Reply to Reviewer 1

We are very grateful to the Reviewer for the evaluation of this manuscript and for raising very interesting points and suggestions.
Apologies for the delay in the reply, due to annual leaves and some other commitments.
Before implementing any changes, we have prepared some answers and reflections, together with suggestions of possible changes that could be made.
We wonder whether these may be in the right direction?
The text of the Referee's report (in normal font type) is followed by our reply in Italic.

Review of egusphere-2026-1741

First demonstration of the combination of observations and datasets from diverse instruments (in a coordinated experiment using KAIRA, EISCAT, GNSS) that enables the extraction of new information about the ionosphere

by Biagio Forte et al.

The title seems rather long and should be shortened.

Yes, it is rather long. We propose a new title as follows::

> *"Combining observations from different instruments (KAIRA all-sky imaging, EISCAT, GNSS) for a novel ionospheric sounding."*

The study provides a novel combination of data from different instruments during a campaign and discusses the observed high-latitude ionospheric changes and effects on VHF and GNSS related radio waves. Generally the manuscript is well written, figures are of good quality, and the discussion clear. But not throughout, and I have suggestions for improvements.

Many thanks for the suggestions.

The term "ionisation gradient" occurs 22 times in the discussion, but in quite different contexts, and I have difficulties to see (a) clear definition(s) of the term and what exactly is meant. In lines 55, 58, 807, 874-875 it is associated with observed ROT values, which are temporal changes. At other places rather spatial gradients seem to be meant, lines 66, 731-732, 857. Generally the discussion of temperal vs spatial changes should be clarified, and assumptions that are made when inferring one from the other should be stated.

We propose inserting the following two paragraphs of text at line 152:

> *"Ionisation gradients in the ionosphere manifest through changes to the electron density over a spatial distance. These gradients introduce inhomogeneities (or irregularities) in the spatial distribution of the electron density in the ionosphere. These ionospheric irregularities can generate propagation effects on radio waves traversing them provided that the ionisation gradients associated with these irregularities are intense enough to*

be detected by a given instrument. In general, irregularities can form over large scales (approximately of the order of tens of kilometres) and over small scales (smaller than approximately few kilometres). In the presence of turbulence, an energy cascade produces irregularities over spatial scales from large to small.

This study estimates ionisation gradients by utilising the evidence from a diverse set of instruments. An important aspect is that some instruments can detect temporal gradients whereas others can detect spatial gradients. Furthermore, with some of these instruments, it is difficult to disentangle spatial gradients from temporal gradients, given the technique utilised to perform the observations (e.g., GNSS). This study attempts to estimate temporal and spatial gradients occurring in the ionosphere from the propagation effects that they generate on measurements from different instruments."

We also propose adding the following text at line 667:

"Some of the instruments can detect temporal gradients whereas other instruments can detect spatial gradients. For example, GNSS can estimate ionisation gradients in terms of TEC changes over time: however, at different times the line of sight to a given GNSS satellite has changed, which implies that spatial gradients from GNSS observations can be inferred only by assuming that the ionisation structures have not changed during the GNSS ray path scanning through them. On the other hand, EISCAT can appreciate ionisation gradients along a given beam direction (by considering the electron density profile along that beam). Changes in ionisation can be noticed between consecutive EISCAT beams: if these beams were pointing along different directions, then spatial gradients can be inferred by assuming that the ionisation structures have not changed during the time that the EISCAT beam was repositioning. In the case of traditional ionospheric measurements, the inference of spatial gradients from temporal gradients is therefore based on the assumption that no changes occurred during the repositioning of beams or of lines of sight to satellite positions. On the other hand, in all-sky imaging mode, KAIRA can detect spatial gradients occurring over the array: when all-sky images are evaluated in time, it is possible to also infer a temporal evolution for these spatial gradients."

Generally spatial gradients along the magnetic field are large scale and weak, because of the high mobility of charge particles along B (an exception is sporadic E mentioned in the manuscript). Perpendicular to B diffusion is greatly Inhibited, and steep and smaller scale gradients can exist. Therefore the orientation of the observations, especially the Cas A line-of-sight with respect to B should be presented, perhaps indicated in Figures etc.

We are in the process of calculating the angle between the KAIRA beams and the magnetic field lines. Once calculated, we will add this detail to the Figure 1 caption.

Lines 50-55: "... temporal fluctuations ... of TEC, ROT from GNSS ... were utilized to infer ... the type of ionisation gradients originating specific propagation effects." Here is not clear to me how spatial gradients can robustly be infered from temporal changes as indicated by ROT and ROTI such inference? GNSS signal paths move through the ionosphere as the GPS/Galileo/GLONASS satellites in MEO. This may justify that detected temporal changes of TEC (ROT) correspond to quasi-stationary ionization structures and density gradients in the ionosphere. For example, Nguyen et al. (2022) studied irregularities and scintillations using ROTI maps. However, especially at high latitudes as is here the case, particle precipitation can be a rapidly changing source of ionisation, and this would not necessarily correspond to spatial density gradients.

This is a very good point. Hopefully, the additional text suggested above (regarding the distinction between spatial and temporal gradients as well as what type of gradients each instrument can detect) can explain this aspect more.
However, we can try to provide an estimate of spatial gradients from GNSS observations, by converting ROT in units of TECU/km. This can be done by estimating the distance between ray paths over consecutive times at either E or F region altitudes.
We had in fact previously attempted a similar calculation on the basis of EISCAT TEC changes although it is not shown in the current version. We will investigate the possibility of adding such "spatial gradient" figures, or if the differences are minor, simply mention the estimate for the spatial gradients obtained from GNSS and EISCAT.

Lines 55: "... the type of ionisation gradients originating specific propagation effects." Linguistically perhaps change ".. originating .." --> ".. causing .." or ".. producing .." or ".. generating .." or so"?

Changed to "causing".

Lines 58-59: "... that weaker ionisation gradients ($|ROT| \lesssim 0.2$ TECU min^{-1}) can induce VHF scintillation but may not be detectable through GNSS and EISCAT ... " I'm not certain about the different connections implied by this statement. VHF scintillations refers to KAIRA observations, while ionisation gradients seem to refer to temporal ROT. EISCAT can sometimes detect spatial ionization gradients but not VHF scintillations (even if one analyzed the EISCAT raw data, EISCAT/ESR is at UHF not VHF). Are you saying that GNSS detects scintillations (though GNSS also would be UHF or L-band in IEEE classification), but EISCAT is not sensitive enough/has insufficient resolution to detect a corresponding gradient? Please clarify.

There are gradients in the ionosphere (i.e., changes to the electron density over a spatial distance or over an interval of time) that can generate temporal fluctuations in the phase and intensity of radio waves received at an observing antenna. In order to be detected by an instrument, these gradients need to be intense enough to induce a change on the wavefront of the radio waves traversing these gradients. Not all the gradients will be capable of inducing intensity scintillation: this only happens if the gradients are intense enough over spatial scales in the inertial subrange (small *scales). Large-scale gradients can still induce phase changes (not intensity scintillation): phase changes caused by large-scale irregularities can be identified by using the rate of change of TEC. Lines 58-59 mean that there can be small-scale irregularities (or gradients) capable of inducing scintillation on VHF radio waves, but without any large-scale irregularities (given the absence of phase fluctuations on GNSS and the absence of any clear structure on EISCAT profiles).*

The text changes we proposed above (after line 152 and after line 667) should also explains this aspect more in detail.

Lines 117-118: "... as well as to extract information on the ionosphere in a reliable approach. This is also true for proposed systems on the far side of the Moon (Gorgolewski, 1965), ..." It is not clear what is meant here. Radio astronomical signals on the far side of the Moon do not need the traverse the Earth's ionosphere (except for communicating possibly pre-analysed results back to Earth)? Or do the authors mean that plasma processes in the solar corona which are remotely similar as in the partially ionized ionosphere would affect radio astronomy?

The radio waves that would be detected from the far side of the Moon would only traverse the heliosphere. Here, the plasma density is much smaller than in the case of the ionosphere. This means that the plasma frequency in the heliosphere is much smaller than in the ionosphere. Therefore, lower radio wave frequencies can be observed from the far side of the Moon as compared to a radio telescope on Earth (where only frequencies above few MHz can traverse the ionosphere).

We can add this clarification as a footnote, if permitted.

Line 168-169: "... UHF/ESR Incoherent Scatter Radars (providing profiles of electron density along directions to Cas A as well as along magnetic field lines)." and Figures 9 and 10. It should be confirmed that the EISCAT UHF data, Figure 9 (a,c,i), Figure 10 (a) and (d) are along Cas A, and ESR, Figure 9 (b,d,f,h), Figure 10 (b,c) are field-aligned? The approximate elevation and azimuth of the Cas A following UHF beam should be mentioned, alternatively the relative angle with respect to the magnetic field.

Yes, EISCAT UHF beams were pointing along the directions to CasA whereas ESR beams were field-aligned.
These details appear at the beginning of section 2.2. We will add the value of the angle between KAIRA's beams and the magnetic field lines to the manuscript, probably as a range of representative values across the experiment, in addition to approximate values for the EISCAT beam's elevation angle.

Line 238: "The interval of time over which the $S4$ is estimated depends on the inertial subrange of the intensity fluctuations ..." --> "... as adjusted according to ..." or similar (because the time interval is chosen by the experimenter). In practice the estimated S4 index can also depend on the sampling rate of the I intensity. In line 213 cadences of 1 or 100 Hz is mentioned, please clarify which was used and if available whether the different cadences of 1 or 100 Hz made any difference for S4 estimation.

Given the value of the Fresnel frequency in the case of KAIRA VHF beamformed observations, the sampling interval of 1 s was enough to capture intensity fluctuations due to scintillation. A higher cadence would not make any difference (there would be no signal at higher sampling frequencies).

The following text will be added to that paragraph:

> *"…density (in this case within the ionosphere) and, in turn, by the temporal sampling interval (the current experiment utilised a 1 s sampling interval, which is enough to capture the intensity fluctuations due to scintillation and consistent with the corresponding Fresnel frequency). Here, an interval of 3 minutes (for a sampling interval of 1 s) was utilised under…"*

Line 421: "... which limited the operation of the single-dish ESR antenna ..." I think that the steerable 32m ESR antenna is meant. The ESR has two separate dishes, a fixed 42m dish pointing anti-parallel to the magnetic field in the F region, and the steerable 32m dish (which could, for example, follow Cassiopeia A).

The experiment used the ESR 42 m antenna to carry out field-aligned observations. The measurements had some gaps due to some technical difficulties.
The following text

> *"…caused technical difficulties which limited the operation of the single-dish 42 m ESR antenna…"*

will be added to that line.

Line 602-603: "... Rate of change of TEC (a measure of phase fluctuations on received radio signals) as observed by several IGS GNSS ground stations)", line 623 "Phase fluctuations as quantified through ROT on GNSS signals ..." Throughout the manuscript "phase fluctuations" are mentioned 23 times, but observationally the authors seem to assume that they are firmly associated with ROT and actually present only ROT to discuss phase fluctuations. According to Imam et al. (2024) and other articles the association is according to my reading not trivial. It should be mentioned that the association of ROT(I) with phase fluctuations is an assumption with limitations. Imam et al. (2024) analysed in depth data from the ISM station in Ny-Ålesund (Svalbard), and the data including actually observed phase fluctuations (σ_φ) perhaps would be available also for this campaign?

Phase fluctuations observed through GNSS here are those originated by irregularities forming over larger spatial scales (larger than approximately few kilometres). These fluctuations are distinct from those associated with phase scintillation, which are induced by small scale irregularities. The correspondence between ROT(I) and phase scintillation is indeed not trivial because (a) of the way the phase scintillation index is calculated and (b) because all irregularities between large and small spatial scales can induce a change to the observed phase.
In the current discussion, we only refer to phase fluctuations from large-scale irregularities. The ROT is a frequency-independent estimate of fluctuations to be

introduced by large scale irregularities (larger than approximately few kilometres in the case of GNSS). The objective here is to estimate ionisation gradients over spatial scales that are comparable between the different instruments: the inertial subrange for GNSS is an order of magnitude smaller than in the case of KAIRA beamformed observations.
Therefore, GNSS phase scintillation would not add any useful information.

The following text can be added to section 2.3:

> *"The emphasis here is to estimate phase fluctuations arising from irregularities forming over spatial scales comparable between the different instruments. In the case of GNSS, the type of phase fluctuations associated with ROT correspond to irregularities forming over spatial scales larger than approximately few kilometres. These spatial scales are comparable to the inertial subrange of the VHF intensity fluctuations detectable through KAIRA beamformed measurements."*

References

Imam, Raman, Lucilla Alfonsi, Luca Spogli, Claudio Cesaroni, Fabio Dovis (2024), On estimating the phase scintillation index using TEC provided by ISM and IGS professional GNSS receivers and machine learning, Advances in Space Research. https://doi.org/10.1016/j.asr.2023.07.039

Nguyen, C.T.; Oluwadare, S.T.; Le, N.T.; Alizadeh, M.; Wickert, J.; Schuh, H. Spatial and Temporal Distributions of Ionospheric Irregularities Derived from Regional and Global ROTI Maps. Remote Sens. 2022, 14, 10. https://doi.org/10.3390/rs14010010

Thank you. It is useful to add citations to these references to the text.