Value of the *Jason-1* Geodetic Phase to Study Rapid Oceanic Changes and Importance for Defining a *Jason-2* Geodetic Orbit[Ⓢ]

G. DIBARBOURE

CLS, Ramonville-Saint-Agne, France

R. MORROW

LEGOS/CTOH, Toulouse, France

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ABSTRACT

Because of the drifting nature of the ground track of *Jason-1* during its geodetic mission (GM), there are 1200 overlap events where the *Jason-1* GM and *Jason-2* tracks align perfectly (less than their altimeter footprint radius) over thousands of kilometers. These overlap events sample homogeneously all longitudes and all time differences (dt) ranging from a few minutes to 10 days or more.

When dt is almost zero, the difference is characterized by altimeter noise and its modulation by waves. As dt increases, the rapid ocean variability is revealed. The first statistical analysis of the 1200 events yields variance maps, spectra, autocorrelation, and space–time scales that are consistent with past observations (e.g., the 3-day phase of *ERS-1*). This paper highlights the value of this *Jason-1* GM overlap dataset for more sophisticated studies of the rapid ocean variability. There are two major limitations: 1) the noise level of Jason-class altimeters prevents analyzing scales smaller than 80 km and 2) short time differences also absorb a fraction of the derivative of slower signals.

These findings are important if a geodetic mission is considered for *Jason-2* in the coming years (e.g., when the satellite starts to exhibit aging problems): a well-chosen geodetic orbit for *Jason-2* has the potential to collect a better distribution of overlap events with *Jason-3*. To that extent, thousands of orbits were screened to find the options that would provide good geodetic and mesoscale sampling and also maximize the overlap sampling of a tentative *Jason-2* GM phase.

1. Introduction

a. Context

Jason-2 was launched in June 2008. Many years later, the altimeter and the platform are still active and performing well. Yet the mission has outlived its expected life span: the nominal mission was 3 years. To that extent, the risk of an onboard anomaly or a critical failure is slowly increasing as discussed by [Dibarboure and Lambin \(2015\)](#). To protect the historical TOPEX/Jason orbit for

Jason Continuity of Service (Jason-CS)/Sentinel-6, the space agencies may decide to move *Jason-2* to a so-called extension-of-life (EoL) orbit, when the risk of losing control of the satellite is judged to be too high.

This situation occurred in the past with *Jason-1*, and [Dibarboure et al. \(2012\)](#) proposed a strategy to maximize the science return of the *Jason-1* EoL orbit. At that stage, *Jason-2* and *Jason-1* were in an interleaved tandem orbit, providing optimal space–time coverage of the mesoscale field. By moving *Jason-1*, the sampling capability was reduced. Moreover, moving to a new ground track involved a small increase in the error budget, due to gridded mean sea surface model errors. Conversely, the EoL phase made it possible to put *Jason-1* on a drifting orbit that would accommodate the needs of the geodetic community, and various orbit options were selected in order to collect a useful geodetic dataset.

Jason-1 was moved to its new orbit in 2012 and the geodetic mission (GM) lasted for approximately

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Corresponding author address: Gerald Dibarboure, CLS, 8-10 Rue Hermes, 31520 Ramonville St-Agne, France.
E-mail: gerald.dibarboure@cls.fr

400 days. [Le Traon et al. \(2015\)](#) recently reported the diminished but still substantial value of *Jason-1* GM for operational oceanography, and [Sandwell et al. \(2014\)](#) reported the unprecedented benefits of extending the *Jason-1* mission with an orbit for geodetic studies.

b. Objectives

This paper focuses on a small subset of the *Jason-1* GM dataset: there are approximately 1200 so-called *overlap events* between the *Jason-2* and *Jason-1* GM. During these events, both satellites stay within 10 km (altimeter footprint radius) and 10 days from one another over tens of thousands of kilometers, thus providing unprecedented observations on the changes in ocean topography at time scales ranging from a few minutes to 10 days (less than a *Jason-2* repeat cycle).

This series of *Jason-2*–*Jason-1* GM overlap events shares some properties with the *ERS-1* 3-day repeat orbit analyzed by [Minster and Gennero \(1995\)](#). Both datasets provide a way to measure higher frequencies than the 10-day repeat orbit of the TOPEX/*Jason* orbit over thousands of kilometers. However, the difference between *Jason-2* and *Jason-1* benefits from better precision (their instrument noise is lower) and accuracy (the orbit determination error is an order of magnitude lower on *Jason*-class missions). *Jason-1* GM overlap events also observe 0- to 10-day differences, whereas *ERS-1* was limited to multiples of 3 days.

These new observations are interesting because rapid sea level time series are usually observed at point locations from deep ocean moorings or tide gauges and rarely over large space scales. Sea level variability can be impacted by the instrument noise and surface roughness conditions, which will be dominant at near-zero lag. Ocean dynamics at 1–10-day time scales include weak diurnal signals, internal waves and tides, the development of submesoscale fronts and filaments or small-scale eddies, the displacement of larger eddies, meanders or planetary waves, and the distinct rapid equatorial trapped baroclinic gravity waves, with spectral peaks of a few days (e.g., [Farrar and Durland 2012](#)). These rapid dynamics play an important role in ocean adjustment and mixing, but their spatial/meridional structure is difficult to observe, yet observations are required to validate their behavior in models.

This paper presents the first analyses of these overlap events in order to illustrate their value for the observation of rapid oceanic dynamics ([section 2](#)). In [section 3](#), we use these findings to revisit the EoL strategy developed for *Jason-1*. Additional criteria are used to find a tentative *Jason-2* EoL orbit that would not only maximize the science return for operational oceanography and geodesy but also collect well-distributed overlap events between *Jason-2* and *Jason-3*.

c. Orbit nomenclature and properties

In this paper, we use the $N+P/Q$ orbit terminology and the notion of subcycles detailed in [Dibarboure et al. \(2012\)](#). The three integers $N+P/Q$ are used to define unambiguously *one fractional number* that corresponds to the exact number of satellite revolutions per nodal day. The fractional number $N+P/Q$ thus defines the satellite altitude and the orbit repeat cycle.¹ The integers N and P are meaningless in this study (only the fractional number $N+P/Q$ matters), and Q defines the repeat cycle in nodal days. Nodal days are defined as the time required for the earth to rotate once *with respect to the orbital plane* [i.e., almost but not exactly one day due to orbital precession; explained in section 8.1.4 of [Chelton et al. \(2000\)](#)].

Subcycles are sometimes called near-repeat cycles (as opposed to exact repeat cycles). [Dibarboure et al. \(2012\)](#) explain how the so-called subcycles of geodetic orbits create an apparent “zonal drift” with respect to the fixed grid of *Jason-2*.

d. Data used

In this paper, we use level 3 along-track sea level anomalies (SLA) from [AVISO \(2015\)](#), described by [Dibarboure et al. \(2011\)](#). More specifically we use the “calibrated SLA” product of the AVISO catalogue [explained and analyzed in [section 2g\(1\)](#)]. [AVISO \(2015\)](#) gives the list of corrections and references they used to construct the sea level anomalies. *Jason-2* SLA are computed as the difference between the sea surface height (SSH) and a local mean sea surface (also known as mean profile) based on 20 years of SSH from TOPEX/Poseidon to *Jason-2*. During its geodetic phase, the SLA from the *Jason-1* GM is calculated relative to a gridded mean sea surface model instead (CNES/CLS, version 2011). This difference is analyzed and discussed in [section 2g\(3\)](#).

2. Using *Jason-1* GM to study rapid oceanic changes

a. Collocating *Jason-1* GM and *Jason-2* to build new observations

An important feature of the *Jason-1* GM orbit is that it has the same inclination and almost the same altitude as

¹ *Jason-2* performs 12.7 (i.e., $12 + 7/10$) revolutions per nodal day, which results in an exact repeat cycle of 10 nodal days or 9.91 calendar days after 127 revolutions. In contrast, the *Jason-1* GM orbit performs $12 + 299/410$ (i.e., approximately 12.729) revolutions per nodal day, which results in a very long exact repeat cycle of 410 nodal days (approximately 406 calendar days).

FIG. 1. Comparison of *Jason-2* and *Jason-1* GM when both satellites are separated by less than 20 min and flying over the same ground track (less than 5 km from one another). (a) The along-track SLA of each altimeter (*Jason-2* in black, *Jason-1* GM in red). (b) The difference between both datasets (raw data in gray, smoothed profile in black). (c) The position of both tracks (*Jason-1* GM is shifted by 2° to avoid a perfect overlap with *Jason-2*) with a zoom highlighting the altimeter footprint of each altimeter.

Jason-2. The consequence is that both datasets have a ground track with the same geometry: the tracks of *Jason-2* and *Jason-1* GM sometimes align perfectly over an entire orbit revolution or more. Note that they can be measuring topography at the same position (spatial offset is less than 10 km) either at the exact same time or not (temporal offset ranges from 0 to 10 days).

In section 2b, we illustrate this property by selecting three samples out of the 1200 overlap events where the *Jason-1* GM and *Jason-2* tracks are within 10 km and 10 days from one another. The space and time distribution of the 1200 overlap events is then analyzed in section 2c. Last, a statistical analysis of all overlap events is carried out in sections 2d–f.

b. Sample overlap events from 20 min to 10 days

To illustrate the overlap methodology, we first select an overlap event occurring in the Pacific Ocean (Fig. 1) where satellites are measuring the topography within

5 km and 20 min from one another. As expected, Fig. 1a shows that the ocean topography measured by both sensors is essentially the same: it ranges from -40 to 30 cm with a standard deviation of 10 cm. Figure 1c illustrates that the geometry of both tracks is identical (*Jason-1* GM is shifted by 2° in order to be visible on the map) and that both SLA profiles are almost identical. The thumbnail zoom in Fig. 1c also gives an overview of how the altimeter footprints (here approximated as 10-km-radius circles) overlap.

Figure 1b shows the difference between both SLA profiles. This residual has a standard deviation of 4 cm. This value should be compared to the intrinsic 1-Hz noise level of Jason-class altimeters: globally on the order of 2.7 cm at 1 Hz and modulated by significant wave height. Dibarboure et al. (2014) have reported that the 1-Hz noise for *Jason-1* and *Jason-2* are not correlated, so one would expect the differences of Fig. 1b to yield a standard deviation of $\sqrt{2} \times 2.7 \text{ cm} = 3.8 \text{ cm}$, that is, very close

FIG. 2. As in Figs. 1b and 1c, but for *Jason-2* and *Jason-1* GM samples separated by (left) 2 and (right) 5 days.

to what is found in this sample. There is approximately $\sqrt{4^2 - 3.8^2} = 1.2$ cm RMS missing, which could be explained by the wave modulation of noise on this specific sample or by an additional mean sea surface (MSS) error on *Jason-1* GM that is discussed by Dibarbouré et al. (2012) and analyzed in section 2g(1). Figure 1b also shows that the difference is mainly composed of high wavenumbers, as expected from a difference dominated by such errors.

The noise floor of *Jason-1* should be compared to the 4–4.5 cm reported by Minster and Gennero (1995) for the 3-day orbit of *ERS-1*. To smooth out the influence of instrumental noise of ERS, they generated sea level anomalies with a 10-km resolution using a Lanczos filter with a 60-km cutoff wavelength, whereas we use standard 1-Hz (7 km) products and apply no smoothing whatsoever.

We also selected a few overlap events with a longer time difference to illustrate the contribution from rapid ocean changes and, in particular, from rapid mesoscale dynamics. Figure 2 shows the difference in sea level anomaly for two *Jason-1*–*Jason-2* overlaps with a 2- and 5-day lag. As in the previous example, the tracks of both satellites are aligned over an entire pass in the

western Pacific Ocean (*Jason-1* GM stays within 10 km of *Jason-2*).

Figure 2a and 2b (2-day lag) show that high-frequency noise is still a major component of the difference. Longer wavelengths (e.g., 100–500 km or more) that were barely visible in the 20-min overlap now become clearly visible. Similarly, the standard deviation is now 5 cm (vs 4 cm for the 20-min overlap): there is an additional $\sqrt{5^2 - 4^2} = 3$ cm RMS of additional energy in this 2-day overlap sample. The 5-day differences (Figs. 2c and 2d) have a standard deviation of 6 cm (i.e., 3.3-cm RMS more than in the case of the 2-day overlap of Fig. 2a) and include a wide range of wavelengths.

c. Distribution of overlap events

There are on average three overlap events per day somewhere in the world. Figure 3a shows the longitude of the equator crossing for some ascending passes of *Jason-2* and *Jason-1* GM during the first 40 days of the GM phase. The vertically aligned red dots show the 10-day repeat orbit used by *Jason-2*. The diagonally aligned blue dots of *Jason-1* GM show the longitude drift associated with the geodetic phase. In this plot, red and blue dots are sometimes overlapping (e.g., 20°E and 9 days,

FIG. 3. Overview of the space-time distribution of overlaps between *Jason-2* and *Jason-1* GM (limited to ascending passes). (a) The longitude of the equator crossing of *Jason-2* (red) and *Jason-1* GM (blue) throughout the 40 first days of the *Jason-1* GM phase. Each overlap event is highlighted with black dots and lines linking the overlapping tracks of each altimeter. (b) The longitude of the equator crossing of all events where *Jason-1* GM is within 10 km and 10 days of *Jason-2* [black lines in (a)]. (c) The distribution of the time difference between *Jason-1* and *Jason-2* measurements during these overlap events. (d) As in (c), but split into four subsequent periods of 90 days. (e) The difference in solar time between *Jason-1* GM and *Jason-2*, as a function of the overlap time difference.

respectively): these are overlap events where the spatial distance is small and the temporal distance is less than a few hours. More frequently, however, the blue dots are vertically aligned with the red dots: these are overlap events for which the temporal offset ranges from 1 to 10 days. These events are highlighted with black lines and dots linking the *Jason-2* and *Jason-1* GM tracks.

A search algorithm can locate all of the overlap events (Fig. 3b, only ascending passes are shown for the sake of clarity). Each dot represents an entire ascending arc

from 66°S to 66°N; Fig. 3b shows their distribution throughout the entire GM phase. Note that many dots are missing from days 290 to 350 due to missing data on either satellite.

The color of each dot in Fig. 3b gives the time difference between both datasets. The overlaps often come in couples: if Jason GM is over a *Jason-2* track with a δt time difference, then it will also provide an overlap with the previous or next *Jason-2* cycle (+10 days or −10 days), which results in a second overlap at $10 - \delta t$. The overlap

events also occur in clusters. It is not possible to find overlap events in all regions at all times, especially if one is looking for a specific delta time (e.g., to study the oceanic variability faster than 3 days). Fortunately, the *Jason-1* GM orbit yields a reasonably homogeneous overlap distribution illustrated by Fig. 3c, where the PDF of overlap time differences is nearly constant, with an average of 60 samples per 1-day time bin for 0–10-day lags.

This homogeneous distribution allows us to carry out statistical studies on the 1200 available samples. To illustrate, the estimation error of the mean SSH spectrum is governed by chi-squared statistics, having twice as many degrees of freedom as the number of samples. So, with 120 independent samples per time difference (e.g., for a 3-day lag), the upper bound of the mean 3-day spectrum uncertainty is on the order of 15%. This is enough to derive a global statistical analysis of the 1200 overlap events given by *Jason-1*. This dataset might be biased by specific intense events or data gaps near the end of the GM phase; however, because of their homogeneous distribution in space and over 400 days, the global results are unlikely to be skewed by an irregular temporal or spatial aggregation (e.g., as opposed to the 3-month dataset collected during the 3-day phase of *ERS-1*).

Yet the number of samples collected with *Jason-1* GM is still limited for regional or seasonal analyses: with approximately 15–30 samples per season (Fig. 3d), the uncertainty of a mean spectrum would be as high as a 30%–50%.

Last, Fig. 3e shows that the solar time of *Jason-1* GM barely drifts away from the solar time of *Jason-2*, essentially because their altitudes are almost the same. At the beginning of the GM phase, the offset in solar time seen with 0-day differences is ~ 5 min; and after 400 days of the GM phase, they are separated by 20 min. Furthermore, the solar time of *both* Jason satellites changes by approximately 12 min day^{-1} (due to a 120-day period of the so-called orbit beta-prime angle), so all overlap events with a time difference of D days will exhibit a solar time difference of $12D \text{ min} \pm 20 \text{ min}$. In other words, the time difference in days is almost an integer value: it is possible to find solar time differences ranging from -2 to 2 h, but it is not possible to find overlaps with a solar time offset ranging from 3 to 21 h. This is a limiting factor to study tides and diurnal effects, since diurnal harmonics largely cancel out in the *Jason-2*–*Jason-1* difference unless they are rapid nonstationary events.

d. Spatial properties

We have collocated the *Jason-1* GM and *Jason-2* tracks during overlap events. We split each sample into subsets of approximately 600 km, avoiding coastal zones

(50 km from the coast) and large data gaps (gaps of 20 km or less were filled by linear interpolation). Overlap events were also divided into bins of time differences (dt) ranging from 0 to 60 days. For visual representation, 1-day bins are shown from 0 to 10 days and 5-day bins are used from 10 to 60 days (e.g., the 58-day bin includes time differences ranging from 56 to 60 days).

Figure 4 shows the global statistical analysis of the overlap events. Figure 4a shows that the SLA difference has a very clean bell-shaped distribution, very peaky for 0-day differences (as expected from 1-Hz noise) and widening as the time difference increases. The associated standard deviations range from 4 cm for 0-day differences to 7 cm for 9-day differences. The samples from section 2b are representative of this global distribution.

If the signals measured by *Jason-1* and *Jason-2* are uncorrelated, then the variance of their difference will measure the sum of both sample variances. To illustrate, a 60-day difference in Fig. 4a would exhibit a very wide bell-shaped curve with a standard deviation larger than the *Jason-2* standard deviation by a factor of $\sqrt{2}$. To that extent, the power spectra from Fig. 4b were normalized by a factor of 0.5 in order to be easily comparable with the black spectrum of *Jason-2*. Furthermore, the smaller scales from 15 to 30 km cannot really be trusted as collocation/reinterpolation behaves like a low-pass filter. We have highlighted this limit as a gray box on the power spectral density (PSD).

At 0 day, the spectrum is almost flat and is dominated by instrument noise, as expected from the observations of section 2b. However, the 0-day spectrum is not perfectly flat. This contrasts with 20-Hz observations from Dibarboure et al. (2014) during the *Jason-2*–*Jason-1* tandem phase, where both altimeters yield a perfectly flat spectrum when they were observing exactly the same surface within 1 min and 300 m from one another. In overlap events, *Jason-1* can be as far as 10 km and 20 min away from *Jason-2*, resulting in small changes in wind/wave or MSS effects that are not perfectly accounted for in current altimetry products [discussed in section 2g(3)].

More importantly, the 1-day (purple) to 5-day (cyan) spectra of Fig. 4b show a rapid increase of the PSD for wavelengths $\lambda > 60$ –70 km. To illustrate, near $\lambda \sim 300$ km the PSD of a 1-day difference exhibits 2.5 times more energy than 0-day differences, and the energy is doubled again from 1- to 2-day differences. Furthermore, 5-day difference spectra have as much energy as 10% of the PSD of *Jason-2*. For longer time differences, the difference spectra increase asymptotically toward the spectrum of *Jason-2*.

This finding is surprising for two reasons: 1) the variance increase is faster than that reported by Minster and

FIG. 4. Global statistical analysis of the *Jason-1* GM–*Jason-2* overlap events. (a) The PDF of the difference from 0- to 9-day differences (purple to red). (b) The mean global spectrum of *Jason-2*–*Jason-1* GM for 0- to 60-day (purple to red) overlaps. *Jason-2* reference curves are in black.

Generro (1995) with *ERS-1*, or by Le Traon (1991) with *Geosat* data; and 2) the PSD primarily increases for wavelengths that are relatively long, rather than the smaller, rapidly moving signals.

This could be explained by two reasons.

- 1) First, the differences between *Jason-1* and *Jason-2* are limited by the noise floor (i.e., 0-day spectrum): it is not possible to observe any signal smaller than the observability limit of a 4-cm white noise (Dufau et al. 2016). The noise floor of a *Jason*-class mission is approximately 2.5 times lower than for *ERS-1*, but the noise floor is doubled in the *Jason-2* to *Jason-1* differences. Consequently, we are primarily inferring rapid changes in the larger scales that are more energetic than twice the noise floor.
- 2) Second, a 1- or 3-day difference is not a perfect measurement of the 1- or 3-day variability: the difference is also capturing a fraction of the derivative of slower signals (discussed in the appendix). For instance, assuming that a given temporal PSD is following an f^{-2} law as reported by Wortham and Wunsch (2014), time differences are merging a wide range of low frequencies (also true for f^{-1} or f^{-3}). This is also a limit of the 1D profiling nature of nadir altimeters: even for slow and stable eddies such those analyzed by Samelson et al. (2014), our overlap events are only isolated profiles across a small subset of eddies or meanders.

e. Correlation and coherence

Figure 5a shows the autocorrelation function for 0- to 60-day differences. The autocorrelation of *Jason-2* is also given. The 0-day curve has a Dirac delta shape expected from a difference dominated by white noise. In contrast, 1 day and beyond exhibit typical SLA autocorrelations (e.g., Le Traon et al. 1990) with a small negative lobe and 0-crossing values ranging from 60 km for 1-day differences to slightly more than 100 km for 60-day differences and *Jason-2*. Our curve for the global ocean is consistent with regional values reported by Stammer (1997) on the order of 120 km in the tropical band and 60–80-km scales for mid- to high latitudes. One might intuitively expect even shorter zero-crossing values for 1- to 5-day time differences, but this is likely explained by reasons 1 and 2 above.

Similarly, Fig. 5b shows the coherence γ^2 between *Jason-1* GM and *Jason-2* as colored 1D curves for 0- to 60-day lags, which exhibit a sigmoid shape. For 0-day differences, the coherence is almost 1 for long wavelengths and it decreases for higher wavenumbers as the incoherent noise of the altimeters becomes dominant.

Assuming that both *Jason* satellites are measuring exactly the same ocean spectrum $S(1/\lambda)$ for wavelength λ and an independent noise $\mathcal{E}_i$, we can define $\alpha(1/\lambda)$ as the ratio between the PSD of the noise floor and the PSD of the signal. In this simple case, the coherence can be approximated by Eq. (1). The key value of $\gamma^2 = 0.25$ is reached when $\alpha = 1$, that is, when the PSD of the

FIG. 5. Global statistical analysis of the *Jason-1* GM-*Jason-2* overlap events. (a) The mean global autocorrelation with zero-crossing values. (b) The γ^2 between *Jason-1* GM and *Jason-2* for 0- to 60-day (purple to red) overlaps. The inset in (b) is the same coherence shown in 2D (colored background) superimposed with the analytical model of Eq. (2) (black lines).

ocean signal reaches the noise floor. This defines the observability limit of ocean dynamics with a signal-to-noise ratio larger than one (Dufau et al. 2016). For our global coherence of 0-day overlap events, this point is reached for $\lambda \sim 81$ km: on average, the noise of Jason-class altimeters prevents us from analyzing scales less than 80 km in *Jason-2*-*Jason-1* differences:

$$\gamma^2(1/\lambda) = \frac{1}{[1 + \alpha(1/\lambda)]^2}. \quad (1)$$

The coherence also decreases as the time difference increases: other colored curves are still sigmoid shaped, but their upper plateau is reached at 0.9 for a 1-day lag, 0.8 for a 4-day lag, etc. The coherence is still affected by the presence of white noise, but here the alpha parameter also contains the rapid ocean variability that decorrelates between *Jason-1* and *Jason-2*.

The insert in Fig. 5b shows the coherence as a 2D image where each grid line is one of the colored 1D curves. The thumbnail is shown in logarithmic scale and as a function of the wavelength λ and time difference dt . In addition to the coherence loss from the instrument noise (right-hand side limit near 80 km), an ellipsoidal feature is also visible: this figure gives an order of magnitude of how fast the shorter ocean signals decorrelate with time. It can be approximated with the 2D sigmoid-type model below:

$$1 - 1/(1 + e^{-8(\sqrt{(\log \lambda + 3)^2 + 0.4[\log(dt) + 0.5]^2} - 1)}). \quad (2)$$

Of interest in Eq. (2) is the square root, which gives some insight about the spatial and temporal decorrelation. For example, the coherence level of 0.25 (blue/cyan) is reached for $dt = 21$ days when $\lambda > 300$ km and only $dt = 10$ days when $\lambda \sim 150$ km. This is consistent with the values reported by Le Traou (1991), where $\gamma^2 \sim 0.1$ for $dt = 17$ days and $\lambda \sim 200$ km. Therefore, our 2D coherence plot complements the existing models obtained with exact repeats ranging from 10 days (TOPEX/Poseidon) to 17 days (*Geosat*).

f. Geographical distribution and temporal properties

The regional variability can be inferred by binning the RMS of 0- to 9-day differences: the maps from Fig. 6a show the result in $10^\circ \times 10^\circ$ boxes. The map of 0-day differences is very homogeneous, although the RMS increases in zones of higher significant wave height values (which modulates the altimeter noise). If we limit the analysis to the high wavenumbers by high-pass filtering the SLA with a 60-km cutoff on *Jason-1* and *Jason-2*, then the geographical distribution is similar for all maps from 0- to 9-day lags (not shown): for these wavelengths, the distribution is not affected by the temporal offset because the instrument noise dominates.

In contrast, as soon as the time difference is not zero, various regions start to emerge in Fig. 6a. With 1-day time differences, an increase in RMS is visible in the western boundary currents and the Antarctic circumpolar region. Rapid mesoscale changes or offsets in sampling of less than 10 km are clearly dominating the

FIG. 6. (a) The binned RMS of *Jason-1* GM–*Jason-2* differences during overlap events ranging from 0 days (upper left) to 9 days (lower right). (b) The 1993–2012 mesoscale variability derived from AVISO maps.

“noise” distribution evident at zero lag. By 3–5 days, energy is also apparent in the western tropical Pacific, the eastern Indian Ocean, and in the intertropical convergence zones.

Figure 7 provides an overview of the variance increase for a small set of regions: the Gulf Stream, Kuroshio, northeast Pacific, tropical Pacific, and Mediterranean Sea. Figure 7a shows a linear increase of the variance in most regions from 0 to 10 days, and Fig. 7b shows that the variance of the difference becomes asymptotically flat as dt increases beyond 10 days. This happens rapidly in the lower energy regions and after 30–40 days in the

western boundary currents. To measure the associated e -folding time, we use the simple analytical model given by Eq. (3). Table 1 also shows that the e -folding radius varies from 19 to 42 days in the different regions and is 26 days for the global oceans (Fig. 7c). The global value is longer than that obtained by Minster and Gennero (1995) with *ERS-1* (e -folding time less than 20 days in strong currents), but it is consistent with the values found by Stammer (1997) with TOPEX/Poseidon or Le Traon (1991) with *Geosat*:

$$V(dt) = K(1 - e^{-dt/\tau}). \quad (3)$$

FIG. 7. Evolution of the global (black) and regional (colors) variance of the *Jason-2*–*Jason-1GM* difference as a function of the dt between both samples. (a) The result for 0- to 10-day differences and (b) 0- to 60-day differences. (c) The result of an analytical model fit. (d) As in (a), but expressed in percentage of the signal variance measured by *Jason-2*.

The difference with [Minster and Gennero \(1995\)](#) is probably explained by the nature of the observations. They obtained their temporal radiuses using a 2D spectral analysis in space and time (repeat orbit), whereas we measure the variance in time differences. As a result, our observation also captures a fraction of the variance of slower dynamics (see [section 2d](#)), which results in measured e -folding radiuses that are longer than what would be observed with a true repeat cycle of one day.

This effect is also visible in [Fig. 7d](#), which is the same as [Fig. 7a](#) but given in percentage of the signal variance measured by *Jason-2*. The 0-day differences show that the measurement noise accounts for 5%–15% of the total variance (note that white noise is often filtered out by the authors cited above), and the variance increases to 30%–50% of the *Jason-2* signal variance for 9-day lags. This is higher than that observed by [Minster and Gennero \(1995\)](#) with their 2D spectral analysis. To that extent, these results emphasize the difficulty of disentangling the

variance of the rapid variability from the modulation of the slow mesoscale that is captured in these observations (the [appendix](#)).

g. Discussion

1) INFLUENCE OF THE INPUT DATASETS

We have carried out this study with a so-called *calibrated* level 3 along-track sea level anomaly product

TABLE 1. The e -folding radius obtained with a fit of the analytical model on the curves from [Fig. 7b](#). [Figure 7d](#) illustrates the model fit for the global ocean.

Region	τ (days)
Global	26.5
Gulf Stream	18.8
Kuroshio	21.2
Northeast Pacific	42.6
Tropical Pacific	34.6
Mediterranean Sea	21.5

from AVISO (2015). In addition to the recently improved corrections, these calibrated data include specific steps for the long-wavelength error reduction. Dibarboure et al. (2011) describes the two-step calibration, derived from Le Traon and Ogor (1998), for the crossover minimization using *Jason-2* as a reference mission, and from Ducet et al. (2000), for the multi-altimeter calibration based on optimal interpolation. This contrasts with the processing used for *ERS-1*, TOPEX, and *Geosat* in the studies mentioned above.

The orbit determination of a Jason-class mission is almost an order of magnitude better than the accuracy of ERS or *Geosat*. Various geophysical corrections are substantially improved in current altimetry standards (e.g., better tidal models or improved dynamical atmospheric corrections). All of these parameters might affect the longer wavelengths of the *Jason-2*–*Jason-1* differences. Furthermore, the *Jason-2*–*Jason-1* multimission calibration mechanism described by Dibarboure et al. (2011) is less aggressive than the polynomial adjustments used in the previous studies.

We performed sensitivity studies to verify that these calibration algorithms improved the quality of all results and that they did not substantially affect our findings.

2) NOISE AS A LIMITING FACTOR

By far the most limiting factor in this type of study is the noise level of Jason-class measurements. The amplitude of 1-Hz measurement noise is larger than the ocean signal for wavelengths smaller than 80 km, and the global spectra at 0-day difference shows an impact in the 80–250-km range as well. This is amplified because the noise of both altimeters is random and uncorrelated, so it becomes additive when taking the difference between two topography profiles. Thus, our analysis of overlap events is limited by *twice* the Jason noise level.

Fortunately, recent studies such as Dibarboure et al. (2014), Garcia et al. (2014), and Amarouche et al. (2014) show that alternative processing techniques could be developed and applied to Jason data in order to reduce the 1-Hz noise. In the future, these techniques would be valuable additions for the study of small-scale ocean topography, and especially for Jason overlaps because of the factor of 2 in SLA differences.

3) ADDITIONAL ERRORS IN THE GEODETIC PHASE OF JASON-1

The 10-km limit we used for collocation between *Jason-2* and *Jason-1* is consistent with the radius of their altimeter footprints, yet the geoid can change a lot over a few kilometers (e.g., Dorandeu et al. 2003). Therefore, it does not cancel out in a *Jason-2*–*Jason-1* difference and it

must be removed from the SSH measurements *before* the comparison. *Jason-1* GM is on a drifting orbit, so AVISO (2015) uses a gridded MSS, namely, the CNES/CLS, version 2011, model. This MSS model is not perfect, and it can generate geoid-related residual errors in our overlap differences.

We observed (not shown) that the variance of 0-day differences always increases when *Jason-1* is shifted spatially from the true collocation with *Jason-2*. We observe a variance increase on the order of 6–7 mm RMS per kilometer. Even at distances less than 10 km away from the *Jason-2* track, using a gridded mean sea surface models yields an additional 1–2 cm in RMS error, consistent with the observations from Dibarboure et al. (2012).

This MSS error remains relatively small with respect to the mean global oceanic variability measured by Jason in Fig. 4 and with respect to the noise floor (doubled in *Jason-2*–*Jason-2* differences), which is on the order of 4 cm RMS. Indeed, the instrumental noise is up to 16 times greater than the MSS error in terms of spectral energy.

3. Consequences for Jason-2

a. Link between overlap events and the orbit to be used for Jason-2 EoL phase

These *Jason-1* GM results could be important for *Jason-2*. If there is a serious risk of losing control of the satellite, then *Jason-2* will be moved to a different orbit (EoL orbit) following the precedent established for *Jason-1*. Moreover, because *Jason-1* was lost on its geodetic orbit, it is likely that *Jason-2* will have to use a *different* GM orbit to reduce the risk of collision with the now uncontrolled *Jason-1* platform.

Dibarboure et al. (2012) defined a strategy and a handful of candidates for the *Jason-1* EoL orbit, but they did not anticipate the notion of overlap events. Consequently, the options they proposed are not optimal with respect to the potential to use *Jason-2* EoL and *Jason-3* to study rapid mesoscale changes.

To illustrate this point, Fig. 8 shows an overview of the overlap events between *Jason-3* (assumed to be on the historical TOPEX track) and a worst-case *Jason-2* EoL orbit (12 + 286/399, selected arbitrarily). Instead of a well-distributed series of overlap couples, this EoL orbit would aggregate all the overlaps in very dense clusters: over a period of 90 days, all the equator crossings of overlap events would be located in a common 180° longitude band, leaving the rest of the ocean unobserved; and each cycle would sample a different zone, making such a dataset more difficult to interpret.

FIG. 8. As in Fig. 3b, but for overlaps between *Jason-3* and an arbitrary *Jason-2* EoL orbit ($12 + 286/399$).

b. Method used to look for *Jason-2* EoL orbits

These findings suggest we can maximize the value of a *Jason-2* EoL geodetic orbit that meets the criteria used by Dibarboure et al. (2012) for good mesoscale and geodetic sampling, but also new criteria designed to provide good sampling of overlap events between *Jason-2* EoL and *Jason-3* (overlap sampling).

Maximizing the *Jason-2* GM–*Jason-3* overlap sampling means that overlap events should be homogeneously distributed in space (longitude of equator crossings) and in time (days throughout the EoL cycle) as opposed to the bad example in Fig. 8. Furthermore, for a given overlap time difference, the space–time distribution must also be as regular as possible (e.g., good distribution of 1-day overlaps).

We can gauge the homogeneity of the overlap sampling by splitting the space/time into bins (e.g., allocating each sample's equator crossing position and time into bins of 10° and 30 days) and then counting how many overlap events occur in each space/time bin. We

want to avoid empty bins, since the region would not be sampled for rapid overlapping events. Our analysis grid is based on the average number of overlaps per day between *Jason-1* GM and *Jason-2*: the grid should be full and regularly sampled when overlap events are not aggregated.²

We tested this methodology on the *Jason-1* GM orbit. Figure 9 shows the distribution in longitude and time of overlap events (red dots) and the number of events in each bin (black and white background) for overlap events of 0–10 days (Fig. 9a) and 1 day (Fig. 9b). As expected from the previous discussions, Fig. 9a exhibits a rather homogeneous sampling, since only 12 bins are empty (out of 216, i.e., 5%). This should be compared to the bad orbit of Fig. 8, which has almost 50% empty bins. Conversely,

² For overlaps of 0–10 days, we use bins of 20° and 30 days and the orbit is rejected if there are at least 15 empty bins. For overlaps of 0–1 day, we use bins of 40° and 60 days and the threshold is seven empty bins.

FIG. 9. (a) The longitude of the equator crossing of all tracks where *Jason-1* GM is within 10 km and 10 days of *Jason-2* (red dots). The background is the number of overlap events in 20° per 30-day bins (color scale). (b) As in (a), but for 1-day overlaps and 40° per 60-day boxes.

Fig. 9b highlights the primary weakness of the *Jason-1* GM orbit: the 0–1-day samples are aggregated in $100^\circ \times 100$ -day bands and there are no samples between these bands. As a result there are 15 empty bins (out of 36, i.e., 27%). Our *Jason-2* screening filter would reject the *Jason-1* GM orbit for this reason.

c. Desirable orbit options for *Jason-2* EoL

We applied this screening methodology to various orbits recommended for the *Jason-1* EoL by Dibarboure et al. (2012) and we found that all of them exhibited the same weakness as *Jason-1* GM. So, we analyzed all of the EoL orbit options (more than 20 000) and we slightly relaxed the geodetic and mesoscale criteria used for *Jason-1* in order to keep more interesting orbits, even if they were not fully optimal on every criterion.

Our three screening filters (geodetic, mesoscale, and overlap) left 70 desirable options, generally located in small altitude bands (already reported by Dibarboure et al. 2012). For each altitude band, we manually selected only one candidate using the mesoscale sampling criteria.

The final list of orbits that are recommended for *Jason-2* EoL is summarized in Fig. 10 (using the $N+P/Q$ terminology; i.e., the number of revolutions per nodal day), as well as their distribution in altitude and their strengths and weaknesses. In Fig. 10, column A gives the uniformity of the mesoscale sampling of *Jason-2* EoL plus *Jason-3* (derived from Dibarboure et al. 2012), column B

gives the density and the uniformity of the geodetic sampling of *Jason-2* EoL plus *Jason-1* GM (derived from Dibarboure et al. 2012; also discussed in section 3d), column C is the overlap criteria from section 2b, and column D gives the collision risk due to debris at each altitude (courtesy of the *Jason-2* operations team). The red box in the left panel shows the forbidden altitude zone, where there is a high risk of collision with the now uncontrolled TOPEX and *Jason-1* platforms.

The best option in this list is arguably $12 + 284/371$ at 1309 km (27 km lower than the nominal TOPEX altitude) for the following reasons (1–3 are the criteria used for *Jason-1* GM):

- 1) It has a 17-day subcycle that is good for mesoscale monitoring because it blends well with the 10-day cycle of *Jason-3*.
- 2) It has a 145-day subcycle and a 371-day repeat cycle that are good for geodesy: the final grid is close to the *Jason-1* GM grid. If *Jason-2* EoL was to die after only half the repeat cycle, it would still provide a coarser but globally homogeneous dataset for geodetic users.
- 3) It has a 4-day subcycle that is favorable for sea-state applications (e.g., assimilation in operational wave models) and that blends well with *Jason-3*'s 3-day subcycle.
- 4) It generates overlap events with *Jason-3* that are well distributed at all time scales. There are no empty bins for the 10-day criterion, and only three empty bins for the 1-day criterion (not shown). This orbit yields a

FIG. 10. Shortlist of desirable options for *Jason-2* EoL: priority list with subcycles and altitude distribution (absolute or relative to the TOPEX/Poseidon historical orbit) and qualitative value with respect to selection criteria of [Dibarboure et al. \(2012\)](#) and [section 3b](#).

high probability of collecting an overlap sample in any region, season, and for any time difference.

- 5) It is far from the uncontrolled TOPEX and *Jason-1* platforms and from the debris orbiting near 1400 km (e.g., from the Globalstar constellation).

Figure 11 shows some characteristics of the 12 + 284/371 orbit. Figure 11a shows the equator-crossing longitude for each ascending pass (red is *Jason-3* on the TOPEX–Jason orbit, blue is the proposed *Jason-2* EoL). The black circles highlight what happens when there is an overlap with an almost 0-day time difference. *Jason-3* and *Jason-2* EoL are measuring the same topography for the pass with the black dashed circle. In this configuration nearby *Jason-2* EoL tracks (dotted circles) are interleaved with *Jason-3*, thus reducing local duplication and mesoscale sampling loss (mesoscale criterion used by [Dibarboure et al. 2012](#)). Figure 11b gives the longitude of equator crossings for all overlap events with *Jason-3*. This panel essentially synthesizes why this orbit passed the screening filters of [section 3b](#).

d. Geodetic sampling

Jason-1 GM has collected a valuable dataset ([Sandwell et al. 2014](#)) with a resolution on the order of 8 km, so it would be natural to use *Jason-2* EoL to improve the geodetic record resolution. In theory, this would be achieved by putting *Jason-2* EoL exactly between *Jason-1* GM tracks to minimize the duplication between both altimeters and to achieve a resolution of 4 km. Unfortunately, an interleaved geodetic mission would require *Jason-2* EoL to use exactly the altitude of *Jason-1* GM, but this is impossible due to collision risks between both satellites.

Any other geodetic orbit will provide irregular sampling between the *Jason-1* GM tracks: in certain regions, *Jason-2* EoL will be perfectly interleaved with the *Jason-1* GM geodetic grid, and in others they will be almost exactly on the same grid. These so-called moiré patterns appear when two grids of different resolution are superimposed.

Figure 11c shows the longitude of ascending equator crossings for one full geodetic cycle of *Jason-1* GM (blue) and *Jason-2* EoL (red). The moiré bands are the alternating lighter/darker zones where the red and blue lines meet: in certain regions *Jason-2* EoL would duplicate measurements from *Jason-1* GM (resolution on the order of 8 km), whereas in others *Jason-2* EoL would complement the *Jason-1* GM grid (resolution of 4 km).

To illustrate the impact of the moiré patterns, the black line of Fig. 11c uses a maximum kernel density estimator: this 4-km radius estimator will be locally maximal when the two grids are perfectly interleaved and minimal when they are perfectly overlapping. The density estimator increases near altimeter tracks but when tracks are too close, they essentially provide duplicate measurements and the observation quality does not increase, resulting in 8-km oscillations modulated by larger arches (moiré bands) that are 41 km long.

The global geodetic sampling capability is similar for all of the selected EoL orbits. In contrast, there are differences in the size of the moiré patterns: the moiré patterns of the orbits listed in Fig. 10 were measured and they range from 20 to 500 km (not shown). Shorter moiré bands (20–40 km) as in Fig. 11c are slightly more desirable, as they spread out duplication and blind zones instead of aggregating them in large unobserved bands.

FIG. 11. As in Fig. 3, but for overlaps between *Jason-3* and a tentative *Jason-2* EoL orbit (namely, $12 + 284/371$ at 1309 km). (a) The black circles in highlight the mesoscale research criteria used by [Dibarboure et al. \(2012\)](#). (c) The moiré pattern (41 km bands at the equator) between the geodetic tracks of *Jason-1* GM (blue) and *Jason-2* EoL (red).

This is accounted for in the column B diagnostics in Fig. 10.

4. Summary and conclusions

Because of the drifting nature of the orbit used for *Jason-1* during its geodetic phase, and the geometry of its ground track (almost the same as for the *Jason-2* orbit), there are 1200 overlap events where both altimeters are measuring the ocean topography over the same track (less than 10 km; i.e., the altimeter footprint radius) over an entire pass, that is, thousands of kilometers. The overlap events sample homogeneously all longitudes and all time differences.

When the time difference is almost zero, the difference is characterized by 1-Hz altimeter noise and its modulation by waves. As dt increases, the rapid ocean

variability is revealed. Our statistical analysis yields variance maps, spectra, autocorrelation, and space–time scales that are consistent with past observations (e.g., 3-day phase of *ERS-1*). These first findings highlight the value of this *Jason-1* GM overlap dataset for more sophisticated studies of the rapid ocean variability but also two major limitations: 1) the noise level of Jason-class altimeters prevents us from analyzing scales smaller than 80 km and 2) short time differences also absorb a fraction of the derivative of slower signals.

These findings are important for *Jason-2* if a geodetic phase is considered in the coming years (e.g., when the satellite starts to exhibit aging problems) because *Jason-2* GM and *Jason-3* have the potential to collect a better dataset if *Jason-2* GM uses an orbit with specific properties. By extending the search criteria used by [Dibarboure et al. \(2012\)](#) for *Jason-1* EoL with new criteria

FIG. A1. Frequency sampling in time differences dt . (a) A simple monochromatic signal with a period of 30 days (plain) and what is measured in 1-day differences of subsequent points (dashed). (b) The fraction of variance of a monochromatic signal measured in $S(t+dt) - S(t)$ as a function of the signal period and dt . (c) The PSD of 1- to 30-day differences (colors) if the true signal PSD is following an f^{-2} power law (black line).

designed to guarantee that overlap events are homogeneously distributed in space and time, we selected a small subset of desirable orbits.

The subset of collocated *Jason-1* and *Jason-2* tracks used in this study can be made available to other scientific users for further studies on the altimeter noise and its geographical modulation, or on the rapid ocean dynamics. The selection of tracks is provided as supplementary material (refer to JTECH-D-16-0015.s1).

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APPENDIX

What is Measured in *Jason-1* GM–*Jason-2* differences?

Because of the nonrepeat nature of overlap events between *Jason-1* GM and *Jason-2*, the observations are randomly distributed samples with 0- to 60-day differences. The major caveat is that a 1-day difference is measuring a wide range of frequencies, not just 1-day variability. Figure A1 illustrates this effect with simple monochromatic signals having periods ranging from 2 to 60 days.

Figure A1(a) shows an example for a 30-day signal (plain line) that is partially observed through 1-day differences (i.e., difference between subsequent dotted points). If the time difference is small with respect to the true period (here, 1 day vs 30 days), then the difference includes a derivative of the true signal and captures a fraction of its variance. Repeating this process for all periods and all time differences, we obtain Fig. A1(b), which shows the fraction of the true signal variance that is absorbed in a SLA difference for dt ranging from 1 to 30 days. To illustrate, the 3-day differences absorb the variance of a wide range of monochromatic signals with periods ranging from 1.5 days ($dt/2$ —aliasing) to 30 days with a peak for monochromatic signals with a period of 6 days ($2dt$). The folding of long periods into the *Jason-2*–*Jason-1* differences decreases with the period ω following a power law of ω^{-2} , that is, f^{+2} , where f is the frequency.

Assuming that the ocean PSD or variance is following an f^{-2} law (as per Wortham and Wunsch 2014), we obtain

Fig. A1(c), which yields an approximation of the frequencies contained in 1- to 30-day differences. For a time difference of dt , the spectrum is flat for periods longer than $2dt$. The spectra then decrease slowly for periods close to dt , and then decrease rapidly for periods smaller than $dt/2$. Thus, measurements based on time difference dt are essentially merging equally all periods that are substantially longer than dt (observation of the derivative) and as small as $dt/2$ (aliasing). Figure A1 is therefore interesting as a warning that *Jason-1* GM–*Jason-2* differences should be interpreted with care, since slower variability is assuredly affecting our results.

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