Edinburgh
Student Journal of Science

Volume 2

ISSN 3049-7930

January 2026

*"If it's a good idea, go ahead and do it.
It is often easier to ask for forgiveness than to ask for permission."*

Grace Hopper

Edinburgh Student Journal of Science

Volume 2

January 2026

ISSN 3049-7930

Published by the University of Edinburgh

Edited and Produced by Jack L Smith

journals.ed.ac.uk/esjs

Edinburgh Student Journal of Science

Volume 2, January 2026

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Physics and Astronomy

Pressure Limiting Instabilities in Tokamaks

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Open Access

Article Type
Letter

Received
30 Jun 2025

Revised
16 Jul 2025

Accepted
30 Jul 2025

Published
18 Sep 2025

DOI
10.2218/esjs.10962

ISSN
3049-7930

Abstract

The plasma pressure achievable in a tokamak fusion reactor may be limited by instabilities like the ideal ballooning mode, a pressure-driven instability that acts to degrade plasma confinement. Here we investigate the sensitivity of the shape of the magnetic flux surface to the ideal ballooning mode; in particular, we modify the parameters describing the shape of magnetic flux surfaces of the equilibrium and perform infinite-n ideal ballooning scans to assess how shaping affects proximity to marginal instability. We find that for the parameter space considered, increasing squareness and elongation could help stabilise the plasma against the ideal ballooning mode instability.

Introduction

Magnetic confinement fusion is a method used by tokamaks to maintain and control high-pressure plasma, with the ultimate goal of generating virtually limitless energy through nuclear fusion. In tokamaks, the magnetic field is helical around the torus due to the superposition of the poloidal (running around the plasma cross-section) and toroidal (running around the tokamak) magnetic fields. An important tokamak parameter is β, the ratio of plasma pressure p to magnetic field pressure, given by $\beta = 2\mu_0 p/B^2$, where μ_0 is the vacuum permeability and B is the magnetic field strength. While high β is desirable for efficiency, β is often limited by various instabilities in the plasma.

One type of pressure-driven electromagnetic instability is the ideal ballooning mode (Connor *et al.* 1978; Connor *et al.* 1979; Dewar *et al.* 1982). It is thought that this pressure-driven instability is important in high confinement (H-mode) plasmas, which is when the plasma is heated to reach a new regime of enhanced confinement. Specifically, this pressure-driven instability is of particular interest near the pedestal, a region of steep pressure gradient at the edge of the plasma that appears in H-mode (ASDEX Team 1989; Snyder *et al.* 2011; Dickinson *et al.* 2012). This study aimed to explore the impact of shaping of tokamak magnetic equilibria on ideal ballooning stability in

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H-mode plasmas, using data from the MAST and MAST Upgrade (MAST-U) spherical tokamaks at the UK Atomic Energy Authority (UKAEA).

Theory

This analysis utilises ideal magnetohydrodynamics (ideal MHD), a description of the plasma as a single fluid assuming quasineutrality and neglecting resistivity (Freidberg 2014). For axisymmetric equilibria, the magnetic field lines lie on nested toroidal magnetic flux surfaces of constant pressure (Wesson 2011). In equilibrium:

$$\boldsymbol{j} \times \boldsymbol{B} = \nabla p \ , \tag{1}$$

where $\boldsymbol{j}$ is the current density and $\boldsymbol{B}$ is the magnetic field. Equation 1 shows that there is no pressure gradient ∇p along the magnetic field lines. The equilibrium for an axisymmetric ideal MHD system can alternatively be written as the Grad-Shafranov differential equation (Wesson 2011). The solution to this equation gives the toroidal current density and poloidal magnetic field across the plasma equilibrium, allowing the calculation of the local equilibria on any flux surface in the plasma.

The ideal ballooning equation can be used to determine if the plasma on a specific flux surface is stable to the ideal ballooning mode. We describe the perturbation from equilibrium with the local displacement vector $\boldsymbol{\xi}(\boldsymbol{r}, t)$, which represents the displacement of the plasma from its equilibrium position as a function of space ($\boldsymbol{r}$) and time (t). The derivation of the ideal ballooning equation (Roach 2023; Cowley 2024) decomposes the perturbations as Fourier modes to be of the form $\boldsymbol{\xi} = e^{-i\omega t} e^{inS} \hat{\boldsymbol{\xi}}$ where ω is frequency, n is the mode number and S is the field line label in a field-aligned coordinate system (Dudding 2022). In this analysis, we take the limit of $n \to \infty$ and assume incompressible perturbations. The ideal ballooning equation is an equation of motion which, when solved, gives us ω^2. If we find $\omega^2 < 0$ then ω must be imaginary so that an unstable eigenmode solution (i.e. an instability) exists that grows exponentially in time by extracting energy from the pressure gradient and magnetic field curvature, thereby limiting plasma confinement.

Methods

Local Equilibrium

The balance between the local forces on the plasma (Equation 1) maintains plasma equilibrium, which can be described as a set of magnetic flux surfaces. Equilibrium reconstruction for a tokamak experiment is carried out by solving the Grad-Shafranov equation on a 2D rectangular grid at a constant toroidal angle in the poloidal plane, essentially taking a cross-section of the plasma in the torus. The equation is solved numerically using Equilibrium reconstruction and fitting code (EFIT) (Lao *et al.* 1985) and experimental measurements (Wesson 2011) as constraints to the solution. For the small scale, highly localised instabilities studied here ($n = \infty$), only the details of the plasma from an extremely narrow layer around a given flux surface are needed.

We take the full 2D equilibrium reconstructions from EFIT and use pyrokinetics code (Patel *et al.* 2024) to extract information from the specified flux surfaces. This approach utilises an analytic parameterisation (Miller *et al.* 1998; Dudding 2022) of the flux surface shape, giving us the Miller flux surface shaping parameters. The parameters we will focus on for this study include the elongation κ_M, triangularity δ_M, and squareness ζ_M (Turnbull *et al.* 1999). The radial derivatives of these parameters are fit using the Grad-Shafranov solution to derive flux surface plots (Figure 1a, c, and e).

Ballooning Solver

Pyrokinetics (Pyro; Patel *et al.* 2024) is a Python package written to standardise calculations of small-scale instabilities in tokamak plasmas. The infinite-n ideal ballooning solver in pyrokinetics was developed by Rahul Gaur (Gaur *et al.* 2023) using an adjoint-based method that solves the derivatives of the ballooning equation with respect to all inputs of the system (Giannakoglou *et al.* 2008). This project uses Pyro to extract the relevant information from EFIT, compute the Miller parameters for local flux surfaces (using an optimisation algorithm), calculate the full local equilibrium, and finally use all of this data in the ballooning solver to solve for ω^2.

It is important to note that the ballooning equation solves for stability only within a localised volume near a specified flux surface, and that the stability of the ideal ballooning mode varies with flux surface, which we label with the normalised poloidal flux ψ_N. To analyse the stability of the ideal ballooning mode across the whole plasma

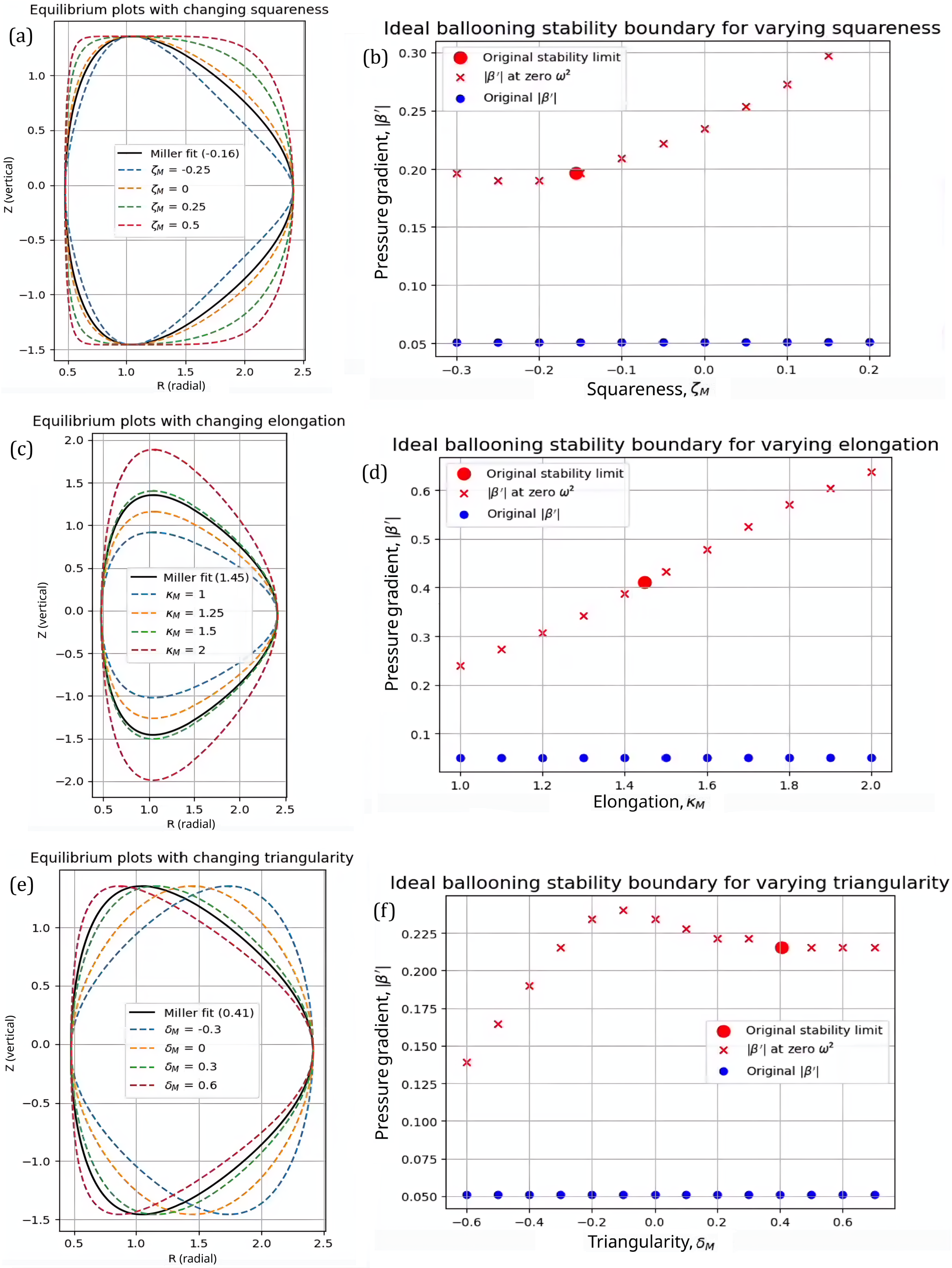

Figure 1: (**a**), (**c**), (**e**): flux surface $\psi_N = 0.97$ for MAST shot 30422 at 326ms, where the solid black line is the Miller parameter fit to the experimental data and the dashed lines are the modified shaping parameters where all other geometry parameters are held to their original values. (**b**), (**d**), (**f**): β' against shaping parameter ζ_M (**b**), κ_M (**d**), and δ_M (**e**) with experimental values as blue dots, the boundary of stability as red crosses and the original shaping and corresponding β' parameter for the flux surface as a red dot. Plot (**b**) at $\zeta_M = 0.2$ does not have a corresponding critical β' value as there is no limit with these particular experimental parameters when only increasing β'.

cross-section we applied the solver over a range of flux surfaces, with data for each surface taken from a global Grad-Shafranov equilibrium solution.

The experimental tokamak plasmas we are examining are not expected to be maintained in a state unstable to ideal ballooning because, if unstable, the ideal ballooning mode causes transport losses of matter and energy that reduces the local pressure gradient to a point where the mode becomes stable again. It is believed that these instabilities limit the size of the pressure gradient possible in certain circumstances, for example in the pedestal of H-mode plasmas. It is particularly interesting to assess the proximity of local equilibria to the stability boundary (where $\omega^2 = 0$) of the ideal ballooning mode. We can do this by computing ω^2 for a range of a parameter that defines the local equilibrium. The ideal ballooning mode is driven by the pressure gradient so it is typical to vary the normalised pressure gradient, β' (defined as $\beta' = \frac{d\beta}{dr}$ where r is the radial coordinate) to assess proximity to marginal stability.

Choice of Experimental Run

The experimental run we choose to analyse in this study is MAST's 30422. This experimental discharge (shot) is used in a previous study of pedestal stability regimes (Imada *et al.* 2024), which analyses the differences in stability to the ballooning mode between MAST and MAST-U plasmas and mainly discusses finite-n MHD ballooning modes. Here we expand on that work by exploring $n = \infty$ ballooning modes in more detail.

We analyse the 326 ms time slice because time trace analysis for this shot suggests that the plasma is most stable at that time. Pressure profile analysis indicates that the plasma is operating in H-mode due to the presence of the pedestal at roughly $\psi_N = 0.95$. The surface at 0.97 has the highest experimental β' and by making β' scans across the plasma cross-section, we can see that it is one of the closest flux surfaces to the limit of stability, making it a good candidate for analysis.

Results

We next explore how shaping can influence the sensitivity of ideal ballooning modes by varying the shaping parameters $\delta_M, \kappa_M, \zeta_M$ of flux surface $\psi_N = 0.97$. Figure 1 suggests that increasing ζ_M and κ_M shifts the stability boundary to higher β' values and therefore acts to make $n = \infty$ ideal ballooning modes more stable. This aligns with a similar analysis we carried out on the MAST-U discharge 45272, which itself has higher κ_M and ζ_M values. Here, a higher pedestal and an increased stability against the ideal ballooning mode was observed when compared to the MAST discharge.

Discussion

A limitation of this study is that such shaping scans are difficult to replicate in experimental plasmas and, generally, only the plasma boundary shape can be directly modified by tweaking the toroidal and poloidal field coils. Furthermore, the internal local flux surfaces must self-consistently satisfy the Grad-Shafranov equation for a given boundary shape, which we do not take into account as we only focus on one surface. Future directions for this work include exploring ideal ballooning mode sensitivity to shaping of the last closed flux surface using fully self-consistent Grad-Shafranov solutions to analyse the full range of flux surfaces for a given time slice (which would be more comparable to experimental data).

Conclusion

This project explored the potential of using the ideal ballooning analysis to inform designers of future tokamaks which shapes of magnetic flux surfaces may be more favourable than others. Local ballooning analysis supports the notion that shaping, especially squareness and elongation, is related to the higher performing pedestals recorded in MAST-U compared to those of MAST. Specifically, it seems to be the increase of squareness and elongation that moves the marginal stability boundary away from the experimental equilibria, thus potentially leading to improved plasma confinement. There was insufficient time to rigorously test whether this method or the extracted conclusions are consistent with observed tokamak plasmas as the shaping study used toy models of the plasma which have not been compared to real discharges. Future work should consider an extended parameter space to understand the generality of these observations, as well as analyse globally consistent solutions of the Grad-Shafranov equation.

Acknowledgements

My supervisors at the UKAEA, Colin M Roach and Harry G Dudding, have been extremely helpful in guiding me through this project. Bhavin Patel has also been a huge help in troubleshooting the Pyrokinetics code used in this analysis, as has Sam Blackmore for pointing out interesting discharges to investigate. This work has been part-funded by the EPSRC Energy Programme [grant number EP/W006839/1].

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Geosciences

Application of a Novel, Mega-event Environmental Impact Assessment Critique Framework: The 34th America's Cup Races Case Study

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Open Access

Article Type
Letter

Received
02 Mar 2025

Revised
11 May 2025

Accepted
12 May 2025

Published
02 Jun 2025

DOI
10.2218/esjs.10616

ISSN
3049-7930

Abstract

Environmental impact assessments have a primary goal of balancing anthropogenic development with environmental protection. While critique methodologies for standard impact assessments are well-established, existing frameworks often fall short in addressing the unique challenges posed by large-scale, temporary events. Thus, this report introduces a novel framework designed for critiquing environmental impact assessments specific to mega-events on their use of science and analysis, adaptation to location and event specific impacts, attention to legacy impacts, and thoroughness of mitigation actions. The 34th Americas Cup Environmental Impact Assessment is then used as a case study to demonstrate the framework's applicability.

Introduction

Environmental Impact Assessments

Environmental Impact Assessments (EIAs) are used to assess, and in turn mitigate, impacts proposed projects may inflict upon an environment. Since their conception, governments of over 100 nations globally have adopted legal requirements and standards for EIAs as a method of scrutinising the development of projects to reduce their negative environmental impacts (El-Fadl *et al.* 2004). Within existing literature, there is ongoing debate over defining the effectiveness of an EIA. For the purposes of this paper, effectiveness refers to how well an EIA functions in achieving a primary goal of environmental stewardship (Caro-Gonzalez *et al.* 2023).

34th America's Cup

In 2010, San Francisco was selected to host the 34th America's Cup (AC34). While the San Francisco Bay has been developed into one of the largest economic gateways to the US, ideal for hosting such a large-scale event. It is

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also home to a diverse marine ecosystem (National Parks Service *et al.* 2012). The America's Cup can provide host cities with a range of economic benefits through race sponsors, domestic and international tourism, and global media exposure, however, the increased anthropogenic event activity and temporary infrastructure required to host hundreds of thousands of visitors can present severe negative impacts on marine ecosystems (Kahane 2021; National Parks Service *et al.* 2012). Following the initial event proposal, federal government agencies have produced a 'mega-event EIA' to help balance human use with environmental protection. The present study introduces a novel framework to critique mega-event EIAs on their performance and will use the AC34 EIA as a case study for its application.

Methods

Mega-event projects are unique in their temporary nature. Event EIAs are often less robust, only considering impacts occurring directly during or leading up to an event, and failing to address event specific activities (Toniolo *et al.* 2017). Additionally, mega-events often rotate to multiple parts of the world, where EIA standards differ (Pölönen *et al.* 2019). A generalised mega-event EIA critique framework is therefore not readily available. The novel framework presented in this study has been developed by collating and adapting previously used frameworks and implementing new critique components.

Results and Discussion

Framework Components

To create a framework that can be applied to different mega-event EIAs, five primary components have been proposed to reflect the necessary aspects of a successful EIA (Table 1). A set of criteria is linked to each component to aid in the assignment of a performance score. The components, criteria, and scoring system have been developed through the consultation of various mega-event EIAs (e.g., AC34, AC36 and London Olympics) as well as an established body of non-event EIA-critique literature to determine the most important components to be added to the framework.

Component A: 'Science and Analysis' assesses the quality and scope of information incorporation, analysis of impacts, and mitigations in an EIA. This component is based on a previously established generalised framework (Emerson *et al.* 2022). Regardless of the specific project for which an EIA is developed, the use of robust scientific data as well as both expert and local consultation is essential to ensuring effective impact management (Singh *et al.* 2020). This component is directly applicable to mega-event EIAs and is therefore incorporated into the current critique system.

Component B: 'Adaptation to Event Location' addresses the challenge of critiquing event EIAs due to the transient nature of mega-events. An event-specific framework must consider both unique local legislation and ecosystems in different locations which may impact their overall performance (Retief *et al.* 2025). Further, local government regulations may inhibit an EIAs performance. In the context of the AC34, event activities spanned across numerous federal organisations and privately owned areas. Federally mandated action was therefore limited to certain areas (National Parks Service *et al.* 2012). By emphasising location-specific factors, this component ensures that an EIA effectively addresses the unique challenges posed by the local environment, ensuring that the event's environmental footprint is properly managed within the context of the legal and ecological system of the host city.

Component C: 'Adaptation to Unique Event Activities' looks to approach the challenges posed by event-specific activities, which differ significantly from those of a typical EIA due to their temporary and specific nature. Existing literature has shown that the specificities of event activities need to be considered within an EIA to accurately predict and mitigate the potential environmental impacts (Toniolo *et al.* 2017). For example, the AC34 resulted in both generalised event impacts, such as spectator infrastructure, in addition to much more specific impacts, such as increased recreational and commercial boat traffic. Targeted mitigation approaches for specific activities are therefore required (National Parks Service *et al.* 2012). Temporary developments, such as the construction of spectator infrastructure, are common for events, but have not been previously considered in standard EIA critiques (Núñez *et al.* 2009). This component has been developed to address these event-specific, often temporary, developments to ensure that the EIA effectively captures and mitigates the diverse range of impacts unique to mega-events.

Component D: 'Attention to Legacy Impacts' evaluates the ability of an event EIA to address the long-term, post-event impacts. This component builds on a previously proposed EIA methodology, which was used for the London Olympics, to highlight significant environmental impacts that can occur during the 'legacy phase' of an event

(Parkes *et al.* 2016). While an event may only last for weeks, legacy impacts can span decades after an event ends. Literature has established the importance of scrutinising the legacy phase for social and economic effects, but a more developed framework is needed to adequately critique the environmental consequences (Collins *et al.* 2009). This component and its associated criteria have been tailored to critique the comprehensiveness of environmental considerations throughout the full life cycle of an event.

Component E: 'Thoroughness of Mitigation Actions' is based on an established critique framework, and evaluates how effectively an EIA achieves its primary goal of preventing and reducing environmental impacts through mitigation (Nisbet *et al.* 2022). All EIAs must be assessed on their ability to protect the environment while balancing sustainable use (Alberts *et al.* 2021). Therefore, this component has been modified and the criteria adapted to specifically address the uniqueness of event-based EIAs.

Calculating a Score

Previous EIA critiques have proposed letter systems in which each framework component is equally considered when assigning a performance grade (Nisbet *et al.* 2022). While these systems have shown some success, they are limited by precision and broader grade bounds which fail to capture subtle variations in performance. The current framework employs a quantitative system, one through five, where 'one' represents an unacceptable standard and 'five' represents an exceptional standard of EIA effectiveness (Table 1). The classification boundaries have been based off previously assessed EIAs and corresponding frameworks (Barker *et al.* 2013; Loomis *et al.* 2018; Veronez *et al.* 2024).

To determine an overall EIA performance score, each of the criteria will be individually assessed using this numerical system. The score will be based on the presence of the criteria within the EIA and the extent to which it has been adequately addressed. The criteria and score requirements have been further described in detail in Table 1 to create a robust, replicable system to minimise assessor interpretation bias and variation. The integration of weighted scoring indices, in addition to the use of multiple assessors (e.g., event organisation committees), has been highlighted as a further method to reduce subjectivity (Chang *et al.* 2013). The individual criteria scores are then averaged to give each component a score. The component scores are then aggregated according to their respective weighting to produce an overall EIA performance rating. Component weightings have been determined based on consultation with the EIAs and established frameworks stated previously.

Framework Application: AC34 Case Study

Based on each component score and respective weighting, the AC34 EIA achieved an overall rating of 3.2. The component breakdown is as follows:

- Component A: 3
- Component B: 4
- Component C: 3
- Component D: 2
- Component E: 4

This rating demonstrates the present EIA is only slightly above an average performance, and highlights multiple, specific, EIA aspects for improvement.

For Component A the AC34 does use credible, existing knowledge and makes effort to address knowledge gaps, however, there is a distinct lack of local knowledge incorporation. In contrast, the 36th AC in New Zealand achieved a 5 in this criterion. The EIA incorporates Māori culture and knowledge throughout the wider event plan to ensure awareness and proper action would be taken to protect sensitive areas (Fresh Info New Zealand 2021). The AC34 received the lowest score in Component D due the absence of a post-event monitoring strategy. Conversely, the 2012 London Olympics developed a Legacy Master Plan Framework, outlining environmental quality monitoring procedures to provide lasting benefits, giving an example of a well-developed monitoring strategy that successfully achieved its set sustainability goals (Gold *et al.* 2015; Greater London Authority 2012).

While the current framework makes effort to acknowledge and reduce variation in assessor interpretation, future work could seek to eliminate this by employing qualitative data analysis software (e.g., NVivo). This method could provide quantitative data on the percentage coverage of a framework component within an EIA to support performance scoring. This framework could be further applied to past and future event EIAs to enhance standardisation and prove both its replicability and value as a method for maintaining a high standard of EIA effectiveness and

Framework Component	**Associated Criteria**
A. Science and Analysis (30%)	A.1 Incorporation of credible, existing knowledge: Does the EIA use scientific literature and previous research to support claims? Is the information from a reputable source?
	A.2 Incorporation of local knowledge: Does the EIA incorporate a public consultation process? How well are local and traditional knowledge perspectives considered in the identification of impacts and proposal of mitigations?
	A.3 Consideration of knowledge gaps: Does the EIA highlight any knowledge gaps in the impact identification process (i.e., lack of information on species behaviour that may put them at risk)? Does the EIA attempt to close such gaps?
	A.4 Use of robust methods: If an EIA attempts to close gaps, or collect further information to support claims are the methods used robust and backed by scientific literature?
B. Adaptation to Event Assessment Location (10%)	B.1 Consideration of location-specific vulnerabilities: Does the EIA address unique sensitive ecosystems, specific species, or critical habitats which may be susceptible to event-related activities (e.g. identifying endangered species that may require further mitigation action to reduce impacts)?
	B.2 Integration of local regulatory frameworks: Does the EIA consider local regulatory constraints in the mitigation of impacts (e.g., acknowledging specific boundary of jurisdiction). The assessor should also consider how the local regulatory system may impact the quality of an EIA. While all assessments should be held to a high standard it is important to acknowledge some governments may limit funding to environmental management and protection.
C. Adaptation to Unique Event Activities (10%)	C.1 Assessment of temporary infrastructure: Does the EIA consider the lifespan of temporary construction projects? Is the decommissioning and post-event process for event venues addressed and considered?
	C.2 Evaluation of event-specific activities: Does the EIA address event-unique activities? Beyond development processes, what further impacts may a mega-event pose on an environment (e.g., large crowd, increased traffic, loud noise disturbances, light pollution).
D. Attention to Legacy Impacts (20%)	D.1 Consideration of long-term, post-event impacts: Does the EIA define a 'legacy period' after the event ends? Does the EIA address what impacts may occur during this period? Does the EIA consider impacts that will occur during the event that may have long-term effects on the environment (e.g., emissions)?
	D.2 Incorporation of a post-event monitoring strategy: Does the EIA include a comprehensive monitoring strategy for the 'legacy phase' of an event? Is the strategy comprehensive, yet feasible, is funding considered?
E. Thoroughness of Mitigation Actions (30%)	E.1 Clear geographic scope of mitigation actions: Does the EIA define the exact geographical location of proposed mitigation actions. Do they only occur within the primary 'footprint' of an event, or do they support spillover benefits?
	E.2 Clear temporal scope of mitigation actions: Does the EIA define how long mitigation actions will occur? Are they primarily focussed on impacts during an event, or will they last into an event 'legacy phase'?
	E.3 Specific actions towards vulnerable species/habitats: Do mitigation actions target specific vulnerabilities? To what extent are mitigations generalised (e.g., ecosystem level, habitat level, species level)?
	E.4 Consideration of mitigation feasibility: Does the EIA provide specific actions for the mitigation process? Are funding estimates provided, are specific organisations highlighted to undertake certain actions?

Score	Description
5 - Exceptional	Significant and thoughtful consideration has been put into framework criteria. The EIA goes beyond 'checking boxes' and works to better environmental management and protection.
4 - Good	Criteria are all considered to a greater extent, but further information could be elaborated upon to provide depth to the report.
3 - Average	This represents the baseline for EIA performance, all criteria are mentioned and considered. Enough detail is present for the assessor to understand the EIA has made a clear attempt to address this component.
2 - Poor	Criteria is mentioned, but are overall lacking, undeveloped, or not considered to a significant degree. Limited information has been provided.
1 - Unacceptable	The criteria are not present in the EIA.

Table 1: Five components labelled A-E make up the proposed critique framework. Each component has been broken down into supporting associated criteria to aid in the assessment process. Each component has been weighted and is aggregated to produce a final performance score.

environmental management. The framework presented in this study could be adopted for broader use, offering a standardised approach to assessing and improving mega-event EIAs across various industries and regions, leading to greater accountability in environmental management practices.

Acknowledgements

I would like to thank Dr. Lea-Anne Henry, my supervisor, for her encouragement to pursue publication of this work and her guidance and support throughout the journey. I also thank the journal editors for their constructive feedback on how best to present this paper within the context of the Edinburgh Student Journal of Science. This publication represents the first study that is not strictly 'data-driven' and takes a broader meta-analytical approach to producing novel work.

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Hilbert-Huang Transform Analysis of Intradecadal Variations in the Length of Earth's Day

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Open Access

Article Type
Letter

Received
26 Sep 2025

Revised
22 Oct 2025

Accepted
27 Oct 2025

Published
12 Nov 2025

DOI
10.2218/esjs.11674

ISSN
3049-7930

Abstract

Intradecadal periods in the length of Earth's day (ΔLOD) reveal angular momentum exchanges as a result of processes in the Earth's core. The properties of two previously identified intradecadal oscillations in the ΔLOD signal with periods of approximately 6 and 8.5 years, respectively, are investigated from 1962 to 2025, using the Hilbert-Huang transform method. Initially, angular momentum contributions from zonal tides and the Earth's atmosphere are removed, before the application of Butterworth bandpass filters to isolate the oscillations. The two intradecadal oscillations are found to have periods of 5.8 ± 0.8 years and 9.1 ± 1.6 years, respectively. The six-year oscillation shows a decaying trend from 2010 onwards, associated with a shortening in the period of oscillation. The eight-year oscillation breaks down between 1995 and 2000, which may be linked with geomagnetic jerk activity.

Introduction

Variations in the rotation rate of the Earth, resulting in changes in the length of Earth's day (ΔLOD), occur due to angular momentum exchanges from mass redistribution and motion in the Earth's fluid envelope and liquid core (Rekier *et al.* 2022). After the removal of the effects of tidal forces and atmospheric angular momentum excitations, several remaining long-term oscillations in ΔLOD can be recognised and attributed to core processes. Two notable intradecadal periods, and the subject of this study, are a 5.9-year period (Abarca del Rio *et al.* 2000; Holme *et al.* 2013), known henceforth as the six-year oscillation (SYO), and an 8.5-year period (Ding 2019; Rosat *et al.* 2023), known hereafter as the eight-year oscillation (EYO). The mechanisms involved in the generation and formation of both the SYO and the EYO remain topics of ongoing research, with a range of models proposed to describe the presence of the two oscillations. The SYO has been proposed to be related to fluid flow at the surface of the outer core (Istas *et al.* 2023; Rosat *et al.* 2023), or to mantle-inner core gravitational coupling modes (Mound *et al.* 2003; Duan *et al.* 2020b). The generation of the EYO has been ascribed to either quasi-geostrophic magneto-Coriolis waves (Gillet *et al.* 2022), or torsional core oscillations (Duan *et al.* 2020a).

Previous studies have used methods such as the normal Morlet wavelet transform (Duan *et al.* 2020a), cubic splines (Madsen *et al.* 2025) and the continuous wavelet transform (Rosat *et al.* 2023) as a means of investigating intradecadal periods in the ΔLOD signal. This study will compare previous findings with those of an alternative method of examination, the Hilbert-Huang transform (HHT). The HHT method allows for the investigation of the oscillatory components and instantaneous frequency (IF) trends of a signal over time, facilitating a greater understanding of the structures and properties of the SYO and EYO. We use the Rayleigh criterion to define upper and lower limits for bandpass filtering in order to isolate the SYO and EYO, respectively, before applying the HHT method to examine and provide information on the nature and behaviour of the signals.

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Data

The period of analysis for this study spans from 01/01/1962 to 01/05/2025. This work uses the EOP 20 C04 ΔLOD series (Bizouard *et al.* 2009), which is a combined series comprising measurements of ΔLOD from a variety of space-geodetic techniques (Gross 2015). The EOP 20 C04 series and fluid envelope angular momentum excitation functions used are provided by the International Earth Rotations and Reference Systems Service (IERS). Between 01/01/1962 and 31/12/1975, the excitation functions computed by Atmospheric and Environmental Research (AER) (Zhou *et al.* 2006) are used. From 01/01/1976 onwards, the model computed by the GFZ Helmholtz-Zentrum für Geoforschung (Dobslaw *et al.* 2010) is used. The angular momentum functions are composed of both mass and motion terms, which are combined for the purpose of this study. The modelling of periodic variations in ΔLOD as a result of zonal tides is conducted as set out by the IERS conventions (Petit *et al.* 2010). This model uses a combination of elastic body tide (Yoder *et al.* 1981), inelastic body tide (Wahr *et al.* 1986), and ocean tide (Kantha *et al.* 1998) models to determine the effects of zonal tides on the Earth's rotation.

Methods

Signal Processing

The contributions from core processes are isolated by subtracting the zonal tidal effects and atmospheric angular momentum functions, in accordance with the method of Mohn et al. (in prep.). To then isolate specific periods, a first-order Butterworth filter is applied in the frequency domain. The Rayleigh criterion is used to select the applied bands, where the criterion dictates, for two periodic components, the smallest measurable frequency separation. For two frequencies, σ_1 and σ_2, this is given by

$$|\sigma_1 - \sigma_2|L > R \tag{1}$$

where L is the recording length of the time series, and R is the Rayleigh constant, with value 1. This can then be used to calculate the Rayleigh periods, P_{min} and P_{max}, which indicate the range of oscillation periods that cannot be distinguished from one another (Pfeffer *et al.* 2023). For a period of interest, P, the Rayleigh periods are

$$P_{\text{min}} = \frac{1}{\frac{1}{P} + \frac{1}{L}} \tag{2}$$

and

$$P_{\text{max}} = \frac{1}{\frac{1}{P} - \frac{1}{L}}. \tag{3}$$

The Hilbert-Huang Transform

The HHT is a two-stage process for the extraction of the oscillatory components and IF trend of a signal over time. The two stages in this process are empirical mode decomposition (EMD) and Hilbert spectral analysis, implemented using the Python package, `emd` (Quinn *et al.* 2021).

Empirical Mode Decomposition

EMD is a method of decomposing a time series function into a small number of oscillatory modes, known as intrinsic mode functions (IMFs) (Huang *et al.* 1998). The structure of each IMF fulfils two conditions (Roberts *et al.* 2007):

1. The difference between the number of extrema and horizontal axis crossings does not exceed a value of one.
2. The average value of the two envelopes of the function, defined by the local maxima and minima, must be zero at every point.

Identified IMFs are extracted until the original signal contains no further oscillatory signals, leaving the residual. Each IMF extracted is the largest remaining frequency mode in the signal. EMD is applied to filtered signals to isolate IMFs of interest.

Hilbert Spectral Analysis

Hilbert spectral analysis uses the Hilbert transform to identify the instantaneous amplitude and frequency of a signal. This method can be applied to signals that exhibit non-linearity and non-stationarity, but the signal must be oscillatory for the method to work successfully (Huang *et al.* 1998; Huang *et al.* 2008). For a function $x(t)$, the Hilbert transform $c(t)$ is given by

$$c(t) = \frac{1}{\pi}\mathcal{P}\int_{-\infty}^{\infty}\frac{x(\tau)}{t-\tau}d\tau \tag{4}$$

where $\mathcal{P}$ denotes the Cauchy principal value of the integral, and τ is a dummy integration variable (Huang *et al.* 2008). From this transformation we acquire the function

$$z(t) = x(t) + ic(t) = \alpha(t)e^{i\theta(t)} \tag{5}$$

for an instantaneous amplitude $\alpha(t)$ and an instantaneous phase function $\theta(t)$. From the instantaneous amplitude and IF $\omega(t)$, given by

$$\omega(t) = \frac{d\theta}{dt}, \tag{6}$$

the marginal Hilbert spectrum $h(\omega)$ is created. This portrays the total energy contribution of each frequency with respect to time, and is created by expressing the amplitude as a function of time and frequency $\mathcal{H}(\omega, t)$ (Huang *et al.* 2008)

$$h(\omega) = \frac{1}{T}\int_{0}^{T}\mathcal{H}(\omega, t)dt, \tag{7}$$

where T is the period of time over which the analysis is concerned.

Results

After the removal of atmospheric and zonal tide effects from ΔLOD, a four- to ten-year bandpass filter (Figure 1, left) is used to understand the range of intradecadal signals present (Gillet *et al.* 2022; Rosat *et al.* 2023). To consider the dominant periodic components of ΔLOD, EMD is applied following bandpass filtering to isolate the principal oscillatory mode, IMF 1. The behaviour of IMF 1 in Figure 1a suggests that there are multiple oscillatory periods present within the IMF, and from Figure 1d we observe two main periods which approximately align with those of the SYO and EYO. This is consistent with Figure 1g, which shows the IF fluctuating between periods of 5 and 10 years, as well as highlighting edge effects at either end of the marginal Hilbert spectrum. There is a deviation in the spectra, with a peak in 2014 at an oscillatory period of ∼4 years.

The SYO is isolated (Figure 1, middle) using a bandpass filter of 5.40 to 7.51 years, generated using the Rayleigh criterion, to obtain an oscillation with a period of 5.8 ± 0.8 years. The SYO, as shown in Figure 1b, with the associated periodic content in Figure 1e, shows an interrupted oscillation beginning in 2010. In 2010, the magnitude of the oscillation begins to decrease, and in Figure 1h we see the onset of a spike in the IF and the instantaneous amplitude drop sharply off. A further minima in the IF is then observed, but due to the presence of edge effects, whether this spike is indicative of any behaviour seen in the SYO remains unknown. This suggests that in 2010, the oscillatory period shortens to outside the bandpass filter range.

The EYO is isolated (Figure 1, right) using a bandpass filter of 7.49 to 9.82 years, generated using the Rayleigh criterion, to obtain an oscillation with a period of 9.1 ± 1.6 years. The EYO signal, as shown in Figure 1c, has a less regular oscillation, which can be associated with a wider spectral window than is contained within the signal (see Figure 1f). In Figure 1c, we observe the magnitude of the signal decrease between 1995 and 2000, with a similar drop in amplitude occurring in the marginal Hilbert spectrum (see Figure 1i), but the magnitude of the signal then recovers.

Discussion

The determined periods of the SYO and EYO in this study are not the expected 5.9-year and 8.5-year periods, but the expected periods do lie within the error range, as given by the Rayleigh criterion. The width of this range is determined by the length of our data series, which is 63 years, and we are unable to differentiate between signals of periods within the error range. Therefore, one of the main limitations of this method for isolation is that, for much finer band limits, further years of expansion of the ΔLOD time series are required.

The trend in the SYO in this study aligns with the observations of Madsen *et al.* (2025), with a breakdown of the signal beginning in 2010, where they determine the subsequent extremum to occur in 2014, giving a 4-year oscillation followed by recovery to a 6-year oscillation, with a shifted phase. We observe a decrease in the instantaneous amplitude and the magnitude of the signal, which both suggest that the energy associated with the oscillation is

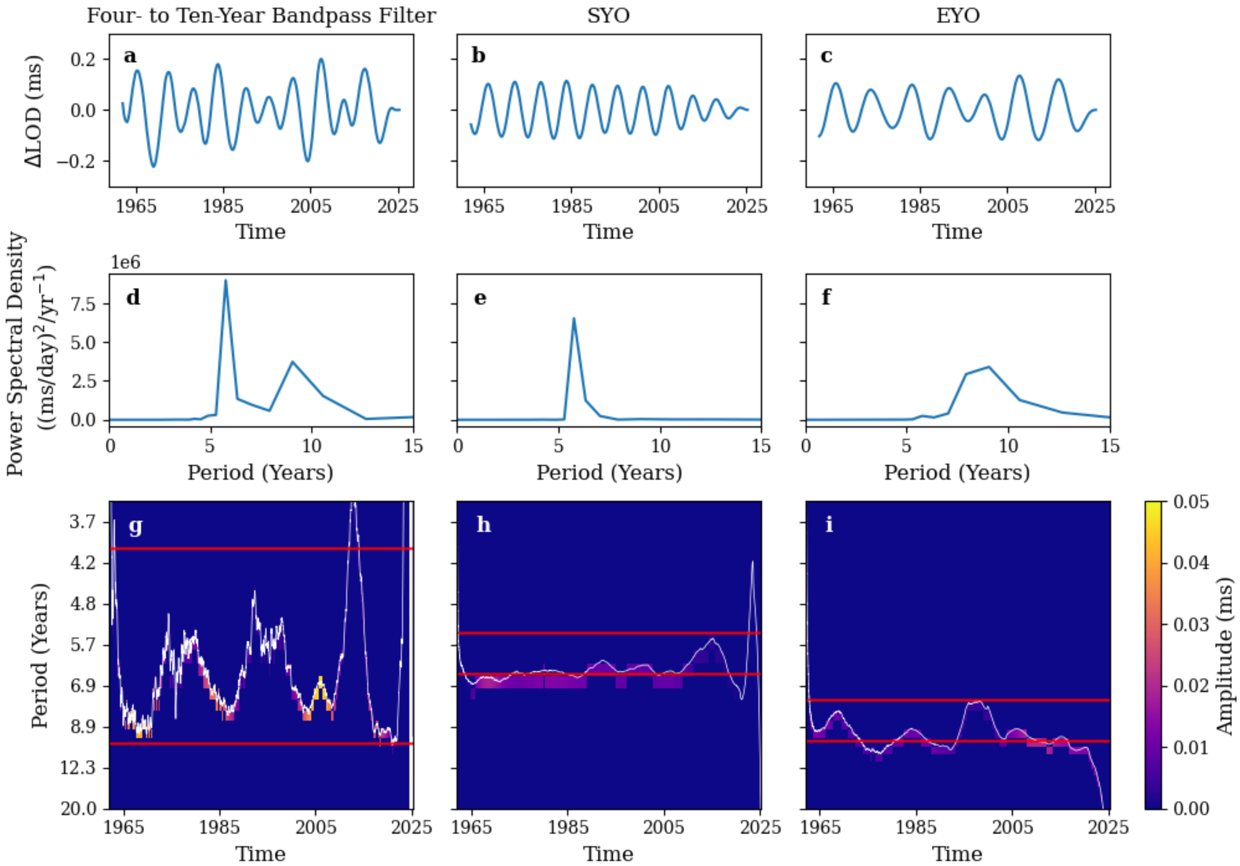

Figure 1: Left column: 4.00–10.00 year bandpass filter on ΔLOD-AT; middle column: 5.40- to 6.51-year bandpass filter on ΔLOD-AT for SYO; right column: 7.49- to 9.82-year bandpass filter on ΔLOD-AT for EYO. (a) IMF 1 of ΔLOD, (b)-(c) timeseries, (d)-(f) periodograms, (g)-(i) marginal Hilbert spectrum. In (g)-(i), the white curve portrays the instantaneous frequency, and the red lines show the upper and lower limits of the bandpass filter.

now no longer within the filter range, supporting a shortened oscillatory period, but no recovery, in the 6-year periodicity of the signal. This likely occurs because the interruption of the 6-year oscillation between 2010 and 2014 is shorter than P_{min}. The reduced period then recovered, but the phase-shifted SYO after 2014 is not resolved by the bandwidth chosen by this study, thus extinguishing the SYO after 2010. This is likely also the phenomenon that leads Duan *et al.* (2020a) to draw the conclusion of a decaying SYO. As such, alternative methods of extracting the SYO have come to different conclusions, suggesting that each method provides different insights into the nature of the SYO.

The activity observed in the EYO shows no decay in magnitude between 2010 and 2025, which indicates that the mechanisms which drove the two oscillations had different sources. Previously, Duan *et al.* (2020a) found the EYO to have a trend of increasing magnitude, whereas we found the trend is broken by an interruption between 1995 and 2000. A phenomenon of low amplitude has previously been observed in the ΔLOD during the 1990s by Holme *et al.* (2013). Holme *et al.* (2013) found this phenomenon arises due to the difficulty in separating anti-correlating intradecadal and interdecadal trends. This could occur in this study due to the wide transition from the passband to the stopband in a first-order Butterworth filter. However, Brown *et al.* (2013) suggest that 1995 to 1998 was a period of frequent jerk activity, and if the EYO and geomagnetic jerks are related, which has been previously proposed by Duan *et al.* (2020a), this may have broken the periodic trend of the signal.

Conclusion

This study investigated intradecadal periods present in the ΔLOD that occur due to angular momentum exchanges as a result of processes in the Earth's core. Initially, the contributions of zonal tides and the Earth's atmosphere are removed, before a first-order Butterworth filter, generated using the Rayleigh criterion, is applied to extract the SYO and EYO. The HHT method is then used to determine the IF of the signal. These oscillations are found to have periods of 5.8 ± 0.8 and 9.1 ± 1.6 years, respectively. The SYO shows a decaying trend from 2010 onwards, associated with a shortening in the period of oscillation, where no recovery of the original period of the signal is observed. Furthermore, the EYO breaks down between 1995 and 2000, which may be linked with geomagnetic jerk activity.

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Journal Acknowledgements

The Edinburgh Student Journal of Science is a result of the hard work of many people. During the course of the second volume, the journal has seen numerous developments in its operations, and my thanks to the editorial board and editorial team for their continuous help with this, particularly Christina, Nitara, David, and Ruaridh. Furthermore, staff from the University of Edinburgh and many other institutions have been greatly useful in helping raise awareness about the journal and its growth and adoption at other Scottish universities. Thank you to all those who have contributed their work or time to this volume.

An additional thank you to Edinburgh Diamond and their team who enable the publication of the journal, as well as our PhD student reviewers who give their time to serve as reviewers.

Jack L Smith

Founder & Editor-in-Chief