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1 Validation of Jason-3 tracking modes over French rivers

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3 Sylvain Biancamaria¹, Thomas Schaedele¹, Denis Blumstein^{1,2}, Frédéric Frappart^{1,3}, François
4 Boy², Jean-Damien Desjonquères^{2,*}, Claire Pottier², Fabien Blarel¹, Fernando Niño¹

5
6 ¹ LEGOS, Université de Toulouse, CNES, CNRS, IRD, UPS - 14 avenue Edouard Belin, 31400
7 Toulouse, France

8 Email addresses: sylvain.biancamaria@legos.obs-mip.fr; thomas.schaedele@legos.obs-mip.fr;
9 denis.blumstein@cnes.fr; fabien.blarel@legos.obs-mip.fr; fernando.nino@legos.obs-mip.fr

10 ² CNES - 18 avenue Edouard Belin, 31401 Toulouse Cedex, France

11 Email addresses: francois.boy@cnes.fr; jean-damien.m.desjonquieres@jpl.nasa.gov;
12 claire.pottier@cnes.fr

13 ³ GET, Université de Toulouse, CNRS, IRD, UPS - 14 avenue Edouard Belin, 31400 Toulouse,
14 France

15 Email address: frederic.frappart@get.obs-mip.fr

16 * Now at JPL - 4800 Oak Grove Drive, Pasadena, CA 91109, USA

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19 Abstract

20 Satellite nadir radar altimeters have been widely used to measure river and lake surface water
21 elevations. They can now retrieve the elevations of some rivers less than 200 m wide. However,
22 as these satellite missions are primarily designed to observe ocean surface topography, they are
23 not always able to observe continental surfaces. For steep-sided rivers (i.e. in river valleys no
24 more than a few km wide and surrounded by slopes over 50 m high), altimeters tend to observe
25 the top of the surrounding topography rather than the river itself.

26 The Jason-3 altimetry mission, launched in January 2016, has an alternative instrument operation
27 mode, the so called Open-Loop (OL) or Digital Elevation Model (DEM) tracking mode. This
28 mode is intended to help overcome this issue, by using an on-board DEM. However it was not
29 used in 2016 as the operational mode because of difficulties in defining an accurate on-board
30 global-scale DEM. Mainland France has been chosen to test the OL tracking mode, as water
31 masks and DEMs of sufficient accuracy are available.

32 Following the launch of Jason-3, Jason-2 (its predecessor) was maintained on the same nominal
33 orbit as its follow-on, for more than 6 months. During this tandem period, data from the first 10
34 Jason-3 cycles (a Jason-2/-3 cycle corresponds to 10 days) were acquired in the traditional
35 Closed-Loop (CL) tracking mode. Jason-3 data from the last 13 cycles were acquired in OL
36 tracking mode. Jason-2 was always in CL tracking mode. Compared to nearby in situ gages and
37 for river wider than 100 m, Jason-3 water elevation anomalies have a RMSE between 0.20 and
38 0.30 m for most reaches. Jason-3 performance over narrow rivers is similar to that of Jason-2. In
39 CL tracking mode, Jason-3 altimeter tends to be locked over the surrounding topography more
40 frequently than Jason-2 (due to the specific post-launch Jason-2 altimeter tuning). This study
41 shows that Jason-2 observed 60% of river reaches studied (48 of 86 reaches), whereas Jason-3 in

42 OL tracking mode was able to measure all river reaches for every cycle. This result clearly
43 highlights the significant advantages of the OL tracking mode for observation of steep-sided
44 rivers. However, further investigations are required to compute an accurate on-board global-scale
45 DEM and to determine those locations where the use of OL tracking mode is or is not
46 appropriate.

47

48 Keywords: Jason-3; altimetry; rivers; Open-Loop/DEM tracking mode

49

50 1. Introduction

51 Continental water plays an important role in the Earth's water and energy cycles, and is at the
52 interface between the atmosphere and the ocean. For climate studies, long-term (i.e. multi-
53 decadal) observations of the time variations in lake and river levels are necessary to estimate lake
54 storage variability and river discharges. These data are also essential for water management, as
55 water is a resource that is vital to human societies. This monitoring has traditionally been
56 performed using in situ gage networks, which are usually operated at local or national level.
57 However, viewed from a global perspective, in situ networks are heterogeneous. The total
58 number of gages has been decreasing over recent decades (IAHS Ad Hoc Group on Global Water
59 Data Sets et al., 2001), and their measurements are not always shared publicly, especially in
60 transboundary basins (Gleason and Hamdan, 2017). That's why, satellite data, including water
61 elevation measurements obtained from radar altimeters have been used since the early 90's as an
62 additional observation system (e.g. Birkett, 1995), even if they cannot replace in situ gages, as
63 noted by Fekete et al. (2012).

64 Since the launch in August 1992 of Topex/Poseidon, developed by NASA (National Aeronautics
65 and Space Administration) and CNES (Centre National d'Études Spatiales), nadir radar
66 altimeters have been widely used to measure ocean surface topography, which was the scientific
67 objective of the mission (e.g. Fu and Cazenave, 2001). However, soon after its launch, the high
68 potential of the altimeter to retrieve river and lake water elevations has been demonstrated by
69 Koblinsky et al. (1993). In the present study, water elevation is defined as the distance from the
70 water surface to a reference surface (an ellipsoid or a geoid). Pioneering studies demonstrated
71 that 24 large lakes (with an area greater than 300 km²) and 8 large rivers (more than 2 km wide)
72 could be measured accurately with, at best, RMSE (Root Mean Square Error) of around 0.04 m
73 and 0.11 m respectively (Birkett, 1995; 1998). Subsequently, radar altimetry has been
74 increasingly used to monitor inland water bodies (for review see for example Crétaux et al.,
75 2017). The launch of Topex/Poseidon was followed by that of several nadir altimetry satellites:
76 ERS-2 in 1995, GFO in 1998, Jason-1 in 2001, ENVISAT in 2002, Jason-2 in 2008, CryoSat-2 in
77 2010, SARAL in 2013, Jason-3 in 2016 and Sentinel-3A in 2016. Online databases (G-REALM,
78 https://www.pecad.fas.usda.gov/cropexplorer/global_reservoir/; Hydroweb,
79 <http://hydroweb.theia-land.fr>; River and Lake database,
80 <http://tethys.eaprs.cse.dmu.ac.uk/RiverLake/shared/main>; DAHITI, <http://dahiti.dgfi.tum.de>;
81 HydroSat, <http://hydrosat.gis.uni-stuttgart.de/php/index.php>) using this series of altimeters have
82 been developed over recent decades to provide freely accessible water elevation time series for
83 selected rivers and lakes. Continuity of measurements is also guaranteed, as many nadir altimetry
84 missions are already scheduled for launch in the near future. These include Sentinel-3B (early
85 2018), Sentinel-3C and -3D (launch dates currently unknown, as they will provide continuity of
86 observation after Sentinel-3A and -3B), Sentinel-6/Jason-CS A (around 2020), and SWOT

87 (around 2021; this satellite will carry not only a nadir altimeter, but also a wide swath altimeter).
88 Even where the instrument footprint on the ground is a few kilometres wide, enhancements made
89 to the instruments, especially after ENVISAT and Jason-2, have improved the ability to observe
90 smaller water bodies (width < 500 m) to an extent not previously thought possible (e.g. Santos da
91 Silva et al., 2010; Michailovsky et al., 2012; Baup et al., 2014; Frappart et al., 2015a; Sulistioadi
92 et al., 2015; Biancamaria et al., 2017). The ability of an altimeter to observe a river is dependent
93 on river width, but is determined to an even greater extent by the “surrounding topography, the
94 observation configuration, previous measurements and the instrument design” (Baup et al., 2014;
95 Biancamaria et al., 2017).

96 Nadir altimeters present some limitations. For instance, they provide elevation measurements
97 only along or close to their track (in the nadir direction or in a quasi-nadir direction) and
98 therefore miss many water bodies (the number of objects overflowed depends on the satellite
99 orbit). In addition, altimeters are mainly designed to observe oceans with the best accuracy. They
100 are not optimized for the monitoring of continental surfaces, which could pose a problem with
101 steep-sided rivers. For these rivers, the altimeter might measure the top of the surrounding
102 topography, instead of the river valley. This problem has been extensively described and
103 discussed by Biancamaria et al. (2017). However, in the future, more researchers and water
104 resources managers will be interested in the water elevation of steep-sided rivers and smaller
105 rivers. It is therefore important to address this issue as soon as possible, in order to obtain the
106 longest possible time series in the coming decades, over regions previously unobserved by
107 altimetry. To do so, CNES has developed an alternative instrument operating mode, usually
108 referred to as “Open-Loop” (OL) or Digital Elevation Model tracking mode or DEM tracking
109 mode. It requires the loading of an along-track DEM on board the altimeter. Very few studies

110 have analysed measurements made for such rivers in this tracking mode, in comparison with the
111 usual “Closed-Loop” (CL) tracking mode (Birkett and Beckley, 2010).

112 The purposes of this study are: (1) to validate measurements of the newly launched Jason-3
113 satellite (17 January 2016) for small to medium-sized rivers (between 35 m and 300 m wide)
114 over mainland France and (2) to study whether the Jason-3 alternative instrument operating mode
115 is able to overcome the problem of the measurement of steep-sided rivers and is therefore
116 advantageous. Section 2 of this paper discusses nadir altimetry and its potential issue with steep-
117 sided rivers. Section 3 introduces the study domain and the validation data used (sub-section
118 3.1), the computation of the Jason-3 on-board DEM over the study domain and the Jason-3 data
119 validation methodology (section 3.2). Section 4 then presents and discusses the results obtained.
120 Finally, some conclusions and perspectives on the use of Jason-3 for the measurement of small to
121 medium-sized rivers, in particular those that are steep-sided, are provided in section 5.

122

123 2. Satellite Nadir Radar Altimetry and the issue of steep-sided water bodies

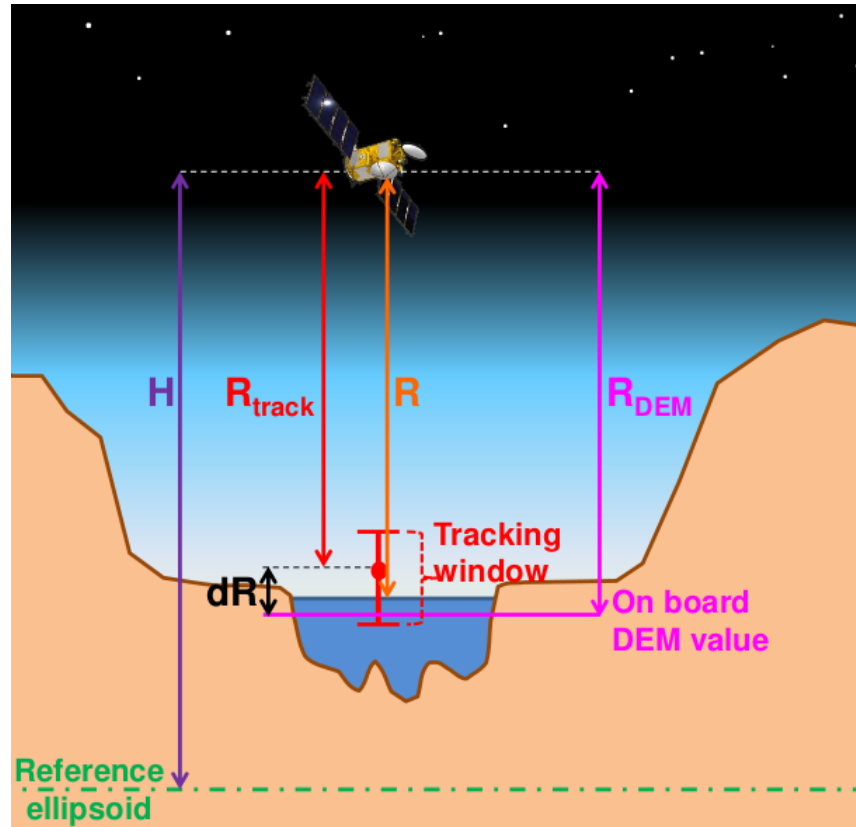
124 2.1. Surface Elevation retrieval from nadir altimetry

125 Nadir altimeters provide water elevation measurements at the intersections between satellite
126 ground tracks and rivers (or lakes/reservoirs). These intersections are usually referred to as
127 “virtual stations” (VS). A more detailed description of water surface elevation estimation from
128 nadir altimetry over continents can be found, for example, in Biancamaria et al. (2017) and in
129 Crétaux et al. (2017). For this reason, essential information only is mentioned in this section.

130 Nadir altimeters emit a radar pulse in the nadir direction (or local vertical, Figure 1) and then
131 record the radar echo using a pulse compression technique. This record, also known as the
132 waveform, contains the value of the returned power as a function of time or, equivalently, of

133 distance between the radar and the reflectors (Chelton et al., 2001; Frappart et al., 2017). The
134 two-way travel time (T), given by the leading edge of the waveform signal, is estimated
135 accurately using a “retracking” algorithm applied to the waveforms by the mission processing
136 centre. This processing is based on the use of a theoretical model built for ocean conditions
137 (Brown, 1977) and provides a high level of precision and accuracy over oceans. Over inland
138 waters, estimation of the two-way travel time is more difficult since the waveform shape,
139 affected by several complex backscattering phenomena, differs markedly from the theoretical
140 model. For these cases, alternative retracking algorithms should be used (e.g. Frappart et al.,
141 2006). The two-way travel time T is converted to the distance between the satellite centre of
142 mass and the ground surface, called the altimeter “range” (R, Figure 1), assuming a constant
143 electromagnetic wave propagation speed equal to the speed of light in vacuum. However,
144 estimates of the range R need to be corrected for propagation delays of the radar signal within
145 the atmosphere (these corrections are labelled $\Delta R_{\text{propagation}}$) and for some known geophysical
146 signals that affect measurement (these corrections are labelled $\Delta R_{\text{geophysical}}$) (e.g. Chelton et al.,
147 2001; Frappart et al., 2017). In our study, $\Delta R_{\text{propagation}}$ includes the ionosphere correction, the dry
148 troposphere correction, and the wet troposphere correction (for more details, see Biancamaria et
149 al., 2017). $\Delta R_{\text{geophysical}}$ corresponds to corrections for crustal vertical motions due to the solid
150 Earth and pole tides. Moreover, the satellite altitude (H, Figure 1) can be calculated with an
151 accuracy better than 0.02 m (e.g. Couhert et al., 2015). All these computations allow for the
152 estimation of the ground elevation above the reference ellipsoid (h) from the nadir altimeter, as
153 follows:

$$154 \quad h = H - (R + \Delta R_{\text{propagation}} + \Delta R_{\text{geophysical}}) \quad (1)$$



155

Figure 1. Conceptual view of nadir altimeter measurements and notations used in this study (the copyright of the Jason-3 satellite image used in this sketch belongs to CNES/Mira Production)

156

157 This study has processed data from the Jason-2 and Jason-3 altimetry missions. The Jason-2
 158 satellite was launched on 20 June 2008 and was developed by CNES, EUMETSAT (European
 159 Organisation for the Exploitation of Meteorological Satellites), NASA, and NOAA (National
 160 Oceanic and Atmospheric Administration). Its main payload comprises the Poseidon-3 dual
 161 frequency (Ku- and C-bands, 13.575 GHz and 5.3 GHz respectively) radar altimeter
 162 (Desjonquères et al., 2010). Jason-2 is on a 10-day repeat cycle orbit at an altitude of 1336 km,
 163 and a 66° inclination. Its ground-track spacing is around 315 km at the equator and 220 km over
 164 mainland France. Jason-3, developed by the same agencies as Jason-2 plus the European Union
 165 (through the Copernicus program), was launched on 17 January 2016 and was put on the same
 166 orbit as Jason-2. The two satellites were 80 seconds apart. Jason-3 has a similar payload to

167 Jason-2, in particular a Poseidon-3 class altimeter (Poseidon-3B). After more than 6 months
168 sharing a common orbit, Jason-2 was put on an “interleaved” orbit on 13 October 2016. This has
169 the same characteristics as its previous orbit, but is shifted in longitude by half the ground-track
170 spacing at the equator.

171

172 2.2. Altimeter tracking modes

173 For technical reasons associated with the pulse compression technique used for emission and
174 owing to the limited signal bandwidth (Chelton et al., 2001), the altimeter records the power
175 returned from the ground over only a limited window of ranges (called “tracking window” on
176 Figure 1). The vertical size of the range window (see Figure 1) for Poseidon-3 class altimeters
177 (i.e. for Jason-2 and Jason-3) is equal to 50 m. As it is orders of magnitude smaller than the
178 altitude of the satellite (around 1336 km), this window needs to enclose the water surface
179 elevation. Otherwise, the altimeter processing unit will not receive any signal backscattered by
180 the river and it will not be possible to derive the actual river elevation. The position of this
181 window (R_{track} on Figure 1) is continuously updated on board to roughly follow the ground
182 topography. This process is called “tracking”. It is performed automatically by the Adaptive
183 Tracking Unit (ATU), based on the analysis of waveforms received previously. More information
184 on the ATU system can be found in Chelton et al. (2001) and Desjonquères et al. (2010). This
185 tracking mode is generally referred to as the “autonomous” or “Closed-Loop” (CL) mode. The
186 retracking processing determines the position of the water surface in the waveform (a distance
187 known as epoch). Finally, the range R is estimated using equation (2).

$$188 \quad R = R_{track} + epoch \quad (2)$$

189 As nadir altimeters are designed to observe oceans, the ATU is not optimized to follow
190 continental surfaces, where elevations may vary by tens to hundreds of meters over an along-
191 track distance of a few kilometres. This is an issue for steep-sided rivers enclosed in valleys that
192 are a few kilometres wide (i.e. similar to the footprint of the instrument) and more than 50 m (i.e.
193 a distance greater than the tracking window size) lower than the surrounding hills. In this case,
194 the altimeter can remain “locked” on the top of the surrounding hills (or even lose tracking data)
195 and never observe the river below. This problem could even occur with slightly shallower
196 valleys. More detailed explanations and specific examples of this issue can be found, for
197 instance, in Biancamaria et al. (2017).

198 A new instrument mode, implemented on board Jason-2, SARAL, Jason-3, and Sentinel-3A/B,
199 was designed by CNES and its contractors to solve this specific issue. It consists in setting the
200 tracking window to an *a priori* value close to the river valley elevation, rather than letting the
201 ATU estimate its position based solely on previous waveforms. This solution requires storing on
202 board *a priori* elevation values for targets of interest (e.g. water bodies), as well as their location
203 along the satellite track. Then, the on-board software uses these *a priori* elevations and the
204 altitude of the satellite computed in real time by the DIODE (Doris Immediate Orbit on board
205 Determination) software to force the tracking window to these positions when the satellite
206 overflies them (Desjonquères et al., 2010). To build the on board tables used by the OL tracking
207 mode, an *a priori* list of targets of interest (therefore a water mask) and an elevation associated
208 with each target is required. Accuracies of both target geolocation and associated elevation are
209 crucial to the observation of these water bodies. Therefore, the OL tracking mode has been used
210 on a very small number of cycles on Jason-2 (cycles 3, 5, 7, 34, 209, and 220) and on SARAL
211 (passes 601 to 800 during cycle 1). The elevations used by Jason-2 over France were taken from

212 the 1 km Altimetry Corrected Elevation global DEM (ACE; Berry et al., 2000) and the water
213 mask from the Generic Mapping Tools (GMT, <http://gmt.soest.hawaii.edu/>) (Desjournès,
214 2009). The *a priori* global DEM used for water body elevations for SARAL was ACE2 (Berry et
215 al., 2010) and the land/water mask was derived from Globcover
216 (http://due.esrin.esa.int/page_globcover.php), supplemented by some water body elevations
217 available on the Hydroweb database.

218 In OL mode, the leading edge of the waveform (therefore the tracking window, see Figure 1)
219 should ideally be centred on the first third of the tracking window. As this window size is around
220 50 m for Jason-2 and Jason-3, CNES estimated that the accuracy for water body *a priori*
221 elevations should be around ± 10 m.

222 The OL tracking mode has not been studied extensively. Birkett and Beckley (2010) evaluated
223 both the CL and the OL tracking modes for Jason-2 over 28 lakes and reservoirs. For these
224 targets, they found that CL and OL modes provide similar results when the water body is
225 observed in both modes, but that the CL mode observed more targets than the OL mode. Birkett
226 and Beckley (2010) assumed that “inadequate resolution and/or data in the DEM” might be the
227 reason for OL mode underachievement in comparison with CL mode. They concluded that the
228 on-board DEM might not be “optimized for all regions”. Biancamaria et al. (2017) showed that
229 some locations in the steep-sided Garonne River valley (within mainland France) could not be
230 observed by nadir altimeters in CL mode. During the first SARAL cycle, two VS were observed
231 in OL mode. The on-board DEM value for one VS was close to the river valley elevation and
232 therefore the river was observed (which was not the case during subsequent cycles in CL mode).
233 However it was not the case for the second VS. The issue was an incorrect water mask and not a
234 lack of accuracy in the *a priori* DEM used to compute the on-board DEM. For this reason

235 Biancamaria et al. (2017) concluded that the on-board DEM is highly dependent on both input
236 water mask and the *a priori* DEM used, which should be internally consistent.
237 The launch of Jason-3 and the need to validate its measurements during 2016 represented a good
238 opportunity to construct a finely tuned on-board DEM over a specific zone, where precise local
239 DEMs are available. The methodology used to achieve this end and the results obtained are
240 presented in the following sections.

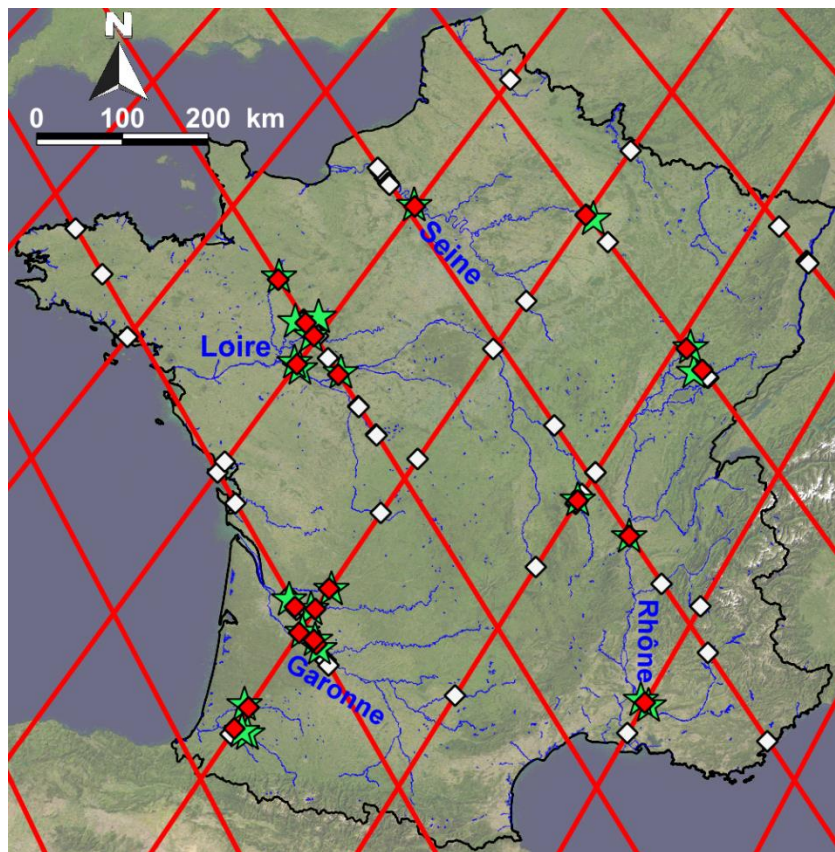
241

242 3. Methods

243 3.1. Study domain and a priori/validation data

244 The study domain chosen to validate Jason-3 measurements over rivers corresponded to
245 mainland France (Figure 2). The four main rivers (ranked by their mean annual discharge at their
246 outlet indicated in brackets) in this study domain are: the Rhône ($1700 \text{ m}^3 \cdot \text{s}^{-1}$), the Loire (900
247 $\text{m}^3 \cdot \text{s}^{-1}$), the Garonne ($600 \text{ m}^3 \cdot \text{s}^{-1}$) and the Seine ($520 \text{ m}^3 \cdot \text{s}^{-1}$). This region was selected because of
248 the large number of in situ gages operated by regional public agencies, i.e. DREALs (Directions
249 Régionales de l'Environnement, de l'Aménagement et du Logement). These observations are
250 collected by the SCHAPI (Service Central d'Hydrométéorologie et d'Appui à la Prévision des
251 Inondations), which releases them publicly via the online 'Banque Hydro' national database
252 (<http://www.hydro.eaufrance.fr>) within a period of a few weeks to a few months. Gages used in
253 this study are shown in Figure 2 (green stars). Their records were downloaded from the Banque
254 Hydro database or obtained directly from the operator (DREALs). For all these gages, water
255 elevations measured were referenced to NGF-IGN69, the official vertical reference system for
256 mainland France. Their measurements were available for the period of interest: the tandem phase
257 when Jason-2 and Jason-3 shared the same orbit and ground track. The time series obtained from

258 these gages have a non-uniform time step, which is dependent on the water elevation stage.
259 Instruments automatically adjust recording time steps to water elevation variations. However, the
260 median time step for all gages is, on average, around 30 minutes.
261 Figure 2 shows Jason-2/-3 tandem phase orbit tracks (red lines) superimposed on the study
262 domain and their 86 intersections or VS (white and red diamonds) with rivers indicated as wider
263 than 50 m in the IGN (Institut National de l'Information Géographique et Forestière) BD
264 Carthage database (available at www.sandre.eaufrance.fr). The VS with the maximum river
265 width (~300 m) is obtained for the most downstream orbit intersection with the Loire River (near
266 La Ménitré, at -0.280°E and 47.393°N).



267
Figure 2. Study domain (Mainland France, delimited by the black line) and the river network (light blue lines) from the IGN BD Carthage database (only rivers wider than 50 m according to this database are shown). Red lines correspond to Jason-2 and Jason-3 tandem phase orbit tracks. White and red diamonds correspond to virtual stations (VS), where Jason-3 on-board DEM values were computed. Red diamonds are virtual stations where Jason-2 and Jason-3 river

elevation time series were compared to in situ gage (green stars) measurements. The background image is derived from the NASA MODIS “Blue Marble Next Generation” image (Stöckli et al., 2005)

268

269 3.2. Jason-3 on-board DEM and validation methodology

270 3.2.1. On-board DEM computation over France

271 The IGN BD Carthage database with rivers wider than 50 m corresponds to the water mask used

272 in this study. These river reaches were intersected with the Jason-2/-3 orbit obtained from the

273 Aviso+ website (<http://www.aviso.altimetry.fr>), leading to the creation of 89 VS. Three

274 intersections with the river network and orbit tracks in the most southern part of the Garonne

275 basin (see Figure 2) were not selected. For these locations the on-board DEM has been set by

276 CNES to the altitude of transponders used for calibrating/validating the altimeter.

277 Next, it was necessary to estimate the DEM values for the 86 selected VS (white and red

278 diamonds on Figure 2). This was achieved using the 25 m resolution DEM from IGN’s BD Alti

279 database (<http://professionnels.ign.fr/bdalti>). The absolute vertical accuracy of this DEM is

280 assessed by IGN at between 2 to 8 m, depending on the local data source used. Elevations are

281 provided as integers and are referenced to the NGF-IGN69 vertical reference system. Rather than

282 simply extracting DEM values at the position of each VS, to take into account the facts that (1)

283 the altimeter ground footprint is a few kilometres wide, (2) the satellite ground track is controlled

284 to within ± 1 km around its nominal position (Dumont et al., 2016) and (3) rivers are in the lowest

285 part of the valley, we computed the minimum elevation over a 2 km radius centred on each VS.

286 Different values of this radius have been investigated (1 km to 5 km). A 2 km radius is a good

287 compromise between having sufficient variation to capture the river elevation (when compared

288 to a small number of VS close to a gage) and not being excessively impacted by elevations

289 outside the river valley targeted. As a quality check, the DEM was inspected visually and

290 comparisons made with Google Earth images for the 22 VS where the difference between the
 291 minimum elevation computed on this circle and the elevation of the closest Banque Hydro
 292 database in situ gage was greater than 10 m. Different cases were observed as follows: the
 293 difference was due to an obvious issue with the gage elevation in the Banque Hydro, the closest
 294 gage was on a different river to the VS, or the VS was on a reservoir and the gage was not (or the
 295 reverse). For each case, the final elevation value was selected manually to take into account the
 296 specificity of each case and the local topography in the vicinity of the VS. For all other VS, the
 297 minimum elevation on the 2 km circle was selected. This radius might change a little for regions
 298 other than France, depending, for example, on the accuracy of the DEM and the water mask. But
 299 the methodology should be fairly robust, easily adapted to any other location, and should not be
 300 specific to French rivers. Finally, these elevations were sent to CNES, which uploaded them on
 301 board Jason-3 on 2 May 2016.

302 3.2.2. Validation of Jason-3 measurements

303 Between 17 February and 2 October 2016, Jason-2 (cycles 281 to 303) and Jason-3 (cycles 1 to
 304 23) flew on the same orbit, 80 seconds apart. Therefore, they observed the same locations almost
 305 simultaneously, which allowed the direct comparison of measurements from both satellites.

306 Jason-2 was in CL tracking mode throughout the study period, whereas thirteen Jason-3 cycles
 307 were in OL tracking mode, for the most part after May 2016 (see Table 1 for cycle numbers and
 308 start dates). Therefore, it is possible to evaluate the benefits of the OL tracking mode for small to
 309 medium-sized steep-sided rivers by comparing Jason-3 cycles in OL mode to Jason-2 data and in
 310 situ measurements.

Table 1. Number and start times of Jason-3 cycles in OL tracking mode, during the shared orbit period with Jason-2

Jason-3 cycles in OL tracking mode	Cycle start time
------------------------------------	------------------

9	06 May 2016
11	26 May 2016
12	05 June 2016
13	15 June 2016
14	25 June 2016
15	05 July 2016
16	15 July 2016
17	25 July 2016
18	04 August 2016
19	13 August 2016
21	02 September 2016
22	12 September 2016
23	22 September 2016

311

312 To validate Jason-3 measurements (section 4), an initial qualitative test was performed to
313 compare Jason-2 and Jason-3 measurements over the 86 VS. For each VS, the absolute
314 difference (noted dR on Figure 1) between R_{track} (the tracked distance between the satellite and
315 the tracking window, see Figure 1 and section 2.2) and R_{DEM} (the distance between the satellite
316 and the position of the surface given by the DEM, see Figure 1) was computed. dR allows to
317 quantitatively estimate how the position of the tracking window in CL mode is far from the on
318 board DEM value (which should be close to the river elevation). Figure 1, illustrates a case when
319 Jason-3 in CL mode successfully observes the river. In this case, dR is smaller than the size of
320 the tracking window. Therefore, dR should provide useful information to assess if a SV in CL
321 mode observe the river (dR much smaller than 50 m) or the surrounding topography (dR higher
322 than 50 m). That's why, in section 4, its temporal mean value for Jason-3 cycles in CL mode is
323 analysed. Similar averages were computed for corresponding Jason-2 data during the same

324 cycles. It allowed us to estimate, on average, how the tracked elevation differs between Jason-2
325 and Jason-3, when their altimeters are both in CL mode and when Jason-3 is in OL mode and
326 Jason-2 is in CL mode. In addition, the backscatter coefficient, which takes a high value in the
327 event that water contributes to the power recorded by the altimeter (e.g. Frappart et al., 2015c),
328 was analysed.

329 For quantitative validation, all VS close to a “Banque Hydro” in situ gage were selected. For
330 these VS, Jason-2 and Jason-3 measurements were processed to extract elevation time series (see
331 section 2.1), without using any *a priori* information from the gage time series. Jason-3 time
332 series were computed using all available measurements, without differentiating between cycles
333 in CL mode and in OL mode. For both Jason-2 and Jason-3, some cycles had valid measurements
334 of river elevations for many VS, whereas other cycles measured the elevations of the surrounding
335 topography. Measurements from the latter cycles were easily excluded, as they were much higher
336 than those of valid cycles. For this reason, some VS time series present observation gaps.

337 A thorough inspection led to the selection of 24 in situ gages (Figure 2, green stars) which were
338 compared to 21 VS (Figure 2, red diamonds). The number of VS selected was different to the
339 number of gages selected, as some VS had two in situ gages sited nearby (one upstream and one
340 downstream), or conversely, some gages were sited close to two VS. The selection criteria were
341 that (1) the distance between gages and VS should be a few kilometres, (2) they should be
342 located on the same river with no large intervening tributaries, and (3) the in situ gage time series
343 should be available from the Banque Hydro or directly from regional DREAL agencies (see
344 section 3.1). More information (WGS84 longitude/latitude coordinates, river width, and the
345 intervening distance) for each pair of gage and VS compared is presented in the supplementary
346 material.

347 To carry out this quantitative assessment for validation purposes, Jason-2 and Jason-3 time series
348 were both compared to the in situ gage time series, using the same statistical tests as Biancamaria
349 et al. (2017): correlation coefficient, mean bias, and Root Mean Square Error (RMSE) between
350 the two time series for absolute water elevations referenced to NGF-IGN69. In situ and altimetry
351 water elevation anomalies were also computed, by removing their respective temporal mean
352 (calculated for the same common dates). The RMSE and the Nash-Sutcliffe (NS) coefficient
353 (Nash and Sutcliffe, 1970) were computed for anomalies. The NS coefficient (which varies
354 between $-\infty$ and 1) was used in this study for its ability to assess the accuracy of the match
355 between two time series, both in time and amplitude. It is more informative than the correlation
356 coefficient, which only provides information about the linear relationship between two time
357 series, without taking into account amplitude agreement (Moriassi et al., 2007). The NS
358 coefficient for absolute elevation is not provided, as a bias is expected between altimetry
359 measurements and the gage time series, caused at least partly by the slope of the river between
360 the VS and the gage.

361 The Jason-2 and Jason-3 data used in this study were taken from the Geophysical Data Records
362 (GDR), version D, provided by the CNES/NASA processing centres and formatted by the Centre
363 de Topographie de l'Océan et de l'Hydrosphère (CTOH, <http://ctoh.legos.obs-mip.fr>) in a
364 consistent NetCDF format with geophysical corrections coherent with previous altimetry
365 missions. The retracking algorithm used in this study is Ice-1/ICE (Wingham et al., 1986), as
366 recommended by Frappart et al. (2006) for continental surfaces. Water elevation time series were
367 computed using Multi-mission Altimetry Processing Software (MAPS) that allows a refined
368 selection of valid altimetry data to build VS (Frappart et al., 2015b). MAPS is a graphical user
369 interface that allows the loading of altimetry data formatted by CTOH that are located within the

370 boundaries of a VS polygon, the computation of water elevations using Eq. 1 and the manual
371 selection/removal of some measurements. These water elevations provided by MAPS correspond
372 to ellipsoid heights. They have then been referenced to NGF-IGN69, for comparison to in situ
373 water elevation time series.

374

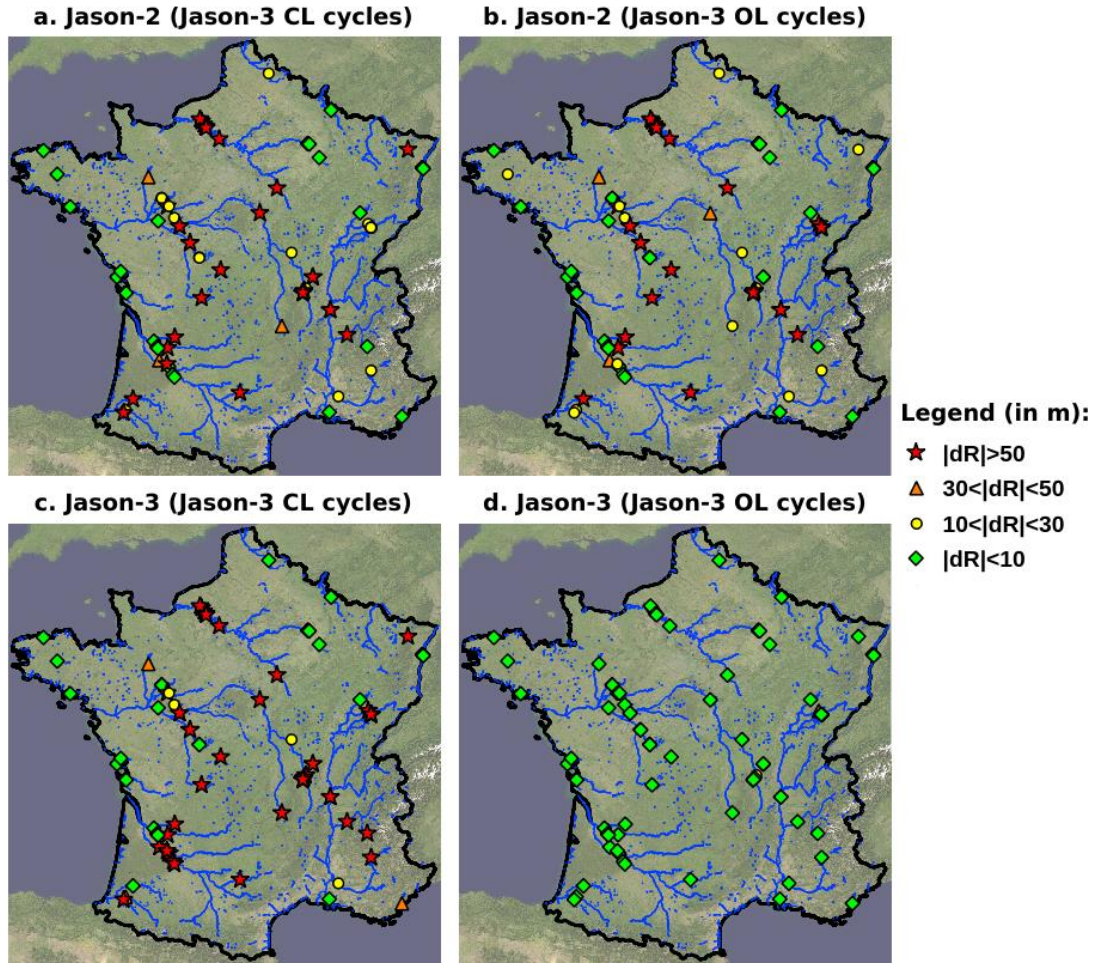
375 4. Results

376 4.1. Jason-3 statistics over the study domain

377 Figure 3 shows maps of Jason-2 and Jason-3 absolute difference dR (see section 3.2.2 and Figure
378 1), averaged over Jason-3 CL mode cycles (Figure 3.a and 3.c) and those where Jason-3 is in OL
379 mode (Figure 3.b and 3.d). As the size of the Jason-2 and Jason-3 tracking window is around 50
380 m, wherever and whenever this difference is greater than 50 m (Figure 3, red diamonds), it can
381 be assumed that the altimeter is locked on the surrounding hills. This figure clearly shows that
382 Jason-2 behaved in a similar manner before (Figure 3.a) and after (Figure 3.b) May 2016. It also
383 shows that Jason-3 exhibited similar behaviour to that of Jason-2 when it was in CL tracking
384 mode (Figure 3.c), with a slight tendency to have a few more VS locked on the surrounding hills
385 (especially in the downstream part of the Garonne River).

386 Table 2 summarizes these results by showing some basic information for the 86 VS. Jason-2
387 behaves consistently over the whole time period. Therefore, the differences between the Jason-3
388 measurements in CL and OL modes can only be explained by the differences in tracking mode.
389 For Jason-2, 25 VS (29% of all VS) are always locked on the top of the topography (first line in
390 Table 2). This number increases to 38 VS (44%) for Jason-3 in CL mode. Around half of the VS
391 had some cycles affected by this behaviour, as 34 (40 %) VS (Jason-2) and 49 (57 %) VS (Jason-
392 3 in CL mode) have an average dR of over 50 m. Table 2 also indicates the mean and the

393 maximum values of the backscatter coefficient σ_0 (in dB) averaged over all VS. The average
394 value of σ_0 over all VS is equal to 29 dB and 25 dB for Jason-2 and Jason-3 in CL mode,
395 respectively. σ_0 tends to be lower over land than over water (smoother and more reflective
396 surface than land, e.g. Frappart et al., 2015c). Therefore, its lower value for Jason-3
397 measurements in CL mode confirms its tendency to be locked on the surrounding topography
398 more often than Jason-2. Nevertheless the σ_0 for both altimeters remain close. However, the
399 average σ_0 for Jason-3 in OL mode increased to 40 dB, confirming that Jason-3 in OL mode
400 observed more rivers than Jason-2. However, it is not sufficient to show that the signal
401 backscattered by the river is measured by the altimeter. There remains the task of checking that
402 these measurements can be converted to useful water elevation time series. For this reason, the
403 next section compares the Jason-2 and Jason-3 time series to in situ water elevation time series.



404

Figure 3. Mean absolute difference (dR) between R_{track} and R_{DEM} (see Figure 1) for Jason-2 (a. and b.) and Jason-3 (c. and d.) for cycles when Jason-3 is in closed-loop mode (approximately between February and May, 2016; a. and c.) and when Jason-3 is in open-loop mode (approximately between May and September, 2016, see Table 1 for the list of cycles; b. and d.)

405

Table 2. Statistics computed using the 86 VS shown on Figure 2 (red and white diamonds) indicating the number of VS for which the min, max, and mean difference between the altimeter tracked height and on-board DEM values (dR) is greater than the size of the tracking window (50 m), values of the mean and max dR (in m) over all VS and the mean and max backscatter coefficient σ_0 (in dB) over all VS

	Jason-2 (J-3 CL cycles)	Jason-3 (CL cycles)	Jason-2 (J-3 OL cycles)	Jason-3 (OL cycles)
Nb VS with $\min(dR) > 50m$	25	38	24	0
Nb VS with $\text{mean}(dR) > 50m$	34	49	35	0
Nb VS with	50	55	50	0

max(dR) > 50m				
Mean(dR) (in m)	50	82	51	-2
Max(dR) (in m)	311	720	299	31
Mean(σ_0) (in dB)	29	25	30	40
Max(σ_0) (in dB)	54	56	53	54

406

407 4.2. Validation of Jason-3 data for the selected gages

408 This section focuses on the 21 VS (Figure 2, red diamonds) that are close to in situ gages (Figure
409 2, green stars) which were selected for a quantitative assessment of Jason-2 and Jason-3 errors
410 (see section 3.2.2).

411 Table 3 and Table 4 show the comparative statistics for in situ, and Jason-2 and Jason-3 satellite
412 time series, respectively, for all VS/gage pairs. Data shown in these two tables suggest that
413 altimeters are capable of accurately monitoring some small rivers, such as the JA-002 VS on the
414 Marne River, which is 40 m wide. On this river both Jason-2 and Jason-3 display an RMSE of
415 0.20 m for water elevation anomalies, whereas the amplitude of the in situ time series at the
416 satellite observation times is much larger (2.72 m). However, this instance is very favourable for
417 altimetry, as the topography is quite flat, with little surrounding vegetation. For Jason-2,
418 correlation coefficients greater than 0.9 are associated mainly with rivers wider than 130 m,
419 whilst for Jason-3, correlation coefficients greater than 0.9 are mainly associated with rivers
420 wider than 100 m. The Jason-2 RMSE for elevation anomalies for these rivers ranged from 0.20
421 to 0.63 m, whereas the Jason-3 RMSE was between 0.11 and 0.28 m. Eight Jason-2 VS (38% of
422 VS selected) were significantly impacted by the surrounding topography, with fewer than 5
423 cycles (out of 23) observing the river valley or with a bias compared to in situ measurements
424 around 50 m or more. All of these VS were observed correctly by Jason-3 only when operating in

425 OL mode (except for JA3-014 for which 7 cycles in CL mode observed the river valley) with a
426 small bias for absolute elevation compatible with what might be expected from the river slope (a
427 couple of metres over a distance of a few kilometres). The same statistics as those shown in
428 Table 3 and 4, but computed only for Jason-3 CL mode cycles and Jason-3 OL mode cycles for
429 both Jason-2 and Jason-3, are presented in the supplementary material associated with this
430 article. They show that the accuracy of Jason-3 measurements is fairly similar for those VS that
431 work well in both CL and OL modes. This result indicates that the OL tracking mode is operating
432 as expected and allows the observation of steep-sided rivers that previously were practically
433 never observed, resolving the issue described in Biancamaria et al. (2017). It should also be
434 noted that Jason-3 observed the river valley for all VS during the 13 OL mode cycles. In Table 4,
435 for VS with only 13 cycles in their time series, these cycles correspond solely to OL mode cycles
436 (there are no observations for CL cycles). This is shown clearly in the tables presented in the
437 supplementary material. There are three Jason-3 VS (JA3-075, JA3-017, and JA3-010) that are
438 always locked on the surrounding topography in CL mode (0 cycle used in Table 4 in the
439 supplementary material), whereas the corresponding Jason-2 VS provide some measurements of
440 the river elevation (i.e. two or more cycles could be used, their bias with in situ measurements is
441 below 50 m, and their correlation coefficient with in situ measurements is above 0.50)..
442 However, it should be noted that, for JA-075 and JA-017 VS, unlike JA-010 VS, even for Jason-
443 3 OL mode cycles or Jason-2 cycles with valid measurements, the RMSEs for water elevation
444 anomalies are still large, because of the small river widths (see supplementary material for these
445 RMSEs). For other Jason-3 VS with 0 cycle used in CL mode, Jason-2 does not provide useful
446 measurements of the river elevation (see supplementary material). For some other VS, the Jason-
447 3 time series had fewer observation dates than the corresponding Jason-2 time series, owing to

448 there being more Jason-3 cycles in CL tracking mode locked on the surrounding topography (see
 449 table in supplementary material). This is consistent with the results obtained by the qualitative
 450 assessment (section 4.1).

Table 3. Correlation coefficient, mean bias, RMSE (m), RMSE for anomalies (m), Nash-Sutcliffe (NS) coefficient for anomalies between Jason-2 and in situ time series. River width at the VS, amplitude (Ampl.) of the in situ time series for dates in common with Jason-2, and the number of these common dates are also provided. Rows shaded red correspond to VS/gage pairs for which the mean bias is around 50 m or more and/or the correlation coefficient is below 0.5 and the NS coefficient for anomalies is negative. Rows shaded orange correspond to VS for which half or more cycles are locked on the surrounding topography (11 or less cycles used)

Jason-2 VS ID	VS Riv. Width (m)	Gage ID	Corr.	Bias	RMSE (m)	RMSE anom (m)	NS anom	Ampl. (m)	Nb cycles used
JA2-074	35	M1511610	0.62	3.33	3.35	0.30	0.26	1.46	23
JA2-075	35	M3230930	0.47	26.07	26.07	0.25	-0.39	0.65	17
JA2-002	40	H5201010	0.97	-2.23	2.24	0.2	0.95	2.72	23
JA2-017	40	U1074020	0.43	12.55	12.57	0.64	0.15	2.64	12
JA2-011	45	P7121510	-	0.25	0.25	-	-	-	1
JA2-014	45	Q1420010	0.88	3.67	3.7	0.44	0.63	1.85	4
JA2-077	45	X3310010	-0.16	-11.39	11.51	1.63	-3.5x10 ⁴	0.05	23
JA2-077	45	X3500010	-0.25	16.42	16.51	1.67	-76.79	0.83	20
JA2-020	60	U0610010	0.87	1.44	1.49	0.39	0.75	3.14	22
JA2-071	60	M0520610	0.62	-5.59	5.59	0.15	0.30	0.59	20
JA2-071	60	M0630610	0.62	5.56	5.57	0.18	0.38	0.71	17
JA2-042	70	K0910010	0.56	1.04	1.16	0.5	-2.05	0.78	5
JA2-012	80	Q5421020	0.8	-34.32	34.32	0.32	0.53	1.56	19
JA2-012	80	Q5501010	0.76	13.73	13.74	0.36	0.30	1.35	19
JA2-094	90	V3130021	0.4	127.92	127.93	2.02	-5.43	1.97	11
JA2-009	110	P5550010	-	3.96	3.96	-	-	-	1
JA2-093	120	V3130021	0.1	126.9	126.96	3.74	-23.98	1.97	13
JA2-010	130	O9190010	0.97	-0.15	0.43	0.4	0.93	4.36	8
JA2-030	155	O9090010	0.91	3.58	3.64	0.63	0.75	4.37	23
JA2-030	155	O9000010	0.91	-3.01	3.08	0.63	0.78	4.53	23
JA2-080	165	H8100021	0.55	82.39	82.4	0.14	0.31	0.66	12
JA2-032	200	O9090010	0.95	0.96	1.03	0.37	0.89	3.56	10
JA2-036	245	P5770010	0.74	3.89	3.98	0.81	-51.61	0.38	20
JA2-064	250	K6830020	0.47	49.18	49.28	3.19	-8.54	3.28	23
JA2-082	300	L8700020	0.99	-0.09	0.37	0.36	0.93	5.5	23
JA2-082	300	L8700030	0.99	1.74	1.75	0.19	0.97	4.73	23

451

Table 4. Correlation coefficient, mean bias, RMSE (m), RMSE for anomalies (m), Nash-Sutcliffe (NS) coefficient for anomalies between Jason-3 and in situ time series. River width at the VS,

amplitude (Ampl.) of the in situ time series for dates in common with Jason-3, and the number of these common dates are also provided. Rows shaded red correspond to VS/gage pairs for which the correlation coefficient is below 0.5 and the NS coefficient for anomalies is negative

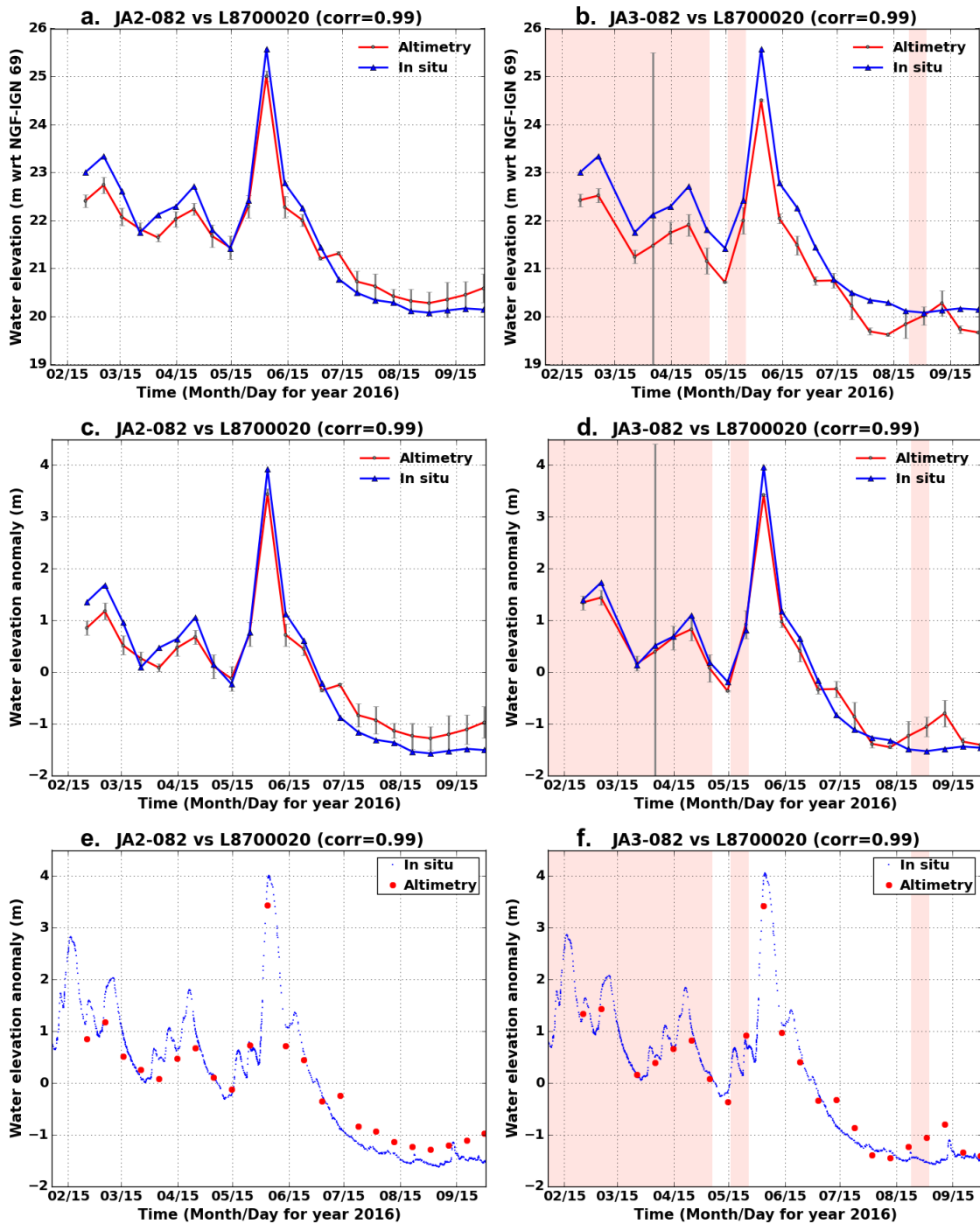
Jason-3 VS ID	VS Riv. Width (m)	Gage ID	Corr.	Bias	RMSE (m)	RMSE anom (m)	NS anom	Ampl. (m)	Nb cycles used
JA3-074	35	M1511610	0.71	2.92	2.94	0.31	0.24	1.46	22
JA3-075	35	M3230930	-0.27	-1.45	1.68	0.85	-26.69	0.74	13
JA3-002	40	H5201010	0.97	-2.62	2.63	0.2	0.95	2.72	23
JA3-017	40	U1074020	0.13	11.67	11.7	0.8	-0.49	2.48	13
JA3-011	45	P7121510	0.86	-0.71	0.88	0.52	-15.34	0.46	13
JA3-014	45	Q1420010	0.84	3.49	3.5	0.23	0.67	1.52	20
JA3-077	45	X3310010	0.35	-12.04	12.13	1.47	-2.6x10 ⁴	0.05	21
JA3-077	45	X3500010	0.25	15.77	15.84	1.45	-53.61	0.82	18
JA3-020	60	U0610010	0.84	1.11	1.18	0.42	0.7	3.14	22
JA3-071	60	M0520610	0.55	-5.91	5.92	0.19	-0.10	0.59	21
JA3-071	60	M0630610	0.51	5.25	5.25	0.21	0.11	0.71	18
JA3-042	70	K0910010	0.94	0.1	0.23	0.21	0.85	1.78	13
JA3-012	80	Q5421020	0.64	-34.83	34.84	0.45	0.2	1.55	18
JA3-012	80	Q5501010	0.65	13.23	13.24	0.42	0.03	1.35	18
JA3-094	90	V3130021	1	0.32	0.33	0.11	0.99	2.6	12
JA3-009	110	P5550010	0.99	2.42	2.43	0.14	0.97	2.94	13
JA3-093	120	V3130021	1	0.51	0.56	0.24	0.94	2.6	13
JA3-010	130	O9190010	0.99	-0.71	0.73	0.16	0.97	2.84	13
JA3-030	155	O9090010	0.95	2.44	2.46	0.28	0.9	2.52	16
JA3-030	155	O9000010	0.96	-4.13	4.13	0.27	0.92	2.6	16
JA3-080	165	H8100021	0.95	0.19	0.34	0.28	0.64	1.76	13
JA3-032	200	O9090010	0.99	0.4	0.42	0.14	0.98	2.52	16
JA3-036	245	P5770010	0.7	3.81	4.01	1.26	-127.05	0.38	21
JA3-064	250	K6830020	0.98	1.54	1.56	0.21	0.96	3.28	13
JA3-082	300	L8700020	0.99	-0.53	0.60	0.28	0.96	5.5	22
JA3-082	300	L8700030	0.99	1.29	1.31	0.20	0.97	4.73	22

452

453 Figures 4, 5, and 6 show the comparison of elevation time series derived from Jason-2 and Jason-
454 3 against in situ data for three pairs of VS/gage: JA-082/L8700020, JA-030/O9000010, and JA-
455 064/K6830020, respectively. Blue lines and dots correspond to gage time series, whereas red
456 lines and dots correspond to nadir altimetry measurements. For the altimetry time series, the grey
457 vertical bar for each observation time corresponds to the mean absolute deviations of all selected
458 altimetry measurements for that time within the VS boundaries computed by MAPS software
459 (see section 2.1 and for more details Frappart et al., 2015b and Biancamaria et al., 2017).

460 In the case shown in Figure 4, Jason-3 cycles perform well in both CL and OL tracking modes,
461 similarly to Jason-2. It shows that the OL mode, when the on-board DEM is accurate, performs
462 as well as the CL mode with valid cycles. Both modes perform well probably because there is an
463 elevation difference of less than 50 m between the surrounding hills and the river valley. The
464 high mean absolute deviation for one Jason-3 cycle (early April 2016) shown in Figures 4.b and
465 4.d is due to an outlier in the selected points within the VS, which may correspond to a
466 measurement of the surrounding topography. In the case shown in Figure 5 all Jason-2 cycles
467 (i.e. in CL tracking mode) observe the river, whereas only 3 (out of 10) Jason-3 cycles in CL
468 (and all cycles in OL) observe the river. Finally, Figure 6 illustrates a Jason-2 VS that never
469 observes the river and remains locked on the surrounding hills, whereas only Jason-3 cycles in
470 OL mode are able to measure the river elevation. All these figures, and in particular their bottom
471 panels show that a Jason-2/-3 sampling period of 10 days is coarse for this type of river.
472 Combining measurements from multiple altimetry missions might be beneficial here. The study
473 time period (mid-February to late September 2016) covered a period of high flows
474 (February/March), a flooding event on the Loire River lasting several days (in early June 2016)
475 and a low flow period (July/September). The altimeter time series allowed sampling of the
476 seasonal cycle (transition from high to low flow periods), but missed local maxima, especially
477 the flood peak on the Loire at VS JA3-064. As previously stated by Biancamaria et al. (2017),
478 Jason-2/-3 time sampling allows the study of the seasonal cycles of small to medium-sized
479 rivers, but will miss high frequency dynamics (periods of hours to a few days). Having
480 measurements of this kind will not assist flood forecasting for the type of rivers presented in this
481 study, but they are important for studying the seasonal cycle, the annual, interannual, and even
482 decadal dynamics of small and medium-sized rivers, especially in areas where no gaging

483 network is present or maintained. The OL tracking mode will help to obtain more observations
 484 from around the world for these types of river.



485

Figure 4. Jason-2 (left panels; a., c. and e.) and Jason-3 (right panels; b., d. and f.) water elevation time series (red lines and red dots) on the Loire River at La Menitré (JA-082) compared to in situ time series (blue lines and blue dots) at Gennes. Top panels (a. and b.) correspond to absolute elevations with reference to (wrt) NGF-IGN69 at satellite observation

times. Middle panels (c. and d.) correspond to elevation anomalies at satellite observation times. Bottom panels (e. and f.) correspond to times series with all available times for both satellite and in situ time series. Pale rose zones on panels b., d., and f. correspond to time periods when Jason-3 altimeter was in CL tracking mode

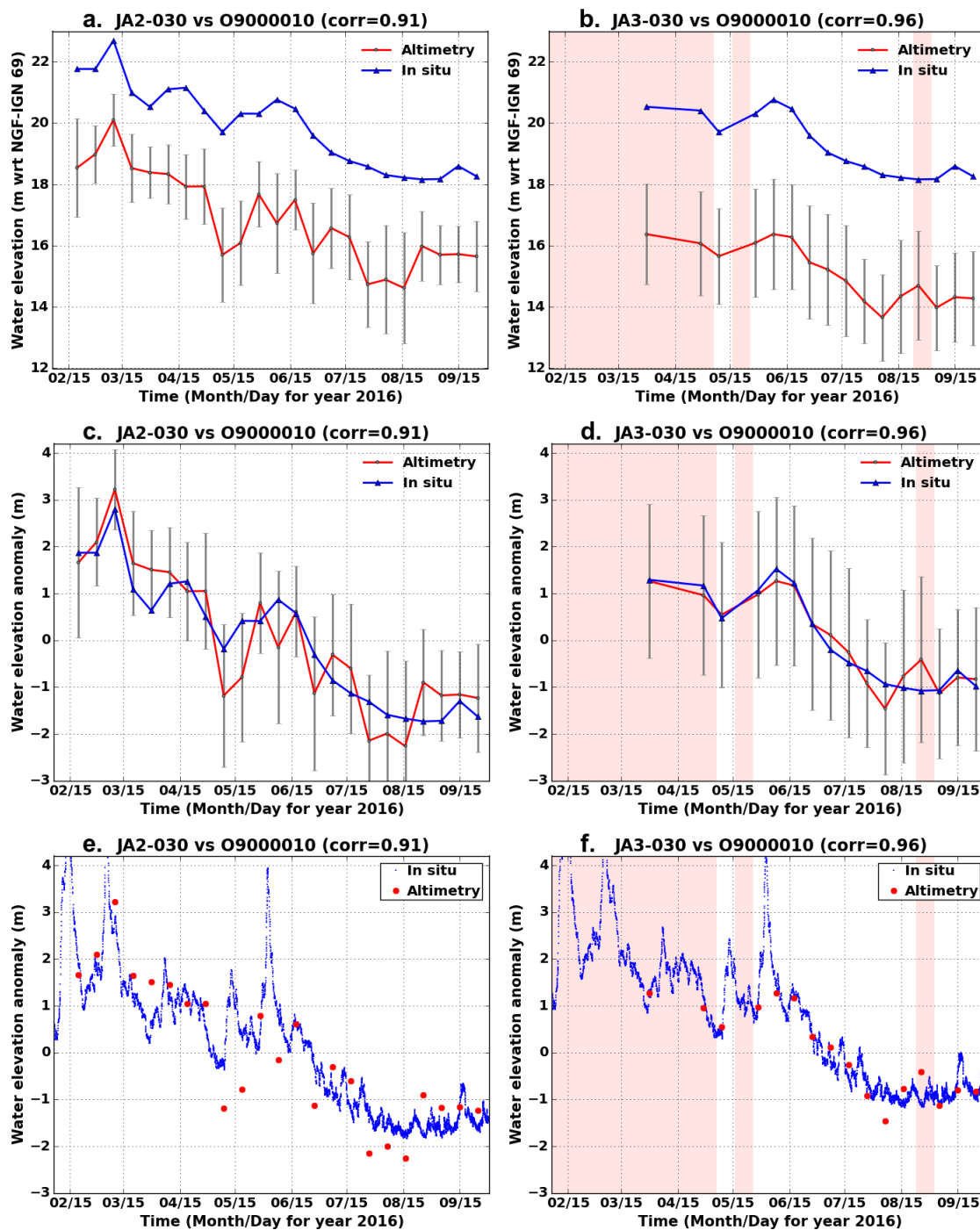


Figure 5. Jason-2 (left panels; a., c. and e.) and Jason-3 (right panels; b., d. and f.) water elevation time series (red lines and red dots) on the Garonne River at Caumont-sur-Garonne (JA-030) compared to in situ time series (blue lines and blue dots) at Tonneins. Panels are

similar to those in Figure 4. Pale rose zones on panels b., d., and f. correspond to time periods when Jason-3 altimeter was in CL tracking mode

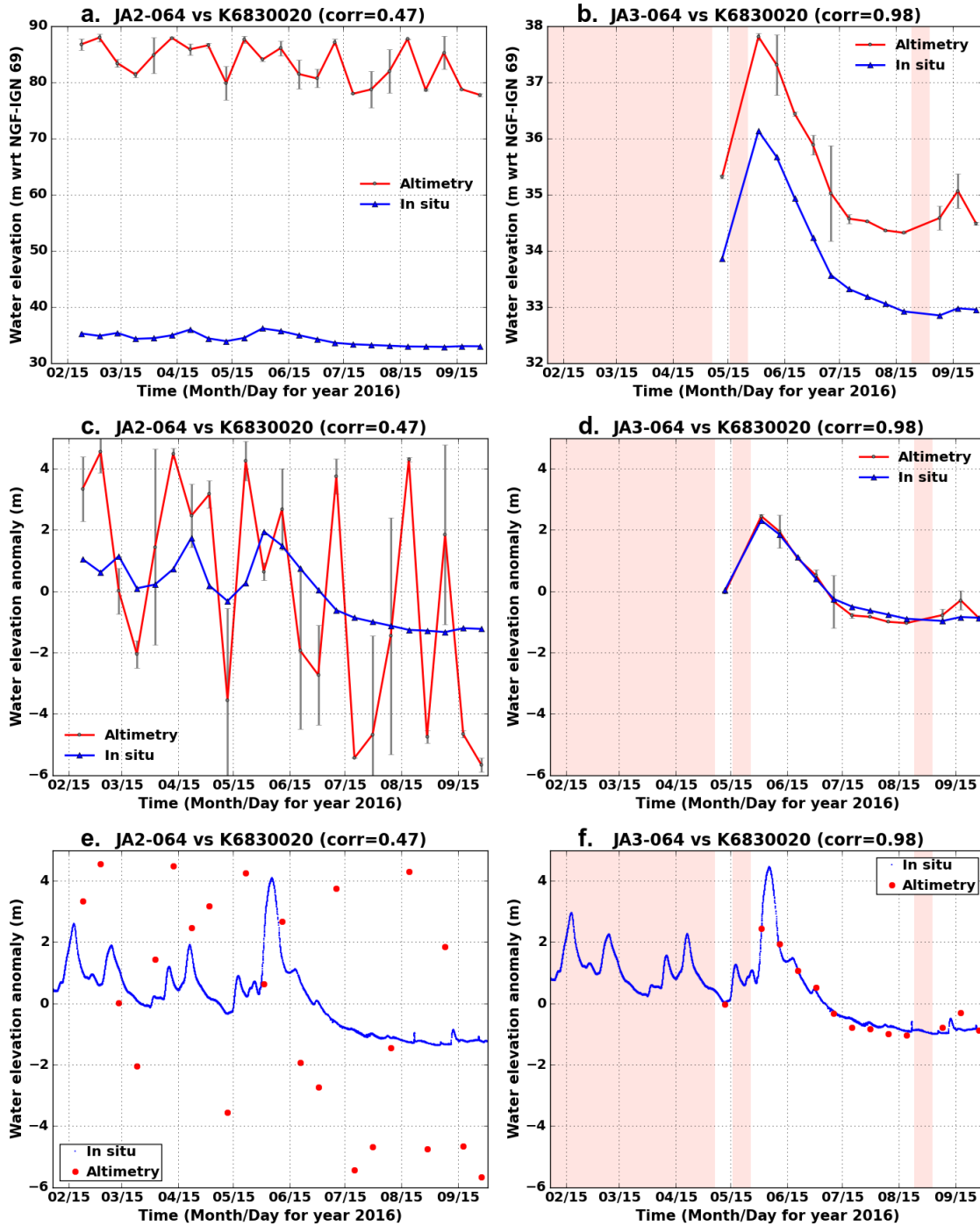


Figure 6. Jason-2 (left panels; a., c. and e.) and Jason-3 (right panels; b., d. and f.) water elevation time series (red lines and red dots) on the Loire River at Saint-Michel-sur-Loire (JA-064) compared to in situ time series (blue lines and blue dots) at Langeais. Panels are similar to those in Figure 4. As Jason-2 is locked on the surrounding topography, panels c. and e. are not

relevant, but are kept for consistency with Figure 4 and Figure 5. Pale rose zones on panels b., d., and f. correspond to time periods when Jason-3 altimeter was in CL tracking mode

486

487 4.3. Discussion on the difference between Jason-2 and Jason-3 performance in CL mode

488 Results from both qualitative (section 4.1) and quantitative (section 4.2) Jason-3 validation

489 assessments showed that Jason-3 in CL tracking mode was more frequently locked on the

490 surrounding topography than Jason-2. Jason-3 and Jason-2 altimeters use the same CL tracking

491 algorithm, called the median tracker. The aim of the median tracker is to “track” as much

492 backscattered energy from the ground as possible, in the hope that the tracked ground

493 corresponds to water bodies. This is a statistical approach, which almost always works, but

494 which does not discriminate between surface types. In other words, in CL tracking mode we

495 cannot give preference to water bodies over other ground targets. The fact that Jason-2 tracks

496 more hydrological targets than Jason-3 in CL mode may appear to be counterintuitive.

497 Although Jason-2 and Jason-3 share a common algorithm, the hardware is not exactly the same.

498 Algorithm parameters values must be adapted to each instrument. They are defined during

499 altimeter ground tuning and testing. These are critical values and are generally not updated in

500 flight unless strictly necessary. Owing to some unexpected in-flight behaviour of Jason-2 (“ghost

501 echoes”) the post-launch modification of the original tuning of the altimeter was unavoidable. A

502 side-effect of this procedure was a slight degradation of radar sensitivity in CL tracking mode.

503 When the altimeter operates in CL mode, it first searches for a backscattered radar signal. For

504 this purpose, it scans from higher to lower altitudes. Then when the energy received by the

505 altimeter is sufficiently strong with respect to its sensitivity, it stops scanning altitudes and locks

506 its tracking loop to the current target altitude.

507

508 In the case of areas with relief, generally the higher the altitude, the weaker the backscattered
509 signal. As the sensitivity of the Jason-2 altimeter has been degraded, the result is that, in
510 principle, for such regions, it will lock its tracker at a lower altitude than the Jason-3 altimeter.
511 As rivers are particularly located in valleys, Jason-2 will have a better chance of tracking a
512 hydrological target than Jason-3.
513 The drawback of the median and more generally the CL tracker is the lack of control and of
514 target prioritization. For this reason, the OL tracking mode was designed to overcome this issue.
515 It has the capability to designate a target and therefore to give highest priority to water bodies.
516 Prior to the Jason-3 launch, it was not anticipated that Jason-2 altimeter tuning was improving
517 water elevation observation over continents. As this modification was not applied to Jason-3 (or
518 to any other past, present or planned altimeter), it should be expected that Jason-3 in CL tracking
519 mode will be locked over surrounding topography for steep-sided rivers more frequently than
520 Jason-2, as shown in this study. However, the yield of Jason-3 in OL tracking mode will be
521 dramatically better than that of Jason-2 if the behaviour observed over mainland France, can be
522 obtained for all global locations.

523

524 5. Conclusions and Perspectives

525 The 6 month period during which the recently launched Jason-3 altimetry mission shared the
526 same orbit as Jason-2 was the perfect time to validate the Jason-3 Closed-Loop (CL) tracking
527 mode and to assess the benefit of the Jason-3 Open-Loop (OL) tracking mode. A high-quality
528 DEM and water mask available from the IGN were used to compute the on-board DEM for the
529 OL mode over mainland France which was loaded onto Jason-3 on 2 May 2016 (the first Jason-3

530 cycles being in CL tracking mode). Accurate water elevations from in situ gages were used to
531 validate both Jason-2 and Jason-3 measurements for river widths between 35 and 300 m.
532 This study has shown that altimeters such as Jason-2 and Jason-3 are able to accurately measure
533 rivers with a width of 100 m or greater with an RMSE for elevation anomalies of around 0.20 to
534 0.30 m. The 10 day sampling period is adapted for observing the seasonal cycle, but misses some
535 local maxima. Smaller rivers could also be observed, but with a higher RMSE and time sampling
536 could be more critical for this type of river.

537 This study demonstrates that Jason-2 and Jason-3 in CL mode provide similar results, although
538 Jason-3 has a tendency to remain locked on the surrounding topography more frequently than
539 Jason-2. This issue is due to a Jason-2 altimeter post-launch tuning, which solved a problem but
540 led to a slight degradation in radar sensitivity. It was not anticipated that this modification would
541 improve observations over continents. As the problem had been resolved on the Jason-3
542 altimeter, this modification was not applied to the Jason-3 CL tracking mode. Of the Jason-2 VS,
543 38% measured the top of the surrounding hills almost all of the time. On the contrary, water
544 elevation measurements were always measured at the corresponding Jason-3 VS in OL mode.
545 Even for Jason-2 VS that were only partially affected by this issue (a small number of cycles
546 locked on the surrounding topography), Jason-3 was able to observe the river in OL mode for all
547 cycles, increasing the number of observation times. This shows the significant advantages
548 provided by the OL tracking mode for steep-sided rivers that were unobserved or only partially
549 observed by previous altimetry missions, thus potentially significantly increasing the number of
550 river reaches that could be monitored worldwide by satellite radar altimeters. Even much wider
551 rivers could benefit from the OL tracking mode if they are located in a narrow river valley (a few
552 kilometres across), or are very close to surrounding hills that are higher than the river elevation

553 by 50 m or more. Jason-3 has greater flexibility than previous missions (i.e. Jason-2 and
554 SARAL) had in OL mode, because small portions (a few kilometres) of the track can be in OL
555 tracking mode (for locations where the water mask and the *a priori* DEM are coherent and
556 sufficiently accurate), while the rest of the track remains in the classical CL tracking mode.
557 Demonstrating the potential of the OL tracking mode is important in the early stages of the
558 Jason-3 mission and also in the context of recently launched (Sentinel-3A), or future altimetry
559 missions (Sentinel-3B planned for launch in early 2018, Sentinel-3C/D whose launch dates are
560 currently unknown, as they will ensure continuity of observation after Sentinel-3A/B, Jason-
561 CS/Sentinel-6 in 2020, SWOT in 2021, and follow-ons), that operate or will operate using this
562 tracking mode. The use of the OL tracking mode will substantially increase the number of river
563 basins that can be monitored using satellite radar altimetry.

564 The OL mode over mainland France successfully provided observations of river stages, because
565 an accurate on-board DEM could be computed, based on accurate local database. Unfortunately,
566 such a database is not available globally and other sources will have to be used for the rest of the
567 world. For some locations where the global DEMs (GDEM) are sufficiently accurate, these could
568 be used to compute the on-board DEM for OL mode. This could be the case for GDEMs such as
569 the latest version of the Shuttle Radar Topography Mission GDEM released in September 2014
570 (see <https://www2.jpl.nasa.gov/srtm/>), the ASTER GDEM (Tachikawa et al., 2011), or the
571 upcoming DLR TanDEM-X GDEM (Zink et al., 2014), whose absolute elevation in some
572 regions has been assessed to be within ± 10 m. They will also need to be coupled with a coherent
573 global water mask more precise than that of Globcover. For example, the global water mask
574 established from satellite imagery computed by Pekel et al. (2016) could represent a good
575 alternative. Some local information provided by the broader scientific community (based on field

576 trip measurements, local maps...) could also be used. For locations where an accurate on-board
577 DEM over water bodies cannot be computed, the altimeter would be left in classical CL tracking
578 mode, to avoid setting the tracking window to an incorrect position for all cycles. In the coming
579 years, more extensive work will be needed to improve the Jason-3 on-board DEM, but also for
580 incoming altimetry missions that are not on the same orbit (for example the Sentinel-3 series of
581 satellites).

582 The benefits of the OL tracking mode for lakes and reservoirs need to be carefully investigated.
583 Similar results are anticipated to those obtained for rivers where an accurate on-board DEM can
584 be computed. However computation of the on-board DEM may be even harder than for rivers, as
585 many reservoirs (and lakes) are in mountainous regions where the DEMs usually available are
586 not accurate to within ± 10 m. Further, for large lakes and reservoirs, the OL tracking mode might
587 not be suitable, as they can display seasonal and/or interannual variations much larger than those
588 of rivers. For such variations, setting the tracking window to one constant value might not be
589 appropriate for all observation times. A potential solution would be to update the on-board DEM
590 on a seasonal basis. Specific studies are needed to investigate these cases.

591

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621

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744

745 List of figure captions:

746 Figure 1. Conceptual view of nadir altimeter measurements and notations used in this study (the
747 copyright of the Jason-3 satellite image used in this sketch belongs to CNES/Mira Production)

748

749 Figure 2. Study domain (Mainland France, delimited by the black line) and the river network
750 (light blue lines) from the IGN BD Carthage database (only rivers wider than 50 m according to
751 this database are shown). Red lines correspond to Jason-2 and Jason-3 tandem phase orbit tracks.

752 White and red diamonds correspond to virtual stations (VS), where Jason-3 on-board DEM
753 values were computed. Red diamonds are virtual stations where Jason-2 and Jason-3 river

754 elevation time series were compared to in situ gage (green stars) measurements. The background

755 image is derived from the NASA MODIS “Blue Marble Next Generation” image (Stöckli et al.,

756 2005)

757

758 Figure 3. Mean absolute difference (dR) between Rtrack and RDEM (see Figure 1) for Jason-2
759 (a. and b.) and Jason-3 (c. and d.) for cycles when Jason-3 is in closed-loop mode (approximately
760 between February and May, 2016; a. and c.) and when Jason-3 is in open-loop mode
761 (approximately between May and September, 2016, see Table 1 for the list of cycles; b. and d.)

762

763 Figure 4. Jason-2 (left panels; a., c. and e.) and Jason-3 (right panels; b., d. and f.) water
764 elevation time series (red lines and red dots) on the Loire River at La Menitré (JA-082)
765 compared to in situ time series (blue lines and blue dots) at Gennes. Top panels (a. and b.)
766 correspond to absolute elevations with reference to (wrt) NGF-IGN69 at satellite observation
767 times. Middle panels (c. and d.) correspond to elevation anomalies at satellite observation times.
768 Bottom panels (e. and f.) correspond to times series with all available times for both satellite and
769 in situ time series. Pale rose zones on panels b., d., and f. correspond to time periods when Jason-
770 3 altimeter was in CL tracking mode

771

772 Figure 5. Jason-2 (left panels; a., c. and e.) and Jason-3 (right panels; b., d. and f.) water
773 elevation time series (red lines and red dots) on the Garonne River at Caumont-sur-Garonne (JA-
774 030) compared to in situ time series (blue lines and blue dots) at Tonneins. Panels are similar to
775 those in Figure 4. Pale rose zones on panels b., d., and f. correspond to time periods when Jason-
776 3 altimeter was in CL tracking mode

777

778 Figure 6. Jason-2 (left panels; a., c. and e.) and Jason-3 (right panels; b., d. and f.) water
779 elevation time series (red lines and red dots) on the Loire River at Saint-Michel-sur-Loire (JA-
780 064) compared to in situ time series (blue lines and blue dots) at Langeais. Panels are similar to

781 those in Figure 4. As Jason-2 is locked on the surrounding topography, panels c. and e. are not
782 relevant, but are kept for consistency with Figure 4 and Figure 5. Pale rose zones on panels b., d.,
783 and f. correspond to time periods when Jason-3 altimeter was in CL tracking mode