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Ionospheric Scintillation Effects on GNSS Signals are Reduced by Variational Mode Decomposition

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Abstract

To mitigate these effects, an adaptive signal decomposition technique called Variational Mode Decomposition (VMD), combined with Detrended Fluctuation Analysis (DFA), is proposed. VMD-DFA effectively decomposes the GNSS signal affected by scintillations into intrinsic mode functions, providing a threshold for detecting and mitigating scintillation noise. Monte Carlo simulations show that the proposed algorithm outperforms the complementary Ensemble Empirical Mode Decomposition method in eliminating amplitude scintillation effects. The algorithm's efficacy is demonstrated on both synthetic (Cornell scintillation model) and real-time measured GNSS data from Rio de Janeiro, Brazil, indicating its potential in mitigating ionospheric amplitude scintillation effects.

Index Terms— Detrended fluctuation analysis (DFA), Global Navigation Satellite System (GNSS), ionospheric scintillation mitigation, variational mode decomposition (VMD).

INTRODUCTION

Ionospheric scintillations can significantly affect the accuracy of GNSS applications, causing signal loss, cycle slips, and reduced availability of satellites. To mitigate these effects, various methods have been proposed, including wavelet filtering, empirical mode decomposition (EMD), ensemble EMD (EEMD), and complementary EEMD (CEEMD). While these methods have shown promising results, they still have limitations, such as sensitivity to noise and lack of mathematical theory [1]. In this context, the letter introduces the application of variational mode decomposition (VMD) in combination with detrended fluctuation analysis (DFA) to mitigate ionospheric scintillation effects on GNSS signals. VMD effectively decomposes the GNSS signal into intrinsic mode functions (IMFs) and a residue, providing a threshold to detect and mitigate scintillation noise [2-4]. This method overcomes some of the limitations of previous techniques, and Monte Carlo simulations show its superiority over complementary EEMD in eliminating amplitude scintillation effects. The proposed algorithm's effectiveness is further demonstrated on both synthetic (Cornell scintillation model) and real-time measured GNSS data from Rio de Janeiro, Brazil, indicating its potential in mitigating ionospheric amplitude scintillation effects [5].

In this letter, the variational mode decomposition (VMD) technique is employed to estimate and mitigate ionospheric scintillation effects on GNSS signals. VMD is a nonrecursive method capable of adaptively extracting intrinsic modes from nonlinear and nonstationary signals simultaneously. It includes the Wiener filter to estimate center frequencies and bandwidths for each intrinsic mode function (IMF), making it suitable for handling noise adaptively. VMD has been extensively used for denoising various types of noisy signals, such as biomedical images and seismic data [6-8]. In this work, VMD is combined with the detrended fluctuation analysis (DFA) algorithm to estimate, mitigate, and reacquire GNSS signals affected by intense ionospheric scintillations. The results demonstrate the effectiveness of VMD-DFA in decomposing the harmonics in the scintillated GNSS signal, allowing for the retrieval of scintillation-free GNSS signals by selecting a robust threshold for different VMD IMFs [9]. This approach shows promise in mitigating the impact of scintillations on GNSS signals and improving the overall accuracy of positioning and navigation systems [10].

II. VMD-DFA ESTIMATION AND MITIGATION OF IONOSPHERIC SCINTILLATION EFFECTS ALGORITHMS

VMD is an adaptive decomposition method for non stationary signals that is fully intrinsic nonrecursive [11]. It simultaneously breaks down an MCS into several band-limited IMFs (BLIMFs) [12]. By determining the best solution to the limited variational model, VMD can adaptively divide the GNSS signal x(t) into K different IMFs. Through iteratively solving the variational model, it determines the centre frequency and bandwidth for each IMF. As a result, [13] is how the constrained variational problem of VMD is expressed.

$$\min_{\{u_k\},\{\omega_k\}} \left\{ \sum_{k=1}^{K} \left\| \partial_t \left(\left[\left(\delta(t) + \frac{j}{\pi t} \right) * u_k(t) \right] e^{-j\omega_k t} \right) \right\|_2^2 \right\}$$

$$\text{S.t.} \sum_{k=1}^{K} u_k(t) = x(t) \qquad (1)$$

where uk(t) and k denote the set of IMFs and their corresponding centre frequencies of the provided GNSS signal for k = 1, 2, 3,..., K, and t is the time script. The Dirac distribution and convolution are indicated, respectively, by the (t) and ().The Hilbert transform is used to transform uk (t) into an analytical signal and is indicated by the component [(t) + (j/t)) uk (t)]. By minimising the sum of variation in the bandwidths of K IMFs, the restricted variational model seeks to replicate the GNSS signal.

$$\begin{aligned} L(\{u_k\},\{\omega_k\},\lambda) &= \alpha \sum_{k=1}^{K} \left\| \partial_t \left[\left(\delta(t) + \frac{j}{\pi t} \right) * u_k(t) \right] e^{-j\omega_k t} \right\|_2^2 \\ &\quad + \left\| x(t) - \sum_{k=1}^{K} u_k(t) \right\|_2^2 + \left\langle \lambda(t), x(t) - \sum_{k=1}^{K} u_k(t) \right\rangle . \end{aligned} \qquad (2)$$

RESULTS AND DISCUSSION

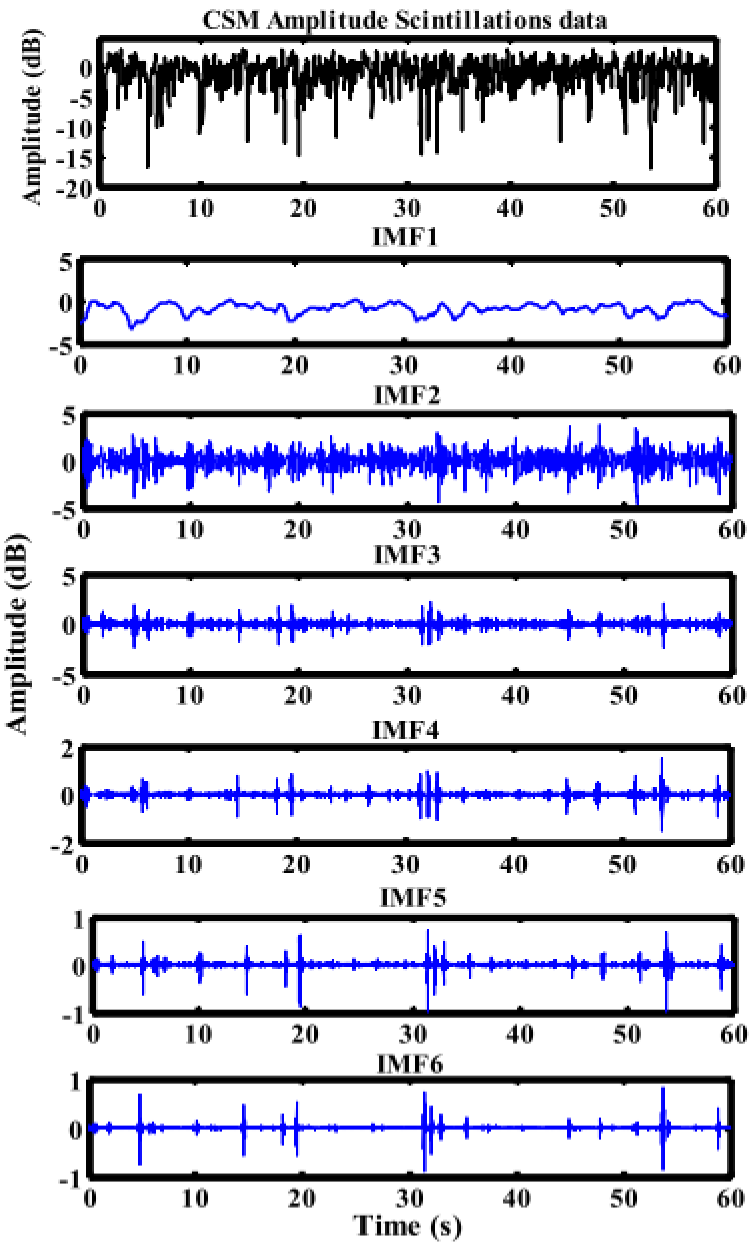


Fig. 1. Severe amplitude scintillation CSM (synthetic) data. Decomposition of CSM data into IMFs using VMD technique.

http://gps.ece.cornell.edu/tools.php. The simulated in-phase (I) and quadrature (Q) accumulations with higher S4 index (S4 = 0.8) and smaller decorrelation time (0 = 0.1 s) are used to generate the CSM-scintillated data. For the study of the simulation results under the severe scintillation condition, the simulated data are collected at 100 Hz for a 60 s period from possible values of 0 S4 1 and 0.1 0 2 s, respectively [16].The first panel of Figure 1 displays the visualisation of severe amplitude scintillation time series collected from the CSM.It should be noticed that the scintillation amplitude deep fades are as low as 16 dB. VMD-DFA and

CEEMD-DFA approaches are used to process the amplitude scintillation data in order to estimate and reduce the scintillation noise. CEEMD and VMD.

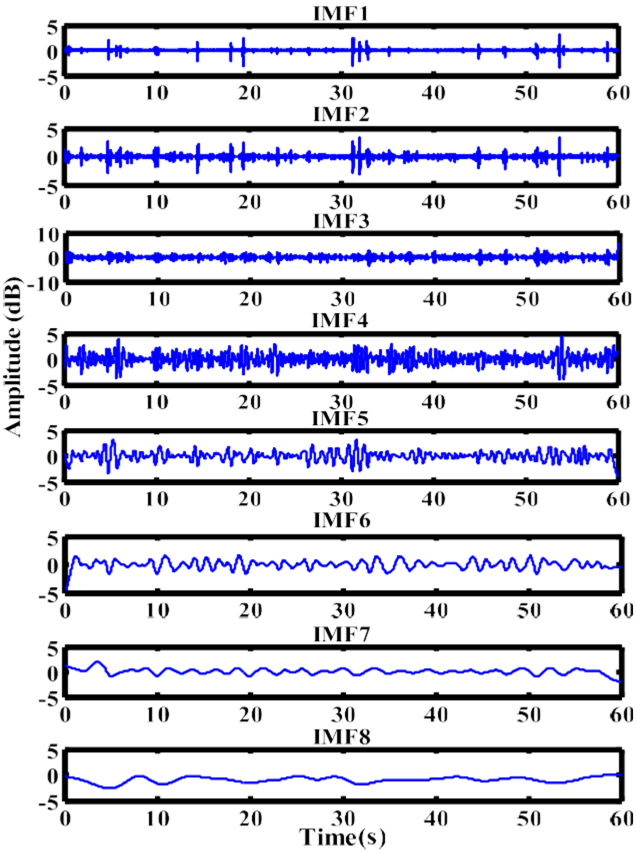
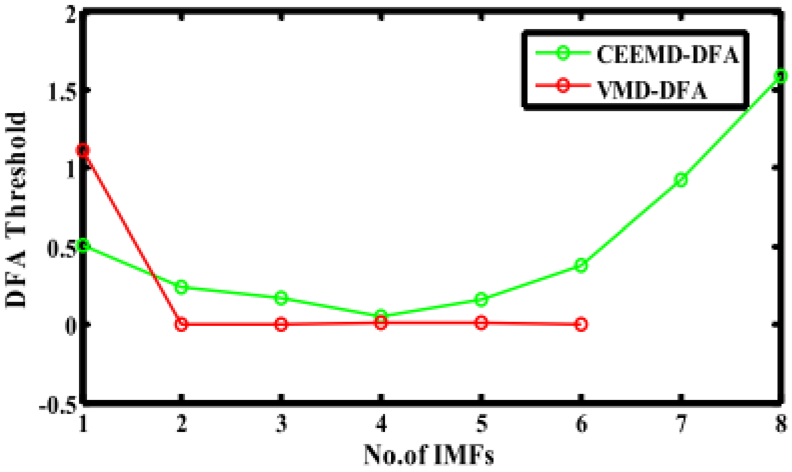


Fig. 2: CSM data decomposition into IMFs using the CEEMD approach.

Fig. 1, panels 2 to 7 illustrate the decomposition of amplitude scintillation data into six intrinsic mode functions (IMFs) using the variational mode decomposition (VMD) technique. On the other hand, Fig. 2 shows eight IMFs decomposed by the complementary ensemble empirical mode decomposition (CEEMD) method. Both VMD and CEEMD effectively capture high and low-frequency oscillations, representing the scintillation noise and the desired signal components of the simulated GNSS signal.The resolution of the six IMFs obtained by VMD is observed to be better than the eight IMFs obtained by CEEMD. This is attributed to the band-limited property of VMD IMFs, which are obtained concurrently instead of recursively. The VMD algorithm's sensitivity to sampling and noise allows its IMFs to extract robust intrinsic features, such as spikes, better than CEEMD during periods of deep fades. The adaptive and efficient interpretation of small fluctuations of amplitude scintillation data is achieved by VMD due to the alternating direction method of multipliers (ADMM) approach and Weiner filter structure embedded in its algorithm.



Using the VMD and CEEMD methods, Fig. 3 shows the DFA threshold for the decomposed IMFs of CSM amplitude scintillation data.

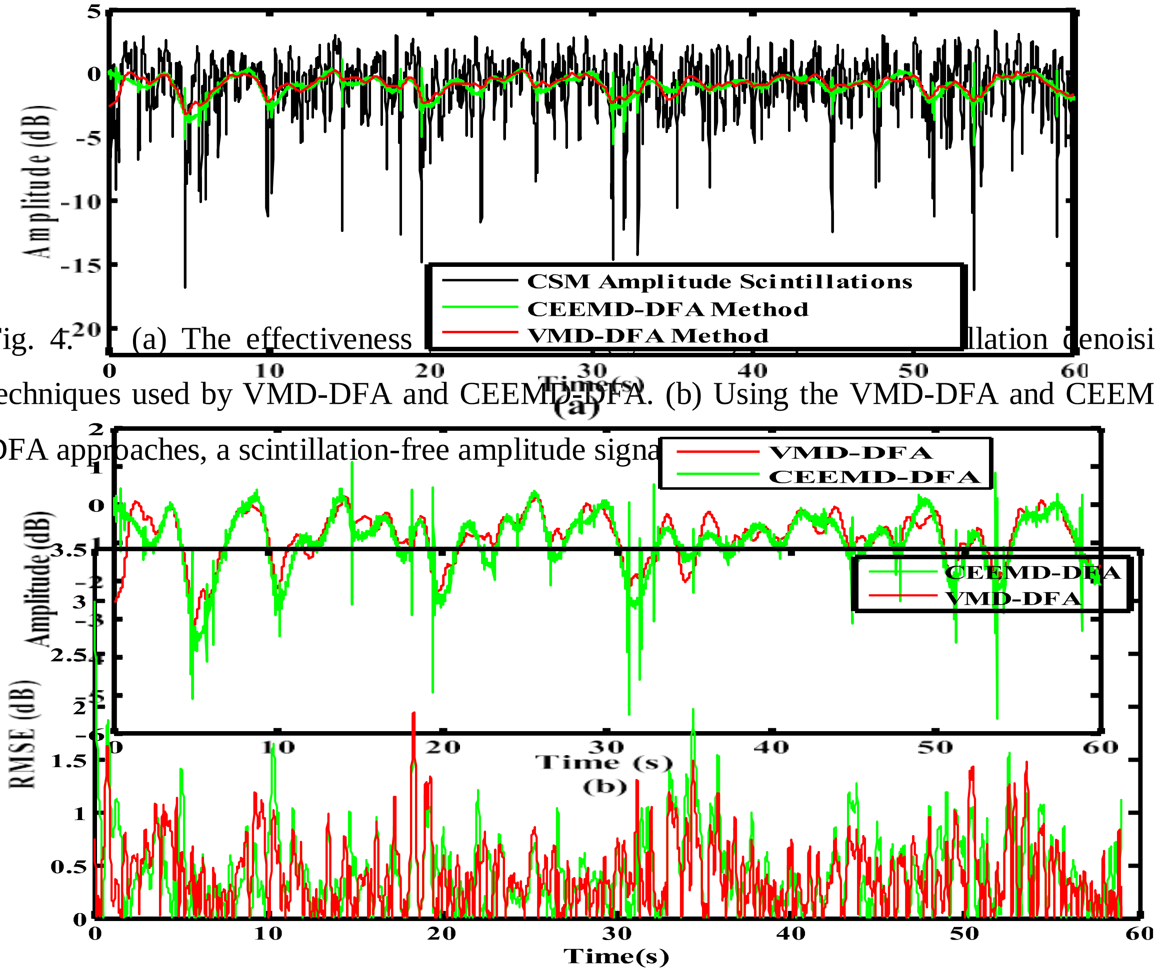


Fig. 4. (a) The effectiveness … llation denoising techniques used by VMD-DFA and CEEMD-DFA. (b) Using the VMD-DFA and CEEMD-DFA approaches, a scintillation-free amplitude signa

Figure 5 shows a comparison between the 200 runs of the proposed VMD-DFA approach for CSM amplitude scintillations and the CEEMD-DFA method.

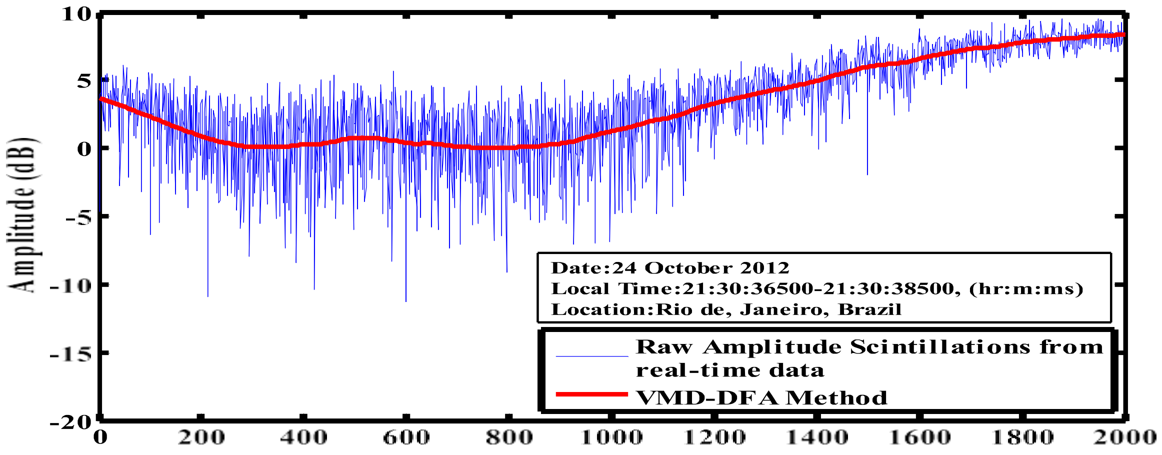


Figure 6 shows the VMD-DFA's denoising performance for amplitude scintillations of Brazil GSNRx data on October 24, 2012 (PRN 12).

The proposed VMD-DFA algorithm was also tested with real-time raw intermediate frequency data obtained from the GNSS Software Navigation Receiver (GSNRx) at Rio de Janeiro, Brazil, during a severe scintillation condition on October 24, 2012 (solar maximum period). The scintillation data was affected by equatorial ionospheric scintillations, and severe scintillation with deep fades was observed during specific time intervals.Fig. 6 shows the application results of the VMD-DFA algorithm on the real-time amplitude scintillations data from Brazil. It can be observed that VMD-DFA successfully mitigated 5–11 dB of scintillations noise caused by ionospheric irregularities. The algorithm effectively removed the adverse effects of scintillations, improving the quality of the GNSS signal at the receiver end.Based on these results, the VMD-DFA algorithm demonstrated its potential as an advanced GNSS signal processing technique for the estimation, mitigation, and reacquisition of GNSS signals under intense ionospheric scintillation conditions. It can be considered as a reliable and efficient method for alleviating the impact of scintillations and improving the performance of GNSS receivers in challenging ionospheric environments.

CONCLUSION

The comparison between VMD-DFA and conventional methods has demonstrated the effectiveness of VMD-DFA in accurately separating arbitrary components, even when the frequency components are close to each other in the amplitude scintillated signal.The VMD-DFA method has successfully denoised 13–14 dB of amplitude scintillation noise from the CSM-scintillated time-series, which is 3–4 dB more than the CEEMD-DFA method, particularly during deep fade periods. Moreover, the proposed algorithm has been tested with real-time measured GNSS data, further confirming its suitability and robustness in estimating and mitigating the impact of ionospheric scintillation effects on GNSS signals.In conclusion, VMD-DFA proves to be a more appropriate and reliable decomposition technique for addressing the challenges posed by ionospheric scintillation on GNSS signals, making it a valuable tool for improving GNSS receiver performance in such adverse conditions.

REFERENCES

1. P. Kintner, B. M. Ledvina, and E. R. De Paula, "GPS and ionospheric scintillations," Space Weather, vol. 5, no. 9, 2007, Art.no. S09003.
2. A. W. Wernik, L. Alfonsi, and M. Materassi, "Ionospheric irregularities, scintillation and its effect on systems," Acta Geophys. Polonica, vol. 52, no. 2, pp. 237–249, 2004.
3. A. Ahmed, R. Tiwari, H. J. Strangeways, N. Rutter, and S. Boussakta, "GPS tracking loop performance using wavelet denoising," in Proc. 7th ESA Workshop Satellite Navigat. Technol. (NAVITEC), Noordwijk, The Netherlands, 2014, p. A6.
4. N. E. Huang et al., "The empirical mode decomposition and the Hilbert spectrum for nonlinear and non-stationary time series analysis," Proc. Roy. Soc. London A, Math., Phys. Eng. Sci., vol. 454, no. 1971, pp. 903–995, Mar. 1998.
5. N. E. Huang, Z. Shen, and S. R. Long, "A new view of nonlinear water waves: The Hilbert spectrum," Annu. Rev. Fluid Mech., vol. 31, pp. 417–457, Jan. 1999.
6. J. R. Yeh, J. S. Shieh, and N. E. Huang, "Complementary ensemble empirical mode decomposition: A novel noise enhanced data analy- sis method," Adv. Adapt. Data Anal., vol. 2, no. 2, pp. 135–156, 2010.
7. R. H. Herrera, J. Han, and M. van der Baan, "Applications of the synchrosqueezing transform in seismic time-frequency analysis," Geophysics, vol. 79, no. 3, pp. V55–V64, 2014.
8. A. Mert and A. Akan, "Detrended fluctuation thresholding for empirical mode

decomposition based denoising," in Proc. 22nd Signal Process. Conf., Sep. 2014, pp. 1212–1216.

9. K. Dragomiretskiy and D. Zosso, "Variational mode decomposition," IEEE Trans. Signal Process., vol. 62, no. 3, pp. 531–544, Feb. 2014.
10. S. Miriyala, P. R. Koppireddi, and S. R. Chanamallu, "Robust detection of ionospheric scintillations using MF-DFA technique," Earth Planets Space, vol. 67, pp. 1–5, Jun. 2015.
11. S. Lahmiri and M. Boukadoum, "Biomedical image denoising using variational mode decomposition," in Proc. IEEE Biomed. Circuits Syst. Conf., Oct. 2014, pp. 340–343.
12. C. K. Peng, S. V. Buldyrev, S. Havlin, M. Simons, H. E. Stanley, and L. Goldberger, "Mosaic organization of DNA nucleotides," Phys. Rev., vol. 49, no. 2, p. 1685, 1994.
13. T. E. Humphreys, M. L. Psiaki, J. C. Hinks, B. O. Hanlon, and P. M. Kintner, Jr., "Simulating ionosphere-induced scintillation for testing GPS receiver phase tracking loops," IEEE J. Sel. Topics Signal Process., vol. 3, no. 4, pp. 707–715, Aug. 2009.