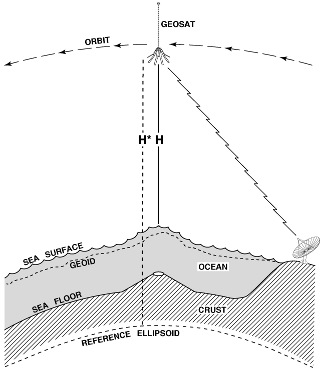
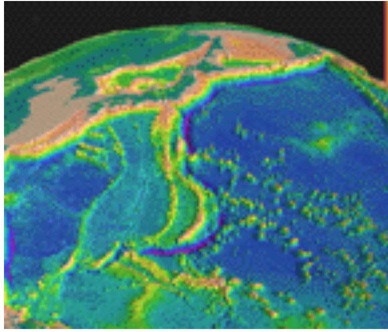


Improved Global Marine Gravity from CryoSat



David T. Sandwell, Emmanuel Garcia and Walter H. F. Smith

5th Coastal Altimetry Workshop, October 16, 2011

- **needs for higher accuracy and resolution gravity**
  - plate tectonics
  - seamounts
  - petroleum exploration
  - predicted bathymetry
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- gravity accuracy improvements over the next 5 years

available altimeter data pre-CryoSat

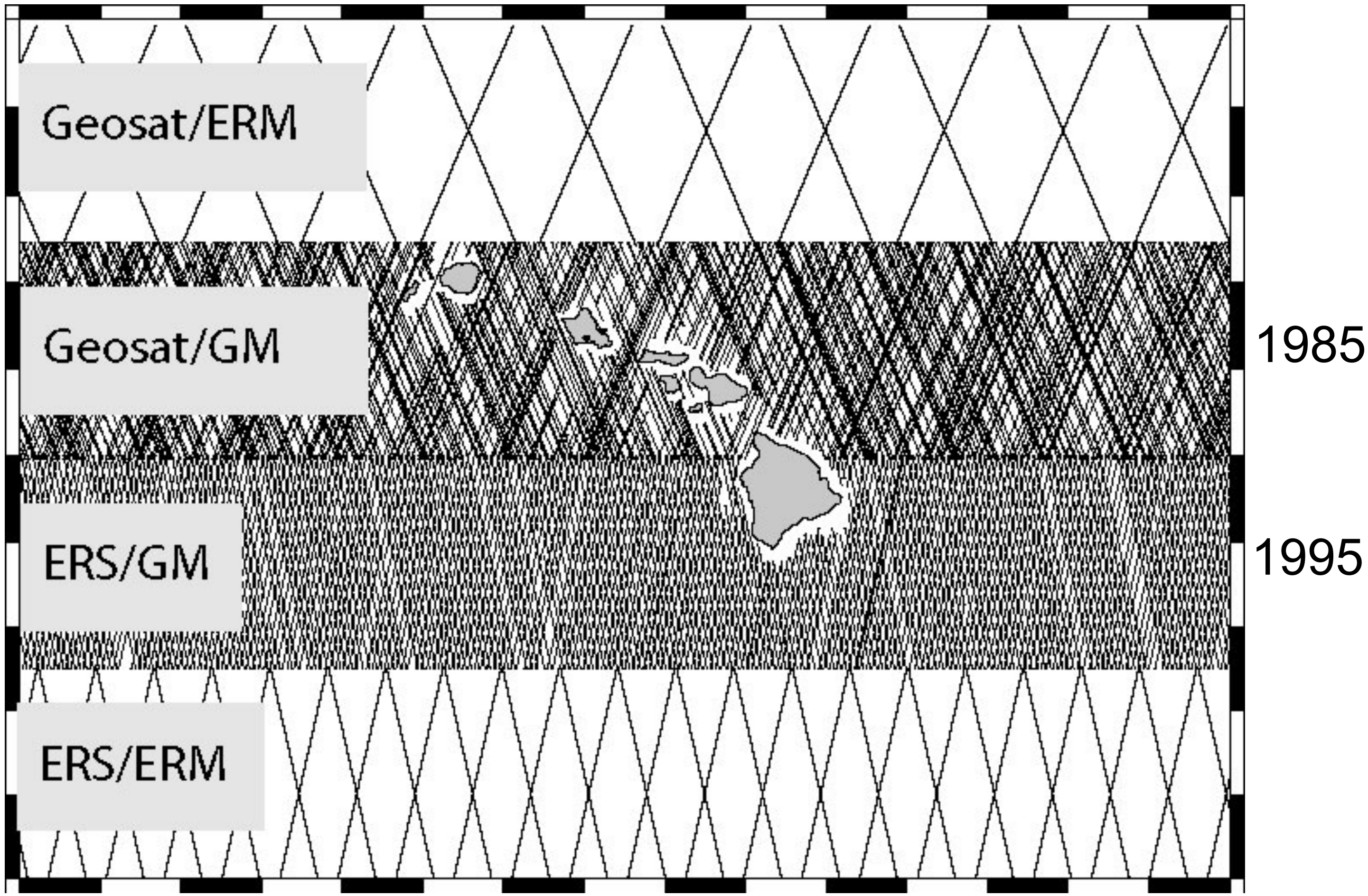
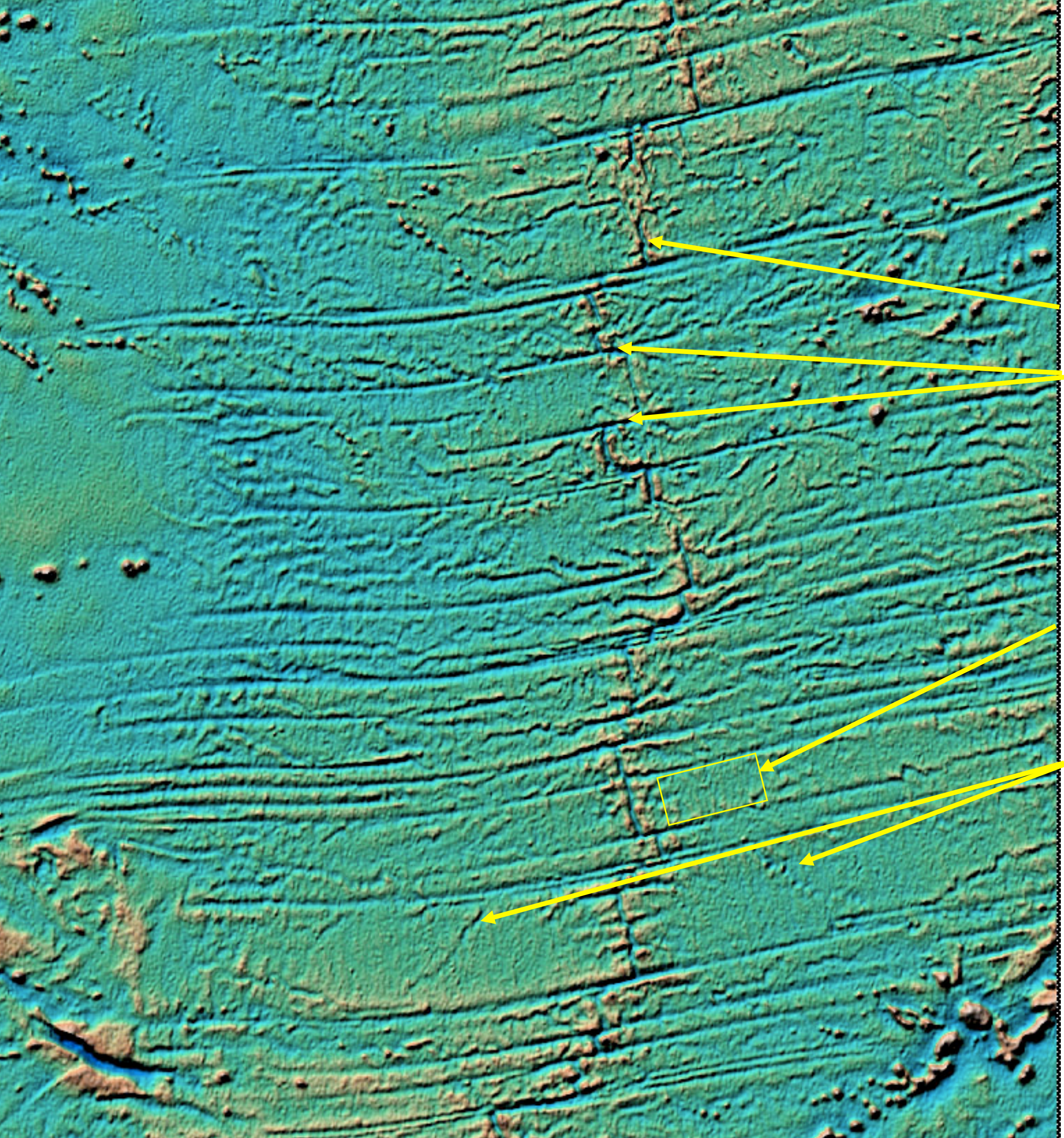


Plate Tectonics: South Atlantic



known:

ridges

transforms

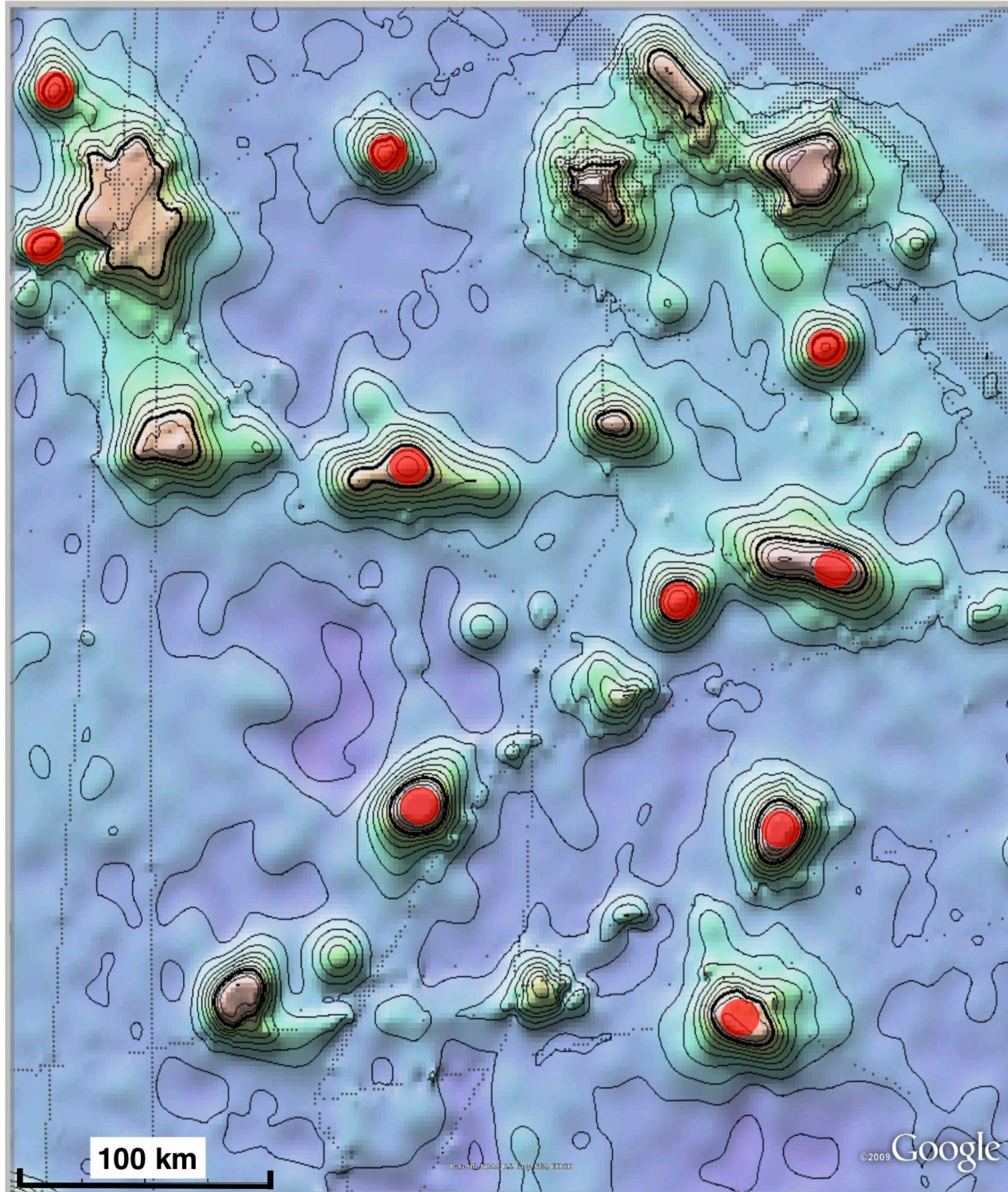
unknown:

abyssal hills

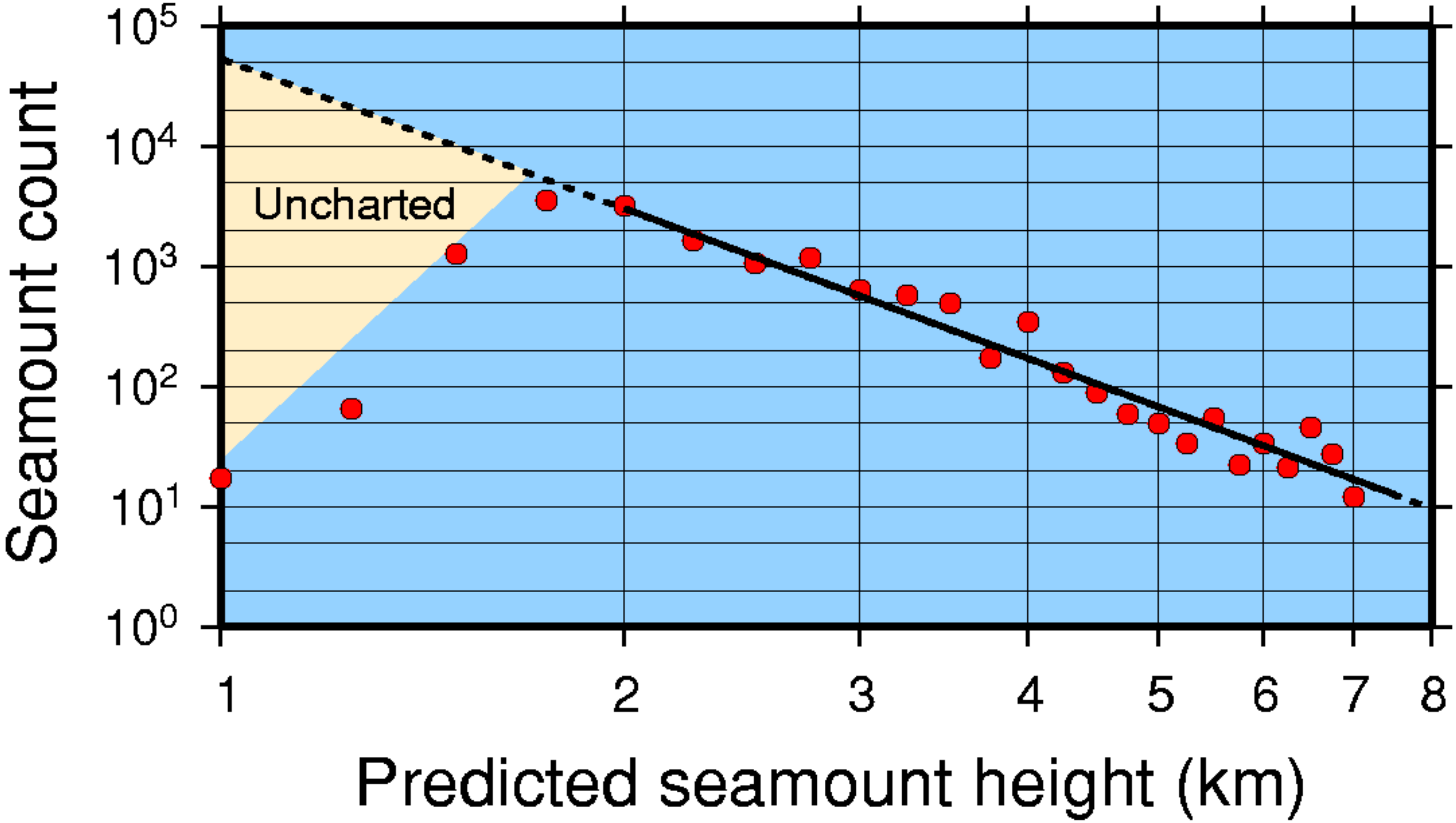
propagating rifts

small seamounts

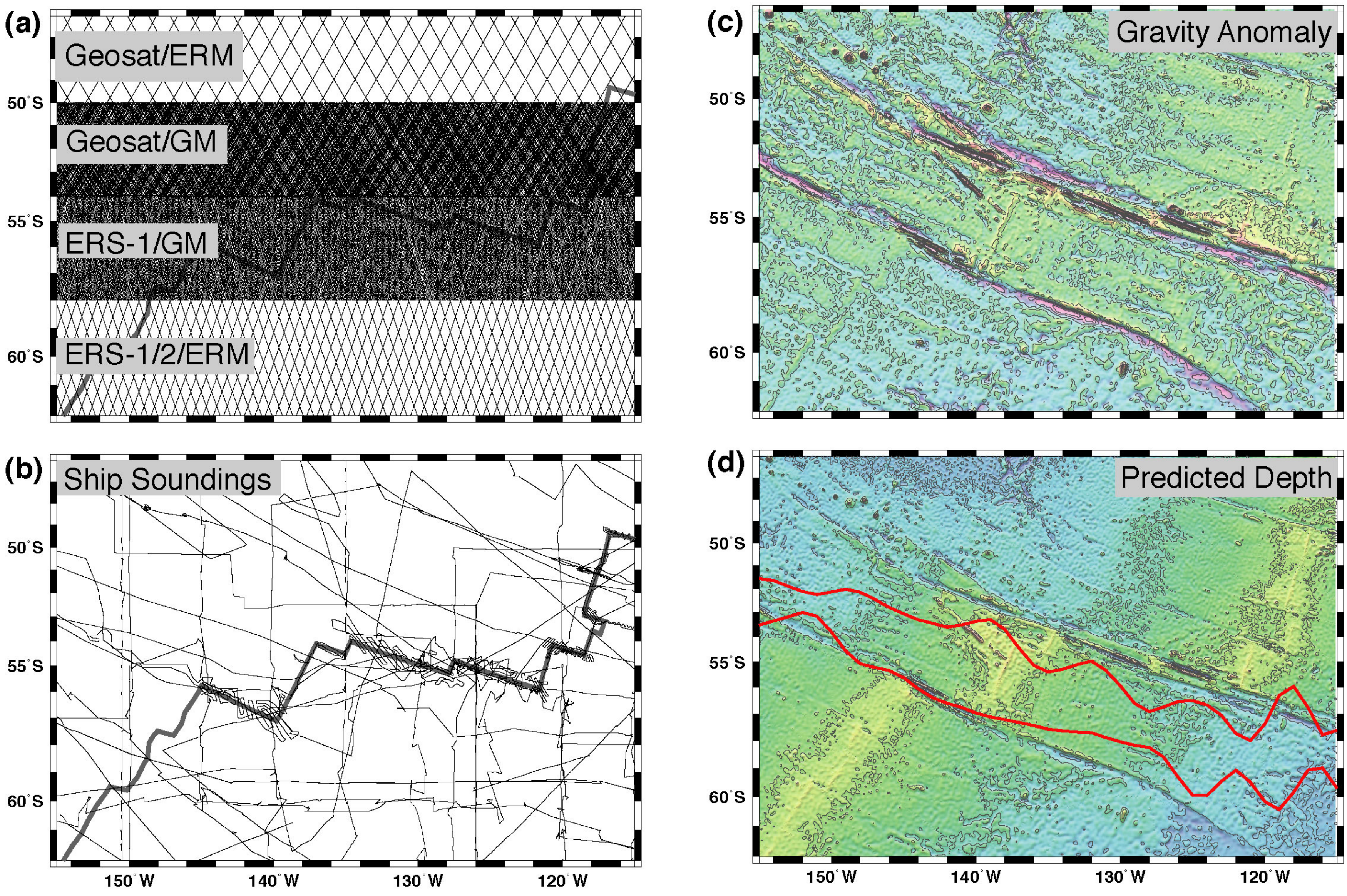
uncharted seamounts > 3 km tall



seamounts [*Wessel*, 2001]



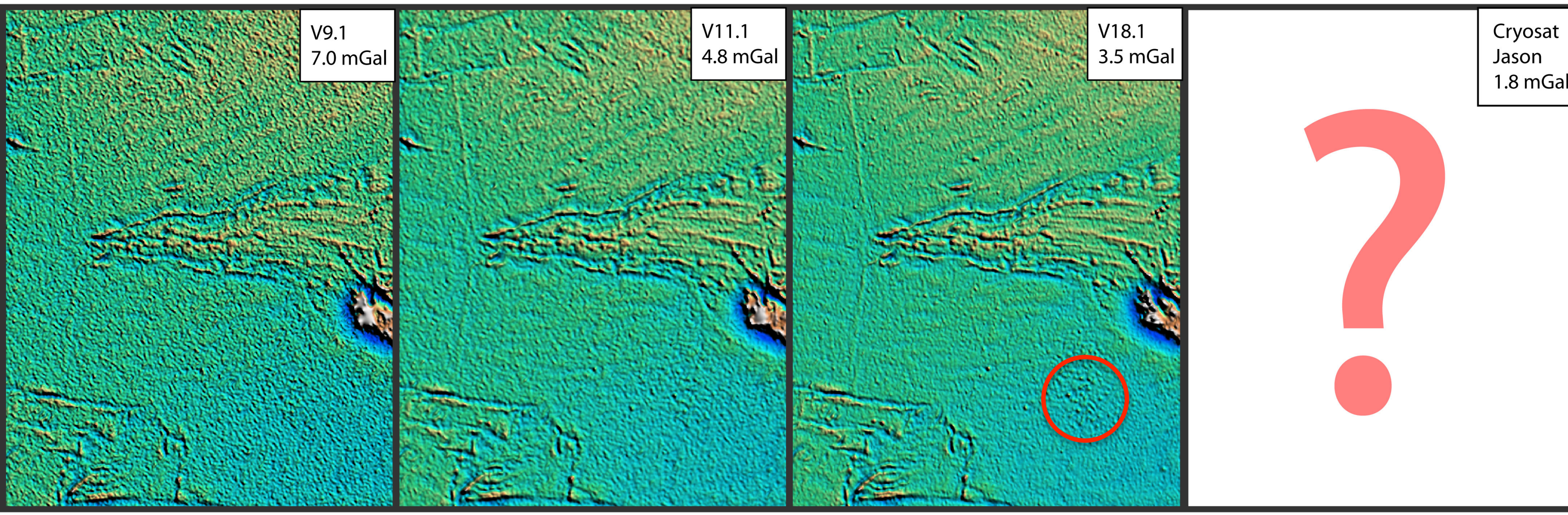
sparse soundings + dense altimetry = global bathymetry



improving predicted bathymetry requires better gravity

Evolution of marine gravity models as seen over the
Galapagos Triple Junction

original data retracked ERS retracked Geosat



1997 2005 2009 2013 +

slope requirement

Φ	disturbing potential
$N = \dfrac{1}{g_o}\Phi$	geoid height
$\Delta g = -\dfrac{\partial \Phi}{\partial z}$	gravity anomaly
$\eta = -\dfrac{\partial N}{\partial x}$	slope of ocean surface

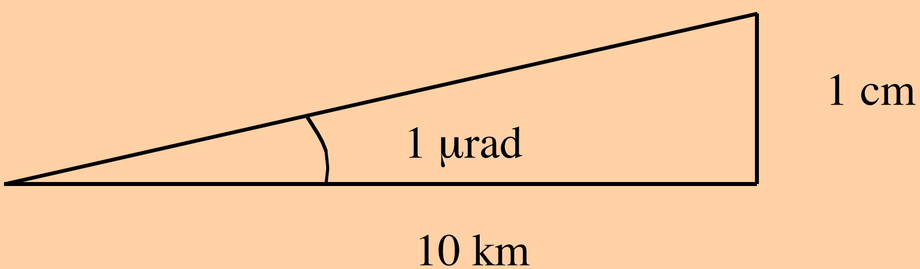
Laplace's equation, assume 2-D anomaly

$$\nabla^2 \Phi = 0 \quad \Rightarrow \quad g_o \frac{\partial \eta}{\partial x} + \frac{\partial g}{\partial z} = 0$$

take fourier transform w.r.t. x

$$\Delta g(k) = i g_o \frac{k}{|k|} \eta(k)$$

1 μrad of slope error ⇔ 1 mGal gravity error



Achieving 1 mGal Gravity Accuracy

- **Improved range precision** -- A factor of 2 or more improvement in altimeter range precision, with respect to Geosat and ERS-1, is needed to reduce the noise due to ocean waves.

- **Fine cross-track spacing and long mission duration** -- A ground track spacing of 6 km or less is required.

- **Moderate inclination** -- Current non-repeat-orbit altimeter data have high inclination and thus poor accuracy of the E-W slope at the equator.

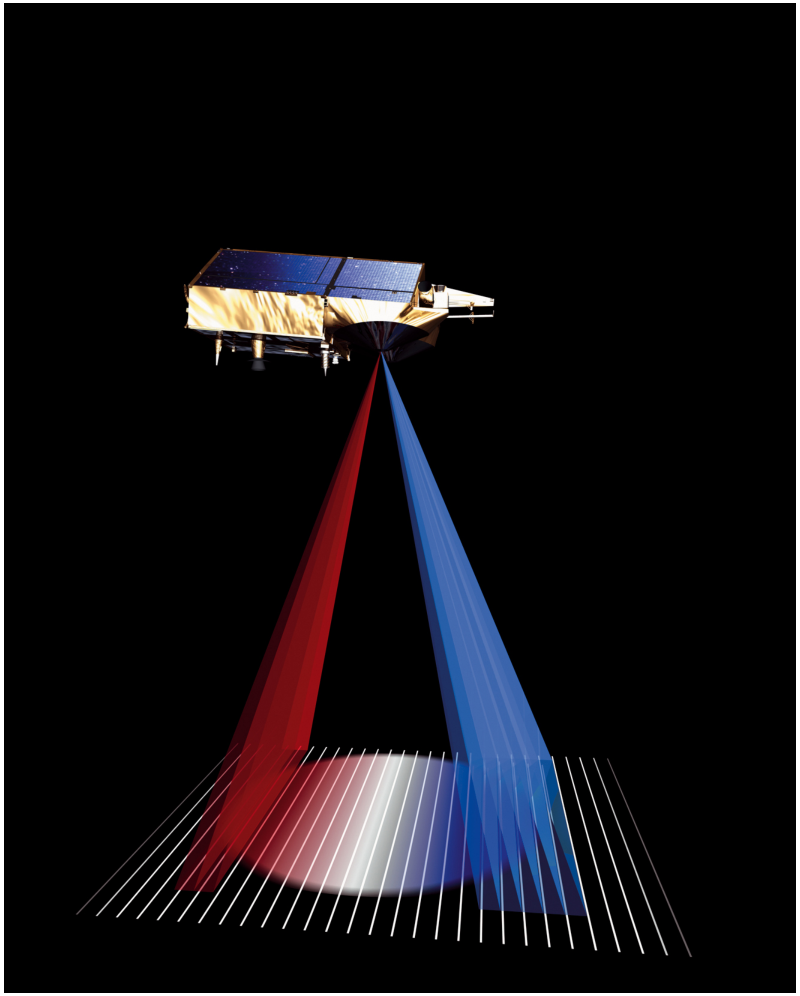
- **Near-shore tracking** -- For applications near coastlines, the ability to track the ocean surface close to shore is desirable.

CryoSat’s Modes

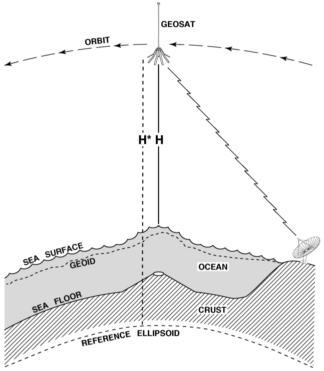
- **LRM** –- conventional mode used by all previous altimeters.

- **SAR** –- synthetic aperture radar mode may provide 2-4 times better range precision.

- **SARIN** -– uses two receiving antennas to also measure cross-track slope.



source: ESA



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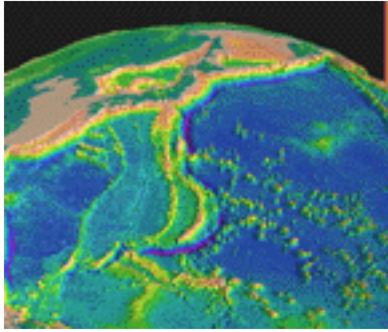

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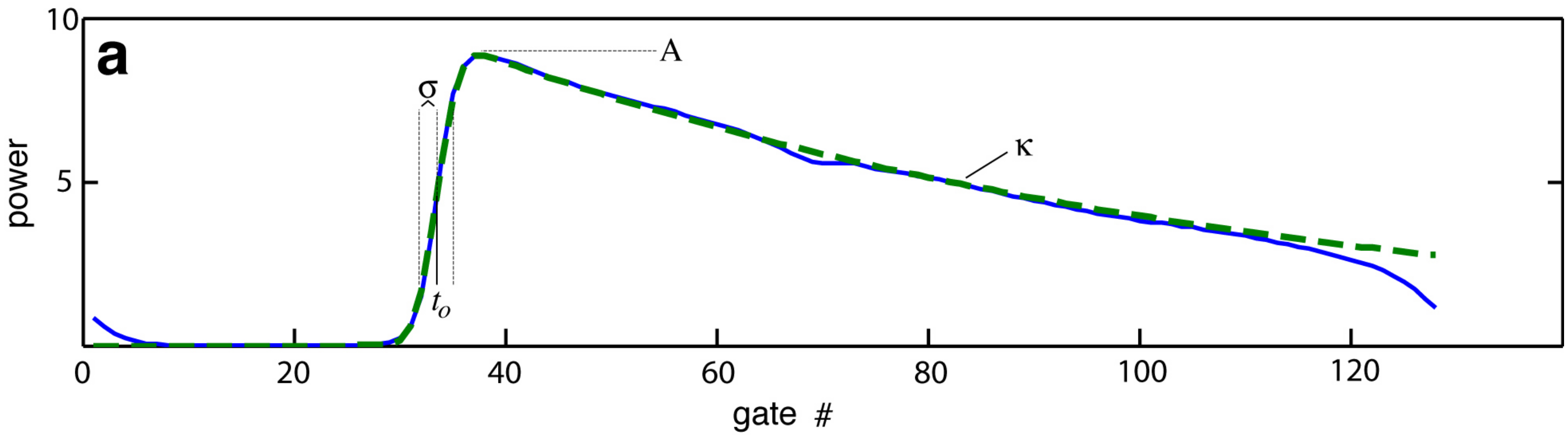
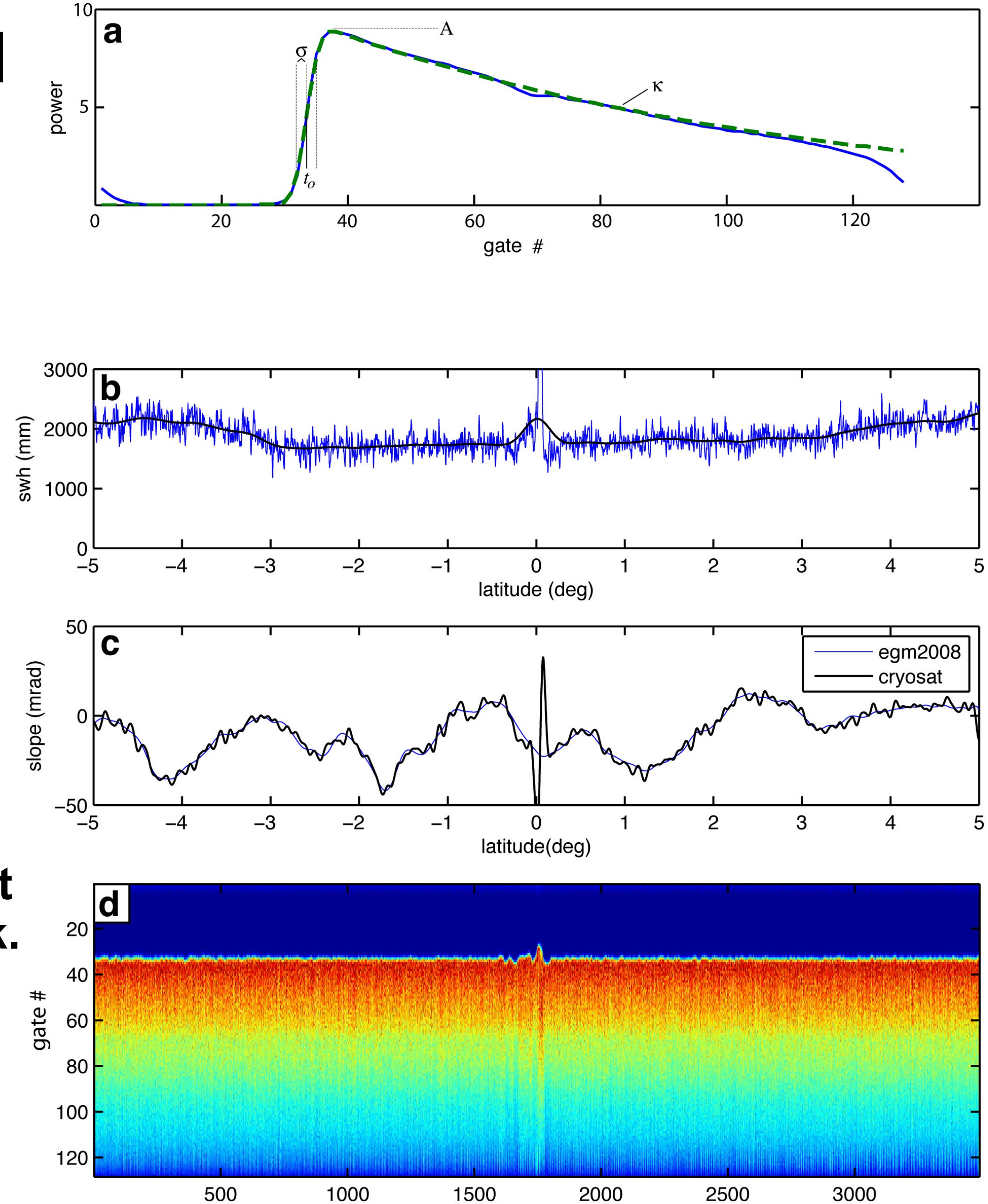
LRM waveform retracking



Estimate 3 parameters: arrival time (t_o), rise time (σ), and power (A).

$$M(A, t_o, \sigma) = \frac{A}{2}\left\{1 + erf(\eta)\right\}; \qquad \eta = \frac{t_o}{\sqrt{2}\sigma}$$

recipe for improved range precision



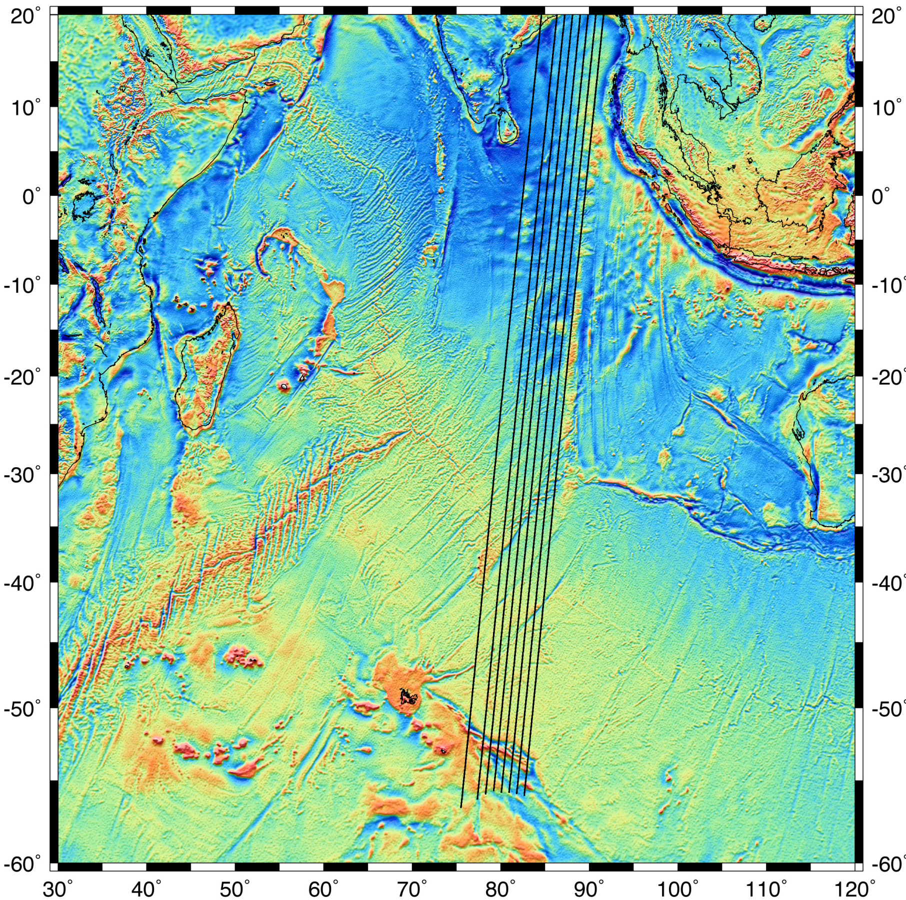
1) retrack waveforms with standard 3-parameter model

2) smooth wave height and amplitude over 40-km

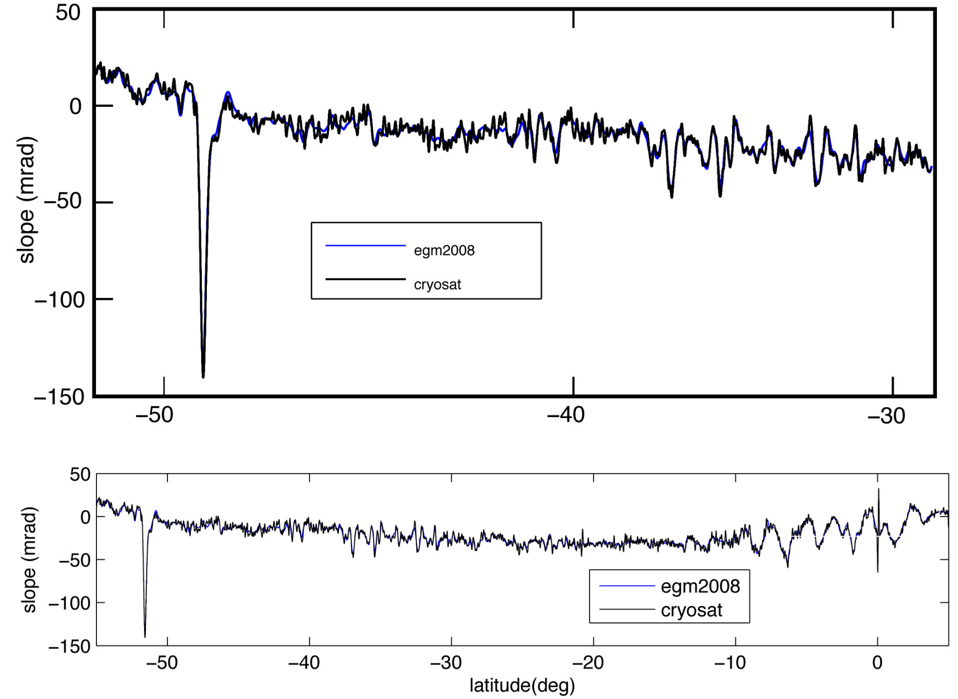
3) retrack waveforms with 2-parameter model

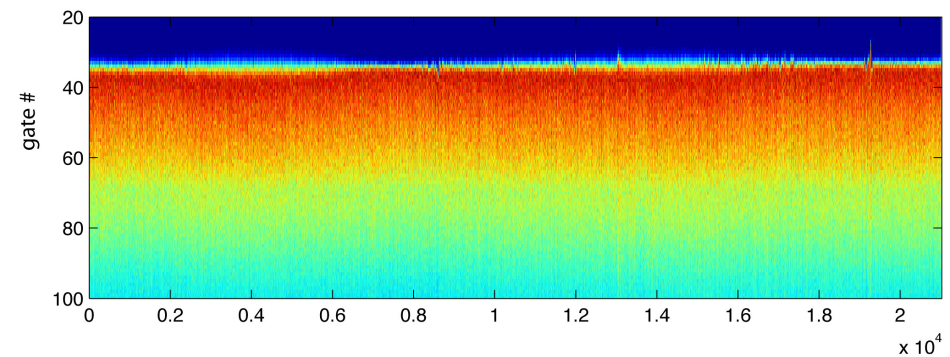
Note: this assumes wave height varies smoothly along track.

example CryoSat LRM L1b sea surface slope vs. EGM2008



David T. Sandwell and Walter H. F. Smith, Marine Gravity Anomaly from Satellite Altimetry, Version 18.1





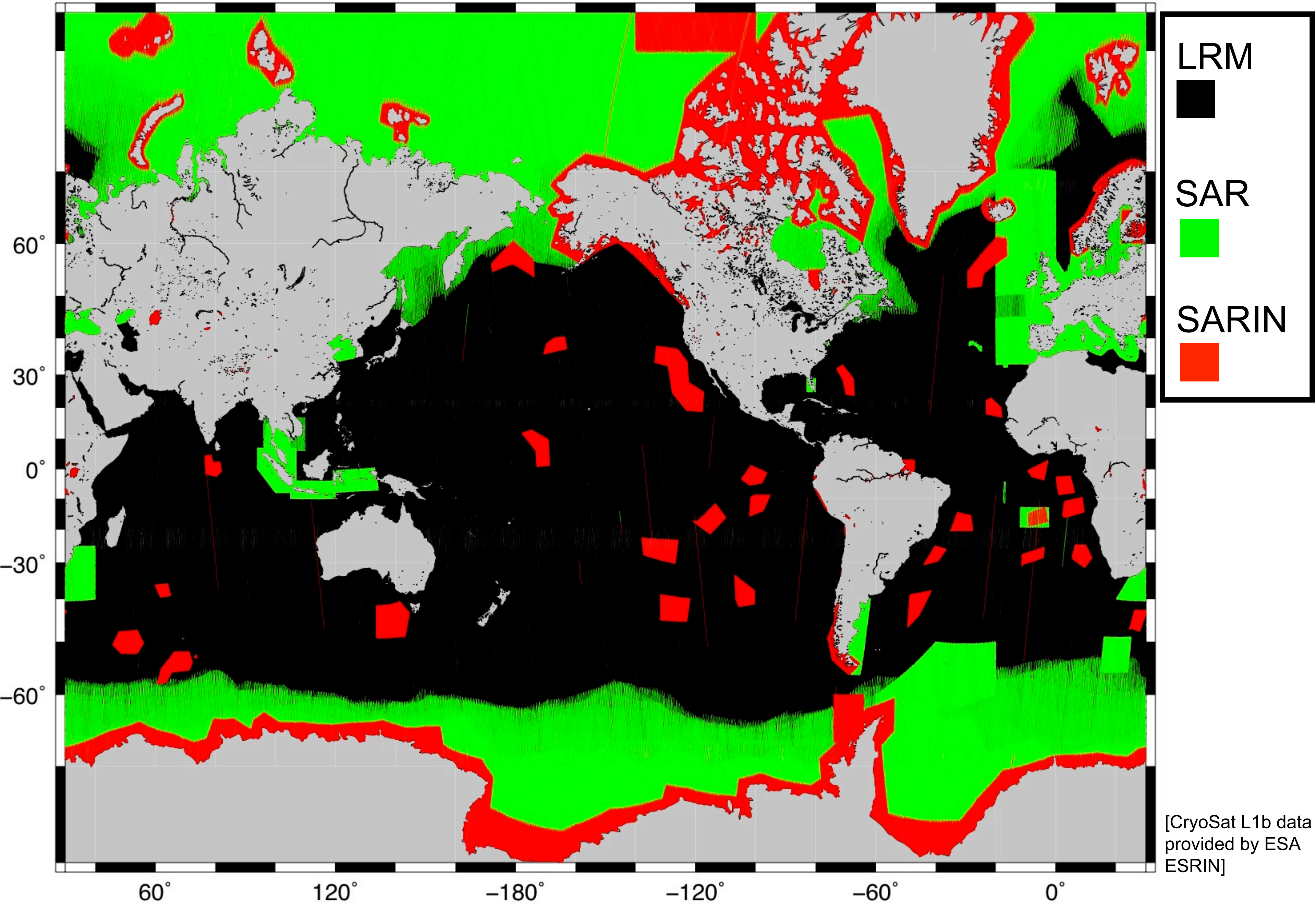
LRM 1b results

2-parameter retracking is 1.2 times better than 3-parameter

CryoSat range precision is 1.4 times better than Geosat and ERS-1/GM

			3-parameter retrack		2-parameter retrack	
profile	# good	# bad	median (μrad)	mad (μrad)	median (μrad)	mad (μrad)
1	20722	327	0.0757	3.0352	0.0120	2.4649
2	20743	305	0.0208	3.3795	-0.0041	2.6484
3	20960	88	-0.1472	2.7753	-0.1556	2.1928
4	20963	83	-0.0240	2.7438	0.0172	2.2733
5	20737	307	-0.0763	3.1039	-0.0687	2.4448
6	20851	191	-0.0131	3.3554	0.0531	2.5796
7	20928	111	-0.0417	3.4093	-0.0313	2.6628
8	21002	29	0.0699	2.6920	0.0141	2.1061
tot	166906	1144		3.0618		**2.4216**
ERS-1				3.5633		3.3133
Geosat				4.576		3.4270

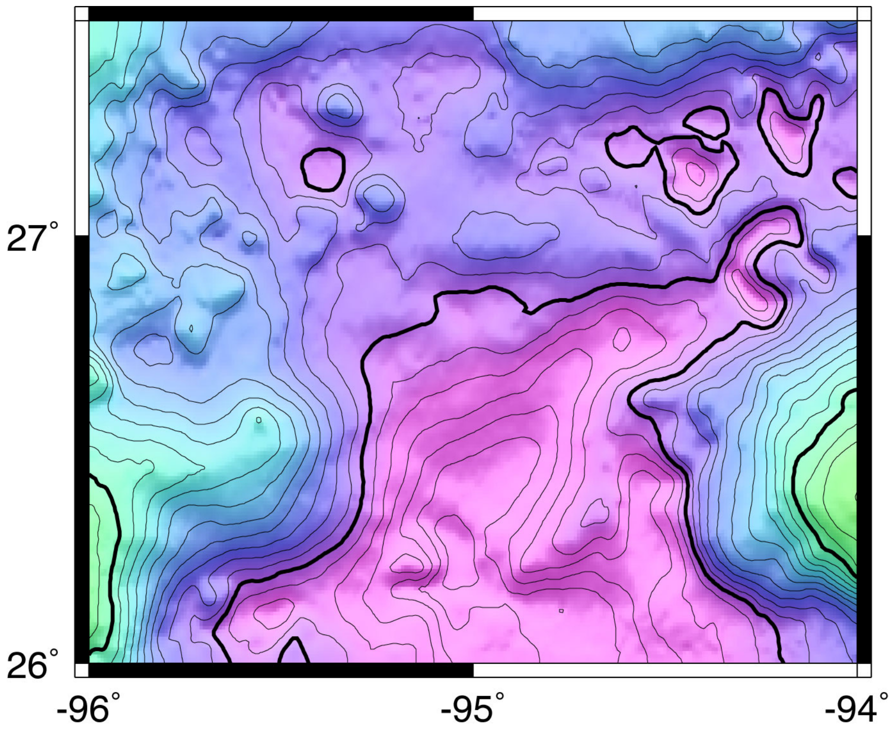
CryoSat Data Acquisition over 13 Months



[CryoSat L1b data provided by ESA ESRIN]

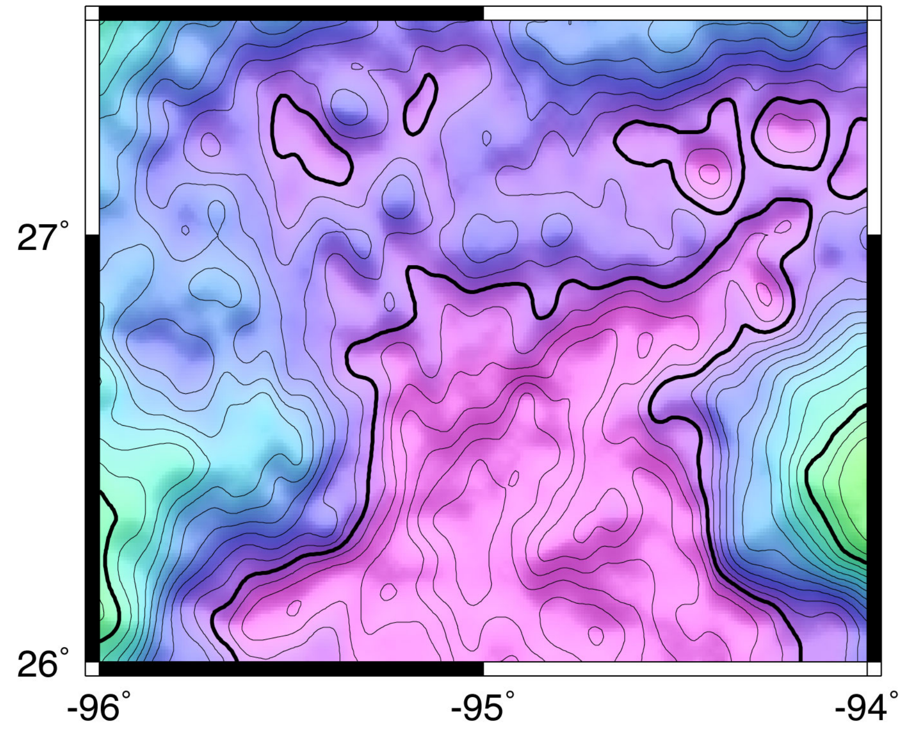
Comparisons in the Gulf of Mexico

ship gravity



source: EDCON

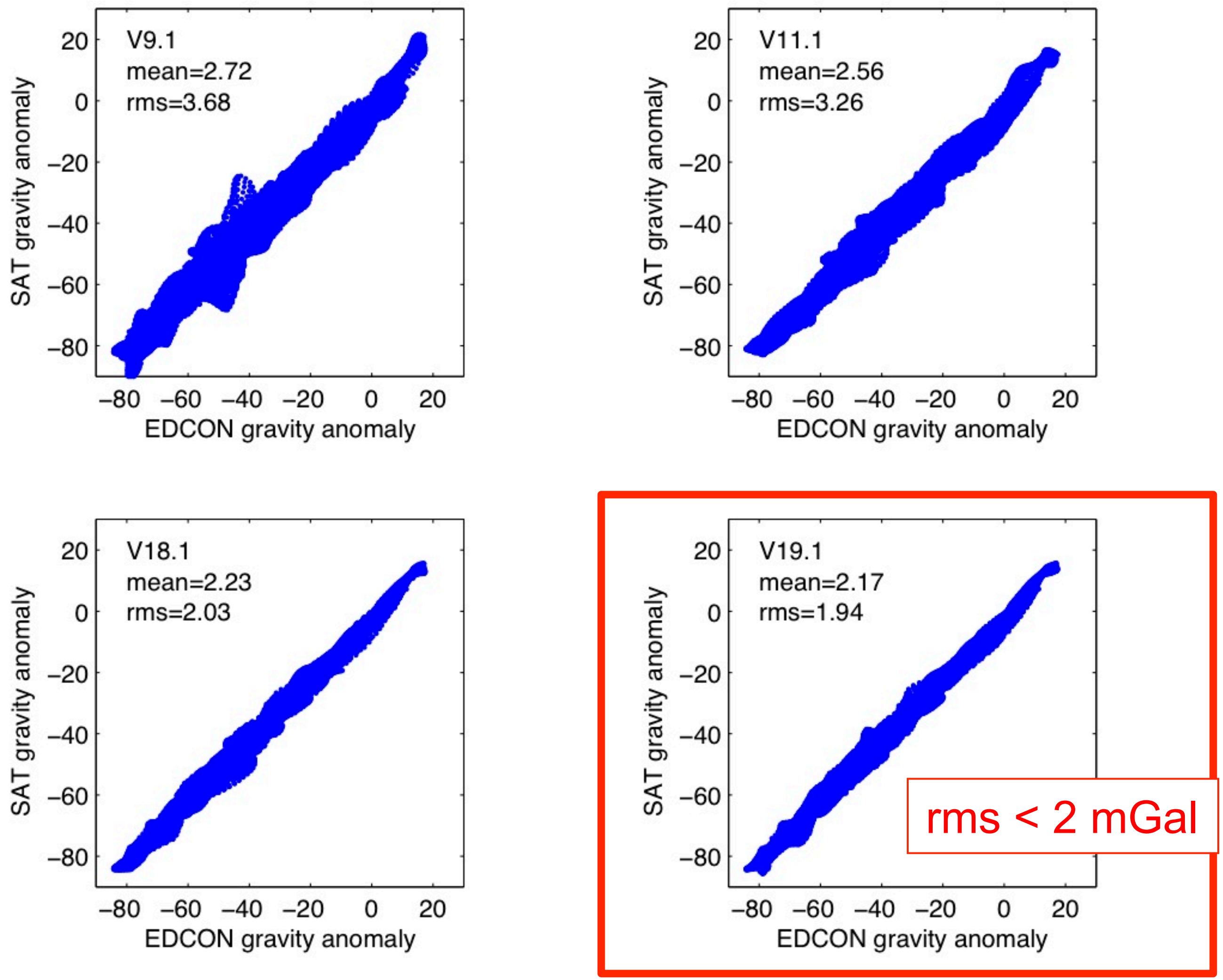
satellite gravity
with CryoSat LRM



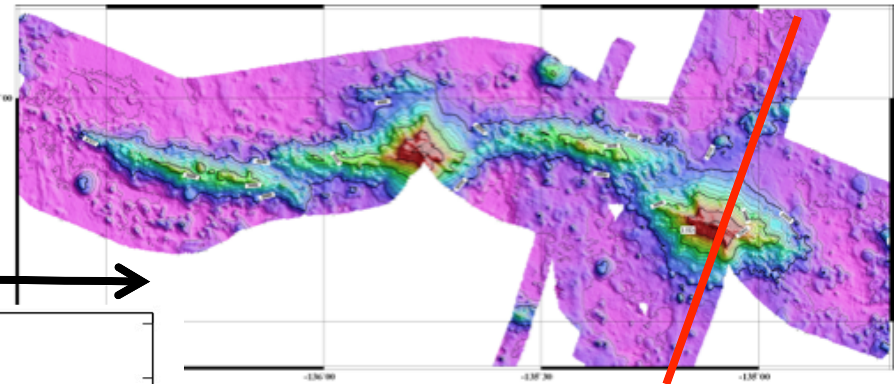
5 mGal contour interval

Comparisons in the Gulf of Mexico

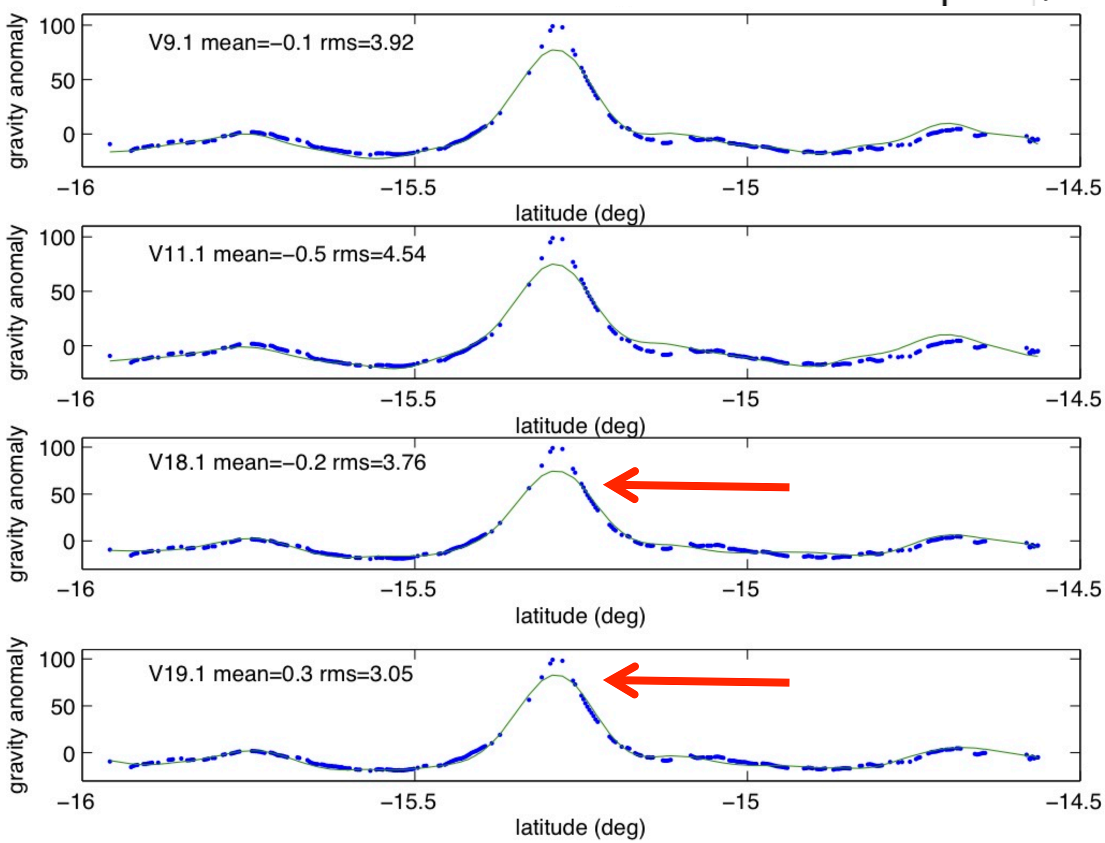
satellite gravity with CryoSat LRM vs. ship gravity



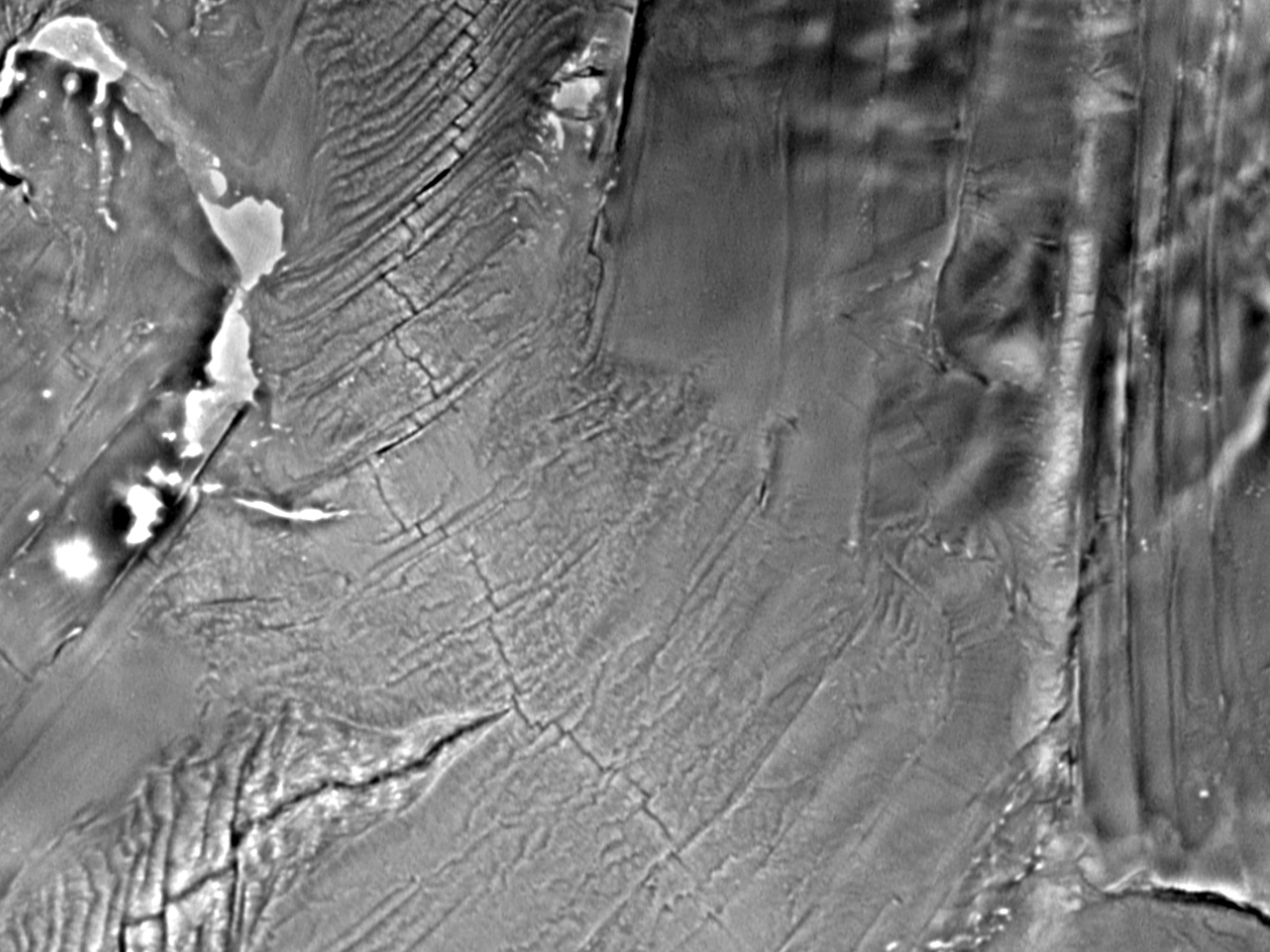
Wahoo Guyot

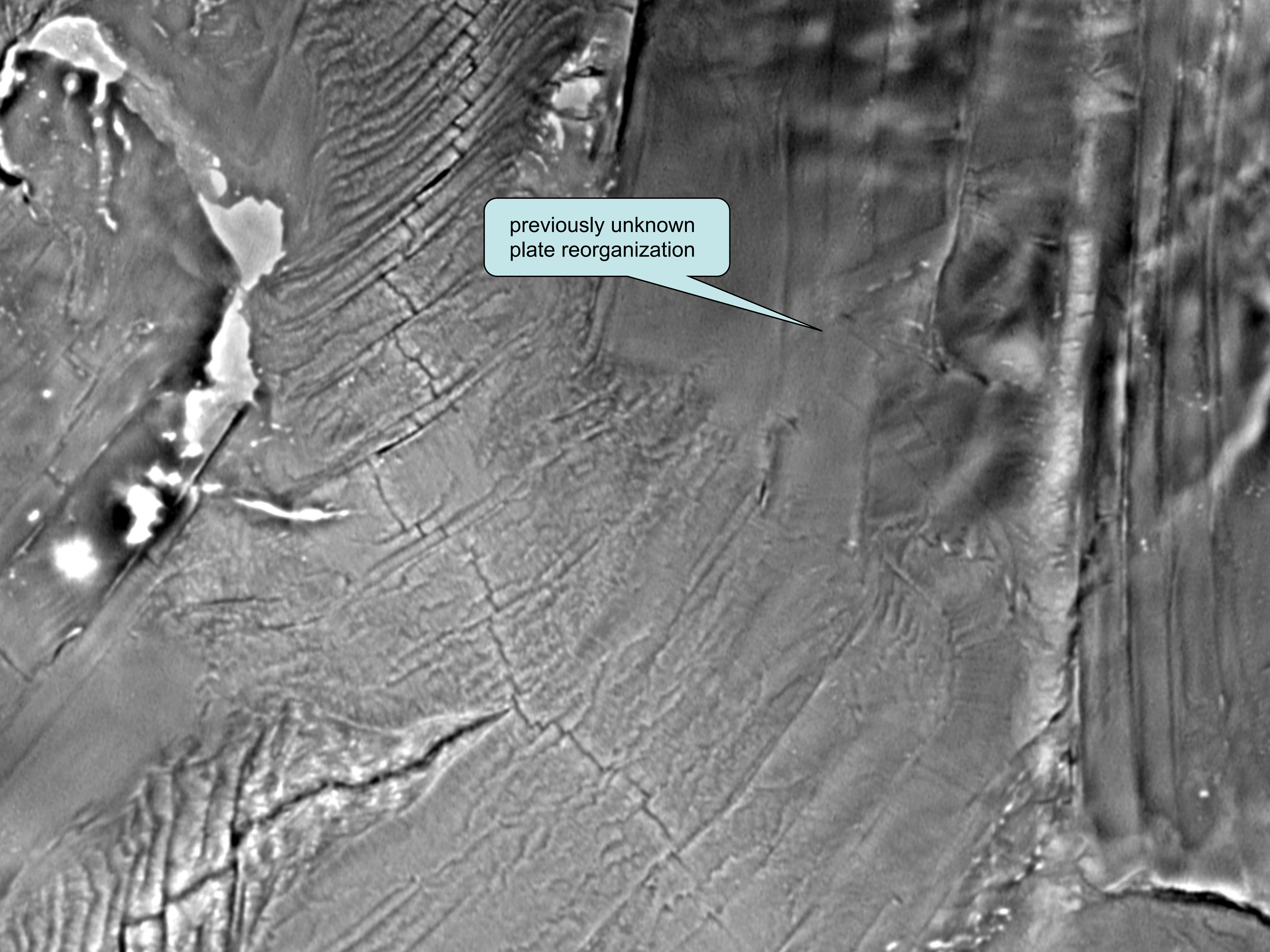


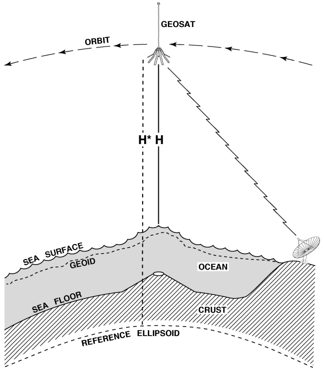
ship gravity (points)
vs. satellite gravity (line)
over ~250 km



improvement due to addition of CryoSat LRM data




previously unknown
plate reorganization



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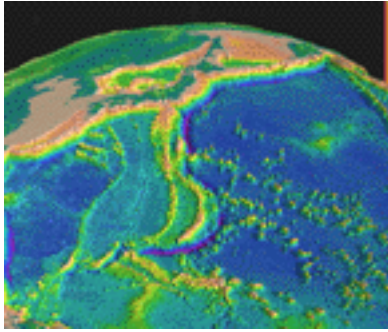

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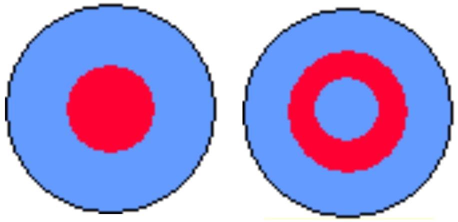
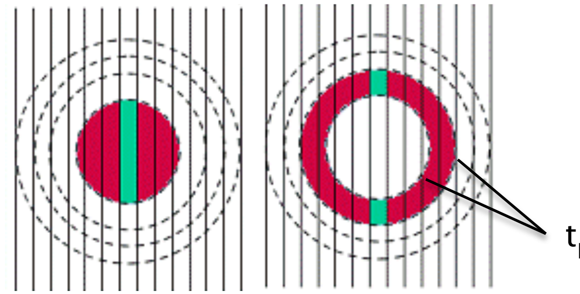
LRM Mode

SAR Mode

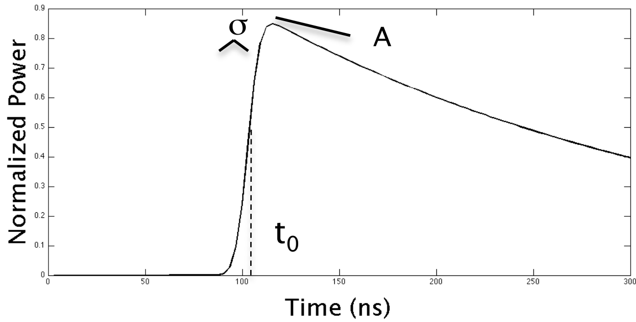
Radar Footprint

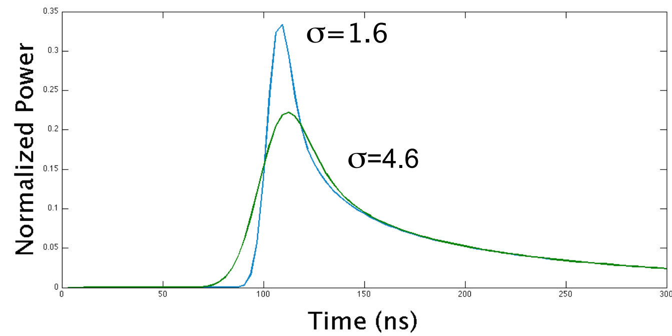




from ESA Radar Altimetry Tutorial

Waveform Shape





Analytic Model

$$M(t) = \frac{A}{2}\left[1 + erf\left(\frac{t - t_0}{\sqrt{2}\sigma}\right)\right]P(t)$$

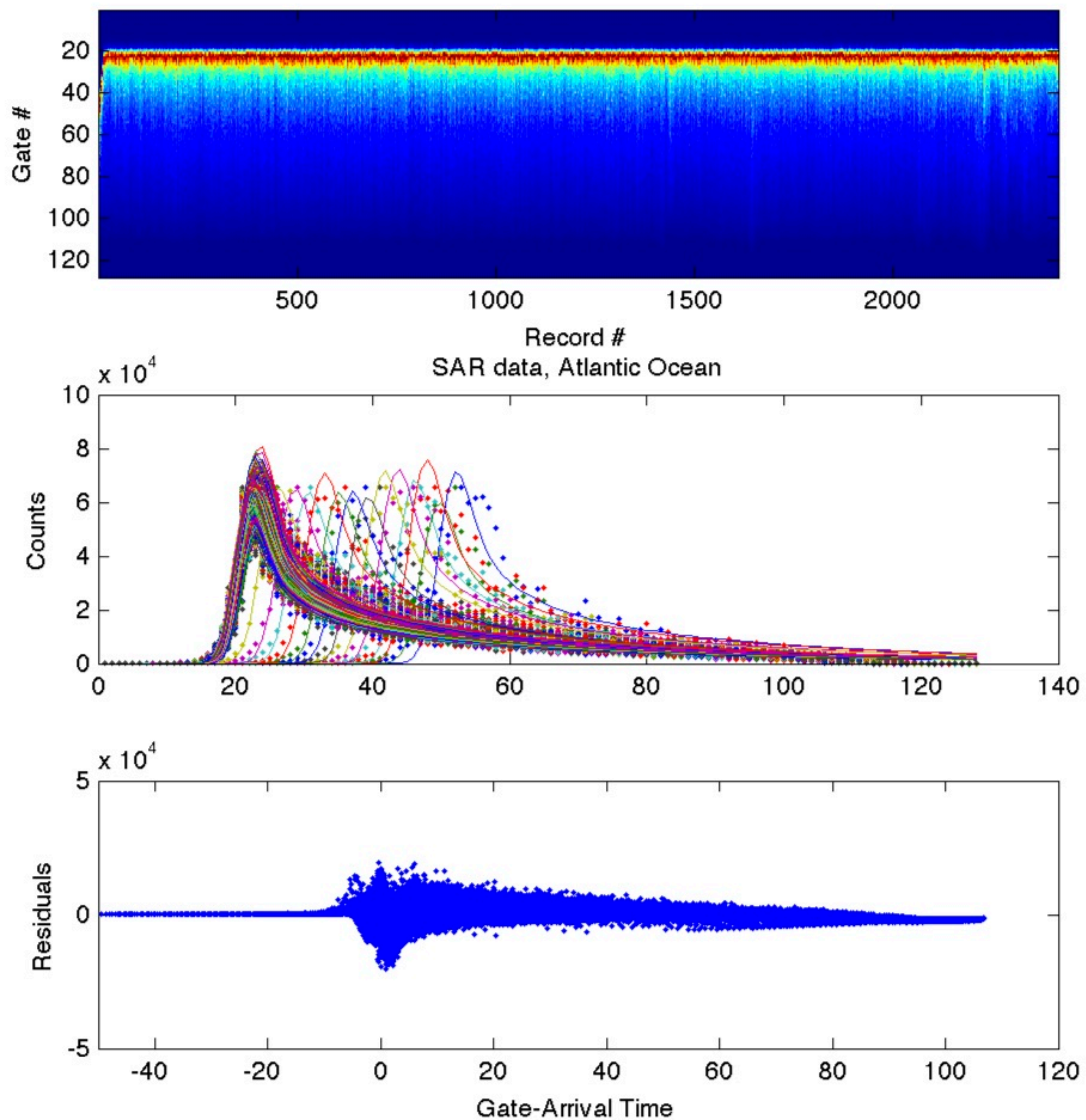
$$P(t) = \begin{cases} 1 & t < t_0 \\ e^{-\alpha(t-t_0)} & t \geq t_0 \end{cases}$$

Brown (1977)

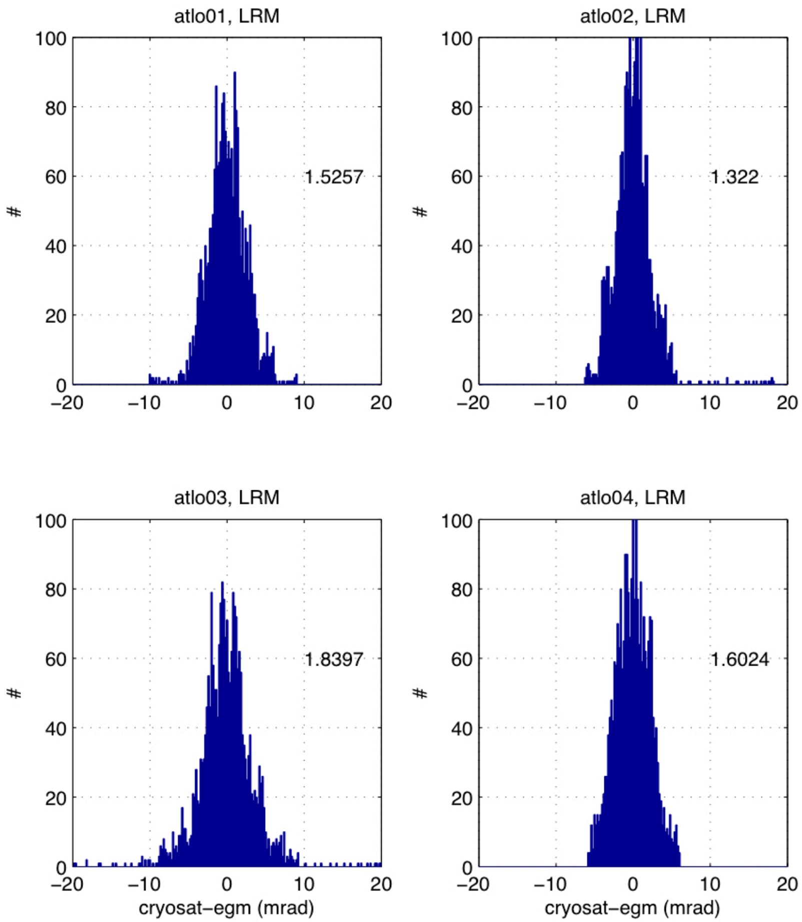
$$M(t) = \frac{A}{4}\sqrt{\frac{2\sigma}{t_p}}\left\{ \begin{array}{l} e^{-\frac{1}{4}\left(\frac{t-t_0}{\sigma}\right)^2} D_{-\frac{3}{2}}\left(-\frac{t-t_0}{\sigma}\right) - \\ e^{-\frac{1}{4}\left(\frac{t-t_0-t_p}{\sigma}\right)^2} D_{-\frac{3}{2}}\left(-\frac{t-t_0-t_p}{\sigma}\right) \end{array} \right\} P(t)$$

$D_n(z)$ is a parabolic cylinder function of order n

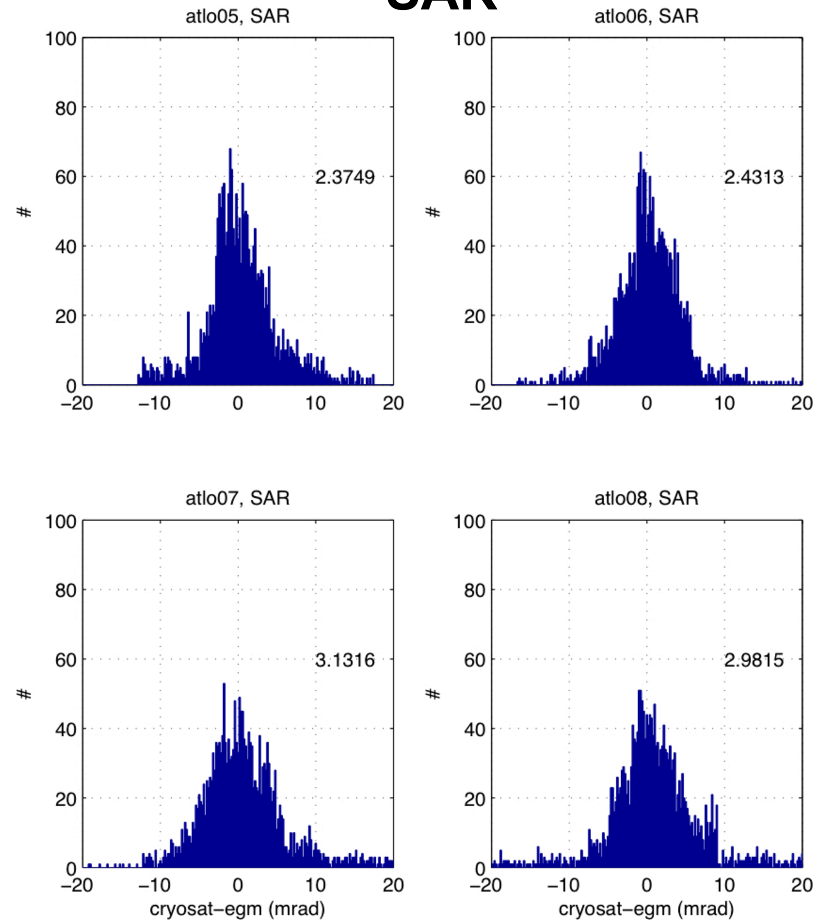
Example fits to SAR track in North Atlantic



LRM



SAR

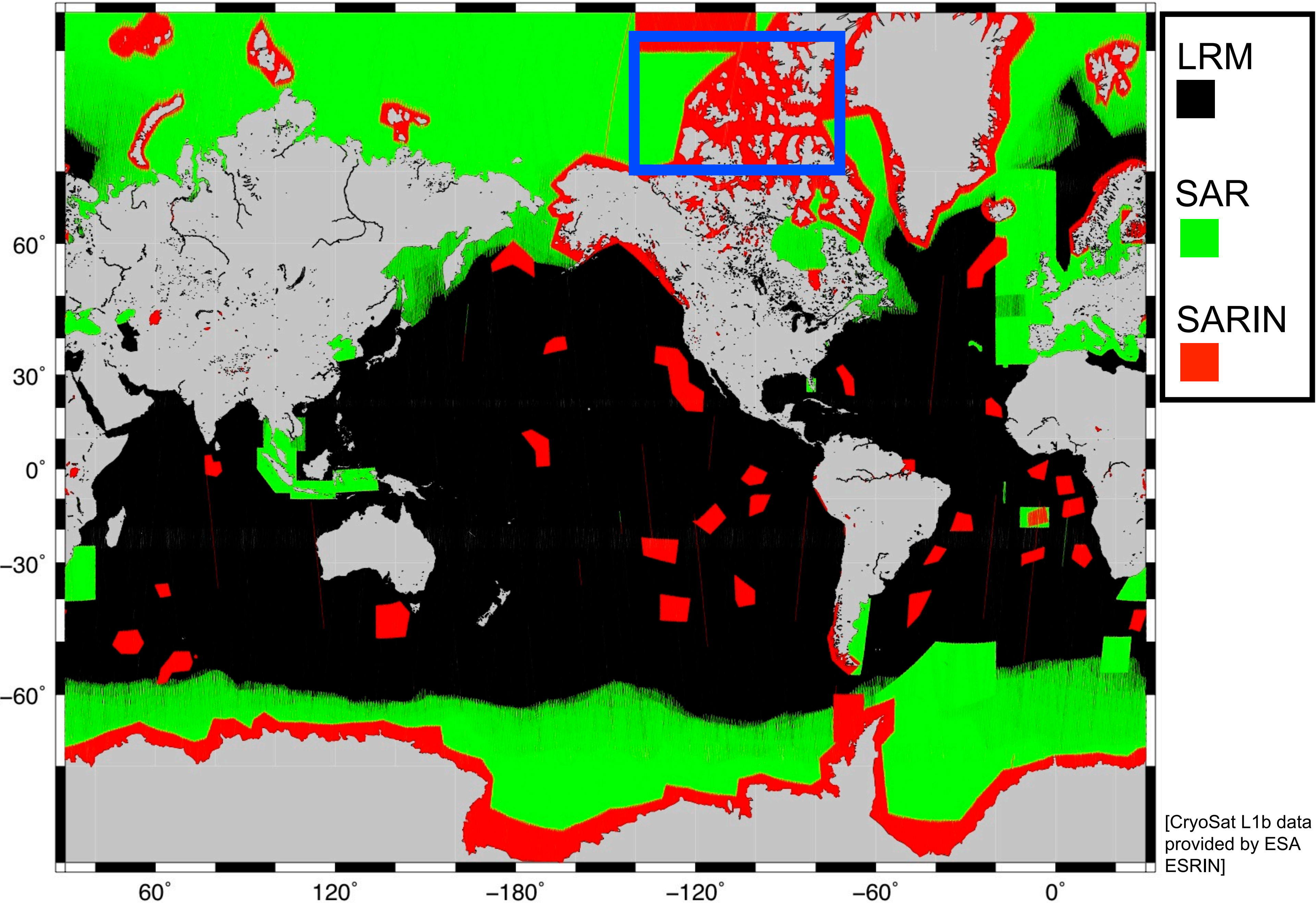


Median absolute deviation of CryoSat LRM slope from EGM2008 slope is 1.56 microradian.

Median absolute deviation of CryoSat SAR slope from EGM2008 slope is 2.72 microradian.

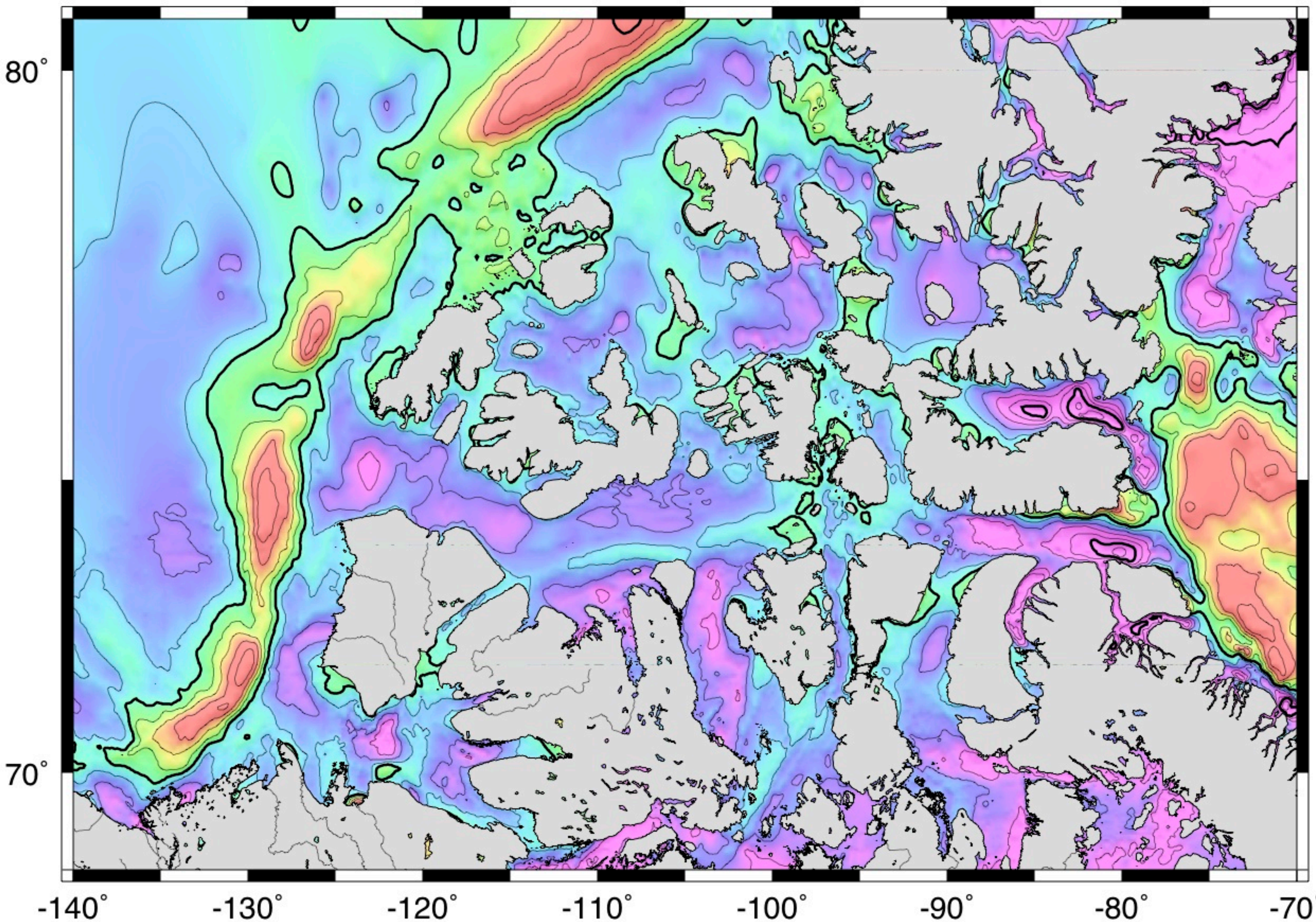
Why is SAR precision worse than LRM precision? incomplete SAR model, bug in our software, need finer gate resolution to capture sharper waveform, ... **We don't know yet.**

Threshold retracking of SAR and SARIN data Canadian Arctic



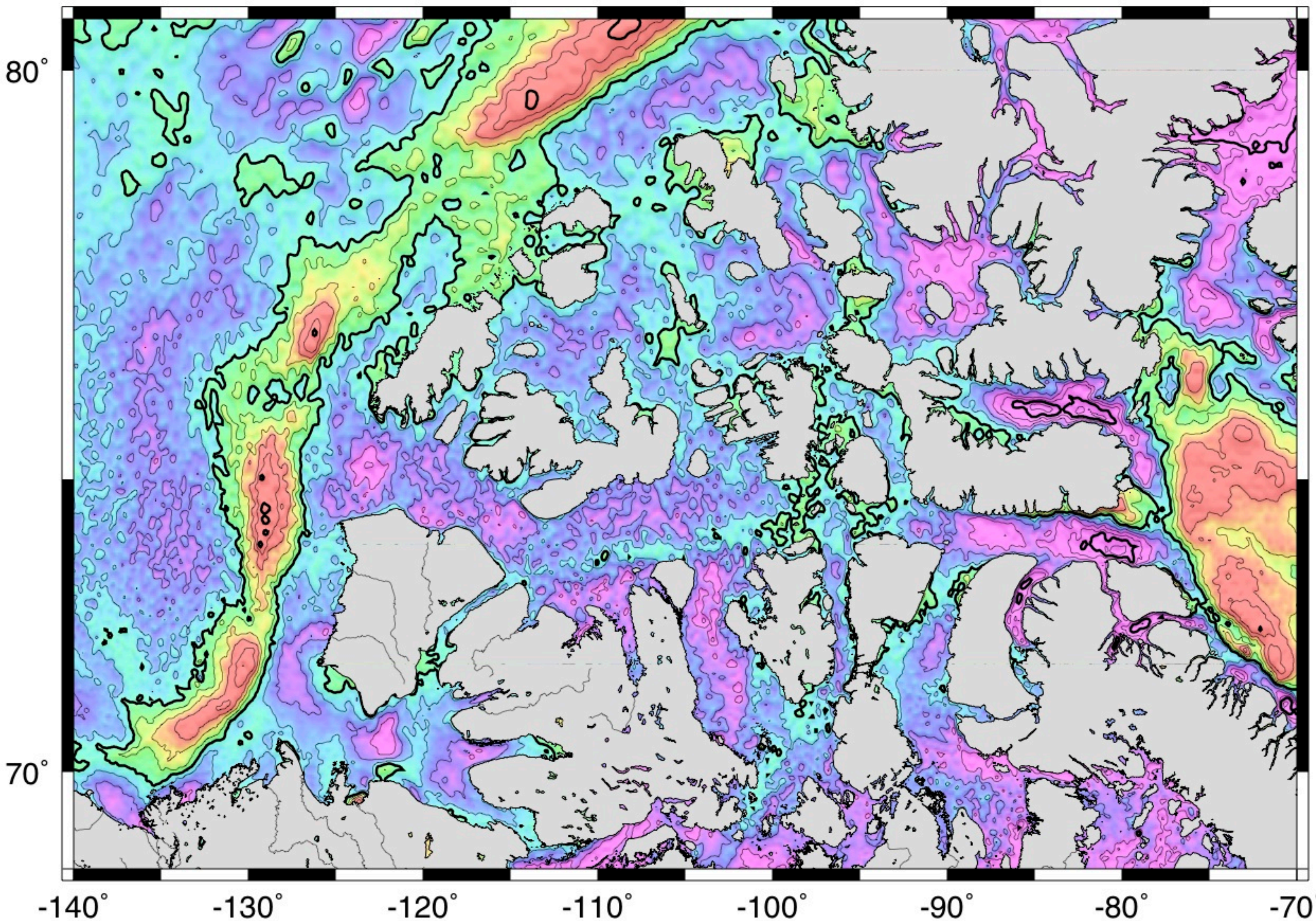
[CryoSat L1b data provided by ESA ESRIN]

Canadian Arctic
Ship Gravity

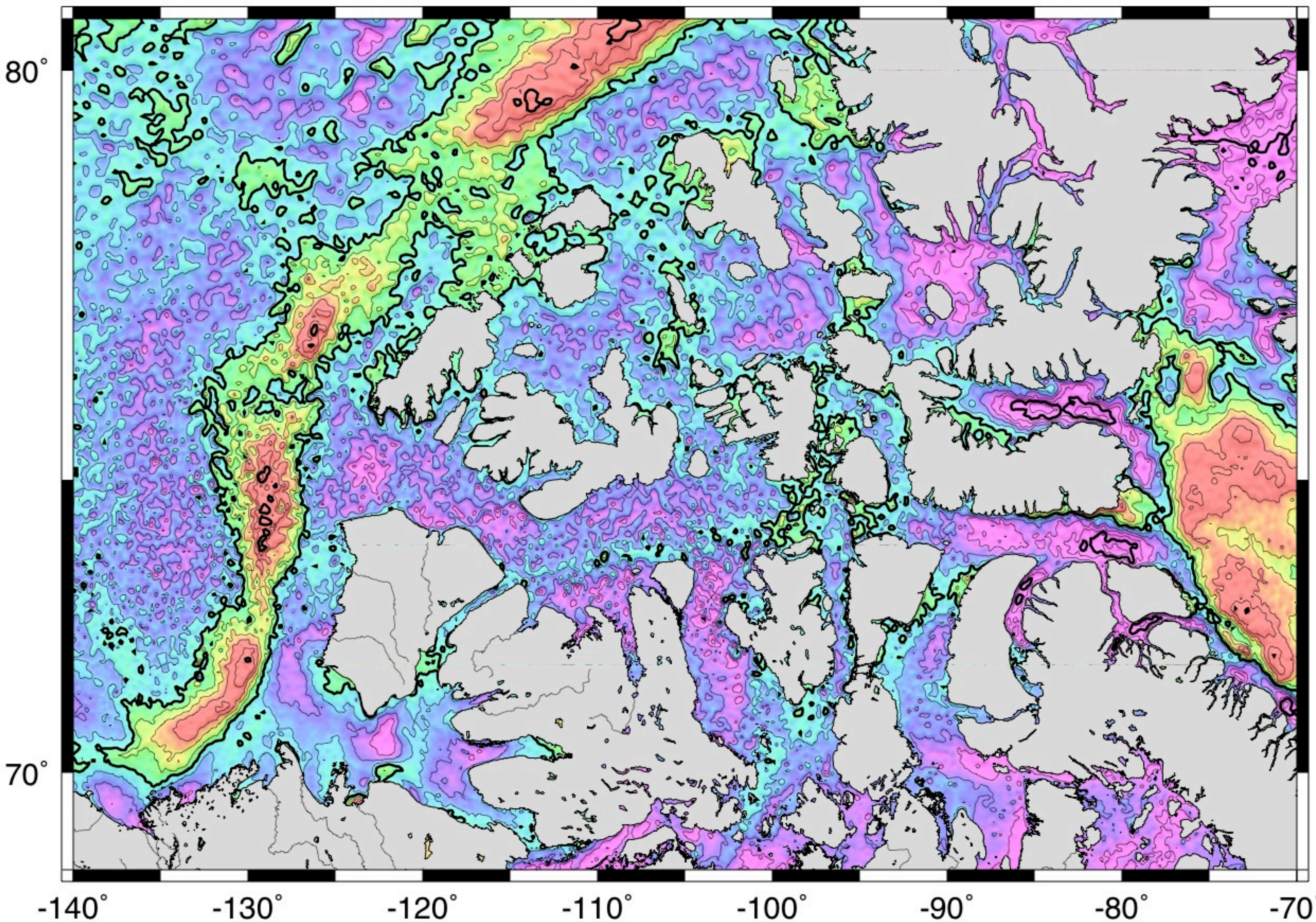


Canadian Arctic

Geosat, ERS-1 + **CryoSat** (threshold retracking)



Canadian Arctic
Geosat and ERS-1



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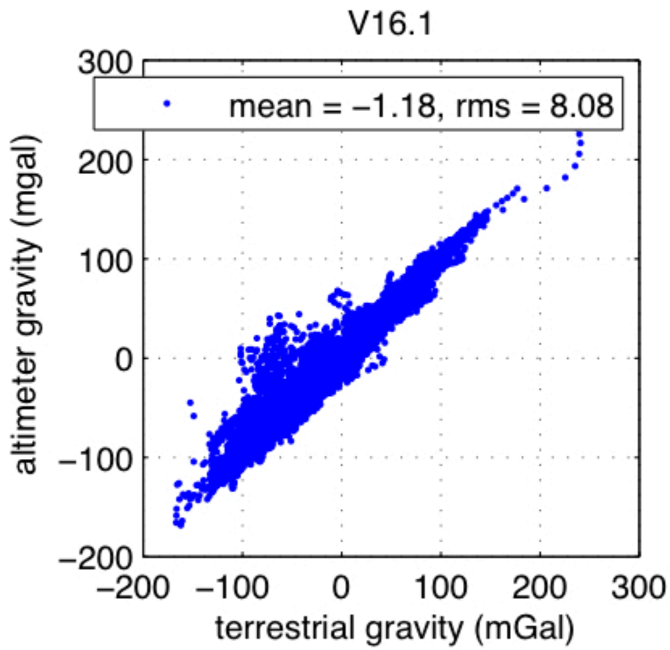
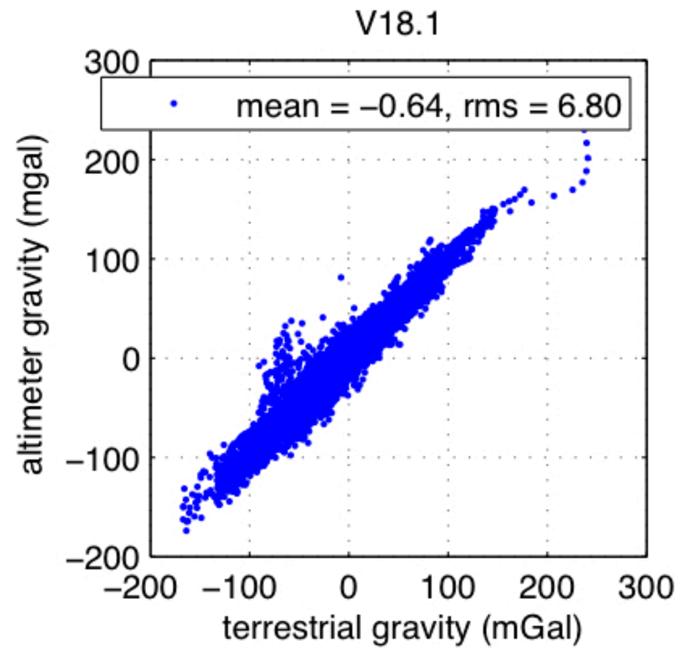
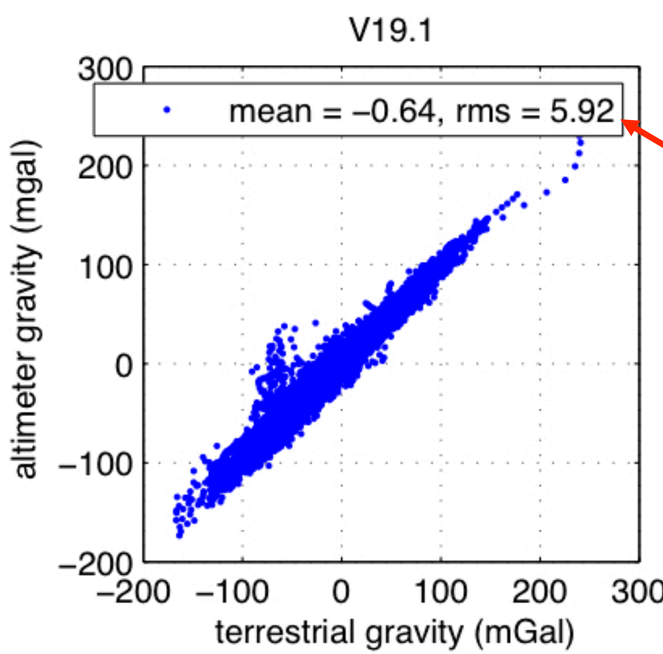
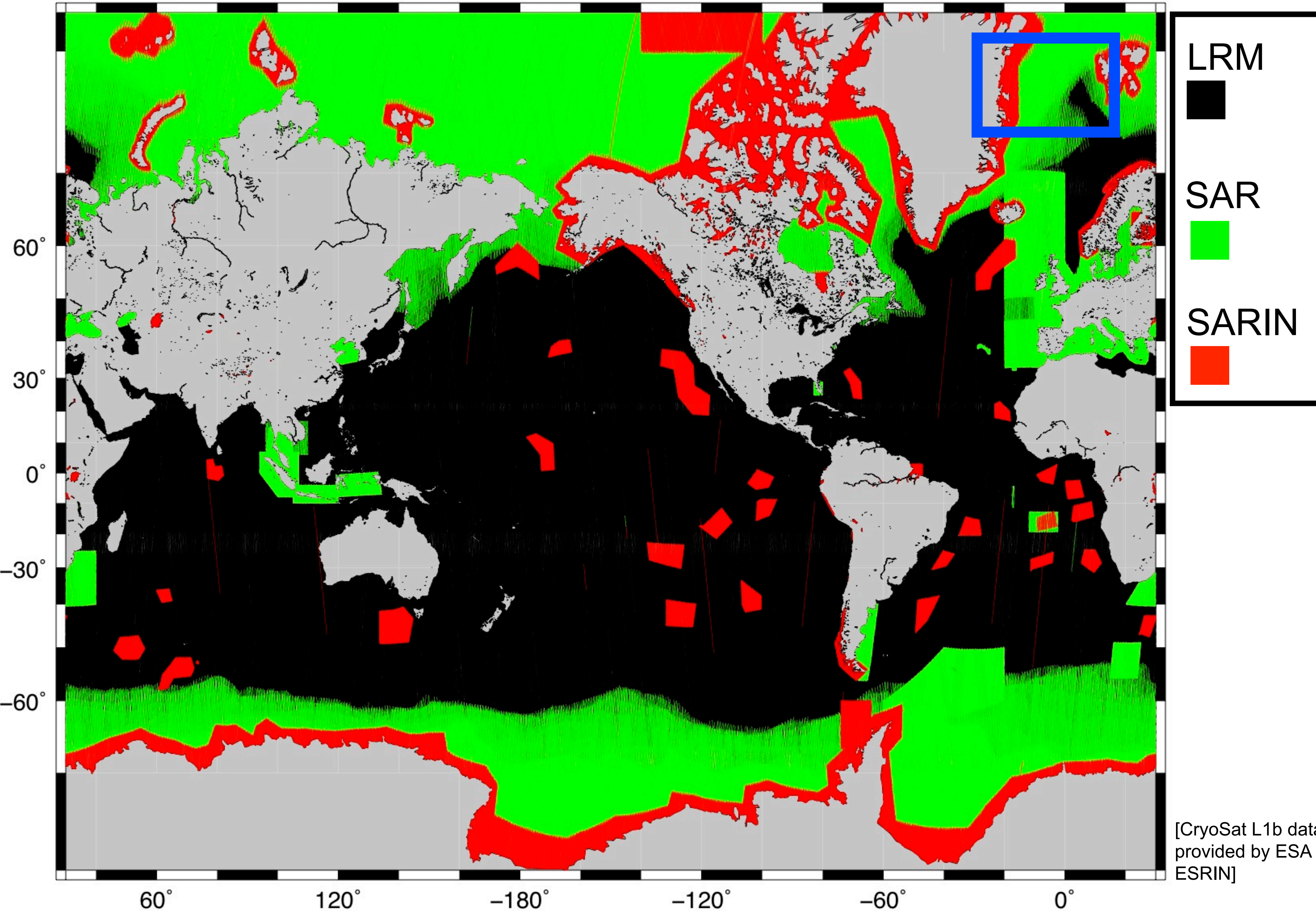






CryoSat (threshold retracking only)
Improves gravity accuracy by ~1 mGal

Threshold retracking of SAR and SARIN data East of Greenland



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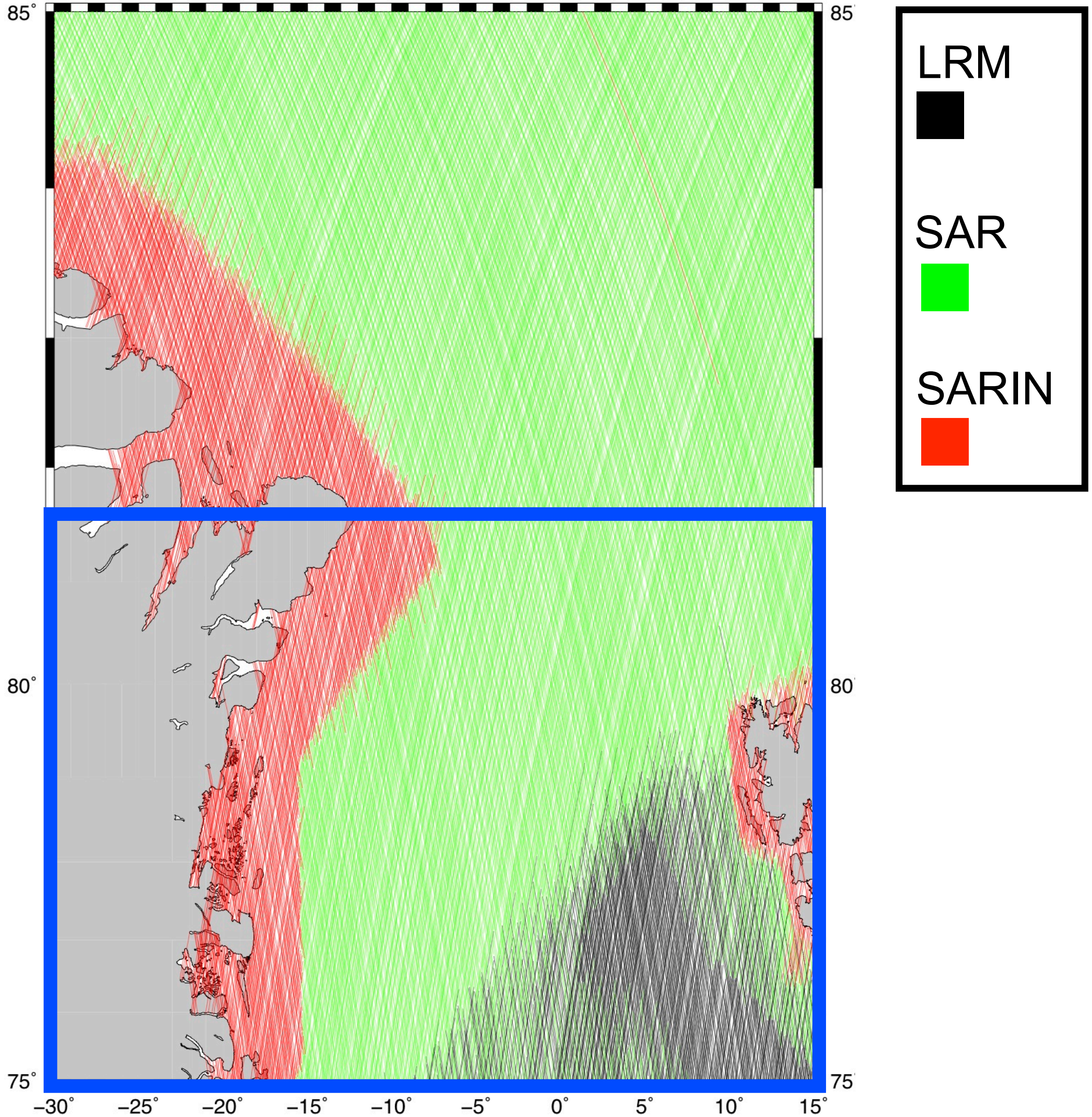
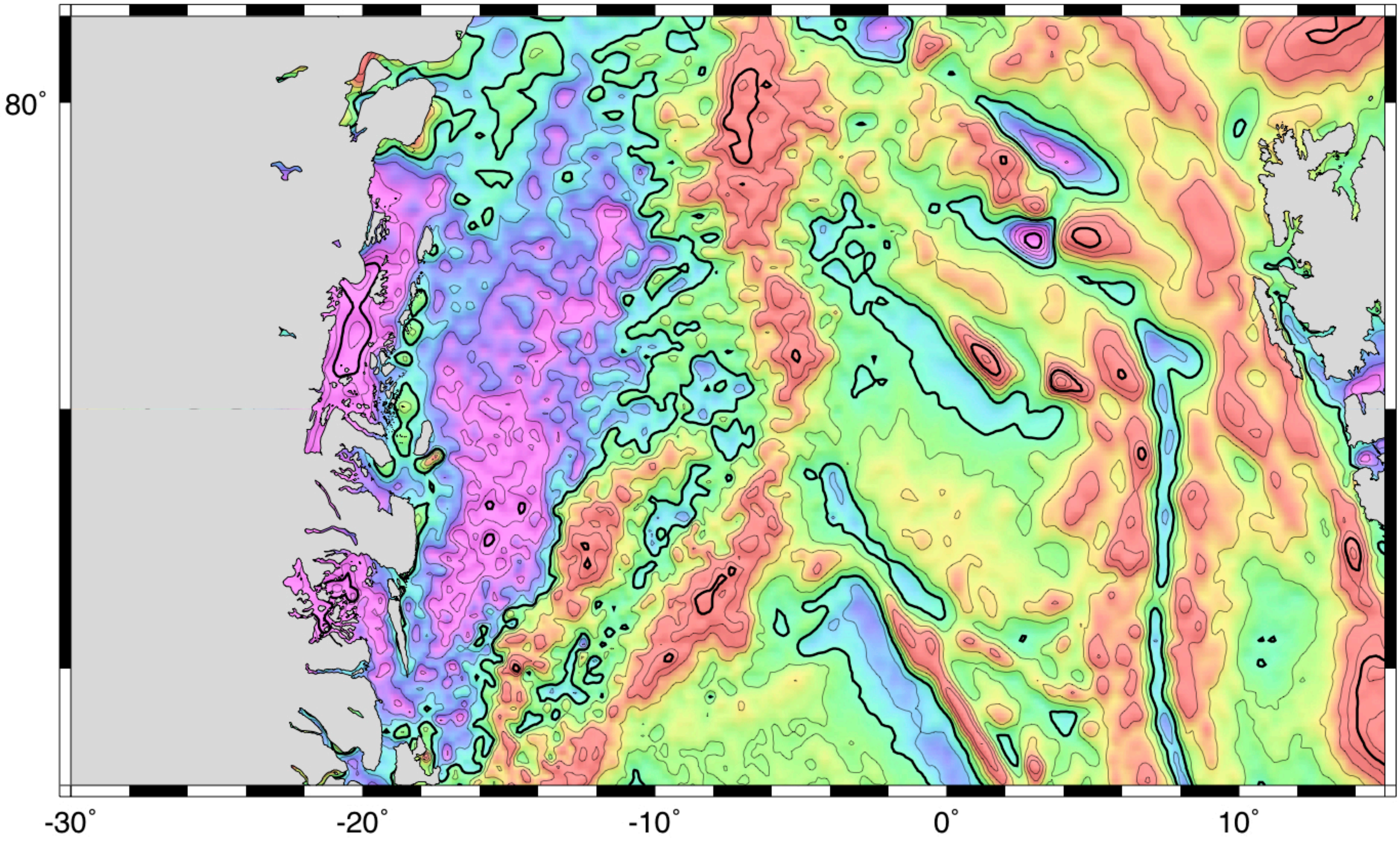
CryoSat Data Acquisition over 13 Months - East of Greenland

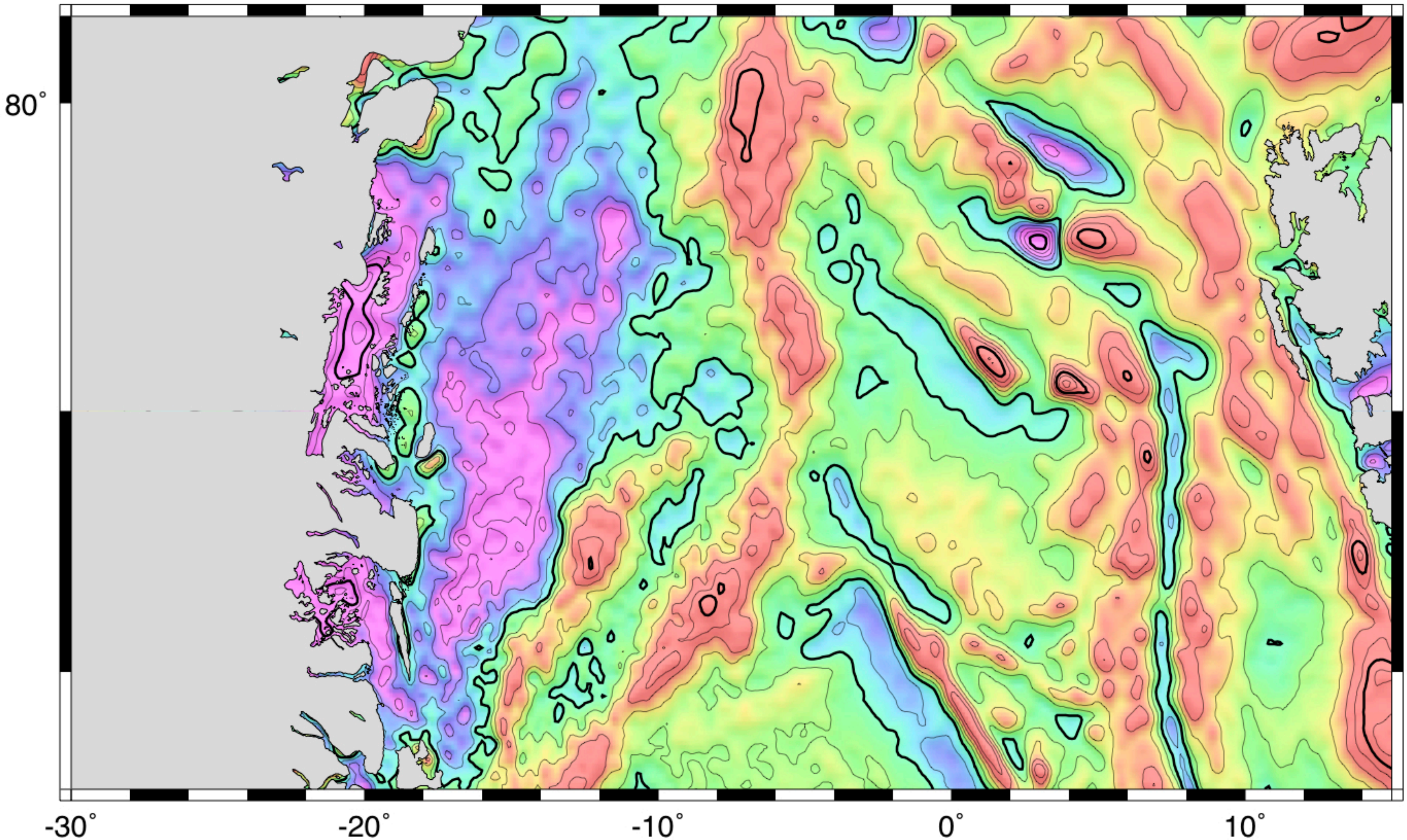


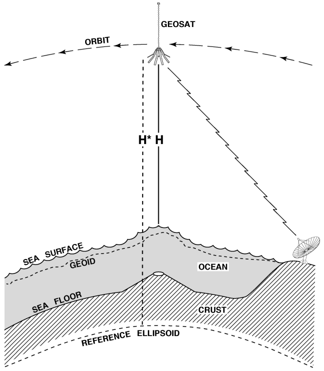
[CryoSat L1b data provided by ESA ESRIN]

East of Greenland
Geosat, ERS-1



East of Greenland
Geosat, ERS-1 + **CryoSat** (threshold retracking)





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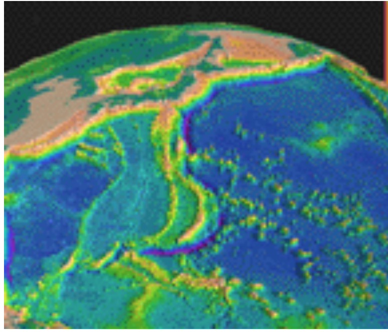

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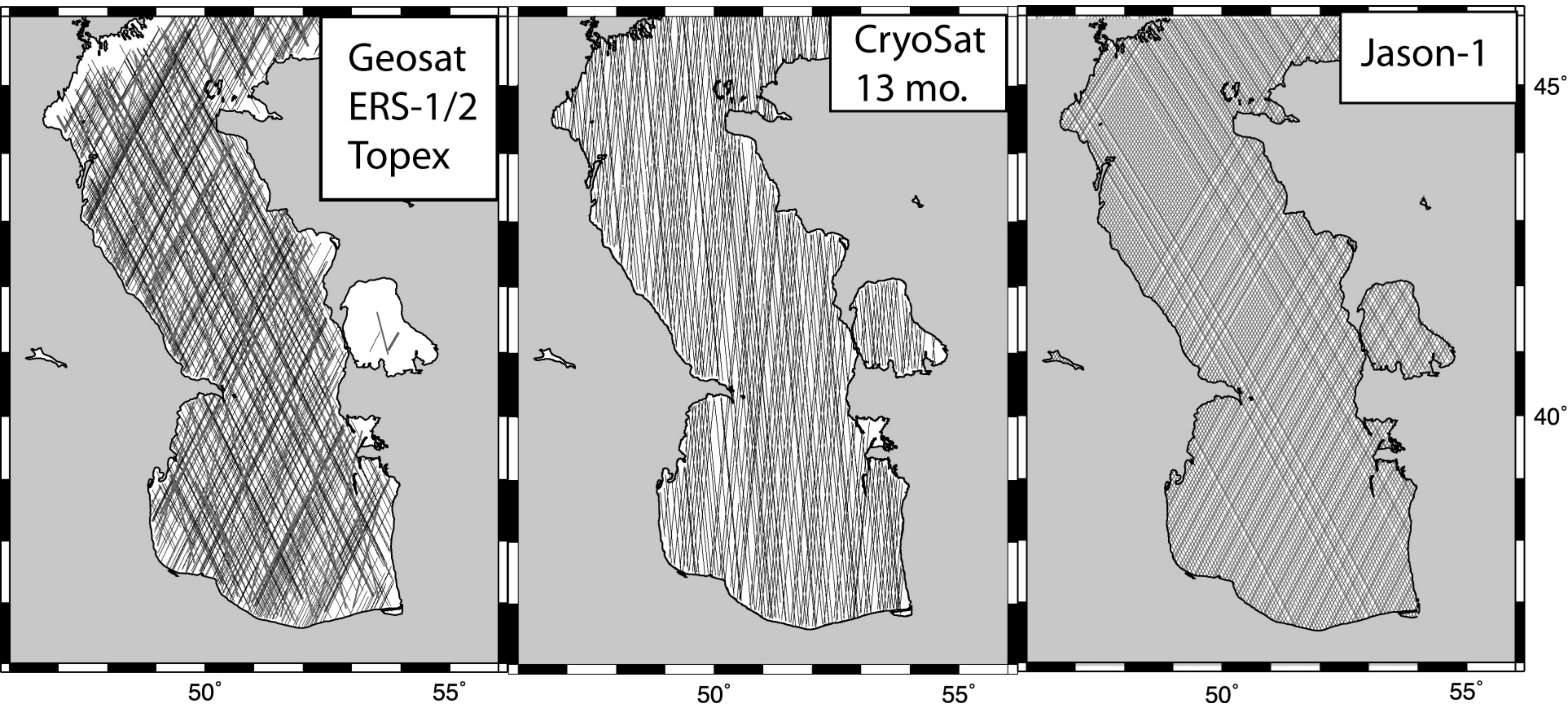
Caspian Sea
altimeter tracks

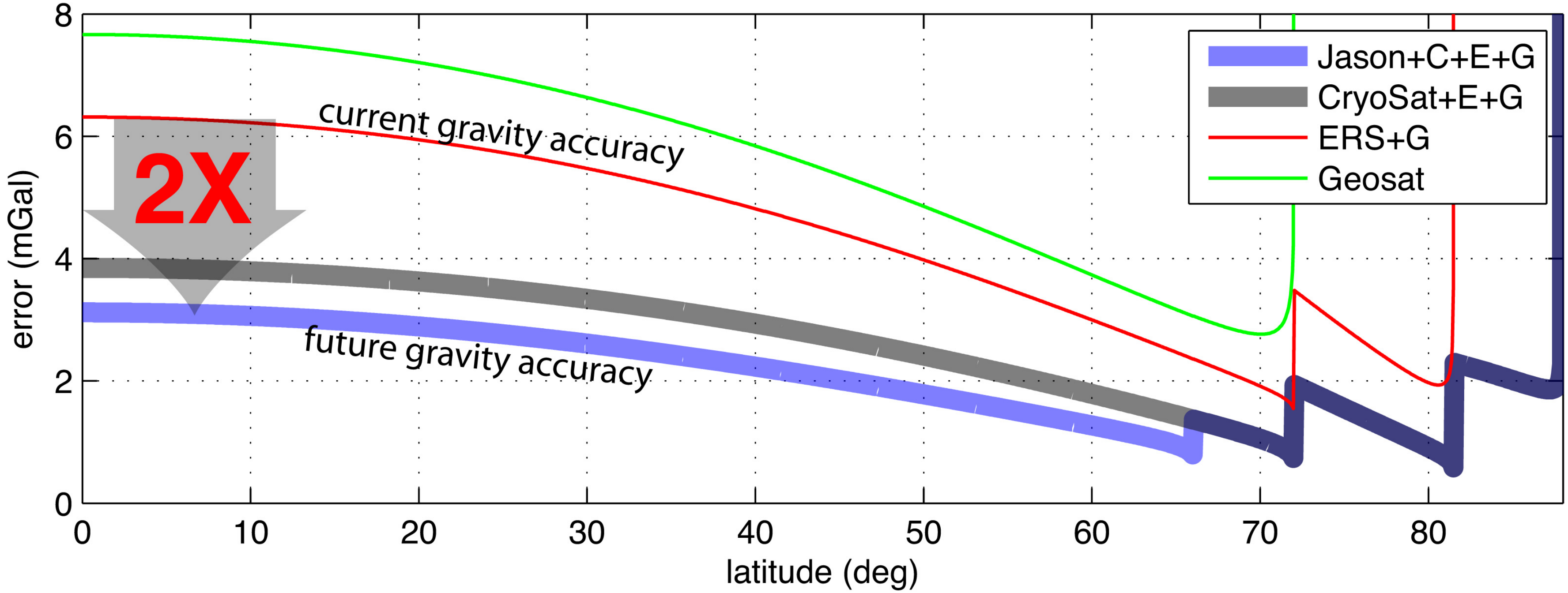
Jason-1

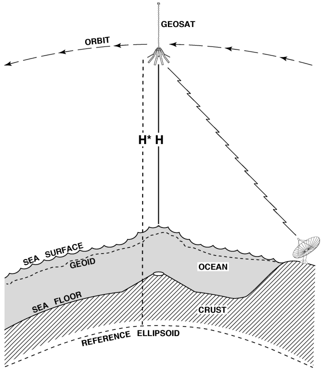
planed 1 yr.
419-days



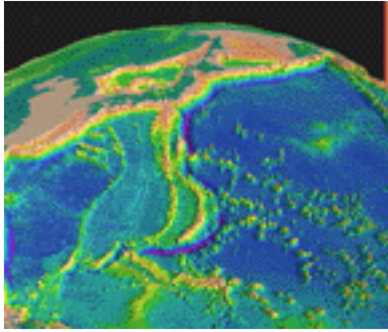
predicted gravity improvement

1.4 better range precision with 3 years of CryoSat and 419 days of Jason





Conclusions



- CryoSat has provided the first dense ocean altimeter coverage since 1996.
- Two-pass retracking of LRM waveforms provides 1.4 times better slope accuracy than Geosat and ERS-1 because of the 2X higher PRF.
- Threshold retracking of SAR and SARIN waveforms provides complete coverage of polar areas even during periods of ice cover.
- We have not (yet) achieved the LRM range precision by retracking SAR and SARIN waveforms.
- If CryoSat survives for more than 3 years we will approach a factor of 2 improvement in the accuracy of global marine gravity.
- Improved gravity will have major payoffs in marine geophysics, physical oceanography/climate, military applications, and ocean exploration.