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


# 1 PyBWE: Python tools for Bandwidth Extrapolation of 2 planetary radar signals

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## 5 Summary

6 **PyBWE** is a Python library containing radar super-resolution methods known as “Bandwidth  
7 Extrapolation” (BWE).

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

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

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

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

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

32 In the regular BWE, the signal is modelled by an autoregressive (AR) model, using the Burg  
33 algorithm. Several improvements to the BWE have been proposed: the **Polarimetric BWE**  
34 (**PBWE**) using the correlation between several polarimetric radar channels for an improved  
35 extrapolation ([K. Suwa & Iwamoto, 2003](#)) ([Kei Suwa & Iwamoto, 2007](#)), or the **State-Space**  
36 **BWE (SSBWE)** using a State-Space model accounting for noise and exponential distortions  
37 in the signal ([Piou, 1999](#)).

38 Also, the BWE can be used to fill a gap between two spectra of multiband radars ([Moore et](#)  
39 [al., 1997](#)). This process is known as **Bandwidth Interpolation (BWI)**.

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

- 42     ▪ PyBWE: implementing the “classic” BWE technique, with an AR model determined by  
43     the Burg algorithm.
- 44     ▪ PyPBWE: implementing the PBWE technique, with a multi-channel AR model determined  
45     by a multi-channel Burg algorithm.
- 46     ▪ PySSBWE: implementing the SSBWE technique, with an ARMA model determined by  
47     a State-Space modelling approach.

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

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

## 54 Statement of need

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

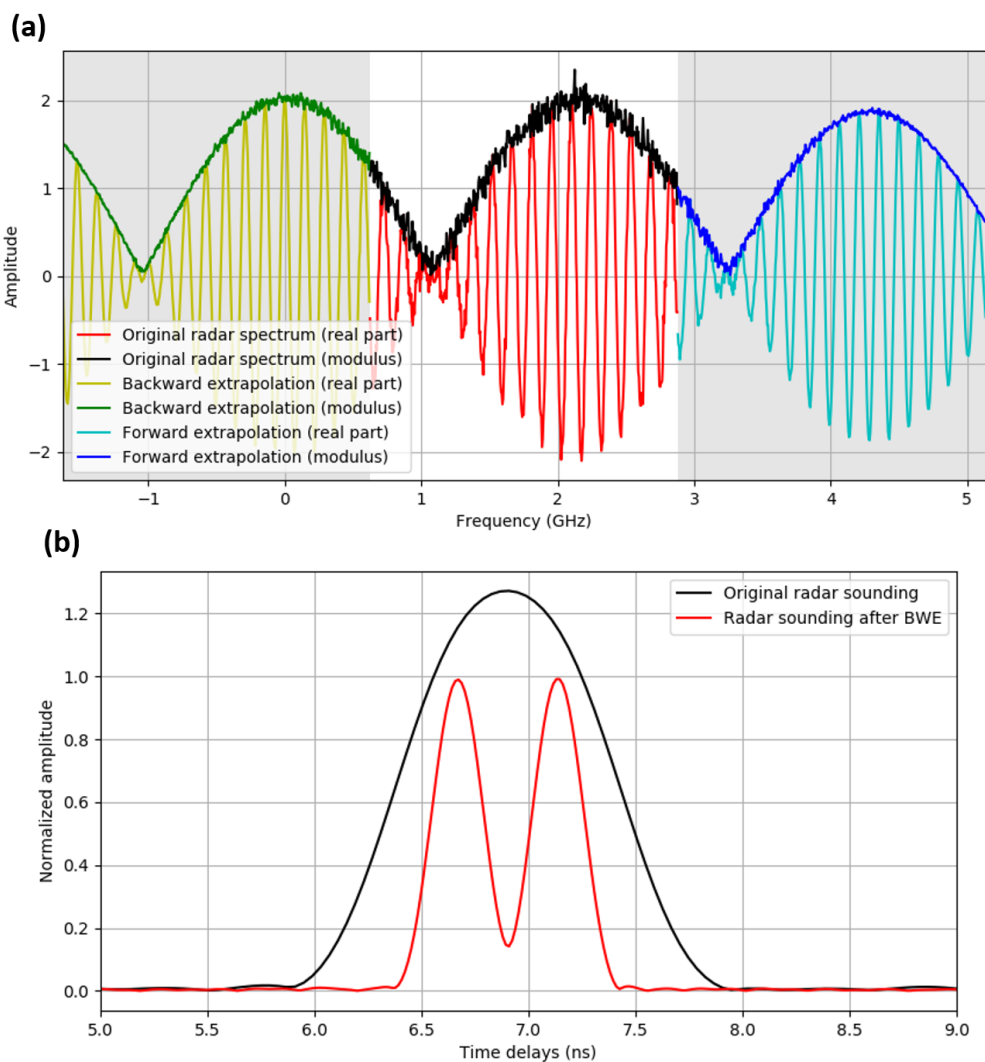
57 Radar sounders unlocked a 3rd dimension in planetary studies, unveiling the subsurface of the  
58 Moon, Mars, Titan and soon Venus and Jupiter’s moons. The design of planetary exploration  
59 instruments being highly constrained, the resolution performances of radar sounders are not  
60 only driven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

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

- 64     ▪ The 1st bathymetry of a Titan sea using Cassini (NASA) radar data ([Mastrogiuseppe et  
65 al., 2014](#))
- 66     ▪ The improvement of the stratigraphic analysis of Martian polar ice sheets using SHARAD  
67     (MRO, NASA) radar sounder data ([Raguso et al., 2018](#))
- 68     ▪ The improvement of the WISDOM (ExoMars, ESA) Ground Penetrating Radar soundings  
69     in preparation of the Rosalind Franklin rover mission ([Oudart et al., 2021](#))
- 70     ▪ The improvement of the MARSIS (Mars Express, ESA) radar sounder resolution by a  
71     factor of 6 using both BWE and BWI ([Gambacorta et al., 2022](#))
- 72     ▪ The BWE helped the estimation of attenuations in the Martian subsurface with the  
73     RIMFAX (Mars 2020, NASA) Ground Penetrating Radar data ([Eide et al., 2022](#))

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

79 In addition, this library could also benefit other radar / sonar applications developed under  
80 harsh constraints, 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) Extrapolation of this spectrum with a parametric model. (b) Corresponding time-domain signal obtained with classic FFT or BWE.

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## 84 References

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

- 90 Cuomo, K. M. (1992). *A bandwidth extrapolation technique for improved range resolution of*  
91 *coherent radar data*. Lincoln Laboratory MIT.
- 92 Eide, S., Casademont, T. M., Berger, T., Dypvik, H., Shoemaker, E. S., & Hamran, S. E.  
93 (2022). Radar attenuation in the shallow martian subsurface: RIMFAX time frequency  
94 analysis and constant q characterization over jezero crater floor. *Geophysical Research*  
95 *Letters*, 50(7). <https://doi.org/10.1029/2022gl101429>
- 96 Gambacorta, L., Raguso, M. C., Mastrogiuseppe, M., & Seu, R. (2022). UWB processing  
97 applied to multifrequency radar sounders: The case of MARSIS and comparison with  
98 SHARAD. *IEEE Transactions on Geoscience and Remote Sensing*, 60, 1–14. <https://doi.org/10.1109/tgrs.2022.3216893>
- 100 Harris, C. R., Millman, K. J., Walt, S. J. van der, Gommers, R., Virtanen, P., Cournapeau, D.,  
101 Wieser, E., Taylor, J., Berg, S., Smith, N. J., Kern, R., Picus, M., Hoyer, S., Kerkwijk,  
102 M. H. van, Brett, M., Haldane, A., Río, J. F. del, Wiebe, M., Peterson, P., ... Oliphant,  
103 T. E. (2020). Array programming with NumPy. *Nature*, 585(7825), 357–362. <https://doi.org/10.1038/s41586-020-2649-2>
- 105 Hunter, J. D. (2007). Matplotlib: A 2D graphics environment. *Computing in Science &*  
106 *Engineering*, 9(3), 90–95. <https://doi.org/10.1109/MCSE.2007.55>
- 107 Kay, S. M., & Marple, S. L. (1981). Spectrum analysis—a modern perspective. *Proceedings*  
108 *of the IEEE*, 69(11), 1380–1419. <https://doi.org/10.1109/proc.1981.12184>
- 109 Mastrogiuseppe, M., Poggiali, V., Hayes, A., Lorenz, R., Lunine, J., Picardi, G., Seu, R.,  
110 Flamini, E., Mitri, G., Notarnicola, C., Paillou, P., & Zebker, H. (2014). The bathymetry  
111 of a titan sea. *Geophysical Research Letters*, 41(5), 1432–1437. <https://doi.org/10.1002/2013gl058618>
- 113 Moore, T. G., Zuerndorfer, B. W., & Burt, E. C. (1997). Enhanced imagery us-  
114 ing spectral-estimation-based techniques. *Lincoln Laboratory Journal*, 10(2),  
115 171–186. <https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=5e09b4f4c00f6f660495a38c279961031a376e59>
- 117 Oudart, N., Ciarletti, V., Le Gall, A., Mastrogiuseppe, M., Hervé, Y., Benedix, W.-S., Plette-  
118 meier, D., Tranier, V., Hassen-Khodja, R., Statz, C., & Lu, Y. (2021). Range resolution  
119 enhancement of WISDOM/ExoMars radar soundings by the bandwidth extrapolation tech-  
120 nique: Validation and application to field campaign measurements. *Planetary and Space*  
121 *Science*, 197, 105173. <https://doi.org/10.1016/j.pss.2021.105173>
- 122 Piou, J. E. (1999). *A state-space technique for ultrawide-bandwidth coherent processing*.  
123 Lincoln Laboratory MIT.
- 124 Raguso, M. C., Mastrogiuseppe, M., Seu, R., & Piazzi, L. (2018, June). Super resolution and  
125 interferences suppression technique applied to SHARAD data. *2018 5th IEEE International*  
126 *Workshop on Metrology for AeroSpace (MetroAeroSpace)*. <https://doi.org/10.1109/metroaerospace.2018.8453529>
- 128 Suwa, K., & Iwamoto, M. (2003). A bandwidth extrapolation technique of polarimetric radar  
129 data and a recursive method of polarimetric linear prediction coefficient estimation. *IGARSS*  
130 *2003. 2003 IEEE International Geoscience and Remote Sensing Symposium. Proceedings*  
131 *(IEEE Cat. No.03CH37477)*. <https://doi.org/10.1109/igarss.2003.1295505>
- 132 Suwa, Kei, & Iwamoto, M. (2007). A two-dimensional bandwidth extrapolation technique  
133 for polarimetric synthetic aperture radar images. *IEEE Transactions on Geoscience and*  
134 *Remote Sensing*, 45(1), 45–54. <https://doi.org/10.1109/tgrs.2006.885406>
- 135 team, T. pandas development. (2020). *Pandas-dev/pandas: pandas (latest)*. Zenodo.  
136 <https://doi.org/10.5281/zenodo.3509134>

137 Virtanen, P., Gommers, R., Oliphant, T. E., Haberland, M., Reddy, T., Cournapeau, D.,  
138 Burovski, E., Peterson, P., Weckesser, W., Bright, J., van der Walt, S. J., Brett, M., Wilson,  
139 J., Millman, K. J., Mayorov, N., Nelson, A. R. J., Jones, E., Kern, R., Larson, E., ... SciPy  
140 1.0 Contributors. (2020). SciPy 1.0: Fundamental Algorithms for Scientific Computing in  
141 Python. *Nature Methods*, 17, 261–272. <https://doi.org/10.1038/s41592-019-0686-2>

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