Supplement of Ann. Geophys., 42, 301–312, 2024
https://doi.org/10.5194/angeo-42-301-2024-supplement

Annales Geophysicae
Open Access

Supplement of

Observations of ionospheric disturbances associated with the 2020 Beirut explosion by Defense Meteorological Satellite Program and ground-based ionosondes

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1 Introduction

Here we provide a set of additional data plots to accompany the results presented in the main text. These additional figures include time series plots of foF2 and the net detrended ΔfoF2 values on 1-6 August 2020, time series plots of hmF2 and the net detrended ΔhmF2 values on 1-6 August 2020, as well as ray reflection diagrams to illustrate the formation of anomalous ionogram traces due to traveling ionospheric disturbances (TIDs).

The foF2, ΔfoF2, hmF2, and ΔhmF2 time series data plots are from 3 ionosonde stations discussed in the main text: Nicosia, Athens, and San Vito. The time series data are auto-scaled ionospheric parameters from the GIRO UML FastChar (https://giro.uml.edu/didbase/scaled.php). The net detrended ΔfoF2 and ΔhmF2 values were derived by subtracting a smooth baseline calculated using 10-point moving average (viz. 50-minute window for Nicosia and Athens; 75-minute window for San Vito). No obvious signs of TIDs associated with the 4 August 2020 Port Beirut explosion were seen in the auto-scaled ionospheric parameter time series plots, reinforcing a point from the main text that the characteristic TID signatures in this case had to be discerned based on anomalous traces in individual ionograms.

The ray reflection diagrams are simplified versions of Munro's (1953) and Heisler's (1958) geometrical explanations for several types of anomalous traces in ionograms that would indicate the presence of TIDs. The ray reflections were based on simple mirror reflection model that only involves regular/specular reflections off the ionospheric isodensity contour, without any ray bending/refraction effects. The main focus is the distinction between situations that would lead to the formation of loop/twist feature versus Y-forking feature as characteristic signatures of TIDs in individual ionograms, where the slant/tilt angle of the TID wavefront (relative to vertical orientation) plays an important role.

[1]Munro (1953), Reflexions from irregularities in the ionosphere, *Proc. R. Soc. Lond.*, A219, 447-463.
[2]Heisler (1958), Anomalies in Ionosonde Records Due to Travelling Ionospheric Disturbances, *Aust. J. Phys.*, 11, 79-90.

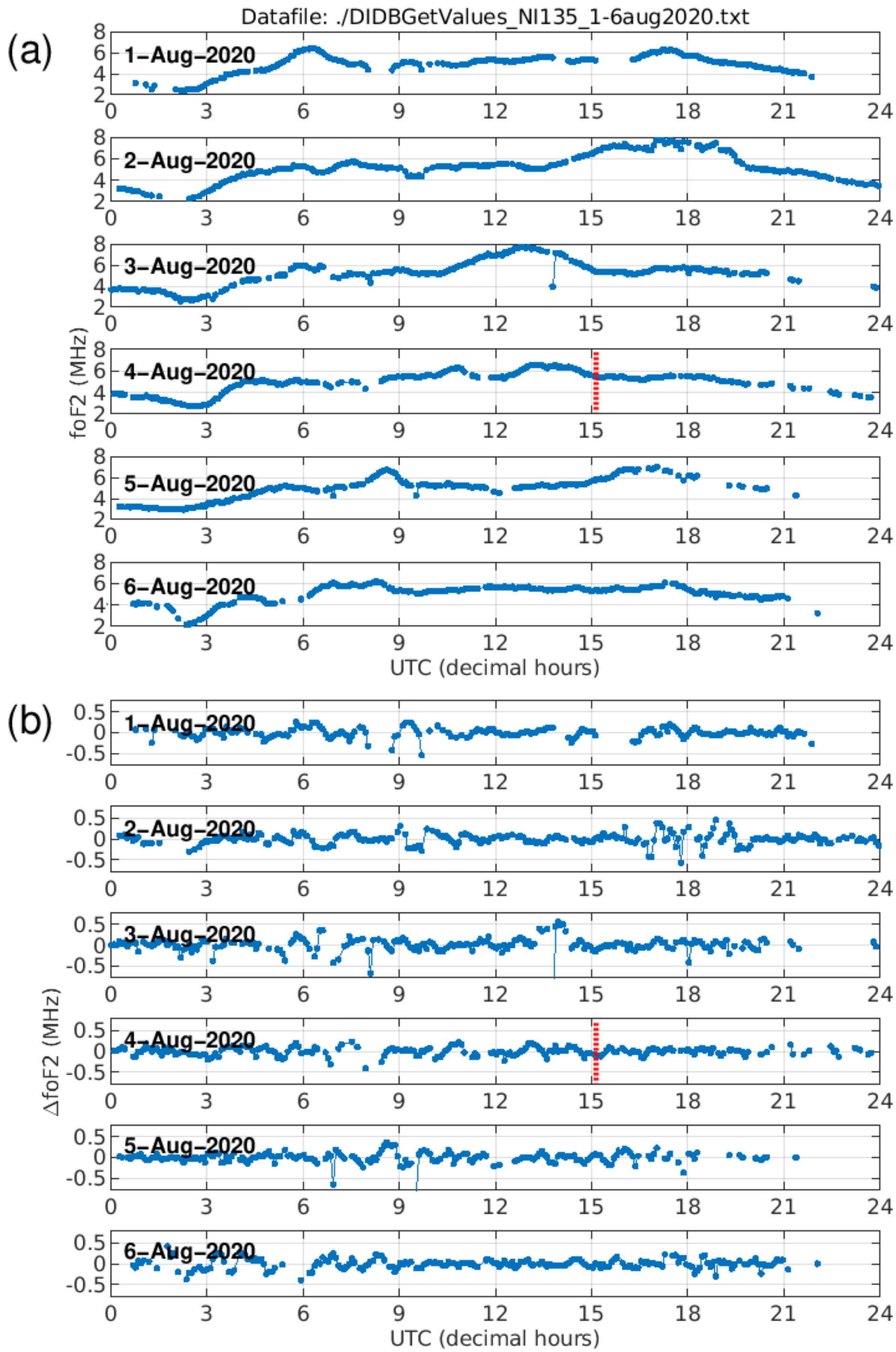

Figure S1. Time series plots of (a) *f*oF2 and (b) detrended *f*oF2 values from the Nicosia ionosonde station on 1-6 August 2020. Dashed vertical red line indicates the time of explosion at Port Beirut on 4 August 2020.

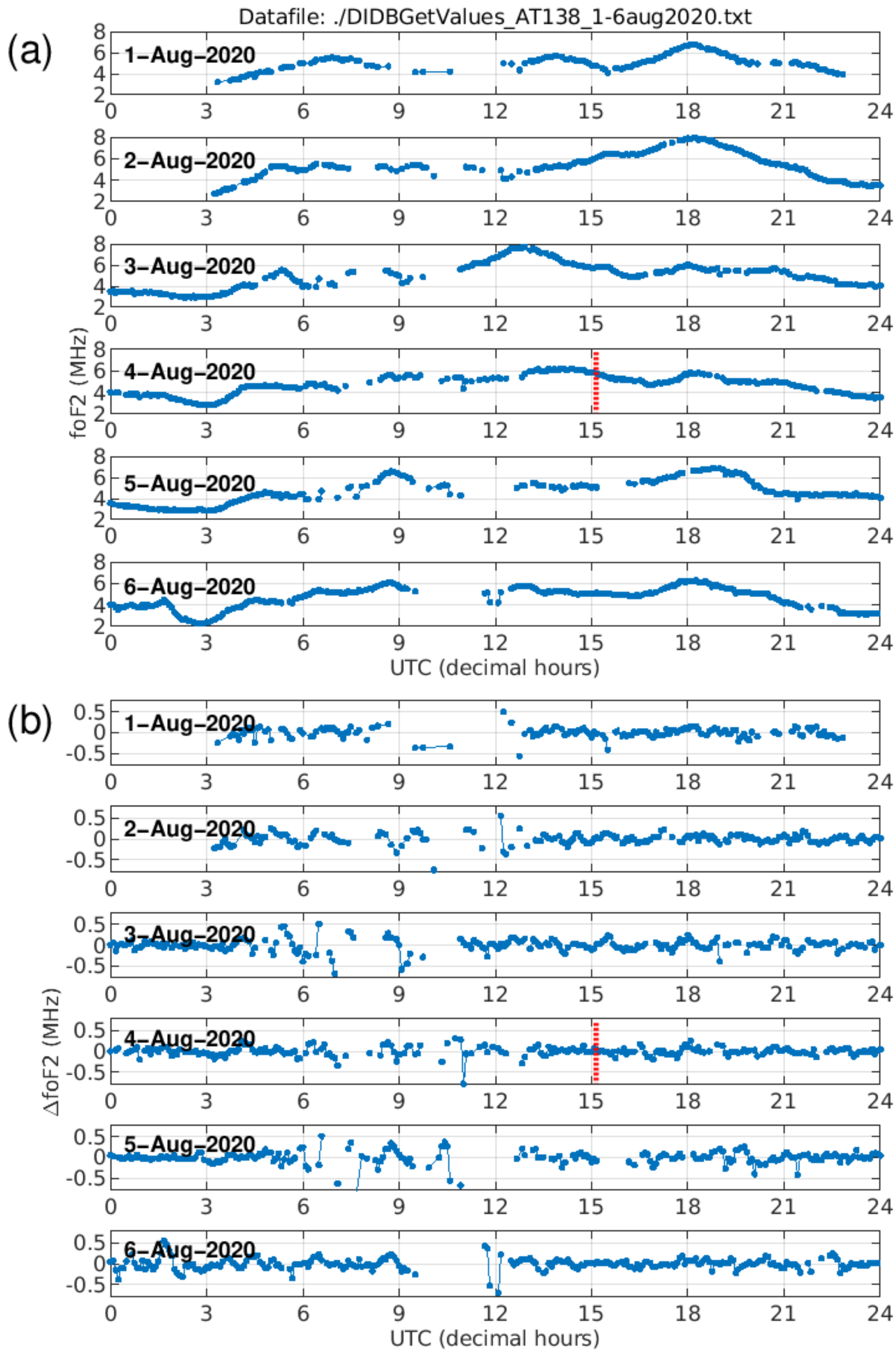

Figure S2. Time series plots of (a) *f*oF2 and (b) detrended *f*oF2 values from the Athens ionosonde station on 1-6 August 2020. Dashed vertical red line indicates the time of explosion at Port Beirut on 4 August 2020.

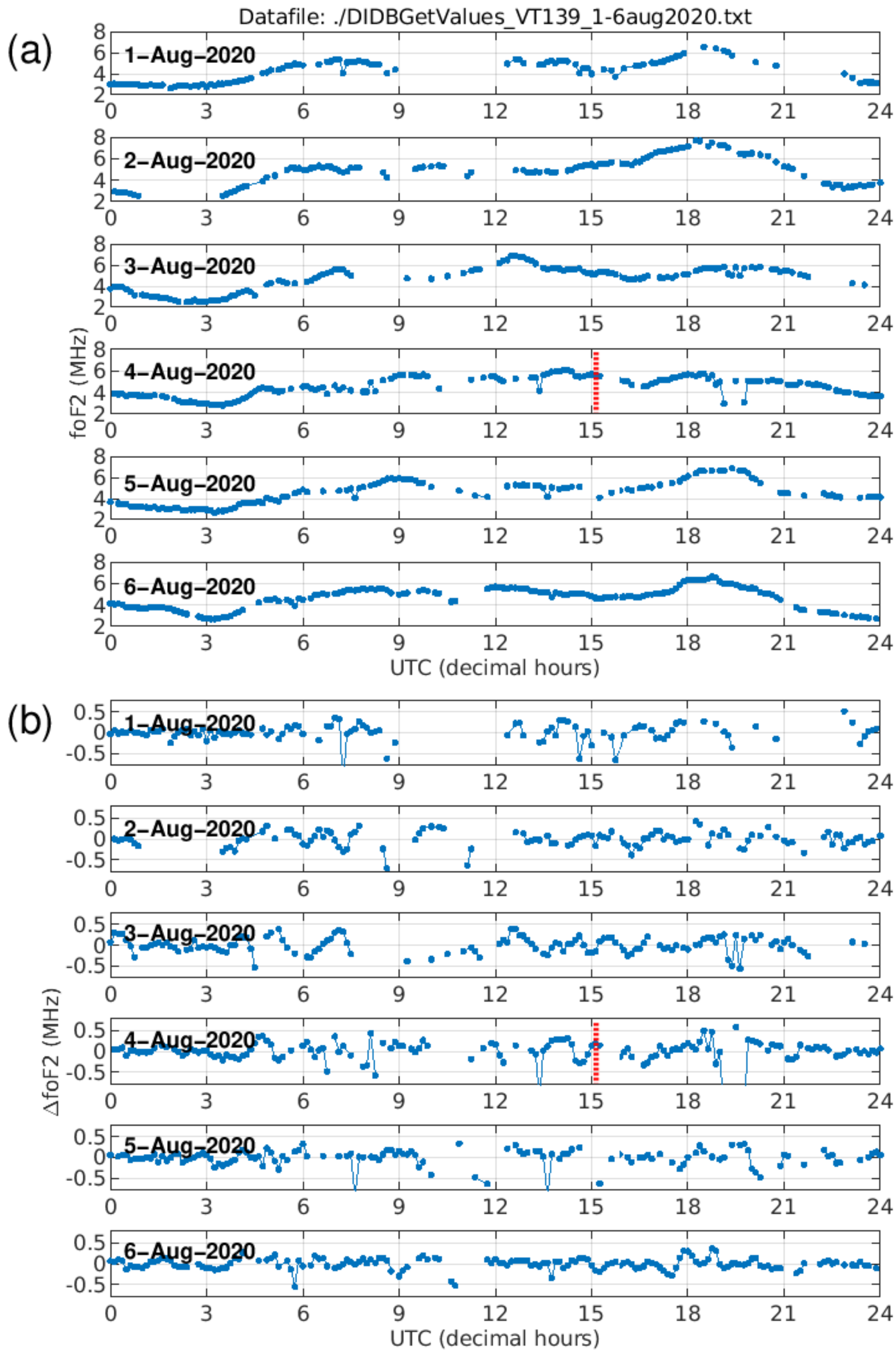

Figure S3. Time series plots of (a) *f*oF2 and (b) detrended *f*oF2 values from the San Vito ionosonde station on 1-6 August 2020. Dashed vertical red line indicates the time of explosion at Port Beirut on 4 August 2020.

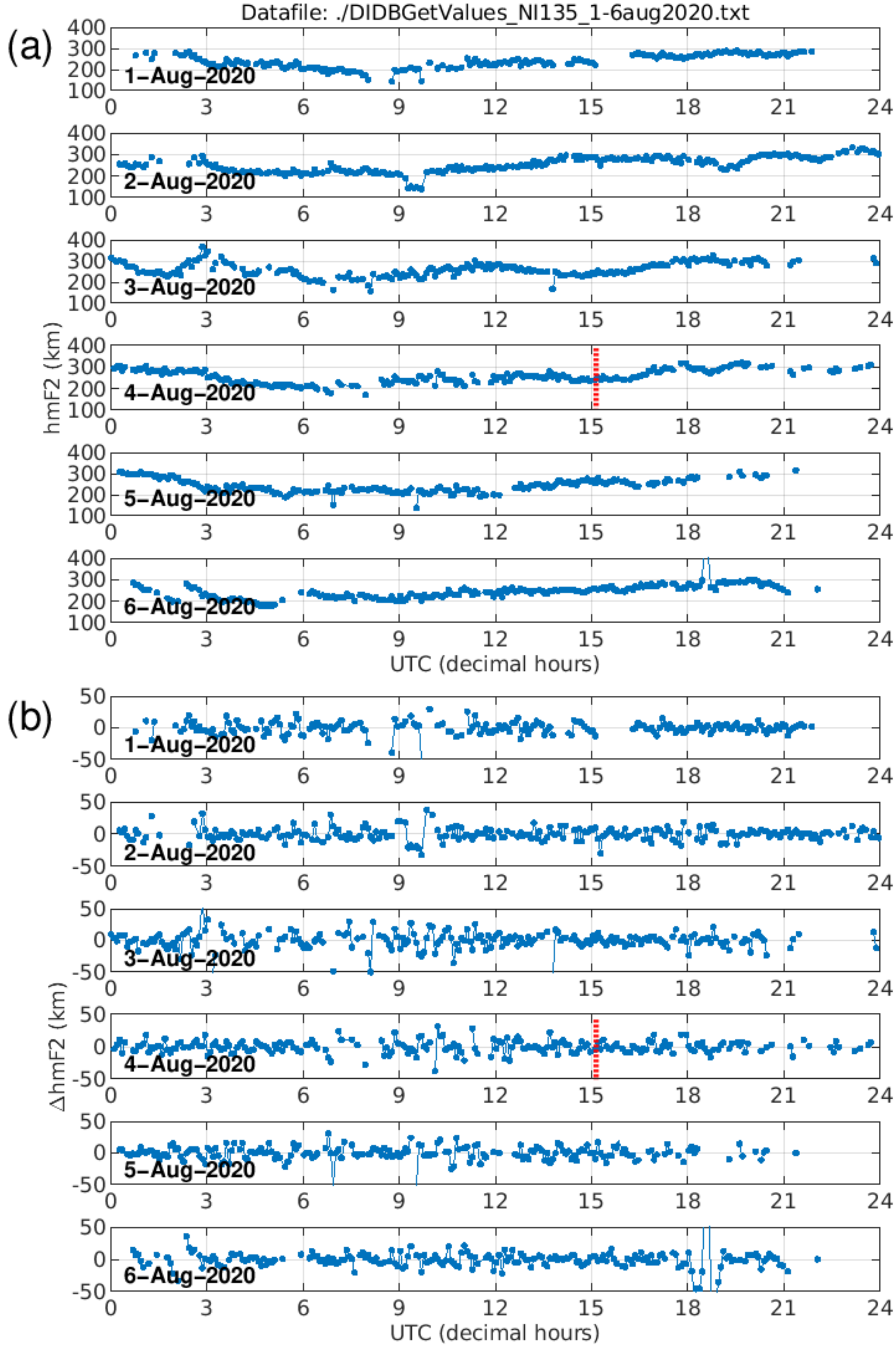

Figure S4. Time series plots of (a) hmF2 and (b) detrended hmF2 values from the Nicosia ionosonde station on 1-6 August 2020. Dashed vertical red line indicates the time of explosion at Port Beirut on 4 August 2020.

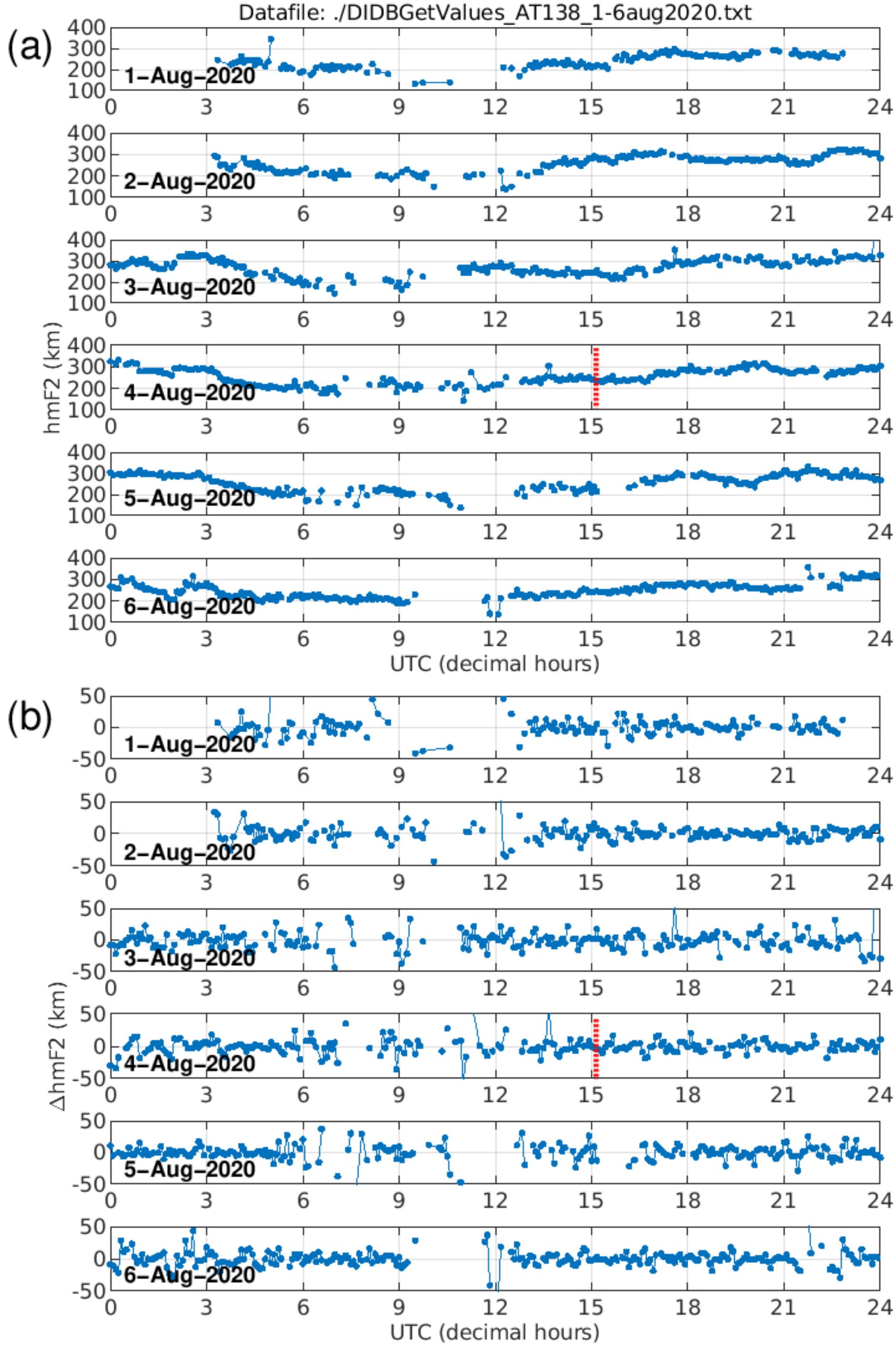

Figure S5. Time series plots of (a) hmF2 and (b) detrended hmF2 values from the Athens ionosonde station on 1-6 August 2020. Dashed vertical red line indicates the time of explosion at Port Beirut on 4 August 2020.

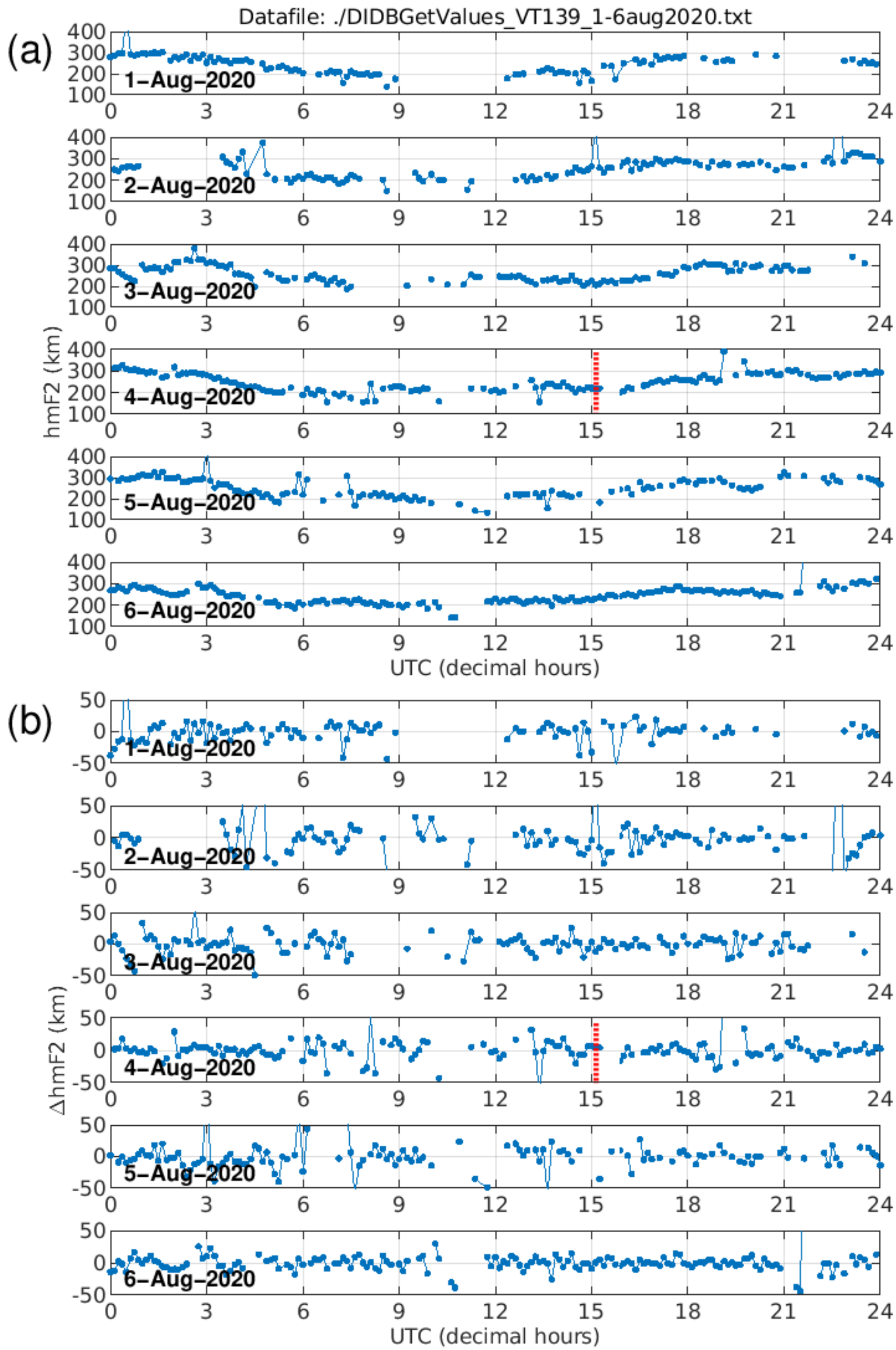

Figure S6. Time series plots of (a) hmF2 and (b) detrended hmF2 values from the San Vito ionosonde station on 1-6 August 2020. Dashed vertical red line indicates the time of explosion at Port Beirut on 4 August 2020.

2 Characteristic Signatures of TIDs in Individual Ionograms

The formations of characteristic loop/twist and Y-forking features in ionograms are the direct result of concave indentation in the ionospheric isodensity contour overhead the ionosonde station. This would be the situation if the ionosonde is located under a trough of the TIDs, with two opposing TID crests on either sides. This geometrical setting can be illustrated using the diagram in Figure S7 below, adapted from Munro (1953) with some modifications.

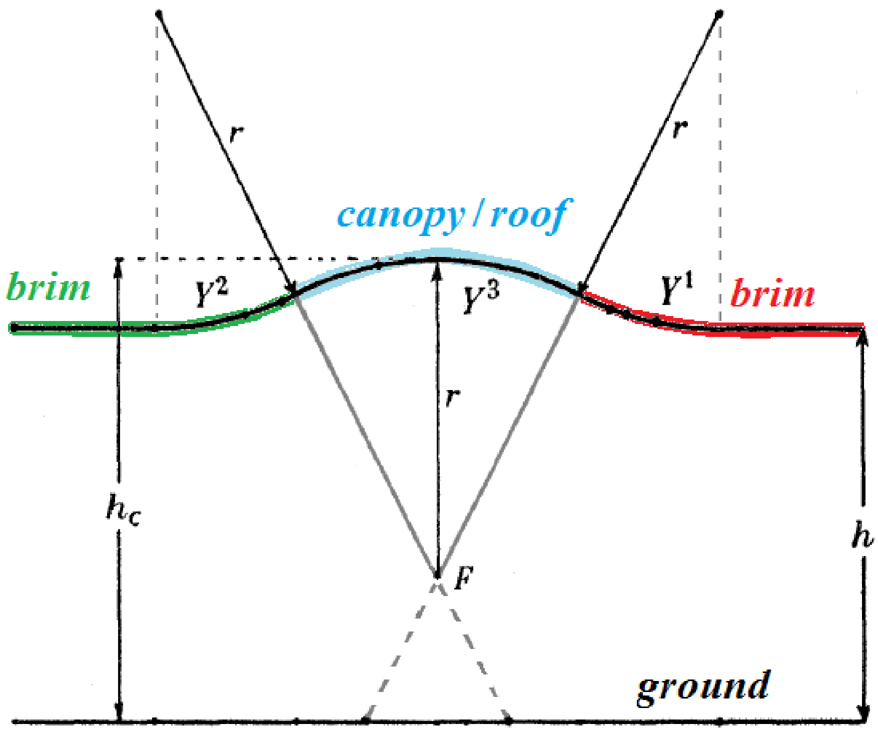

Figure S7. Diagram of concave indentation in ionospheric isodensity contour, which leads to the formation of anomalous ionogram traces.

As in Munro's (1953) paper, the indentation in ionospheric isodensity contour is constructed using a set of circular arcs and straight-line segments. The middle part of the indentation may be called the canopy/roof (colored cyan; labeled Y^3). The two sides of the indentation may be called the brims (colored red/green; labeled Y^1/Y^2). The brims smoothly extend to the ambient (straight-line) parts of the isodensity contour. Depending on the position of the ionosonde (at ground level) relative to the indentation, return signals may come from the left brim, the right brim, and/or the canopy. A geometrical construction of indentation in the isodensity contour based on circular arcs and straight-line segments allows a straightforward rule for determining whether the ionosonde will receive a return signal or not. Normal ray incidence on the isodensity contour would result in a return signal back to the ionosonde, where normal direction is pointing radially away from the center of the corresponding circle. Otherwise, there would be no return signal back to the ionosonde.

The loop/twist feature can occur if the ionosonde is positioned asymmetrically with respect to the center of the indentation, and the TID wavefront is significantly slanted/tilted from the vertical. On the other hand, the Y-forking feature will occur if the ionosonde is positioned symmetrically with respect to the center of the indentation, and the TID wavefront has little/no tilt (i.e. relatively close to vertical orientation). These geometrical configurations are illustrated in the diagrams in Figure S8 below, adapted from Munro (1953) with some modifications.

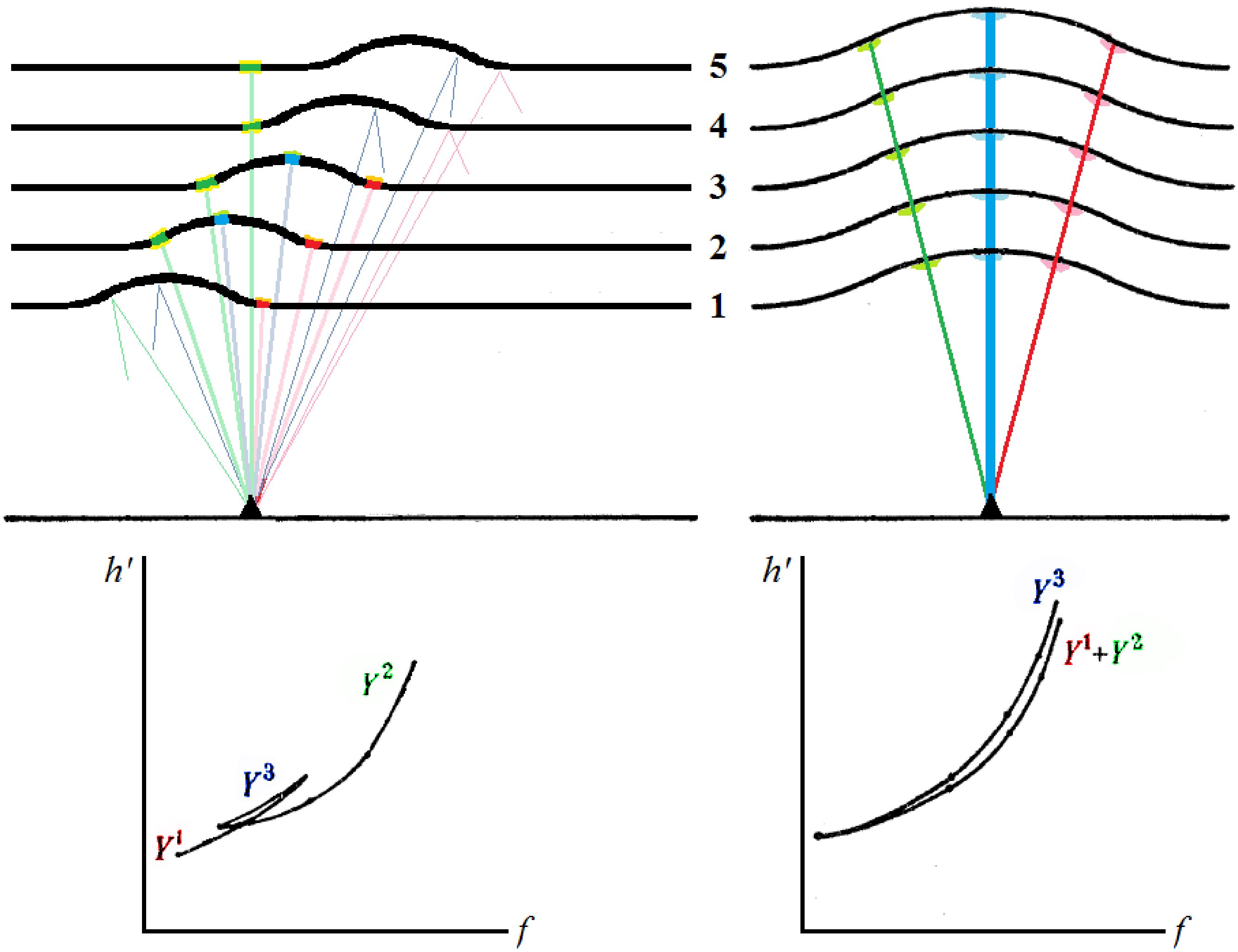

Figure S8. Schematic diagram of situations that lead to the formation of loop/twist feature and Y-forking feature in the ionogram traces.

In Figure S8, five representative ionospheric isodensity contours at increasing heights are shown, numbered accordingly. A few sample rays from the ionosonde are drawn, generally aimed at either the brims or the canopy/roof of the indentation at each contour level. Rays that are launched toward the left (right) brim are displayed with green (red) color; whereas rays that are launched toward the canopy/roof are displayed with blue color. Some of the emitted rays do not result in a successful return signal for the ionosonde, representing situations where normal incidence is impossible given the configuration. For clarity, if an emitted ray results in a successful return signal, the location of the reflection is marked/highlighted on the corresponding isodensity contour.

The diagrams on the left in Figure S8 illustrate the configuration that leads to a loop/twist feature in an ionogram. Due to the tilt angle of the TID structure, direct returns from the right brim (red color) only come from the lowest isodensity contours (No. 1-3). At higher contour lines (No. 4 and 5), the rays reflected by the right brim of the indentation cannot return because the right brim is located too far toward the right to allow normal incidence. This causes the return echoes from the right brim (labeled Y1) to appear only at lower frequencies of the synthetic ionogram. The opposite happens with rays that are directed toward the left brim (green color). In this case, due to the tilt angle of the TID structure, direct returns cannot happen at the lowest contours (No. 1) since the left brim is located too far toward the left. Direct returns from the left brim can only come from the higher contours (No. 2-5) as the overhead contour straightens out at higher altitudes. This causes the return echoes from the left brim (labeled Y2) to occur primarily at higher frequencies in the synthetic ionogram. Meanwhile, direct returns from the canopy/roof of the indentation (blue color) can only happen from some intermediate altitudes (contours No. 2 and 3) due to the highly selective focusing properties of concave mirror. This causes the return echoes from the canopy (labeled Y3) to appear only within a narrow frequency interval. Collectively, the clustering and uneven separation of these three types of rays (canopy and left/right brims) at different altitudes creates the loop/twist feature in the synthetic ionogram.

The diagrams on the right in Figure S8 illustrate the configuration that leads to a Y-forking feature in an ionogram. Here the ionosonde is simultaneously looking at two different cross-sections of the ionosphere: one directly overhead (reflection from the canopy/roof of the indentation) and the other obliquely from the sides (reflections from the two symmetrically positioned brims of the indentation). This gives rise to the Y-forking feature in the synthetic ionogram.