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Key Points:

- Artifacts and aliasing in repeat leveling can result from systematic errors, surveying inconsistencies, and seasonal ground motion
- Rigorous field procedures and careful timing of repeat surveys are needed to avoid misinterpretation of derived vertical land motion
- Historical leveling provides some constraint on the linear extrapolation of vertical land motion derived from contemporary time series

Supporting Information:

- Supporting Information S1
- Data Set S1
- Figure S1
- Table S1

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On the Use of Repeat Leveling for the Determination of Vertical Land Motion: Artifacts, Aliasing, and Extrapolation Errors

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Abstract Leveling remains the most precise technique for measuring changes in heights. However, for the purposes of determining vertical land motion (VLM), a time series of repeat leveling measurements is susceptible to artifacts and aliasing that may arise due to systematic errors, seasonal surface fluctuations, motions occurring during a survey, and any inconsistencies in the observation conditions among epochs. Using measurements from 10 repeat leveling surveys conducted twice yearly along a profile spanning ~40 km across the Perth Basin, Western Australia, we describe the observation, processing, and analysis methods required to mitigate these potential error sources. We also demonstrate how these issues may lead to misinterpretation of the VLM derived from repeat leveling and may contribute to discrepancies between geologically inferred rates of ground motion or those derived from other geodetic measurement techniques. Finally, we employ historical (~40-year-old) leveling data in order to highlight the errors that can arise when attempting to extrapolate VLM derived from a geodetic time series, particularly in cases where the long-term motion may be nonlinear.

1. Introduction

Geodetic leveling is a land surveying technique that can determine height differences accurate to a few millimeters over tens of kilometers (e.g., Bomford, 1971, p. 246; Torge & Müller, 2012, p. 218; Vaníček et al., 1980). Repeat leveling provides a time series of heights from which vertical land motion (VLM) can be derived and subsequently interpreted with respect to geodynamic, geophysical, and anthropogenic processes. Prominent applications include crustal deformation monitoring (e.g., Amoruso et al., 2005; D'Anastasio et al., 2006; Kostoglodov et al., 2001; Schlatter et al., 2005), measuring glacial isostatic adjustment (e.g., Kall et al., 2014; Koohzare et al., 2008; Mäkinen & Saaranen, 1998), the estimation of land subsidence due to the withdrawal of subsurface fluids or gasses (e.g., Chi & Reilinger, 1984; Hsu et al., 2015; Liu & Huang, 2013), volcanology (e.g., Dzurisin et al., 2002; Lanari et al., 2004; Poland et al., 2017), and natural disaster monitoring (e.g., Albattah, 2003; Dobrovolsky, 2006; Rikitake, 1972). Although continuous Global Positioning System (GPS) measurements provide a higher temporal sampling (e.g., daily solutions), and interferometric synthetic aperture radar (InSAR) provides a greater spatial coverage and resolution, leveling remains the most precise method for measuring height differences (e.g., Fuhrmann et al., 2015; Guglielmino et al., 2011; Kall et al., 2016) and usually provides the longest temporal coverage due to the availability of historical measurements that can date back more than 100 years in some countries (e.g., Bilham, 2001; Giménez et al., 2000; Kooi et al., 1998). Consequently, repeat leveling is now commonly utilized in multisensor programs for the measurement of VLM (e.g., Aobpaet et al., 2013; Tizzani et al., 2015; Vestøl, 2006).

Leveling observations, as with all geodetic measurements, are subject to systematic errors (e.g., Bomford, 1971, ch. 3.06; Entin, 1959; Kukkamäki, 1980). These typically have a small magnitude and can be masked by random error, but if allowed to accumulate over long distances they may degrade the quality of subsequent VLM interpretations (e.g., Vaníček et al., 1980). Seasonal fluctuations in ground height can also bias the interpretation of repeat leveling data if not properly separated from the secular VLM. These seasonal motions can result from the swelling and contraction of expansive soils in response to precipitation (e.g., Demoulin, 2004; Masia et al., 2004; Vittuari et al., 2015), the cycle of aquifer drawdown and recharge (e.g., Bawden et al., 2001; Bell et al., 2008; King et al., 2007), elastic deformation of the ground surface due to changes in mass loading (e.g., Lambert, 1970; Tazima et al., 1984; van Dam et al., 2001), and additional factors of a thermal or hydrodynamic origin (e.g., Dong et al., 2002; He et al., 2017;

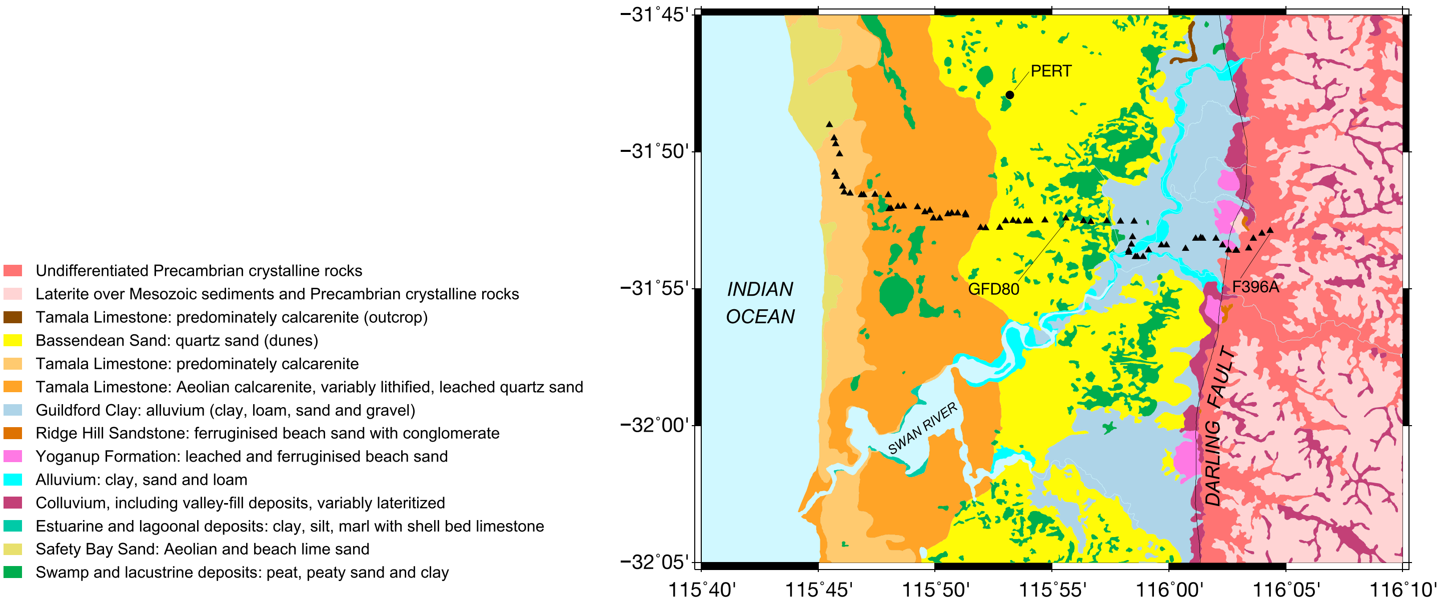

Figure 1. Location of the repeat leveling profile across the Perth Basin, Western Australia. Benchmarks are represented by black triangles, and the IGS station PERT by a black circle. Surface geology data digitized from Davidson (1995).

van Dam & Wahr, 1998). Artifacts may also be introduced into a time series of repeat leveling by changes in surveying instrumentation or field practices, or by any ground motion that occurs between the observations constituting a discrete measurement epoch. These potential error sources may contribute to the discrepancies observed between leveling and geologically inferred VLM (e.g., Amighpey et al., 2016; Brown & Oliver, 1976; Demoulin, 2004), or to discrepancies between leveling and other geodetic measurements such as sea level records, continuous GPS, and InSAR (e.g., Ekman, 1996; Hung et al., 2010; Lubitz et al., 2013).

In this paper, we review the numerous sources of artifacts and aliasing that can be introduced into a time series of repeat leveling measurements and demonstrate how these may be misinterpreted in the study of VLM. In doing so, we also outline the observation, processing, and analysis methods required to obtain more accurate VLM estimates from repeat leveling. Our analyses make use of a campaign of repeat high-precision two-way leveling data from a ~40 km profile across Perth, Western Australia (Figure 1), surveyed twice yearly in 10 epochs between 2012 and 2017. Previous GPS- and InSAR-based determinations of VLM in the Perth Basin show it to be small-magnitude subsidence (associated with groundwater extraction) in the order of 3–7 mm/year with a seasonal signal of ~4 mm amplitude (Featherstone et al., 2012, 2015; Parker et al., 2017). We also analyze historical (~40-year-old) leveling data in order to estimate VLM in the Perth Basin over a longer period of time, and to investigate the errors that may arise through linear extrapolation of geodetic time series.

2. Measurement of VLM Using Repeat Leveling

We use our case study over the Perth Basin to outline the methodology required to measure VLM from repeat leveling, including the application of systematic error corrections and least squares adjustment, the identification of artifacts in the time series, and the use of maximum likelihood estimation (MLE) to parameterize the motion across a profile of benchmarks.

2.1. Corrections for Systematic Errors

Leveling measurements are susceptible to a wide range of systematic error sources, and the first approach to mitigating these errors is to maintain strict adherence to recognized standards and practices during all field surveys (e.g., Federal Geodetic Control Committee, 1984, ch. 3.5; Intergovernmental Committee on Surveying and Mapping, 2007, ch. 2.4).

Level staff scale errors and those due to thermal expansion cannot be eliminated by field practices and so require deterministic corrections (e.g., Craymer et al., 1995; Rüeger, 1997, 2003, p. 40). The correction parameters for the invar staves employed in our repeat leveling campaign were determined in a laser interferometry calibration at the Geodetic Laboratory of the Technical University of Munich, Germany.

To account for any small discrepancies between backsight and foresight lengths, a collimation correction derived from daily “two-peg” tests was applied automatically by the Leica DNA03 digital leveling instrument used in our survey campaign. The correction for Earth curvature (given in any land surveying textbook) was also applied to the data, although this accumulated to a maximum of ~0.5 mm over the full ~40 km length of the profile.

Atmospheric refraction is considered the most complex source of systematic error affecting leveling observations (e.g., Angus-Leppan, 1979; Breznikar & Aksamitauskas, 2012; Holdahl, 1981; Kukkamäki, 1938, 1939; Shaw & Smietana, 1983; Skeivalas, 2005; Stein et al., 1986; Strange, 1981). The variability of atmospheric conditions within and between each epoch of a repeat leveling campaign has the potential to introduce artifacts into the resulting time series. Angus-Leppan (1979) developed a refraction correction model that relates vertical temperature gradients to other observable meteorological parameters by estimating the heat flux near the Earth’s surface (cf. Holdahl, 1981), thus eliminating the need for multiple temperature measurements along the level staff as required in other correction models. The Angus-Leppan (1979) correction was applied to all observations collected during our repeat leveling campaign, utilizing the “unstable atmosphere” version, which is most appropriate for daytime observations, and the flat-terrain approximation. The sloped-terrain version of the correction (cf. Filmer et al., 2009) was not applied in this study as Filmer (2010, ch. 4) showed the difference to be negligible across the Australian continent. All requisite local meteorological parameters were recorded during the field surveys.

Due to the nonparallelism of equipotential surfaces of the Earth’s gravity field, leveled height differences are path-dependent (e.g., Heiskanen & Moritz, 1967, ch. 4), a manifestation of the so-called holonomity problem (Sansò & Vaníček, 2006). Dynamic heights have the same characteristics as geopotential numbers and thus overcome the holonomity problem, but through scaling by normal gravity they are assigned the more intuitive units of length (e.g., Featherstone & Kuhn, 2006). All measurements collected in our repeat leveling campaign were converted to dynamic height differences using gravity observations collected at each benchmark in 2015 (Schack et al., 2018), and GRS80 normal gravity (Moritz, 1980) calculated for the mean latitude of the profile. This proved to have a negligible impact on the derived VLM as the same route was leveled in all epochs (see the further discussion in section 3.3), although repeat gravimetry was not observed concurrently with the repeat leveling (cf. Heck & Mälzer, 1983; Wellman & Tracey, 1987) because measurement noise swamps the small subsidence signal in the Perth Basin (Featherstone et al., 2012).

Corrections were not applied to account for the tidal influence of the Sun and Moon on the equipotential surfaces of the Earth’s gravity field (e.g., Jensen, 1950). While these errors have a maximum possible effect of ~0.08 mm per kilometer leveled, they are azimuth-dependent and may be considered negligible over our predominately east-west oriented profile (e.g., Bretreger, 1986; Vaníček & Krakiwsky, 1986, p. 599). Furthermore, we did not apply corrections for the systematic accumulation of discrepancies between forward and reverse measurements (cf. Giménez et al., 2000; Kall & Jürgenson, 2008; Kostoglodov et al., 2001), as we attribute this observation to equipment settlement/rebound errors that are effectively eliminated in the mean of the two-way measurements (e.g., Bomford, 1971, p. 240; Craymer & Vaníček, 1986; Rüeger, 2003, p. 46; Torge & Müller, 2012, p. 218).

Figure 2a shows the accumulated total of all systematic error corrections applied to each survey in our repeat leveling campaign (staff scale calibration, staff thermal expansion, Earth curvature, atmospheric refraction, and gravity), with refraction accounting for the most significant proportion (average ~87%). As evident in the correlation with topography (Figure 2b), refraction and staff errors are slope-dependent (e.g., Bomford, 1971, p. 240; Jackson et al., 1980). We performed a similar analysis to that of Stein (1981) and identified no significant correlation to suggest the presence of any such slope-dependent errors after having applied the corrections described above. Note that large systematic errors in the Austral spring 2013 survey (red line in Figure 2a) are attributed to the use of fiberglass level staves and extended sight lengths of up to 80 m during conditions of higher temperatures than the other Austral spring surveys (see the further discussion in section 2.3).

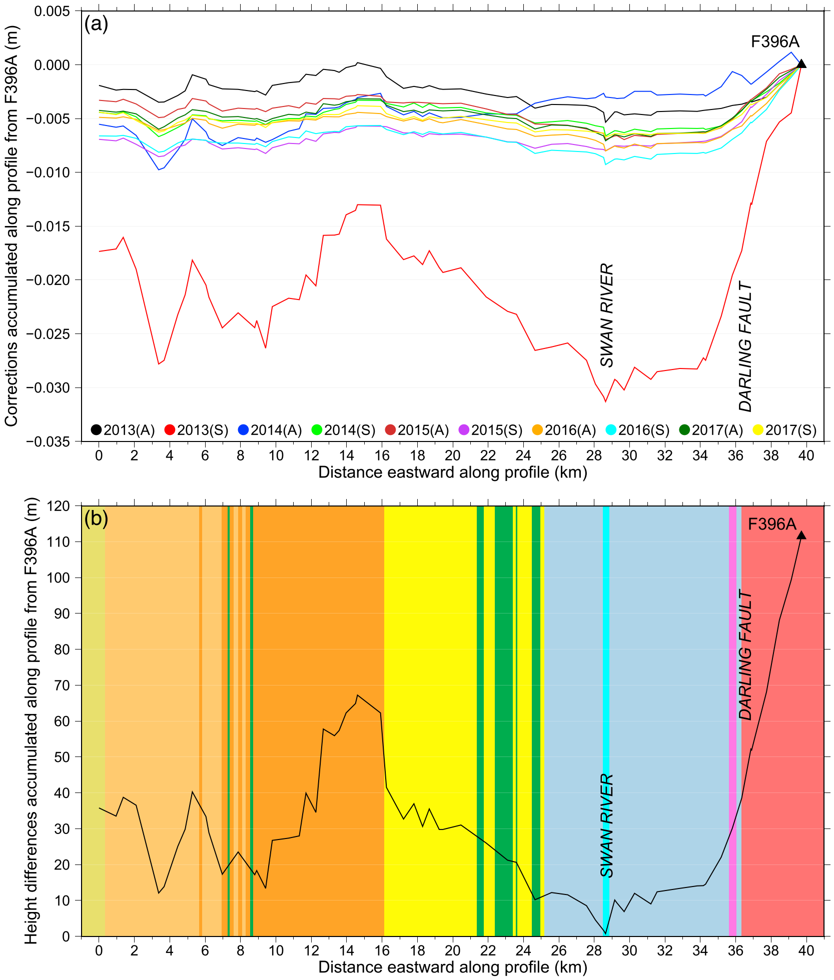

Figure 2. (a) Cumulative sum of all systematic error corrections (staff scale calibration and thermal expansion, Earth curvature, atmospheric refraction, and gravity) applied to the repeat leveling surveys across the Perth Basin. Survey times are denoted Austral autumn (A) and Austral spring (S). (b) Elevation along the repeat leveling profile (heights above mean sea level), with surface geology regions as per Figure 1.

2.2. Adjustment of Leveling Data

For each survey in our repeat leveling campaign, the forward and reverse height differences were measured between all adjacent benchmarks along the profile in Figure 1. After applying corrections for systematic errors (section 2.1), each survey was least squares adjusted using the public-domain software SNAP (Land Information New Zealand; http://www.linz.govt.nz/data/geodetic-services/download-geodetic-software), with the benchmark F396A held fixed in each case (location shown in Figure 1). For our campaign, the least squares adjustment was analogous to the calculation of a weighted mean of the two-way observations, but nevertheless provided a useful error estimate for each benchmark's adjusted height by the propagation of measurement uncertainties along the profile. Observations were weighted according to $c\sqrt{d}$, where d is the distance in kilometers between benchmarks and c is a constant (e.g., Vaníček et al., 1980). The value of c required to achieve unity of the a posteriori variance factor (shown in the final column of Table 1) provides an estimate of the internal precision of the leveling observations (e.g., Filmer & Featherstone, 2009).

2.3. Isolation of Incongruous Surveys

Prior to the analysis of a geodetic time series, it is important to consider any inconsistencies within or among repeat measurements that may impact subsequent estimations of VLM. This is exemplified in the first three epochs of our repeat leveling campaign over the Perth Basin.

Table 1
Summary of the Repeat Leveling Campaign Across the Perth Basin (2012–2017)

	Survey	Dates of survey	Time-span (days)	Serial number of level staves (invar; *fiberglass*)	Number of setups	Sight lengths (m)		Observation weighting (mm per √km)
						Mean	Standard deviation	
(1)	Aus. autumn 2013	26 Nov 2012 to 04 Jul 2013	221	27690, 26909	1713	26.2	±7.5	0.59
(2)	Aus. spring 2013	24 Oct 2013 to 16 Dec 2013	54	*2222* (97%); 27690, 26909 (3%)	1205	36.9	±17.0	1.09
(3)	Aus. autumn 2014	16 Apr 2014 to 06 May 2014	21	*2222*, *2092* (91%); 27690, 26909 (9%)	1460	30.5	±13.8	0.74
(4)	Aus. spring 2014	10 Sep 2014 to 02 Oct 2014	23	27690, 26909	1938	23.4	±7.2	0.53
(5)	Aus. autumn 2015	10 Mar 2015 to 08 Apr 2015	30	27690, 26909	1876	24.0	±7.3	0.44
(6)	Aus. spring 2015	31 Aug 2015 to 07 Oct 2015	38	27690, 26909	1954	23.1	±7.2	0.37
(7)	Aus. autumn 2016	17 Mar 2016 to 19 Apr 2016	34	27690, 26909	1848	24.3	±7.1	0.44
(8)	Aus. spring 2016	14 Sep 2016 to 31 Oct 2016	48	27690, 26909	1855	24.1	±7.2	0.45
(9)	Aus. autumn 2017	05 Apr 2017 to 02 May 2017	28	27690, 26909	1904	23.5	±7.3	0.42
(10)	Aus. spring 2017	30 Aug 2017 to 11 Oct 2017	43	27690, 26909	1852	24.2	±7.1	0.49

Intrasurvey ground motion may contaminate a time series of repeat leveling where any relative motion of the benchmarks between the start and end of a discrete measurement epoch violates the underlying assumption of temporal coherence when the height differences are accumulated (e.g., Castle & Elliott, 1982; Castle & Gilmore, 1992; Chi et al., 1980; Galloway & Burbey, 2011; Vaníček et al., 1980). Hence, the total time taken to complete each survey may affect the accuracy of VLM derived from a repeat leveling campaign, and especially so in areas of rapid seasonal or secular VLM. Most of our surveys were completed in less than six weeks (Table 1). However, the first epoch of the campaign (Austral autumn 2013) was surveyed in three components separated at ~11 km and ~34 km by interludes of 98 days and 105 days, respectively. In section 2.4, we show that some benchmarks in the profile are subsiding at rates of up to ~4 mm/year and fluctuating seasonally with amplitudes of up to ~27 mm. Consequently, this survey was contaminated by both secular and seasonal motion over its two temporal discontinuities.

Repeat leveling that has been conducted using different equipment (level instrument, staves, etc.) or employing different surveying standards/techniques (sight lengths, allowable misclose, etc.) may introduce artifacts into the analysis of VLM (e.g., Bitelli et al., 2000; Demoulin & Collignon, 2000; Jackson et al., 1980; Savage & Church, 1974). The second and third epochs of our repeat leveling campaign (Austral spring 2013 and Austral autumn 2014) were conducted with fiberglass staves (Table 1). These are inherently less accurate than invar staves (used in all of our other surveys) due to greater errors of calibration, thermal expansion, and errors introduced by imperfect joins in the telescoping sections (e.g., Rüeger, 1997, 2003). Compounding the issue, sight lengths of up to 80 m were observed during these two surveys. Extended sight lengths are known to reduce the accuracy of the systematic refraction correction (section 2.1) and also exacerbate the "turbulent scintillation" component of refraction error (e.g., Brunner, 1979; Holdahl, 1982; Strange, 1981; Whalen, 1981). This resulted in significantly lower data quality as indicated in the final column of Table 1.

Based on the critique presented in this section, the first three epochs of our repeat leveling campaign (Austral autumn 2013, Austral spring 2013, and Austral autumn 2014) will be omitted from the analysis following in section 2.4, but will be reintroduced in sections 3.1 and 3.2 to demonstrate their detrimental effect on the derived VLM.

2.4. Time Series Analysis

The corrected and least squares adjusted heights derived from each of the repeat leveling surveys constitute a time series which we now use to estimate VLM at each benchmark of the profile in Figure 1. As shown in Table 1, our time series consist of discrete measurements with a sampling frequency of approximately six months, but because the surveys each span between three and seven weeks, we opted to align each height in the time series to the specific date that the respective benchmark was surveyed. These time series data are provided in Data Set S1.

Independent evidence from continuous GPS, groundwater records, and InSAR show that VLM in the Perth Basin is characterized by seasonal fluctuation about a secular trend (Featherstone et al., 2012, 2015; Parker et al., 2017). Although Featherstone et al. (2015) revealed nonlinear VLM due to temporal variations in groundwater extraction rates, it was shown that the secular trend could be sufficiently modeled by a piecewise linear function over relatively short intervals (e.g., two to seven years). Therefore, assuming that the seasonal signal consists of an annual sinusoid, the functional model with which we describe each benchmark's height (H) over the duration of the repeat leveling campaign is:

$$\mathrm{H} = a + b\mathrm{t} + A\sin(2\pi(\mathrm{t} + \Phi)) + \varepsilon \tag{1}$$

where t is the elapsed time in years since 1 January of the year of the initial survey, *a* and *b* are the intercept and velocity parameters of the linear component of the model, *A* and Φ are the amplitude and phase parameters of the seasonal component, and ε is a noise term.

In order to estimate the parameters of equation (1) for the time series at each benchmark, we have employed the Create and Analyze Time Series (CATS) software (Williams, 2008). Although this software has been utilized in the analysis of many other geodetic time series (e.g., Baldi et al., 2009; Becker et al., 2012; King & Santamaría-Gómez, 2016; Wöppelman et al., 2009), we believe that this is the first time that it has been applied to repeat leveling data. CATS employs the MLE method in which the probability function is maximized through iterations of the data covariance matrix $\boldsymbol{C}$, as well as the estimated parameters of the functional model in equation (1), which together determine the residuals $\widehat{\boldsymbol{r}}$ from the weighted least squares fit to the *N* epochs in the time series (Langbein & Johnson, 1997):

$$\mathrm{lik}(\widehat{\boldsymbol{r}}, \boldsymbol{C}) = \frac{1}{(2\pi)^{N/2}(\det\boldsymbol{C})^{1/2}}\exp\left(-\frac{1}{2}\widehat{\boldsymbol{r}}^T\boldsymbol{C}^{-1}\widehat{\boldsymbol{r}}\right) \tag{2}$$

or

$$\mathrm{MLE} = \ln[\mathrm{lik}(\widehat{\boldsymbol{r}}, \boldsymbol{C})] = -\frac{1}{2}\left[\ln(\det\boldsymbol{C}) + \widehat{\boldsymbol{r}}^T\boldsymbol{C}^{-1}\widehat{\boldsymbol{r}} + N\ln(2\pi)\right] \tag{3}$$

CATS is able to apply a range of different noise models (ε) to account for the various forms of temporal correlation that may be present within a time series (Williams, 2008). Most time series of geodetic or geophysical measurements exhibit some level of colored noise (e.g., Agnew, 1992; Langbein & Johnson, 1997; Williams, 2003), however we are unaware of any previous investigation into the noise characteristics of repeat leveling and are unable to draw any significant conclusions from our relatively small data set (cf. Jiang & Zhou, 2015; Langbein, 2012; Williams et al., 2004, Table 2). We therefore employ the "variable white" noise model throughout this study, where the noise components in each height measurement in the time series are assumed to be uncorrelated (i.e., $\boldsymbol{C}$ in equation (3) is diagonal) and Gaussian-distributed with zero mean. The uncertainties in the heights computed from the least squares adjustments (section 2.2) are taken as formal a priori estimates of the white noise amplitudes (thereby accounting for the relative precision across the different surveys), with CATS then estimating a scaling factor to be applied to these values.

Figure 3 depicts the parameters of equation (1) estimated by CATS for a representative benchmark (GFD80; location shown in Figure 1), while the results for the complete profile are provided in Figure S1 and summarized in Figure 4. Note that since leveling is a differential technique, the heights in each benchmark's time series are measured relative to F396A (held fixed in the adjustments described in section 2.2). This reference benchmark is set directly into bedrock on the granitic Yilgarn Craton east of the Darling Fault (Figure 1), which we assume is not subject to any VLM over the duration of the campaign (cf. Jakica et al., 2011). Strictly, however, the benchmark heights (and consequently all secular and seasonal VLM parameters presented in this study) are only determined relative to this assumed-stable point.

The linear velocity parameter estimated by CATS for each benchmark in the profile is plotted in Figure 4a (revealing subsidence of a few millimeters per year over the period 2014–2017), together with error bars describing the uncertainties in these rates computed under the variable white noise model. These results are also given in Table S1. Note that the velocity is not significantly different from zero until ~5 km west of the reference benchmark F396A (i.e., west of the Darling Fault), highlighting a distinct differential between the observed VLM in the Perth Basin and any absolute VLM of the Yilgarn Craton (which we have assumed to be zero).

As this may be the first time that CATS has been applied to such a small number of data points, we noticed that the software underestimates the uncertainty in the linear velocity parameter by a factor of $\sqrt{\frac{N}{N-2}}$, which

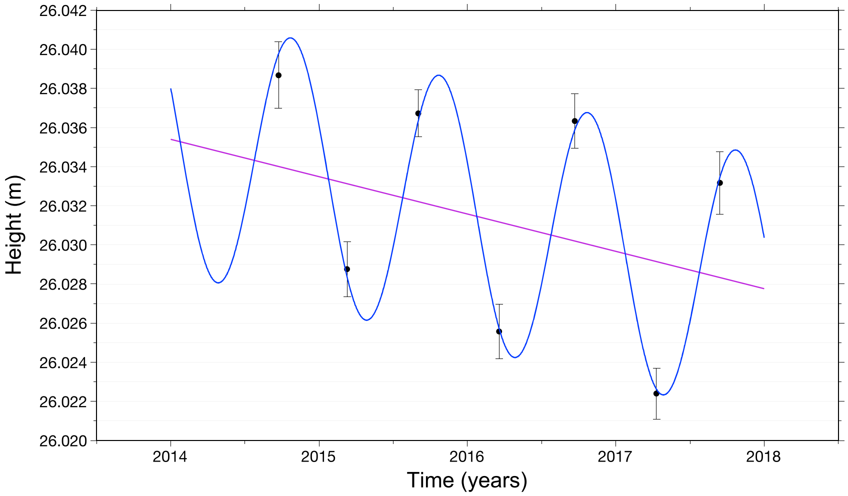

Figure 3. Time series of height at representative benchmark GFD80 over the seven epochs between Austral spring 2014 and Austral spring 2017, with the CATS-derived parameters of equation (1) depicted in blue (linear component in purple) and employing the variable white noise model. The error bars represent the uncertainties in the heights (one sigma) computed from the least squares adjustment of the corresponding survey (section 2.2).

was later confirmed by S. D. P. Williams (personal communication, 16 Jan 2017). While negligible for large data sets, the effect is significant for this study and these uncertainties have been scaled up accordingly throughout this paper.

We also used CATS to estimate the parameters of the functional model in equation (1) using weighted least squares instead of MLE. This approach assumes that only white noise is present in the time series (with magnitude defined by the formal a priori errors in the data) and does not estimate any scaling factor or additional noise terms (Williams, 2008). These results, also included in Table S1, revealed negligible differences in the estimated linear velocity parameters (as well as in their uncertainties) compared to those derived using MLE with a variable white noise model. Although the two methods produced similar results for our study, we advocate the application of MLE in the analysis of geodetic time series as it allows for the consideration of more sophisticated noise characteristics (including non-Gaussian colored noise) and may be applied without any formal estimates of the a priori errors in the data. All subsequent discussion in this paper will employ the results obtained using MLE.

We acknowledge that the seasonal signal estimated from our repeat leveling measurements (amplitude, Figure 4b; and phase, Figure 4c) is underdetermined given that we have only two surveys conducted at approximately the same time each year. A quarterly survey frequency or higher is desirable in order to better resolve the characteristics of seasonal VLM. Nevertheless, the annual amplitudes computed from the leveling time series are corroborated by continuous GPS measurements at the International GNSS Service (IGS) station PERT (~8 km north of the profile; Figure 1) over the concurrent three integer years (i.e., 2014–2017). Processing the daily GPS solutions from the Nevada Geodetic Laboratory (http://geodesy.unr.edu/gps_timeseries/tenv3/IGS08/PERT.IGS08.tenv3) in CATS and applying a flicker-plus-variable-white noise model (e.g., Mao et al., 1999; Williams et al., 2004; Zhang et al., 1997) reveals an annual amplitude of 3.37 ± 0.79 mm (with a negligible and statistically insignificant semiannual amplitude of 0.27 ± 0.58 mm). This is in general agreement with all leveling benchmarks between ~16 km and ~20 km eastward along the profile that reside in the same Bassendean Sand formation (refer to Figure 4b).

Precipitation in Perth follows a reasonably well-defined seasonal cycle, with approximately 90% of the city's annual rainfall occurring between April and September. The repeat leveling profile crosses various surface geology boundaries (Figure 1), and therefore the ground beneath the benchmarks may exhibit different soil characteristics such as moisture capacity and swelling/contraction rates. Acknowledging the uncertainty with which these boundaries have been mapped (Davidson, 1995), Figure 4 suggests that the benchmarks within each geological unit exhibit a reasonably coherent seasonal signal (cf. Chi & Reilinger, 1984; Demoulin, 2004), with the section of limestone/sand between ~10 km and ~18 km eastward along the profile providing the

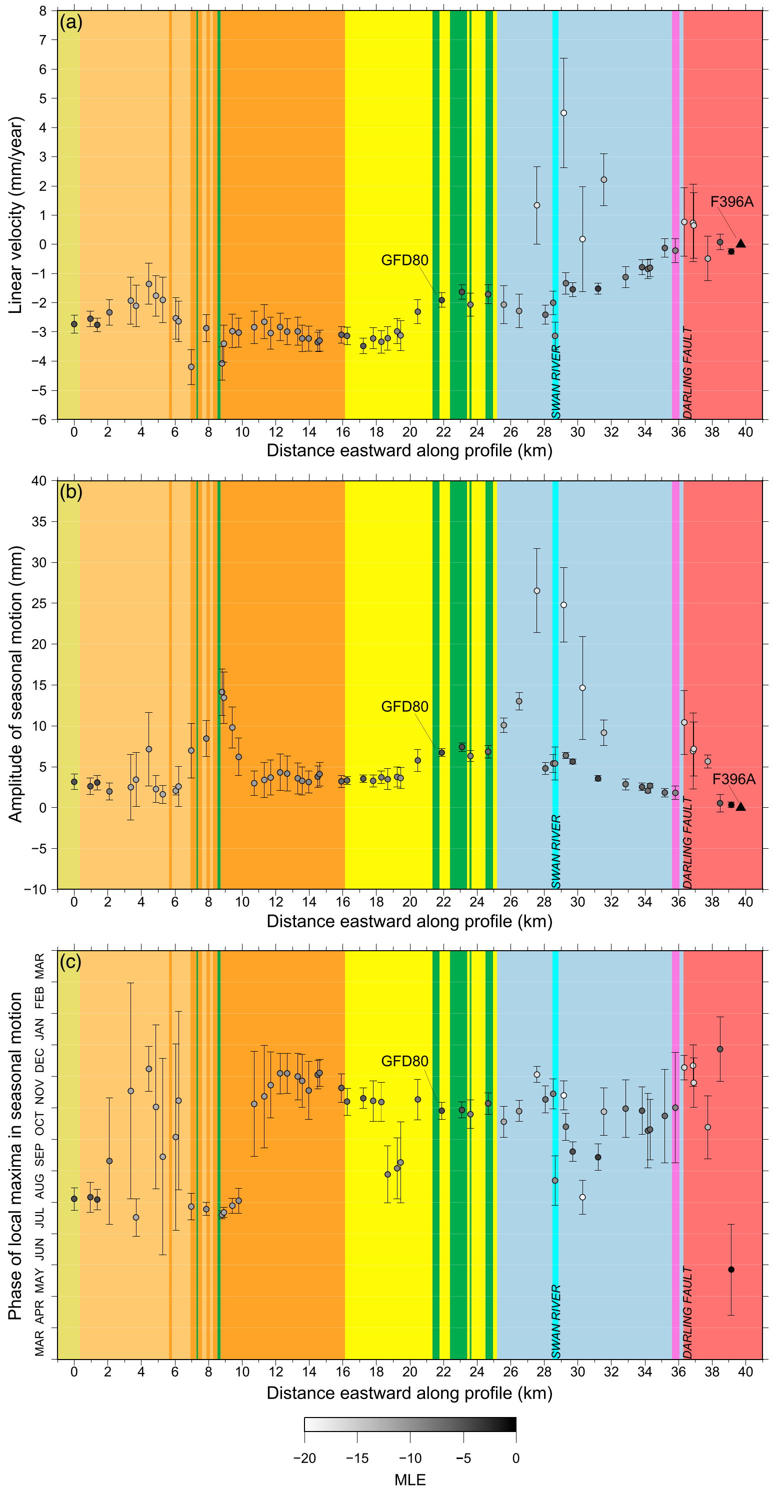

Figure 4. CATS-derived parameters of equation (1) (using a variable white noise model) for all benchmarks along the repeat leveling profile, covering the seven measurement epochs between Austral spring 2014 and Austral spring 2017: (a) linear velocity; (b) amplitude of the seasonal motion; and (c) phase of the seasonal motion (expressed as the position of the local maxima of the sinusoid). Surface geology regions as per Figure 1. The error bars represent the uncertainties computed by CATS at the one-sigma level, with those in (a) having been scaled up by factor 1.1832. The grayscale circles depict the MLE value from equation (3) computed for each benchmark, where a more positive value indicates a better fit to the data. Standardization of these MLE values to account for the dependency on the number of epochs was not necessary since this was identical for every benchmark.

strongest example of this coherence. Note also that the two benchmarks west of the fixed reference point F396A have negligible seasonal amplitude since they too are set in bedrock on the granitic Yilgarn Craton (i.e., no expansive topsoils).

Figure 4a shows that the profile across the Perth Basin is predominately subsiding (i.e., negative velocity), with the exception of four benchmarks located near the Swan River (GF17A, WS354, GFD39, and BEL49) whose time series suggest either uplift or a negligible secular VLM (refer to plots provided in Figure S1). A more plausible explanation for the results at these four points, supported by the fact that their MLE values are among the lowest in the profile, is that the functional model containing an annual sinusoid of constant amplitude and phase is not able to accurately describe their more complex VLM, especially given that we have only two surveys per year. Clays and porous soils in this area (i.e., river sediments) make these benchmarks more susceptible to groundswell (for instance, the height of WS354 changes by as much as 47 mm over six months), and variations in rainfall, river volumes, and other seasonal factors may manifest as a time-variable signal (e.g., Bennett, 2008; Chen et al., 2013; Davis et al., 2012). Furthermore, the swelling/contracting ground surface in this area will be more vulnerable to aliasing if the repeat surveys are not able to consistently capture the same phase of the seasonal VLM (cf. section 3.4). Therefore, the results at these four benchmarks are to be considered outliers (but see the further discussion in section 4.1).

3. Artifacts and Aliasing in Time Series of Repeat Leveling

Artifacts and aliasing may be introduced into a time series of repeat leveling by inconsistencies in surveying practices and instrumentation, systematic errors in the observations, and intrasurvey and seasonal ground motion. Using the data collected from our repeat leveling campaign in the Perth Basin, we demonstrate the potential impact that these issues may have on the derived estimates of VLM. In each of these cases we use the representative benchmark GFD80 as an exemplar, while the results for all other benchmarks are provided in Table S1. As we are primarily interested in subsidence over the Perth Basin, and since the seasonal signal is underdetermined in this study, we restrict our analysis to the linear velocity parameter (b) from equation (1).

We also identify some examples from the literature where these sources of artifacts and aliasing may have affected the estimates of VLM, many of which cite a discrepancy between leveling-derived VLM and geological evidence, or between leveling and other geodetic measurement techniques. Many published studies that employ repeat leveling provide limited information regarding the nature of the surveys or the handling of the data, but the papers that we cite are sufficiently descriptive to enable our assessment. Importantly, we do not intend to refute these studies.

3.1. Inconsistent Surveying Instrumentation or Field Practices

As discussed in section 2.3, the Austral spring 2013 and Austral autumn 2014 surveys were conducted with fiberglass staves and employed different field practices with respect to all other surveys in our repeat leveling campaign (refer to Table 1). Consequently, these epochs were not used in the estimates of VLM described in section 2.4, but in this first simulation CATS is applied to the time series in which they are included. The Austral autumn 2013 epoch was contaminated by the separate issue of intrasurvey motion, so is omitted from this simulation and discussed in section 3.2.

The example in Figure 5 demonstrates how variations in the surveying instrumentation or field practices employed during a repeat leveling campaign can contaminate the time series and bias the estimated VLM. Such inconsistencies are often present in other applications of repeat leveling (e.g., Aubrey & Emery, 1986; Dzurisin et al., 2002; Fuhrmann et al., 2015; Giménez et al., 2000; Motagh et al., 2006; Schlatter et al., 2005), particularly those that analyze combinations of historical and contemporary data where evolutions in surveying instrumentation and practices may generate spurious VLM (cf. section 4).

3.2. Intrasurvey VLM

Intrasurvey ground motion may affect any epoch of a repeat leveling campaign in which there is a large time difference between the constituent measurements (particularly in the presence of any rapid secular or seasonal VLM), as height differences are usually treated as having been observed at the same instance in time when accumulated along a profile. As discussed in section 2.3, the first epoch of our repeat leveling campaign was observed in three separate components (each approximately three months apart; Table 1). This survey

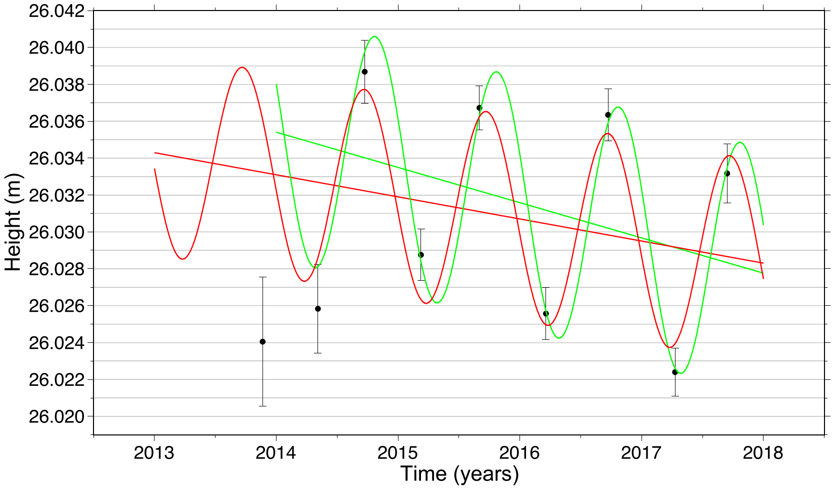

Figure 5. Comparison of functional models estimated by CATS at benchmark GFD80: (red; section 3.1) −1.20 ± 0.84 mm/year linear velocity estimated from the time series that includes the two surveys conducted with fiberglass level staves (Austral spring 2013 and Austral autumn 2014); (green; section 2.4) −1.91 ± 0.24 mm/year linear velocity estimated from the time series that does not include these two aberrant surveys.

was omitted from the VLM analysis in section 2.4 but is included for the simulation in this section. The Austral spring 2013 and Austral autumn 2014 surveys (conducted with fiberglass staves; section 3.1) are omitted from this simulation.

The example in Figure 6 demonstrates how intrasurvey motion in any epoch of a repeat leveling campaign can introduce artifacts into the time series. Benchmarks should be regarded as being in constant vertical motion, and therefore, surveys must be completed in as short a time-span as possible. There are many examples of repeat leveling applications that may be susceptible to intrasurvey motion (e.g., D'Anastasio et al., 2006; Jackson & Bilham, 1994; Kooi et al., 1998; Vestøl, 2006; Wellman & Tracey, 1987), particularly those covering large distances or where multiple surveys conducted at different times have been amalgamated to form a contiguous profile (often featuring interludes ranging from several months to many tens of years; cf. section 4).

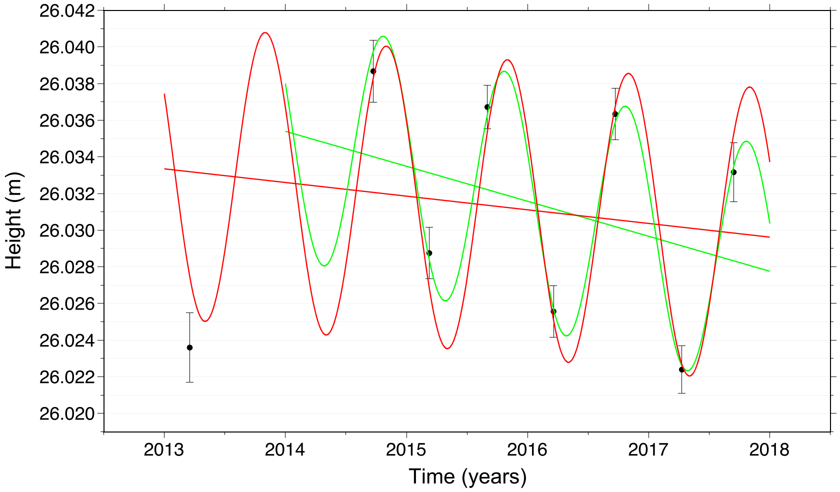

Figure 6. Comparison of functional models estimated by CATS at benchmark GFD80: (red; section 3.2) −0.74 ± 0.59 mm/year linear velocity estimated from the time series that includes the epoch affected by intrasurvey motion (Austral autumn 2013); (green; section 2.4) −1.91 ± 0.24 mm/year linear velocity estimated from the time series that does not include this survey.

3.3. Systematic Errors

Systematic errors can introduce artifacts into a time series of repeat leveling that may result in spurious VLM interpretation, particularly where surveying instrumentation and practices vary (cf. section 3.1) such that the errors are not consistent across epochs. One notable example is the controversial “Palmdale bulge” in southern California, where it has long been argued that this apparent tectonic uplift was an artifact from systematic errors in the leveling data and variations in observation sight lengths (Castle et al., 1976; Jackson et al., 1980; Kerr, 1981; Mark et al., 1981; Strange, 1981; Holdahl, 1982; Castle et al., 1983a, 1983b; Strange, 1983; Stein, 1984; Strange, 1984; Castle et al., 1985; Craymer & Vaníček, 1986; Stein et al., 1986; Mark et al., 1987; Reilinger, 1987; Stein et al., 1987; Craymer & Vaníček, 1989; Stein et al., 1989; Castle & Gilmore, 1992; Craymer et al., 1995). In our repeat leveling campaign, each survey was corrected for systematic errors as described in section 2.1. We now apply CATS to the same seven surveys analyzed in section 2.4, but this time using the uncorrected leveling data.

The velocities computed in this simulation differ by a maximum of 0.38 mm/year with regard to those derived in section 2.4, with all differences falling within the bounds of the uncertainties reported by CATS. We attribute this to all surveys (excluding those three discussed in section 2.3) having been carried out under similar observation conditions (instrumentation, survey route, sight lengths, etc.) such that the systematic errors have a similar effect on each survey (cf. Figure 2a) and subsequently little influence on the estimated VLM (cf. Demoulin & Collignon, 2000; Vaníček & Krakiwsky, 1986, p. 622). However, the influence of systematic errors may be more significant in other applications of repeat leveling in which the observation conditions are not as well-controlled (e.g., Bilham, 2001; Hsu et al., 2015; Kall et al., 2014; Kostoglodov et al., 2001; Verdonck, 2006; Vigny et al., 2007; cf. section 4). Therefore, we advocate that rigorous corrections (cf. section 2.1) should always be applied to prevent artifacts in the time series that reflect changes in the observation conditions as opposed to genuine VLM.

3.4. Seasonal Aliasing

The inclusion of seasonal (e.g., annual or semiannual) signals in the VLM functional model has become common practice in the analysis of geodetic time series such as those from continuous GPS (e.g., Blewitt & Lavallée, 2002; Bos et al., 2010; He et al., 2017) and InSAR (e.g., Bell et al., 2008; Hu et al., 2016; Reeves et al., 2011). However, this issue is rarely taken into consideration in applications of repeat leveling, presumably due to a lack of available data with sufficient temporal frequency. Aliasing with seasonal ground motion may lead to misinterpretation of the VLM derived from repeat leveling, as demonstrated in the simulations in this section where a linear trend is fitted to selected pairs of epochs. The potential impact of this aliasing depends on the relative magnitudes of the secular trend and seasonal signal present in the area: a large secular trend will be less sensitive to a small seasonal signal, and conversely, a small secular trend (such as that in the Perth Basin) will be more sensitive to a large seasonal signal.

In the first simulation in this section, the Austral spring 2014 and Austral spring 2017 epochs were selected as illustrated by the blue line in Figure 7 for benchmark GFD80. This example demonstrates that by conducting the leveling surveys at a consistent time of the year (i.e., in-phase), the risk of aliasing with seasonal ground motion can be reduced. However, this assumes that the seasonal motion is accurately modeled by an annual sinusoid of constant amplitude and phase (cf. Bennett, 2008; Chen et al., 2013; Davis et al., 2012), which should be ascertained using higher-frequency surveys or independent measurements such as continuous GPS or InSAR.

In the other two simulations in this section, the effect of seasonal aliasing is accentuated by deriving the linear velocity from two epochs that are separated in phase by a half-cycle. In one case (purple line in Figure 7; Austral spring 2014 to Austral autumn 2017), the subsidence rate has been artificially inflated by aliasing with the seasonal ground motion, while the other case (red line in Figure 7; Austral autumn 2015 to Austral spring 2017) is even more extreme as it indicates a spurious uplift.

In other VLM applications of repeat leveling (e.g., Bürgmann et al., 1997; Ching et al., 2011; Lanari et al., 2004; Liu & Huang, 2013; Ozener et al., 2013; Savage & Svarc, 2010; cf. section 4) the phase of the repeat surveys is often unknown (or perhaps ignored), which may lead to similar such biases in the estimated velocities in the presence of a large seasonal signal. In order to reduce the potential for aliasing, repeat

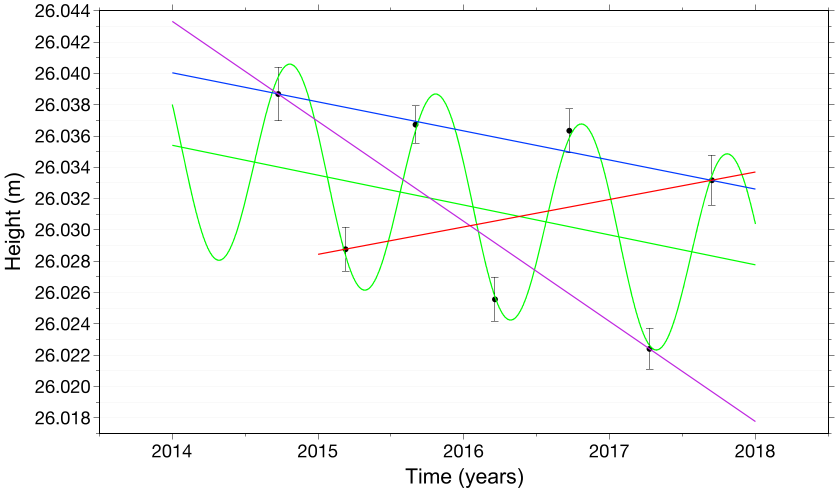

Figure 7. Comparison of functional models estimated by CATS at benchmark GFD80: (blue; section 3.4) −1.85 ± 0.80 mm/year linear velocity estimated from the straight line fitted between two epochs that are measured in-phase (Austral spring 2014 and Austral spring 2017); (purple; section 3.4) −6.39 ± 0.80 mm/year linear velocity estimated from the straight line fitted between two epochs that are measured approximately six months out-of-phase (Austral spring 2014 and Austral autumn 2017); (red; section 3.4) +1.76 ± 0.80 mm/year linear velocity estimated from the straight line fitted between two epochs that are measured approximately six months out-of-phase (Austral autumn 2015 and Austral spring 2017); (green; section 2.4) −1.91 ± 0.24 mm/year linear velocity estimated from the linear-plus-seasonal functional model fitted to the seven epochs between Austral spring 2014 and Austral spring 2017.

surveys should always be conducted at the same time of the year, but with a greater frequency than annually wherever feasible in order to gain a better understanding of any seasonal signals that may be present in the area.

4. Extending Time Series Analysis Using Historical Leveling Data

In section 2.4, we used time series of repeat leveling in order to estimate VLM in the Perth Basin over three integer years (i.e., 2014–2017). From a geophysical perspective, one may also be interested in determining whether these results (Figure 4) provide an accurate description of the VLM expected over a longer period of time, for instance, to quantify the total subsidence that has occurred since the commencement of groundwater extraction, or to predict the ongoing vertical displacements that may occur if this trend persists into the future.

Historical leveling data typically date back much further than other geodetic measurements such as continuous GPS and InSAR, and where available, should remain an integral component of any VLM monitoring program (e.g., D'Anastasio et al., 2006; Fuhrmann et al., 2015; Vestøl, 2006). In this section, we employ archived historical leveling data from the Perth Basin to investigate whether the results derived from our contemporary repeat leveling campaign may be reliably extrapolated over time.

4.1. Historical Leveling to Estimate VLM Over a Longer Period of Time

While the repeat leveling campaign described in Table 1 was designed expressly for monitoring VLM due to groundwater extraction in the Perth Basin, the majority of the leveling data collected by Landgate (the Western Australian geodetic agency) over the past ~50 years has been for the general purpose of maintaining the State's geodetic network (physical benchmarks) and its connections to the Australian Height Datum (Roelse et al., 1975). Prior to 2013, there was no single dedicated survey that connected the benchmarks of the profile in Figure 1. Consequently, in order to obtain an historical profile of heights with which to compare our contemporary measurements, we must utilize leveling data collected to a variety of different standards and under different observation conditions. Such variations in the surveying instrumentation and practices may introduce artifacts (cf. section 3.1), as could the influence of systematic errors (cf. section 3.3) since there is insufficient metadata available to apply suitable corrections (cf. section 2.1). We might also expect this

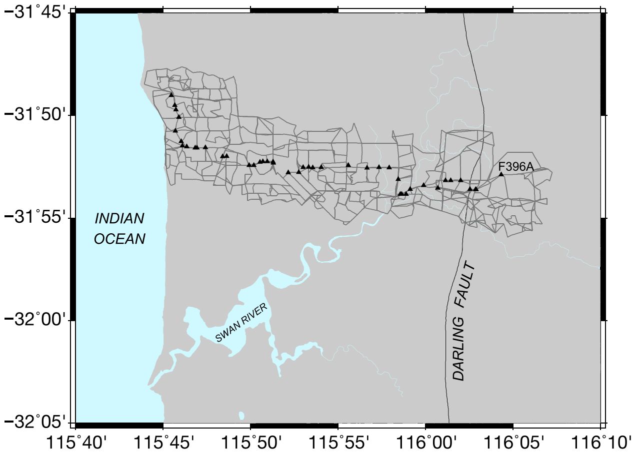

Figure 8. Historical leveling network across the Perth Basin (gray lines; median survey date ~1975), encompassing 44 benchmarks in common with the contemporary repeat leveling profile (black triangles; cf. Figure 1) including the reference benchmark F396A.

historical data to be affected by aliasing with seasonal ground motion and by intrasurvey motion where benchmarks have been leveled at different times of the year and with significant interludes between measurements (cf. section 3.2, 3.4).

In an attempt to mitigate these potential error sources, we have collected a large quantity of redundant leveling data constituting a network of closed circuit loops to a distance of ~4 km either side of the contemporary profile as shown in Figure 8. These leveling lines (comprising a total of 2,725 height differences between 1,016 benchmarks over a distance of 976 km) were identified from historical map sheets and then manually digitized from hardcopy archives of the original field observations. The majority of this data was surveyed in the early 1970s (median date ~1975).

As per the contemporary surveys (section 2.2), the historical leveling network in Figure 8 was least squares adjusted with respect to the fixed benchmark F396A. In order to achieve unity of the a posteriori variance factor, the observations were weighted according to $4.07\sqrt{d}$ where d is the distance in kilometers between benchmarks. This suggests a precision one order of magnitude lower than the contemporary leveling (cf. Table 1), however, caution must be used in making this comparison as the contemporary profile has much less redundancy than the historical network.

Figure 9 shows the linear rates of VLM (*b* from equation (1), using a variable white noise model) estimated by CATS for the extended time series of leveling that includes both the height derived from the historical network (~1975) and the heights from the seven contemporary surveys (2014–2017; section 2.4). These rates are also provided in Table S1. The amplitude and phase of the CATS-derived seasonal signal, being weighted toward the higher-frequency contemporary leveling, were very similar to that in Figure 4 and so are not

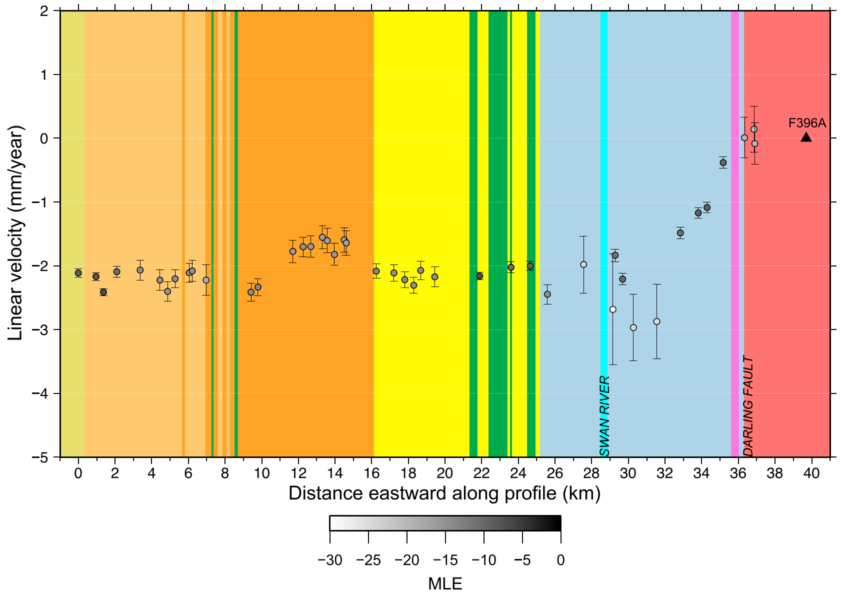

Figure 9. CATS-derived linear velocity (*b* from equation (1), using a variable white noise model) fitted to the time series containing the height derived from the historical leveling (~1975) and the seven heights from the contemporary repeat leveling (2014–2017; section 2.4). The error bars represent the uncertainties computed by CATS at the one-sigma level, having been scaled up by factor 1.1547 (refer to section 2.4). The grayscale circles depict the MLE value from equation (3) computed for each benchmark, where a more positive value indicates a better fit to the data. Standardization of these MLE values to account for the dependency on the number of epochs was not necessary since this was identical for every benchmark. Surface geology regions as per Figure 1.

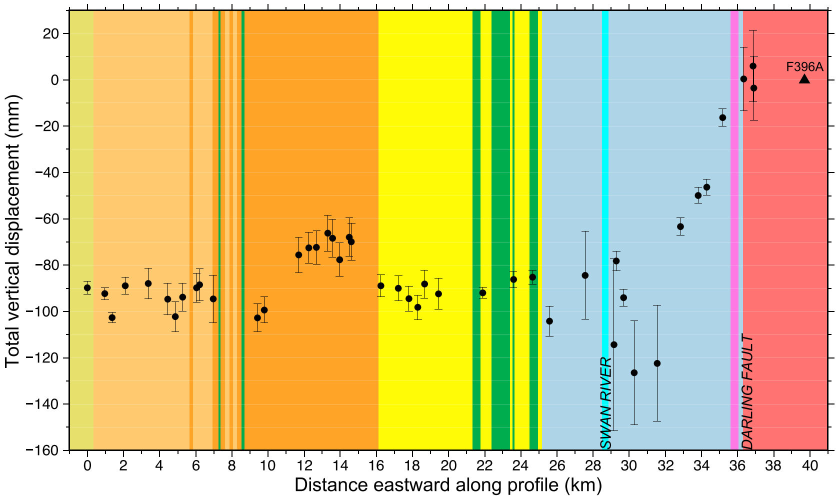

Figure 10. Total vertical displacements along the repeat leveling profile (~1975–2017), computed by multiplying the linear rates from Figure 9 by the length of each benchmark's extended time series (~42 years). The error bars represent the uncertainty in these displacements (one sigma) propagated from the uncertainties in the CATS-derived linear rates. Surface geology regions as per Figure 1.

repeated here. Note that the inclusion of the historical data has assimilated the four outliers identified in Figure 4a into a more consistent pattern of subsidence across the profile (albeit with larger uncertainties attributed to the scatter in their contemporary measurements). This demonstrates that the secular trend in VLM, when derived from a time series with a longer temporal coverage, may be more robust against short-term fluctuations and artifacts (e.g., seasonal ground motion) whose magnitudes are smaller than the long-term secular displacements.

Multiplying each of the linear rates from Figure 9 by the length of the extended time series (~42 years) provides an estimate of the total vertical displacement over this time period. As opposed to a direct comparison of the heights at either end of the time series, this method incorporates information from all available epochs of data, is less influenced by seasonal aliasing, and allows for propagation of errors based on the uncertainties reported by CATS. These displacements are plotted in Figure 10, revealing ~90 mm of subsidence across the Perth Basin (relative to the assumed-stable Yilgarn Craton).

4.2. Extrapolation Errors

The historical leveling data from the Perth Basin provides a constraint on the extrapolation of the VLM derived from our contemporary time series in section 2.4. Figure 11 shows the differences between the adjusted heights from the historical leveling network (~1975; Figure 8) and those estimated by extrapolating the parameters of equation (1) derived from the contemporary repeat leveling (2014–2017; Figure 4) to the same date (i.e., $t \sim -39$ years). At many of the benchmarks, notably in the central region of the profile, this discrepancy is in the order of ~50 mm (i.e., more than half of the total vertical displacement in Figure 10).

To some extent, the discrepancies in Figure 11 may be influenced by errors in the historical leveling (refer to section 4.1) or in the relatively short contemporary time series of repeat leveling. However, while the linear functional model in equation (1) may be satisfactory over the duration of the contemporary survey campaign (i.e., 2014–2017), VLM can be influenced by a range of factors so should not be assumed linear over any long period of time. Such is the case in the Perth Basin, where the variable rate of subsidence has been associated with the concurrent rate of groundwater extraction by independent evidence in Featherstone et al. (2015, Table 2). Although the historical leveling data reveal the total vertical displacements that occurred between ~1975 and 2017 (Figure 10), the large gap in the extended time series obscures any nonlinear motion that may have occurred in the intervening ~40 years (cf. Amoruso et al., 2005; Bendick et al., 2000; Islam et al., 2016; Mäkinen & Saaranen, 1998; Vaníček & Hamilton, 1972). In order to distinguish nonlinear motion from errors in the measurements, and thus provide an accurate determination of the VLM over an extended timescale, we require more regularly sampled data collected over a longer period of time.

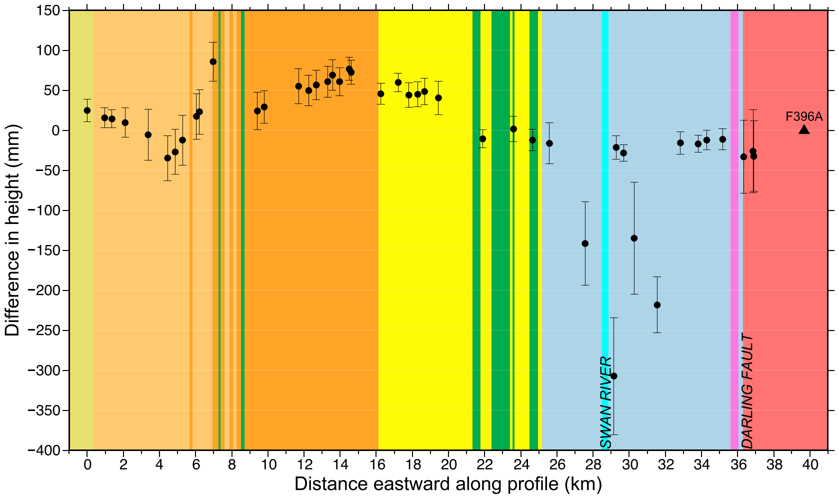

Figure 11. Difference between the heights measured by the historical leveling (~1975) and those from the linear functional model fitted to the contemporary repeat leveling (2014–2017; section 2.4) extrapolated to the same date. Positive differences denote an overestimated magnitude of subsidence suggested by the extrapolated heights. The error bars represent the uncertainties of these differences (one sigma) propagated from the uncertainties in the CATS-derived functional model parameters for the contemporary leveling and the uncertainties in the least squares adjusted heights from the historical leveling. Surface geology regions as per Figure 1. The four outliers near the Swan River (identified in Figure 4a) again manifest in these results.

5. Summary and Conclusion

Using a case study in the Perth Basin, Western Australia, we have demonstrated the methodology for estimating VLM from repeat leveling. We reviewed various sources of artifacts and aliasing that may contaminate a time series of repeat leveling and which may thereby contribute to discrepancies with geological evidence or the VLM estimates from other geodetic measurement techniques. In order to mitigate these potential error sources and prevent misinterpretation of the leveling-derived VLM, we advocate (1) consistent instrumentation and field practices across all surveys, (2) the application of rigorous corrections for systematic errors, (3) each repeat survey to be completed in as short a time-span as possible, and (4) repetitions to be made in-phase with any seasonal ground fluctuations (e.g., at the same time of the year in the presence of an annual signal). We have shown that historical leveling data provide some constraint on the extrapolation of VLM derived from contemporary observations, and highlighted the ambiguity involved in attempting to extrapolate geodetic time series in the presence of VLM that may be nonlinear over an extended timescale.

Data Statement

The repeat leveling time series data employed in this study are provided in Data Set S1. The continuous GPS time series data from the IGS station PERT are available through the Nevada Geodetic Laboratory (http://geodesy.unr.edu/gps_timeseries/tenv3/IGS08/PERT.IGS08.tenv3).

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