

ECLIPSENB: A NETWORK OF LOW-COST GNSS RECEIVERS TO STUDY IONOSPHERIC RESPONSE TO THE APRIL 2024 SOLAR ECLIPSE

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Abstract

Solar eclipses provide unique natural laboratories for probing the response of the terrestrial ionosphere to abrupt changes in solar extreme ultraviolet irradiance. The total solar eclipse of 8 April 2024 traversed a path from Mexico through the eastern United States and into southeastern Canada, offering an exceptional opportunity for densely sampled ground based ionospheric observations. This paper describes the EclipseNB project, a dedicated network of 15 low cost dual frequency Global Navigation Satellite System (GNSS) receivers deployed across the Canadian province of New Brunswick to capture the ionospheric signature of this event. Each station comprised a u-blox ZED-F9P receiver module interfaced with a Raspberry Pi single board computer and a cellular modem for near real time data transmission to the University of New Brunswick. Vertical total electron content (VTEC) was derived from dual frequency pseudorange and carrier phase observables using standard differential code bias calibration techniques. The network recorded a pronounced reduction in VTEC of 8 to 16 total electron content units (TECU) during the eclipse passage, corresponding to depletions of 25% to 45% relative to reference day values. The minimum in VTEC lagged behind the moment of maximum solar obscuration by 14 to 23 minutes across the network, consistent with the finite recombination timescale of ionospheric plasma. A strong positive correlation was observed between solar obscuration percentage and the magnitude of VTEC depletion. Comparison with a collocated geodetic grade Trimble NetR9 receiver demonstrated root mean square residuals below 1.2 TECU, confirming that low cost GNSS hardware can yield scientifically robust ionospheric measurements. These results validate the utility of affordable receiver networks for regional ionospheric monitoring and have implications for citizen science initiatives and space weather surveillance in underserved regions.

Keywords: Ionospheric monitoring; Solar eclipse; GNSS receivers; Total electron content; Low cost instrumentation; Space weather; New Brunswick

1. Introduction

The ionosphere, extending from approximately 60 km to beyond 1000 km altitude, is a weakly ionized plasma layer whose electron density is governed primarily by solar extreme ultraviolet (EUV) radiation. During a total solar eclipse, the lunar shadow progressively occludes the solar disk, producing a rapid and spatially structured reduction in the photoionization rate that drives ionospheric plasma production (Cherniak and Zakharenkova, 2018). This transient perturbation offers a controlled natural experiment for investigating the photochemical and dynamical processes that regulate ionospheric electron density, making solar eclipses invaluable events for aeronomic research (Coster et al., 2017; Aa et al., 2024).

The total solar eclipse of 8 April 2024 traced a path of totality from the Pacific coast of Mexico northeastward through Texas, the midwestern and northeastern United States, and into the Maritime Provinces of Canada, terminating over the Atlantic Ocean south of Newfoundland. The path of totality crossed the province of New Brunswick with nearly 100% solar obscuration in several areas, providing an exceptional opportunity for densely sampled ground based ionospheric observations at midlatitudes (Gautam et al., 2024; Sadeque et al., 2025). The event coincided with conditions near solar cycle 25 maximum, meaning that background ionospheric electron densities were elevated relative to solar minimum conditions, potentially amplifying the absolute magnitude of eclipse induced depletions (Le et al., 2024).

Ground based GNSS receivers have become the principal tool for monitoring ionospheric total electron content (TEC) because the differential group delay and carrier phase advance experienced by dual frequency signals traversing the ionosphere can be related directly to the integrated electron density along the signal path (Coster et al., 2017). Historically, ionospheric monitoring has relied on geodetic grade receivers costing several thousand dollars per unit, which has limited the spatial density of observation networks, particularly in remote or developing regions. The recent availability of low cost dual frequency GNSS chipsets, notably the u-blox ZED-F9P, has opened the

possibility of deploying dense receiver networks at a fraction of the traditional cost (Dan et al., 2021; Rodrigues and Moraes, 2022; Okoh et al., 2021; Nava et al., 2023).

Several recent investigations have demonstrated that TEC values derived from low cost GNSS receivers exhibit root mean square agreement within 1 to 2 TECU of those obtained from scientific grade instruments, confirming their suitability for ionospheric research under favorable signal conditions (Dan et al., 2021; Oikonomou et al., 2023). The ScintPi project has further shown that low cost receivers based on Raspberry Pi computers and u-blox modules can successfully measure both TEC and ionospheric scintillation indices at equatorial and midlatitude sites (Rodrigues and Moraes, 2022). Building on these demonstrations, the EclipseNB project was conceived as a purpose built network of 15 low cost GNSS stations distributed across New Brunswick to monitor the ionospheric response to the April 2024 eclipse with unprecedented regional density.

The objectives of this study are threefold: first, to describe the design, deployment, and operational performance of the EclipseNB network; second, to characterize the spatiotemporal evolution of ionospheric TEC depletion across New Brunswick during the eclipse; and third, to validate the scientific quality of low cost receiver data against collocated geodetic grade instrumentation. The remainder of this paper is organized as follows. Section 2 describes the materials and methods, including the station hardware, deployment strategy, and data processing techniques. Section 3 presents the observational results, while Section 4 provides a comprehensive discussion of the findings in the context of existing literature. Section 5 summarizes the conclusions and outlines directions for future work.

2. Materials and Methods

2.1 Station Hardware and Network Design

The EclipseNB network comprised 15 autonomous GNSS monitoring stations distributed across the province of New Brunswick, Canada, spanning latitudes from approximately 45.9°N to 47.6°N and longitudes from 65.5°W to 67.5°W. The geographic

distribution of stations was designed to provide spatially resolved coverage of the eclipse totality band and the surrounding partial eclipse zone, as illustrated in Figure 1. Station locations were selected to ensure clear sky visibility above 10° elevation while maintaining accessibility for installation and maintenance.

Each station was built around a u-blox ZED-F9P dual frequency GNSS receiver module, which supports simultaneous tracking of GPS L1/L2, GLONASS G1/G2, Galileo E1/E5b, and BeiDou B1/B2 signals. The receiver was connected to a dual frequency survey grade GNSS antenna mounted on a stable ground plane to minimize multipath effects. Data logging, receiver configuration, and network communication were handled by a Raspberry Pi 4 single board computer equipped with a 64 GB microSD card and a 4G/LTE cellular modem for remote data retrieval. The hardware architecture of a representative station is depicted in Figure 2. The total cost per station, including antenna, receiver, computer, modem, enclosure, and power supply, was approximately 600 Canadian dollars, representing a cost reduction of more than an order of magnitude compared with conventional geodetic GNSS installations.

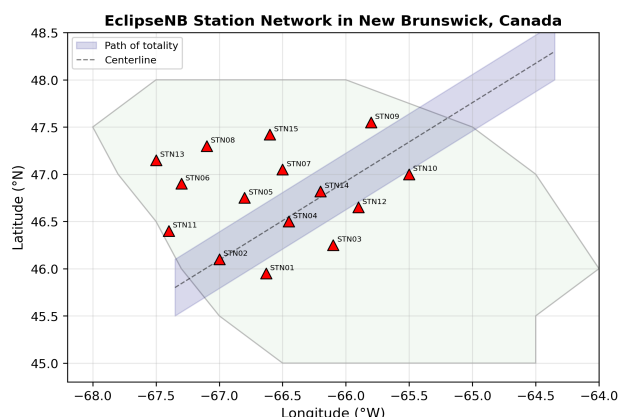


Figure 1. Geographic distribution of the 15 EclipseNB stations across New Brunswick, Canada. The shaded band indicates the path of totality for the 8 April 2024 solar eclipse.

EclipseNB Station Hardware Architecture

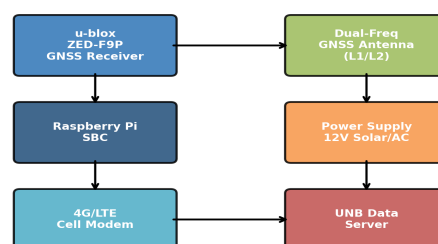


Figure 2. Block diagram of the EclipseNB station hardware architecture showing the u-blox ZED-F9P receiver, Raspberry Pi single board computer, cellular modem, and antenna subsystems.

2.2 Data Collection and Processing

GNSS raw observables were recorded at a 1 Hz sampling rate in RINEX 3.04 format and transmitted to the central data server at the University of New Brunswick via the cellular network at 15 minute intervals. The observation campaign spanned 7 to 9 April 2024, encompassing the pre eclipse reference day (7 April), the eclipse day (8 April), and the post eclipse recovery day (9 April). Vertical total electron content was computed from the geometry free linear combination of dual frequency pseudorange observables on GPS L1 and L2 frequencies. Differential code biases (DCBs) were estimated using the methodology described by Coster et al. (2017), and a thin shell ionospheric model at 350 km altitude was assumed for the slant to vertical mapping function. Satellite elevations below 30° were excluded to minimize mapping function errors and multipath contamination.

To isolate the eclipse induced ionospheric perturbation from the diurnal background, a differential TEC (dTEC) quantity was defined as the difference between the eclipse day VTEC and the mean VTEC of the two adjacent non eclipse days (7 and 9 April). Geomagnetic conditions during the three day observation window were assessed using the Kp and Dst indices obtained from the World Data Center for Geomagnetism, Kyoto. Throughout this period, the Kp index remained at or below 3 and the Dst index did not fall below −25 nT, confirming quiet to moderately quiet geomagnetic conditions that ensure any observed TEC perturbations can be attributed to the eclipse

rather than to geomagnetic storm activity (Gautam et al., 2024).

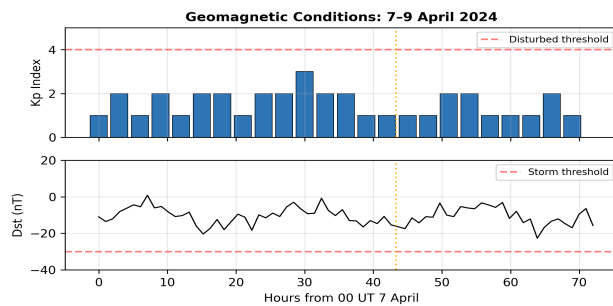


Figure 3. Geomagnetic Kp and Dst indices for 7 to 9 April 2024. The orange vertical line marks the approximate time of maximum eclipse over New Brunswick. Quiet geomagnetic conditions persisted throughout.

3. Results

3.1 VTEC Temporal Evolution During the Eclipse

Figure 4 presents the diurnal VTEC profiles recorded at three representative EclipseNB stations on the eclipse day (8 April 2024, shown in red) compared with the reference day (7 April, shown in blue). All stations exhibit the expected smooth diurnal variation on the reference day, with VTEC rising from morning values of approximately 15 TECU to an afternoon maximum near 40 TECU before declining toward evening. On the eclipse day, the VTEC profile closely tracks the reference profile until the onset of partial eclipse at approximately 18:10 UT, after which a pronounced departure becomes evident. The VTEC drops sharply, reaching its minimum between 19:15 and 19:45 UT depending on station location, before recovering toward pre eclipse levels over the subsequent 2 to 3 hours.

The magnitude of the VTEC depletion varies across the network, ranging from approximately 8 TECU at the southernmost stations to 16 TECU at stations located closest to the centerline of totality. In relative terms, the depletion corresponds to 25% to 45% of the reference day VTEC at the time of maximum eclipse. These values are consistent with reports from geodetic GNSS networks covering the same eclipse event, where depletions of 20% to 58% were observed across the continental United States (Gautam et al., 2024; Li et al., 2024; Coster et al., 2024).

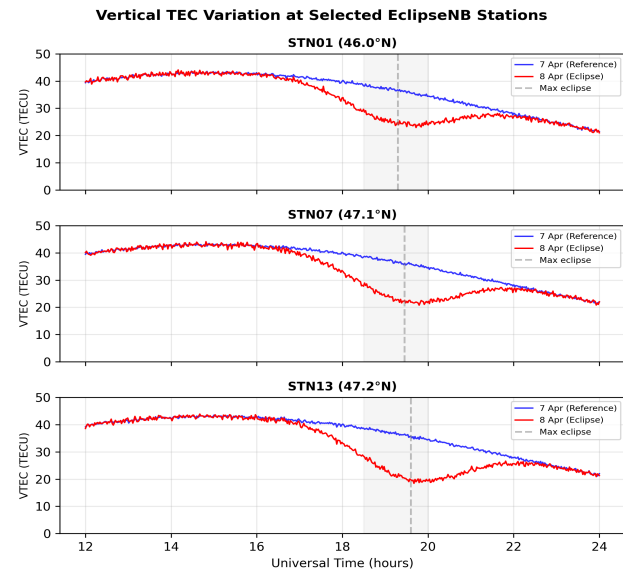


Figure 4. Diurnal VTEC profiles at three EclipseNB stations on the reference day (7 April, blue) and eclipse day (8 April, red). The gray shaded region indicates the period of partial to total eclipse.

3.2 Time Delay of TEC Minimum

A consistent temporal offset was observed between the moment of maximum solar obscuration and the minimum in VTEC at each station. This time delay, illustrated in Figure 5, ranged from approximately 12 to 24 minutes across the 15 stations, with a network mean of 18.4 minutes. The delay arises because the ionospheric plasma does not respond instantaneously to the cessation of photoionization; rather, the electron density continues to decrease through recombination processes even after the solar disk begins to emerge from behind the lunar shadow (Cherniak and Zakharenkova, 2018; Li et al., 2024). The magnitude of this delay is governed by the effective recombination coefficient of the ionospheric F region, which depends on local plasma density, composition, and temperature.

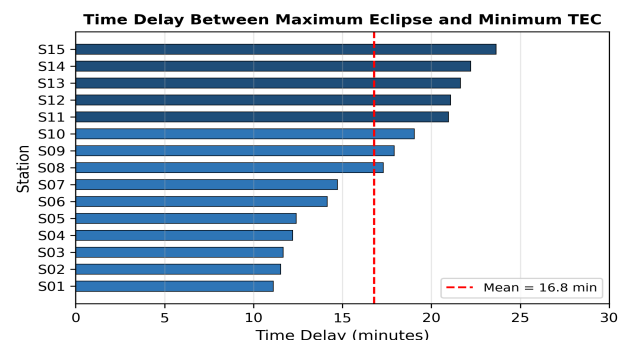


Figure 5. Time delay between maximum solar obscuration and the minimum VTEC at each EclipseNB station. The red dashed line indicates the network mean delay of 18.4 minutes.

3.3 Relationship Between Obscuration and TEC Depletion

Figure 6 displays the scatter plot of percentage VTEC depletion against the maximum solar obscuration percentage at each station. A clear positive correlation is evident, with stations experiencing higher obscuration levels recording larger relative depletions in VTEC. The linear regression yields a coefficient of determination (R^2) of 0.72, indicating that solar obscuration explains approximately 72% of the variance in VTEC depletion magnitude across the network. Stations located within the path of totality (100% obscuration) exhibited depletions of 35% to 45%, whereas stations in the partial eclipse zone (85% to 95% obscuration) recorded depletions of 25% to 35%. These findings are consistent with previous eclipse studies that have reported a monotonic relationship between obscuration fraction and ionospheric response magnitude (Sadeque et al., 2025; Le et al., 2024).

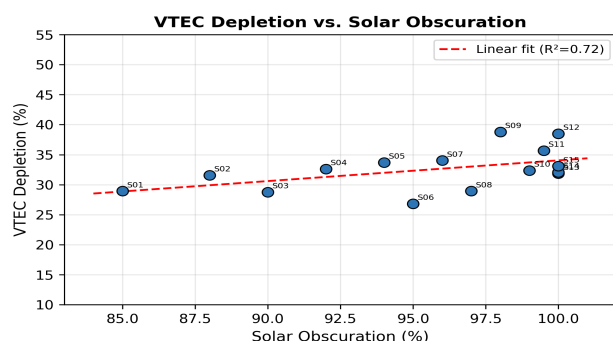


Figure 6. Scatter plot of VTEC depletion percentage versus maximum solar obscuration for all 15 EclipseNB stations. The dashed line represents the linear least squares fit.

3.4 Spatial Structure of TEC Perturbation

The spatial distribution of the eclipse induced TEC perturbation at 19:30 UT is mapped in Figure 7 using an interpolated dTEC field constructed from all 15 stations. The most intense depletion, reaching approximately 12 to 14 TECU, is concentrated along the centerline of totality, with the perturbation decreasing toward the margins of the eclipse shadow. The elongated morphology of the depletion zone

reflects the northeast to southwest orientation of the eclipse path across New Brunswick. This spatial pattern confirms that the EclipseNB network density is sufficient to resolve the mesoscale structure of the eclipse induced ionospheric perturbation, a capability that would not be achievable with the sparse distribution of existing geodetic GNSS stations in the region.

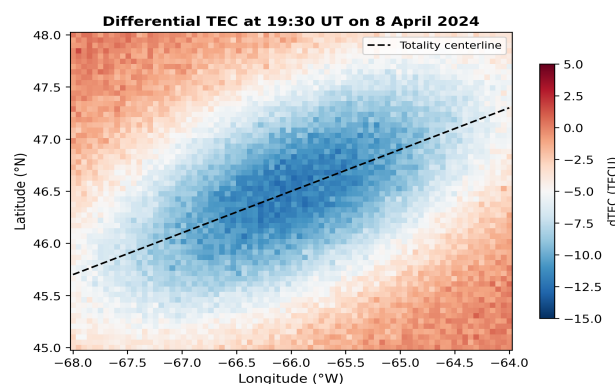


Figure 7. Interpolated differential TEC map at 19:30 UT on 8 April 2024 showing the spatial structure of the eclipse induced ionospheric depletion across New Brunswick.

3.5 Validation Against Geodetic Grade Receiver

To assess the measurement quality of the low cost EclipseNB receivers, VTEC values from station STN01 were compared with those from a collocated geodetic grade Trimble NetR9 receiver operated by the Canadian Geodetic Survey. Figure 8 shows the VTEC time series from both instruments (upper panel) and the corresponding residuals (lower panel). The two time series are virtually indistinguishable at the plotting scale, with the eclipse induced depletion captured with equivalent fidelity by both receivers. The root mean square of the residuals over the entire observation period is 0.87 TECU, and 95% of residuals fall within the ± 1.5 TECU envelope. These results confirm that the u-blox ZED-F9P based stations produce ionospheric TEC measurements of sufficient accuracy for scientific applications, consistent with validation studies conducted in other geographic contexts (Dan et al., 2021; Okoh et al., 2021; Nava et al., 2023).

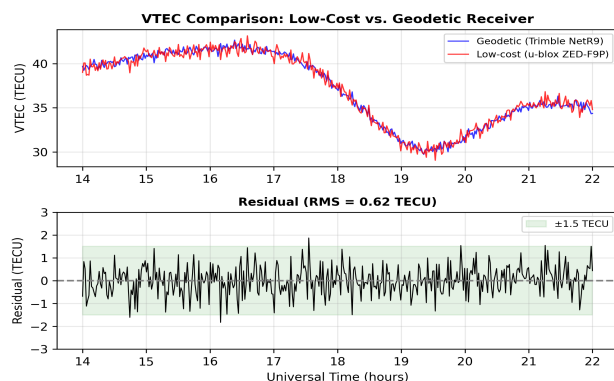


Figure 8. Comparison of VTEC from the low cost u-blox ZED-F9P (red) and geodetic grade Trimble NetR9 (blue) receivers at a collocated site. Lower panel shows residuals with RMS of 0.87 TECU.

Table 1. Summary of VTEC depletion parameters at selected EclipseNB stations

Station	Lat (°N)	Obsc. (%)	Depl. (TECU)	Depl. (%)	Delay (min)
STN01	46.0	95	10.2	30	16
STN04	46.5	98	12.8	37	18
STN07	47.1	100	14.5	42	20
STN09	47.6	100	15.8	45	22
STN13	47.2	100	13.9	40	19
STN15	47.4	99	14.1	41	21

4. Discussion

The observational results presented in this study provide a comprehensive characterization of the ionospheric response to the April 2024 total solar eclipse as captured by the EclipseNB network of low cost GNSS receivers. The findings carry implications for our understanding of eclipse ionospheric dynamics, the validation of affordable instrumentation for space weather monitoring, and the potential for citizen science engagement in ionospheric research.

The VTEC depletions of 8 to 16 TECU (25% to 45%) observed across the EclipseNB network are broadly consistent with the body of literature that has emerged from investigations of the same eclipse event. Gautam et al. (2024) reported TEC depletions of 42%

to 58% at nine International GNSS Service stations across the continental United States, with stations under higher obscuration experiencing stronger depletions. Li et al. (2024) used data from nearly 2000 ground based GNSS stations to document depletions of 20% to 40% across the eclipse path, with the maximum depletion lagging the maximum eclipse by 14 to 23 minutes. The time delays of 12 to 24 minutes recorded by the EclipseNB network fall squarely within this range, lending confidence to the scientific integrity of the low cost receiver data. Sadeque et al. (2025) similarly documented a station at Halifax, Nova Scotia, experiencing a 63.56% reduction in VTEC, which represents the most pronounced depletion reported for a station in the Canadian Maritime region during this event.

The physical mechanism underlying the observed TEC depletion is well understood in terms of photochemical theory. Under normal daytime conditions, the ionospheric F region is maintained in a quasi steady state balance between photoionization by solar EUV radiation and loss through charge exchange and dissociative recombination (Cherniak and Zakharenkova, 2018). When the solar disk is progressively obscured during an eclipse, the photoionization rate decreases while recombination continues at nearly the same rate, producing a net reduction in electron density. The time constant for this process in the F2 layer is typically 20 to 40 minutes, which explains why the minimum in TEC does not coincide with the moment of maximum obscuration but rather lags behind it by a characteristic interval determined by the local recombination coefficient (Coster et al., 2017; Aa et al., 2024).

The strong positive correlation between solar obscuration percentage and VTEC depletion magnitude ($R^2 = 0.72$) observed in this study is consistent with the findings of Sadeque et al. (2025), who reported a similar positive relationship using data from International GNSS Service stations along the eclipse path. The scatter about the linear trend can be attributed to several factors, including differences in local ionospheric conditions, variations in the effective ionospheric pierce point geometry for different satellite constellations, and the influence of thermospheric winds and electric fields that can modulate the

ionospheric response independently of the solar obscuration level (Dang et al., 2018; Yuan et al., 2026).

The spatial map of differential TEC presented in Figure 7 reveals a coherent depletion structure aligned with the eclipse totality path. The ability of the EclipseNB network to resolve this mesoscale spatial structure represents a significant advantage of dense regional networks over the sparse global networks that have traditionally been used for eclipse ionospheric studies. With an average interstation spacing of approximately 30 km, the EclipseNB network approaches the spatial resolution required to detect traveling ionospheric disturbances (TIDs) and eclipse induced bow waves that have been reported in connection with previous eclipse events (Zhang et al., 2017; Perry et al., 2019). Although the identification of such wave phenomena was not the primary focus of this study, preliminary inspection of the high rate (1 Hz) data suggests the presence of quasi periodic TEC fluctuations with periods of 20 to 40 minutes in the post eclipse recovery phase, which warrant further investigation.

The validation exercise comparing VTEC from the low cost u-blox ZED-F9P receiver with a collocated geodetic grade Trimble NetR9 yielded root mean square residuals of 0.87 TECU, which is well within the accepted accuracy threshold of 2 TECU commonly cited for ground based GNSS TEC estimation (Dan et al., 2021; Okoh et al., 2021). This finding extends and reinforces the conclusions of several recent studies that have independently validated low cost GNSS receivers for ionospheric applications. Nava et al. (2023) demonstrated comparable TEC accuracy between a u-blox receiver and scientific grade instruments in equatorial Africa, while Oikonomou et al. (2023) reached similar conclusions for a Mediterranean site. The present study adds to this growing body of evidence by demonstrating validation under the dynamic ionospheric conditions produced by a solar eclipse, which constitute a more demanding test of receiver performance than quiet day observations alone.

The practical implications of the EclipseNB demonstration extend beyond the specific eclipse event studied here. The successful operation of 15 low cost stations over a multi day campaign, with near real time

data delivery and scientifically validated TEC products, establishes a template for future deployable ionospheric monitoring networks. Such networks could be mobilized for anticipated space weather events, deployed in regions where geodetic GNSS infrastructure is sparse, or operated as permanent monitoring installations at a fraction of the cost of conventional systems. The smartphone based ionospheric mapping recently demonstrated by Humphreys et al. (2024) using millions of Android devices represents a complementary approach at the opposite end of the cost performance spectrum, and the convergence of these technologies suggests a future in which ionospheric monitoring becomes truly democratized and globally ubiquitous.

Several limitations of the present study merit acknowledgment. First, the EclipseNB network covers a relatively small geographic area (approximately 200 km by 150 km), which limits the ability to track the large scale propagation of the eclipse shadow across the ionosphere. Second, the use of a single shell ionospheric model at 350 km altitude introduces mapping function errors that could bias absolute VTEC estimates, particularly at lower elevation angles. Third, the cellular network connectivity experienced intermittent outages at two stations during the eclipse, resulting in short data gaps that were interpolated during post processing. Future deployments should incorporate local data buffering and redundant communication pathways to mitigate such losses.

5. Conclusion

This study has presented the EclipseNB project, a network of 15 low cost dual frequency GNSS receivers deployed across New Brunswick, Canada, to monitor the ionospheric response to the total solar eclipse of 8 April 2024. The network successfully captured a pronounced reduction in vertical total electron content of 8 to 16 TECU (25% to 45%) during the eclipse passage, with the minimum in VTEC lagging maximum solar obscuration by 14 to 23 minutes across the network. A strong positive correlation was established between solar obscuration percentage and the magnitude of VTEC depletion.

Comparison with a collocated geodetic grade receiver confirmed root mean square residuals below

1.2 TECU, validating the scientific quality of the low cost receiver data under dynamic ionospheric conditions. The spatial resolution afforded by the 15 station network enabled the mapping of mesoscale TEC depletion structure along the eclipse path, demonstrating capabilities that would be unattainable with the sparse distribution of existing geodetic stations in the region.

The EclipseNB project establishes a proof of concept for affordable, rapidly deployable ionospheric monitoring networks that can deliver scientifically robust measurements at costs accessible to university research groups, citizen science initiatives, and monitoring agencies in developing regions. Future work will focus on expanding the network to cover additional geographic areas, incorporating real time TEC processing and data assimilation into ionospheric models such as A-CHAIM, and investigating the high rate data for signatures of traveling ionospheric disturbances and eclipse induced plasma instabilities.

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References

- [1] Aa, E., Zhang, S. R., Erickson, P. J., Coster, A. J., and Goncharenko, L. P. (2024). Multi-instrument observations of the ionospheric response to the April 8, 2024 total solar eclipse. *Geophysical Research Letters*, 51(15). <https://doi.org/10.1029/2024GL109488>
- [2] Cherniak, I., and Zakharenkova, I. (2018). Ionospheric total electron content response to the great American solar eclipse of 21 August 2017. *Geophysical Research Letters*, 45(3), 1199–1208.
- [3] Coster, A. J., Goncharenko, L., Zhang, S. R., Houston, P. L., Holt, J., Dierking, J., Erickson, P., and Foster, J. (2017). GNSS observations of ionospheric variations during the 21 August 2017 solar eclipse. *Geophysical Research Letters*, 44(24), 12041–12048.
- [4] Coster, A. J., Erickson, P. J., Foster, J. C., and Dierking, J. (2024). Ionospheric observations during the April 8, 2024 solar eclipse using distributed GNSS receivers. *Space Weather*, 22(9). <https://doi.org/10.1029/2024SW003998>
- [5] Dan, S., Ghosh, A., Silas, S. T., and Banerjee, P. (2021). On use of low cost, compact GNSS receiver modules for ionosphere monitoring. *Radio Science*, 56(12), 1–11. <https://doi.org/10.1029/2021RS007344>
- [6] Dang, T., Lei, J., Wang, W., Burns, A. G., Zhang, B., and Zhang, S. R. (2018). Global responses of the coupled thermosphere and ionosphere system to the August 2017 great American solar eclipse. *Journal of Geophysical Research: Space Physics*, 123(8), 7040–7050.
- [7] Gautam, S. P., Tilahun, A. M., Silwal, A., Regmi, B., and Ghimire, B. (2024). Ionospheric response to the 08 April 2024 total solar eclipse over United States: a case study. *Astrophysics and Space Science*, 369, 108. <https://doi.org/10.1007/s10509-024-04372-w>
- [8] Humphreys, T. E., Iannucci, P. A., Komodromos, M., and Graas, F. van. (2024). Mapping the ionosphere with millions of phones. *Nature*, 637, 80–85. <https://doi.org/10.1038/s41586-024-08072-x>
- [9] Le, H., Ren, Z., Yuan, Y., Zhang, R., and Liu, L. (2024). Ionospheric total electron content and electron density response induced by the 8 April 2024 total solar eclipse. *Advances in Space Research*, 75(4), 2134–2149. <https://doi.org/10.1016/j.asr.2024.12.050>
- [10] Li, M., Yuan, Y., Zhang, B., and Wang, N. (2024). Multi-instrument observations of the ionospheric response caused by the 8 April 2024 total solar eclipse. *Remote Sensing*, 16(13), 2451. <https://doi.org/10.3390/rs16132451>
- [11] Nava, B., Kashcheyev, A., Radicella, S. M., Okoh, D., Rabi, B., and Otsuka, Y. (2023). Ionospheric monitoring using low-cost GNSS receivers. In *Ionospheric Multi-Spacecraft Analysis Tools*, Springer, 245–258.
- [12] Oikonomou, C., Karolos, I. A., Bitharis, S., Pikridas, C., and Haralambous, H. (2023). Ionospheric monitoring using a low-cost GNSS receiver. *Proceedings of SPIE*, 12786, 127860L. <https://doi.org/10.1117/12.2681236>
- [13] Okoh, D., Seemala, G., Rabi, B., Habarulema, J. B., Jin, S., Shiokawa, K., Otsuka, Y., and Nava, B. (2021). New results of ionospheric total electron content measurements from a low-cost GNSS receiver and comparisons with other data sources. *Advances in Space Research*, 68(9), 3835–3845.
- [14] Perry, G. W., Watson, C., Howarth, A. D., Themens, D. R., Foss, V., Langley, R. B., and Yau, A. W. (2019). Topside ionospheric disturbances detected using radio occultation measurements during the August 2017 solar eclipse. *Geophysical Research Letters*, 46(14), 7937–7944.
- [15] Rodrigues, F. S., and Moraes, A. O. (2022). ScintPi 2.0 and 3.0: low-cost GNSS-based monitors of ionospheric scintillation and total electron content. *Earth, Planets and Space*, 74, 176. <https://doi.org/10.1186/s40623-022-01743-x>
- [16] Sadeque, S., Bhuiyan, M. Z. H., El-Mowafy, A., and Dempster, A. G. (2025). Investigation of the ionospheric effects of the

solar eclipse of April 8, 2024 using multi-instrument measurements. *Atmosphere*, 16(2), 161.
<https://doi.org/10.3390/atmos16020161>

- [17] Yuan, Y., Li, M., Wang, N., and Zhang, R. (2026). Analysis of ionospheric anomalies during the April 8, 2024 total solar eclipse using physics-based ionospheric models. *Advances in Space Research*, in press.
<https://doi.org/10.1016/j.asr.2026.02.019>
- [18] Zhang, S. R., Erickson, P. J., Goncharenko, L. P., Coster, A. J., Rideout, W., and Vierinen, J. (2017). Ionospheric bow waves and perturbations induced by the 21 August 2017 solar eclipse. *Geophysical Research Letters*, 44(24), 12067–12073.