3065 km, group delay ≈ 10.2264 ms) occurs for $f = 4$ MHz and $\Delta = 2.5^\circ$.

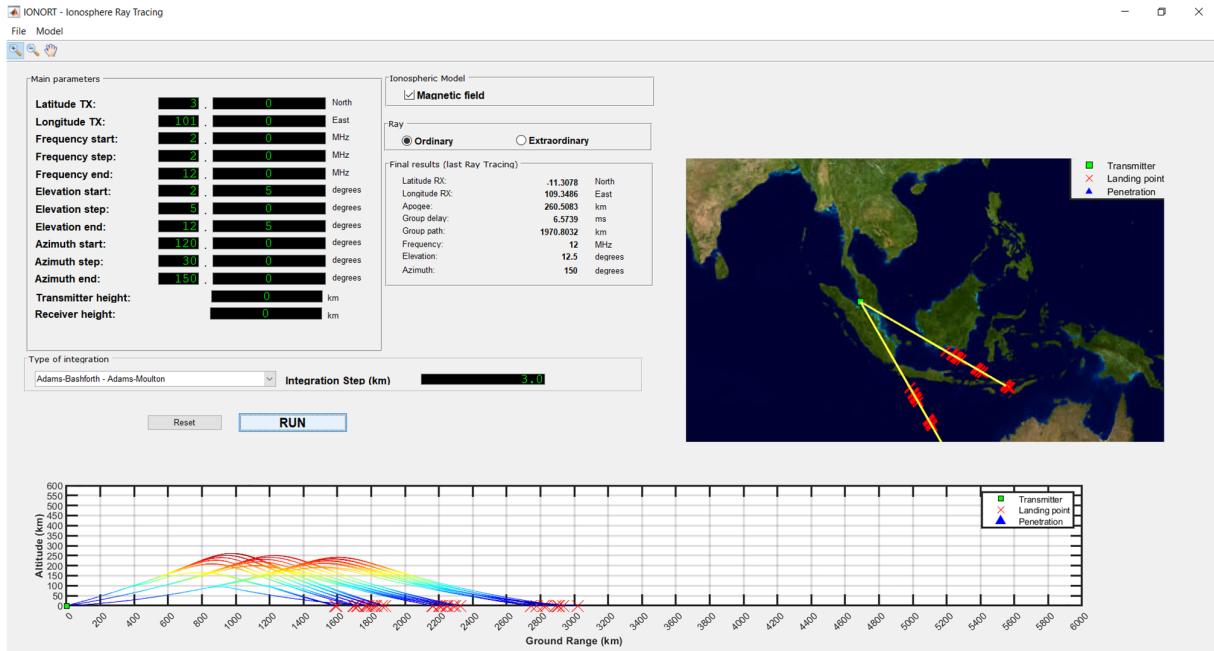


Figure S1. Ray tracing results over the equatorial zone of the South-East Asia, for the O ray, simulating a transmitter positioned in Kuala Lumpur for the epoch 28 November 2022 at 12:00 UT. The geographical map shows that the farthest landing points reach the Indonesian archipelago and Indian Ocean for $\alpha = 120^\circ$ and $\alpha = 150^\circ$, respectively. Looking at the altitude vs ground range plot no penetration case is observed.

2. Figure S2 shows the ray tracing results obtained for the epoch 29 July 2022 at 09:00 UT, for the O propagation mode, simulating a transmitter positioned in Quito (0.1° S, 78.3° W; Ecuador), and setting the loop cycles in frequency from 3 to 21 MHz (with a step of 3 MHz), and in elevation angle from 5° to 15° (with a step of 5°). An azimuth value equal to 135° was chosen. The minimum length path (≈ 1163 km, group delay ≈ 3.8821 ms) occurs for $f = 3$ MHz and $\Delta = 15^\circ$, while the maximum length path (≈ 3225 km, group delay ≈ 10.7587 ms) occurs for $f = 12$ MHz and $\Delta = 5^\circ$.

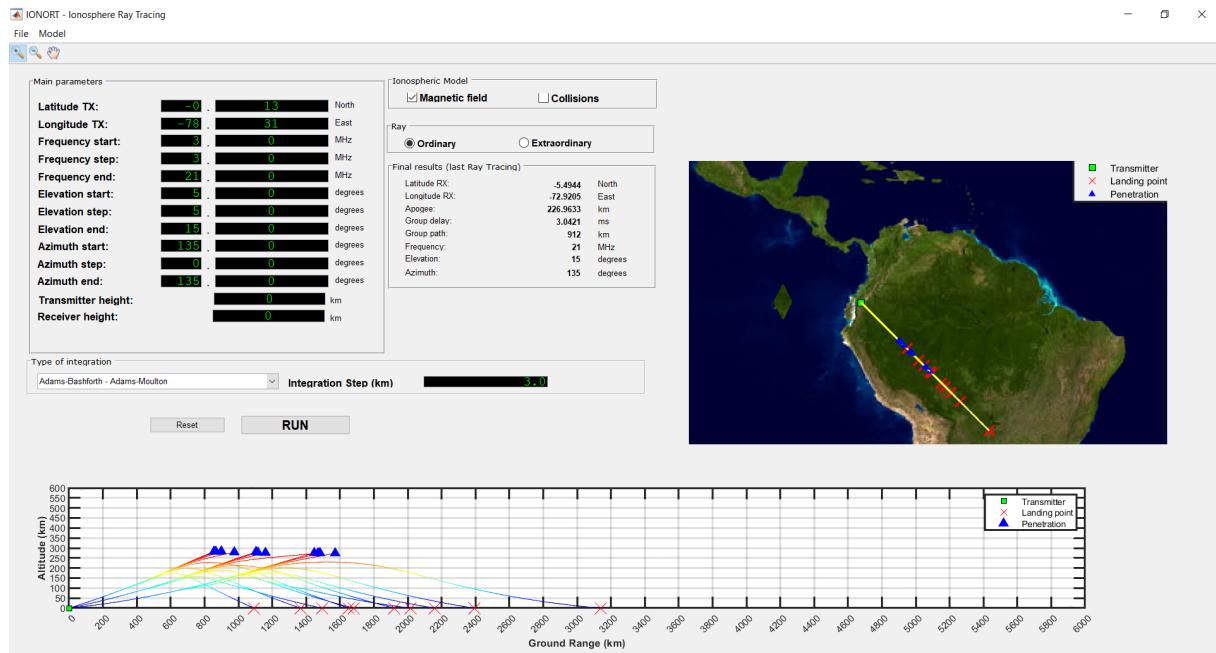


Figure S2. Ray tracing results over the equatorial zone of the South America, for the O ray, simulating a transmitter positioned in Quito for the epoch 29 July 2022 at 09:00 UT. The geographical map shows that the farthest landing point occurs over Brazil. Looking at the altitude vs ground range plot is evident that only 10 rays are reflected to the ground, in all other cases the ray penetrates the ionosphere.

3. Figure S3 shows the homing result obtained for the epoch 8 December 2022 at 19:00 UT, for the O propagation mode, simulating a transmitter located in Maserù (29.3° S, 27.4° E; Lesotho) and a receiver located at Cape Town (33.9° S, 18.4° E; South Africa). The corresponding oblique ionogram shows a MUF for the simulated radio link (ground range ≈ 998 km) of 11.5 MHz.

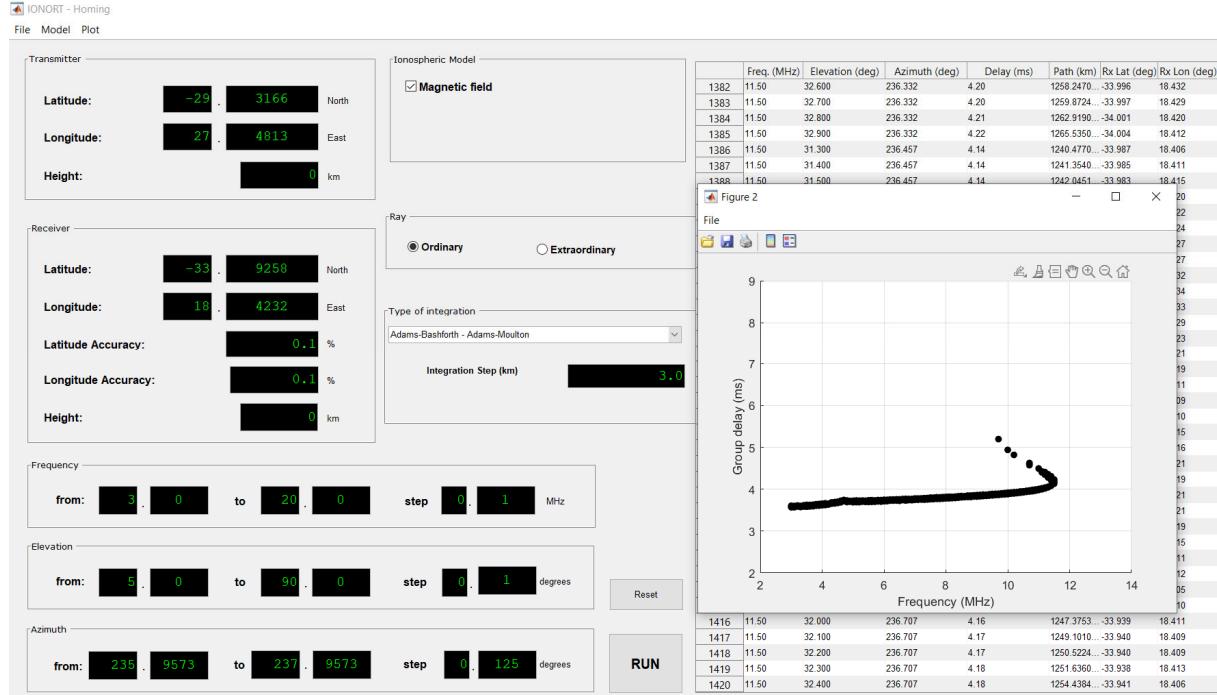


Figure S3. Example of homing simulation obtained in the Southern Africa for the epoch 8 December 2022 at 19:00 UT, for the O propagation mode. The left side of the GUI shows the main input parameters that are: the geographic coordinates of both the transmitter (Maserù) and the receiver (Cape Town); the loop cycles in frequency (3-20 MHz, step = 0.1 MHz), elevation (5° - 90° , step = 0.1°), and azimuth (235.9° - 237.9° , step = 0.125°). The right side of the GUI shows the list of the “winner triplets”, in the specific case 1420 triplets reach the target. The synthetic oblique ionogram obtained plotting the 1420 pairs frequency vs group time delay is also shown.

4. Figure S4 shows the homing result for the same radio link considered in Figure S3, for the X propagation mode. The corresponding oblique ionogram shows that the MUF is 11.7 MHz.

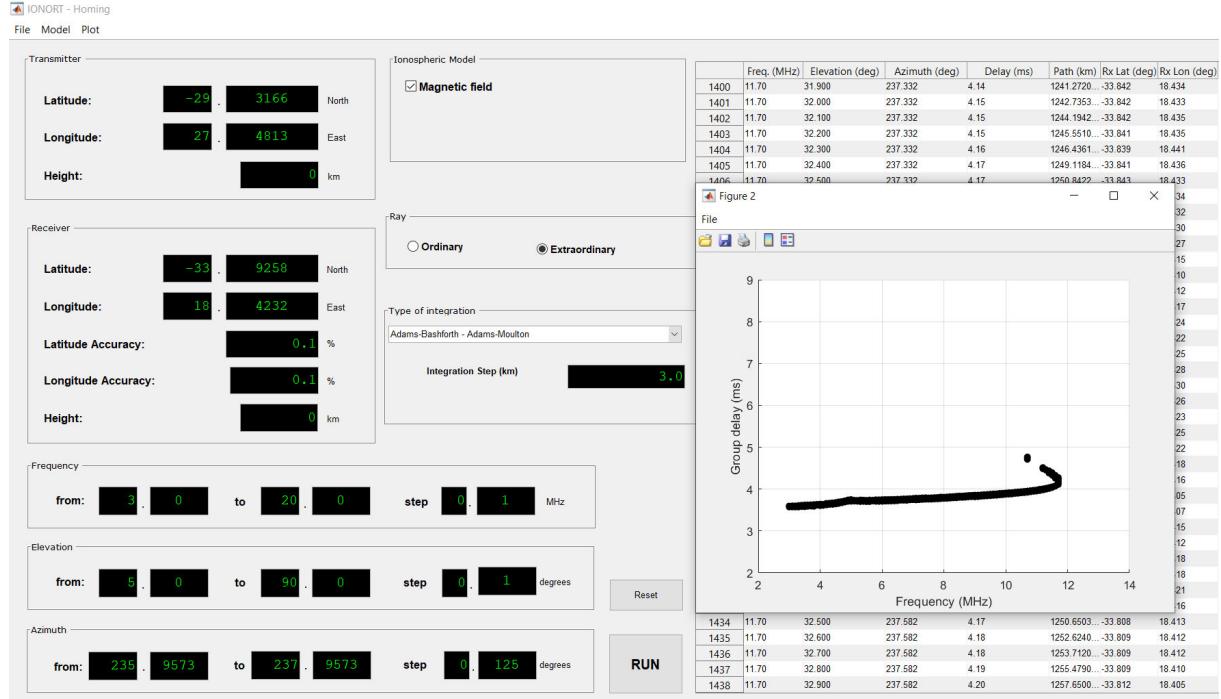


Figure S4. Example of homing simulation obtained in the Southern Africa for the epoch 8 December 2022 at 19:00 UT, for the X propagation mode. The left side of the GUI shows the main input parameters that are: the geographic coordinates of both the transmitter (Maserù) and the receiver (Cape Town); the loop cycles in frequency (3-20 MHz, step = 0.1 MHz), elevation (5° - 90° , step = 0.1°), and azimuth (235.9° - 237.9° , step = 0.125°). The right side of the GUI shows the list of the “winner triplets”, in the specific case 1438 triplets reach the target. The synthetic oblique ionogram obtained plotting the 1438 pairs frequency vs group time delay is also shown.

5. Figure S5 illustrates the O trace of Figure S3 and X trace of Figure S4 plotted together to better visualize their differences.

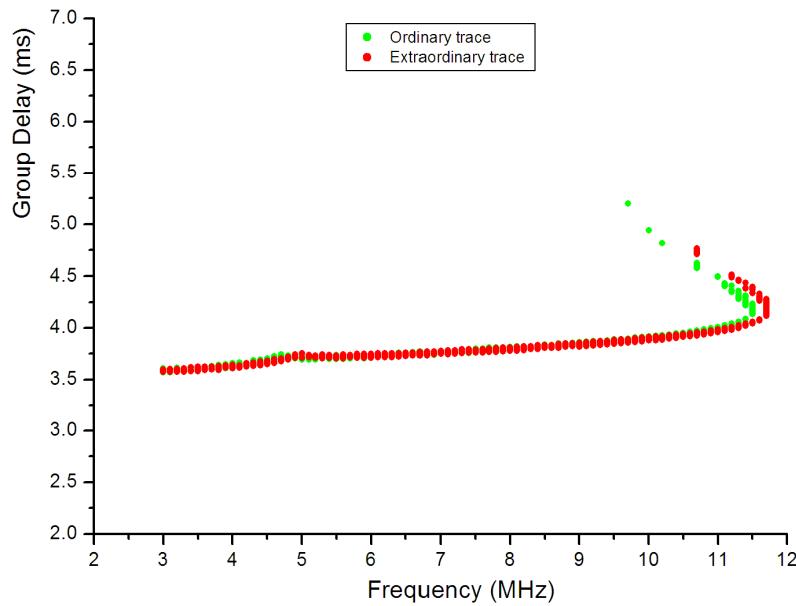


Figure S5. The O (green) and X (red) oblique ionograms shown in Figures S3 and S4 are here plotted together. The MUF value of the X trace exceeds that of the O trace by 0.2 MHz.

6. Figure S6 shows the homing result obtained for the epoch 9 August 2022 at 23:00 UT, for the O propagation mode, simulating a transmitter located in Kathmandù (27.7° N, 85.3° E; Nepal) and a receiver located at Xining (36.6° N, 101.7° E; China). The corresponding oblique ionogram shows a MUF for the simulated radio link (ground range \approx 1828 km) of 14.0 MHz.

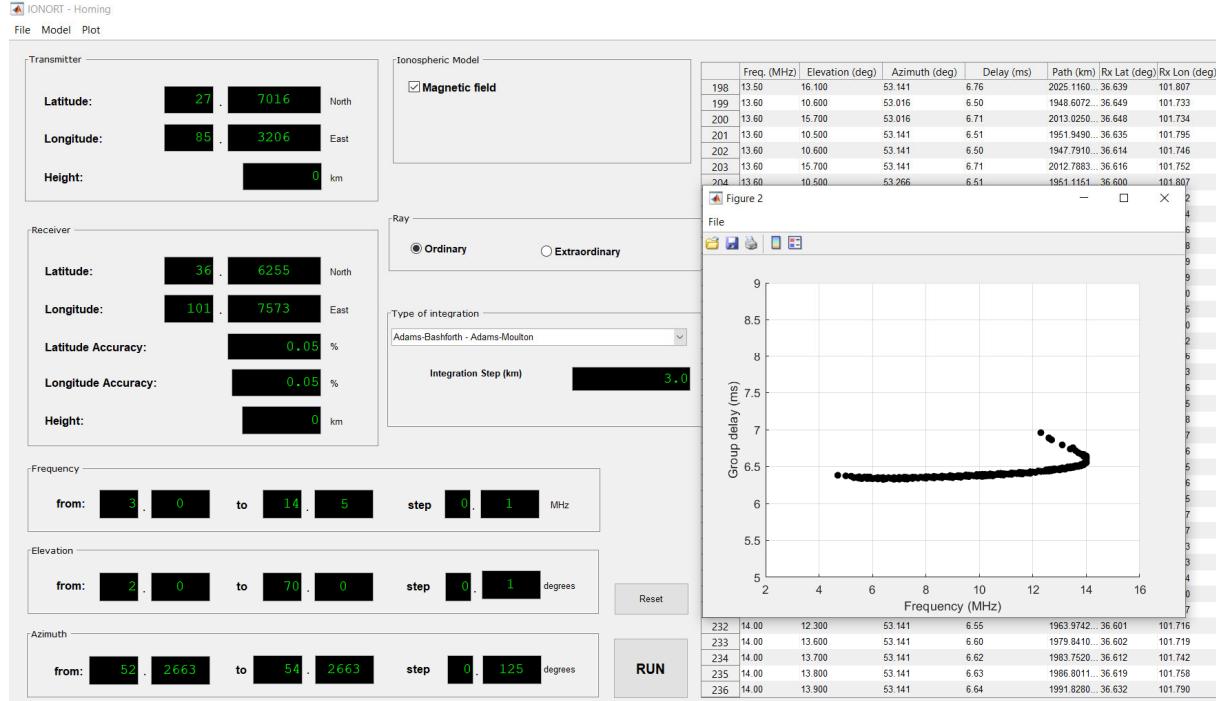


Figure S6. Example of homing simulation obtained in the Central Asia for the epoch 9 August 2022 at 23:00 UT, for the O propagation mode. The left side of the GUI shows the main input parameters that are: the geographic coordinates of both the transmitter (Kathmandù) and the receiver (Xining); the loop cycles in frequency (3.0–14.5 MHz, step = 0.1 MHz), elevation (2° – 70° , step = 0.1°), and azimuth (52.2° – 54.2° , step = 0.125°). The right side of the GUI shows the list of the “winner triplets”, in the specific case 236 triplets reach the target. The synthetic oblique ionogram obtained plotting the 236 pairs frequency vs group time delay is also shown.

7. Figure S7 shows the homing result for the same radio link considered in Figure S6, for the X propagation mode. The corresponding oblique ionogram shows that the MUF is 14.2 MHz.

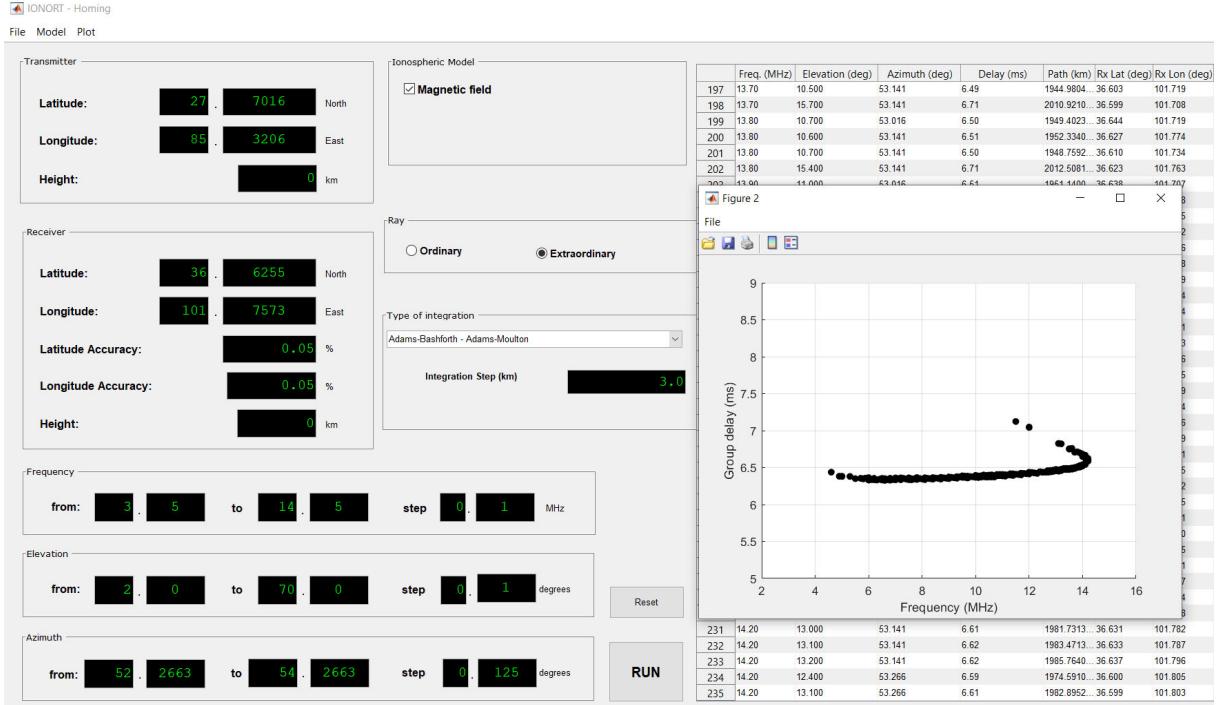


Figure S7. Example of homing simulation obtained in the Central Asia for the epoch 9 August 2022 at 23:00 UT, for the X propagation mode. The left side of the GUI shows the main input parameters that are: the geographic coordinates of both the transmitter (Kathmandu) and the receiver (Xining); the loop cycles in frequency (3.0–14.5 MHz, step = 0.1 MHz), elevation (2°–70°, step = 0.1°), and azimuth (52.2°–54.2°, step = 0.125°). The right side of the GUI shows the list of the “winner triplets”, in the specific case 235 triplets reach the target. The synthetic oblique ionogram obtained plotting the 235 pairs frequency vs group time delay is also shown.

8. Figure S8 illustrates the O trace of Figure S6 and X trace of Figure S7 plotted together to better visualize their differences.

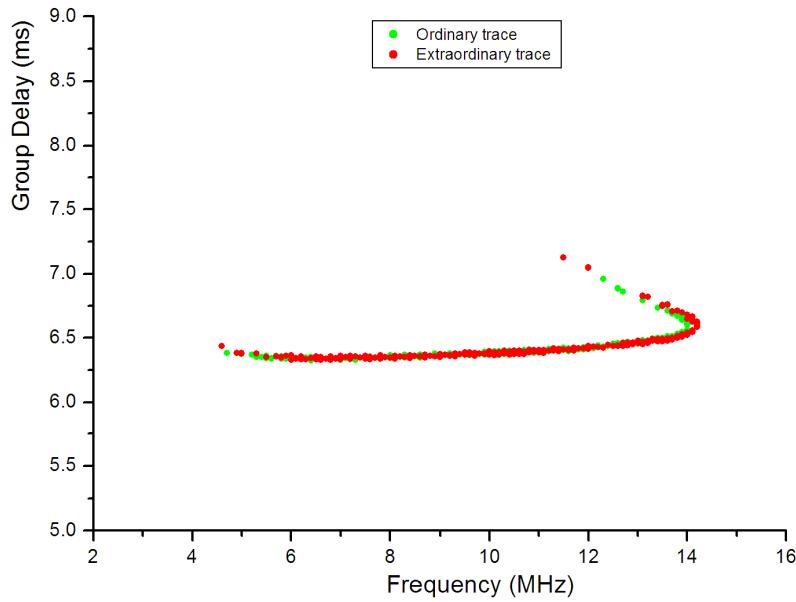


Figure S8. The O (green) and X (red) oblique ionograms shown in Figures S6 and S7 are here plotted together. The MUF value of the X trace exceeds that of the O trace by 0.2 MHz.