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DATA ARTICLE

The accurate digitization of historical sea level records

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Abstract

Understanding regional sea level variations is crucial for assessing coastal vulnerability, with accurate sea level data playing a pivotal role. Utilizing historical sea level marigrams can enhance datasets, but current digitization techniques face challenges such as bends and skews in paper charts, impacting sea level values. This study explores often-overlooked issues during marigram digitization, focusing on the case study of Dún Laoghaire in Ireland (1925–1931). The methodology involves digitizing the original marigram trace and underlying grid to assess offsets at the nearest ft (foot) interval on the paper chart, corresponding to changes in the water level trace for each hour interval. Subtracting the digitized value from the known value (the actual measurement) allows for the determination of differences, which are then subtracted from each hourly trace value. After adjusting for offsets ranging from −3.962 to 13.716 mm (millimetres), the study improves the final accuracy of sea level data to approximately the 10 mm level. Notably, data from 1926 and 1931 exhibit modest offsets (<7 mm), while other years show more substantial offsets (>9–14 mm), emphasizing the importance of adjustments for accuracy. Such 10 mm accuracy is compatible with requirements of the Global Sea Level Observing System. Comparing the adjusted digitized data with other survey data shows similar amplitudes and phases for Dún Laoghaire in both the historical and modern datasets, and there is an overall mean sea level rise of 1.5 mm/year when combined with the available data from the Dublin region.

KEYWORDS
digitization, historical data, sea level

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1 | INTRODUCTION

Globally, mean sea level (MSL) is rising at a rate of 3–4 mm/year, and this rise is accelerating (Nerem et al., 2018; Dangendorf et al., 2017, 2019; Van Alphen et al., 2022). Knowledge of changes in historical sea level rise is key to understanding coastal vulnerability and risks. In Ireland, over 40 digital tide gauges, installed in the 2000s and managed by the Office of Public works (OPW) and the Marine Institute, are used to record present-day sea-level changes, forming part of the National Tide Gauge Network (Cámaro Garcia et al., 2021; Dwyer, 2013). However, data prior to the 21st century are rare in Ireland. Ireland has some long-term records of mean sea level, and these records are limited to the northeast of the country (Dublin Port from 1938, Belfast Harbour from 1901/1902, and Malin Head from 1958) (Figure 1, inset map). Nevertheless, only Belfast Harbour is digitized to high frequency at 10-min intervals (Murdy et al., 2015). Historical Marigram records are a graphical representation of tidal data for a given period of time. A single trace usually represents a day, while multiple overlapping traces may represent a week on a sheet of graph paper. Marigram records originate from historical gauges equipped with rotating paper chart recorders, used to measure tidal fluctuations. A float within a vertical stilling well, connected to an ink pen tracing measurements on graph paper fixed to a mechanized rotational drum, records the tidal rise and fall (Das, World Meteorological Organization, 1978; International Hydrographic Bureau, 1960; Murdy et al., 2015). Prior to the digital era, these traces were usually recorded on graph paper, with the X-axis representing hours and the Y-axis representing height, often in feet relative to Chart Datum. Marigram datasets exist in various locations throughout Ireland. For example, datasets are available from Belfast Harbour (1901/1902–2010),

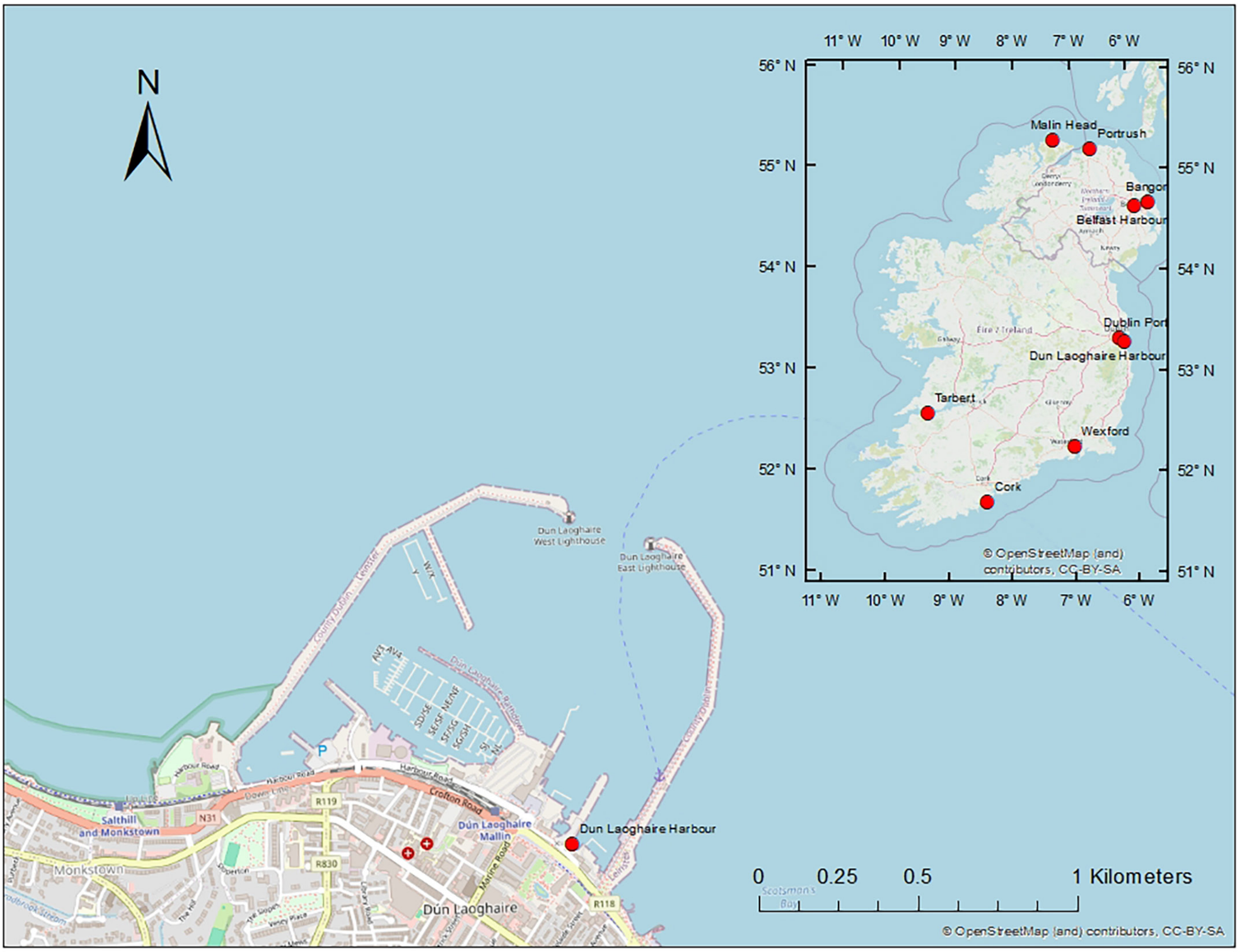

FIGURE 1 Shows the main map indicating the approximate location of Dún Laoghaire Harbour, where the marigram data was recorded. The inset map displays the known locations of other historical sea level data in Ireland.

Dublin Port (1923–2003), Dún Laoghaire Harbour (mid-1920s and early 1930s), Cork (primarily Tivoli data recovered in the 1970s and 1980s), Kerry (Tarbert from the 1960s) and Wexford (Kilmokea, potentially with data from the 1960s, and other locations noted by Murphy et al., 2003), as shown in Figure 1's inset map. Otherwise, Ireland has numerous locations of historical sea level data recorded, with many additional sites located mainly to the north (see Figure 1). Some of these locations have been catalogued by the Permanent Service for Mean Sea Level (PSMSL), as documented by Holgate et al. (2013).

Marigram structures can vary depending on their time span and can be complex to digitize. There is a plethora of software available to digitize raw images, regardless of their structures, which can successfully extract data from an image. One well known software developed in the 2000s is the NUNIEAU tool kit for the digitization of marigrams. This software is used in an automated way to speed up the digitization of marigrams and increase the accuracy of digitization (Bradshaw et al., 2015; Pons et al., 2016; Ullmann et al., 2005). However, there are limitations to this software. Where there are multiple traces overlapping on a marigram image of poorer quality, the software falters and struggles to detect the correct traces, especially if the traces do not match the predicted tide. As NUNIEAU has poor ability to digitize blurred or overcrossing traces, this requires human cleaning. Murdy et al. (2015) digitized marigrams using the proprietary Biosoft software 'UnGraph' (no longer available), which allowed them to trace over the marigram traces quickly. They note that UnGraph is better able to find its way over complex crossovers than NUNIEAU.

It is not a difficult task to find a software that can digitize marigram traces. However, even with the appropriate software selections, one must be mindful of the issues associated with digitizing, some of which are obvious while others are quite hidden. One common issue with digitization is the barrel lens distortion of images (Talke & Jay, 2017). A Barrel distortion is an optical effect that causes straight lines to appear curved outward, resembling a barrel shape, in images captured with a camera or observed through a lens system. Two other very common issues in the digitization of historical marigram records are timing errors and datum shifts (GLOSS Group of Experts 13 Meeting, 2013; Gouriou et al., 2013). Digitizing marigrams presents several challenges. These include lens distortions, skews or shifts in the image, variations in trace thickness, ink quality issues like blur, clock stoppages, gaps in recordings, missing data and minor inconsistencies such as changes in line thickness affecting the digitized values accuracy.

The aim of this paper is to illustrate the importance of validating digitized data and removing as many potential digitizing sources of error as possible (using open-source software) to keep the data within historical sea level data accuracy of 10 mm (millimetres) or 1 cm (centimetres). The methodology involves (i) digitizing scanned marigrams at hourly intervals; (ii) identifying sources of error within 10 mm accuracy by computing offsets between the original and adjusted data; (iii) comparing the digitized (unadjusted) data with the rectified (adjusted) data; and (iv) validating and contextualizing the adjusted data by comparing it with nearby site data. The 10 mm accuracy aimed for in this study is consistent with that specified by the Global Sea Level Observing System (GLOSS) for tide gauge records (Intergovernmental Oceanographic Commission (IOC), 2012).

2 | DATA DESCRIPTION AND DEVELOPMENT METHODOLOGY

2.1 | Data location and description

The dataset located from Dún Laoghaire Harbour (formally known as Kingstown) near Dublin (Figure 1) used in this paper ranges from 1925 to 1931. There are noticeable discrepancies in data quality across different years, ranging from very well-documented marigrams to instances of poor quality with significant data blurring and missing segments, particularly during periods when the tide gauge ceased operation. One issue is that there are sporadic gaps where more than half a year of 1930 is missing. Table 1 provides information on the number of available images, an approximation of the percentage of good and poor-quality images among the available images and the number of missing images. It is expected that each year should have approximately 52 marigrams. However, in some cases, this number may be higher, particularly when there is less than 1 week of traces in a marigram.

The marigram images are of mixed quality traced in ink. Some images are of very good quality while many others have issues such as ink trace blur, gaps in the data from tide gauge stoppages and prolonged gaps in the data (1930 with more than 6 months loss of data). The datum for this data is CD (Chart Datum). The chart's X-axis represents hours, ranging from 24 to 0, with forenoon tides on the right and afternoon tides on the left, while the Y-axis measures height in feet relative to CD (Figure 2). The X-axis orientation in this chart differs from other marigram images, such as those in Belfast Harbour (Murdy et al., 2015)

TABLE 1 Description of the number of images and their quality for each year, categorized as good or poor.

Year	Number of images	% good/reasonable quality images (Approx)	% poor quality images (Approx)	Number of missing images
1925	50 (1 partial copy image)	80	20	3
1926	38	76	24	14
1927	45	71	29	7
1928	37	70	30	15
1929	52	77	23	0
1930	22	64	36	30
1931	41	68	32	11

Note: Poor quality images are most often defined as those with two or more traces that are significantly broken, faded, replaced with pencil, illegible, or containing spurious thick lines.

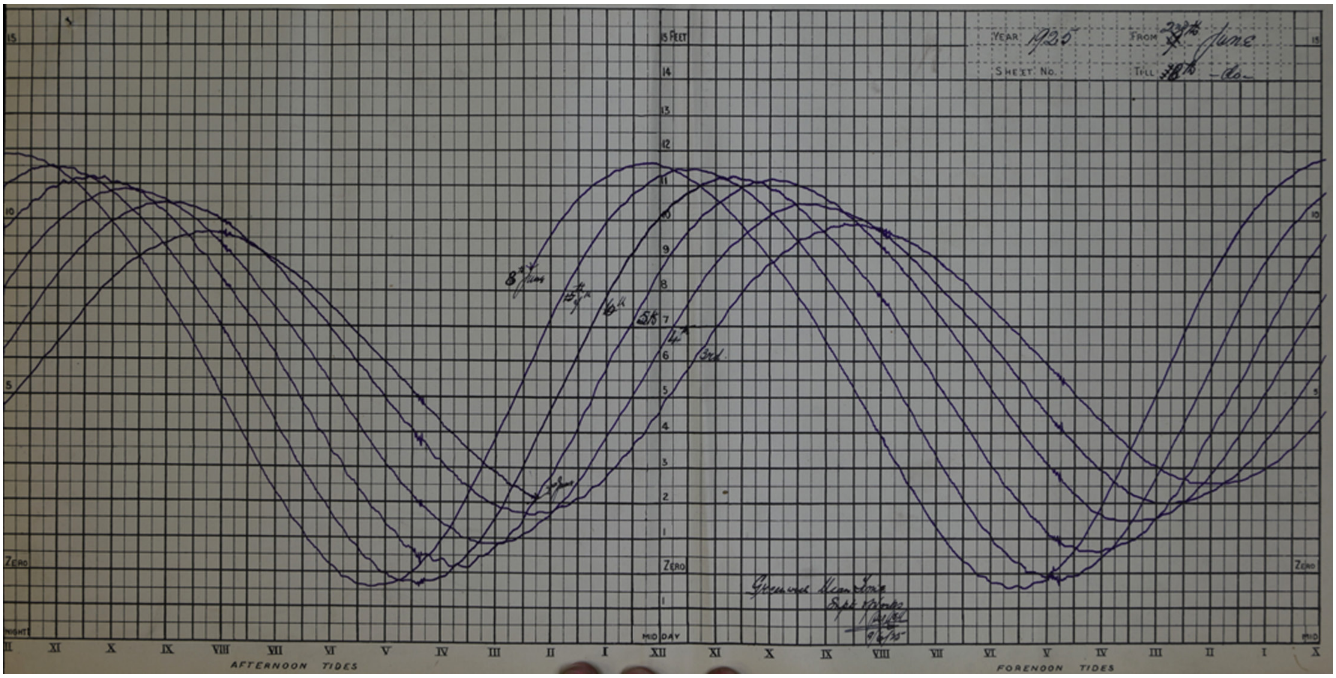

FIGURE 2 Shows a marigram in Dún Laoghaire from June 1925, with the X-axis representing time in hours (ranging from 24 to 0) and the Y-axis indicating the water level in feet relative to CD.

and Dublin Port, which start at 0 and end at 24 h, moving from left to right.

2.2 | Data preparation

A Metis EDS professional digital scanner was used in the digitization of all historical marigram archives, the same scanner that was employed in the scanning and digitization of rainfall records (Ryan, 2021; Ryan et al., 2018). Marigrams were scanned as TIFF images, converted to JPG format and organized in date order using an appropriate naming convention (e.g. 15–22nd_June_1931) based on their respective date and year.

2.3 | Development of digitization methodology

2.3.1 | Point digitization of scanned images at hourly intervals

There are many open-source digitizing tools such as DataThief (2023), Engauge Digitizer (2023), WebPlotDigitizer (Rohatgi, 2022) and GetData Graph Digitizer (2023). In this instance, free open-source software was tested (Engauge Digitizer, WebPlotDigitizer and GetData Graph Digitizer) for digitizing marigrams.

However, a limitation of many of these software packages was that they were only available as desktop versions. Online web versions were preferred because they offered greater versatility, allowing access from different desktops without the need for downloading and installation. The Online PlotDigitizer (2023) and WebplotDigitizer software packages were investigated. PlotDigitizer's free version had limited resources, such as restricted zooming capabilities, and required additional purchases for certain components. WebPlotDigitizer, created by Ankit Rohatgi, was equally as useful at extracting points and was open source, allowing zoom in options and scaling. Consequently, it was selected as the appropriate digitizing software.

When calibrating the X and Y grid of the marigram image in WebPlotDigitizer, the X-axis (hours) is scaled from 0 to 24, while the Y-axis (ft) is scaled from 2 to 10. We begin the Y-axis scaling at the 2-ft (foot) interval instead of 0 because this upper value typically exhibits less skewness along the line, offering a more reliable reference point for scaling all images consistently. The X-axis is scaled at both ends (0 and 24), ensuring comprehensive coverage, whereas the Y-axis is scaled in the centre of the image, where each ft interval is labelled (Figure 3).

Accurate scaling of marigrams is essential to mitigate potential axis offsets. For instance, the second ft interval (2 ft) is often chosen as Y1 due to its straighter alignment, which minimizes overall distortions compared to starting at 0. However, exceptions may arise. If the line at 2 ft exhibits distortion or reduced line thickness, or if the 24-h mark is compromised, alternative intervals may be chosen to enhance accuracy. For example, the value at the zero- or first-ft interval (in some cases) could be chosen instead of 2 ft, or the previous 23-h mark could be scaled to 23 instead of 24, provided it aligns with the ft value selected. To ensure uniform interpretation and mitigate potential distortions, the marigram data in this study was calibrated with the values of interest consistently aligned with the top line thickness for both upper and lower bounds.

The steps taken to ensure as accurate as possible calibration do not remove or reduce the overall distortions or skews in the image; the methodological steps taken to do this are discussed in the next Section (2.3.2).

Data typically recorded at tide gauge stations in the UK has hourly data up to the 1990s and better resolution data (15 min) from the 2000s onwards (Woodworth et al., 2017). Hourly intervals are suitable for calculating MSL and tidal and non-tidal residuals, and for tidal work (Pugh et al., 2021.; Pérez-Gómez et al., 2021). Owing to the age and coarse resolution of many marigram images, hourly intervals were appropriate for digitizing the Dún Laoghaire records. A point is manually positioned, as closely as possible to the centre of the line thickness, on each marigram trace at every hour (0–23) to obtain each daily record (Figure 4), ensuring accuracy. The centre is chosen as the best fit for accuracy because placing the point too high or too low on the trace would not accurately reflect the actual hourly values. Twenty-four (24) points were placed on each marigram trace, corresponding to the

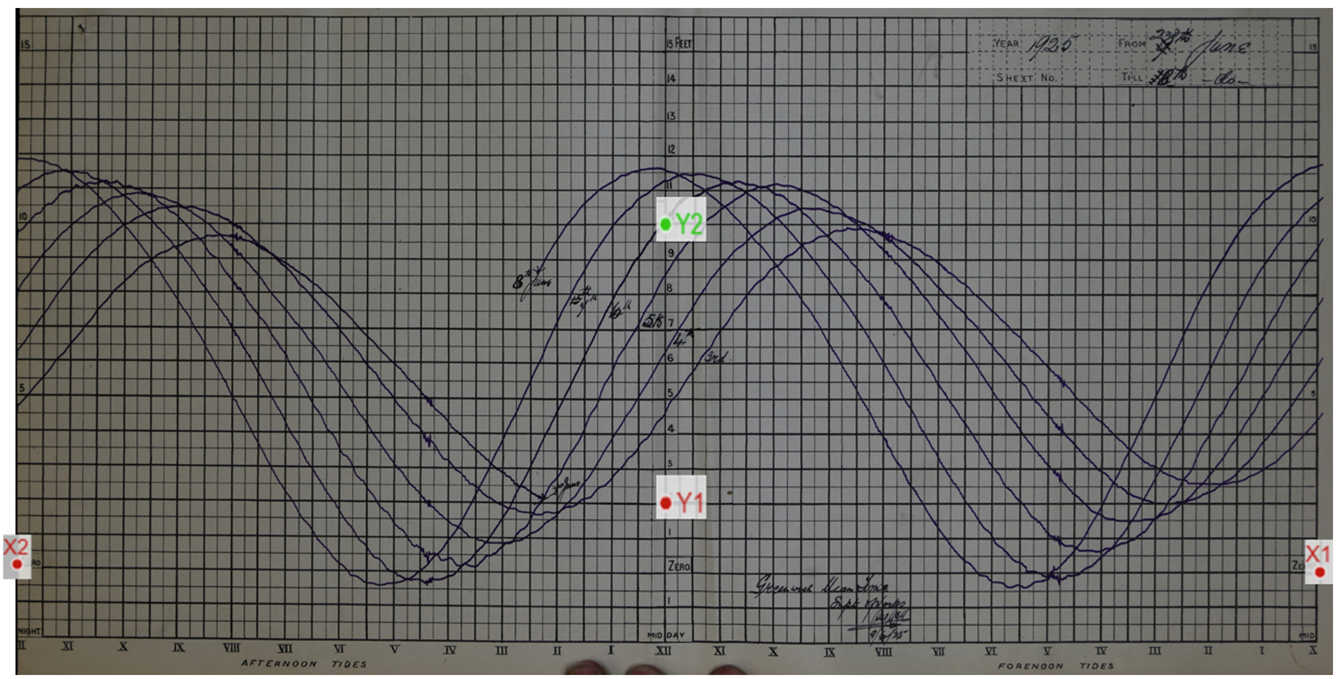

FIGURE 3 Illustrates the scaling process in WebPlotDigitizer. The X-axis (X1 = 0-hour, X2 = 24-h) and Y-axis (Y1 = 2 ft, Y2 = 10 ft) are defined.

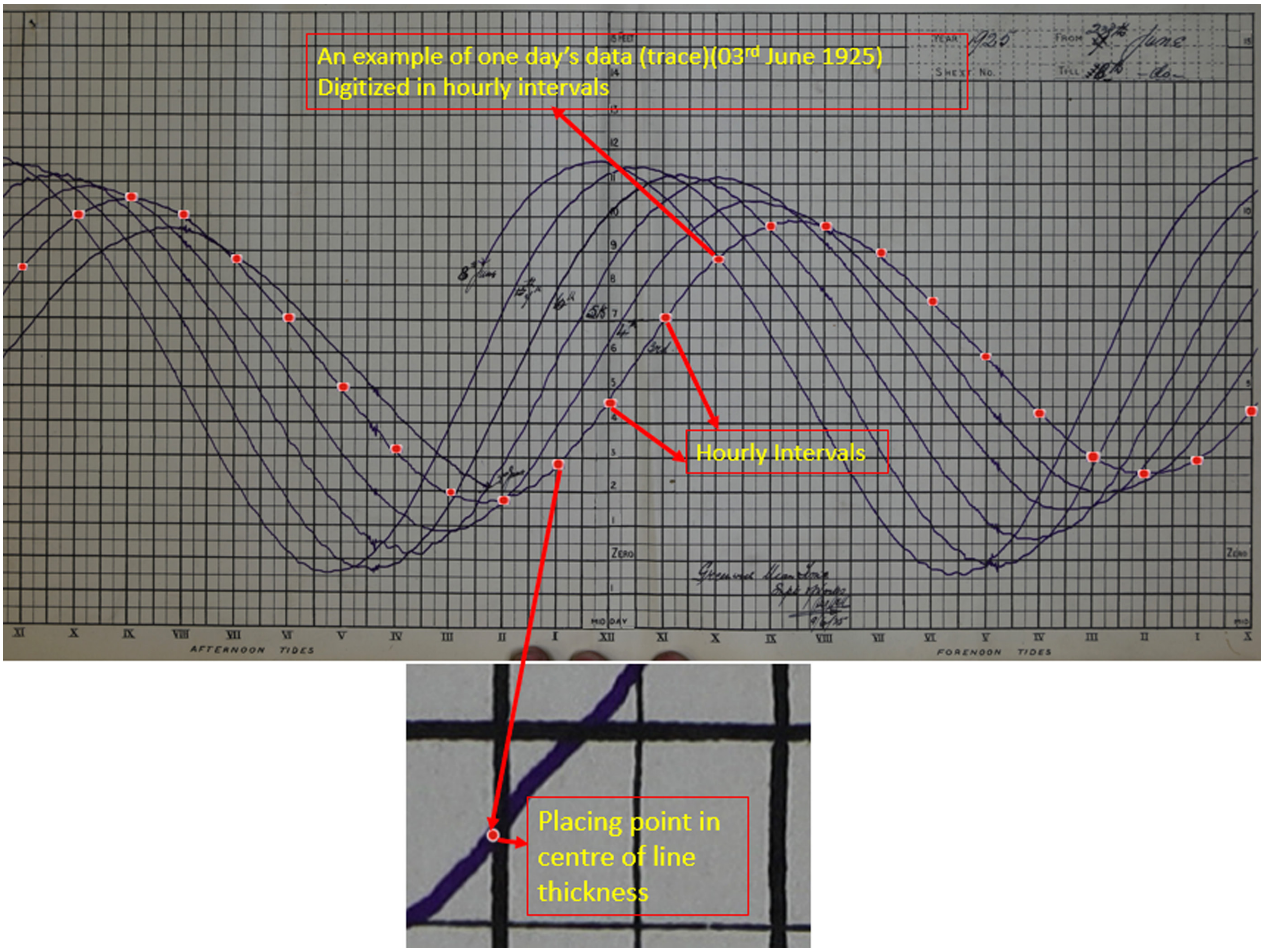

FIGURE 4 Manually point placing at each hour in the marigram trace, here the point is placed as closely as possible to the middle of the trace for the given hour.

0–23 h period on the day in question. Providing context for this observation is important. The 24-h point on each marigram trace slightly differed from the 0-h point on the subsequent day's trace. Notably, the 24-h trace appeared cropped at the end of the images, inaccurately representing its actual value. As the 24-h trace from each day is also reproduced by the 0-h point on the following day, it was omitted from each daily digitization.

The centring of the point on the trace in each image is important. However, where the traces are narrow, as in 1925, uncertainties in placing the point at the centre would not be significantly problematic. If, for example, the point was placed close to the top or bottom of the trace provided, it would not significantly offset the data. Tests were made on digitized marigrams and, generally, where some of the traces on the marigram, were not perfectly centred, offsets for the entire 7 days on the marigram versus the same marigram perfectly centred only gave small offsets (1–5 mm).

2.3.2 | Overcoming issues of image skews and distortions

There are distortions in images stemming from the camera used for the scans (Akondi et al., 2021; Stankiewicz et al., 2018), and there are hidden shifts or skews in the image. In addition, there could already have been skews in the paper marigrams themselves, resulting in the lines of the grid not being straight, thus resulting in offsets (Figure 5). Also, there are issues where line thickness reduces on the X-axis.

While methods were developed to try and resolve some common issues, such as the sharp contrast between the background paper and pencil line (Talke et al., 2020), issues of skews remain. These issues are problematic because they can distort both the X and Y axes, leading to inaccuracies in recorded values during digitization. This can result in discrepancies of 1 cm or more when using software packages.

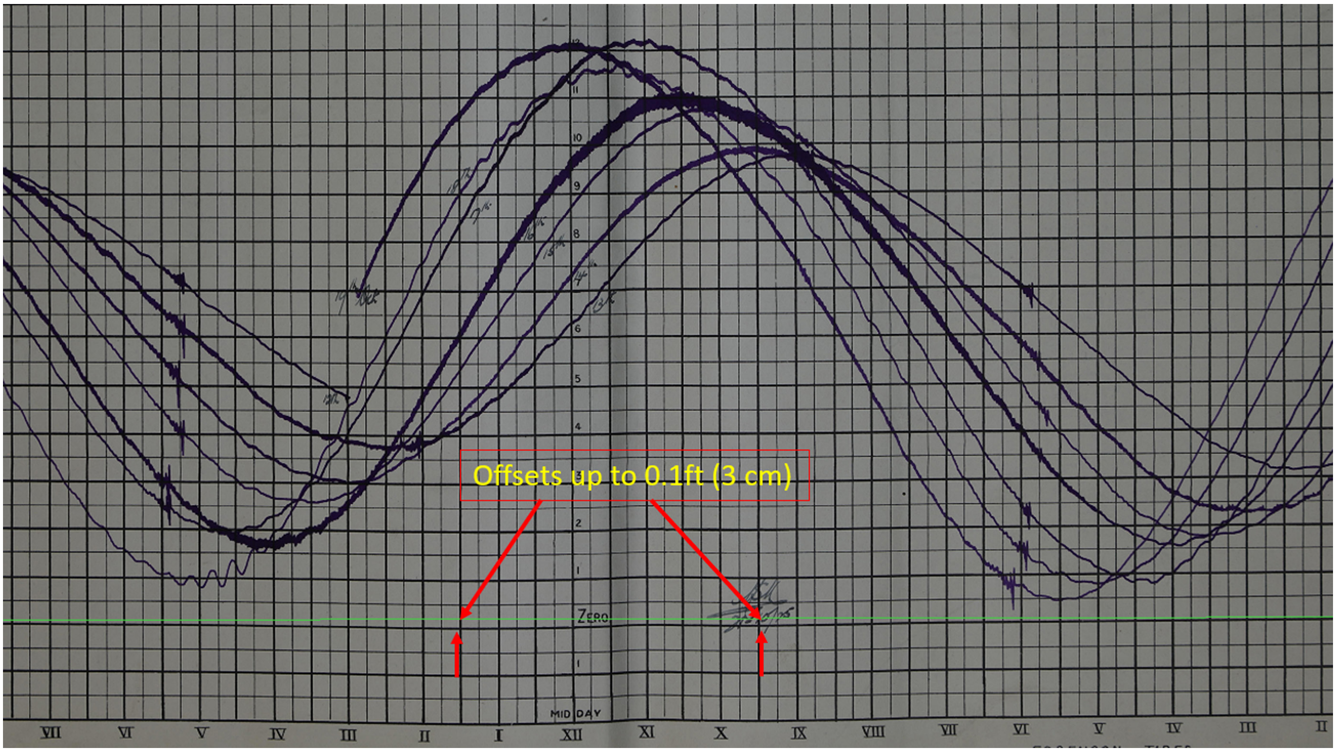

FIGURE 5 Green line straight across shows the offset of the marigram from the straight line showing that values would be off considerably in some places. (Note this is a different marigram than other image examples and is more zoomed in).

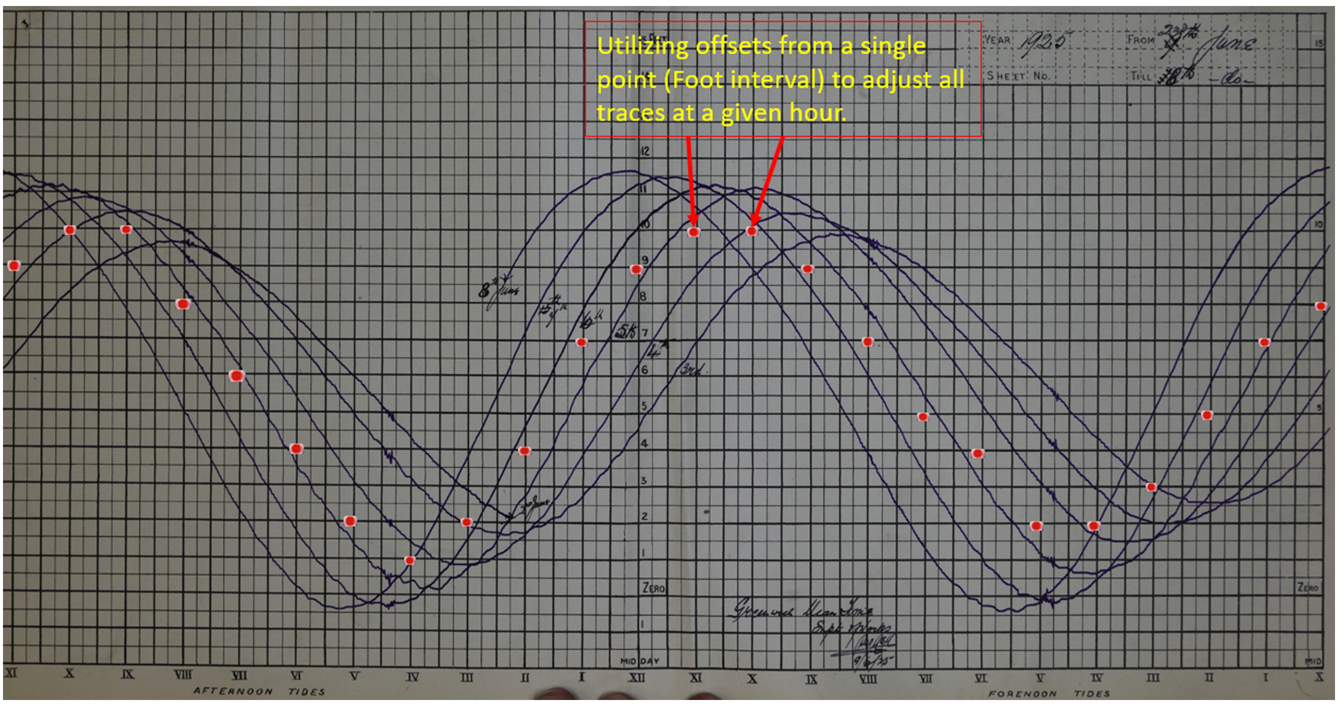

FIGURE 6 Demonstrates the Reduced Grid Approach, where a single point is placed at the midpoint (ft interval) of marigram traces per hour to offset discrepancies. However, this method may lead to reduced accuracy due to variations in offsets between upper and lower traces.

To correct skews, bends and distortions, the images were initially straightened and realigned using MATLAB®. Despite the apparent improvement, which gives the appearance of reduced tilts and skews, the actual value offsets recorded by WebPlotDigitizer in the initially distorted areas persisted in the realigned images. The persistence of value offsets despite the apparent improvement in image quality can be attributed to the inherent distortions present in the original images.

Using a reduced grid approach, a single point (selecting a ft interval in the middle of the traces) was placed at each hour on the image, adjusted to match the trace's value offsets for that hour (Figure 6). However, this method's accuracy may vary across the image; especially in areas with significant offsets such as the lower and upper traces. Despite its potential benefits for achieving overall accuracy within 10 mm in some cases and reducing digitization time, it may result in inaccuracies in hourly adjustments compared to other methods discussed.

To address these challenges, a new technique was developed. In this method, the underlying grid of the marigram is digitized at each hour by identifying the nearest ft interval in the grid (Figure 7). If the nearest ft interval was offset from its actual value, a correction would be applied. For example, if the trace at a given hour touched the 3-ft interval, but it was recorded as 3.09 ft in WebPlotDigitizer, the digitized values would need to be adjusted by 0.09 ft for that given hour. In some instances, using the nearest ft interval may not be possible due to a blur of ink trace or a distortion. In such cases, we use the ft interval that is closest. For example, if the trace falls between 3 and 4 ft, closer to 3 ft, but there is an issue, at 3 ft, such as a distortion or blur of ink trace, we would use the 4 ft point.

A flow chart (Figure 8) describes the entire approach. It begins with the digitization of traces, followed by capturing the grid values at each nearest ft interval for the given hour on the daily marigram traces, calculating offsets (recorded nearest ft less its actual ft) and so forth down to adjusting the digitized data for better accuracy. It is essential to digitize the underlying grid. This method involves applying adjustments to each digitized marigram by saving the relevant grid values associated with each marigram, and subsequently using these saved values to modify the digitized data.

2.4 | Data management and quality control

Quality flags were applied to identify and flag any erroneous data (UNESCO/IOC, 2020) arising from issues such as tide gauge stoppages or any bad data. All marigram images were thoroughly inspected and marigram traces with stoppages or loss of data, including big spurious thick lines often seen near clock stoppages, bad quality data with extremely faded traces or other possible errors were excluded. In some cases, there were minor clock stoppages

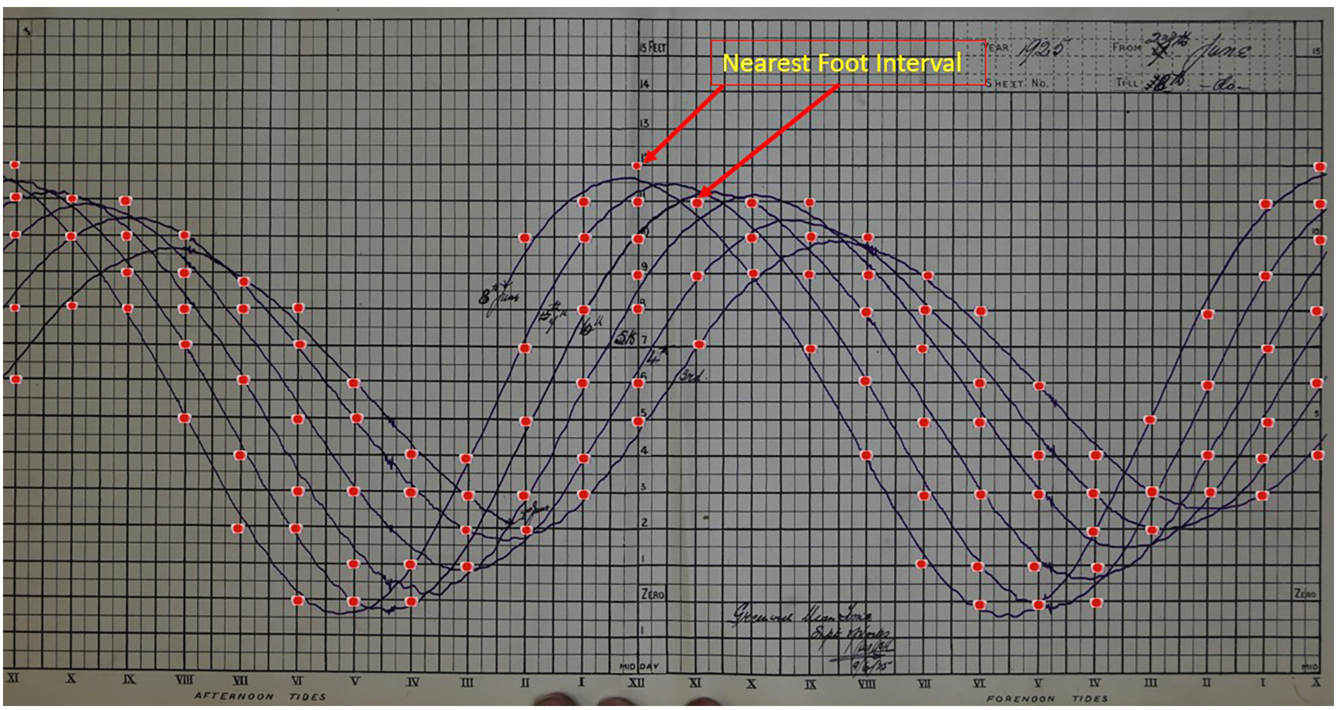

FIGURE 7 Digitizing the underlying grid of a marigram at each nearest ft interval for each hour is used to accurately estimate the value of the trace between two different ft intervals at the point intersecting the marigram trace.

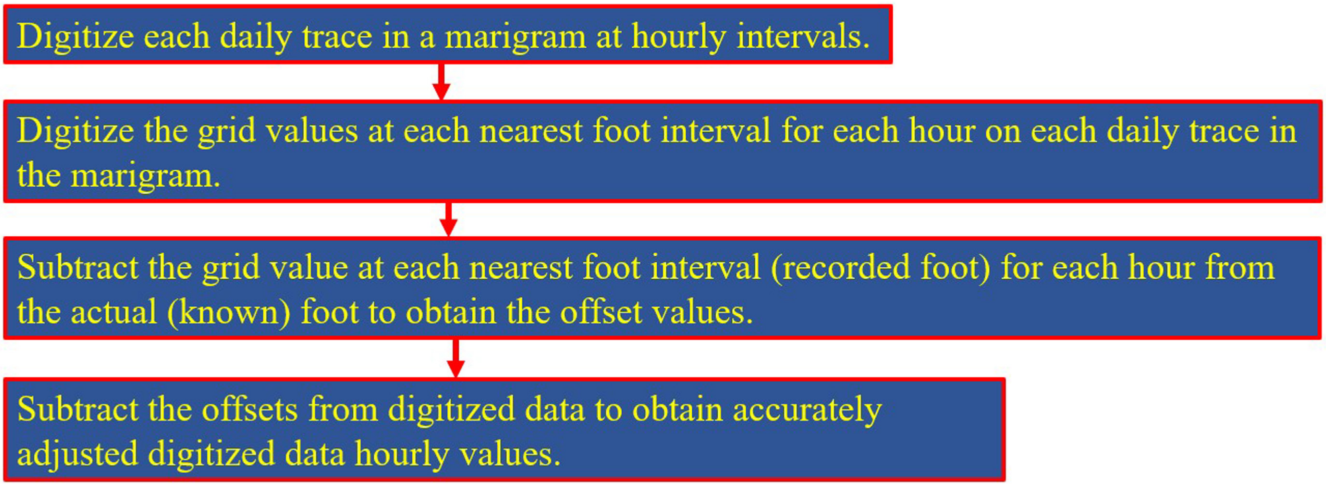

FIGURE 8 Simplified flow chart of the Methodology employed to accurately adjust marigram data.

with a broken pencil trace rejoining the trace. However, instances with stoppages, even if occurring only once during any hour, were generally excluded from the analysis. This exclusion was implemented due to the potential inaccuracies in recordings associated with these stoppages. Nevertheless, marigrams with small malfunctions in the pen trace, as long as they did not stop at the hourly intervals, were included. Checks were conducted to ensure that the continuing trace was not offset. Any trace which had data missing (sometimes on half day traces leading into a new marigram) was discarded if the trace did not touch any of the hourly intervals.

In some cases, marigrams with mostly bad data were entirely discarded. However, in many instances where at least some of the traces were noted as good quality even in poorer quality images, they were included in digitization. In some years, such as 1930, if a trace had a solid pencil trace joining a pen trace, and if the trace was shaped correctly overall, and provided the pencil trace did not predominate much of the trace, it was kept. Traces that exhibited irregular shapes, including abrupt changes or irregular patterns on marigrams, were discarded, as they may indicate data malfunctions. It was observed in a few marigram images where the end of a trace ended at the 14th hour and started on a new marigram at the 14th hour, there were offsets of over 0.5 ft. In one instance, for the 14th June 1926, it was observed that the 14th hour value was 9.78 ft, but where the 14th started on a new marigram its value was 10.54 ft, showing a significant offset between the marigrams of 0.76 ft. This is quite a substantial offset between the marigrams. In these cases, mainly the last value on the previous marigram was chosen as correct due to the presumed continuity of the data stream. The decision is informed by the potential for operational perturbations, such as drum changes or calibration inconsistencies, which may introduce variability in subsequent measurements. Thus, prioritizing the last recorded value on the preceding marigram aligns with the aim of minimizing the influence of such operational factors on data integrity.

TABLE 2 Number of days in each year digitized after quality approval check.

Year	Number of days
1925	288
1926	226
1927	222
1928	218
1929	299
1930	105
1931	232

In 1925, three distinct marigrams were available: one from the 02nd to the 09th of November, another from the 07th to the 14th of November, and a third from the 09th to the 16th of November. This availability of three marigrams during overlapping dates can be attributed to the need for re-recording and additional monitoring efforts aimed at improving data quality. Due to stoppages in some of the traces and instances of bad data, supplementary recordings were likely conducted to ensure comprehensive and reliable data collection. Notably, the first marigram exhibited malfunctions during the period of the 02nd to the 09th of November, with a thick spurious line detected on the 07th and incomplete missing data on the 08th and 09th. Only data from the 08th and 09th of November were utilized from the second image (covering 07th to 14th November), which shared overlapping dates. However, the third marigram, covering the period from the 09th to the 16th of November, was selected for use for the remaining traces due to the image's longer date span. In the common overlapping part of the second and third image traces, variations in the height of the trace for the 09th were observed.

There was no full year of data in any of the years concerned due to the data exclusion criteria and missing marigrams, resulting in days with good data. Table 2 summarizes the number of days in each year.

All digitized and quality-controlled marigrams were merged into a data file for their respective year. For the final quality check, one third of the marigrams were randomly re-digitized. Any offsets exceeding 5 mm between the original and repeat digitization's were subsequently adjusted with the re-digitized data. Both the unadjusted data and data adjusted for offsets were analysed for consistency and accuracy.

2.5 | Datum conversion of data

The adjusted digitized data for 1925–1931 were converted from ft to m (metres) and adjusted to ODM (Ordnance Datum Malin). CD (Chart Datum) was 1.75 ft above OD (Ordnance Datum Dublin) (ODD) (Figure 9). Notably, ODD is 2.722 m below ODM (Personal communication from the Office of Public Works—OPW). Data were corrected to factor in the 2.722 m difference. The adjusted digitized data were converted to m (metres), and the difference between ODM (2.722 m) and CD (1.75 ft converted to metres) was subtracted from the adjusted digitized data.

2.6 | Data validation

To validate the adjusted digitized data, we conducted an analysis of tidal constituents, with a particular focus on the predominant M2 component (Pugh & Woodworth, 2014). The Amplitude (m) and Phase Lag (°) were extracted for the M2 component using the oce Package in R, a specialized tool for oceanographic tidal analysis (Kelley et al., 2022). The Greenwich Phase Lags are calculated using the Oce package in R. The analysis covered all months for each year, except for several exceptions. In 1926, April was excluded due to significant data gaps. In 1927, December was discarded due to substantial data loss. In 1931, February, March and December were excluded due to large data gaps. The year 1930 was omitted from the analysis because it only contained 105 days of scattered data, making it unsuitable for calculating M2 (Amplitude and Phase Lag). Only 1925 and 1929 had the M2 calculated based on data from all their months. Additionally, the Dun Laoghaire Harbour data recorded in 1842 and 2014 underwent the same Amplitude and Phase Lag calculations using the oce package to provide a basis for comparison with the 1925–1931 data. The M2 calculations (using the oce package) were carried out on the data converted to m (metres) at ODM, ensuring consistency in units and reference datum for the analysis.

3 | RESULTS

3.1 | Examining the unadjusted and adjusted data (pre-ODM and ODM conversion) and the adjusted digitized data post ODM conversion

The offsets between digitized (unadjusted) and adjusted digitized data, in feet relative to CD (Chart Datum), and the adjusted digitized data, converted to ODM (Ordnance Datum Malin), are summarized in Table 3. The most significant differences occur in the years 1927–1929, with each year exhibiting an offset exceeding 13 mm between the digitized and adjusted data. Notably, in 1928, the largest deviation of 13.716 mm was observed. Conversely, 1926 shows a modest offset within the 10 mm accuracy range. In 1931, an outlier stands out with an adjusted MSL increase of just under 4 mm, deviating from other years. The years 1925 and 1930 closely approach the 10 mm offset, falling just over 0.5 mm short. Treating 1931 as an exception and averaging offsets for 1925–1930 reveals an average offset exceeding 10 mm. These results highlight that unadjusted, digitized data may often exhibit a significant offset beyond the 10 mm accuracy range. Table 3 outlines the MSL relative to m (metres) at ODM for each year (using the adjusted digitized data), representing the adjusted sea level data converted to ODM.

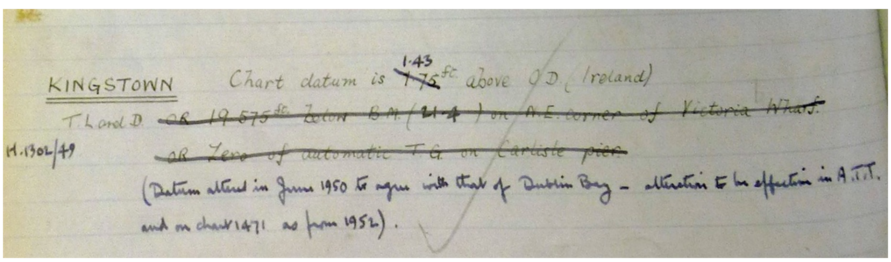
KINGSTOWN Chart datum is ~~1.75~~ 1.43 ft. above O.D. (Ireland)
T.L. and D. ~~OR 19.575 ft. below B.M. (21.4) on N.E. corner of Victoria Wharf.~~
H.1302/49 ~~OR Zero of automatic T.G. on Carlisle pier.~~
(Datum altered in June 1950 to agree with that of Dublin Bay – alteration to be effective in A.T.T. and on chart 1471 as from 1952).

FIGURE 9 Dun Laoghaire (formally known as Kingstown) Ledger provides the CD height of 1.75 ft above OD/ODD Ireland pre-1950. Value was adjusted to 1.43 ft post 1950.

TABLE 3 Comparison of Yearly MSL values pre-ODM conversion (unadjusted and adjusted data) and converted to ODM for the adjusted data only.

Year	Digitized MSL (ft)	Adjusted MSL (ft)	Difference (ft)	Difference (mm)	Adjusted MSL converted to ODM (m)
1925	6.488	6.457	0.031	9.449	−0.221
1926	6.604	6.583	0.021	6.401	−0.182
1927	6.529	6.485	0.044	13.411	−0.212
1928	6.642	6.597	0.045	13.716	−0.178
1929	6.399	6.355	0.044	13.411	−0.252
1930	6.496	6.465	0.031	9.449	−0.218
1931	6.516	6.529	−0.013	−3.962	−0.199

TABLE 4 Shows the Amplitude and Phase Lags of Dún Laoghaire data (1930 excluded due to poor data availability).

Year	Amplitude (m) M2	Phase lag (°) M2
1842	1.27	323.1
1925	1.31	325.6
1926	1.30	327
1927	1.30	326.5
1928	1.26	327.4
1929	1.26	326.3
1931	1.25	324.9
2014	1.36	325.2

Note: No Nodal adjustments made to this data.

3.2 | Validation of tidal data

The M2 Amplitudes and Phase Lags for Dún Laoghaire, spanning from the initial survey in 1842 to the latest available data in 2014, are summarized in Table 4 (1930 excluded due to poor data availability). Notably, during the years 1925–1931, the Amplitudes showed close agreement, with a standard deviation of 0.03 m. The Phase Lags also demonstrated consistency, characterized by a standard deviation of 0.9°.

The Amplitudes and Phase Lags for the initial and latest survey years (1842 and 2014) closely align with the 1925–1931 data. All yearly Amplitudes fall within the range of 1.25–1.36 m, and Phase Lags range from 323.1° to 327.4°. When amalgamating the entire dataset (1842, 1925–1931 and 2014), the Amplitude standard deviation is 0.04 m, and the Phase Lags standard deviation is 1.4°, reinforcing the consistent nature of tidal characteristics over time.

4 | DISCUSSION OF RESULTS

The results of this paper highlight the significance of accurate marigram digitization, revealing potential offsets of up to 14 mm. Notably, in the years 1926 and 1931, only modest offsets were observed, well within the 10 mm accuracy (Intergovernmental Oceanographic Commission (IOC), 2012). Regarding the adjusted digitized data, it is crucial to note that without corrections, the results would exhibit many offsets, some exceeding 13 mm, immediately altering the data by nearly 10 mm. Three years (1927–1929) out of the seven had offsets exceeding 13 mm, while 1925 and 1930 were just over 0.5 mm short of reaching the 10 mm threshold. Examining rates of change over time, offsets of 10 mm or more could distort the data values and compromise accuracy.

Consideration may be given to employing a reduced grid approach, assigning a single-point value to adjust for all trace offsets at a given hour, as outlined in the methodology (Figure 6). While this approach would be less labour-intensive, it comes at the cost of potentially mis-scaling many adjusted values, given that the trace values on the upper and lower bounds of the image would differ and may not always result in overall offsets within 10 mm. Regardless of the quality of the marigrams, whether utilizing an automated digitization tool package (Pons et al., 2016) or a manual point-based digitization method, both approaches necessitate the readjustment of values to ensure accuracy. The findings presented in this study emphasize the significance of this process. Even software packages capable of adjusting image tilts cannot eliminate inherent hidden distortions in marigram images, significantly impacting the accuracy of data values.

The close alignment of M2 Amplitudes and Phase Lags across the 7 years of adjusted digitized data signifies stability in the timing and magnitude of tidal variations. The small Amplitude standard deviation of 0.03 m during 1925–1931 indicates minimal variability, emphasizing the reliability of these values. Similarly, the standard deviation of Phase Lags, approximately 0.9°, though relatively small, indicates a close proximity of Phase Lag values to the mean. When considering data from 1842, 1925–1931 and 2014 together, the Amplitude standard deviation of 0.04 m and a Phase Lags standard deviation of 1.4° illustrate the consistency in the nature of tidal characteristics. However, the 1842 comparison data covers late June to August, spanning parts of both months, suggesting potential complexities in interpreting its Phase Lag and Amplitude. These findings highlight the consistency of tidal patterns over the studied years, illustrating that the data aligns well together.

When comparing the Dun Laoghaire Harbour data with available Belfast Harbour data, notable similarities emerge in the daily averages (Figure 10). Visual examinations reveal consistent positive peaks of daily averages. These peaks are observed concurrently throughout various months in both Belfast Harbour and Dun Laoghaire Harbour datasets. Similarly, smaller negative peaks align temporally in each year for both locations. The remarkable consistency in the frequency of occurrences across the datasets is particularly significant. While the geographical separation between Dun Laoghaire Harbour and Belfast Harbour introduces some differences in peak occurrences, the Dun Laoghaire Harbour data exhibits similar patterns each year, albeit with more data gaps.

The correlation coefficient of 0.715 between the water level data (daily averages) from Dun Laoghaire Harbour and Belfast Harbour (Figure 11) indicates a strong relationship between the observations at these two locations. This high correlation suggests that fluctuations in water levels at one site reliably correspond to those at the other. However, it's worth noting that while the correlation is strong, there may be instances of scatter in high water levels, indicating some degree of variability. This variability could be influenced by factors such as tidal patterns, weather events or local geography (Orford & Murdy, 2015; Woodworth, 2010). Nevertheless, the significant correlation highlights the overall coherence and synchronicity of water level patterns between the two harbours, reinforcing the reliability and consistency of the recorded data across both locations.

The adjusted digitized data from Dun Laoghaire Harbour were compared with surveys conducted in 1842 and 2014 within the same harbour. Additionally, comparisons were made with the Dublin Port Mean Tide Level (MTL) dataset spanning from 1938 to 2016 (Shoari Nejad et al., 2021), and with Howth MSL data from The Marine Institute covering the years 2007–2018. The observed values align with a reported rise in annual mean sea level, as illustrated in Figure 12, with a linear trend represented by a dashed line, with the grey envelope indicating the variability in the data. On average, there is an increase of around 1.5 mm/year. It is worth noting that some years in the Dublin Port dataset do not fit with a rise in sea level, as previously reported (Shoari Nejad et al., 2022). However, a detailed discussion on the issues and variability in this data is beyond the scope of this paper. The Howth data also indicates a rise in sea level when compared with Dún Laoghaire and Dublin Port data.

5 | POTENTIAL DATASET USE AND LIMITATIONS

5.1 | Dataset use

The yearly adjusted Mean Sea Level (MSL) values for 1925–1931 in Dún Laoghaire exhibit significant variability. The absence of months in some years may skew annual averages, especially for spring, autumn or winter months, affecting yearly MSL calculations. Due to data quality issues and missing records, calculating MSL on a full year, as recommended by PSMSL (2023), was not always possible.

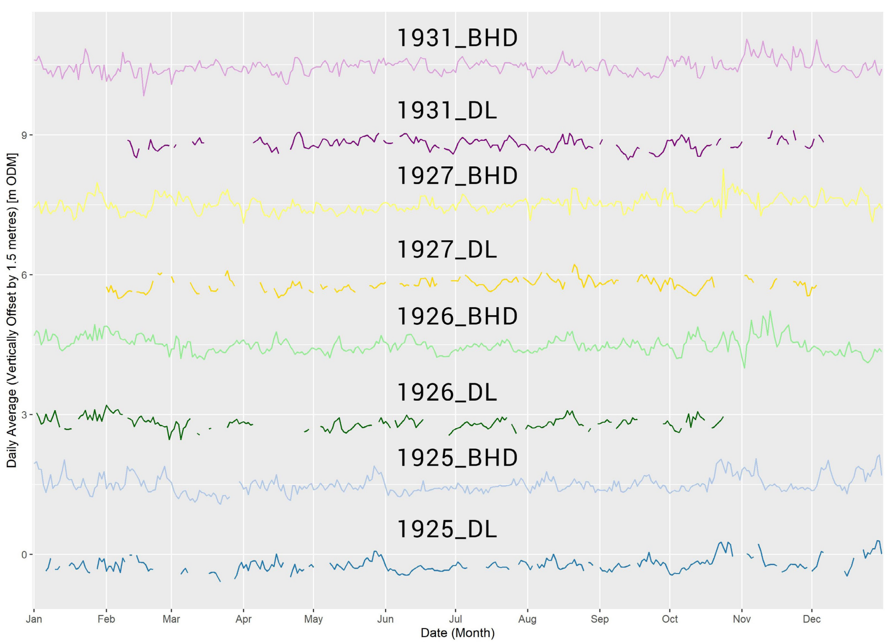

FIGURE 10 Shows daily average water levels for Dún Laoghaire Harbour (DL) and Belfast Harbour (BHD) comparisons, with each yearly record vertically offset by 1.5 m for visualization. Records from 1928 to 1930 are missing for Belfast Harbour.

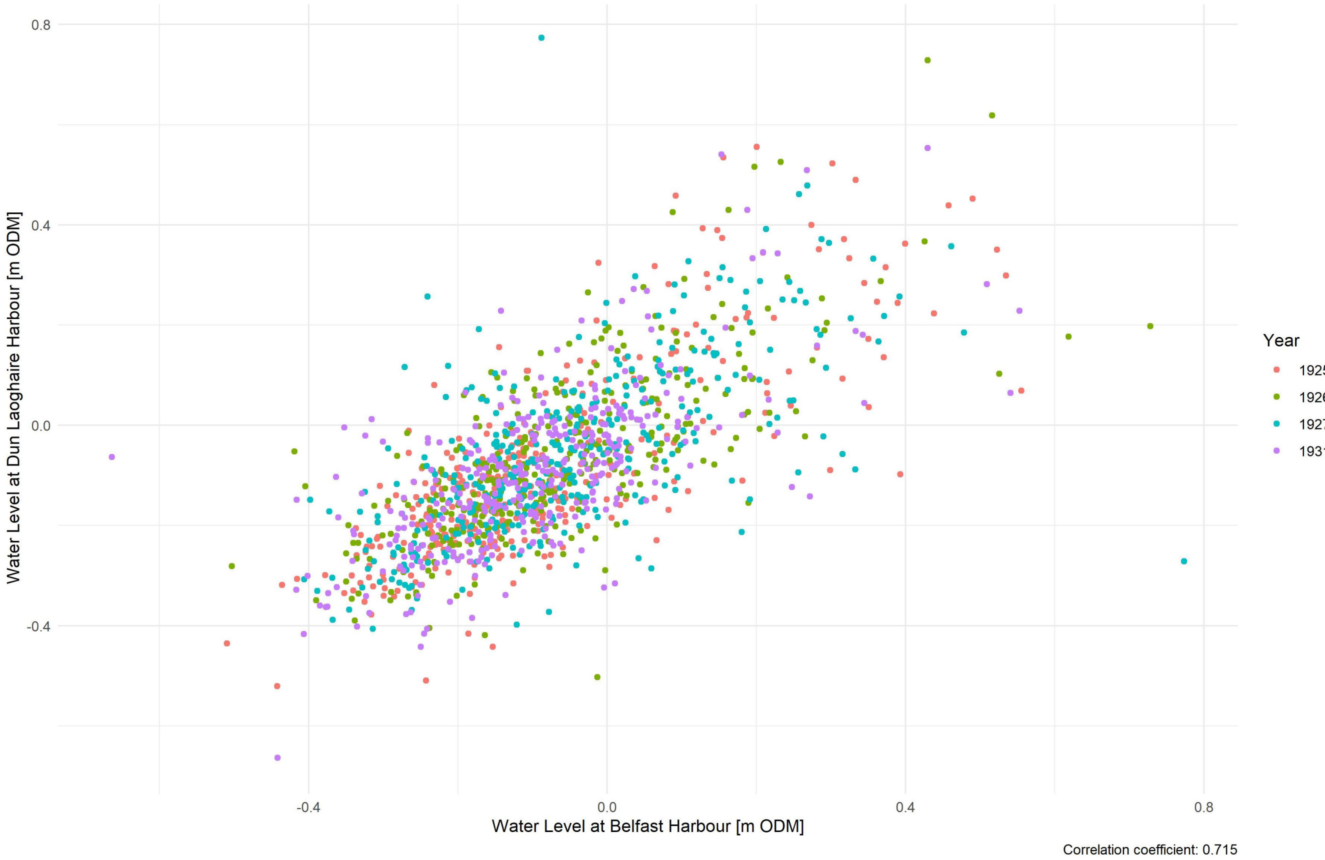

FIGURE 11 Presents a combined plot of water levels (daily averages) for Dun Laoghaire Harbour and Belfast Harbour, showing a strong correlation coefficient of 0.715 between the two locations. However, there is notable scatter among the high waters.

However, for the focus of accurate digitization in this paper, this limitation is acceptable. Notably, 1925 and 1929 provide the most complete data, representing lower MSL levels. This suggests potential for further investigation, including breaking down the data into smaller time series for seasonal or monthly analyses, as demonstrated by Pugh et al. (2021) in a similar context. The protocol for discarding traces with missing data prioritized quality standards, focusing on severe fading or thick lines indicative of errors. For future work, consideration could be given to interpolating discarded daily traces with gaps where possible, potentially increasing the number of data points in the time series and enabling more comprehensive analyses. The data generated in this methodological paper can be utilized for additional tidal analysis and more accurate estimations of sea level rise in Dublin from historic times.

5.2 | Limitations of dataset

Issues that are commonly associated with tide gauges include instrumentation error (Lennon, 2015). Additionally, problems such as blur, accuracy, time gaps, missing data, bad data, clock errors and datum errors are commonly associated with marigrams (Latapy et al., 2022). The marigram recording instrumentation is prone to error, and the actual value may not always be centred within the line thickness, particularly when the pen wears down. Many of these issues occur in the Dún Laoghaire dataset. It must be noted there is a limit to the accuracy in digitizing the marigrams and performing adjustments regardless of what technique is used will not remove the inherent sources of instrumentation error such as potential inaccurate recordings (caused by the changing of the drum) which we have not addressed in this paper. The year 1930 is an exception. Due to its small and sporadic timeseries, it should be treated with caution as there was much bad data and numerous stoppages. There are also some distortions in the image where even using the nearest ft to correct small offsets can remain. Where bad distortions occur, usually on the lower bounds of some images (where lens distortions often occur), the values may correct themselves in the middle of the given ft. While this would mean the offset adjustment could alter the actual value in some cases, it would not be enough to significantly impact the accuracy of the data. However, this point needs to be noted. The accurate digitization of these records is time-consuming. Overall, it can take up to 6 days to process a year of data:

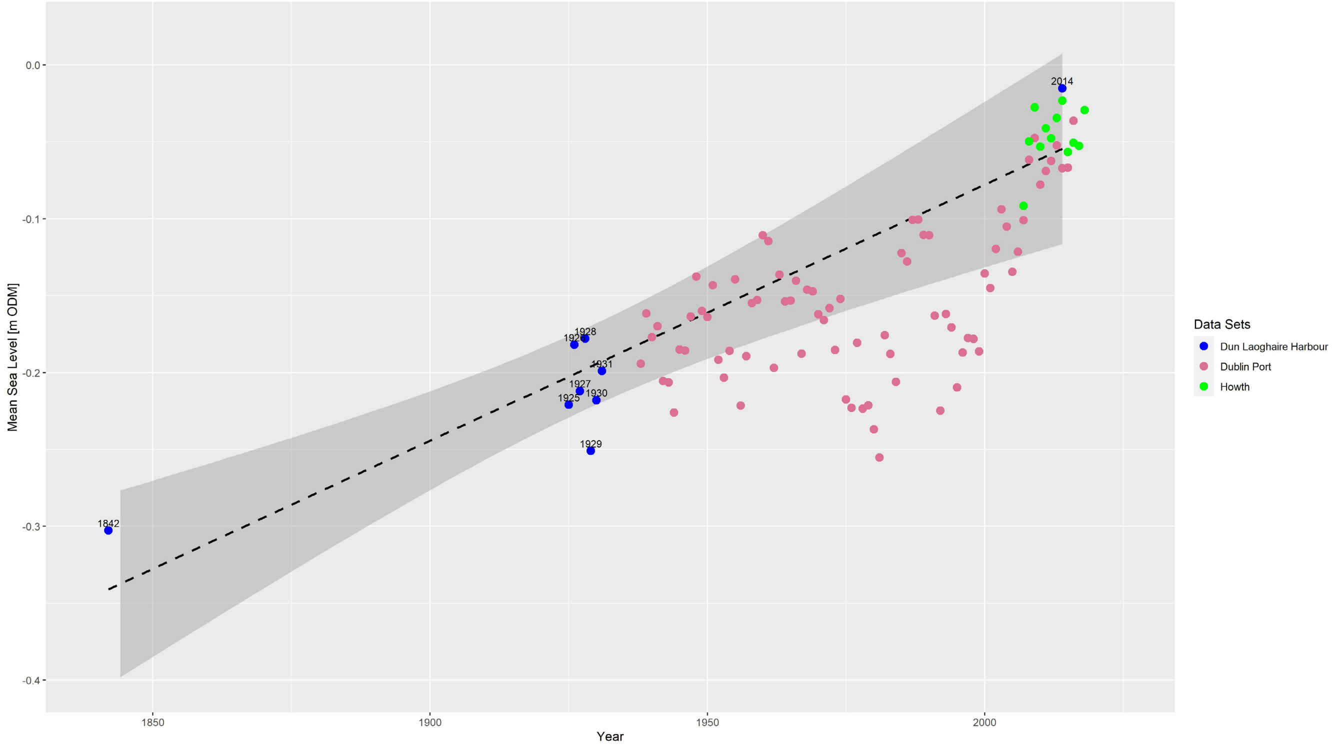

FIGURE 12 Adjusted (digitized data) annual MSL values for Dún Laoghaire Harbour (1925–1931), 1842 and 2014, compared with Dublin Port data (1938–2016) and Howth data (2007–2018). Dashed line: linear trend; Grey envelope: data variability.

two to 3 days for digitizing (excluding digitizing the underlying grid values for adjustment) and another 3 days for digitizing the grid values for adjustments.

6 | DATASET ACCESS

The data are freely available from the open access PANGAEA data publisher (https://doi.org/10.1594/PANGAEA.967078) (McLoughlin et al., 2024). The dataset comprises three main levels of data. Level 0 contains compressed zip files with raw marigram images from 1925 to 1931, organized into subfolders for Good_Quality_Images and Poor_Quality_Images. These separate the good and poor-quality images. Level 1 provides digitized data for each year in a compressed zip file, featuring Excel files (named for each year) with columns for hour (representing the time each point is digitized), height (in ft relative to CD) and datetime. These files, suffixed with '_DL_Digitized', contain raw digitized data without adjustments to hourly intervals. Level 2 presents adjusted data in a compressed zip file (with a structure similar to level 1), where values have been corrected for offsets by subtracting the nearest ft grid values from known ft values. Each adjusted data file (year), suffixed with '_DL_Adjusted', includes columns for hour (representing the time of measurement), height (in ft relative to CD) and datetime, the height values are adjusted for offsets ensuring accuracy within 10 mm (1 cm). Additionally, the Grid_Values zip (folder) contains yearly Excel files with columns for hour (representing the time of measurement), recorded foot interval, actual foot interval, offsets and datetime. Although not one of the main levels, this data is crucial for ensuring the overall accuracy of the adjusted data.

7 | CONCLUSION

The aim of this methodological paper was to bring the accuracy of the marigram data within 10 mm (1 cm), which has been achieved. We have effectively digitized 7 years of data from paper marigrams in Dun Laoghaire Harbour, Ireland, covering the period from 1925 to 1931 at hourly intervals. A methodology has been developed based on freely available open-source software, enabling point-based digitization of the marigram traces. A method of adjustments was developed to correct for distortions in the underlying images. Finally, the adjusted digitized data was converted to m (metres) at ODM. The recovered data is consistent with an overall rise in sea level.

The final data was validated by:

1. Local tidal Amplitudes in Dun Laoghaire Harbour, Dublin, ranged from 1.25 to 1.36 m, with Phase Lags ranging from 323.1° to 327.4°.
2. Daily MSL values from another tide gauge in Ireland, for common years (1925–1927 and 1931) exhibited

remarkably similar patterns, with almost identical peaks and troughs.

3. Annual MSL values in the Dublin region, after adjustment and correction, aligned with data from other sources, demonstrating an annual sea level rise of around 1.5 mm.

These validations reinforce the reliability of the adjusted digitized marigram data and support the evidence for a continuous sea level rise in the region.

AUTHOR CONTRIBUTIONS

Patrick J. McLoughlin digitized the data and wrote the manuscript. Gerard D. McCarthy also provided additional data for comparison. Gerard D. McCarthy, Glenn Nolan, Rosemarie Lawlor and Kevin Hickey all played roles in refining the paper draft by providing suggestions and improvements.

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CONFLICT OF INTEREST STATEMENT

The authors declare they have no conflict of interest in relation to this work undertaken.

DATA AVAILABILITY STATEMENT

The data associated with this paper is accessible from the Pangaea data repository at (https://doi.org/10.1594/PANGAEA.967078).

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