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## Article

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# Evaluation of a GNSS-derived RTK-RISK indicator against global space-weather indices during the May 2024 geomagnetic storm

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## ABSTRACT

Severe space-weather events can produce rapid temporal and spatial ionospheric disturbances that degrade high-precision Global Navigation Satellite System (GNSS) positioning. This study evaluates a regional GNSS-derived RTK-RISK indicator against independent global space-weather and geomagnetic indices during the extreme geomagnetic storm of 11 May 2024. RTK-RISK combines regional Rate of Total Electron Content Index (ROTI) variability and spatial vertical total electron content (VTEC) gradients derived from a Latvian continuously operating reference station network. The indicator and its individual components were compared with the geomagnetic Dst and Kp indices, the interplanetary magnetic field Bz component, its southward component Bs, solar-wind speed, and the coupling proxy  $V_{sw}B_s$ . Spearman rank correlation was used as the principal measure of association. The strongest statistically significant simultaneous relationship with RTK-RISK was observed for Dst ( $\rho = -0.63$ ). Kp showed a positive association of  $\rho = 0.65$ , although this relationship did not reach statistical significance ( $p = 0.078$ ,  $N = 8$ ) at its native 3-h resolution. Significant simultaneous associations were also observed for  $B_s$  ( $\rho = 0.41$ ),  $B_z$  ( $\rho = -0.40$ ), and  $V_{sw}B_s$  ( $\rho = 0.35$ ). The signs of these relationships were physically consistent with enhanced geomagnetic activity and southward interplanetary magnetic field conditions. The results indicate that the independently derived regional RTK-RISK indicator responds coherently to global space-weather conditions and provides a locally resolved measure of ionospheric disturbance relevant to RTK positioning reliability.

## Introduction

The ionosphere is one of the principal environmental factors affecting the performance of Global Navigation Satellite System (GNSS) positioning. Variations in ionospheric electron density modify the propagation of GNSS signals and can introduce spatially and temporally varying delays. Although dual-frequency observations largely remove the first-order ionospheric contribution, rapid temporal variations, strong spatial gradients, and small- to medium-scale plasma irregularities can still degrade carrier-phase positioning, ambiguity resolution, and the reliability of real-time kinematic (RTK) and network RTK solutions<sup>2,3</sup>. For differential positioning in particular, ionospheric conditions become increasingly important as the spatial separation between reference and rover receivers increases. Regional ionospheric disturbance indicators can therefore provide useful information on the expected reliability of high-precision GNSS positioning<sup>2</sup>.

GNSS observations also provide an effective means of monitoring the ionosphere itself. Total electron content (TEC) derived from dual-frequency GNSS observations is widely used to describe large-scale variations in ionospheric electron density, whereas the Rate of TEC Index (ROTI) is commonly applied to characterize shorter-term ionospheric irregularities<sup>4-6</sup>. ROTI is derived from the variability of the temporal rate of change of slant TEC and can be calculated using observations from standard geodetic GNSS receivers. Previous studies have demonstrated that enhanced ROTI values are associated with disturbed ionospheric conditions, plasma irregularities, scintillation, and degradation of GNSS positioning performance<sup>6-9</sup>. Recent multi-GNSS investigations have further shown that ROTI can be strongly related to conventional scintillation indicators and that increasing ionospheric irregularity may coincide with reduced positioning accuracy and reliability<sup>9</sup>. However, ROTI represents primarily the temporal variability of the ionosphere and does not directly describe the spatial decorrelation of ionospheric delays between geographically separated GNSS stations.

The ionospheric state is controlled by a complex combination of solar, interplanetary, magnetospheric, thermospheric, and electrodynamic processes. Independent solar-wind and geomagnetic parameters therefore provide an important external

reference for evaluating whether a GNSS-derived disturbance indicator reflects the broader space-weather environment. The north–south component of the interplanetary magnetic field (IMF),  $B_z$ , is particularly important because sustained southward IMF enhances solar-wind energy transfer into the terrestrial magnetosphere through magnetic reconnection. Solar-wind speed,  $V_{sw}$ , provides additional information on the intensity of the incident solar-wind flow, while combinations of solar-wind velocity and the southward IMF component can be used as simplified indicators of solar-wind–magnetosphere coupling. At the terrestrial response level, the planetary Kp index and the disturbance storm time (Dst) index are widely used to characterize global geomagnetic activity and geomagnetic storm intensity, respectively<sup>12–14</sup>.

Relationships between GNSS-derived ionospheric parameters and geomagnetic or solar-wind conditions have been investigated in numerous previous studies. Liu et al. analysed TEC and ROTI responses during a high-speed solar-wind event using solar-wind velocity, IMF  $B_z$ , Kp, Dst, and additional coupling parameters, showing that enhanced ionospheric irregularities occurred in association with disturbed solar-wind and geomagnetic conditions<sup>10</sup>. Such studies demonstrate the value of comparing locally or regionally derived ionospheric quantities with independent measurements representing different stages of the Sun–Earth interaction chain. More recently, Wang et al. developed a global ionospheric disturbed index based on ROTI derived from a large GNSS station network and investigated its statistical relationships with several external parameters, including Kp, Dst, SYM-H (symmetric H-component geomagnetic), Ap, F10.7, and upper-atmospheric wind fields<sup>11</sup>. These results support the concept that GNSS-derived ionospheric disturbance measures can be independently evaluated using established space-weather and geomagnetic indices.

The extreme geomagnetic storm of 10–11 May 2024 provides a particularly suitable event for such an evaluation. The storm was associated with multiple Earth-directed coronal mass ejections and resulted in exceptionally disturbed solar-wind, magnetospheric, and ionospheric conditions. Independent investigations of the event reported a minimum Dst of approximately  $-412$  nT together with strong variations in GNSS-derived TEC, detrended TEC, and ROTI at geographically distributed stations<sup>15</sup>. Analyses covering the interval from 8 to 13 May 2024 showed that ionospheric irregularities were substantially enhanced during the principal storm period compared with the surrounding less disturbed intervals. Storm-time ROTI values of several  $\text{TECU min}^{-1}$  were reported at some stations, while the magnitude and temporal evolution of the response differed considerably between geographic regions<sup>15</sup>. The combination of extreme geomagnetic activity, pronounced ionospheric disturbances, and extensive independent observations makes the May 2024 event an appropriate case for evaluating the behaviour of a regional GNSS-derived disturbance indicator.

To address the specific requirements of RTK positioning, a GNSS-derived RTK-RISK indicator was previously developed to combine two complementary characteristics of regional ionospheric behaviour: temporal variability represented by ROTI and spatial variability represented by vertical TEC (VTEC) gradients<sup>1</sup>. The method uses robust regional statistics and quantile-based normalization to combine these two components into a single dimensionless indicator intended to represent ionospheric conditions relevant to RTK positioning reliability<sup>1</sup>. The motivation for combining the two components is that differential GNSS positioning may be affected not only by rapid temporal changes in electron content but also by spatial decorrelation of ionospheric delays between reference and rover locations. Consequently, an indicator based only on ROTI may not fully describe ionospheric conditions relevant to regional RTK performance.

The RTK-RISK indicator is derived exclusively from regional GNSS observations and therefore provides a local representation of ionospheric disturbance conditions. However, an indicator intended for operational GNSS applications should not be evaluated only using the observations from which it is derived. External comparison with independent measurements describing the global space-weather environment provides an additional means of determining whether variations in the regional GNSS-derived indicator are physically consistent with the evolution of the geomagnetic storm. Previous studies have investigated relationships between individual ionospheric quantities such as TEC and ROTI and global geomagnetic activity<sup>10,11,15</sup>, but considerably less attention has been given to the external evaluation of a composite RTK-oriented indicator that simultaneously incorporates temporal ionospheric irregularity and spatial TEC gradients.

The objective of this study is therefore to evaluate whether the GNSS-derived RTK-RISK indicator reflects independently observed global space-weather and geomagnetic conditions during the extreme May 2024 geomagnetic storm. RTK-RISK and its individual ROTI and spatial-gradient components are compared with IMF  $B_z$ , the derived southward IMF component  $B_s$ , solar-wind speed  $V_{sw}$ , the coupling proxy  $V_{sw}B_s$ , and the geomagnetic Kp and Dst indices. Spearman rank correlation is used as the principal measure of association between the regional GNSS-derived quantities and the external space-weather parameters. The analysis addresses three principal questions: (1) whether RTK-RISK varies consistently with independent global space-weather and geomagnetic indicators; (2) whether the temporal ROTI and spatial VTEC-gradient components exhibit different relationships with these indicators; and (3) which external parameters show the strongest association with the regional GNSS-derived disturbance state. A secondary time-shift analysis is additionally used to examine the sensitivity of the observed relationships to short temporal offsets, but the primary evaluation is based on simultaneous correlations. The study therefore provides an independent external evaluation of RTK-RISK during one of the most intense geomagnetic disturbances of the current solar cycle.

## Results

### Storm-time evolution of RTK-RISK and space-weather conditions

Figure 1 summarizes the temporal evolution of the regional RTK-RISK indicator, its ROTI and spatial-gradient components, and the principal space-weather parameters during 11 May 2024. The analysed interval was characterized by strongly disturbed geomagnetic conditions, with pronounced southward excursions of IMF  $B_z$ , elevated solar-wind speed, high Kp values, and strongly negative Dst.

The RTK-RISK indicator reached its highest values during the early part of the day and subsequently decreased during the storm recovery phase, with several secondary enhancements later in the day. At 5-min resolution, RTK-RISK had a median value of 0.188 and reached the upper bound of 1.0. The regional ROTI component had a median of 0.257 TECU min<sup>-1</sup> and a maximum of 1.130 TECU min<sup>-1</sup>. The spatial-gradient component had a median of 0.297 TECU km<sup>-1</sup> and reached a maximum of 1.737 TECU km<sup>-1</sup>.

IMF  $B_z$  ranged from approximately -44.7 to +15.2 nT, while solar-wind speed varied between approximately 660 and 951 km s<sup>-1</sup>. These conditions are consistent with the exceptionally disturbed solar-wind and geomagnetic environment associated with the May 2024 storm.

### Simultaneous association between RTK-RISK and global space-weather indices

The primary evaluation was based on simultaneous Spearman rank correlations between RTK-RISK and the independent space-weather and geomagnetic parameters. The strongest statistically significant association was observed for Dst, with a Spearman coefficient of  $\rho = -0.631$  ( $p = 9.39 \times 10^{-4}$ ,  $N = 24$ ). The negative sign is physically consistent with the definition of Dst: increasingly negative values represent stronger geomagnetic storm conditions and coincided with higher RTK-RISK.

Kp showed a positive association with RTK-RISK, with  $\rho = 0.655$  ( $p = 0.078$ ,  $N = 8$ ). Because Kp is defined at 3-h resolution, only eight independent intervals were available during the analysed day. The association therefore did not reach statistical significance at the 0.05 level, although higher Kp values generally coincided with higher regional GNSS-derived ionospheric risk.

The high-resolution IMF parameters showed similarly consistent behaviour. IMF  $B_z$  was negatively correlated with RTK-RISK, with  $\rho = -0.401$  ( $p = 1.40 \times 10^{-12}$ ,  $N = 288$ ), whereas the derived southward IMF component  $B_s$  showed a positive association of  $\rho = 0.411$  ( $p = 3.82 \times 10^{-13}$ ,  $N = 288$ ). Because  $B_s = \max(-B_z, 0)$ , the opposite signs of these two relationships are physically consistent and indicate that increasingly southward IMF conditions were associated with enhanced regional ionospheric disturbance.

The solar-wind coupling proxy  $V_{sw}B_s$  also showed a positive association with RTK-RISK, with  $\rho = 0.352$  ( $p = 5.61 \times 10^{-9}$ ,  $N = 260$ ). Solar-wind speed alone showed a weaker negative relationship, with  $\rho = -0.323$  ( $p = 8.75 \times 10^{-8}$ ,  $N = 262$ ). This negative association should be interpreted cautiously because solar-wind speed remained elevated during parts of the recovery phase when RTK-RISK had already decreased.

The resulting simultaneous correlations are summarized in Fig. 2.

### Response of the temporal and spatial RTK-RISK components

The individual RTK-RISK components exhibited different relationships with the external space-weather parameters, indicating that the composite indicator contains information from two physically distinct aspects of regional ionospheric behaviour.

For the geomagnetic Dst index, the strongest relationship was observed with the spatial-gradient component,  $\text{GRAD}_{LV}$ , for which the simultaneous Spearman correlation reached  $\rho = -0.769$  ( $p = 1.14 \times 10^{-5}$ ,  $N = 24$ ). This association was substantially stronger than that obtained for the ROTI component alone ( $\rho = -0.425$ ,  $p = 0.038$ ,  $N = 24$ ). A similar contrast was observed for Kp: the spatial-gradient component showed  $\rho = 0.618$  ( $p = 0.103$ ,  $N = 8$ ), whereas the ROTI component showed  $\rho = 0.284$  ( $p = 0.495$ ,  $N = 8$ ). Neither association reached statistical significance at the 0.05 level, reflecting the limited number of independent 3-h Kp intervals available within the single analysed day.

The high-resolution IMF parameters showed a different pattern. For IMF  $B_z$ , the correlations with  $\text{ROTI}_{LV}$  and  $\text{GRAD}_{LV}$  were  $\rho = -0.282$  and  $\rho = -0.403$ , respectively. The corresponding correlations for  $B_s$  were  $\rho = 0.293$  and  $\rho = 0.404$ . Thus, the spatial-gradient component again showed a stronger simultaneous relationship with the IMF orientation than the ROTI component.

For the coupling proxy  $V_{sw}B_s$ , the spatial-gradient component showed  $\rho = 0.370$  ( $p = 7.22 \times 10^{-10}$ ), compared with  $\rho = 0.237$  ( $p = 1.15 \times 10^{-4}$ ) for ROTI. Solar-wind speed alone exhibited the largest contrast between the two components: its correlation with  $\text{GRAD}_{LV}$  was  $\rho = -0.526$  ( $p = 5.18 \times 10^{-20}$ ), whereas no statistically significant monotonic association was observed with  $\text{ROTI}_{LV}$  ( $\rho = -0.085$ ,  $p = 0.170$ ).

The contrasting behaviour of the composite indicator and its temporal and spatial components is illustrated in Fig. 3.

These results indicate that the spatial VTEC-gradient component contributed substantially to the external consistency of the composite RTK-RISK indicator and that the storm-time regional response cannot be characterized by ROTI alone.

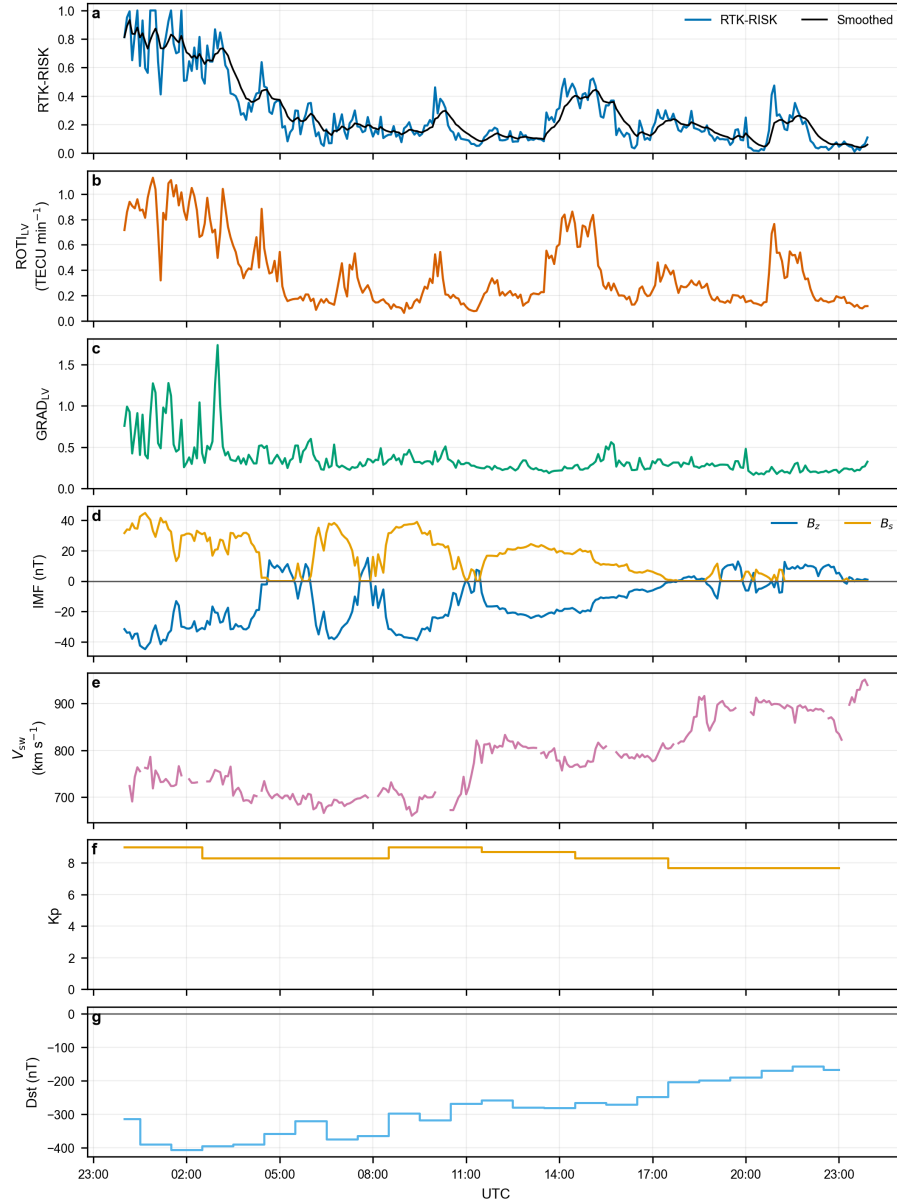


**Figure 1.** Temporal evolution of the regional RTK-RISK indicator and its components together with space-weather conditions on 11 May 2024. Panels show: (a) RTK-RISK and its smoothed representation; (b) regional ROTI; (c) regional spatial VTEC-gradient metric; (d) IMF  $B_z$  and its southward component  $B_s$  in GSM coordinates; (e) solar-wind speed  $V_{sw}$ ; (f) Kp; and (g) Dst. All times are given in UTC.

### Sensitivity to temporal offsets

A secondary time-shift analysis was performed to determine whether the simultaneous associations were sensitive to temporal displacement between the external parameters and RTK-RISK. The resulting correlation curves showed substantial variation over the tested  $\pm 12$ -h interval.

For IMF  $B_z$ ,  $B_s$ , and the coupling proxy  $V_{sw}B_s$ , the strongest absolute Spearman correlations over the unrestricted search interval occurred at large negative offsets of approximately 10–12 h.

Kp and Dst also produced strong coefficients at non-zero temporal offsets. However, these offset-dependent maxima are not interpreted as physical response times because the analysed variables contain strong storm-scale trends and temporal autocorrelation.

The time-shift analysis was consequently treated as a sensitivity analysis rather than as an independent validation criterion. The primary conclusions of the study are based on the simultaneous correlations described above.

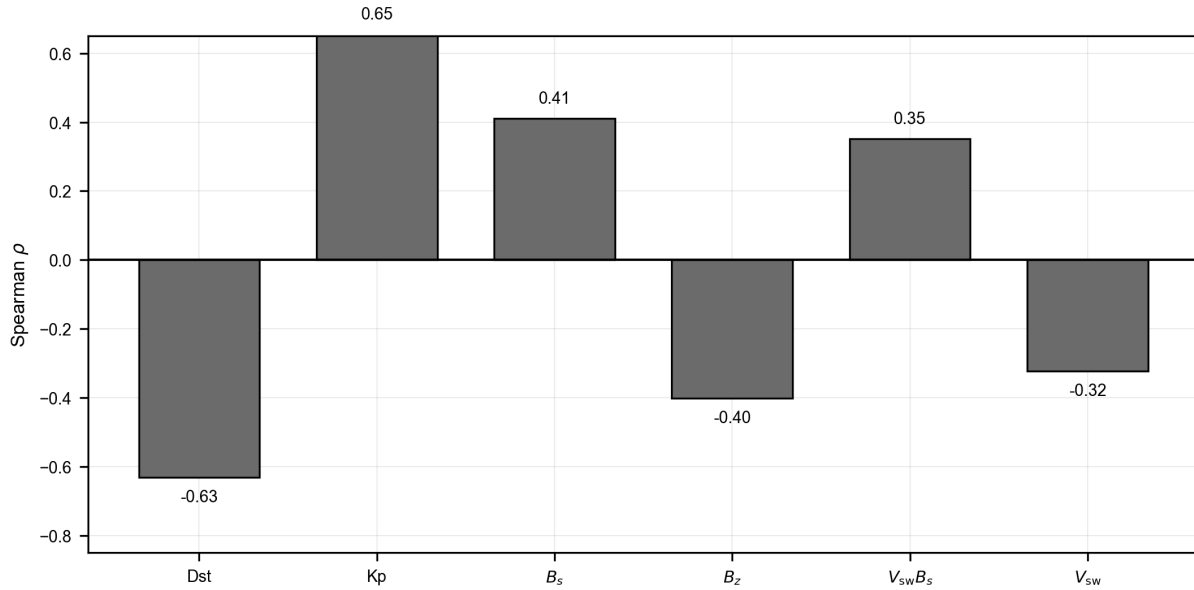


**Figure 2.** Simultaneous Spearman rank correlation coefficients between RTK-RISK and the analysed global space-weather and geomagnetic parameters on 11 May 2024. Positive coefficients indicate a direct monotonic association, whereas negative coefficients indicate an inverse monotonic association.

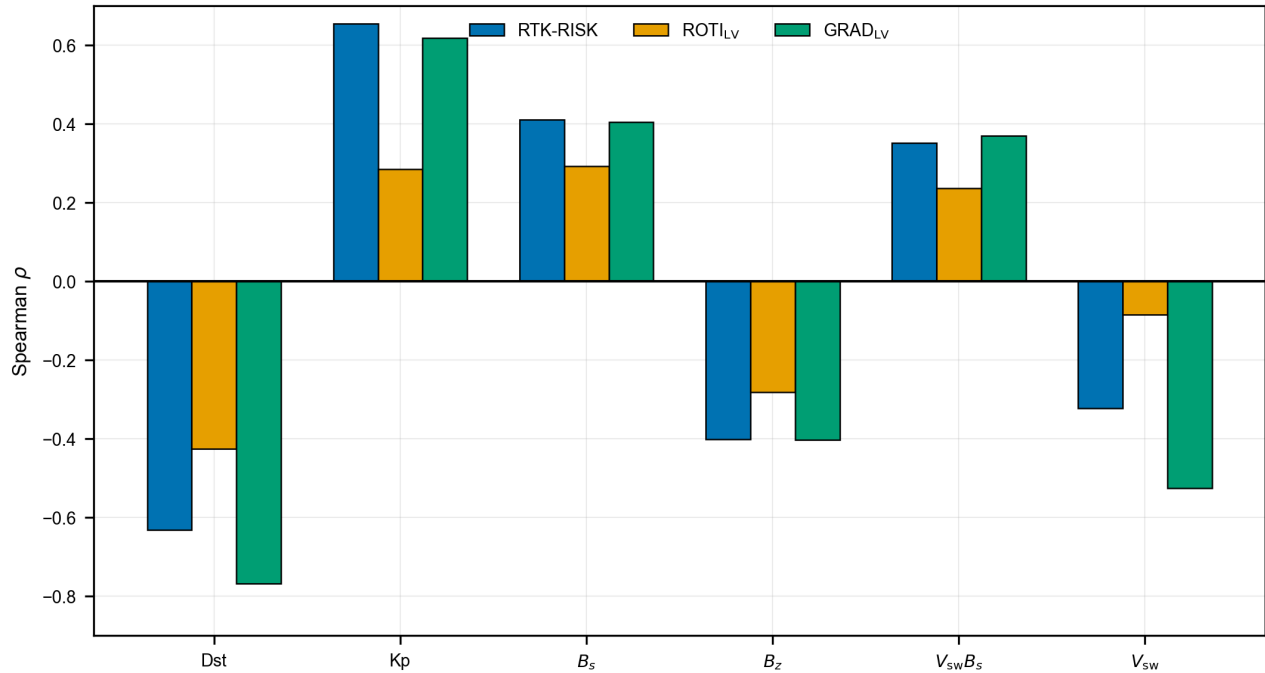


**Figure 3.** Comparison of simultaneous Spearman rank correlation coefficients for the composite RTK-RISK indicator, the regional temporal component ROTILV, and the regional spatial-gradient component GRADLV with the analysed global space-weather and geomagnetic parameters on 11 May 2024.

F10.7 solar radio flux showed no meaningful simultaneous intra-day correlation because the parameter was constant over the analysed day at the temporal resolution of the source product. It was therefore excluded from the principal correlation analysis.

**Table 1.** Simultaneous Spearman rank correlations between the analysed space-weather parameters and RTK-RISK, regional ROTI, and the regional spatial-gradient component on 11 May 2024.

| Parameter   | Resolution | RTK-RISK | ROTI <sub>LV</sub> | GRAD <sub>LV</sub> |
|-------------|------------|----------|--------------------|--------------------|
| $B_z$       | 5 min      | -0.401   | -0.282             | -0.403             |
| $B_s$       | 5 min      | 0.411    | 0.293              | 0.404              |
| $V_{sw}$    | 5 min      | -0.323   | -0.085             | -0.526             |
| $V_{sw}B_s$ | 5 min      | 0.352    | 0.237              | 0.370              |
| Kp          | 3 h        | 0.655    | 0.284              | 0.618              |
| Dst         | 1 h        | -0.631   | -0.425             | -0.769             |

### Summary of the external evaluation

Overall, the RTK-RISK indicator exhibited statistically significant and physically consistent simultaneous associations with several independent global space-weather and geomagnetic parameters. Among the statistically significant relationships, the strongest association with the composite indicator was obtained for Dst. Kp showed a relatively strong positive association ( $\rho = 0.655$ ), but this relationship did not reach statistical significance ( $p = 0.078$ ,  $N = 8$ ) at the native 3-h resolution. Southward IMF  $B_s$ , IMF  $B_z$ , and the  $V_{sw}B_s$  coupling proxy showed significant associations.

The analysis of the individual components demonstrated that the spatial VTEC-gradient component was particularly strongly related to geomagnetic storm conditions, reaching  $\rho = -0.769$  with Dst. This result supports the inclusion of spatial ionospheric variability in the composite RTK-RISK formulation and indicates that the indicator captures storm-time behaviour that is not represented by ROTI alone.

## Discussion

### External consistency of the RTK-RISK indicator

The principal result of this study is that the regional GNSS-derived RTK-RISK indicator exhibited statistically significant and physically consistent relationships with several independent global space-weather and geomagnetic parameters during the extreme geomagnetic storm of 11 May 2024. The strongest statistically significant simultaneous association was observed with Dst. Kp exhibited a slightly larger correlation coefficient in absolute magnitude ( $\rho = 0.655$ ), but the Kp comparison was based on only eight independent 3-h intervals and did not reach statistical significance ( $p = 0.078$ ). Significant relationships were also obtained for the southward IMF component  $B_s$ , IMF  $B_z$ , and the solar-wind coupling proxy  $V_{sw}B_s$ .

This consistency is important because RTK-RISK is derived exclusively from regional GNSS observations and does not use geomagnetic or solar-wind information in its formulation. The observed relationships therefore provide an independent external evaluation of the indicator. Increasingly negative Dst values coincided with increasing RTK-RISK, while increasing Kp and  $B_s$  were associated with increasing RTK-RISK. Similarly, increasingly negative IMF  $B_z$ , corresponding to stronger southward IMF conditions, was associated with higher RTK-RISK. The signs of these relationships are consistent with the physical interpretation of enhanced solar-wind–magnetosphere coupling and increasing geomagnetic disturbance.

Previous studies have demonstrated relationships between GNSS-derived TEC or ROTI and geomagnetic activity<sup>10,11,15</sup>. The present results extend these findings by showing that a composite GNSS-derived indicator specifically designed for RTK applications also follows independently observed global storm conditions. Unlike indices based exclusively on TEC or ROTI, RTK-RISK combines temporal ionospheric variability with spatial VTEC gradients<sup>1</sup>. This distinction is particularly relevant for differential GNSS positioning, where spatial decorrelation between the ionospheric conditions at reference and rover locations may directly affect ambiguity resolution and positioning reliability.

### Relationship with geomagnetic indices

Dst exhibited the strongest statistically significant simultaneous association with the composite RTK-RISK indicator, with a Spearman coefficient of approximately  $\rho = -0.63$ . This relatively strong relationship is physically plausible because Dst represents the large-scale geomagnetic response of the magnetosphere during storm development, whereas RTK-RISK characterizes the corresponding regional ionospheric disturbance relevant to GNSS positioning.

The strong Dst relationship should not, however, be interpreted as evidence that Dst directly drives RTK-RISK. Both quantities represent responses at different stages of the coupled Sun–magnetosphere–ionosphere system. Dst primarily reflects the development of the magnetospheric ring current, whereas the GNSS-derived indicator reflects changes in ionospheric electron-density structure over Latvia. The observed negative correlation therefore demonstrates temporal coherence between the global geomagnetic storm state and the regional ionospheric response rather than a direct causal relationship.

Kp also showed a positive association with RTK-RISK. Higher Kp values generally coincided with higher regional ionospheric disturbance levels. The Spearman coefficient ( $\rho = 0.655$ ) was slightly larger in absolute magnitude than that obtained for Dst; however, only eight independent 3-h Kp intervals were available during the analysed day, and the association did not reach statistical significance ( $p = 0.078$ ). The coarse temporal resolution and small number of independent Kp intervals therefore limit the statistical power of the comparison, and direct comparison of the Kp and Dst correlation magnitudes should be made cautiously.

### Relationship with IMF and solar-wind forcing

The IMF parameters provided an independent measure of upstream space-weather forcing. IMF  $B_z$  showed a negative correlation with RTK-RISK, whereas its derived southward component  $B_s$  showed a positive correlation of similar magnitude. This opposite-sign behaviour is expected from the definition

$$B_s = \max(-B_z, 0), \quad (1)$$

and provides an internal consistency check for the analysis.

Southward IMF conditions enhance magnetic reconnection at the dayside magnetopause and facilitate increased transfer of energy and momentum from the solar wind into the magnetosphere. The observed increase in RTK-RISK during stronger southward IMF conditions is therefore physically consistent with enhanced magnetosphere–ionosphere forcing.

The positive relationship obtained for the coupling proxy  $V_{sw}B_s$  further supports this interpretation. Although this quantity represents only a simplified coupling measure, it incorporates both solar-wind speed and southward IMF orientation and showed a clearer physically interpretable relationship with RTK-RISK than solar-wind speed alone. More sophisticated coupling functions have been proposed to describe solar-wind–magnetosphere energy transfer<sup>13</sup>; however, the simplified  $V_{sw}B_s$  quantity was sufficient for the present event-based comparison.

Solar-wind speed alone showed a moderate negative correlation with RTK-RISK. This result should not be interpreted as indicating that higher solar-wind speed reduces ionospheric disturbance. During the analysed interval, solar-wind speed remained elevated during parts of the storm recovery period, while RTK-RISK had already decreased from its earlier maximum. The resulting negative correlation therefore likely reflects the temporal evolution of different storm phases rather than a simple direct relationship between solar-wind speed and ionospheric risk. This illustrates the importance of considering magnetic-field orientation together with solar-wind velocity when evaluating short-term ionospheric responses.

### Different behaviour of the ROTI and spatial-gradient components

An important result of the present analysis is that the temporal and spatial components of RTK-RISK did not respond identically to the external space-weather parameters. In several comparisons, the regional spatial-gradient component,  $GRAD_{LV}$ , showed substantially stronger correlations with the external indices than the regional ROTI component.

The most pronounced example was Dst, for which the spatial-gradient component reached a Spearman correlation of approximately  $\rho = -0.77$ , compared with approximately  $\rho = -0.43$  for  $ROTI_{LV}$ . Similarly, the spatial-gradient component showed stronger relationships with Kp, IMF  $B_z$ ,  $B_s$ , and  $V_{sw}B_s$  than the temporal ROTI component.

This difference suggests that the May 2024 storm produced pronounced regional spatial restructuring of the ionosphere in addition to enhanced short-term temporal variability. Such behaviour is particularly important for RTK positioning because differential GNSS techniques rely on spatial correlation of ionospheric errors between reference and rover locations. A strong spatial VTEC gradient can therefore degrade RTK performance even when local short-term TEC variability is comparatively moderate.

The result provides additional justification for the composite structure of RTK-RISK. ROTI alone represents rapid temporal changes along individual satellite links, whereas the spatial-gradient component represents horizontal differences in the regional ionospheric field. Their combination therefore captures two different mechanisms through which disturbed ionospheric conditions can affect regional RTK positioning.

This interpretation is consistent with previous studies emphasizing the importance of both temporal and spatial TEC gradients for high-precision GNSS applications<sup>28–30</sup>. It also supports the original motivation of the RTK-RISK formulation, in which the temporal and spatial components were intentionally combined rather than relying on a single ionospheric disturbance measure<sup>1</sup>.

### Comparison with ROTI-based disturbance indices

ROTI-based indices have been widely applied to characterize ionospheric irregularities at regional and global scales<sup>4–6,20</sup>. More recently, Wang et al. developed an ionospheric disturbed index based primarily on ROTI and demonstrated statistical relationships with geomagnetic and solar-activity parameters including Kp, Dst, SYM-H, Ap, and F10.7<sup>11</sup>.

The present approach differs from a ROTI-only disturbance index in two principal ways. First, RTK-RISK was developed specifically for applications related to RTK positioning reliability rather than as a general ionospheric disturbance index. Second, the indicator combines temporal ROTI variability with spatial VTEC gradients. The current results demonstrate that this spatial component contains substantial information related to the global geomagnetic storm state.

The strong correlation between  $\text{GRAD}_{\text{LV}}$  and Dst suggests that a regional RTK-oriented indicator should not necessarily be reduced to a ROTI-only metric. During the analysed event, the spatial ionospheric structure appears to have contributed significantly to the external consistency of the composite indicator.

### Sensitivity to temporal offsets

The exploratory time-shift analysis showed that correlation coefficients can vary substantially when the space-weather and GNSS-derived time series are shifted relative to each other. In some cases, relatively strong correlations were obtained at large positive or negative offsets.

These long-offset maxima were not interpreted as physical response times. The analysed event contains strong storm-scale temporal trends, and both the external space-weather quantities and the GNSS-derived ionospheric indicators exhibit substantial autocorrelation. Consequently, similar parts of the storm-time profiles can align at several temporal offsets and generate mathematically strong correlations without representing a physically meaningful propagation or response delay.

For this reason, the present evaluation is based primarily on simultaneous correlations. The time-shift results are interpreted only as a sensitivity test demonstrating that the statistical relationships depend partly on the temporal structure of the storm.

A dedicated analysis of ionospheric response times would require a longer observation interval, physically constrained lag windows, treatment of serial autocorrelation, and preferably several independent geomagnetic events. Such an analysis is beyond the scope of the present study.

### Influence of processing and quality control

The treatment of carrier-phase discontinuities was found to be important for obtaining physically meaningful ROTI values. If STEC differences are calculated across a cycle slip, the resulting artificial TEC discontinuity can generate extremely large ROT values that subsequently contaminate the moving ROTI window.

In the present processing chain, detected cycle slips and temporal data gaps were therefore treated as boundaries between independent observation arcs. ROT was not calculated across these boundaries. After this correction, the maximum regional storm-time ROTI was approximately  $1.1 \text{ TECU min}^{-1}$ , compared with substantially larger artificial values obtained when discontinuities were not explicitly segmented.

The VTEC processing was also made geometrically consistent by using the same spherical single-layer ionosphere with a height of 450 km for both STEC-to-VTEC conversion and IPP determination. This avoids the use of different mapping assumptions in the temporal and spatial parts of the processing chain.

These processing considerations are particularly important when ionospheric indices are intended for quantitative comparison with external space-weather quantities. Apparent statistical relationships can otherwise be influenced by processing artefacts rather than by genuine ionospheric variability.

### Limitations

Several limitations should be considered when interpreting the results.

First, the present analysis is based on a single extreme geomagnetic storm day. The observed correlation strengths therefore characterize this particular event and should not be interpreted as universal relationships applicable to all geomagnetic conditions. Validation using additional disturbed and quiet periods is required to assess the robustness and generality of the results.

Second, the analysis is geographically limited to the Latvian GNSS reference-station network. Ionospheric responses vary strongly with latitude, longitude, local time, season, and geomagnetic configuration. The relationships obtained for Latvia may therefore differ from those observed at equatorial, auroral, or other mid-latitude regions.

Third, the analysed time series are temporally autocorrelated. Conventional correlation significance levels assume a larger degree of sample independence than is present in strongly structured storm-time data. The reported  $p$  values should therefore be interpreted together with the correlation magnitudes and physical consistency of the relationships rather than as standalone evidence.

Fourth, the temporal resolution of the external parameters differs. IMF and solar-wind variables were evaluated at 5-min resolution, Dst at 1-h resolution, and Kp at its native 3-h resolution. Direct comparison of correlation magnitudes across all parameters should therefore be made cautiously.

Finally, correlation demonstrates statistical association but does not establish a unique causal mechanism. The ionospheric response during a major geomagnetic storm results from multiple coupled processes, including magnetospheric convection, particle precipitation, thermospheric dynamics, electric fields, and neutral winds. The present study evaluates whether the

regional GNSS-derived indicator is consistent with the broader global disturbance environment rather than attempting to isolate individual physical mechanisms.

### Implications for regional RTK monitoring

Despite these limitations, the results demonstrate that a regional GNSS-derived indicator designed for positioning applications can provide information consistent with independent global space-weather observations. This is relevant for operational RTK monitoring because the indicator is derived directly from the same type of GNSS observations used by regional reference-station networks.

Global geomagnetic and solar-wind indices describe the overall space-weather environment, but they do not directly quantify the local ionospheric conditions experienced by an RTK network. RTK-RISK provides a complementary regional representation by combining temporal irregularity and spatial ionospheric gradients. The present external evaluation indicates that increases in this locally derived indicator occur coherently with independently observed periods of enhanced geomagnetic and solar-wind disturbance.

The approach therefore has potential for operational monitoring of ionospheric conditions relevant to regional RTK positioning. Further evaluation over multiple storms, quiet periods, seasons, and independent positioning datasets is required before the indicator can be considered fully validated for operational use.

## Methods

### GNSS observations and processing framework

The regional ionospheric parameters were derived from observations of the Latvian continuously operating GNSS reference-station network. Dual-frequency GPS and Galileo observations were processed using a sequential Python-based processing chain to derive slant total electron content (STEC), vertical total electron content (VTEC), ionospheric pierce points (IPPs), the Rate of TEC Index (ROTI), regional VTEC gradients, and the composite RTK-RISK indicator.

The analysis presented in this study was performed for 11 May 2024 (day of year 132), during the main phase and early recovery of the extreme May 2024 geomagnetic storm. All calculations were performed in Coordinated Universal Time (UTC). Only observations with satellite elevation angles equal to or greater than 20° were retained in order to reduce low-elevation multipath effects and increased ionospheric mapping uncertainty.

The processing methodology follows the GNSS ionospheric framework used in the previously developed RTK-RISK approach<sup>1</sup>. The present study extends that methodology by comparing the resulting regional disturbance indicator and its individual components with independent global space-weather and geomagnetic parameters.

### Slant total electron content estimation

Dual-frequency code and carrier-phase observations were used to derive ionospheric total electron content. GPS observations were processed using the L1 and L2 frequencies, while Galileo observations used the E1 and E5a frequencies. Prior to TEC estimation, satellite Observable-Specific Bias (OSB) corrections were applied to the code observations following the processing framework of the previously developed RTK-RISK methodology<sup>1</sup>. Daily CODE Bias-SINEX products were used, with the appropriate OSB correction selected according to satellite and RINEX observable type. The corrected code observations were subsequently used for carrier smoothing and for establishing the absolute level of the carrier-phase-derived TEC. For two carrier frequencies  $f_1$  and  $f_2$ , the ionospheric conversion factor was defined as

$$K = \frac{f_1^2 f_2^2}{40.3 (f_1^2 - f_2^2)}. \quad (2)$$

The geometry-free code-derived TEC was calculated from smoothed dual-frequency pseudorange observations as

$$\text{TEC}_P = \frac{K(P_{2,\text{sm}} - P_{1,\text{sm}})}{10^{16}}, \quad (3)$$

where  $P_{1,\text{sm}}$  and  $P_{2,\text{sm}}$  are OSB-corrected, carrier-smoothed code observations and TEC is expressed in TEC units (TECU), where 1 TECU =  $10^{16}$  electrons  $\text{m}^{-2}$ .

Carrier smoothing of the OSB-corrected code observations was performed using a stateful Hatch-type filter with a maximum smoothing length of 100 epochs. The smoothing state was restarted when a cycle slip was detected or when the temporal separation between consecutive observations exceeded 120 s.

Carrier-phase-derived TEC was calculated as

$$\text{TEC}_\phi = \frac{K(L_1 - L_2)}{10^{16}}, \quad (4)$$

where  $L_1$  and  $L_2$  denote carrier-phase measurements converted to metres.

Because carrier-phase TEC contains an unknown phase ambiguity, the phase-derived series was levelled to the code-derived TEC separately for each station–satellite arc. The levelling offset was estimated using the median difference

$$b_{\text{lev}} = \text{median}(\text{TEC}_P - \text{TEC}_\phi), \quad (5)$$

using only epochs not flagged as cycle slips. At least 100 valid samples were required for the estimation of the levelling offset.

The preliminary slant TEC was then obtained as

$$\text{STEC}_{\text{raw}} = \text{TEC}_\phi + b_{\text{lev}}. \quad (6)$$

After phase levelling, receiver differential code bias corrections, estimated from the observations using the robust procedure of the RTK-RISK processing framework<sup>1</sup>, were subsequently applied:

$$\text{STEC} = \text{STEC}_{\text{raw}} - \text{DCB}_{\text{rec}}. \quad (7)$$

This procedure provides a continuous carrier-phase-based STEC series while retaining the absolute level supplied by the code observations. Similar approaches based on dual-frequency GNSS observations are widely used for regional TEC estimation<sup>16, 17, 22</sup>.

### Vertical TEC and ionospheric pierce points

Slant TEC was converted to vertical TEC using a spherical single-layer ionospheric model with an ionospheric shell height of 450 km. The elevation-dependent mapping factor was calculated as

$$M(E) = \left[ 1 - \left( \frac{R_E}{R_E + H_{\text{ion}}} \right)^2 \cos^2 E \right]^{-1/2}, \quad (8)$$

where  $E$  is the satellite elevation angle,  $R_E = 6371$  km is the adopted mean Earth radius, and  $H_{\text{ion}} = 450$  km is the ionospheric shell height.

Vertical TEC was then calculated as

$$\text{VTEC} = \frac{\text{STEC}}{M(E)}. \quad (9)$$

The same 450-km single-layer geometry was used to determine ionospheric pierce points (IPPs). Receiver and satellite positions were represented in Earth-centred Earth-fixed coordinates, and the intersection of the receiver–satellite line of sight with the spherical ionospheric shell was calculated. The resulting IPP coordinates were transformed to geodetic latitude and longitude.

Using the same shell height for both STEC-to-VTEC mapping and IPP determination ensured a geometrically consistent representation of the regional ionosphere. Epochs identified as cycle slips were excluded from IPP calculations.

### ROT and ROTI calculation

Short-term ionospheric variability was characterized using the Rate of TEC (ROT) and the Rate of TEC Index (ROTI). For each continuous station–satellite arc, ROT was calculated from consecutive STEC observations as

$$\text{ROT}_i = 60 \frac{\text{STEC}_i - \text{STEC}_{i-1}}{t_i - t_{i-1}}, \quad (10)$$

where  $t_i - t_{i-1}$  is expressed in seconds. The factor 60 converts the resulting rate to TECU  $\text{min}^{-1}$ . ROTI was defined as the standard deviation of ROT within an approximately 5-min moving window:

$$\text{ROTI} = \sqrt{\langle \text{ROT}^2 \rangle - \langle \text{ROT} \rangle^2}, \quad (11)$$

where the angle brackets denote averaging over the moving time window. This definition follows the conventional ROTI formulation introduced for GNSS-based monitoring of ionospheric irregularities<sup>4</sup> and subsequently applied in regional and global ionospheric studies<sup>5,6,9,20</sup>.

Particular attention was given to carrier-phase discontinuities. Detected cycle-slip epochs were treated as boundaries between independent continuous arcs. ROT was not calculated across a cycle slip, nor across temporal gaps greater than 120 s. The cycle-slip epoch itself was excluded, and the first valid observation after the discontinuity initiated a new ROT segment. Consequently, a carrier-phase discontinuity could not propagate into the 5-min ROTI window as an artificial high-amplitude ROT value.

For the 30-s observation interval used in the present dataset, the nominal 5-min ROTI window contained approximately 10 observations. A minimum of five valid ROT samples was required to estimate ROTI within a window.

### Regional ROTI component

The station–satellite ROTI measurements were converted into a regional disturbance quantity using the previously developed RTK-RISK methodology<sup>1</sup>. First, ROTI observations for each station–satellite arc were aggregated using a 120-s moving median in order to reduce the influence of individual high-frequency fluctuations.

At each analysis epoch, the regional ROTI component was defined as the 95th percentile of the available filtered ROTI observations:

$$\text{ROTI}_{\text{LV}}(t) = Q_{0.95} [\text{ROTI}_j(t)], \quad (12)$$

where  $j$  represents the available station–satellite observations and  $Q_{0.95}$  denotes the 95th percentile.

The use of a high regional quantile was intended to characterize the disturbed part of the regional ionosphere without making the indicator dependent on a single satellite link or an isolated extreme observation.

### Regional spatial VTEC-gradient component

The spatial component of RTK-RISK was derived from the regional VTEC field. For each reference station, VTEC observations were aggregated within 120-s intervals using the median. Epochs with fewer than three simultaneously available stations were not used for regional gradient estimation.

The station VTEC values were interpolated onto a regular geographical grid using linear interpolation. The analysis domain extended from 20.5° to 28.5°E and from 55.3° to 58.4°N, using a grid spacing of 0.25°. For gradient calculation, the angular grid spacing was converted to approximate horizontal distances using 111.32 km per degree of latitude and  $111.32 \cos(\bar{\varphi})$  km per degree of longitude, where  $\bar{\varphi}$  denotes the mean latitude of the grid.

The horizontal magnitude of the interpolated VTEC gradient was calculated as

$$G_{\text{VTEC}} = \sqrt{\left( \frac{\partial \text{VTEC}}{\partial x} \right)^2 + \left( \frac{\partial \text{VTEC}}{\partial y} \right)^2}. \quad (13)$$

Accordingly,  $G_{\text{VTEC}}$  and  $\text{GRAD}_{\text{LV}}$  are expressed in TECU  $\text{km}^{-1}$ . The regional spatial-gradient metric was defined as the 95th percentile of the valid grid-cell gradient magnitudes:

$$\text{GRAD}_{\text{LV}}(t) = Q_{0.95} [G_{\text{VTEC}}(x, y, t)]. \quad (14)$$

A high-quantile representation was used to capture locally enhanced ionospheric gradients while reducing sensitivity to isolated numerical extremes. The importance of both temporal and spatial TEC gradients for GNSS applications has been demonstrated in previous studies<sup>28–30</sup>.

## RTK-RISK construction

The regional temporal and spatial disturbance quantities have different physical units and numerical ranges. They were therefore independently normalized using robust lower and upper quantiles. For a generic regional parameter  $X(t)$ , the normalized quantity was calculated as

$$R_X(t) = \text{clip} \left[ \frac{X(t) - Q_{0.05}(X)}{Q_{0.95}(X) - Q_{0.05}(X)}, 0, 1 \right], \quad (15)$$

where  $Q_{0.05}$  and  $Q_{0.95}$  are the 5th and 95th percentiles of the corresponding daily time series, and clip restricts the normalized value to the interval  $[0, 1]$ .

The normalized temporal and spatial components were then combined using equal weights:

$$\text{RTK-RISK}(t) = 0.5 R_{\text{ROTI}}(t) + 0.5 R_{\text{GRAD}}(t). \quad (16)$$

The resulting RTK-RISK indicator is dimensionless and ranges from 0 to 1. The formulation follows the quantile-based composite methodology previously introduced for regional RTK positioning reliability<sup>1</sup>.

For visualization and comparison with lower-resolution external indices, the full-resolution RTK-RISK series was additionally aggregated into 5-min median values. A causal exponentially weighted smoothing with a 15-min half-life was used only for visualization; the underlying unsmoothed RTK-RISK values were retained for the primary statistical analysis unless otherwise stated.

## Space-weather and geomagnetic parameters

Independent space-weather parameters were obtained from the NASA OMNI database. High-resolution solar-wind and interplanetary magnetic field observations were taken from the OMNI high-resolution dataset, while geomagnetic indices were obtained from the corresponding hourly OMNI product.

The following external parameters were analysed:

- the GSM north–south component of the interplanetary magnetic field,  $B_z$ ;
- solar-wind speed,  $V_{\text{sw}}$ ;
- the geomagnetic disturbance storm time index, Dst;
- the planetary geomagnetic activity index, Kp.

The southward IMF component was derived from  $B_z$  as

$$B_s = \max(-B_z, 0), \quad (17)$$

such that  $B_s = 0$  under northward IMF conditions and increases with the magnitude of southward IMF.

A simplified solar-wind–magnetosphere coupling proxy was calculated as

$$C_{\text{VB}} = V_{\text{sw}} B_s. \quad (18)$$

This quantity was used to represent the simultaneous contribution of solar-wind velocity and southward IMF orientation to enhanced magnetospheric forcing.

Missing-value flags in the OMNI data were removed before further processing. In addition, physically implausible values were excluded prior to calculation of  $B_s$  and  $V_{\text{sw}} B_s$ .

The Kp quantity in the OMNI hourly product is stored as Kp multiplied by 10 and was therefore converted to the conventional 0–9 scale according to

$$K_p = \frac{K_{p,\text{OMNI}}}{10}. \quad (19)$$

Dst was evaluated at its native 1-h resolution. Kp is defined at 3-h resolution; although Kp values were obtained from the OMNI hourly product, repeated hourly entries within each 3-h Kp interval were treated as a single 3-h value. The regional GNSS quantities were therefore aggregated to corresponding 3-h intervals for comparison with Kp.

F10.7 solar radio flux was initially retrieved as an additional background solar-activity parameter but was excluded from the principal intra-day correlation analysis because it is effectively a daily quantity and therefore provided no independent temporal variability during the analysed day.

## Temporal alignment of GNSS and space-weather data

All datasets were converted to UTC before statistical comparison. The regional RTK-RISK series was available at substantially higher temporal resolution than the geomagnetic indices. Consequently, data were compared only after temporal aggregation to a common analysis interval appropriate for each parameter.

For the primary simultaneous comparison, RTK-RISK, ROTI<sub>LV</sub>, and GRAD<sub>LV</sub> were paired with the corresponding space-weather observations representing the same analysis interval.

OMNI high-resolution solar-wind and IMF observations are already propagated to a near-Earth reference location. No additional propagation time from the upstream spacecraft to Earth was therefore added in the present analysis.

IMF  $B_z$ ,  $B_s$ ,  $V_{sw}$ , and  $V_{sw}B_s$  were evaluated at 5-min resolution. Dst was compared with 1-h aggregated GNSS quantities, whereas Kp was compared with GNSS quantities aggregated to the corresponding 3-h Kp intervals.

## Statistical analysis

The principal objective was to determine whether the regional GNSS-derived RTK-RISK indicator varied consistently with independent global space-weather conditions. Spearman's rank correlation coefficient ( $\rho$ ) was selected as the principal statistic because it measures monotonic association without requiring normally distributed variables or a linear relationship.

Separate correlations were calculated between each external parameter and

1. the composite RTK-RISK indicator;
2. the regional temporal component, ROTI<sub>LV</sub>;
3. the regional spatial-gradient component, GRAD<sub>LV</sub>.

The primary analysis used simultaneous observations, hereafter referred to as simultaneous correlation. Pearson correlation coefficients were additionally calculated as a complementary measure of linear association but were not used as the principal validation criterion.

For each comparison, the number of paired observations, correlation coefficient, and statistical significance were recorded. The sign of each correlation was interpreted together with the physical definition of the external parameter. For example, increasing geomagnetic disturbance corresponds to increasingly negative Dst, whereas increasing Kp and  $B_s$  represent increasing disturbance or southward IMF forcing. Therefore, a physically consistent relationship is expected to have opposite signs for Dst and positive disturbance measures.

## Sensitivity to temporal offsets

A secondary time-shift analysis was performed to evaluate whether the observed correlations were sensitive to short temporal offsets between the external forcing parameters and the regional GNSS response. This analysis was treated as exploratory and was not used as the primary criterion for evaluating RTK-RISK.

For a space-weather parameter  $X$  and RTK-RISK series  $R$ , the shifted correlation can be represented as

$$\rho(\tau) = \rho_s[X(t - \tau), R(t)], \quad (20)$$

where  $\tau$  denotes the temporal offset and  $\rho_s$  is Spearman's rank correlation coefficient.

Because the physical meaning and temporal resolution of the analysed parameters differ, lag maxima obtained from unrestricted long time windows were not interpreted as physical response times. The time-shift analysis was therefore used primarily as a sensitivity test to determine whether the simultaneous relationships persisted under modest changes in temporal alignment.

## Quality control

Several quality-control procedures were applied throughout the processing chain. Observations below 20° elevation were excluded. Carrier-phase smoothing was restarted after cycle slips and temporal gaps exceeding 120 s. Cycle-slip epochs were excluded from phase-levelling statistics and were treated as discontinuity boundaries during ROT and ROTI calculation. ROT was never calculated across a detected discontinuity.

The effectiveness of this procedure was verified by inspecting high-ROTI intervals before and after cycle-slip segmentation. Before segmentation, carrier-phase discontinuities could generate artificial STEC jumps and unrealistically large ROT and ROTI values. After discontinuity handling was introduced, the regional ROTI values during the analysed storm remained within a physically plausible range, with a daily regional maximum of approximately 1.1 TECU min<sup>-1</sup>.

All derived quantities used in the statistical analysis were inspected for missing values and non-physical fill values before correlation calculations.

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## Author contributions statement

A.V. conceived and designed the study, developed the RTK-RISK methodology, implemented the GNSS and space-weather data processing workflows, and performed the statistical and correlation analyses. A.C. contributed to the geodetic and ionospheric processing framework and methodological evaluation. J.Z. contributed to the interpretation of the GNSS positioning implications and the evaluation of the results. J.V. contributed to algorithm evaluation, interpretation of the results, and manuscript preparation. A.V. prepared the initial manuscript draft and figures. All authors reviewed and approved the final manuscript.

## Additional information

### Competing interests

The authors declare no competing interests.

### Data availability

GNSS observation data used in this study were obtained from the Latvian permanent GNSS reference-station network (LatPos). Dual-frequency multi-constellation RINEX observations from GPS and Galileo stations were used to derive STEC, VTEC, ROTI, ionospheric pierce points, regional VTEC gradients, and the RTK-RISK indicator. The analysis presented in this study was performed for 11 May 2024 (day of year 132). LatPos RINEX data are publicly available free of charge; access requires prior user registration and account approval through the official LatPos data request interface:

<https://latpos.lgia.gov.lv/SBC/User/Xpos/RinexDataRequest>

Satellite Observable-Specific Bias (OSB) products used in the GNSS TEC processing were obtained from the Center for Orbit Determination in Europe (CODE). The products are available through the official AIUB CODE product browser:

<https://www.aiub.unibe.ch/download>

Solar-wind, interplanetary magnetic field, and geomagnetic data were obtained from the NASA Space Physics Data Facility (SPDF) OMNI database. High-resolution OMNI data were used for the GSM  $B_z$  component of the interplanetary magnetic field and solar-wind speed  $V_{sw}$ , whereas the OMNI hourly product was used as the source for the Kp and Dst geomagnetic indices. Dst was analysed at 1-h resolution, whereas Kp was treated at its native 3-h resolution. The derived southward IMF component  $B_s$  and the coupling proxy  $V_{sw}B_s$  were calculated from these publicly available OMNI parameters. OMNI data and documentation are available from:

<https://omniweb.gsfc.nasa.gov/>

High-resolution OMNI data are available from:

[https://omniweb.gsfc.nasa.gov/form/omni\\_min.html](https://omniweb.gsfc.nasa.gov/form/omni_min.html)

Hourly OMNI data are available from:

<https://omniweb.gsfc.nasa.gov/form/dx1.html>

The OMNI high-resolution solar-wind and IMF observations are propagated to a near-Earth bow-shock reference location prior to distribution and were used without applying an additional upstream-to-Earth propagation correction.

Solar X-ray flare information used for event context and figure annotation was obtained from publicly available GOES and associated space-weather data products. These data were used only as supplementary event information and were not included as predictors in the principal correlation analysis.

All intermediate and derived datasets used in the statistical analysis, including regional ROTI, regional VTEC-gradient, RTK-RISK, merged space-weather time series, and correlation results, were generated from the publicly accessible source data described above. No proprietary datasets were used in this study.

### Code availability

The processing and analysis workflow was implemented in Python using standard scientific libraries, including NumPy, Pandas, SciPy and Matplotlib. The workflow covers GNSS observation processing, STEC and VTEC estimation, ROT and ROTI calculation with cycle-slip segmentation, regional VTEC-gradient estimation, construction of the RTK-RISK indicator, NASA OMNI space-weather data processing, temporal alignment, and statistical correlation analysis.

The principal algorithms, equations, processing parameters, temporal resolutions, and quality-control procedures required to reproduce the results are described in the Methods section. The source code and configuration files used to generate the results presented in this study are available from the corresponding author upon reasonable request.

All numerical computations were performed using double-precision floating-point arithmetic.

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