

“AstroComb(v.1.0): Non-linear, Multi-channel, Probabilistic Cyclostratigraphic Analysis”

<https://doi.org/10.5194/egusphere-2025-6145>

Manuscript by Iris Fernandes, Klaus Mosegaard, Aske L. Sørensen,

Mohammad Youssof, Nicolas Thibault, and Tais W. Dahl

Review by Stephen R. Meyers

Table of Contents for this Review

- 1. An introduction to this review with some general comments**
- 2. The historical context of astrochronologic testing and calibration methods, with respect to the proposed *AstroComb* methodology**
- 3. An evaluation of the *AstroComb* methodology**
- 4. Some more detailed comments on the manuscript presentation**
- 5. References**

1. An introduction to this review with some general comments

This study proposes a quantitative statistical methodology for astronomical time scale calibration and development, designated as *AstroComb*. The objective of the study is an important one that has broad relevance to the geoscience community. Astrochronology has become a central approach in the calibration of the geological timescale (GTS 2020: Gradstein et al., 2020), the evaluation of Earth System evolution (Hays et al., 1976; Pälike et al., 2006), and the reconstruction of the history of the Solar System, including Earth-Moon history (Ma et al., 2017; Meyers & Malinverno, 2018). Consequently, improvements in astrochronologic methodologies, especially uncertainty quantification, can result in advancements across multiple domains of geoscience and also astronomy. I’m delighted to see new work on this topic, and to provide feedback.

In evaluating statistical methods such as the one presented in this manuscript, there are three criteria that are essential to consider:

Criteria 1: Does the proposed methodology have a solid theoretical statistical foundation (in other words, is the method theoretically valid)?

Criteria 2: Does the proposed method differ substantially from existing published methods, and does the scholarship recognize the prior related methods?

Criteria 3: Are the concepts of the methodology as described in the manuscript implemented appropriately in the coded software, such that it can correctly accomplish what it proposes to do.

I appreciate that the authors have provided access the *AstroComb* Matlab code on Zenodo (<https://zenodo.org/records/17966228>), which permitted a comprehensive evaluation of all three criteria. I will provide a detailed assessment below, but first I present a brief summary. In principle, the methodology looks to have solid statistical foundation (**Criteria 1**), although there are some critical details that need to be addressed in the manuscript before this can be fully

demonstrated. The proposed method is conceptually similar to a method previously published by Malinverno et al. (2010), which is not referenced in the present manuscript (**Criteria 2**). An important innovation of the present study is the evaluation of multi-channel data. Finally, the presentation of the methodology in the manuscript is not yet sufficient to appropriately convey what the *AstroComb* Matlab code is doing (**Criteria 3**). Once these issues are addressed, as well as a number of other improvements to the manuscript presentation for the sake of clarity and accuracy, I would recommend acceptance of the manuscript by *Geoscientific Model Development*, as an appropriate venue for publication.

I hope that the authors find the suggestions in this review helpful, and I would be happy to serve as a referee for a revised version of the manuscript that incorporates the recommendations.

With best wishes,

Dr. Stephen R. Meyers, Vilas Distinguished Professor
Department of Geoscience
University of Wisconsin-Madison

2. The historical context of astrochronologic testing and calibration methods, with respect to the proposed *AstroComb* methodology

Below I provide some background on the history of astrochronologic method development – for which there is no thorough up-to-date review available (to my knowledge). I do not expect the authors to incorporate all of this review in their manuscript; it is presented here to communicate to the authors how their proposed method ‘fits’ within the existing methodologies, for appropriate scholarship/citation.

2.1 SUMMARY: THE FOUR CLASSES OF METHODS

The problem of calibrating and testing cyclostratigraphic records in ‘deep time’, beyond the limits of the theoretical astronomical solutions (approx. 60 Ma; e.g., Laskar et al., 2004; Laskar, 2020), is an important one. There are essentially four classes of inverse approaches that have been proposed to evaluate timescale uncertainty and simultaneously derive an optimal sedimentation rate in such ‘deep time’ cyclostratigraphic data. (Note: there are many other quantitative cyclostratigraphic methods that are not summarized here, but those listed below are inverse methods that constrain timescale simultaneously while evaluating the fit of data to astronomical frequencies, beyond the 60 Ma limit of the theoretical astronomical solutions. They do not require initial assumptions relating a particular bedding cycle to a particular astronomical period.)

CLASS 1: The first type of ‘deep time’ inverse approach for comprehensively evaluating timescale uncertainty in cyclostratigraphic data was developed by Meyers & Sageman (2007), known as “Average Spectral Misfit” or *ASM*. This approach identifies statistically significant power spectrum peaks in cyclostratigraphic data, and tests the identified frequencies (cycles/meter) against predicted astronomical frequencies (e.g., originally from Berger et al., 1992), using a grid of sedimentation rates to evaluate plausible timescales. The *ASM* method

accounts for resolution limits of the data and astronomical target frequencies, and also provides a Monte Carlo null-hypothesis significance test. The method was adapted to use a moving window (*eASM*) to allow evaluation of records with unsteady sedimentation rates (Meyers et al., 2012).

CLASS 2: The second type of ‘deep time’ inverse approach for comprehensively evaluating timescale uncertainty in cyclostratigraphic data was developed by Malinverno et al. (2010), and this was the first formal Bayesian inverse method. Instead of identifying the location (frequency) of significant power spectrum peaks (as in ASM), the Malinverno method calculates the power spectrum and evaluates the power concentrated in astronomical frequencies, relative to a noise model (formally, as likelihood). Trayler et al. (2024) adapted the Malinverno et al. (2010) approach, further incorporating radioisotopic constraints (*AstroBayes*). Another method that explicitly evaluates the concentration of power at astronomical frequencies following calculation of the power spectrum is the ‘power ratio accumulation method’ (Peng et al., 2023).

CLASS 3: The third type of ‘deep time’ inverse method for comprehensively evaluating timescale uncertainty in cyclostratigraphic data was developed by Meyers (2015; *TimeOpt*), and later adapted and enhanced (Meyers & Malinverno, 2018; Meyers, 2019; Malinverno & Meyers, 2024; Hoang et al., 2025). Below, I present a history of the development of this class of methods.

- Meyers (2015) introduced the regression model framework for astrochronologic testing in the “time domain”, rather than the “frequency domain” (in contrast with CLASSES 1, 2, 4). Meyers & Malinverno (2018; *TimeOptMCMC*) further developed the approach as a Bayesian inversion methodology “to quantitatively link astronomical theory with geologic observation, allowing a reconstruction of Proterozoic astronomical cycles, fundamental frequencies of the solar system, the precession constant, and the underlying geologic timescale, directly from stratigraphic data.” *TimeOptB* and *TimeOptBMCMC* (Malinverno and Meyers, 2024) introduced improvements/enhancements of the original *TimeOptMCMC* method. All of these methods require relatively stable sedimentation in the analysis interval.
- The *TimeOptTemplate* and *eTimeOpt* methods (Meyers, 2019) were designed to evaluate unsteady sedimentation rates within the analysis interval (non-Bayesian), and the *AstroGeoFit* method (Hoang et al., 2025) introduced a genetic algorithm coupled to the *TimeOptMCMC/TimeOptBMCMC* Bayesian regression model framework to evaluate unsteady sedimentation histories.
- Note that *TimeOpt* (Meyers, 2015), *TimeOptTemplate* (Meyers, 2019), *TimeOptB* (Malinverno & Meyers, 2024) and *AstroGeoFit* (Hoang et al., 2024) also provide a null-hypothesis significance test, to help guard against false attribution of observed stratigraphic signals to astronomical forcing.

CLASS 4: The fourth type of ‘deep time’ inverse approach for comprehensively evaluating timescale uncertainty in cyclostratigraphic data was developed by Li et al. (2018; *COCO* and *eCOCO*). This method compares the shape of the measured cyclostratigraphic power spectrum

to a theoretical astronomical target power spectrum, using a Pearson correlation coefficient, following the calibration of the measured power spectrum across a grid of different plausible timescales (sedimentation rates). The method also provides a Monte Carlo null-hypothesis significance test. I will note that a fundamental challenge in the execution of this approach is the lack of knowledge, a priori, about the appropriate 'shape' of the astronomical target spectrum (the relative importance of eccentricity, obliquity and precession components). The other methods listed above (CLASS 1-3) do not have this limitation.

Considering this historical context, the proposed *AstroComb* method fits into **CLASS 2**, and is similar in its fundamental concept to the method of Malinverno et al. (2010), which evaluates a range of sedimentation rates and seeks to maximize spectral power (formally, as likelihood) at the astronomical target frequencies. More on that is presented in the review below.

3. An evaluation of the *AstroComb* methodology

3.1 SOURCE CODE

Based on the Matlab source code *AstroComb_1_0_FP.m*, I ascertain that the following algorithm is implemented in this study (in a simplified representation, considering only one variable/channel for this description):

1. Read in stratigraphic data series (depth and variable of interest, e.g., Al)
2. Apply a moving window of specified size (e.g., 3.3 meters) to the data series, incrementing across depth (e.g., every 0.2 mm), and for each data window, calculate an amplitude spectrum with background removed, as follows:
 - 2.1 Detrend data in window (quadratic function)
 - 2.2 Taper data (Tukey taper)
 - 2.3 Pad the tapered data on both sides of the data series (with zeros)
 - 2.4 FFT the tapered and padded data, then return the amplitude spectrum
 - 2.5 Estimate and remove the background spectrum using fast L1 fit of sum of 3 decaying exponentials
3. Compute sedimentation rate posteriors. For each data window:
 - 3.1 Calculate the equivalent frequency (cycles/m) for each theoretical astronomical line (cycles/kyr) using a grid of potential sedimentation rates. [NOTE: for this review, the theoretical astronomical lines will henceforth be referred to as the "astronomical target frequencies"]
 - 3.2 Loop over all sedimentation rates and astronomical target frequencies; use a smooth, monotonic sigmoid function to estimate probability of amplitude peaks at target frequencies in the data spectrum, given specified sedimentation rate (following background removal in step 2.5)
 - 3.3 Calculate product for posterior pdf of sedimentation rate
4. Using above information, compute time-depth posterior

3.2 *AstroComb* methodology described in the manuscript

The manuscript presents a description of the *AstroComb* methodology in **Section 2**. A key step is the generation of a “synthetic spectrum” (Equation 2), as a function of sedimentation rate (scalar, r), and the amplitude of the astronomical target frequencies (vector, α). With respect to this, the discussion in the manuscript gives an incorrect impression of how the analysis is actually conducted. Evaluation of the Matlab code indicates that Equation 2, in its full form, is not being used to generate the “synthetic spectra” as suggested (lines 164-169), as the amplitudes are not considered (vector, α). Furthermore, there is discussion in the manuscript regarding the shape of the spectral peaks in the synthetic spectra (vector, \mathbf{w}), but the shape of spectral peaks are not considered in the “synthetic spectra” generation in the Matlab code. Instead, the code is concerned with sedimentation rate, and its impact on the location of the target astronomical frequencies (step 3.2).

It is important for the manuscript text to be clearer about what is being done, in terms of how the algorithm is conducting the analysis and evaluating the fit of the “data” to the “model”. For example, there is no indication about the quadratic detrending of the data series in each window, or the spectral background estimation using a sum of 3 decaying exponentials, etc. (see **Section 3.1**). The methodology description in the manuscript should be sufficient such that the code can, with appropriate expertise and time, be reproduced. In other words, a reader should not be required to consult the code for an accurate description of the essential methodology.

Some additional comments on the *AstroComb* algorithm:

- The *AstroComb* method can be considered an adaptation of the method of Malinverno et al. (2010). Reference to that study, as providing a precedence, is essential.
- A key innovation of *AstroComb* is the simultaneous evaluation of multichannel data. The only other instance I know of doing so is in a 2023 GSA conference abstract by Trayler et al. (2023; <https://gsa.confex.com/gsa/2023AM/meetingapp.cgi/Paper/393427>). The *AstroBayes* approach also uses an adaptation of the method of Malinverno et al. (2010).
- When implementing the multichannel approach, it is important to note that covariance of geochemical data is common, while elements also express variable signal/noise. Appropriate treatment of the covariance/likelihoods is typically important when combining multiple datasets. It would be helpful if the authors spoke more to this issue.
- Appropriate determination of the spectral background is critical to the estimation of the probabilities/likelihoods, and this has been a topic of considerable debate in the cyclostratigraphic community (see reviews in Vaughan et al., 2011; Meyers, 2012; Vaughan et al., 2014, Meyers, 2019; Weedon, 2022). I found it interesting that *AstroComb* uses an L1 fit of the sum of 3 decaying exponentials for the spectral background fitting, as this is not typical in cyclostratigraphy. This may be a valid approach for some data sets, but the fit of the model to the data spectrum background (“spectral continuum”) must be validated for the probabilities to be reliable (e.g., see Malinverno and Meyers, 2024).
- Please provide additional theoretical justification for the probability estimation approach (e.g., Equations 4-7), which is used instead of the more typical approach for spectra (e.g., Malinverno et al., 2010).

- Since *AstroComb* is a moving window approach, the results are smoothed at the scale of the window size (as is the case with *eASM*, *eTimeOpt* and *eCOCO*); this is like a lowpass filter. Thus, the lack of smoothing claimed in the manuscript text appears overstated (lines 13-15 of abstract).
- *AstroComb* uses an overlapping moving window, while the method of Malinverno et al. (2010; see also *AstroBayes* of Trayler et al., 2024, which builds on this method) defines the analysis segments, based on an initial assessment of stable stratigraphic intervals. There are advantages to both approaches. Explicitly defining the “layer boundaries”, can help to optimize detection using prior stratigraphic knowledge and evaluation, and can guard against overinterpretation. The overlapping window approach can help to resolve shorter term shifts in sedimentation rate variability.
- Related to the last comment, prior to the application of *AstroComb* and other such methods, it is important to evaluate bedding stability using time-frequency methods (e.g., spectrogram or evolutive harmonic analysis; Meyers et al., 2001), and to consider the stratigraphic context (including biostratigraphy, available geochronology, etc.), to inform the analysis (e.g., potential hiatus, etc.).
- The Kullback-Leiber information measure (Equation 13) is an intriguing addition to the methodology. I suspect that it will be unfamiliar to most readers, so it would be helpful to provide discussion of what it means, in a more generally accessible manner. For example, explain what is meant by “information content”.
- A potential challenge for *AstroComb* and other methods that seek to reconstruct variable sedimentation rates (*eASM*, *eTimeOpt*, *eCOCO*, *AstroGeoFit*) is that, due to changing signal/noise, one may be inferring astronomical signals through intervals where they are not present. While some methods provide hypothesis testing in an attempt to guard against this, nonetheless, it is not unusual to see intervals with dubiously low signal/noise. It will be important for the authors to speak to this issue, to guide users on when the *AstroComb* results are reliable. For example, it seems that the Kullback-Leibler information measure is useful for this purpose, but more guidance on this would be helpful.

4. Some more detailed comments on the manuscript presentation

Here I provide some additional detailed comments by line number, to supplement the recommendations above.

Lines 13-15: As noted above, the sedimentation rates derived from *AstroComb* are smoothed at the scale of the window. This provides a limit on the resolution of sedimentation rate changes throughout a stratigraphic record, similar to other ‘windowed’ approaches (e.g., *eASM*, *eTimeOpt*, *eCOCO*).

Line 17: The use of the term “astronomical tie points” might be a bit confusing to readers. In principle, the derived “floating time scales” can be anchored to reliable radioisotopic/biostratigraphic/chemostratigraphic/magnetostratigraphic data. For the last ~60 Ma the theoretical astronomical solutions (“astronomical tie points”) also provide a means for anchoring astronomical time scales (given other appropriate constraints, e.g., paleomag data).

Lines 19-22: As noted earlier in this review, numerous approaches have been previously developed that combine cycle detection and stratigraphic modeling, and the approach here is similar to the method of Malinverno et al. (2010). It is critical to discuss this in the manuscript.

Line 20: The claim of "preserving fine-scale depositional variability" is overstated here, as the scale is fundamentally limited by the size of the moving window. For example, the approach cannot resolve precession-scale variability. Note that methods to resolve such "bedding-scale" sedimentation variability have been published (e.g., Schiffelbein and Dorman, 1986; *Gamma method* of Kominz and Bond, 1990; *TimeOptTemplate* of Meyers, 2019; *Alpha method* of Ma et al., 2020).

Lines 27: For appropriate scholarship, please add citation(s) for astrochronology as a methodology (e.g., Hinnov, 2013 and references therein).

Lines 28-33. The description here of methods could be improved. Based on the references, I would replace "repetitive spectral features" with "repetitive bedding cycles", and replace "spectral filtering" with "spectral analysis". The passage mentions numerous other methods (*TimeOpt*, *TimeOptMCMC*, *AstroGeoFit*, *eTimeOpt*, *eCOCO*, etc.) all of which are inverse methods that tune to astronomical target frequencies, in some fashion or other. The passage is missing key methodologies, including the one that is most similar to *AstroComb*, which is Malinverno et al. (2010). See **Section 2** of this review for more information.

Line 34: Change "Despite sedimentation is" to "Despite the fact that sedimentation is"

Line 45: change "has been" to "was"

Lines 34-49. The statements noted here about the challenge of variable sedimentation are indeed key issues that need to be carefully considered. In this regard, the *AstroComb* method has the same fundamental limitations as many other published moving window methods (e.g., *eASM*, *eTimeOpt*, *eCOCO*).

Lines 47-49. For appropriate scholarship, this passage should reference prior work that makes the same claim (see **Section 2** of this review).

Line 58. As *AstroComb* is a moving window method, fundamentally it imposes a smoothing (constant sedimentation rate within the analysis window).

Lines 60-64: As noted earlier, the primary innovation here is the use of multichannel data, while the basic framework builds on the method of Malinverno et al. (2010) (see **Sections 2 & 3**).

Lines 74: The Kullback-Leiber information measure is an intriguing addition to the methodology (see **Section 3** of this review)

Lines 77-78: Here, sub-precession scale changes in sedimentation are mentioned with reference to another algorithm that is not yet published ("ProBE4T"; Fernandes et al., 2026). I have not been able to locate ProBE4T online. Featuring unpublished work so prominently as motivation

for *AstroComb* in the introduction strikes me as putting the cart-before-the-horse. An indication of future development of *AstroComb* in the discussion section would be the place to discuss next steps. Note that other methods do exist that can resolve sub-precession scale variability given certain constraints (e.g., Schiffelbein and Dorman, 1986; *Gamma method* of Kominz and Bond, 1990; *TimeOptTemplate* of Meyers, 2019; *Alpha method* of Ma et al., 2020). Finally, note that the Fernandes et al. (2026) citation in the reference list is for an algorithm titled "Probe4t".

Line 86: remove "here"

Lines 101-112: This section of the manuscript doesn't sound like a "workflow of AstroComb", but rather a description of the outline of the manuscript.

Line 111: change "evaluate" to "evaluates"

Lines 113-115: The use of multichannel data is a key innovation (the only other instance I know of is in a 2023 GSA conference abstract by Trayler et al. (2023; <https://gsa.confex.com/gsa/2023AM/meetingapp.cgi/Paper/393427>))

Line 121: The manuscript correctly notes that the *AstroComb* method works "under the assumption that certain stratigraphic signals (e.g., elemental variability) reflect astronomical forcing." Therefore, before interpreting *AstroComb* results as reliable, it is important to test this assumption, which is a key component of many of the published methods (*ASM*, *TimeOpt*, *TimeOptTemplate*, *TimeOptB*, *COCO*, *AstroGeoFit*, etc.). It should be noted in the manuscript that initial hypothesis testing is prudent, before applying *AstroComb*, and a range of published methods are available to do so.

Lines 145-146: For the discussion of the distortion of spectra, it would be good to reference past studies that have addressed this, such as Schiffelbein and Dorman (1986), Ripepe and Fischer (1991), Herbert (1994) and Meyers et al. (2001).

Line 149: Note that there are two components to the theoretical astronomical solutions: the orbital part and rotational component (see Laskar, 2020).

Line 166: Change "computed data spectra" to "computed synthetic spectra"

Equations 4, 5, 7, 8: Please use a different notation for "a", which has already been used as the vector of amplitudes (Equations 2 and 3).

Figure 2: Please indicate the depths on the y-axis.

Figure 3: It would be valuable to show a time-frequency analysis (spectrogram, evolutive harmonics analysis) with the same window size. Are the time-frequency results compatible with the *AstroComb* results?

Lines 264-265 and 337: Change "elements" to "elemental"

Line 291: Change "beteen" to "between"

Lines 293-209: Add a reference to Malinverno et al. (2010)

Line 297: Change “orbital” to “astronomical”

Lines 297-300: There have been a number of important modeling advances that have improved our ability to provide uncertainty estimates on the target astronomical frequencies in the geologic past, including Waltham (2015, already in the reference list), Farhat et al. (2022, already in the reference list), and Hoang et al. (2021; not in the reference list). Some methods explicitly include these uncertainties, for example *TimeOptBMCMC* and *AstroGeoFit*.

Line 327: Change “sedimentologist” to “sedimentologists”

Line 341: Please specify that the code was written in Matlab.

5. References

- Berger, A., Loutre, M. F., and Laskar, J. (1992). Stability of the astronomical frequencies over the Earth’s history for paleoclimate studies: *Science* 255, 560–566.
- Farhat, M., Auclair-Desrotour, P., Boué, G., & Laskar, J. (2022). The resonant tidal evolution of the Earth-Moon distance. *Astronomy & Astrophysics*, 665, L1. <https://doi.org/10.1051/0004-6361/202243445>
- Gradstein, F.M., Ogg, J.G, Schmitz, M.D., Ogg, G.M. (2020). *Geologic time scale 2020*, Elsevier.
- Hays, J. D., J. Imbrie, and N. J. Shackleton (1976). Variations in the Earth’s orbit: Pacemaker of the ice ages, *Science*, 194, 1121–1132.
- Herbert, T.D. (1994). Reading orbital signals distorted by sedimentation: models and examples, in de Boer, P.L., and Smith, D.G., eds., *Orbital Forcing and Cyclic Sequences: International Association of Sedimentologists, Special Publication 19*, p. 483–507.
- Hinnov, L.A. (2013). Cyclostratigraphy and its revolutionizing applications in the Earth and planetary sciences. *Geol. Soc. Am. Bull.* 125, 1703–1734.
- Hoang, N. H., Mogavero, F., & Laskar, J. (2021). Chaotic diffusion of the fundamental frequencies in the Solar System. *Astronomy & Astrophysics*, 654, A156. <https://doi.org/10.1051/0004-6361/202140989>
- Hoang, N., Laskar, J., Hara, N. C., Wu, Y., Sultanov, A., Sinnesael, M., Westerhold, T., and Bujons, P. (2025). *AstroGeoFit. A Genetic Algorithm and Bayesian Approach for the Astronomical Calibration of the Geological Timescale, Paleoceanography and Paleoclimatology*, 40, e2024PA005021. <https://doi.org/10.1029/2024PA005021>.
- Kominz, M.A., Bond, G.C. (1990). A new method of testing periodicity in cyclic sediments: application to the Newark Supergroup. *Earth Planet. Sci. Lett.* 98, 233–244.
- Laskar, J. (2020). Chapter4—Astrochronology. In F.M. Gradstein, J.G. Ogg, M.D. Schmitz, & G.M. Ogg (Eds.), *Geologic timescale 2020* (pp. 139–158). Elsevier. <https://doi.org/10.1016/B978-0-12-824360-2.00004-8>.

- Laskar, J., P. Robutel, F. Joutel, M. Gastineau, A. C. M. Correia, and B. Levard (2004). A long-term numerical solution for the insolation quantities of the Earth, *Astron. Astrophys.*, 428, 261–285.
- Li, M., Kump, L.R., Hinnov, L.A., Mann, M.E. (2018). Tracking variable sedimentation rates and astronomical forcing in Phanerozoic paleoclimate proxy series with evolutionary correlation coefficients and hypothesis testing: *Earth Planet. Sci. Lett.* 501, 165–179.
- Ma, C., Meyers, S.R., Sageman, B.B. (2017). Theory of chaotic orbital variations confirmed by Cretaceous geological evidence. *Nature* 542, 468–470.
- Ma, C., Meyers, S.R., Hinnov, L.A., Eldrett, J.S., Bergman, S.C., Minisini, D. (2020). A method to decipher the time distribution in astronomically forced sedimentary couplets, *Marine and Petroleum Geology* 118, 104399.
- Malinverno, A., Erba, E., Herbert, T.D. (2010). Orbital tuning as an inverse problem: chronology of the early Aptian oceanic anoxic event 1a (Selli Level) in the Cismon APTICORE. *Paleoceanography* 25, PA2203. <https://doi.org/10.1029/2009PA001769>.
- Malinverno, A., Meyers, S.R. (2024). Bayesian estimation of past astronomical frequencies, lunar distance, and length of day from sediment cycles, *Geochemistry, Geophysics, Geosystems*, 25, e2023GC011176.
- Meyers, S.R. (2015). The evaluation of eccentricity-related amplitude modulation and bundling in paleoclimate data: an inverse approach for astrochronologic testing and time scale optimization. *Paleoceanography* 30 (12), 1625–1640.
- Meyers, S.R. (2019). Cyclostratigraphy and the problem of astrochronologic testing. *Earth-Science Reviews* 190, 190–223. <https://doi.org/10.1016/j.earscirev.2018.11.015>
- Meyers, S.R. (2012). Seeing red in cyclic stratigraphy: spectral noise estimation for astrochronology. *Paleoceanography* 27, PA3228.
- Meyers, S.R., Malinverno, A. (2018). Proterozoic Milankovitch cycles and the history of the solar system. *Proc. Natl. Acad. Sci.* <https://doi.org/10.1073/pnas.1717689115>.
- Meyers, S.R., Sageman, B.B. (2007). Quantification of deep-time orbital forcing by average spectral misfit. *Am. J. Sci.* 307 (5), 773–792.
- Meyers, S.R., Sageman, B., Hinnov, L. (2001). Integrated quantitative stratigraphy of the Cenomanian-Turonian Bridge Creek Limestone Member using evolutive harmonic analysis and stratigraphic modeling. *J. Sediment. Res.* 71, 627–643.
- Meyers, S.R., Sageman, B.B., Arthur, M.A. (2012). Obliquity forcing of organic matter accumulation during Oceanic Anoxic Event 2. *Paleoceanography* 27, PA3212.
- Pälike, H., R. D. Norris, J. O. Herrle, P. A. Wilson, H. K. Coxall, C. H. Lear, N. J. Shackleton, A. K. Tripathi, and B. S. Wade (2006). The heartbeat of the Oligocene climate system, *Science*, 314, 1894–1898.
- Peng, C., Zou, C., Wu, H., Zhang, S., Kouamelan, K.S., Wang, C. (2023). Evaluating geophysical logs as proxies for cyclostratigraphy in lacustrine deposits using power ratio accumulation, *Palaeogeography, Palaeoclimatology, Palaeoecology* 614, 111428
- Ripepe, M., Fischer, A.G. (1991). Stratigraphic rhythms synthesized from orbital variations. In: Franseen, E.K., Watney, W.L., Kendall, C.G.St.C., Ross, W. (Eds.), *Sedimentary Modeling*.

Computer Simulations and Methods for Improved Parameter Definition: Kansas State Geological Survey, Bulletin Vol. 233. pp. 335–344.

Schiffelbein, P., Dorman, L. (1986). Spectral effects of time–depth nonlinearities in deep sea sediment records: a demodulation technique for realigning time and depth scales. *J. Geophys. Res.* 91, 3821–3835.

Trayler, R.B., Meyers, S.R., Sageman, B.B., Schmitz, M.D. (2024). Bayesian integration of astrochronology and radioisotope geochronology, *Geochronology*, 6, <https://doi.org/10.5194/gchron-6-107-2024>.

Vaughan S, Bailey R.J., Smith D.G. (2014). Cyclostratigraphy: data filtering as a source of spurious spectral peaks, From: Smith, D. G., Bailey, R. J., Burgess, P. M. & Fraser, A. J. (eds) *Strata and Time: Probing the Gaps in Our Understanding*. Geological Society, London, Special Publications, 404, <https://doi.org/10.1144/SP404.11>

Vaughan, S., Bailey, R. J. and Smith, D.G. (2011). Detecting cycles in stratigraphic data: Spectral analysis in the presence of red noise, *Paleoceanography*, 26, PA4211, doi:10.1029/2011PA002195.

Weedon, G. (2022). Problems with the current practice of spectral analysis in cyclostratigraphy: Avoiding false detection of regular cyclicity, *Earth-Science Reviews* 235, 104261.