Response (Anonymous Referee #2)

Comment: This paper derived the global marine gravity model, SDUST2022GRA, by combining altimeter data from nadir-looking satellites and from ICESat-2. The cross-track geoid gradients were determined using the three-pair laser beams of ICESat-2, a capability not available from nadir-looking altimeters. These cross-track geoid gradients, which are primarily oriented in the east-west direction, are instrumental in improving the accuracy of the east-wast components of geoid gradients, thereby enhancing the marine gravity model. This paper is interesting and worth publishing after addressing the key points identified herein.

Reply: Thank you for your comments and meticulous check of our manuscript that make the manuscript more interesting and informative. Below, please find our point to point responses to the comments in the list of revisions.

Comment 1 Lines 210-215: When determining the cross-track geoid gradients, the authors only used the data with 'the closest time'. Although time-related signals affect ICESat-2 SSHs, the time for the SSHs from the ICESat-2's three-pair beams is close. Ignoring the time factor may yield more results.

Reply: Thank you very much for your comments. The method of determining the cross-track geoid gradients is rephrased:

Because three beams of ICESat-2 observations are not exactly simultaneous, the cross-track GG is determined, according to the following steps. (1) One track with good observations (maximum number of each beam) from two-beam altimeter data is selected as the reference altimeter data. (2) Based on the reference beam observations, the cross-track GG is determined within a time and azimuth threshold. (3) If the number of GGs is more than one on each reference observation, only the cross-track GG with an azimuth closet to perpendicular to the orbit inclination is used to recover gravity anomalies. A schematic diagram of determining the cross-track gt13 GGs from ICESat-2 altimeter data is shown in Fig. 3. The cross-track GG determination strategy is defined as follows:

$$\begin{cases} \text{Reference\_beam} = \text{Max}[\text{Num}_{\text{gt1}}, \text{Num}_{\text{gt3}}] \\ \left|T_i - T_{ref}\right| \le T\_Threshold \\ \left|\alpha_{GG,i} - \alpha_{ref\_inc}\right| \le A\_Threshold \\ \text{Cross\_track\_GG} = \text{Min}[\alpha_{GG,i} - \alpha_{ref\_inc}] \end{cases} \quad (7)$$

where Num_{gt1}, Num_{gt2}, and Num_{gt3} are the number of each beam observations, respectively. T_{ref} is the observation time of reference beam, T_i is the observation time of the other beam, $\alpha_{GG,i}$ is the azimuth of GG derived from two-beam observations at the number i . α_{ref_inc} is a reference azimuth perpendicular to the orbit inclination. $T\_Threshold$ is a time threshold, and 1 s is selected as time threshold to reduce the effect of random errors, $A\_Threshold$ is an azimuth threshold, $\pi/4$ serves as a azimuth threshold to obtain GGs with azimuth toward east-west direction.

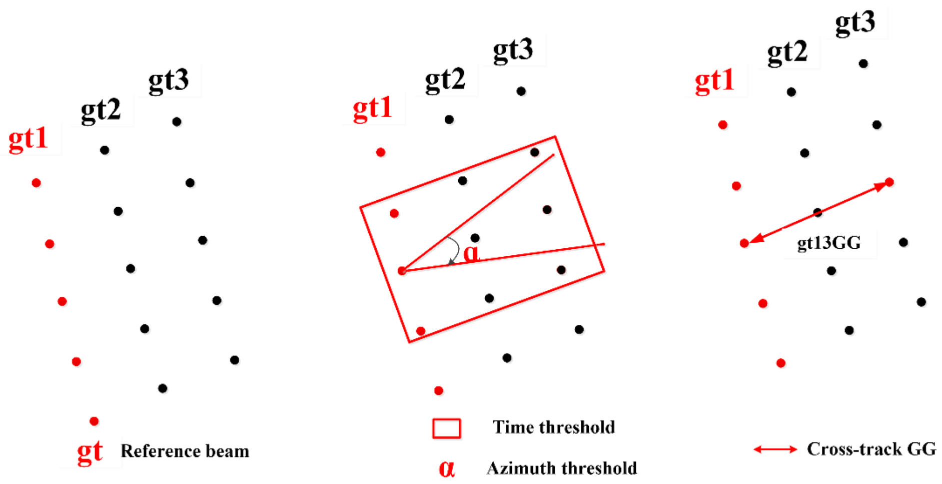

Figure 3 The schematic diagram of determining the cross-track geoid gradients from gt1 and gt3 beams of ICESat-2

For the determination of cross-track GG of ICESat-2, it is necessary to select the associated SSHs from different beam observations. Otherwise, a cross-track GG with an azimuth that inclined to the north direction may not be able to mitigate the unbalanced accuracy of DOV.

Comment 2 Figure 3 and Table 5: Three types of cross-track geoid gradients (g12, g23, and g13) were obtained (Fig. 3). The accuracy of g13 was much higher than that of g12 and g23 (Table 5). Therefore, only g13 was used to derive the marine gravity model. However, the differences in the STD for the three types of geoid gradients are due to the distance rather than the accuracy of ICESat-2 SSHs. A more reasonable explanation should be provided.
Reply: Thank you very much for your valuable suggestions. We used the along-track GGs and gt13 cross-track GGs to recovering marine gravity anomaly model. The main reason for exclusively using the gt13 cross-track GGs is that the configuration yields a high accuracy for gravity anomalies recovery compared to other combinations. Table 4 provides statistic on the difference between gravity anomalies recovered from ICESat-2 and shipborne gravity. Our analysis indicates that combining gt13 cross-track GGs results in better accuracy than combining gt12 or gt23 cross-track GGs.
For this reason, we analyses the number of observations from three beams, the precision of SSHs and GGs. The precision of SSHs is a critical factor influencing the precision of GGs. The RMS of SSH crossover discrepancies from three beam observations is listed in Table 6. While the precision of SSHs from the gt2 beam observation is slightly superior to that from the gt1 or gt3, it is not straightforward to determine that the precision of cross-track GGs. The precision of GGs is not only related to the precision of SSHs, but also to the distance between the two points. Furthermore, we analyzed the quality (number and standard deviation) of along-track and cross-track GGs, as shown in Table 5. The STD of difference between gt13 GGs and the reference gravity field is closer to that of along-track GGs than gt12 and gt23. Additionally, the number of gt2 beam observation is less than gt1 or gt3 beam observations, resulting in the number of gt13 cross-track GGs being more than that other cases. Therefore, the combination of along-track and gt13 cross-track GGs is used to recover marine gravity anomalies.

Table 4 Differences between ICESat-2 altimeter-derived gravity and ship-borne gravity (Unit: mGal)

Gravity anomaly model	Max	Min	Mean	STD	RMS

gt1+gt2+gt3	50.83	-48.28	-0.13	5.56	5.56
gt12+gt1+gt2+gt3	49.35	-48.18	-0.10	5.66	5.66
gt23+gt1+gt2+gt3	54.92	-54.98	-0.06	5.70	5.70
gt12+gt23+gt1+gt2+gt3	47.07	-46.75	-0.07	5.65	5.65
gt13+gt1+gt2+gt3	49.54	-48.05	-0.03	5.42	5.42

Table 5 The number and STD of residual GGs from ICESat-2

Residual GGs	gt1	gt2	gt3	gt12	gt23	gt13
Number	302407	250988	301138	202492	200312	209769
STD(urad)	1.93	1.88	1.91	2.66	2.75	1.94

Table 6 The RMS of SSH crossover discrepancies

Altimetry	Satellite Mission	Average along-track ground distance (km)	Crossover discrepancies (30 d)	
			RMS before adjustment (m)	RMS after adjustment (m)
Laser altimetry	ICESat-2/gt1	7.1	0.131	0.117
	ICESat-2/gt2	7.1	0.128	0.109
	ICESat-2/gt3	7.1	0.138	0.119
GM (Radar altimetry)	SARAL/DP	7.0	0.110	0.085
	Cryosat-2	6.4	0.082	0.060
	H2A	6.5	0.103	0.076
	J2	5.8	0.114	0.088
	J1	5.8	0.108	0.079
	E1	6.4	0.117	0.097
ERM (Radar altimetry)	Sentinel-6A SAR	5.8	0.022	0.013
	Sentinel-3A SAR	6.7	0.027	0.018
	Sentinel-3B SAR	6.7	0.035	0.026
	SARAL	7.0	0.034	0.020
	HY-2A	6.5	0.030	0.020
	HY-2B	6.5	0.032	0.024
	T/P-Jason_A	5.9	0.027	0.018
	T/P-Jason_B	5.9	0.026	0.019
	Envisat_A	7.5	0.033	0.022
	Envisat_B	7.5	0.042	0.024
	ERS-2	6.6	0.040	0.034
	GFO	6.7	0.034	0.019

Specific and minor comments

1. Line 15: In this manuscript, 'across-track' should be corrected to 'cross-track'.

Reply: Thanks. This 'across-track' is corrected to 'cross-track' as the suggestion in all sections.

2. Line 30: The 13% improvement in the marine gravity field is significantly impressive, but ICESat-2 only improved by 0.12 mgal, which could mislead readers.

Reply: Thank you for your valuable comments. The percentage contribution is redefined as $\frac{RMS_{\text{SDUST2022GRA}} - RMS_{\text{SDUST2021GRA}}}{RMS_{\text{SDUST2022GRA}}} \times 100\%$ and the improvement is recalculated. The sentence is rephrased: the percentage contribution of ICESat-2 to the improvement of gravity anomaly model is 4.3% in low-middle latitude regions, and it is increasing in coastal regions.

3. Line 40: The authors confused the 'DOV' and 'geoid gradient (GG)' concepts. In this manuscript, DOV is geoid gradients, but they are opposite. The along-track GGs (and cross-track GG from ICESat-2) are used to determine the north and east components of GG on a regular grid using LSC. Therefore, this sentence should be:'Normally, the north and east components of deflection of the vertical (DOV) on a regular grid, derived from along-track geoid gradients, is ...'

Reply: Thanks for your thoughtful comments. The sentence is rephrased:

Normally, the north-south component and east-west component of deflection of the vertical (DOV) on a regular grid, derived from along-track geoid gradients (GGs), is used to recover marine gravity anomaly model by inverse Vening-Meinesz formula or Laplace's equation (Sandwell and Smith 1997; Hwang et al., 2002).

Because of the satellite ground-tracks inclination of the north-south direction, the precision of the north component of the altimeter-derived DOV model is generally higher than the east component (Che et al., 2021; Jin et al. 2022). The unbalanced accuracy of DOV components severely restricts the improvement of the gravity anomaly model (Hwang 1998, Annan and Wan 2021).

4. Line 140: Should it be 'satellite-derived gravity anomaly models'?

Reply: Thank you for your suggestion. The sentence is rephrased:

In general, shipborne gravity anomalies have a higher accuracy and spatial resolution than the altimeter-derived gravity anomaly model on ship routes.

5. Line 143: Please modify this sentence to: The gross errors in the shipborne gravity data were removed. I would like to know if the shipborne data, which removed the long-wavelength errors based on XGM2019e, were used to assess all the marine gravity models described in this manuscript.

Reply: Thank you very much for your good comments. The sentence is rephrased:

The gross errors in the shipborne gravity data were removed. The shipborne gravity data, which removed outliers and long-wavelength errors based on XGM2019e, were used to assess all marine gravity anomaly models. Table 10 presents the difference between altimeter-derived gravity anomaly models (NSOAS22, DTU17 SIO V32.1, SDUST2022GRA) and all shipborne gravity anomalies. Table 13 presents the RMS of difference between SDUST2021GRA and all shipborne gravity anomalies.

Table 10 The difference between gravity anomaly models and global shipborne gravity (Unit: mGal)

Region	Model	Max	Min	Mean	STD	RMS
Global ocean [80°S, 82°N]	NSOAS22	99.46	-81.17	-0.10	5.73	5.73
	DTU17	99.25	-71.85	-0.13	5.42	5.42
	SIO V32.1	77.17	-86.24	-0.10	5.18	5.18
	SDUST2022GRA	96.79	-68.51	-0.08	5.07	5.07
Low-middle latitude	NSOAS22	78.04	-81.17	-0.07	5.26	5.26

regions [60°S, 60°N]	DTU17	78.44	-71.85	-0.12	4.89	4.89
	SIO V32.1	76.25	-86.23	-0.06	4.65	4.65
	SDUST2022GRA	64.44	-67.00	-0.09	4.43	4.43
High-latitude regions [80°S, 60°S)& (60°N, 82°N]	NSOAS22	99.46	-70.56	-0.47	9.76	9.77
	DTU17	99.25	-68.48	-0.25	9.82	9.82
	SIO V32.1	77.17	-76.54	-0.51	9.53	9.54
	SDUST2022GRA	96.79	-68.48	-0.26	9.69	9.69

Table 13 The percentage contribution of ICESat-2 altimeter data in global ocean region

Region	**$RMS_{SDUST2021GRA}$ (mGal)**	**$RMS_{SDUST2022GRA}$ (mGal)**	**ΔRMS (mGal)**	**Percentage Contribution**
Global ocean	5.19	5.07	0.12	2.3%
Low-middle latitude regions	4.63	4.43	0.20	4.3%
High-latitude regions	9.73	9.69	0.04	0.4%

6. Line 150. Why is the accuracy of shipborne data 2.82 mGal?

Reply: Thanks for your comments. The precision of shipborne gravity data is not provided along with the gravity data. Thus, the precision of shipborne gravity is verified by the discrepancies of gravity anomalies at crossover points. The RMS of discrepancies is 3.99 mGal. The precision of shipborne gravity anomalies, about 2.82 mGal, is derived by dividing RMS by the square root of two based on the error propagation law. It is generally consistent with the shipborne gravimeter measurements of 1-3 mGal magnitude (Zaki et al. 2022).

7. Please provide this abbreviation 'geoid gradient'. when it first appear.

Please provide the full name of STD. Cnn is not described in this manuscript. Please change it to 'error variance of GGs'.

Reply: Thanks for your suggestion. We add the abbreviation 'geoid gradient', when it first appear in Line 39. The sentence is rephrased: The residual along-track GG is derived by

We apologize for the missing of full name of STD and the description of Cnn. The sentence is rephrased: where is the standard deviation (STD) of GGs to determine the error variance (Cnn in LSC) of GGs.

8. In equation (3), The two parameters (t0 and t1) are very important. Please provide specific values.

$$f(t) = a_0 + a_1(t - t_0) + \sum_{i=1}^{n}\left[C_i \cos(i\omega(t - t_0)) + S_i \sin(i\omega(t - t_0))\right] \qquad (3)$$

Reply: Thank you very much for your comments. t0 and t1 are two parameter used to determined the angular frequency in the trigonometric polynomial. t0 and t1 are the beginning and end observation times of each ground track, respectively. For each track observations, the value is not the same.The detail of crossover adjustment is described in Huang et al. (2008).

9. How to compute this parameter? The initial value $D_{\Delta g,0}$.

The termination condition of the iteration is that the difference between the adjacent error of GG is less than a threshold. Please provide specific.

Reply: Thanks for your thoughtful comments. The initial value $D_{\Delta g,0}$ is determined using

The each altimeter-derived gravity anomaly model is recovered from the initial error of GGs derived by the RMS of crossover discrepancies, include the Ku-band and Ka-band altimeter data. The precision of altimeter-derived gravity anomalies can be calculated by

$$D_{model\_ship} + v = D_{\Delta g} + D_{shipborne}$$

Where D_{model_ship} represent the variance of difference between altimeter-derived gravity anomaly model and shipborne gravity anomalies, $D_{shipborne}$ represent the variance of shipborne gravity anomalies, $D_{\Delta g}$ is the error variance of altimeter-derived gravity. The SARAL(Ka-band)-derived gravity anomaly model is recovered from the initial error of GGs derived by the RMS of crossover discrepancies. Then, the initial value $D_{\Delta g,0}$ is determined by above equation.

The termination condition of the iteration is less than a threshold. The threshold is determined from the RMS of fitted residuals of parameters solution (β_0 and β_1). The Threshold is 0.04 mGal, which provided after solving (β_0 and β_1) in Section 4.2.

10. Do you want to present that 'We presented a method for processing multi-beam observations from ICESat-2' ?

Reply: Thank you very much for your comments. The sentence is rephrased:

The cross-track GGs processing method is presented from ICESat-2 multiple beam observations.

11. The used LSC for the determination of DOV is. Please add the reference: (Hwang and Parsons, 1995)

    Lines 230 and 235, please add Reference.

    Equations (9) and (11) should not be provided as an independent formula.

Reply: Thank you very much for your valuable suggestion. We corrected the sentence and added Reference. In addition, Equations (9) and (11) are provided in the text not as an independent formula.

The sentence is rephrased:

We determined the DOV components by LSC as (Hwang and Parsons, 1995)

In Lines 230 and 235, we added References. The sentence is rephrased:

Therefore, the covariance matrices ($C_{\xi e}$, $C_{\eta e}$ and C_{ee}) are obtained by (Hwang and Parsons, 1995)

The gravity anomaly model is recovered by the inverse Vening-Meinesz formula as (Hwang, 1998)

Reference

Hwang, C.: Inverse Vening Meinesz formula and deflection-geoid formula: applications to the predictions of gravity and geoid over the South China Sea, J. Geodesy, 72(5), 304-312, https://doi.org/10.1007/s001900050169, 1998.

Hwang, C., and Parsons, B.: Gravity anomalies derived from Seasat, Geosat, ERS-1 and

TOPEX/POSEIDON altimetry and ship gravity: a case study over the Reykjanes Ridge, Geophys. J. Int., 122(2), 551-568, https://doi.org/10.1111/j.1365-246X.1995.tb07013.x, 1995.

12. When resampling the ICESat-2 data, would additional errors caused by resampling or interpolation appear?

Reply: Thanks for your suggestion. The resampling is an important method for altimeter data processing. We added the introduction about resampled method in Section 3.2.

The ICESat-2 SSH observations at varying length scales is resampled at 1 Hz for each beam in order to obtain a uniform distribution of SSHs. In the resampling, we fitted SSHs at varying length scale by a quadratic polynomial in latitude to reduce the effect of the high-frequency noise and outlier. Each of the 1-s SSHs is used to solve polynomial coefficients and then produced SSHs in the median of the latitude. When the number of observations is less than the minimum number for the solution of polynomial coefficients, the 1-s SSHs are averaged directly to 1 Hz. The used quadratic polynomial function of latitude is (Yu and Hwang, 202)

$$l_i + v_i = a\varphi_i^2 + b\varphi_i + c \quad (6)$$

where l_i is the SSH observation at point i with in a time threshold, v_i is the residual at point i, φ_i is the latitude at point i, and a, b, c are the coefficients of the quadratic polynomial.

13. In table 4. What does 'STD'mean? What is the difference between 'STD' and 'RMS'?

Reply: Thank you very much for your comments. The STD accounts for the deviation of individual data points from the mean, where as RMS accounts for the absolute magnitude of those data points. In there, the STD and RMS is determined from the difference between ICESat-2 recovered gravity anomalies and shipborne gravity anomalies. The Table 4 is corrected as:

Table 4 Differences between ICESat-2 altimeter-derived gravity and ship-borne gravity (Unit: mGal)

Gravity anomaly model	Max	Min	Mean	STD	RMS
gt1+gt2+gt3	50.83	-48.28	-0.13	5.56	5.56
gt12+gt1+gt2+gt3	49.35	-48.18	-0.10	5.66	5.66
gt23+gt1+gt2+gt3	54.92	-54.98	-0.06	5.70	5.70
gt12+gt23+gt1+gt2+gt3	47.07	-46.75	-0.07	5.65	5.65
gt13+gt1+gt2+gt3	49.54	-48.05	-0.03	5.42	5.42

14. The STD of g13 is much smaller than those of g12 and g23. The reason is that the distance of g13 (please see Fig. 3 and Eq. (1)) is half of that of g12 and g23. But we could not conclude that g13 is much accurate than g12 and g23.

Reply: Thanks for your thoughtful comments. The error variance of GG from each altimeter data can be derived using the error propagation law of Eq. (1) while ignoring the distance error of two points, as

$$m_e^2 = \frac{m_{ssh,pt1}^2 + m_{ssh,pt2}^2}{d_{pt1\_pt2}^2} \quad (2)$$

Thus, the GGs error is correlated with the distance and SSH observations error. The STD of g13 is much smaller than those of g12 and g23, but it could not conclude that gt13 is much accurate than gt12 and gt23. We corrected the explanation. The sentence is rephrased:

The total amount of gt13 GGs is generally consistent with gt12 and gt23, but the STD of difference between gt13 GGs and the reference gravity field is close to that of along-track GGs than gt12 and gt23.

15. The contribution of ICESat-2 to the marine gravity model is the difference between the RMSs of SDUST2021GRA and SDUST2022GRA. It has nothing to do with the reference field. The 13% improvement in the marine gravity field is significantly impressive, but ICESat-2 only improved by 0.12 mgal, which could mislead readers.

Reply: Thank you very much for your valuable comments. The percentage contribution is redefined. The sentence is rephrased:

The percentage contribution of ICESat-2 to the improvement of the gravity anomaly model is defined as $\frac{RMS_{\text{SDUST2022GRA}} - RMS_{\text{SDUST2021GRA}}}{RMS_{\text{SDUST2022GRA}}} \times 100\%$ representing the ratio of the improvement of the gravity model recovered by incorporating ICESat-2 to the improvement of the gravity model recovered from all altimeter data, as shown in Table 13.

Table 13 The percentage contribution of ICESat-2 altimeter data in global ocean region

Region	**$RMS_{SDUST2021GRA}$ (mGal)**	**$RMS_{SDUST2022GRA}$ (mGal)**	**△RMS (mGal)**	**Percentage Contribution**
Global ocean	5.19	5.07	0.12	2.3%
Low-middle latitude regions	4.63	4.43	0.20	4.3%
High-latitude regions	9.73	9.69	0.04	0.4%