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PyBWE: Python tools for Bandwidth Extrapolation of planetary radar signals

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Summary

PyBWE is a Python library containing radar super-resolution methods known as "Bandwidth Extrapolation" (BWE).

Range resolution enhancement is one of the main challenges in radar signal processing. It is driven by the time resolution of radar soundings, and the speed of electromagnetic waves in the sounded material. Time resolution being limited by the frequency bandwidth of the instrument, the same applies to range resolution: the larger the bandwidth, the more enhanced the resolution.

Fast Fourier Transform techniques are efficient and robust for spectral estimation, but their performances in time resolution are limited by the inverse of the bandwidth, and the necessary application of windowing to reduce the impact of side-lobes. For this reason parametric spectral estimation techniques have been introduced (Kay & Marple, 1981). Based on a signal model, assuming deterministic properties of the signal, the output of such techniques yields an enhanced resolution. However, parametric techniques are less robust than classic Fourier transform ones, in particular in the presence of noise or distortions.

The **Bandwidth Extrapolation technique** (**BWE**) is a compromise between a classic Fourier transform and a parametric spectral estimation technique (Cuomo, 1992). A parametric model is fitted to the measured signal's spectrum, this model is then used to extrapolate this spectrum forward and backward, and the spectrum is eventually Fourier transformed using an IFFT. The extrapolation factor is equal to the resolution enhancement, and can be up to 3 in practical cases.

The extrapolation of a radar spectrum is indeed possible, as it can be modelled by a sum of complex sine-waves with different amplitudes, frequencies and phases. Each of these complex sine-waves corresponds to a target echo in time-domain. In practical cases, this deterministic signal is corrupted by various sources of noise, distorsions, and can be dampened by losses in the sounded material. Hence the limitation of a radar spectrum extrapolation.

An example of application on a synthetic planetary radar spectrum, inspired by the WISDOM (ExoMars, ESA) planetary radar (Ciarletti et al., 2017), is shown in Figure 1.

In the regular BWE, the signal is modelled by an autoregressive (AR) model, which coefficients are determined with the Burg algorithm. Several improvements to the BWE have been proposed:

- The **Polarimetric BWE** (**PBWE**) accounting for the correlation between several polarimetric radar channels with a multi-channel AR model, which coefficients are determined by a multi-channel Burg algorithm (Suwa & Iwamoto, 2003) (Suwa & Iwamoto, 2007).
- The **State-Space BWE** (**SSBWE**) accounting for noise and distorsions in radar signals with an autoregressive moving-average (ARMA) model, which coefficients are determined by State-Space identification (Piou, 1999).

Also, the BWE can be used to fill a gap between two spectra of multiband radars (Moore et al., 1997), or for Electromagnetic Interference (EMI) removal (Piazzo et al., 2019). This process is known as **Bandwidth Interpolation** (**BWI**).

This library contains 3 packages, each containing a different BWE technique, based on a different signal model:

- PyBWE: implementing the "classic" BWE technique.
- PyPBWE: implementing the PBWE technique.
- PySSBWE: implementing the SSBWE technique.

Each package contains an integrated solution to directly apply the complete BWE process to a given radar spectrum, as well as all the individual functions for modelling and extrapolation.

This library relies on Numpy (Harris et al., 2020) for the linear algebra, on Scipy (Virtanen et al., 2020) for matrix operations and data processing functions used in test and examples, on Matplolib (Hunter, 2007) for figure display in examples, and on Pandas (team, 2020) for performance tests data handling.

Statement of need

If the BWE can be applied to any radar signal, it has been extensively applied to planetary radar sounders in the last decade.

Radar sounders unlocked a 3rd dimension in planetary studies, unveiling the subsurface of the Moon, Mars, Titan and soon Venus and Jupiter's moons. The design of planetary exploration instruments being highly constrained, the resolution performances of radar sounders are not only driven by the scientific objectives of a mission. In this context, the BWE is a powerful tool to get further insights on the subsurface structure and composition from a given radar sounder.

Here is a non-exhaustive list of successful BWE applications in planetary science:

- The 1st bathymetry of a Titan sea using Cassini (NASA) radar data (Mastrogiuseppe et al., 2014)
- The improvement of the stratigraphic analysis of Martian polar ice sheets using the SHARAD (MRO, NASA) radar sounder data, after both BWE and EMI removal by BWI (Raguso et al., 2018) (Raguso et al., 2023).
- The improvement of the WISDOM (ExoMars, ESA) Ground Penetrating Radar soundings in preparation of the Rosalind Franklin rover mission (Oudart et al., 2021)
- The improvement of the MARSIS (Mars Express, ESA) radar sounder resolution by a factor of 6 using both BWE and BWI between different frequency band modes (Gambacorta et al., 2022)
- The EMI removal by BWI helped the estimation of attenuations in the Martian subsurface with the RIMFAX (Mars 2020, NASA) Ground Penetrating Radar data (Eide et al., 2022)

However, the planetary science community has few radar experts, and to our knowledge no open-source integrated BWE solutions existed before the release of this library, limiting the planetary radar application of this technique. For this reason, we propose in this library integrated BWE solutions for all planetary scientists, as well as the individual functions for planetary radar experts.

In addition, this library could also benefit other radar / sonar applications developed under harsh contraints, impacting the reachable range resolution.

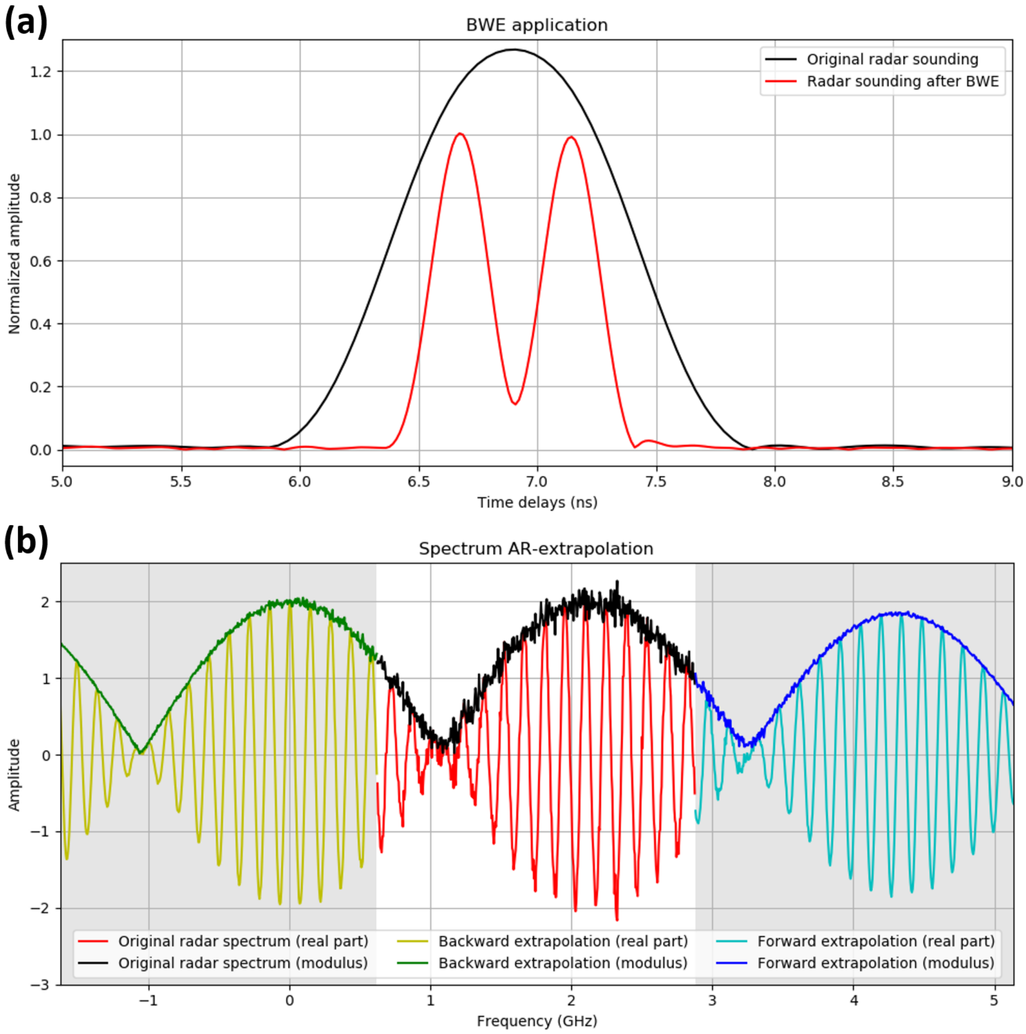

Figure 1: An example of BWE application to a synthetic planetary radar spectrum, with 2 targets in free-space separated by a distance of 7 cm, below the instrument's resolution limit with IFFT and Hamming windowing. This spectrum is generated with 2 complex sine-waves of amplitude 1, corrupted by a white-noise of standard deviation 0.1 (SNR = 20 dB), for frequencies between 0.5 and 3 GHz. (a) Time-domain signal obtained with classic FFT or BWE. (b) Extrapolation of the spectrum with a parametric model.

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References

Ciarletti, V., Clifford, S., Plettemeier, D., Le Gall, A., Hervé, Y., Dorizon, S., Quantin-Nataf, C., Benedix, W.-S., Schwenzer, S., Pettinelli, E., Heggy, E., Herique, A., Berthelier, J. J., Kofman, W., Vago, J. L., Hamran, S. Erik., & WISDOM Team, the. (2017). The WISDOM radar: Unveiling the subsurface beneath the ExoMars rover and identifying the best locations for drilling. *Astrobiology*, *17*(6–7), 565–584. https://doi.org/10.1089/ast.2016.1532

Cuomo, K. M. (1992). *A bandwidth extrapolation technique for improved range resolution of coherent radar data*. Lincoln Laboratory MIT.

Eide, S., Casademont, T. M., Berger, T., Dypvik, H., Shoemaker, E. S., & Hamran, S. E. (2022). Radar attenuation in the shallow martian subsurface: RIMFAX time frequency analysis and constant q characterization over jezero crater floor. *Geophysical Research Letters*, *50*(7). https://doi.org/10.1029/2022gl101429

Gambacorta, L., Raguso, M. C., Mastrogiuseppe, M., & Seu, R. (2022). UWB processing applied to multifrequency radar sounders: The case of MARSIS and comparison with SHARAD. *IEEE Transactions on Geoscience and Remote Sensing*, *60*, 1–14. https://doi.org/10.1109/tgrs.2022.3216893

Harris, C. R., Millman, K. J., Walt, S. J. van der, Gommers, R., Virtanen, P., Cournapeau, D., Wieser, E., Taylor, J., Berg, S., Smith, N. J., Kern, R., Picus, M., Hoyer, S., Kerkwijk, M. H. van, Brett, M., Haldane, A., Río, J. F. del, Wiebe, M., Peterson, P., … Oliphant, T. E. (2020). Array programming with NumPy. *Nature*, *585*(7825), 357–362. https://doi.org/10.1038/s41586-020-2649-2

Hunter, J. D. (2007). Matplotlib: A 2D graphics environment. *Computing in Science & Engineering*, *9*(3), 90–95. https://doi.org/10.1109/MCSE.2007.55

Kay, S. M., & Marple, S. L. (1981). Spectrum analysis—a modern perspective. *Proceedings of the IEEE*, *69*(11), 1380–1419. https://doi.org/10.1109/proc.1981.12184

Mastrogiuseppe, M., Poggiali, V., Hayes, A., Lorenz, R., Lunine, J., Picardi, G., Seu, R., Flamini, E., Mitri, G., Notarnicola, C., Paillou, P., & Zebker, H. (2014). The bathymetry of a titan sea. *Geophysical Research Letters*, *41*(5), 1432–1437. https://doi.org/10.1002/2013gl058618

Moore, T. G., Zuerndorfer, B. W., & Burt, E. C. (1997). Enhanced imagery using spectral-estimation-based techniques. *Lincoln Laboratory Journal*, *10*(2), 171–186. https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=5e09b4f4c00f6f660495a38c279961031a376e59

Oudart, N., Ciarletti, V., Le Gall, A., Mastrogiuseppe, M., Hervé, Y., Benedix, W.-S., Plettemeier, D., Tranier, V., Hassen-Khodja, R., Statz, C., & Lu, Y. (2021). Range resolution enhancement of WISDOM/ExoMars radar soundings by the bandwidth extrapolation technique: Validation and application to field campaign measurements. *Planetary and Space Science*, *197*, 105173. https://doi.org/10.1016/j.pss.2021.105173

Piazzo, L., Raguso, M. C., Seu, R., & Mastrogiuseppe, M. (2019). Signal enhancement for planetary radar sounders. *Electronics Letters*, *55*(3), 153–155. https://doi.org/10.1049/el.2018.7284

Piou, J. E. (1999). *A state-space technique for ultrawide-bandwidth coherent processing*. Lincoln Laboratory MIT.

Raguso, M. C., Mastrogiuseppe, M., Gambacorta, L., Di Achille, G., & Seu, R. (2023). Range resolution enhancement of SHAllow RADar (SHARAD) data via bandwidth extrapolation technique: Enabling new features detection and improving geophysical investigation. *Icarus*, 115803. https://doi.org/10.1016/j.icarus.2023.115803

Raguso, M. C., Mastrogiuseppe, M., Seu, R., & Piazzo, L. (2018, June). Super resolution and interferences suppression technique applied to SHARAD data. *2018 5th IEEE International Workshop on Metrology for AeroSpace (MetroAeroSpace)*. https://doi.org/10.1109/metroaerospace.2018.8453529

Suwa, K., & Iwamoto, M. (2003). A bandwidth extrapolation technique of polarimetric radar data and a recursive method of polarimetric linear prediction coefficient estimation. *IGARSS*

2003. 2003 IEEE International Geoscience and Remote Sensing Symposium. Proceedings (IEEE Cat. No.03CH37477). https://doi.org/10.1109/igarss.2003.1295505

Suwa, K., & Iwamoto, M. (2007). A two-dimensional bandwidth extrapolation technique for polarimetric synthetic aperture radar images. *IEEE Transactions on Geoscience and Remote Sensing*, *45*(1), 45–54. https://doi.org/10.1109/tgrs.2006.885406

team, T. pandas development. (2020). *Pandas-dev/pandas: pandas* (latest). Zenodo. https://doi.org/10.5281/zenodo.3509134

Virtanen, P., Gommers, R., Oliphant, T. E., Haberland, M., Reddy, T., Cournapeau, D., Burovski, E., Peterson, P., Weckesser, W., Bright, J., van der Walt, S. J., Brett, M., Wilson, J., Millman, K. J., Mayorov, N., Nelson, A. R. J., Jones, E., Kern, R., Larson, E., … SciPy 1.0 Contributors. (2020). SciPy 1.0: Fundamental Algorithms for Scientific Computing in Python. *Nature Methods*, *17*, 261–272. https://doi.org/10.1038/s41592-019-0686-2