Persistent nighttime SNR modulation in 80 m band HF links: evidence for regional-scale ionospheric coherence

Abstract
Long-term observations of HF propagation in the 80 m band were carried out using WSPR signal-to-noise ratio (SNR) data collected over a three-month period on multiple regional paths in Central Europe. The analysis reveals the presence of a persistent nocturnal modulation of the received SNR, recurring night after night with a remarkably similar temporal structure, despite variations in amplitude and short-term propagation conditions. This behaviour is consistently observed across different transmitter–receiver pairs, indicating a coherent ionospheric origin rather than local or instrumental effects. The persistence of the observed modulation over timescales of weeks to months suggests the existence of a stable nocturnal ionospheric regime, characterised by intrinsic large-scale undulations of the reflecting layers. Atmospheric gravity waves and travelling ionospheric disturbances are interpreted as secondary mechanisms capable of organising and enhancing the observed structures, but not as the primary source of the modulation. These results indicate that the 80 m band, in combination with the distributed WSPR network, can be effectively used as a passive diagnostic tool for monitoring the dynamics of the nighttime ionosphere on regional scales.

January 9, 2026

Flavio Egano, ik3xtv
www.qsl.net/ik3xtv

Persistent nighttime SNR modulation in 80 m band HF links: evidence for regional-scale ionospheric coherence

Introduction

High-frequency (HF) radio wave propagation is strongly influenced by the structure and dynamics of the ionosphere, particularly during nighttime conditions, when the absence of direct solar radiation significantly alters the chemical and dynamical equilibrium of the ionised layers. In this regime, HF propagation becomes highly sensitive even to moderate variations in electron density and in the geometry of the reflecting layers, making the signal-to-noise ratio (SNR) an effective indicator of ionospheric conditions along the propagation path. It is well established that the nighttime ionosphere can host travelling ionospheric disturbances (TIDs), often associated with the propagation of atmospheric gravity waves (AGWs), capable of modulating electron density over a wide range of spatial and temporal scales. However, most existing studies focus on specific events or on limited observation windows, while the long-term behaviour of the HF ionosphere over timescales of weeks to months, under predominantly quiet geomagnetic conditions, remains less thoroughly explored. In this context, low-power digital beacon networks such as the Weak Signal Propagation Reporter (WSPR) system provide an opportunity for continuous and distributed observations of HF propagation. The 80 m band is particularly sensitive to nighttime ionospheric variations, owing to the predominance of short- and medium-range paths and to reflection geometries close to vertical incidence. The aim of this work is to analyse nocturnal signal-to-noise ratio modulations observed in 80 m WSPR links across multiple regional paths, using a dataset spanning three consecutive months. The objective is to characterise the persistence and temporal and spatial coherence of the observed behaviour, and to discuss the relative roles of intrinsic ionospheric dynamics and modulation mechanisms associated with atmospheric gravity waves.

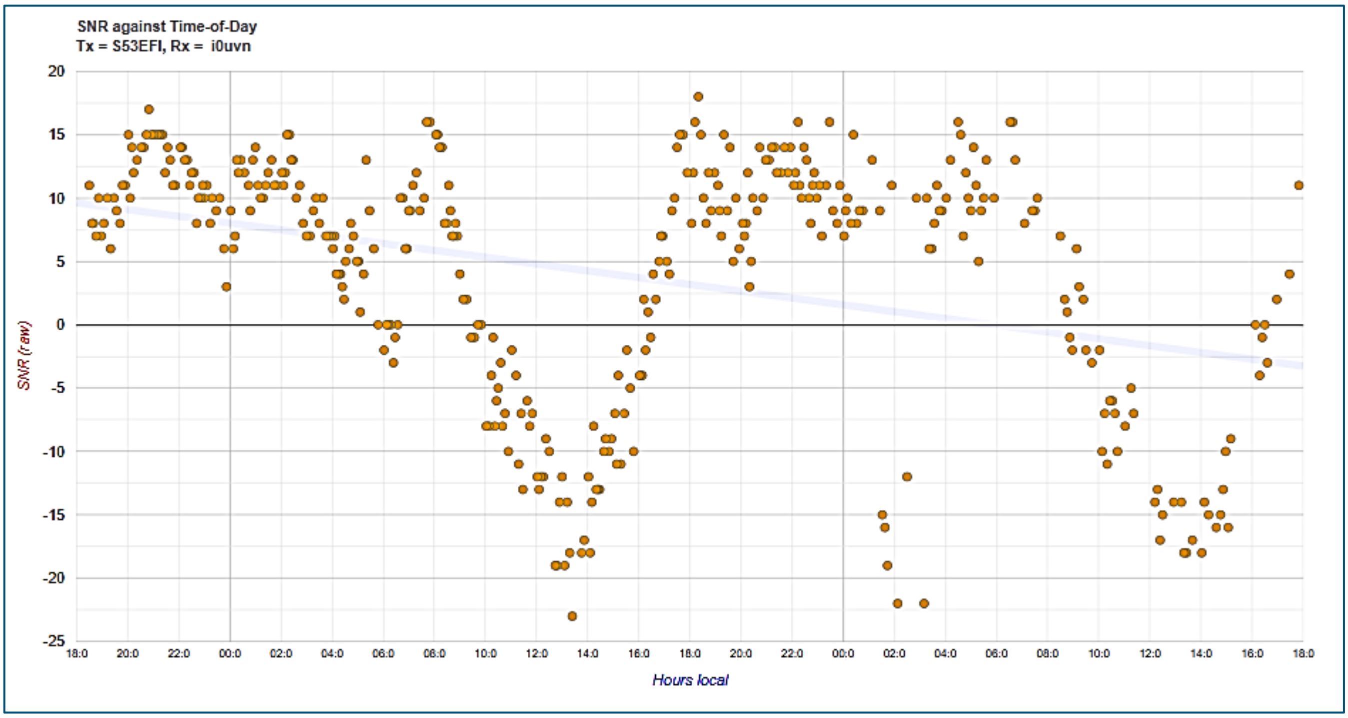

Figure 1. Signal-to-noise ratio (SNR) of the WSPR signal transmitted by station S53EFI and received by I0UVN in the 80 m band, over the 48-hour interval of 19–20 October 2025. A clear diurnal modulation of the SNR is evident, with a pronounced minimum during daytime hours around local noon and higher average values during nighttime. During the night, quasi-periodic SNR oscillations are observed, with characteristic timescales of approximately 2–3 hours and amplitudes of several decibels, repeating in a similar manner over the two

consecutive nights. This behaviour suggests the superposition of a long-term diurnal variation and ionospheric undulations acting on meso-regional spatial scales.

2.1 Data source and link selection

The data analysed in this study were obtained from WSPRnet, the public database of the Weak Signal Propagation Reporter (WSPR) network. WSPR is a time-synchronised digital transmission protocol designed for weak-signal HF propagation studies: each beacon transmits a standardised 110-second message containing callsign, locator, and transmitter power, using a narrow-band four-tone FSK modulation referenced to UTC. In the present analysis, the transmitting station operated with a nominal power of 0.5 W and transmitted on the standard WSPR frequency of 3.570 MHz, within the 80 m amateur band. Reception reports are automatically uploaded by monitoring stations to WSPRnet, where each entry includes timestamp, frequency, SNR, estimated noise level, and transmitter–receiver metadata. The figures and time-series representations used in this work were generated through the WSPR Rocks platform, which provides a structured interface for querying and visualising WSPRnet data while preserving the original temporal resolution and numerical values of the reports. The analysis focuses on 80 m band links (3.5–3.6 MHz), selected for their high sensitivity to nighttime ionospheric variability and for the predominance of short- and medium-range propagation paths. The transmitting station S53EFI is located in Slovenia, while the receiving stations considered in this study are situated in Switzerland (HB9VQQ), Austria (OE9TAV), and central Italy (I0UVN), with great-circle distances up to approximately 600 km. This geometry emphasises regional-scale ionospheric effects while limiting the contribution of long-range propagation modes.

2.2 Data processing and analytical approach

For each selected link, SNR values were analysed as a function of local time, in order to highlight diurnal and nocturnal variations and to compare the observed behaviour across consecutive nights and longer observation intervals. The analysis was performed using the raw SNR values reported by the WSPR system, without applying automatic normalisation or filtering, in order to preserve the original temporal structure of the signal. The adopted approach is observational and descriptive, aimed at identifying recurring temporal patterns rather than deriving precise spectral parameters. In particular, nocturnal SNR oscillations were characterised in terms of their characteristic timescales and amplitudes through direct inspection of the time series, avoiding the application of spectral transforms to intrinsically non-stationary signals. This approach allows a clear distinction between:

- The background variation associated with the day–night cycle,
- Modulations on hourly timescales, and
- Rapid fluctuations on timescales of seconds, attributable to scintillation or multipath interference effects.

3.1 Temporal behaviour of SNR and initial evidence

The figures presented in this study were generated using the WSPR Rocks platform, an analysis and visualisation interface providing access to the WSPRnet database. The system allows the selection of specific transmitter–receiver links and the representation of signal-to-noise ratio (SNR) time series over variable time intervals, while preserving the original temporal resolution of the reception reports. Figure 1 shows the SNR behaviour for a representative 80 m band link over a 48-hour interval. In addition to the diurnal modulation associated with the day–night cycle, the presence of quasi-periodic nocturnal SNR oscillations is clearly evident, with characteristic timescales of several hours. These oscillations are superimposed on a relatively stable nighttime mean level and typically exhibit amplitudes ranging from a few to several decibels. A notable feature is the similarity of the observed behaviour across the two consecutive nights, both in terms of the characteristic timescales of the oscillations and their overall distribution. This repeatability suggests that the observed variations are unlikely to be caused by random effects or instrumental fluctuations, and instead reflect a systematic behaviour of the ionospheric propagation medium.

3.2 Persistence of oscillations on a weekly timescale using a different station

To verify the persistence of the nocturnal SNR oscillations and their independence from the characteristics of a single station, the analysis was extended to a different propagation link than that shown in Figure 1, involving a different receiving station. Figure 2 shows the SNR behaviour in the 80 m band over a period of seven consecutive days. In this case as well, a clear separation between daytime and nighttime regimes is observed, with recurring daytime minima and higher average SNR levels during nighttime hours. Within the nocturnal interval, structured SNR oscillations emerge, with characteristic timescales on the order of 2–3 hours, analogous to those observed for the previous link. Despite differences in station and propagation geometry, the nocturnal behaviour remains coherent from night to night and qualitatively comparable to that discussed in the previous section. This result indicates that the observed modulations are not linked to a specific local configuration, but instead represent a recurring feature of nighttime ionospheric propagation.

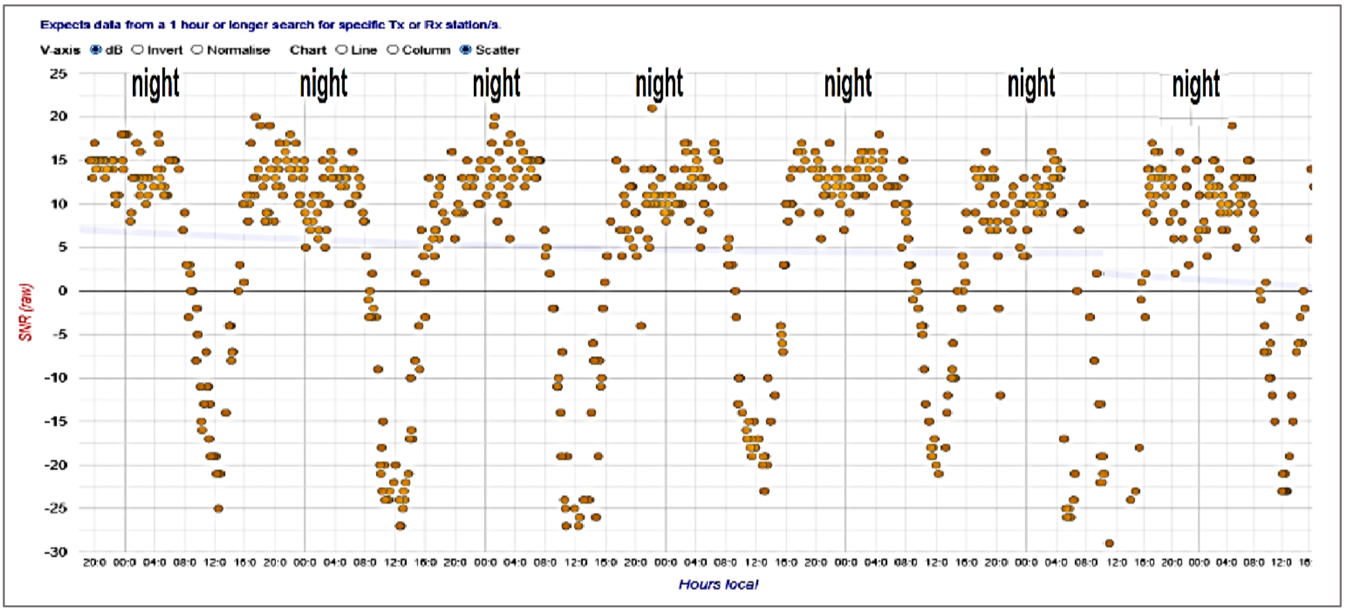

Figure 2. Signal-to-noise ratio (SNR) of the WSPR signal transmitted by station S53EFI and received by HA5GB in the 80 m band over a seven-day interval during the first week of January 2026. A clear day–night modulation is observed, together with structured nocturnal SNR oscillations that persist coherently from night to night throughout the analysed week.

3.3 Coherence on a monthly timescale with an additional station

The analysis was further extended to a longer time interval, on the order of one consecutive month, using a third propagation link operating in the 80 m band and involving an additional receiving station. Figure 3 shows the SNR behaviour for this link on a monthly timescale. Even on this longer temporal scale, the observed behaviour remains consistent with that discussed in the previous sections. A marked separation between daytime and nighttime regimes is again evident, accompanied during nighttime hours by a structured modulation of the SNR that repeats persistently throughout the analysed period. Differences between individual nocturnal events are mainly expressed in terms of amplitude and mean SNR level, while the overall temporal structure of the oscillations remains comparable. The observation of the same behaviour across different links and stations further supports the interpretation of the phenomenon as an intrinsic characteristic of nighttime ionospheric propagation in the 80 m band.

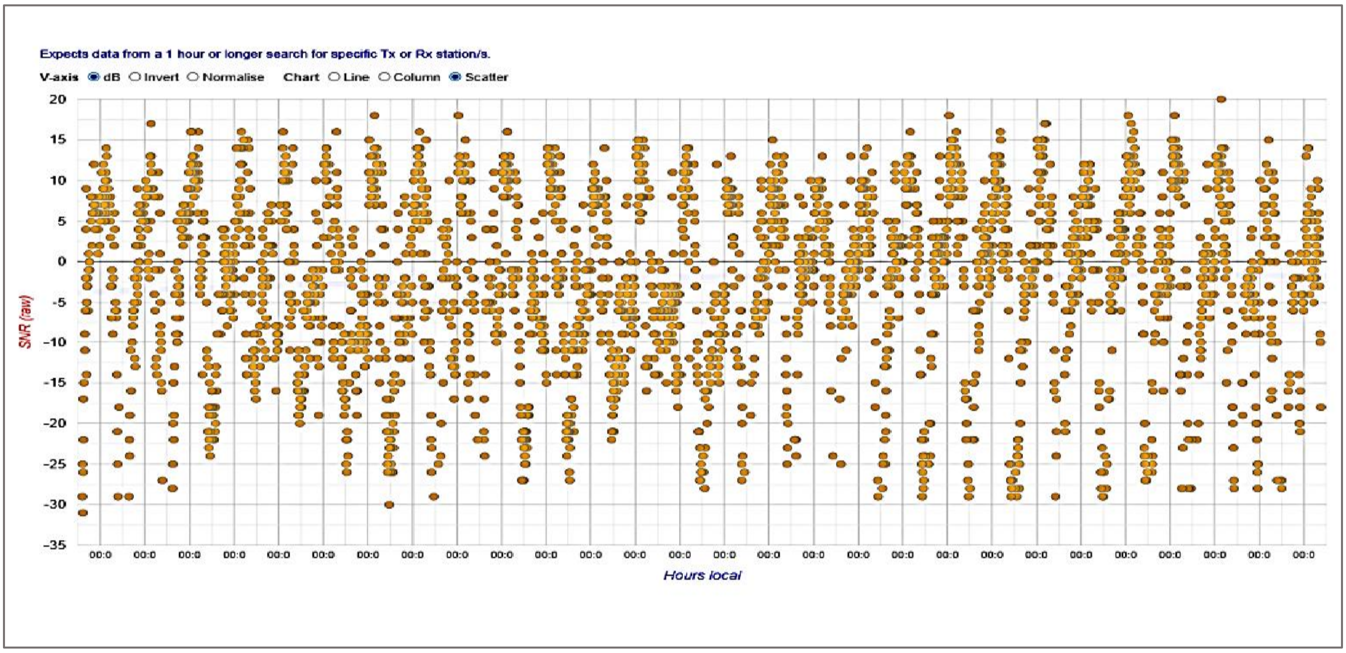

Figure 3. Signal-to-noise ratio (SNR) of the WSPR signal transmitted by station S53EFI and received by HB9VQQ in the 80 m band, over an approximately one-month interval. A persistent day–night modulation is observed, together with structured nocturnal SNR oscillations that recur throughout the analysed period, despite changes in the receiving station relative to the previous figures.

3.4 Spatial coherence of the phenomenon on a regional scale

After demonstrating the temporal persistence of nocturnal SNR oscillations on timescales ranging from individual nights to monthly intervals, and their independence from the specific receiving station, the analysis can be extended to the spatial dimension of the phenomenon. In particular, attention is focused on assessing the coherence of the observed behaviour across different propagation links operating simultaneously and distributed over a regional geographic scale. A comparative analysis of multiple WSPR links operating in the 80 m band, with propagation paths spanning different areas of central and southern Europe, shows that nocturnal SNR oscillations tend to occur simultaneously or quasi-simultaneously across multiple links, despite differences in absolute SNR levels and oscillation amplitudes. The temporal structure of the nocturnal modulations, however, appears comparable, suggesting a common origin linked to ionospheric conditions over extended regions. This spatial coherence indicates that the observed phenomenon cannot be attributed to local effects, such as environmental variations at individual stations or receiver-specific noise conditions, but instead involves significant portions of the nighttime ionosphere. The observed behaviour is consistent with the presence of ionospheric undulations organised on regional spatial scales, capable of coherently modulating HF propagation conditions along multiple paths simultaneously.

4 Limitations and robustness of the analysis

The analysis presented in this work is based on indirect observations of ionospheric conditions, obtained through monitoring the signal-to-noise ratio (SNR) of WSPR signals in the 80 m band. It is therefore appropriate to discuss the main methodological limitations of the adopted approach, as well as the elements that support the robustness of the results. First, WSPR data are characterised by discrete and non-continuous sampling, determined by the temporal structure of transmissions and by the availability of participating stations. In addition, the received SNR represents a composite quantity, influenced not only by ionospheric conditions along the propagation path, but also by local factors such as radio noise levels, antenna characteristics, and receiver configuration. A further limitation arises from the essentially two-dimensional nature of the available information, which does not allow a direct reconstruction of the three-dimensional ionospheric structures responsible for the observed modulations. Consequently, the physical interpretation of the phenomenon necessarily remains qualitative and relies on comparisons with models and observations previously reported in the literature. Despite these limitations, several elements indicate that the presented results are robust. In particular, nocturnal SNR oscillations exhibit temporal persistence on timescales ranging from individual nights to several months, and appear coherently across different links and stations. The repetition of the phenomenon under different operational conditions significantly reduces the likelihood that the observed modulations are due to instrumental or local effects. Moreover, the spatial coherence observed on a regional scale suggests an origin related to extended ionospheric processes rather than to localised causes. Taken together, these elements support the interpretation of nocturnal SNR modulations as an intrinsic feature of nighttime ionospheric propagation in the 80 m band, within the limits of an observational analysis based on WSPR data.

5.1 The ionosphere as an intrinsically undulated medium

It is now well established that the ionosphere does not represent a stable or approximately planar reflecting surface, but rather a highly dynamic medium whose spatial structure and temporal evolution result from the continuous interaction between neutral atmospheric components, ionospheric plasma, and electromagnetic fields. The electron density profile Ne(h,t) is shaped by a variety of coupled physical processes, including neutral wind circulation in the thermosphere, diurnal variations in the photoioniation–recombination balance, large-scale electric fields, atmospheric gravity wave (AGW) activity, and latitudinal and longitudinal gradients in atmospheric composition. The combined action of these processes gives rise to an ionospheric structure that is intrinsically irregular and undulated, characterised by spatial inhomogeneities spanning a wide range of temporal and spatial scales. As a consequence, the effective ionospheric reflecting region exhibits slow variations and quasi-periodic undulations that are consistent with the dynamic nature of the medium. Even under geomagnetically quiet conditions, small-amplitude fluctuations in electron density and in the effective reflection height are expected to persist, producing gradual and structured variations in HF propagation paths.

From the perspective of HF radio propagation, such intrinsic ionospheric undulations can lead to several observable effects, including slow modulations of the effective radio path length due to changes in reflection height and incidence angle, quasi-periodic oscillations of received signal strength with characteristic timescales ranging from tens of minutes to several hours, and a gradual nocturnal drift in signal level associated with the nighttime reconfiguration of the ionospheric F region in the absence of solar photoionization. Within this framework, the observed nocturnal SNR oscillations do not necessarily require the presence of well-defined travelling ionospheric disturbances (TIDs) as the sole explanatory mechanism. Instead, TIDs can be interpreted as more organised and coherent manifestations of an underlying wave-like behaviour that is intrinsically present in the ionosphere. The more irregular or weakly coherent components of the observed modulations may reflect the natural response of the ionosphere to a combination of atmospheric and thermodynamic forcing processes acting on the coupled thermosphere–ionosphere system. This interpretation is consistent with the systematic presence of structured nocturnal SNR modulations, their absence during daytime hours, and their morphological coherence across distinct and geographically separated propagation paths. Together, these features support a physical picture in which the nighttime ionosphere exhibits persistent three-dimensional and temporal variability of electron content, attributable both to its intrinsic undulated morphology and to the possible superposition of travelling ionospheric disturbances with variable wavelengths and phase velocities.

5.2 Implications for WSPR-based ionospheric sensing

The results presented in this study highlight the potential of WSPR-based observations as an effective tool for passive sensing of ionospheric dynamics on regional spatial scales. Although originally designed for weak-signal communication experiments, the WSPR network provides a dense, geographically distributed set of continuous HF propagation measurements that can be exploited for ionospheric diagnostics. In the 80 m band, nighttime propagation is particularly sensitive to variations in the structure of the ionospheric F region: small changes in electron density, effective reflection height, or propagation geometry can produce measurable variations in the received signal-to-noise ratio. Recent HF Doppler studies further support this interpretation, showing that HF propagation is an extremely sensitive probe of ionospheric variability: during nighttime it exhibits regular oscillations with characteristic periods of 1–3 hours, and during geomagnetic disturbances it responds coherently over wide regional scales. This behaviour is fully consistent with the structured nocturnal SNR modulations observed across multiple WSPR links in the present work. As shown in the previous sections, such variations manifest as persistent, structured oscillations with characteristic timescales of a few hours, recurring across different links, stations, and time intervals. The observation of coherent SNR modulations across multiple, geographically separated propagation paths suggests that WSPR measurements are capable of capturing ionospheric processes extending over meso-regional scales. Although WSPR does not provide direct measurements of electron density profiles or drift velocities, the statistical and comparative analysis of SNR time series can reveal persistent patterns indicative of underlying ionospheric dynamics. When combined with independent geophysical data, such as geomagnetic indices or atmospheric models, WSPR-based observations may therefore contribute to a more comprehensive understanding of the coupled thermosphere–ionosphere system and its intrinsic variability.

5.3 Regional-scale coherence and response to external forcing

Further evidence of ionospheric coherence on a regional scale is provided by the comparative analysis of WSPR reception from the transmitting station S53EFI over multiple geographically separated receivers in Central Europe. In particular, data collected over a five-week interval from OE9TAV (Austria), I0UVN (central Italy) and HB9VQQ (Switzerland) reveal a strong similarity in the temporal evolution of the signal-to-noise ratio (SNR), despite differences in propagation distance and path geometry. While absolute SNR values differ due to local factors such as antenna characteristics and ambient noise levels, the overall temporal morphology of the SNR curves appears highly consistent across all receiving stations. A well-defined diurnal pattern is observed, with enhanced SNR during nighttime hours and progressive attenuation after sunrise. More importantly, the nighttime evolution of the signal exhibits comparable transitions and modulations across all links, indicating a synchronised ionospheric response over a spatial scale of several hundred kilometres. This interpretation is further supported by the observation of a distinct event occurring during the night of 11–12 November 2025, when a pronounced and near-simultaneous decrease in SNR was detected around 03:30 UTC at three independent receiving stations (HB9VQQ, HA5GB, and I0UVN). The temporal coincidence of the signal attenuation across multiple regional paths constitutes direct evidence of a coherent ionospheric disturbance affecting a large portion of the nighttime European ionosphere. The event coincided with a strong solar disturbance, associated with an X-class solar flare and the subsequent development of a severe geomagnetic storm (G4). Under such conditions, enhanced particle precipitation and increased ionisation in the lower ionosphere are known to produce significant HF absorption, particularly in the D region, while concurrent modifications of the F-region structure can degrade NVIS propagation in the 80 m band. The observed regional-scale SNR reduction is therefore consistent with a large-scale ionospheric response to space weather forcing, clearly distinguishable from the more regular nocturnal modulations attributed to intrinsic ionospheric dynamics. Taken together, these observations demonstrate that the nighttime ionosphere can exhibit a high degree of spatial coherence, both under quiet conditions—where intrinsic undulations dominate—and during disturbed periods, when external forcing produces a synchronised response over extended geographic areas. This reinforces the interpretation of 80 m WSPR propagation as a sensitive and distributed diagnostic of ionospheric behaviour on meso- to regional spatial scales.

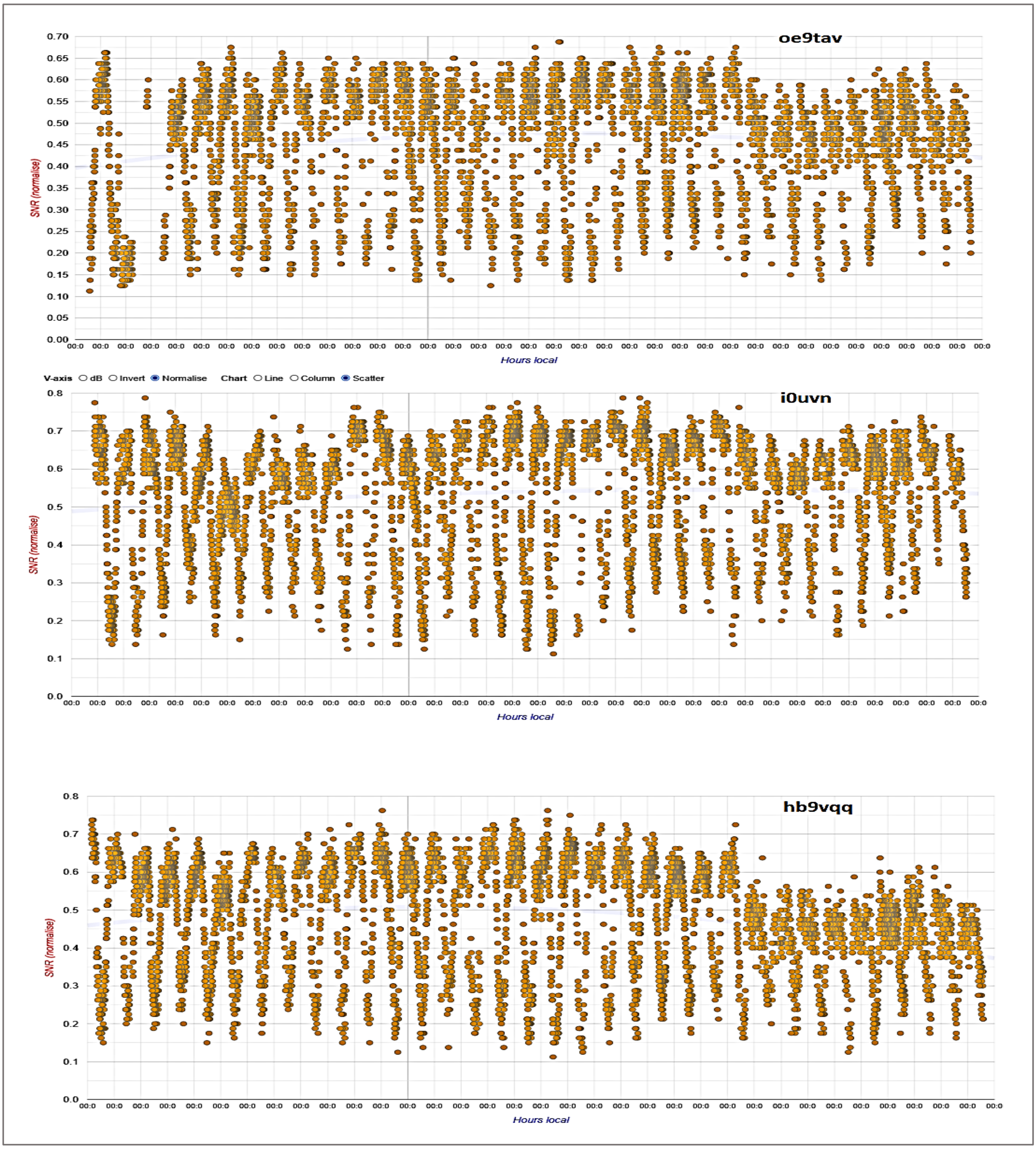

Figure 4 Comparison of the signal-to-noise ratio (SNR) time series of the WSPR signal transmitted by S53EFI in the 80 m band and received at OE9TAV (Austria), I0UVN (central Italy), and HB9VQQ (Switzerland) over an interval of approximately five weeks, spanning December 2025 to January 2026. Although absolute SNR values differ due to local factors such as antenna characteristics and ambient noise levels, the curves exhibit a strong similarity in their temporal evolution, with coherent diurnal and nocturnal patterns across all stations. This behaviour indicates a synchronised ionospheric response on a regional spatial scale extending over several hundred kilometres.

5.4 Geomagnetic storm response

The near-simultaneous SNR drop observed around 03:30 UTC on 12 November 2025 across the three receiving stations (HB9VQQ, HA5GB, and I0UVN) cannot be attributed to intrinsic atmospheric wave activity such as MSTIDs. Instead, it represents a coherent ionospheric response to an external large-scale forcing. Geospace data confirm that the event coincided with the main phase of a severe geomagnetic storm (G4), triggered by a CME associated with an earlier X5.1 solar flare. The extreme values of the planetary Kp index and the pronounced negative excursion of the Dst index indicate that both the magnetosphere and ionosphere were undergoing intense energy input. Under such conditions, the observed attenuation of the 80 m signal is consistent with (i) enhanced D-region absorption due to energetic particle precipitation, and (ii) structural modifications of the F region affecting NVIS propagation. This event highlights the ability of 80 m WSPR links to act as sensitive, synchronised probes of ionospheric disturbances driven by space weather, clearly distinguishable from the regular nocturnal modulations associated with intrinsic ionospheric dynamics.

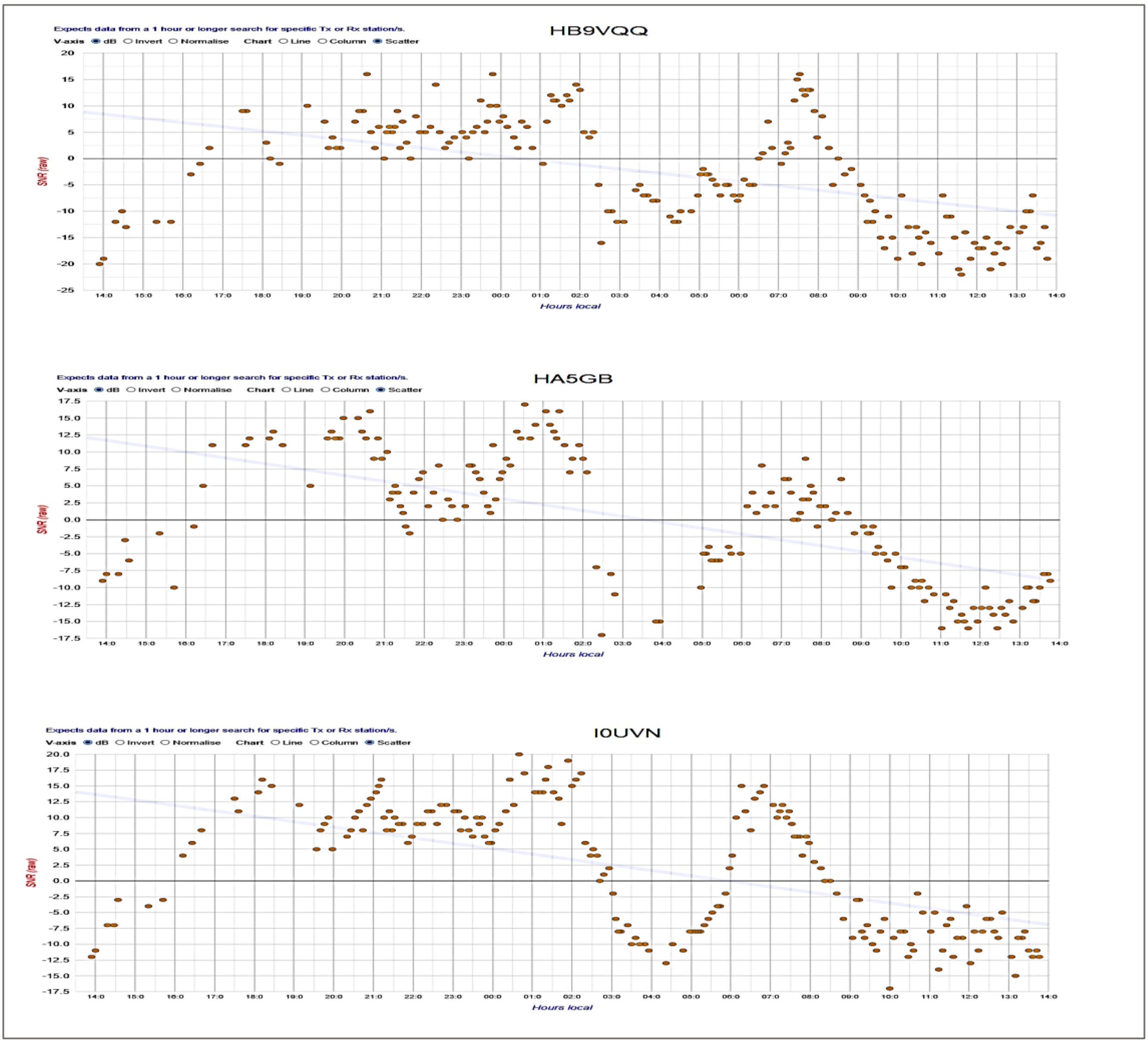

Figure 5. Signal-to-noise ratio (SNR) of the WSPR signal transmitted by S53EFI and received by HB9VQQ (Switzerland), HA5GB (Hungary), and I0UVN (Italy) over a 48-hour interval. Although the plot includes both daytime and nighttime reception, the analysis focuses on the nocturnal interval. The simultaneous SNR drop around 04:30 local time highlights a coherent ionospheric response on a regional scale, consistent with the impact of a real-time detected X-class solar flare.

5.5 Extension to lower frequencies: evidence from 160 m

Although the present analysis focuses on the 80 m band, preliminary observations carried out in the 160 m band show a qualitatively similar nocturnal behaviour. In this band, due to strong daytime attenuation associated with D-region absorption, propagation is observable almost exclusively during nighttime hours. Figure 6 shows the signal-to-noise ratio (SNR) of a 160 m WSPR link over a representative nighttime interval, where a slow evolution of the mean nighttime level is accompanied by clearly organised and structured oscillations. At these lower frequencies, HF propagation is even more sensitive to ionospheric conditions, particularly to variations in effective reflection height and electron density gradients. The observation of qualitatively similar SNR modulations in both the 80 m and 160 m bands therefore indicates that the phenomenon is not band-dependent, but reflects an intrinsic property of the nighttime ionospheric medium.

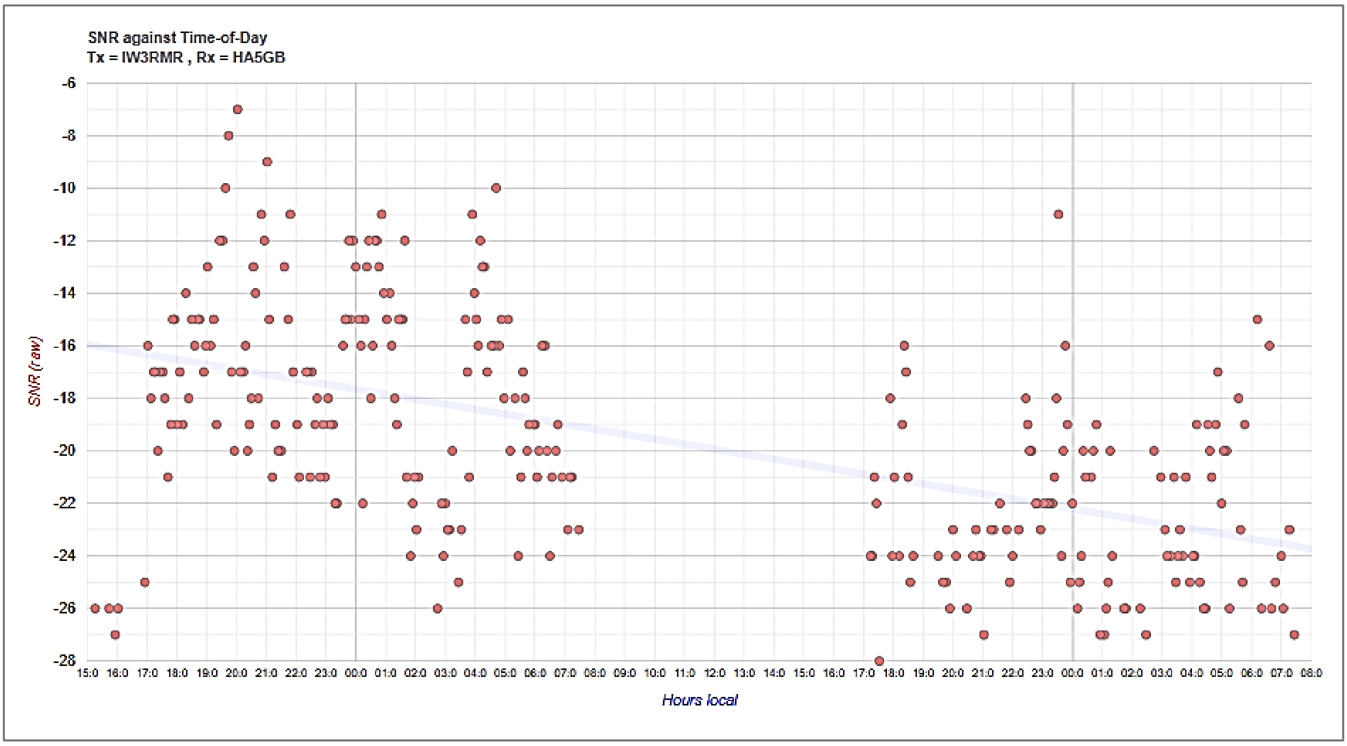

Figure 6. Signal-to-noise ratio (SNR) of the 160 m WSPR signal transmitted by station IW3RMR and received by HA5GB over a representative nighttime interval, in a band characterised by predominantly nocturnal propagation. The time series shows a slow evolution of the mean level, with superimposed slow and structured SNR modulations.

6 Conclusions

In this work, systematic WSPR observations in the 80 m band were analysed to investigate nighttime ionospheric propagation under geomagnetically quiet and moderately disturbed conditions. The study focused on the temporal behaviour of the received signal-to-noise ratio (SNR), exploiting the extensive spatial and temporal coverage provided by the WSPR network. The results show that nocturnal SNR variations are not random, but exhibit structured oscillations with characteristic timescales of a few hours. These oscillations persist over multiple nights, extend over weekly and monthly intervals, and are observed consistently across different propagation links and receiving stations. The repetition and coherence of the observed patterns indicate that the phenomenon represents a recurring feature of nighttime ionospheric propagation in the 80 m band. Comparative analysis of multiple, geographically separated links further reveals a degree of spatial coherence on a regional scale, suggesting that the observed modulations are not driven by local or instrumental effects, but instead reflect ionospheric processes acting over extended areas. This behaviour is consistent with a physical picture in which the nighttime ionosphere exhibits intrinsic undulations and slow temporal variability of the F-region structure, potentially influenced by atmospheric gravity waves and related mesoscale dynamics. Although WSPR measurements provide only indirect information on ionospheric parameters, the present results demonstrate that systematic analysis of WSPR SNR data can yield meaningful insight into ionospheric variability. In particular, the 80 m band proves to be highly sensitive to small changes in nighttime ionospheric structure, making it a valuable band for passive ionospheric sensing. Overall, this study highlights the potential of WSPR as a complementary observational tool for investigating nighttime ionospheric dynamics on meso-regional scales. Future work combining WSPR-based analyses with independent ionospheric measurements and atmospheric modelling may further clarify the physical mechanisms underlying the observed SNR modulations and improve the interpretation of HF propagation variability.

References

- WSPR at Midlatitudes from KN4NBI: A Year of Data at Solar Minimum
- Doug Richards (KN4NBI), HamSCI
- Fernandes, S., Perry, G., Trigo, T., Frissell, N., & Gibbons, J. (2025). Ionospheric Variability's Impact on HF Propagation: Insights from Grape V1 Doppler Residuals and PHaRLAP Ray Tracing
- WSPR.Rocks by Phil VK7JJ
- WSPRnet - Weak Signal Propagation Reporter Network