Article

Supplementary Material for: Advantages of Geostationary Satellites for Ionospheric Anomaly Studies: Ionospheric Plasma Depletion Following a Rocket Launch

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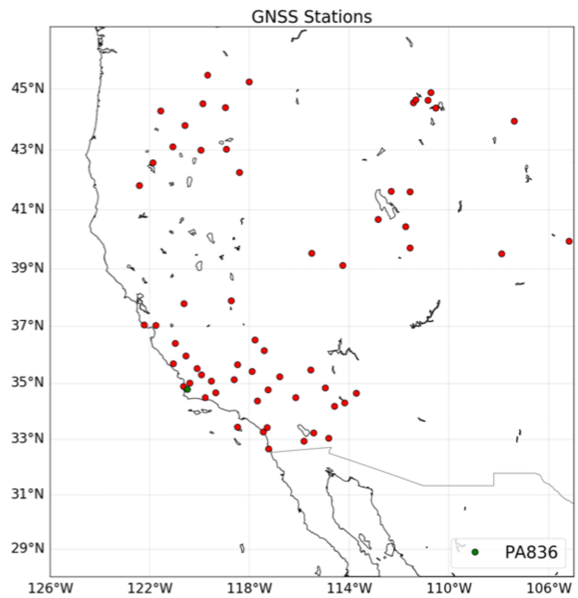

Figure 1. Map indicating the network of GNSS stations (red dots) used in this paper. The green dot represents the ionosonde site PA836.

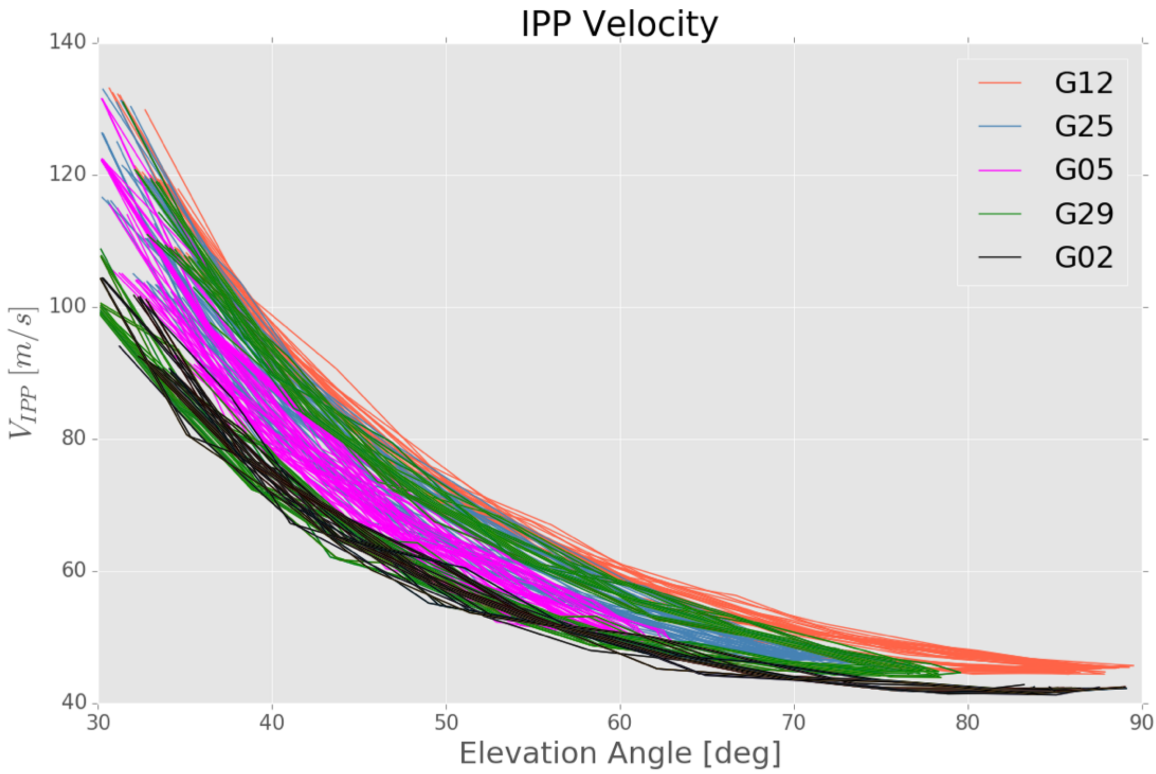

Figure 2. IPP Velocity magnitude plotted as a function of the elevation angle computed for 5 GPS satellites in view from the network of GNSS stations in Fig. S1. It is clear that the magnitude of the Vipp vector increases for lower elevation angles. A first attempt to model the IPP velocity as a function of the elevation angle is described in [25] using an Earth's spherical approximation.

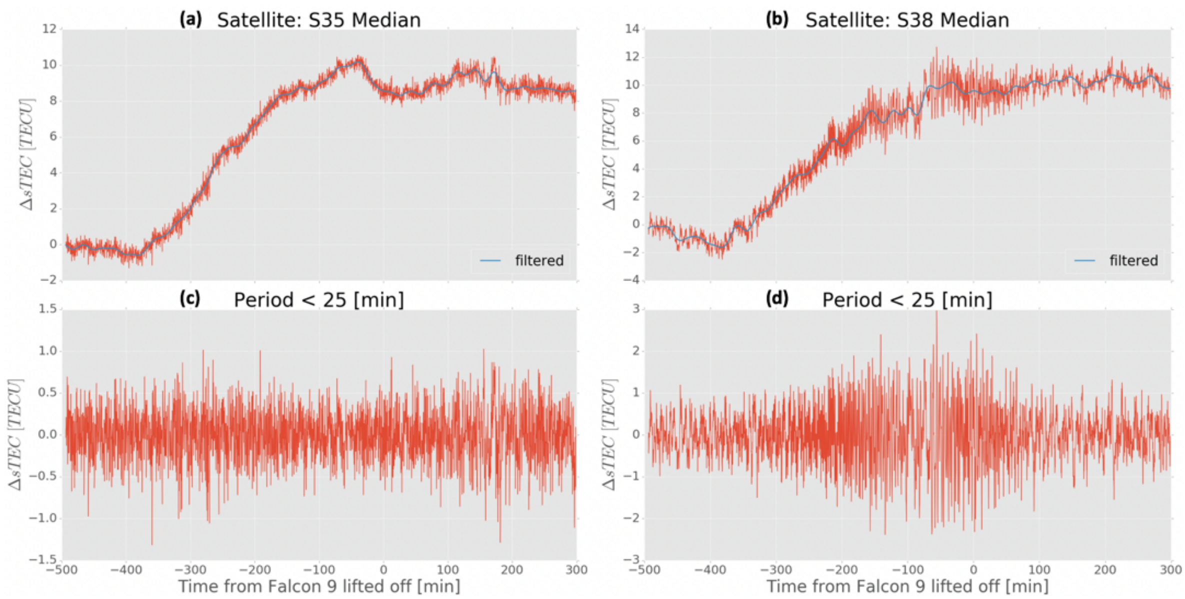

Figure 3. (**a**, **b**) show the median curves (red) computed from the unfiltered VARION-GEO $\Delta sTEC$ solutions located more than 700 km away from the ionospheric hole, for satellites S35 and S38, respectively. The blue curves represent the low- pass filter. (**c**, **d**) show the residuals between the median and the low-pass filter. These residuals represent the high- frequency noise term extracted for the two GEO satellites.

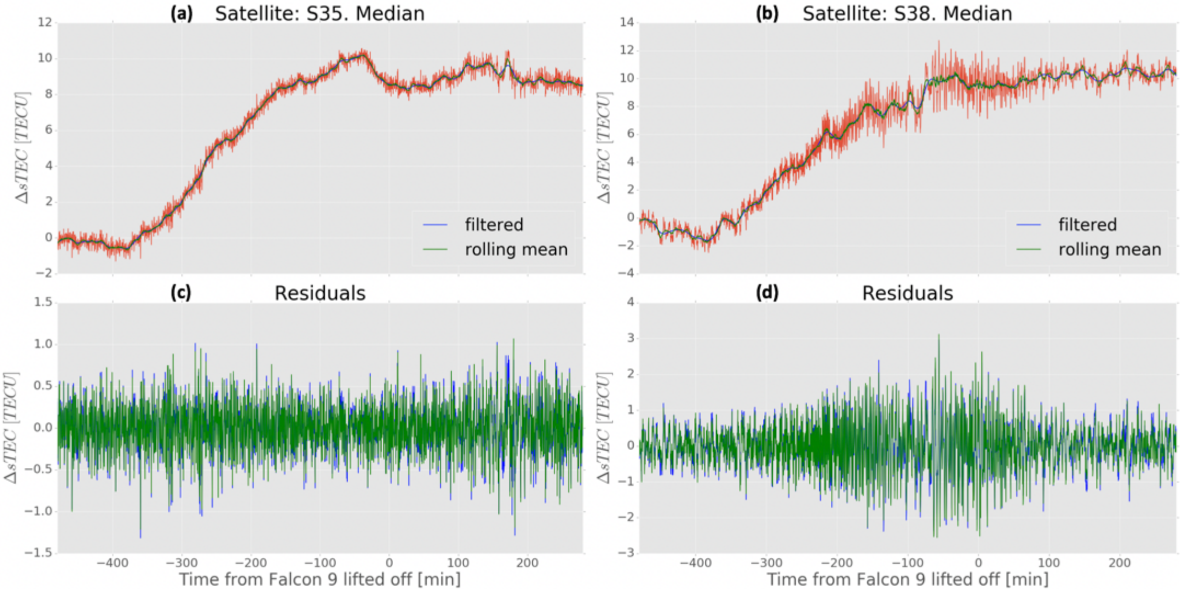

Figure 4. (**a**, **b**) show the median curves (red) computed from the unfiltered VARION-GEO $\Delta sTEC$ solutions located more than 700 km away from the ionospheric hole, for satellites S35 and S38, respectively. The blue curves represent the low- pass filter, and the green curves represent the rolling mean. (**c**, **d**) show the residuals between the median and the low-pass filter (blue), and between the median and the rolling mean (green). These residuals represent the high-frequency noise term extracted for the two GEO satellites, and a good agreement was found between the low-pass filter and the rolling mean filtering technique.

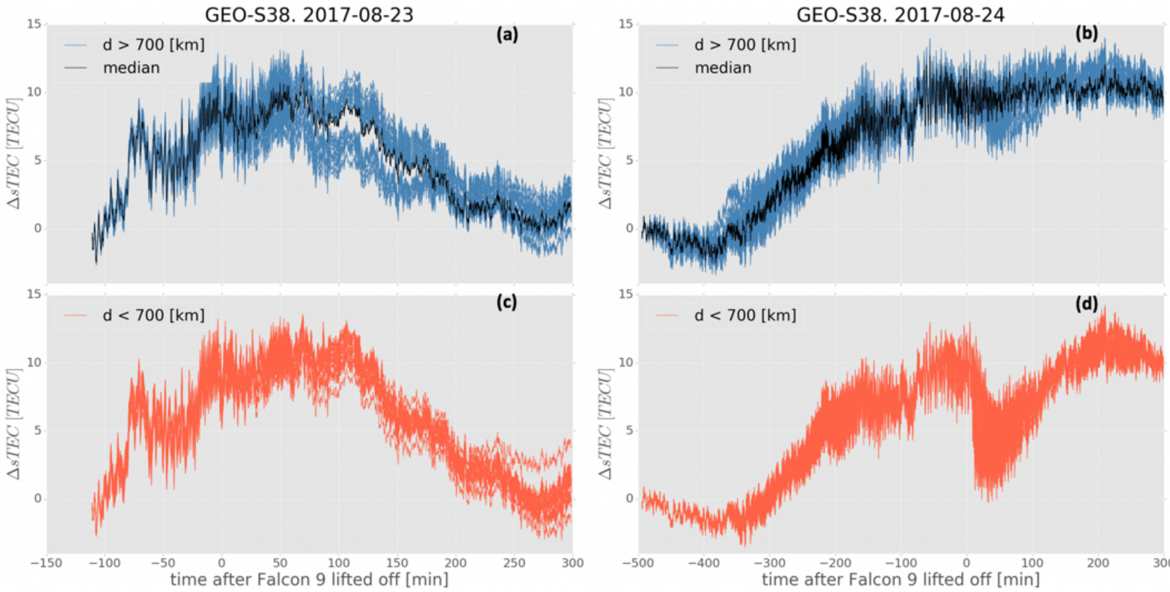

Figure 5. VARION-GEO $\Delta sTEC$ results for satellite S38. Day before (left column) and day of the event (right column). The first row (**a**, **b**) represents the unfiltered VARION-GEO $\Delta sTEC$ solutions far from the ionospheric hole (distance greater than 700 km). Time zero represents the time of the Falcon 9 launch (11:51 a.m. PDT). The second row (**c**, **d**) represents the unfiltered VARION-GEO $\Delta sTEC$ solutions close to the ionospheric hole (distance smaller than 700 km).

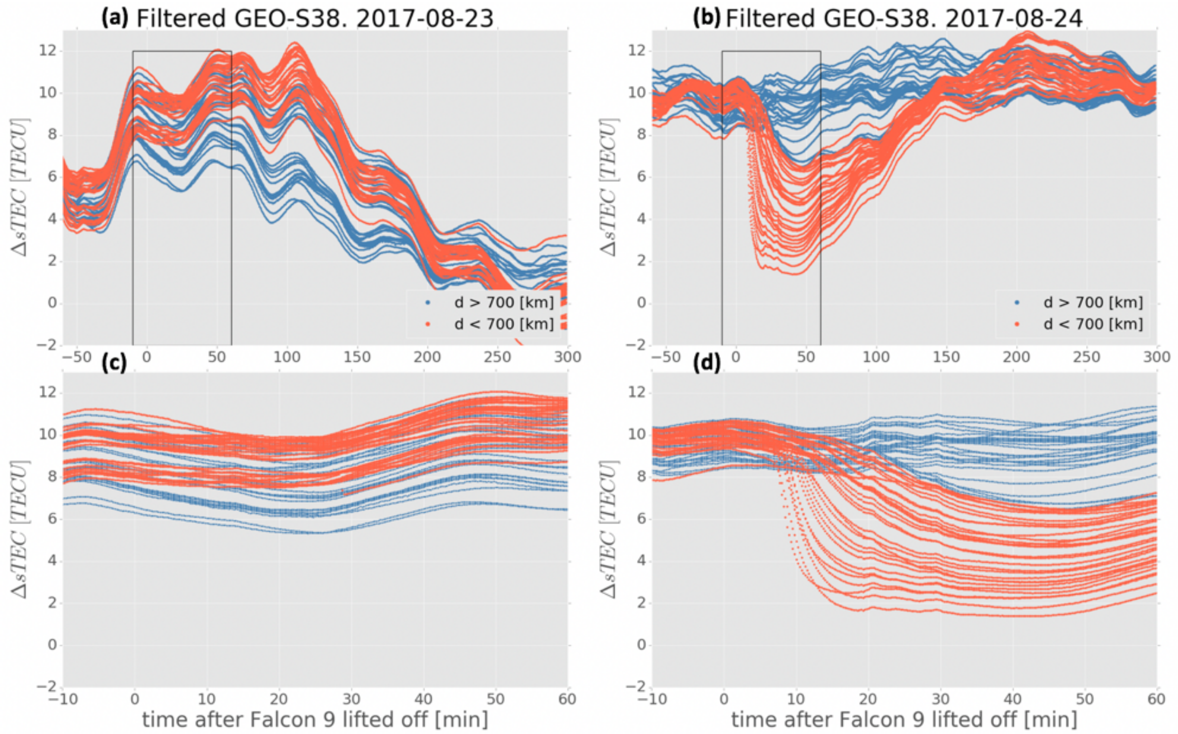

Figure 6. Filtered VARION-GEO $\Delta sTEC$ results for satellite S38. Day before (left column) and day of the event (right column). The first row (**a**, **b**) represents the solutions far from the ionospheric hole (blue curves) and close to the ionospheric hole (red curves). Time zero represents the time of the Falcon 9 launch (11:51 a.m. PDT). The second row (**c**, **d**) is a zoom in 10, 60 min before and after the launch. The ionospheric depletion is clearly captured by the filtered VARION-GEO solutions near the ionospheric hole for the day. No depletion is showed either the day before or far from the hole.

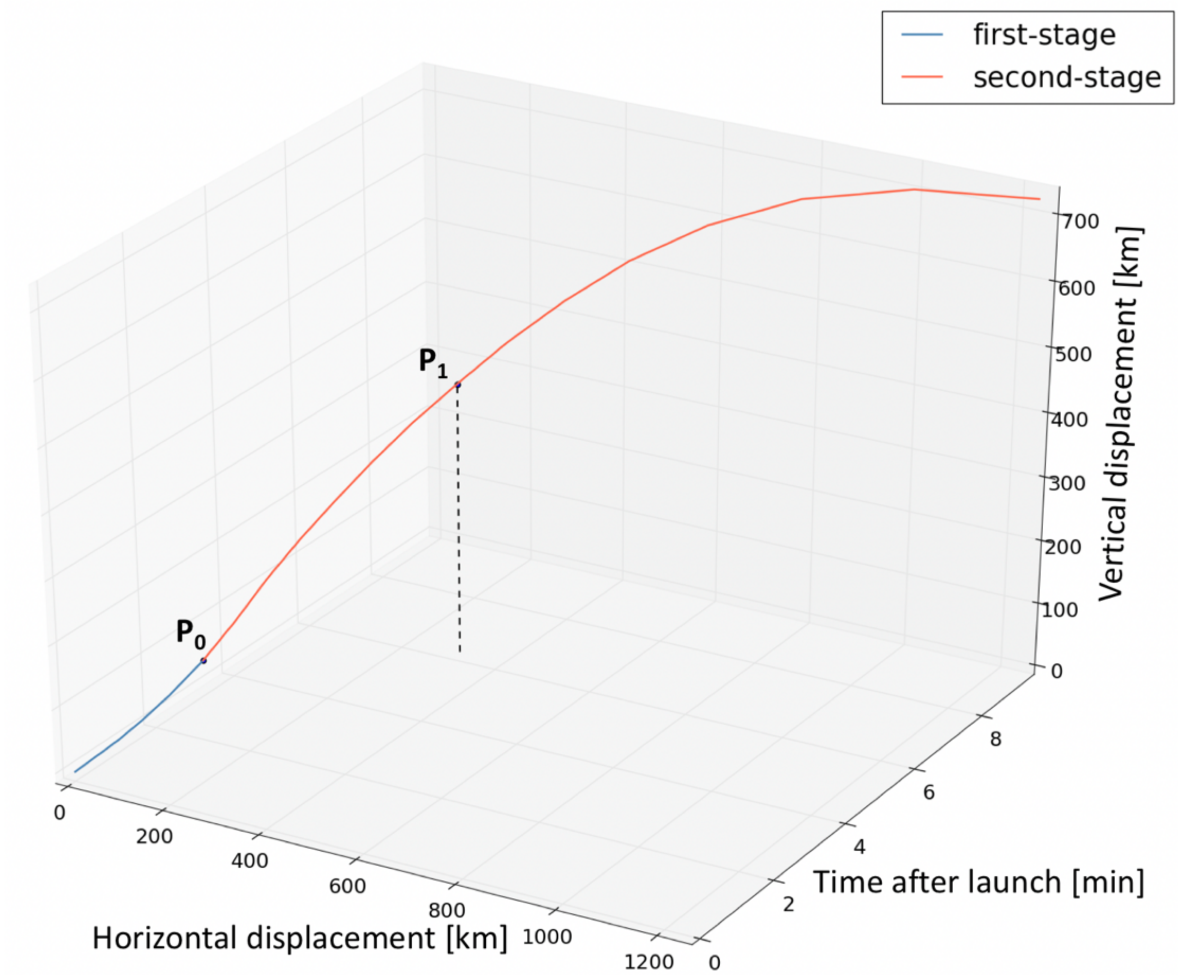

Figure 7. Falcon 9 estimated vertical and horizontal displacements as a function of time. P_0 represents the moment when the first-stage ended and the second-stage engine started burning throughout the 85 to 721 km altitude range. P_1 is the point we considered as emission source in the diffusion model simulation. In P_1 (6.25 min after launch), the rocket travelled 360 km horizontally and 450 km vertically.

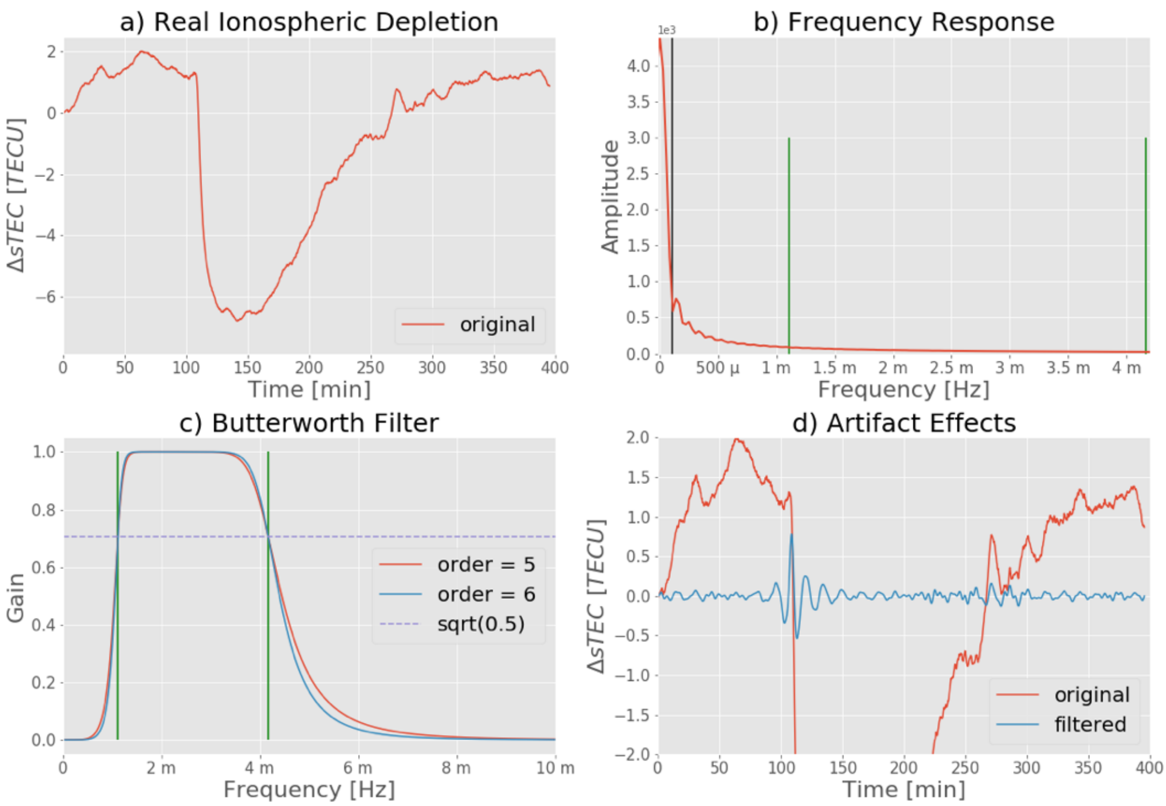

Figure 8. Frequency response to a non-periodic signal. In (**a**) the VARION-GEO $\Delta sTEC$ time series, as detected by satellite S35 at station P215. The frequency content of this signal (**b**) clearly highlights that most of the spectral energy is between 0 and 1/T Hz, where T is around 3 hours (black vertical line), which is due to the dominant period of the recovery from the depletion phenomenon. Due the abrupt decrease of TEC when depletion develops, if we apply a band- pass Butterworth filter of 5th order for the band 4-15 minutes (represented by the two vertical lines in (**b**) and (**c**)), and we transform back to the time domain, we generate a clear artifact (**d**) in the sTEC time series, known as Gibbs (or "ringing") effect around the epoch of depletion starting time

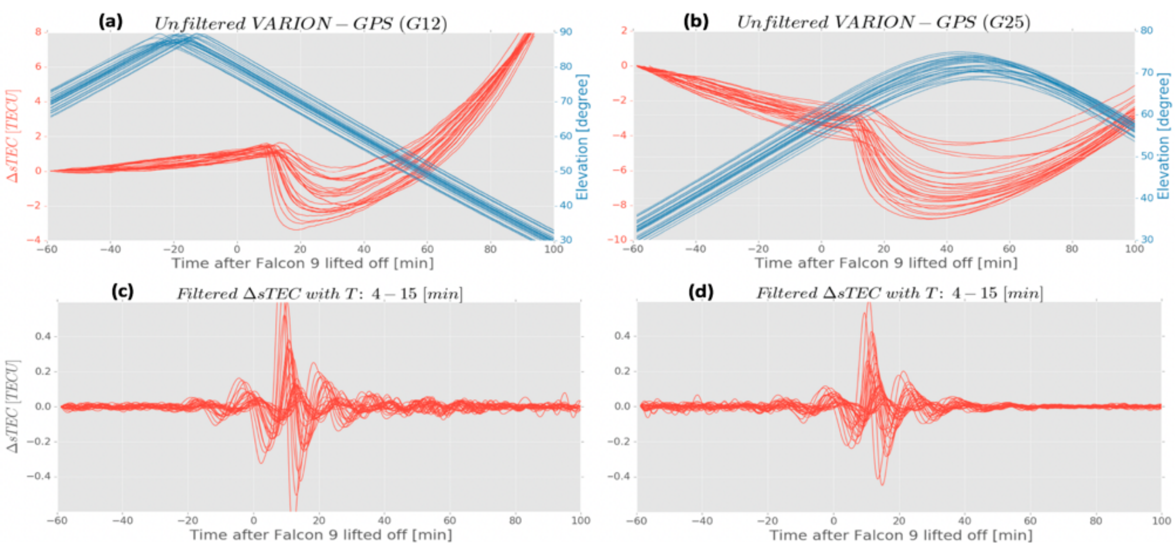

Figure 9. The effect of the Butterworth band-pass filter (4-15 minutes) applied to the VARION-GPS $\Delta sTEC$ solutions for satellites G12 and G25. This standard filtering technique clearly generates a non-physical sTEC perturbation (so called Gibbs effect) in the time series (**c**, **d**).

It has to be underlined that the highlighted Gibbs effect can well explain the giant circular shock acoustic wave found in [20]; in fact, this artifact effect is clearly evident both in GEO (Figure S8) and in MEO (Figure S9) satellites data, independently from their positions (therefore it is an isotropic effect), with similar amplitudes (around 0.4-0.5 TECU) and epoch of secondary depletion (around 15 minutes after the launch), which are in good agreement with the results presented in [20]. In addition, the Figure 2 at page 175 of [20] shows a clear Gibbs effect: the ionosphere disturbance is evident also before the rocket launch. Overall, the claimed giant circular shock acoustic wave, not found in our investigation, can be just an artifact due to the improper use of Butterworth filter.

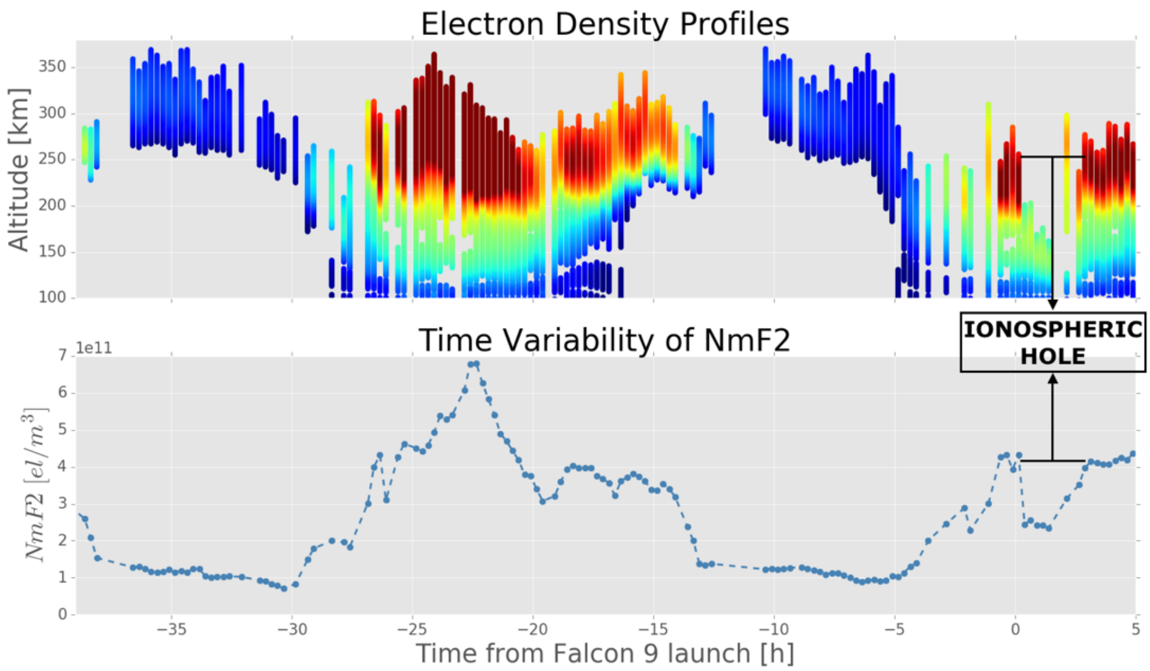

Figure 10. (**a**) Ionosonde electron density profiles, and (**b**) and NmF2 time variability extracted from the site PA836 every 15 minutes. The time interval considered is about 45 hours ranging 40 hours prior and 5 after the Falcon 9 launch. The rocket induced ionospheric hole occurred around 1 hour before the ionosphere reached its expected daily maximum of ionization (around 13:00 PDT).

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Conflicts of Interest: The authors declare no conflict of interest.