The Unique Role of Jason-2 Geodetic Mission for High Resolution Gravity Field Modelling

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Key Points

Jason-2 is unique in performing a controlled geodetic mission as part of the Extension-of-life phase with 4 km groundtrack spacing.

Mission-rewind to recover missing tracks following safe-holds for Jason-2 was found to be extremely important for gravity field modelling.

Our finding support interleaving a possible Jason-3 GM with Jason-2 to bisect the Jason-2 GM creating a 2 km GM after 2 years.

Abstract

The Geodetic Mission (GM) of Jason-2 was planned to provide ground-tracks with a systematic spacing of 4 km after 2 years and 2 km after 4 years to increase the spatial resolution of global altimetric gravity fields. Jason-2 ceased operation after 2 years of GM but provided a fantastic dataset. We highlight and evaluate the improvement to the gravity field which has been derived from the GM. The ageing Jason-2 suffered from several safe-holds and instrument outages. Here, we try to quantify the effect of safe-holds on marine gravity and discuss suitable approaches advising future GM like Jason-3. We evaluate the importance of attempting to “rewind” the mission to recover missing tracks as well as the possibility to continue an existing GM by using the same orbital plane. The latter idea would allow bisecting the already 2-years Jason-2 GM creating a 2 km grid after 2 years of Jason-3 GM.

Plain Language Summary.

In this paper we investigate the final extension-of-Life phase of Jason-2 and its importance and impact on high resolution gravity field mapping. Jason-2 has been a unique satellites in the sense that it performed a controlled and accurate mapping of the Ocean’s surface 4 km resolution during 2 years of operation for the first time.

During the extension-of-life phase the ageing Jason-2 satellite encountered several safe-holds resulting in missing tracks and no available sea surface heights observations. For the first time, a mission rewind maneuver was performed by the space agencies to recover the missing tracks and we demonstrate its fundamental importance to gravity field modelling and suggest this to be considered for future geodetic missions.

For the upcoming extension-of-life phase of Jason-3 we suggest interleaving Jason-3 with Jason-2 to bisect the already 2-years Jason-2 GM creating a 2 km GM after only 2 years and this way mapping even finer scale gravity field signal.

1 Introduction

A number of satellite altimeters have performed a “Geodetic Mission” (GM) during their lifetime (i.e. Geosat, ERS-1, Cryosat-2, Jason1/2 and Saral/AltiKa). The GM is basically a Long Repeat Orbit (LRO) where the orbital pattern is designed for mainly geodetic purposes. This means that the spatial sampling it optimized to map short wavelength in the geoid or gravity field at the price of no or long temporal sampling. Typically, the GM consist of one or more repeated or interleaved LRO (Cryosat-2 has repeated LRO, Jason-2 interleaved LRO). For geodetic purposes the smallest possible cross-track resolution is the ultimate goal in order to map the finest scales in the gravity field as the cross-track distance governs the gravity signal which can be resolved. As an example: 8 km resolution requires a little more than 1 year GM and 4 km requires a little more than 2 years of SSH observations at Jason orbital altitude.

Exact repeat missions (ERM) are primarily designed for oceanographic purposes to map oceanographic signals optimally. This requires frequent temporal sampling at the price of coarse spatial sampling. As an example, the Jason-1 ERM sampled the ocean every 9.9156 days at 314 km across-track spatial sampling. Subsequently, the satellite was moved into a LRO mission with 7.5-km across-track spatial sampling but with a temporal sampling of 406 days.

The GM and ERM missions mutually support each other in the sense that the GM drives the mapping of the fine structures in the Mean Sea Surface (MSS) model (Andersen et al., 2015), which are applied to derive accurate sea level anomalies for the ERM. ERM are important to derive long-term mean for the MSS. With more satellites flying in recent years, ERM are also becoming increasingly important in determining ocean variability, which in-turn can be used to correct the GM data (Dufau et al., 2016).

When the Jason satellites have served their main commitment to oceanographic science and ensured the tandem mission obligations with future missions in the same orbit and the satellites are getting toward the end of their lifetime an Extension of Life (EoL) phase is considered. During the EoL phase the old satellite is moved away from the nominal orbit located at 1336 km altitude. Moving the satellite away from the nominal orbit prevents a collision of the satellite with active and future missions that must fly in a prescribed orbital tube to achieve multi-decadal measurement along the tracks that were initiated by TOPEX in 1992. Through orbital maneuvers, the satellite is lowered or raised a number of kilometers into the EoL orbit which eventually will become the graveyard orbit for the satellite.

During their EoL missions, Long Repeat Orbits (LRO) were selected for both Jason-1 and Jason-2, where for each the repeat was longer than 1 year. Contingent on the remaining lifetime of the satellites, the LRO could be interleaved to create a GM with very high spatial resolution in a systematic and controlled way.

Resolution of current global altimetric gravity models is around 12 km wavelength resolving 6km (Sandwell et al. 2014, Andersen et al., 2017) partly limited by the 8-km groundtrack spacing of previous GM (Geosat, ERS-1, Cryosat-2). The Jason-2 is unique in this way, as it is the first GM mission planned so that the ground-track distances could be systematically bisected beyond 8 km to provide 4 km at 2 years and 2 km after 4 years. The ongoing SARAL/AltiKa mission provides the most accurate sea level observations (Sandwell et al., 2019), but the SARAL GM is un-controlled, making it more difficult to resolve the short wavelengths in the gravity field in a systematic way.

During the EoL both Jason-1 and Jason-2 have suffered from a number of safe-holds causing one or more of the instruments onboard the satellite to be shut-off. This is typically due to ageing of the instrument onboard the satellite or due to collision avoidance. Most noticeable is the last safe-hold of Jason-2 causing the instrument to be shut-off for around 100 days.

The errors in the derived altimetric marine gravity grids originate in omission and commission errors (Pujol et al., 2018). The omission errors will be dominated by the spatial distribution of the data. Lack of data, related to duration and safe-holds will increase this error. The commission errors are largely related to measurement errors such as the range precision, the retracker and oceanographic noise, but also errors due to an imperfect gridding process. In this paper we mainly study the omission error on the gravity field modelling due to the spatial distribution of data.

We have investigated altimetric marine gravity fields from the Jason-1 and Jason-2 Long Repeat Orbits or GM in order to demonstrate the value of designing these EoL missions with multiple LRO cycles interleaved to gather the best spatial coverage. Safe-holds will ultimately lead to a degradation of the derived gravity field and we quantify the impact of these using observations from sub-cycles of Jason-1 and Jason-2. As an example, we derived gravity from the two 378-days LRO cycles of Jason-2 and the two 178-days sub-cycle of Jason-1 as these (sub)cycles were affected differently by safe-holds. Such analysis is important to guide future EoL missions (most profoundly the EoL for Jason-3) and their strategies to remedy the effect of future safe-holds.

2 Geodetic Mission orbit choice for Jason-1 and 2

Jason-1 was launched in 2002. When it had served its main commitment to oceanographic science and ensured the tandem mission obligations towards Jason-2 an EoL mission was researched and initiated in 2012 (Bronner and Dibarboure, 2012). During the EoL for Jason-1 the satellite was put into a LRO with a 406-day cycle with a ground track resolution of 7.5 km serving geodetic purposes (Sandwell et al. 2014). The Jason-1 GM lasted from 7 May 2012 until 21 June 2013 when the mission was terminated due to instrument failure. Fortunately, Jason-1 collected exactly one full GM cycle of 406 days before the mission was terminated shortly after, when the orbit became the graveyard orbit for Jason-1.

When designing the LRO for both Jason-1 and Jason-2 a number of simulations were performed (Dibarboure, 2012; Dibarboure and Morrow, 2016) and a number of orbit choices were investigated prior to the selection of the final orbit. The simulations are performed to optimize the usefulness of the LRO for both geodesy and oceanography by designing the orbit with a number of sub-cycles of varying length. During each sub-cycle a near-regular ground track pattern is measured. This pattern automatically shifts longitudinally for each following sub-cycle. The choice and duration of the sub-cycles are normally governed by their utility for oceanographic purposes, but also with consideration of their value to geodesy in the event that the GM terminates early due to satellite failure. These considerations are important for the subsequent gravity field modelling in two ways. First, they ensure that safe-holds will result in outages scattered evenly throughout the globe. Second, they enable the possibility of rewinding the LRO by one or more sub-cycles in case of longer safe-holds. This proved particularly important for the final cycle of Jason-2. The final choice of orbits and sub-cycles for Jason-1 and Jason-2 LRO are shown in Table S1.

Upon designing the EoL of Jason-2 one could argue to inject Jason-2 in another 406 days LRO interleaved with the Jason-1 GM in a similar orbit to speed up geodetic sampling and get a 4 km sampling by combining the 406 days of Jason-1 and 2. Unfortunately, such interleaved GM would require Jason-2 EoL to use exactly the same orbital altitude of Jason-1GM, which was avoided due to collision risks. Consequently, another EoL orbit at another altitude had to be selected. Such orbit provided irregular sampling with the Jason-1GM where the tracks were on nearly identical locations in some regions but perfectly interleaved in other regions. These so-called moiré patterns appear when two grids of different resolution are superimposed (Dibarboure et al, 2012).
The consequence of this is, that Jason-2 was planned to perform its own dedicated multiyear GM gradually filling up the globe with denser and denser ground tracks through multiple cycles of interleaved LRO.

Through a number of simulations following the work by Dibarboure (2012) and Dibarboure and Morrow, 2016) a LRO orbit for Jason-2 with clear advantages to both geodetic and oceanographic research was selected and on July 11th 2017 Jason-2 began measuring the first cycle of the LRO. This had a 371-day repeat period at an altitude of 1309km (27km lower than the nominal TOPEX altitude). This resulted in an across track distance of around 8.5 km at the Equator.
The partnership between NOAA, NASA and CNES agreed to extend the Jason-2 mission for an additional two years, from 1 January 2018 until the end of 2019 considering to extend with EoL with two further cycles thereby lowering the groundtrack distance by a factor of two to a little over 2 km after 4 years.

On July 18th 2018 Jason-2 successfully completed the first LRO cycle and operations started to move the satellite into its new groundtrack in-between the ground tracks of the first LRO cycle. This entailed a shift of the ground track of a little more than 4 km, which was completed on the 25th of July, where the second LRO cycle was initiated. In theory, the second LRO cycle should be completed by 31 July 2019 resulting in a systematic groundtrack distance of a little more than 4 km. Unfortunately, Jason-2 only managed to perform 350 days of the planned 371 days of the second LRO before the mission was terminated on October 8th, 2019.

2.1 Safe-holds

When the EOLs of the Jason satellites were initiated, both satellites were around 10 years old and ageing, and during the LRO both satellites encountered safe-holds to safeguard the instrument and to extend the mission as long as possible. These are shown in Table 1.

Satellite	Start date	End date	Duration
Jason-1	28/02/2013	18/03/2013	18 days
Jason-2 Cycle 1	14/09/2017	13/10/2017	30 days
	20/02/2018	02/03/2018	9 days
Jason-2 Cycle 2	19/10/2018	25/10/2018	6 days
	26/12/2018	07/01/2019	14 days
	16/02/2019	24/05/2019	100 days (21 days*)

Table 1. Safe-holds for Jason-1 and Jason-2 during the two LRO cycle. Courtesy of Christoph Marechal, CNES. *se explanation in the text on mission "rewind" maneuver to remedy the safe-hold.

During the LRO Jason-1 completed one sub-cycle of 179 days without safe-hold but suffered one safe-hold of 18 days during the second sub-cycle. For Jason-2 the story is more dramatic. Both LRO cycles suffered from several safe-holds lasting a total of more than 30 days. The last and most severe safe-hold lasted 100 days from February 16th, 2019 until May 24th 2019. The second LRO cycle should, in theory have be completed by July 31st 2019, but the partnership between NOAA, NASA and CNES agreed to conduct an orbital maneuver and "rewind" the mission by 79 days to recover the missing observations. Rewinding the mission to recover gaps is possible because the LRO orbit is designed with multiple interleaved sub-cycles and a relatively cheap maneuver (in terms of fuel) can "rewind" the mission by a sub-cycle (e.g., 17, 79 or 145 days). It is, in theory, possible to rewind the mission by any amount of days, but at significant increased fuel cost and this is normally avoided. By rewinding the mission by 79 days the resulting gap in data collection due to the safe-hold was limited to 21 days. In theory, the second LRO should have been completed on October, 21st 2019. Unfortunately, the instruments ceased working just 20 days before this date.

3 Marine gravity from Jason subsets

To aid in the design of future GM we have investigated a number of different sub-sets of Jason data. First of all, we studied the importance of establishing a GM with multiple LRO cycles interleaved to gather the best spatial coverage and hereby lowering the cross-track distance as much as possible in a controlled way. Here we compared gravity from the first 178-days sub-cycle of Jason-1 (cross track distance 17 km) with gravity from the first cycle of Jason-2 (cross track distance of 8.5 km) and gravity derived from the full 406 days GM (cross track distance = 7.5 km) and finally gravity derived from the full 2x371 days GM of Jason-2 (cross track distance of 4.25 km). Figure 1 illustrates the altimetric data in a subset close to Bermuda in the Northwest Atlantic Ocean.

Safe-holds have shown to have a significant impact on the quality of the derived gravity field. In order to quantify the impact of these we compared gravity computations using observations the two 371-days cycles of Jason-2 and the two 178-days sub-cycle of Jason-1 as these (sub)-cycles were affected differently by safe-holds. During the first 179-days sub-cycle of Jason-1 the mission only encountered normal accidental outages of around 10 tracks. During the second sub-cycle the satellite encountered 18 days or 10% data-loss.

Jason-2 encountered 2 safe-holds during the first LRO cycle, losing data for 39 days or 11% data loss, and 41 days safe-hold plus 20 days early failure resulting in 17% data loss for the second LRO. The geographical distribution of the tracks is seen in Figure 1.

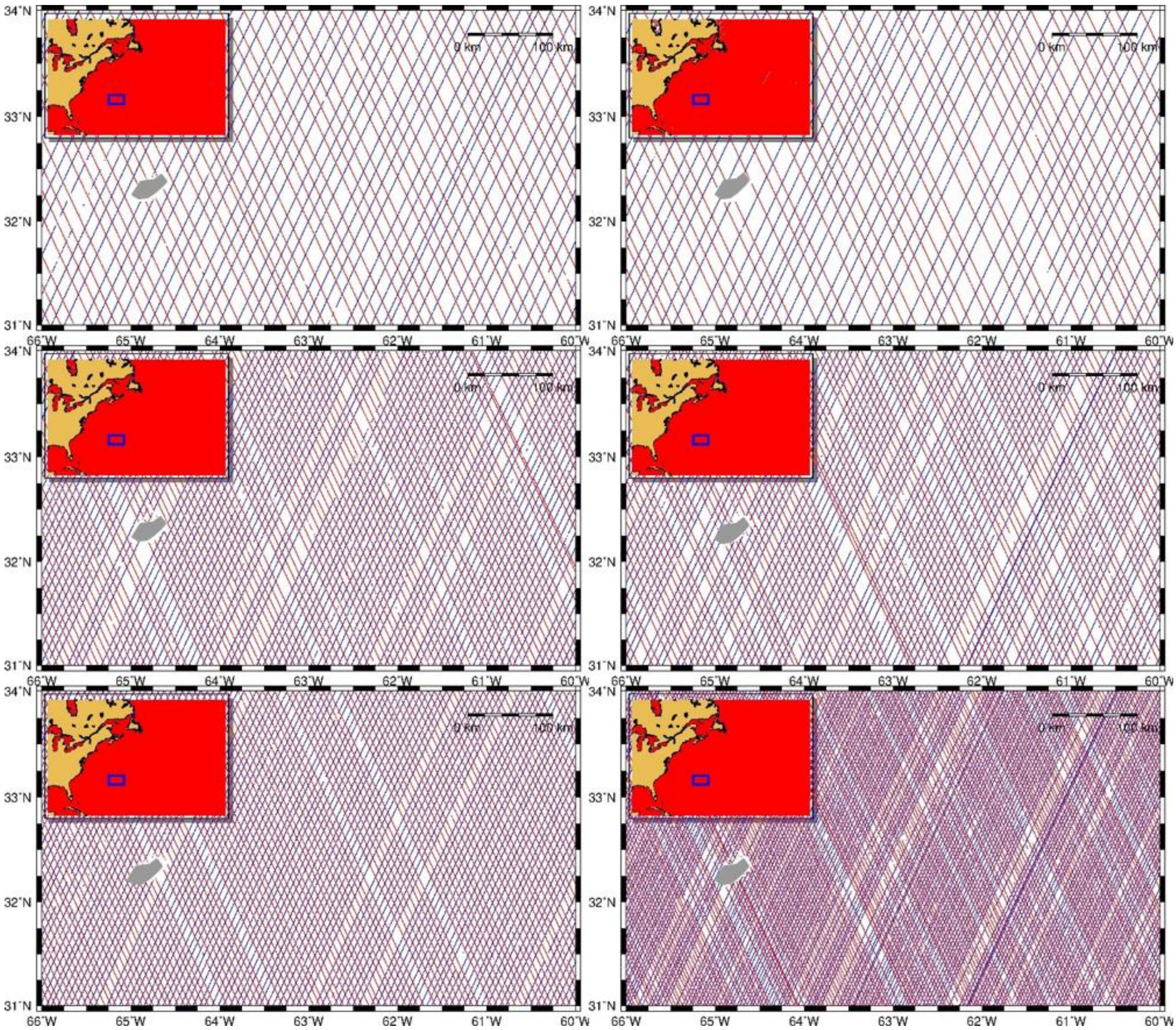

Figure 1. Geographic distribution of Jason GM altimeter measurements for a section in the NW Atlantic Ocean close to Bermuda (in grey). Upper left: J1 sub-cycle 1, Upper right: Jason 1 sub-cycle 2; Center left: J2 LRO Cycle 1, Center right: Jason 2 LRO cycle 2; Lower left: J1 Entire GM; Lower right: Jason 2 Entire GM (Both LRO cycles)

3.1 Marine Gravity observations

A high-precision dataset with its assessed accuracy superior to ~2 mGal was obtained through a cooperation with the (U.S.) National Geospatial-Intelligence Agency (NGA). Over 1.4 million high quality measurements are distributed within the northwest Atlantic Ocean bounded by (20°~90°W, 20°~55°N) and their observed marine gravity anomalies are shown in Figure S1.

4 Geoid slope and gravity anomalies evaluation

The Sensor Geophysical Data Record (SGDR) altimeter data products including 20 Hz waveforms are obtained from the Archiving, Validation and Interpretation of Satellite Oceanographic (AVISO) data service. In order to compare results between Jason-1 and Jason-2 is is important that the two datasets have the same range precision to ensure that the differences we are seeing are not due to different commission errors related to the instrument onboard the two satellites. This investigation is described in detail in Supporting information Text S1

Gravity anomalies can be derived from altimetric sea surface height observations by isolating the geoid height (Andersen et al., 2017) or from the geoid slopes (Sandwell et al., 2014). In this investigation, we decided to derive the gravity anomalies using the geoid slopes using the method detailed in Supporting information Text S2.

A global evaluation of the impact of the various combinations of the Jason subsets can be performed by comparing with the multi-mission global slope grid SS V28.1. The median absolute deviation of the along-track slopes with respect to the full model is a good indication of the un-modelled signal in the Jason subsets combined with the noise in the altimeter profiles (Sandwell et al., 2019). The median absolute deviation of the along-track slope data with respect to the full (V28.1) slope grids is calculated and gridded within the latitudinal range of 66°N and 66°S. These are shown in Figure 2 which illustrates the oceanographic noise related to the major current systems and the residual geoid noise which is generally significantly smaller. As the Jason measurements accumulate with time, the RMS decreases from 2.8 μrad for sub-cycle 1 of Jason 1 to 2.4 μrad for Jason 2 cycle 1 to 2.25 μrad for J-2 full GM. (1 μrad of surface slope is 1 mm change in sea surface height per 1 km of horizontal distance.)

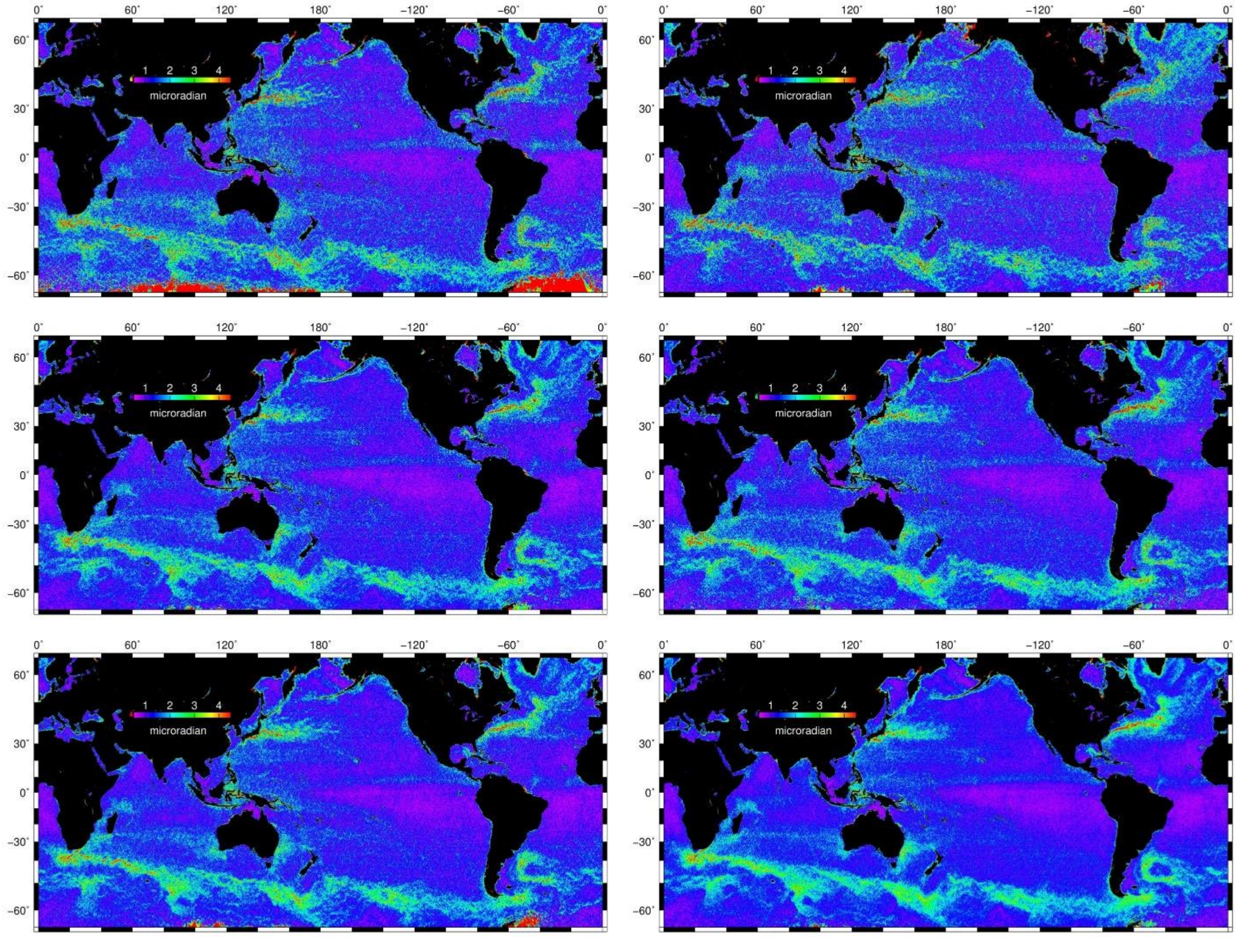

Figure 2. Median absolute of along-track sea surface slope differences with respect to the SSV28.1 vertical deflection model derived from a multi-satellite altimeter dataset. Upper left: J1 sub-cycle 1, Upper right: Jason 1 sub-cycle 2; Center left: J2 LRO Cycle 1, Center right: Jason 2 LRO cycle 2; Lower left: J1 Entire LRO; Lower right: Jason 2 Entire GM (Both LRO cycles)

The derived marine gravity grids at 1’x1’ resolution were spline interpolated to the location of the marine gravity observations and the standard deviation of the differences are shown in Table 2. This table also highlights the difference in the standard deviation for shallow water regions close to the coast and for deep water regions.

	All depth	< 50 meters	>2000 meters
No. Of Observation	1409700	122108	900969
J1 Sub-cycle 1	5.36	5.25	5.13
J1 Sub-cycle 2	5.53	5.95	5.37
J1 Full GM	4.66	5.14	4.34
J2 LRO cycle 1	4.83	5.40	4.43
J2 LRO cycle 2	4.92	5.55	4.66
J2 Full GM	4.08	4.21	3.72

Table 2. Comparison with marine gravity data shown in Figure S2. The values in mGal are shown for all depth and for shallow water (less than 50 meters) and for deep water (greater than 2000 meters).

It is clear how the length of the GM directly affects the accuracy with which gravity can be derived from the Jason observations. The shortest GM corresponding to the first 179-day cycle of J1 shows a STD of 5.35 mGal with marine gravity observations. Gravity from the first J2 371-day LRO compares at 4.83 mGal and the 406-day GM of Jason-1 compares at 4.66 mGal. Gravity from the full J2 GM corresponding to 742 days compares at 4.08 mGal. The latter is nearly 20% better than gravity from one 371-day LRO cycle of Jason-2. The two interleaved LRO cycles of Jason-2 were only efficiently operating for 640 days, as the Jason-2 GM suffered from nearly 100 days of safe-hold despite mission rewind. This indicates that the comparison could have been significant better had the two LRO cycles been completed.

Safe-holds degrade the derived marine gravity. Comparing the Jason-2 1st and 2nd LRO cycles which encountered 39 and 60 days (40 days safe-hold plus 20 days early mission termination) exhibit 4.83 vs 4.92 mGal respectively. The numbers are also inferior to gravity derived from Jason-1 GM at 4.66 mGal. However, this GM lasted 30 days longer and only had 18 days of safe-holds. The impact is even larger for particularly coastal regions as also indicated in Table 2. Safe-hold degradation becomes more significant when comparing the Jason-1 first and second sub-cycle where the numbers are 5.36 and 5.53 mGal, respectively. The 18 days safe-hold corresponds to 10% of the time of the second cycle but resulted in a degradation of roughly 5% overall, with degradation in coastal regions of more than 10% (from 5.25 to 5.95 mGal).

When the second sub-cycle of Jason-1 was completed the satellite naturally transferred into a subsequent 3rd sub-cycle repeating the same ground track pattern along shifted tracks. The question arises if it would be better to design future GM to “rewind” the mission to remedy any significant safe-hold or to continue with the subsequent sub-cycle.

This was examined by adding data from the 3rd sub-cycle to the “safe-hold” affected 2nd sub-cycle of Jason-1. Adding 20 or even 50 days achieved an accuracy of 5.47 and 5.40 mGal, which is still inferior to the comparison from the first sub-cycle. However, the result after 50 days (nearly 1/3 of a sub-cycle) approaches the same accuracy as could have been achieved by a “mission rewind”. Unfortunately Jason-1 ceased operating at this stage. A possible “mission rewind” is even more important in the coastal zone. Here the degradation from 5.25 to 5.95 mGal for the second cycle only improves to 5.82 and 5.77 adding altimetry from 20 and 50 additional days from sub-cycle 3. This is somewhat expected as shorter wavelengths will dominate more in the shallow coast zone. This stresses the importance of seriously considering “rewinding missions” in case of significant safe-holds for future GM.

In case the graveyard orbit of Jason-2 could be used for a future Jason-3 LRO in a way that avoids collision risk, we explore the idea of moving Jason-3 into interleaved tracks with Jason-2 and bisecting the already 2-years or 4 km Jason-2 GM creating a 2 km grid after only 2 years of Jason-3 GM. This approach would re-use and build on the existing 2 years of Jason-2 GM rather than starting over with a new ground track pattern for the Jason-3 GM.

We created a grid from the first 371-day cycle for Jason-2 (having data for 332 days) and the first two 179-days sub-cycles of Jason-1 (totally 340 days) to directly compare the effect of a 2-years systematically densified GM versus two separate 1-year un-coordinated GM affected by the moiré patterns (Dibarboure et al, 2012). The investigation showed that the standard deviation increases from 4.08 mGal for the 2-year densified mission to 4.20 mGal for 2 years of un-coordinated GM. For coastal regions the numbers increase significantly more from 4.21 mGal to 4.50 mGal. The difference might appear small but it is important and it should be noted that Jason-2 suffered from significant safe-hold problems during the second cycle. Hence the gain from densifying an existing GM will be significantly larger than starting all over with a new GM in a different orbit.

5 Summary and recommendations

The GM carried out as the EoL mission for Jason-2 was the first systematic attempt to provide satellite ground-tracks with a systematic track distance of 4 km after 2 years (and planned 2 km after 4 years). The track distance is a limiting factor to the derived global altimetric gravity fields.

Starting out with data from the first 179-day cycle of J1 (track distance of 17 km) we found a standard deviation of 5.35 mGal with marine gravity observations. Gravity from the first 371-days LRO of Jason-2 (track distance of 8.5 km) compared at 4.83 mGal and the 406-day GM of Jason-1 compares at 4.66 mGal (track distance of 7.8 km). Gravity from the full Jason-2 GM corresponding to 742 days and a track density of 4.3 km clearly compared favorable at 4.08 mGal demonstrating the value of gradually decreasing the track-distance using multiple LRO for the GM. The result was obtained despite the fact that Jason-2 was only efficiently measuring for 642 days of the planned two LRO cycles lasting 742 days.

During its GM Jason-2 suffered from significant safe-holds. The most noticeable was a 100-day safe-hold in early 2019. The partnership between NOAA, NASA and CNES agreed to conduct an orbital maneuver and “rewind“ the mission by 79 days to recover the missing observations and limit the safe-hold gap to 21 days. This was the first time such was attempted for a GM and stresses the importance of an LRO orbit design having multiple interleaved sub-cycles.

Investigating the two 179-day sub-cycles of Jason-1 GM (one was nearly complete and one suffered 18 days or 10% data loss) showed that it very important to consider recovering data from significant safe-holds for future GM mission rather than just continuing the GM into the next interleaved cycle. Jason-3 will be the next satellite to be considered for a GM as its successor Sentinel-6/Jason-CS is scheduled for launch on 10 November 2020.

Rewinding the GM to recover mission tracks is particularly important as global marine gravity continues to increase in accuracy with more and more GM data becoming available and integrated with the Jason altimetry (e.g. from the uncontrolled GM of SARAL/AltiKa).

Considering minimizing the effect of significant safe-holds is equally important for Mean Sea Surface determination paramount to deriving accurate sea level anomalies. Here the GM data governs the accuracy of the fine scales of the MSS. This is particularly important for future high-resolution altimetric mission like the NASA/CNES Surface Water and Ocean topography (SWOT) to be launched in 2022.

In case collision risk between Jason-2 and Jason-3 in the same graveyard orbit could be assessed and found to be controlled we explored the idea of moving Jason-3 into tracks interleaved with Jason-2 and bisecting the already 2-years or 4 km Jason-2 GM creating a 2 km grid after only 2 years of GM. This would enable a global gravity field and more importantly a global MSS with unprecedented resolution in time for the SWOT mission. If technically possible our findings strongly recommend to reuse the Jason-2 LRO orbit with Jason-3 to bisect and densify the geodetic grid in a regular way as opposed to a new GM orbit where the grids will not be aligned and therefore will have Moirè patterns.

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