Geopotential Model Improvement Using POCM_4B Dynamic Ocean Topography Information: PGM2000A

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GEOPOTENTIAL MODEL IMPROVEMENT USING POCM_4B DYNAMIC OCEAN TOPOGRAPHY INFORMATION: PGM2000A

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The two-year mean (1993-1994) Dynamic Ocean Topography (DOT) field implied by the POCM_4B circulation model was used to develop normal equations for DOT, in a surface spherical harmonic representation. These normal equations were combined with normal equations from satellite tracking data, surface gravity data, and altimeter data from TOPEX/Poseidon and ERS-1. Several least-squares combination solutions were developed in this fashion, by varying parameters such as the maximum degree of the estimated DOT and the relative weights of the different data. The solutions were evaluated in terms of orbit fit residuals, GPS/Leveling-derived undulations, and *independent* DOT information from *in situ* WOCE hydrographic data. An optimal solution was developed in this fashion which was originally presented at the 1998 EGS meeting in Nice, France. This model, designated here PGM2000A, maintains the orbit and land geoid modeling performance of EGM96, while improving its marine geoid modeling capability. In addition, PGM2000A's error spectrum is considerably more realistic than those of other contemporary gravitational models and agrees well with the error spectrum of EGM96.

We will present the development and evaluation of PGM2000A, with particular emphasis on the weighting of the DOT information implied by POCM_4B. We will also present an inter-comparison of PGM2000A with the GRIM5-C1 and TEG-4 models. Directions for future work and problematic areas will be identified.

Overview

- DOT implied by the POCM-4B model of *Semtner and Chervin*.

  The time-averaged DOT field over two years (1993 and 1994) was evaluated, based on 9.9-day “snapshots” of the field (coincident with TOPEX/POSEIDON repeat cycles). Normal equations in spherical harmonics to L_{max}=30 were developed using the POCM_4B DOT as “data”.

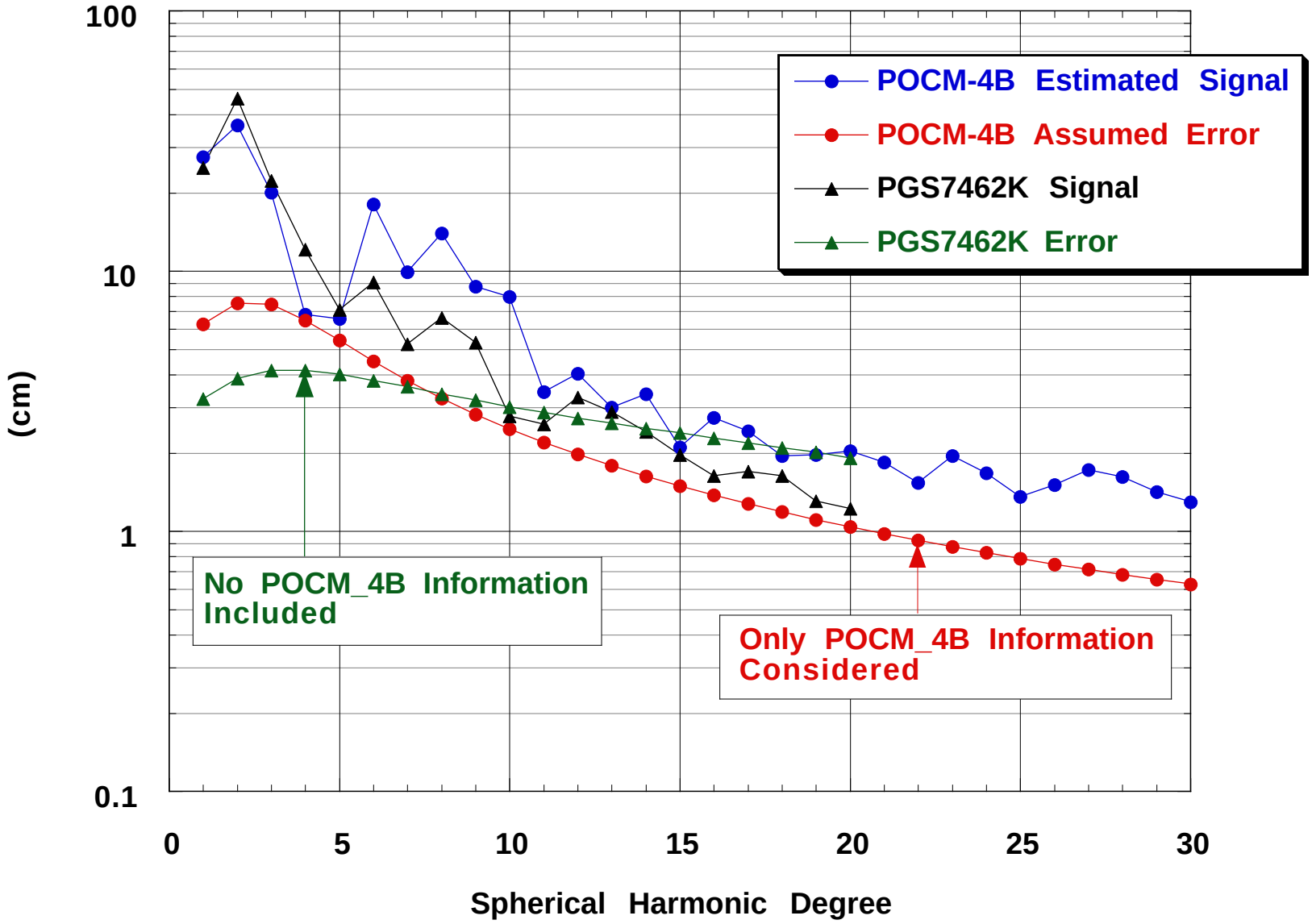
- A combination geopotential solution designated PGS7462k, forms the base field to which the OCM DOT information will be added.

  The PGS7462k normal equations contain geopotential terms to N_{max}=70, and DOT terms to L_{max}=30.

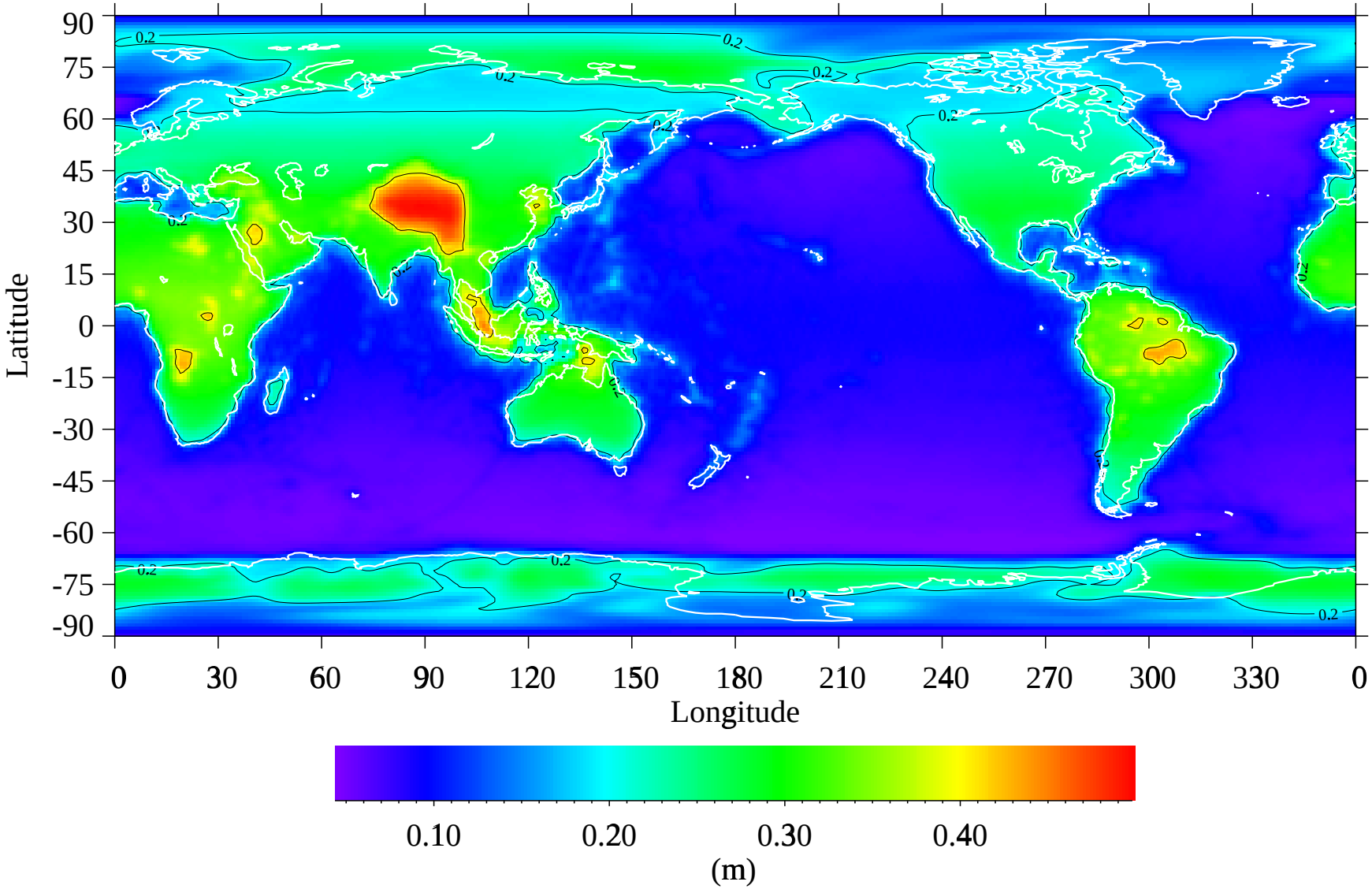
  PGS7462k contains T/P altimeter data covering the same time period over which the OCM's output was averaged.

- PGM2000A was developed through the combination of PGS7462k with the POCM_4B DOT normal equations.

RMS Dynamic Ocean Topography Signal and Error per Spherical Harmonic Degree

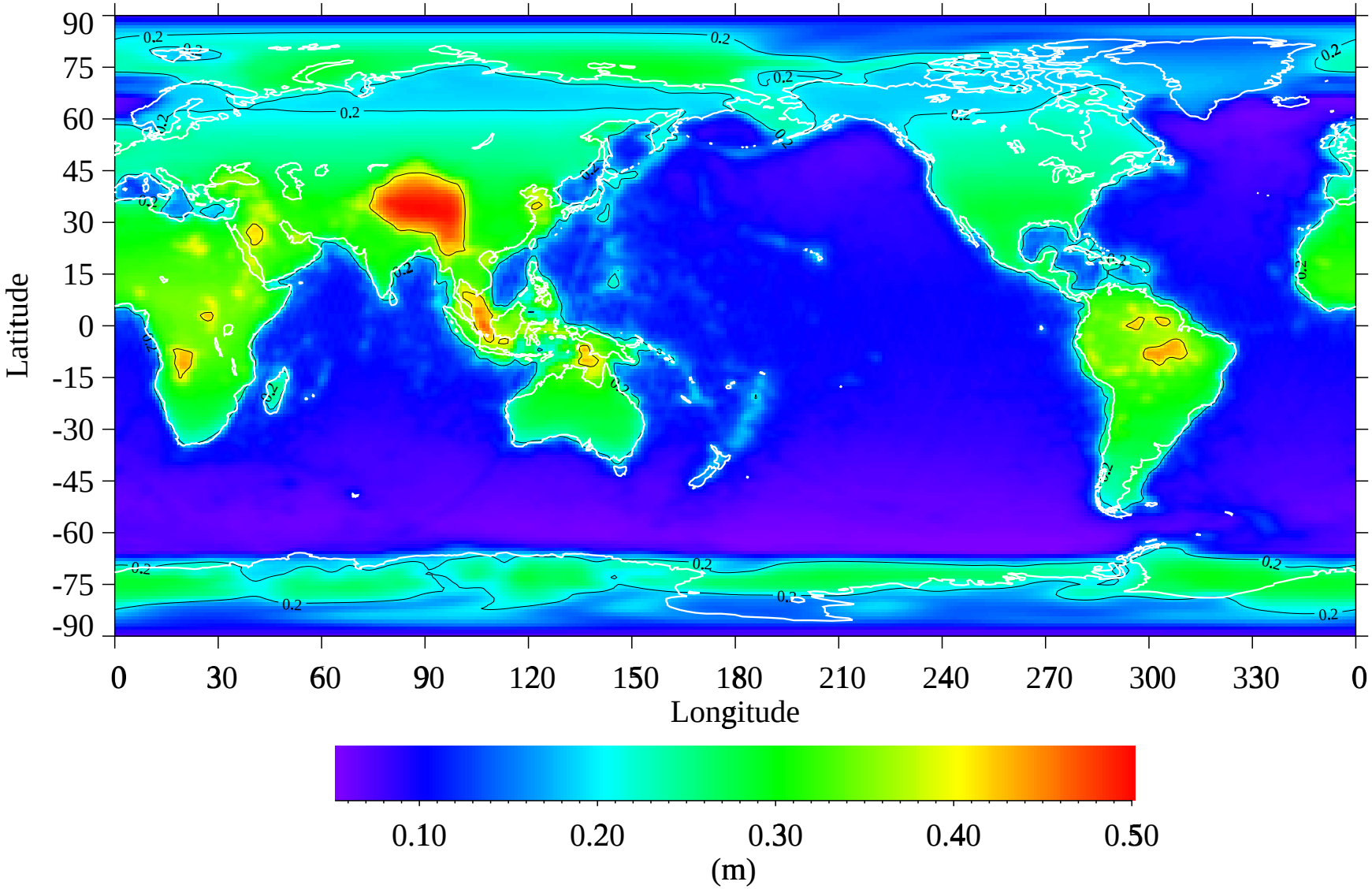


EGM96
Geoid Undulation S.Dev. (Nmax=70) RMS=0.18 m



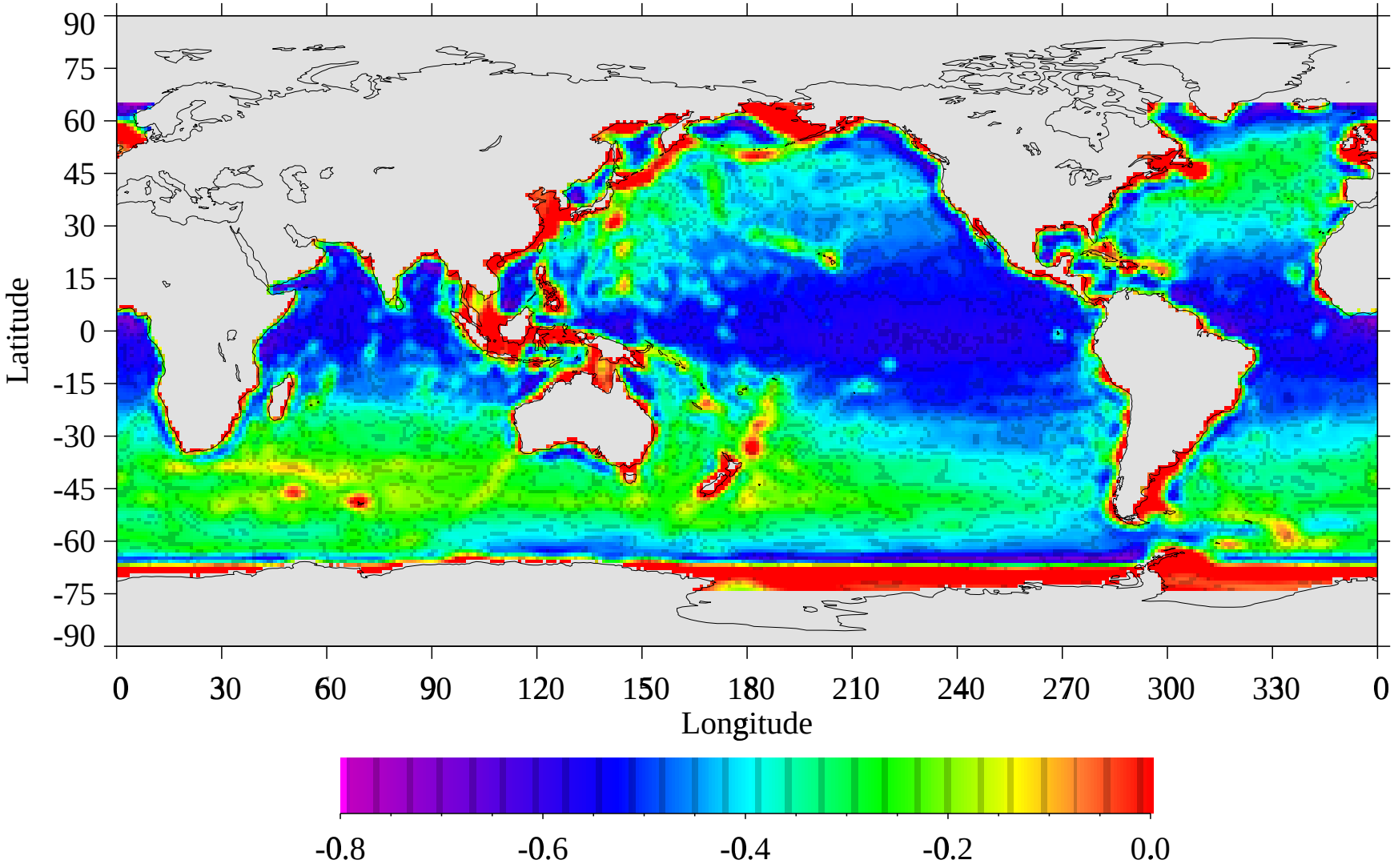
Data Range : (0.0436000 , 0.498100) Color/Contour Range : (0.0436000 , 0.498100) Contour Interval: 0.200000 Number of Valid Points : 65341 Number of Excluded Points : 0
EGM96.geoiderror.ps

PGM2000A
Geoid Undulation S.Dev. (Nmax=70) RMS=0.19 m



Data Range : (0.0526000 , 0.500300) Color/Contour Range : (0.0526000 , 0.500300) Contour Interval: 0.200000 Number of Valid Points : 65341 Number of Excluded Points : 0
PGM2000A.geoiderror.ps

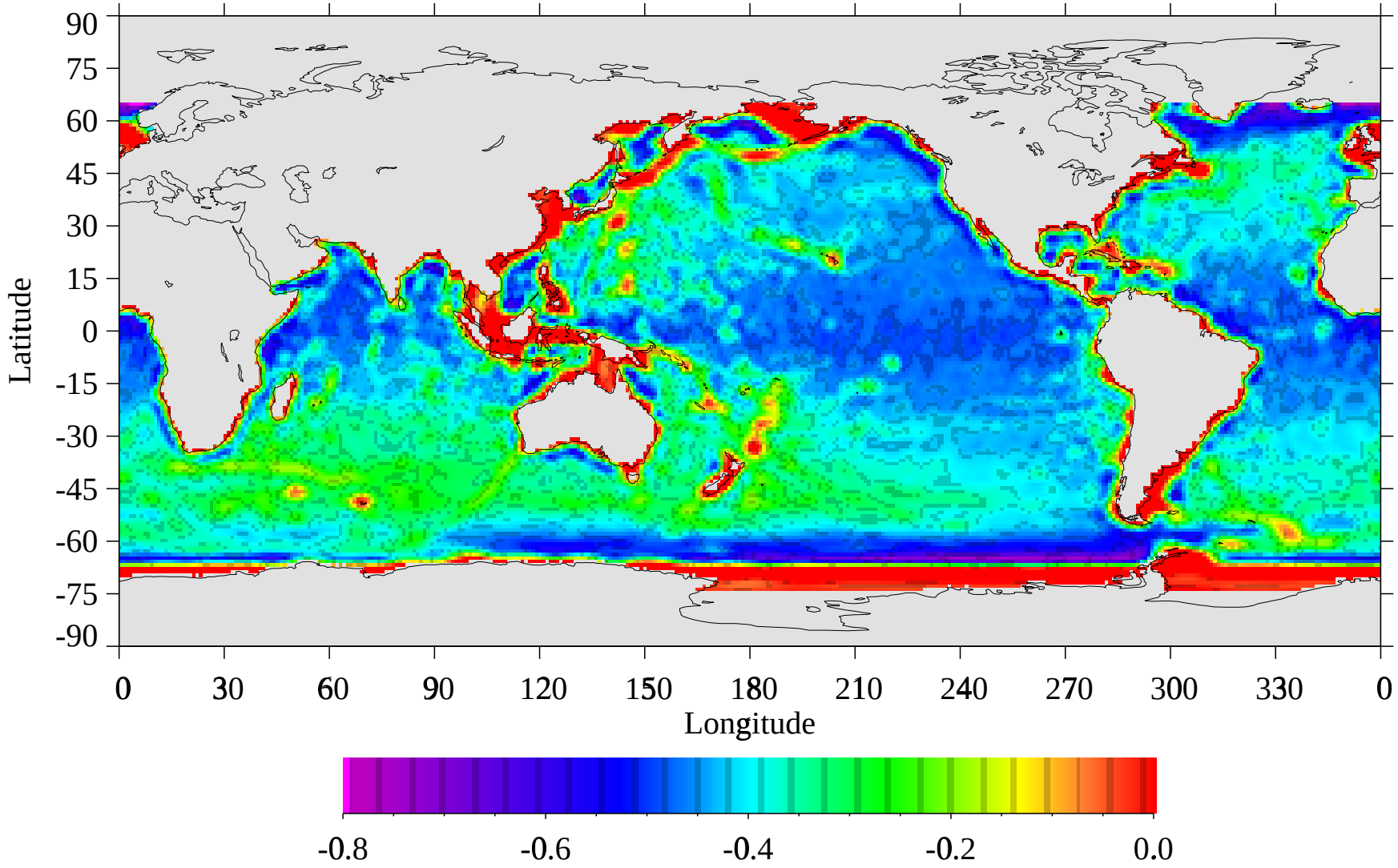
Correlation Between Geoid (Nmax=70) and DOT (Nmax=20)
EGM96 RMS=.40



Data Range : (-0.785600 , 0.342200) Contour Range : (-0.800000 , 0.00000) Number of Valid Points : 36216 Number of Excluded Points : 29125

EGM96.corNssterror.ps

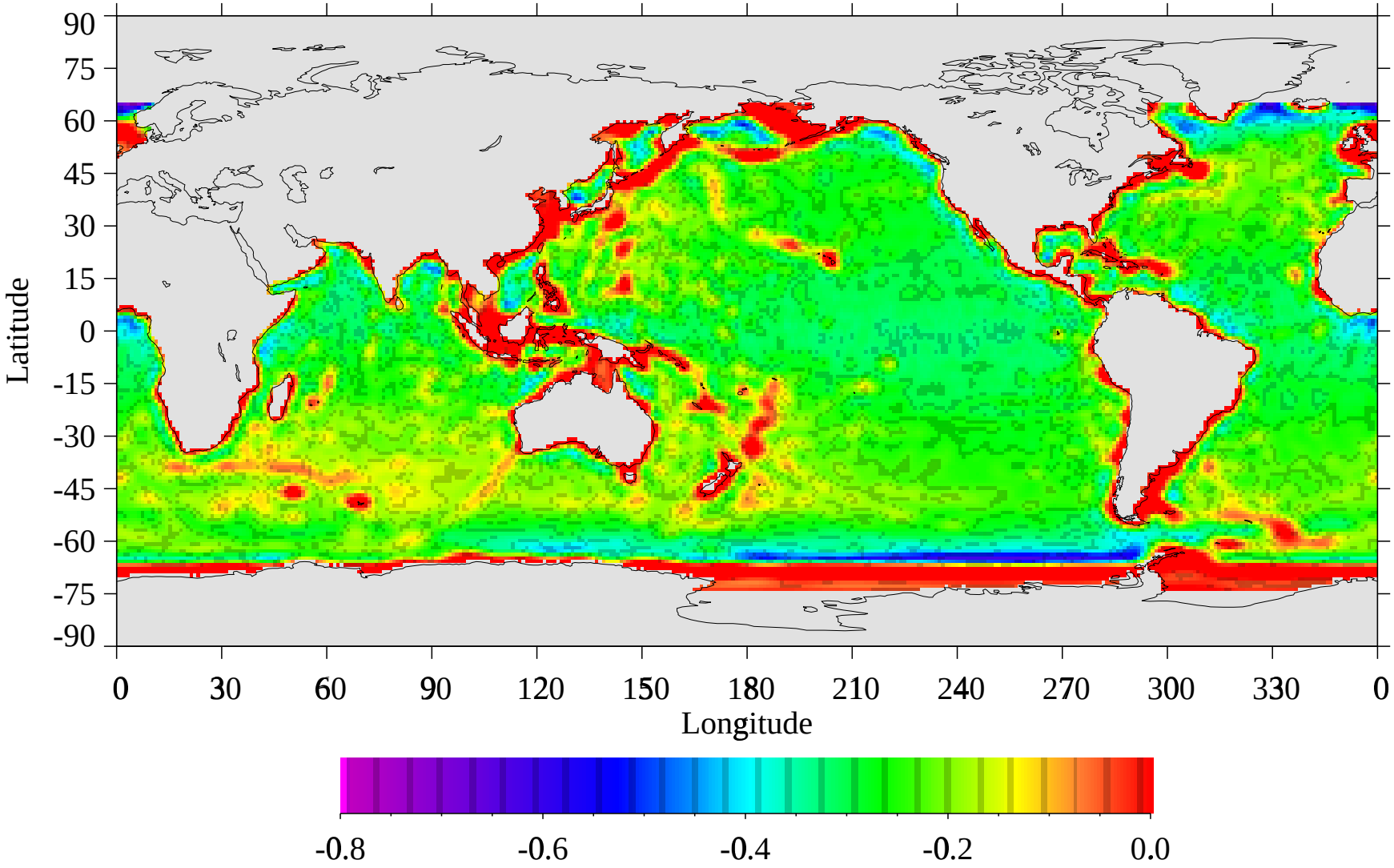
Correlation Between Geoid (Nmax=70) and DOT (Nmax=30)
PGM2000A Without POCM_4B RMS=.38



Data Range : (-0.817200 , 0.281600) Contour Range : (-0.800000 , 0.00000) Number of Valid Points : 36216 Number of Excluded Points : 29125

PGM2000A_noPOCM4B.corNssterror.ps

Correlation Between Geoid (Nmax=70) and DOT (Nmax=30)
PGM2000A RMS=.24



Data Range : (-0.733100 , 0.287900) Contour Range : (-0.800000 , 0.00000) Number of Valid Points : 36216 Number of Excluded Points : 29125

PGM2000A.corNssterror.ps

Gravitational Model Evaluation

- Emphasis on marine geoid and orbit performance, ***without*** complete disregard to land geoid performance

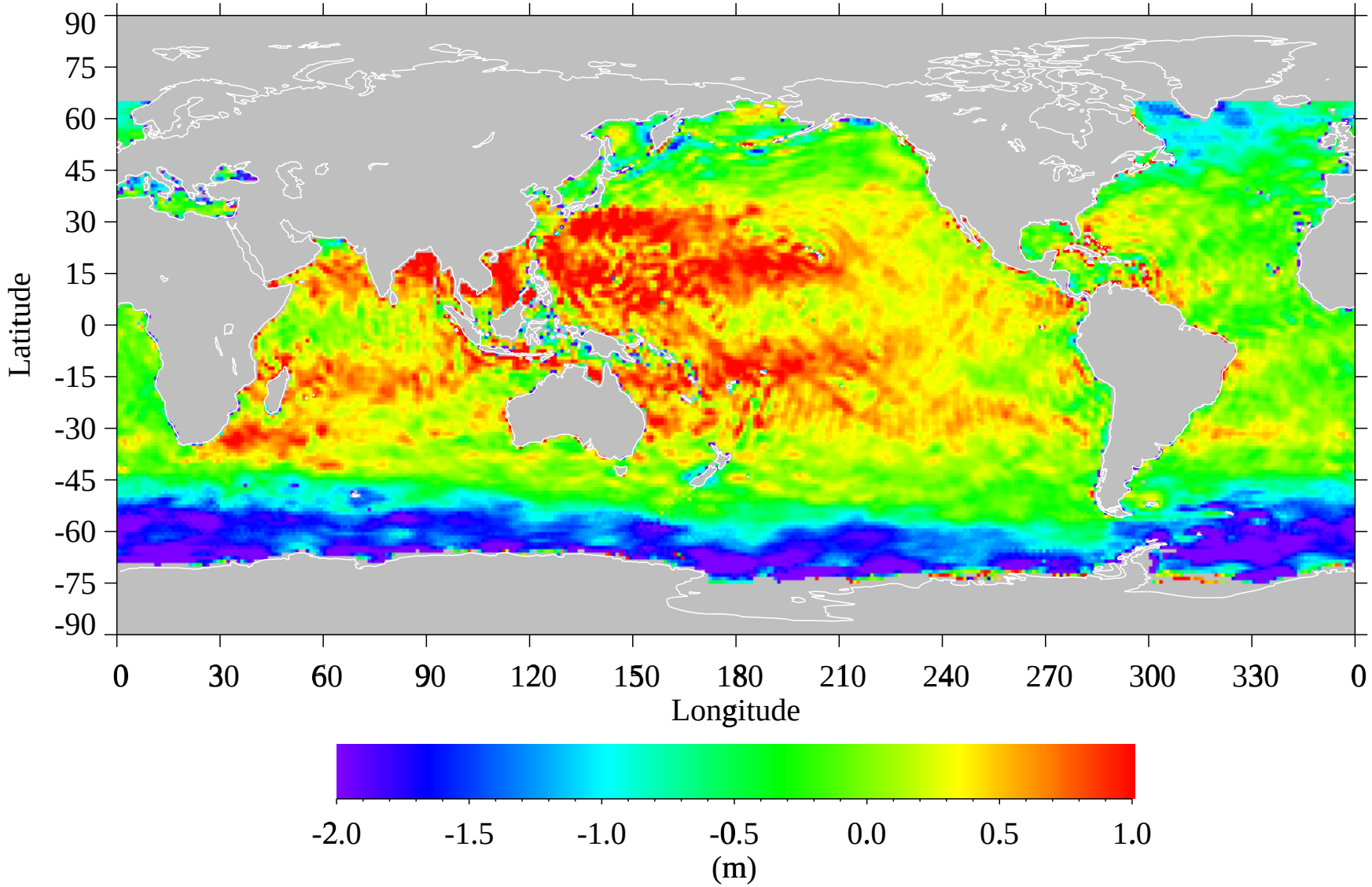
- Focus on the most recent, ***publicly available*** models:

TEG-3	Nmax = 70	[*Tapley et al.,* 1996]
EGM96	Nmax = 360	[*Lemoine et al.,* 1996]
GRIM5-C1	Nmax = 120	[*Gruber et al.,* 2000]
TEG-4	Nmax = 180	[*Tapley et al.,* 2000]
PGM2000A	Nmax = 360	[*Pavlis et al.,* 2000]

Evaluation Tests

1. DOT evaluation using the GSFC00.1 MSS minus geoid model
2. Comparisons with hydrographic estimates (WOCE) of relative DOT
3. Current velocity comparisons with NOAA drifting buoy data
4. Orbit fit comparisons
5. Comparisons with GPS/Leveling-implied geoid undulations
6. Error spectra inter-comparisons

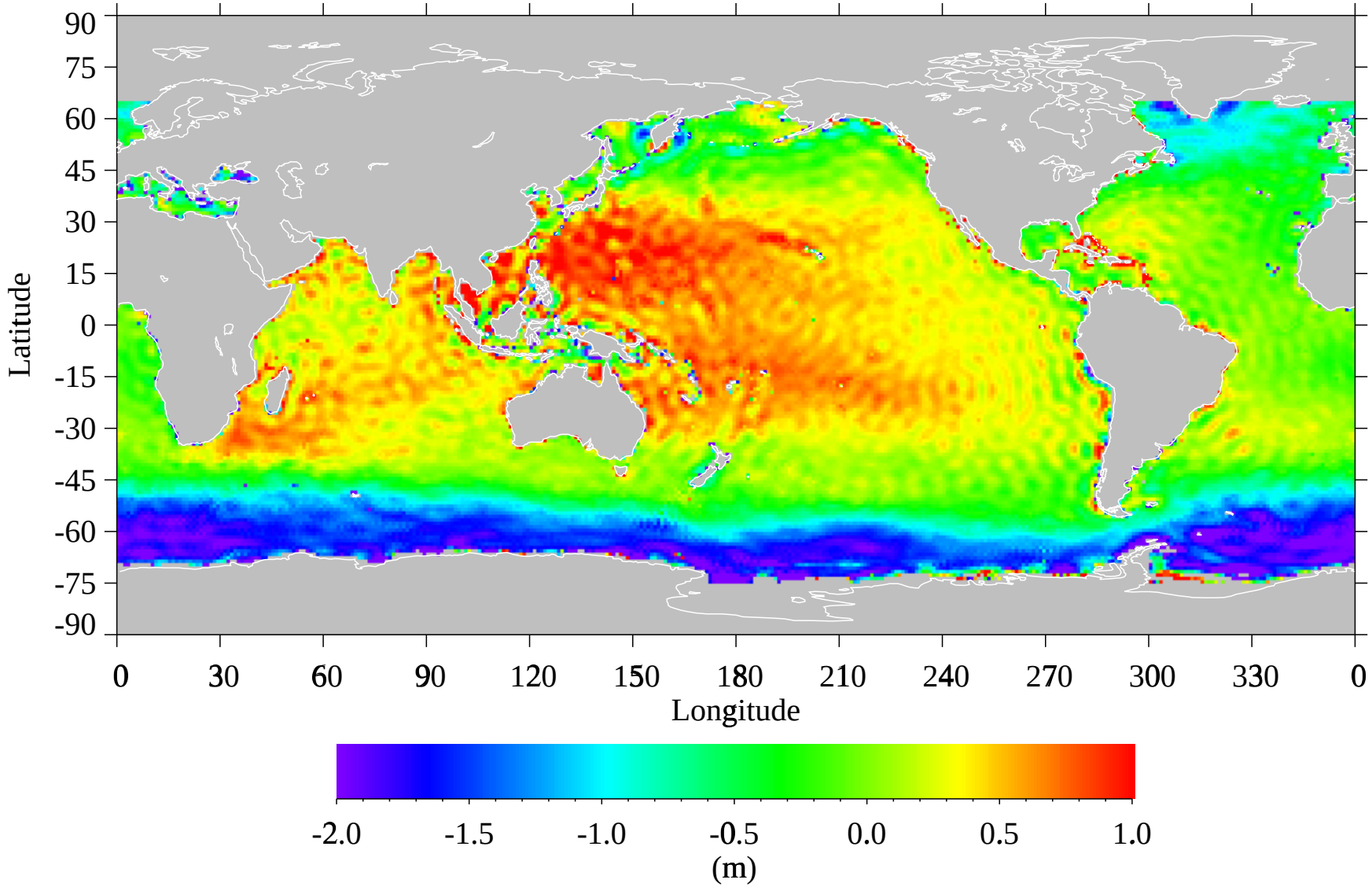
1 Deg. Aver. GSFC00.1 MSS Minus GRIM5C1_EGM96 Geoid (Nmax=360)



Data Range : (-3.39985 , 2.59060) Color/Contour Range : (-2.00000 , 1.00000) Contour Interval: 0.0800000 Number of Valid Points : 34499 Number of Excluded Points : 30301

GSFC00.1_SSH_valid_GMTo-GRIM5C1_min60.dhp.ps

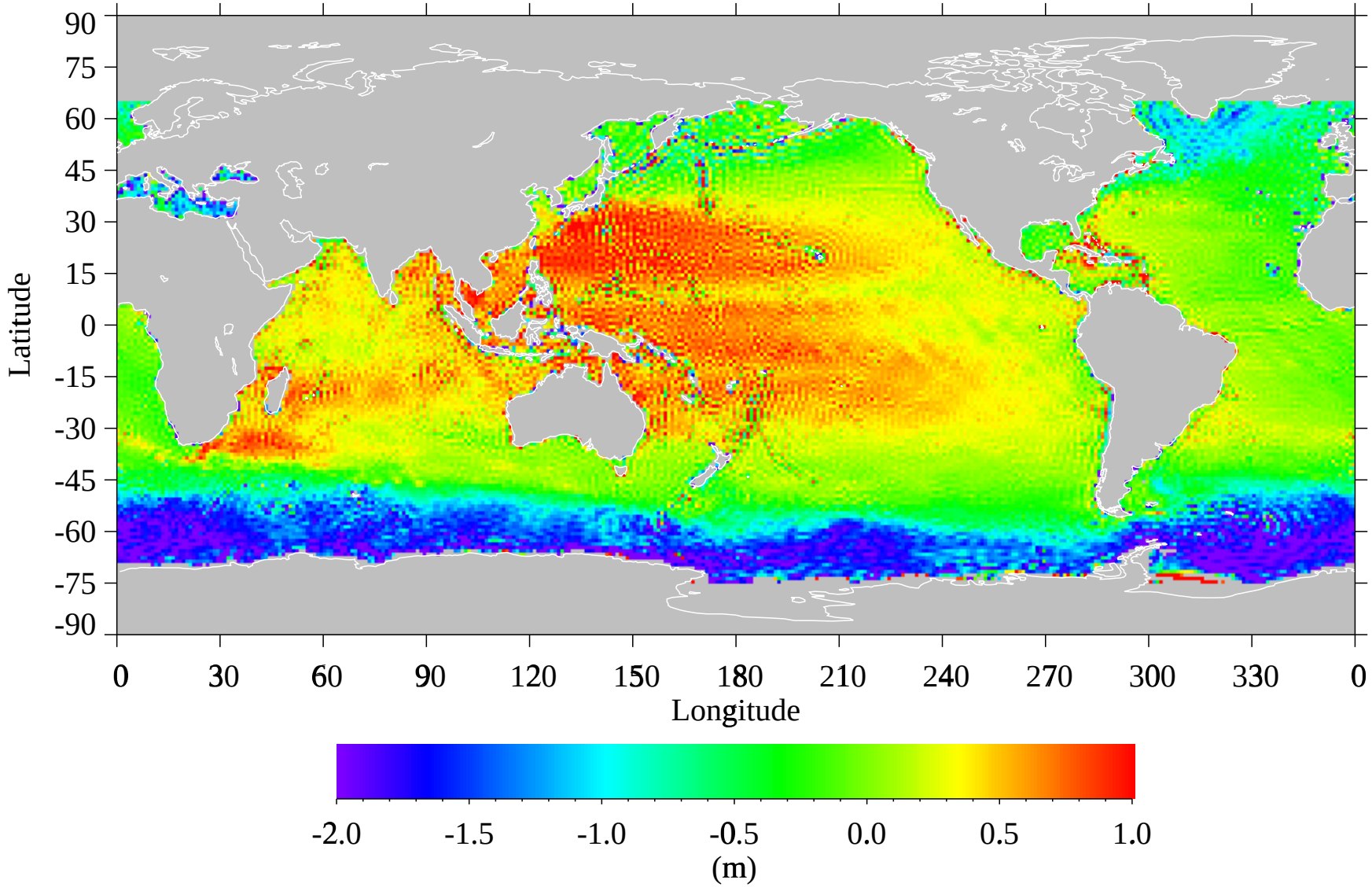
1x1 Deg. Aver. of GSFC00.1 MSS Minus TEG-3_EGM96 Geoid (Nmax=360)



Data Range : (-3.37904 , 2.58865) Color/Contour Range : (-2.00000 , 1.00000) Contour Interval: 0.0800000 Number of Valid Points : 34481 Number of Excluded Points : 30319

GSFC00.1_SSH_valid_GMTo-TEG3_min60.dhp.ps

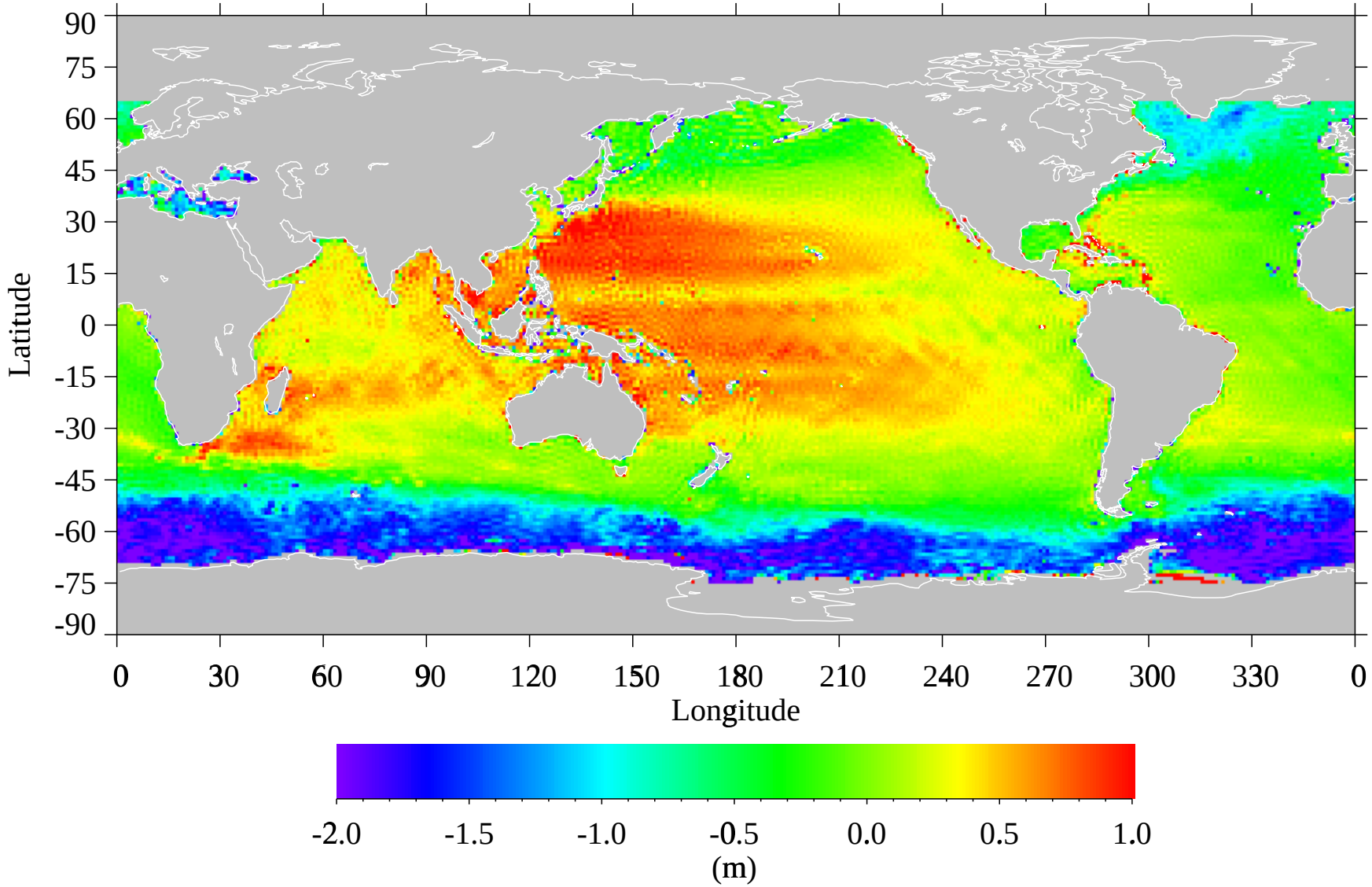
1x1 Deg. Aver. of GSFC00.1 MSS Minus TEG-4 Geoid (Nmax=180)



Data Range : (-3.40581 , 2.58829) Color/Contour Range : (-2.00000 , 1.00000) Contour Interval: 0.0800000 Number of Valid Points : 34499 Number of Excluded Points : 30301

GSFC00.1_SSH_valid_GMTo-TEG4a_min60.dhp.ps

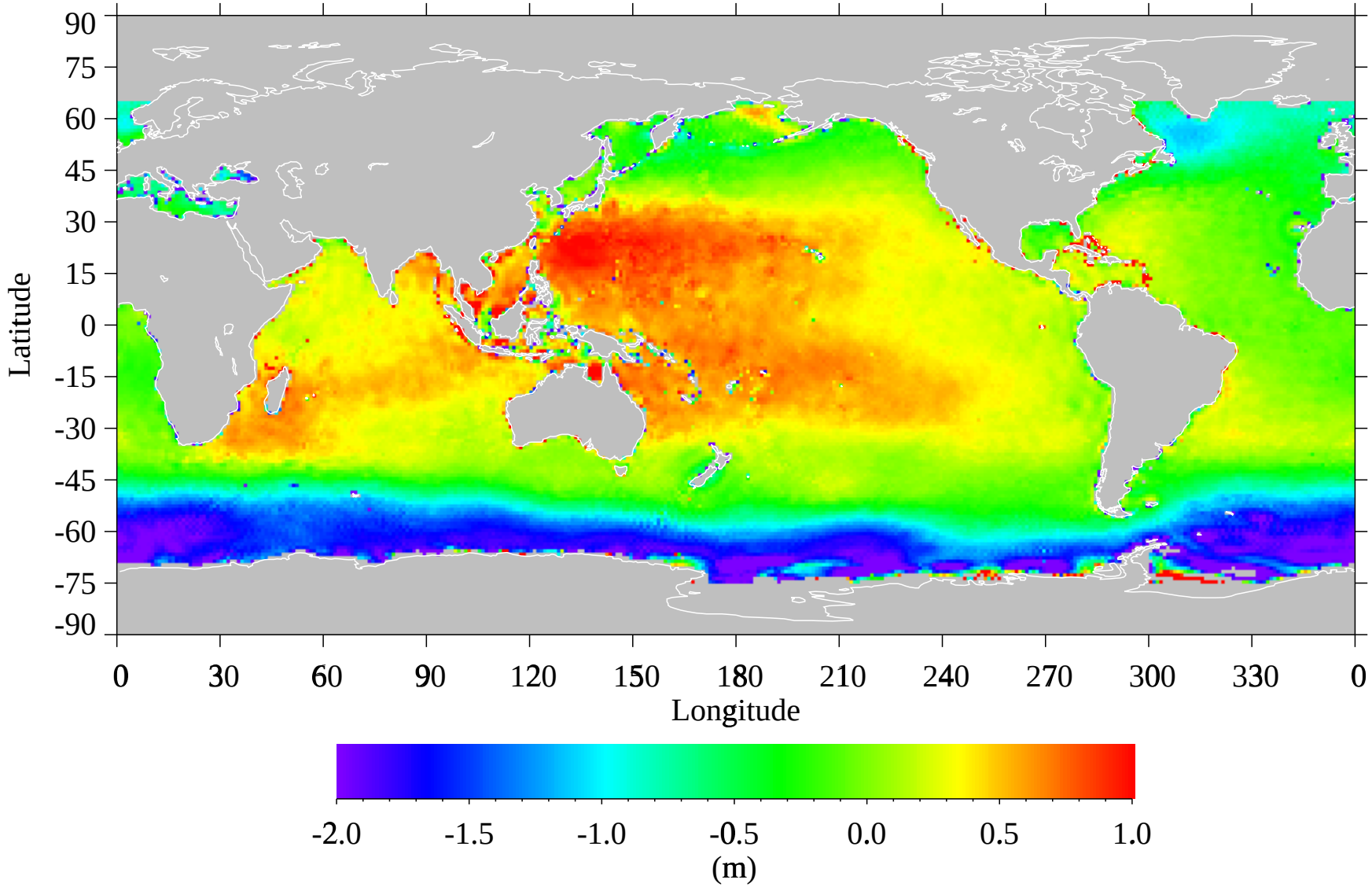
1x1 Deg. Aver. of GSFC00.1 MSS Minus TEG-4_EGM96 Geoid (Nmax=360)



Data Range : (-3.39209 , 2.53480) Color/Contour Range : (-2.00000 , 1.00000) Contour Interval: 0.0800000 Number of Valid Points : 34511 Number of Excluded Points : 30289

GSFC00.1_SSH_valid_GMTo-TEG4_min60.dhp.ps

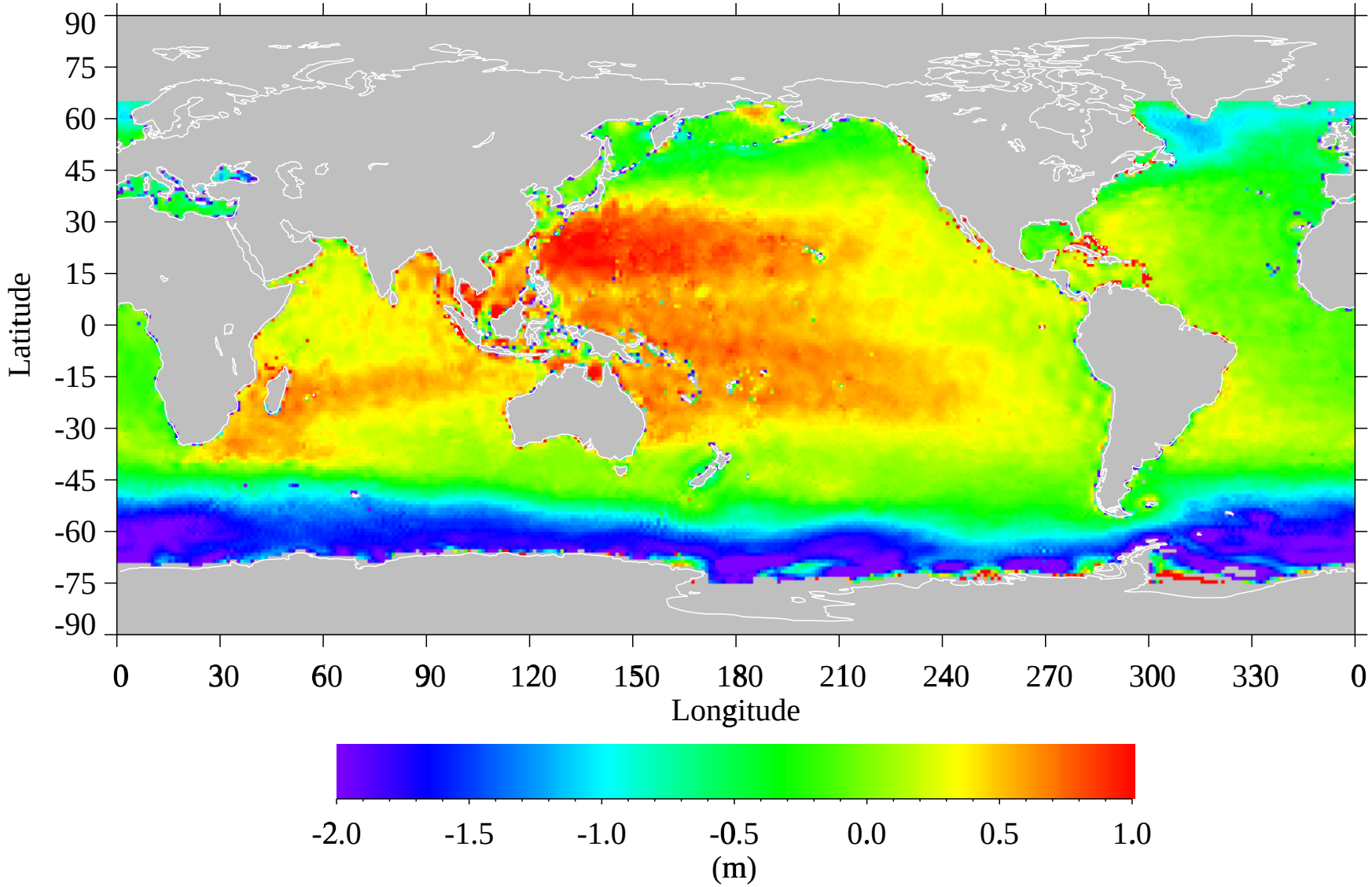
1x1 Deg. Aver. of GSFC00.1 MSS Minus EGM96 Geoid (Nmax=360)



Data Range : (-3.40761 , 2.58668) Color/Contour Range : (-2.00000 , 1.00000) Contour Interval: 0.0800000 Number of Valid Points : 34474 Number of Excluded Points : 30326

GSFC00.1_SSH_valid_GMTo-EGM96_min60.dhp.ps

1x1 Deg. Aver. of GSFC00.1 MSS Minus PGM2000A Geoid (Nmax=360)



Data Range : (-3.40718 , 2.58663) Color/Contour Range : (-2.00000 , 1.00000) Contour Interval: 0.0800000 Number of Valid Points : 34478 Number of Excluded Points : 30322

GSFC00.1_SSH_valid_GMTo-PGM2000A_min60.dhp.ps

Comparison With WOCE Hydrographic Data

$$\Delta = \zeta_{Hydro.} - \zeta_{Model}$$

ζ_{Model} is computed from each SH model to a specific N_{max}.

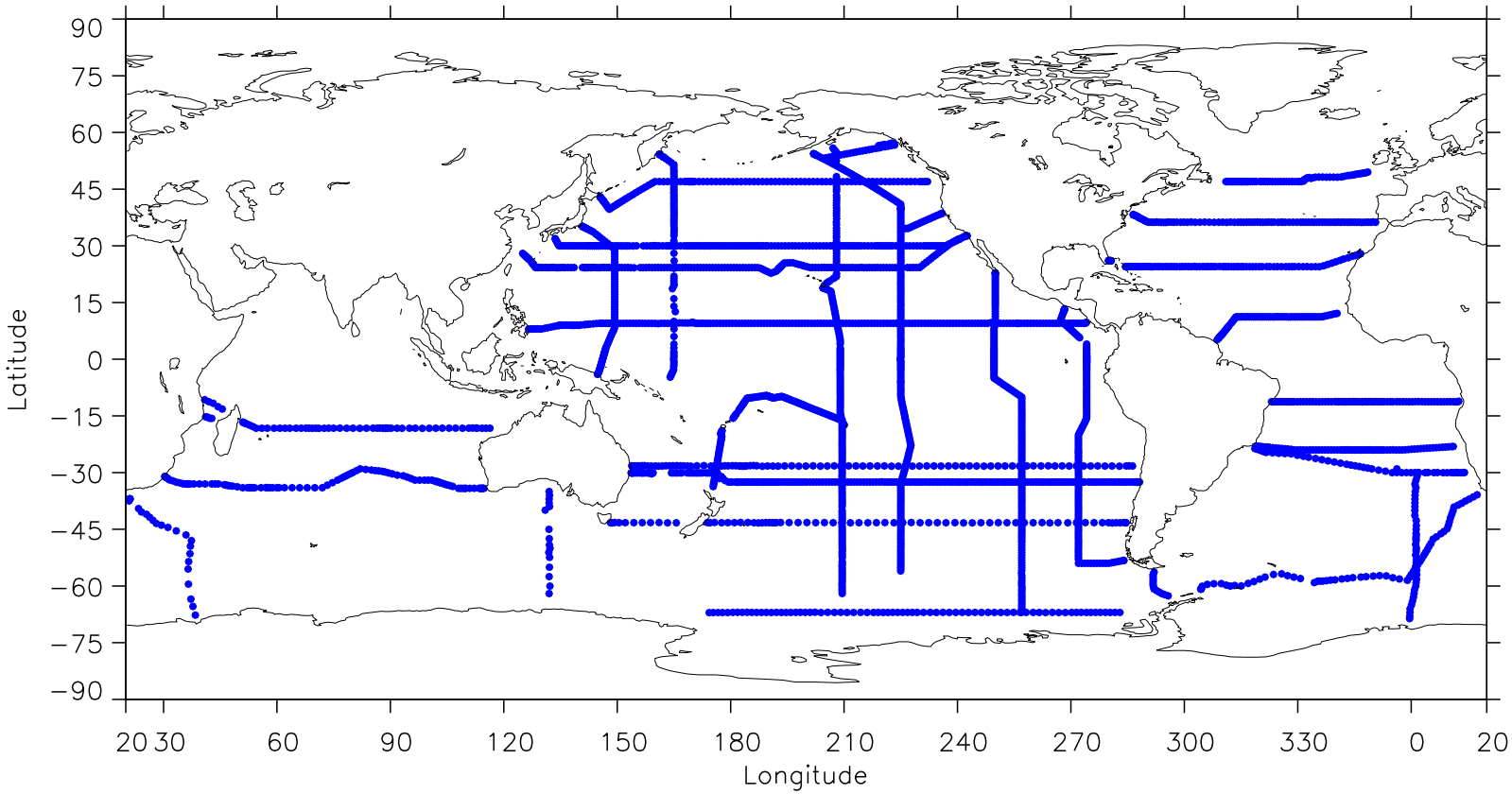
σ_1 is the weighted (by number of points per section) standard deviation of Δ, after removing a bias per section.

σ_2 is as σ_1 but after removing a bias and a tilt per section.

ρ is the weighted correlation between $\zeta_{Hydro.}$ and ζ_{Model}.

Model (Nmax)	σ_1 (cm)	σ_2 (cm)	ρ (%)
GRIM5-C1 (20)	**13.8**	**12.2**	**76.1**
TEG-3 (20)	11.9	10.8	77.9
TEG-4 (36)	10.9	10.0	82.5
EGM96 (20)	11.0	10.2	81.4
PGM2000A (30)	**10.4**	**9.6**	**84.7**

Location of WOCE Hydrographic Sections Used in the Tests

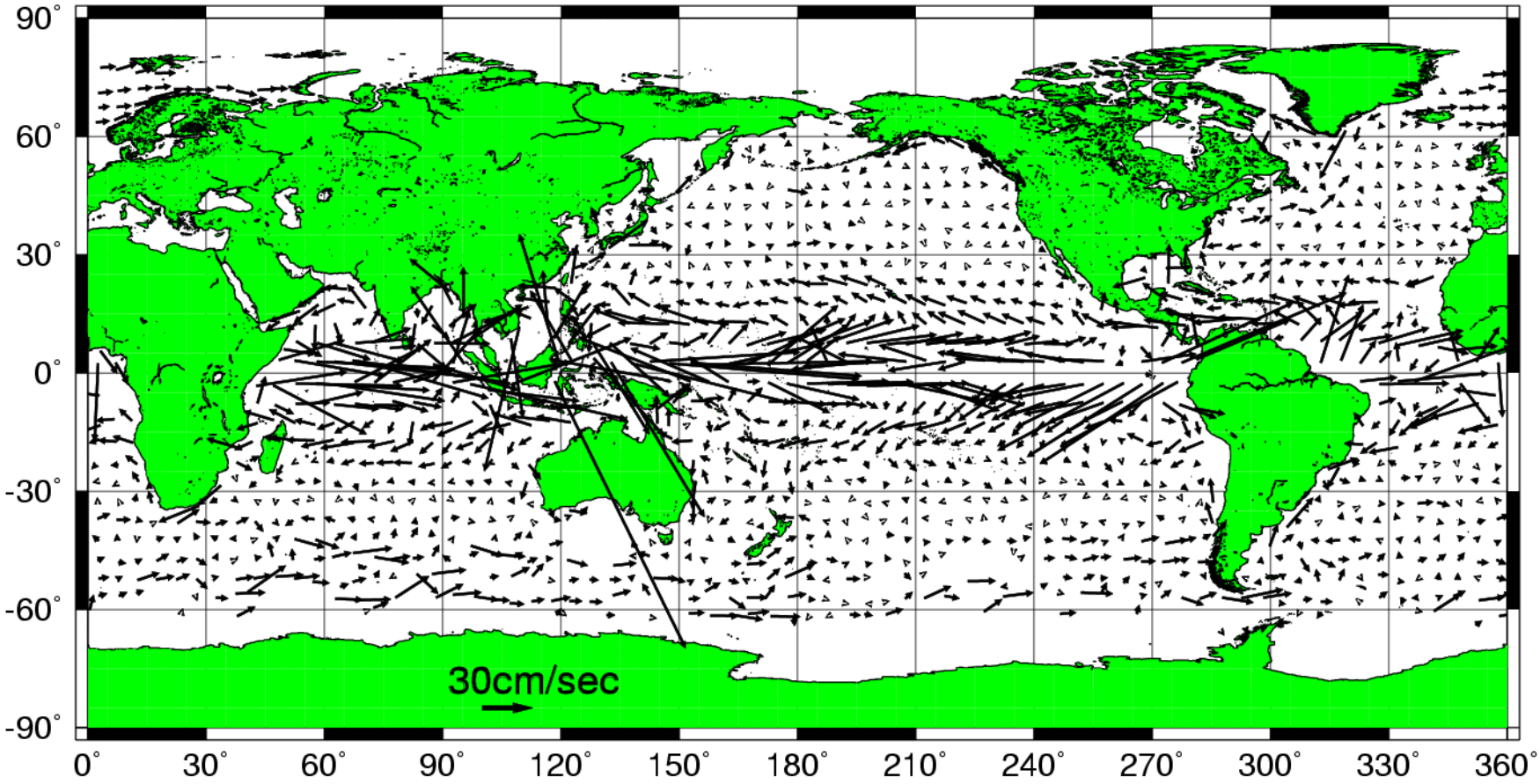


RMS : 160.017 Mean : 113.685 Number of Points : 3225 Data Range (−128.950 , 376.170) Color Range : (−2000.0000 , 2000.0000)
../psf/data.12c.plot.ps

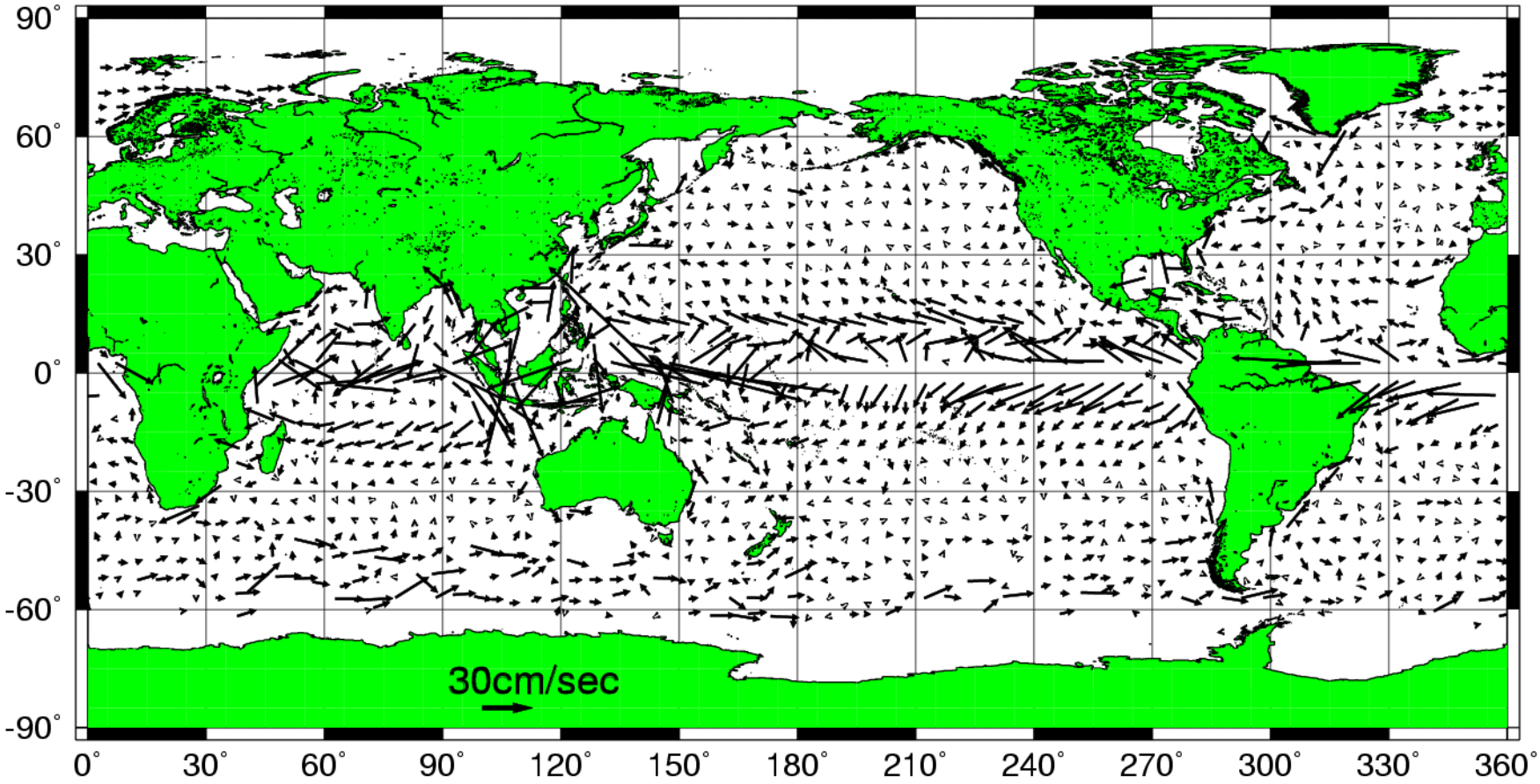
Current Velocity Comparisons Between NOAA Drifting Buoy Data and Model-Implied Values. Units are cm/s.

Model		Nmax=20		Nmax=30		Nmax=36	
		Max |•|	S. Dev.	Max |•|	S. Dev.	Max |•|	S. Dev.
GRIM5-C1	Δu	113	17.0				
	Δv	158	10.0				
	ΔV	176	15.8				
TEG-3	Δu	123	11.0				
	Δv	78	7.2				
	ΔV	125	9.8				
TEG-4	Δu	77	11.0	96	13.3	84	9.4
	Δv	122	9.0	159	10.1	149	8.0
	ΔV	141	10.5	180	13.0	156	9.3
EGM96	Δu	47	8.6				
	Δv	101	6.7				
	ΔV	111	7.7				
PGM2000A	Δu	57	8.8	62	8.0		
	Δv	72	6.6	75	6.8		
	ΔV	78	7.7	84	7.4		

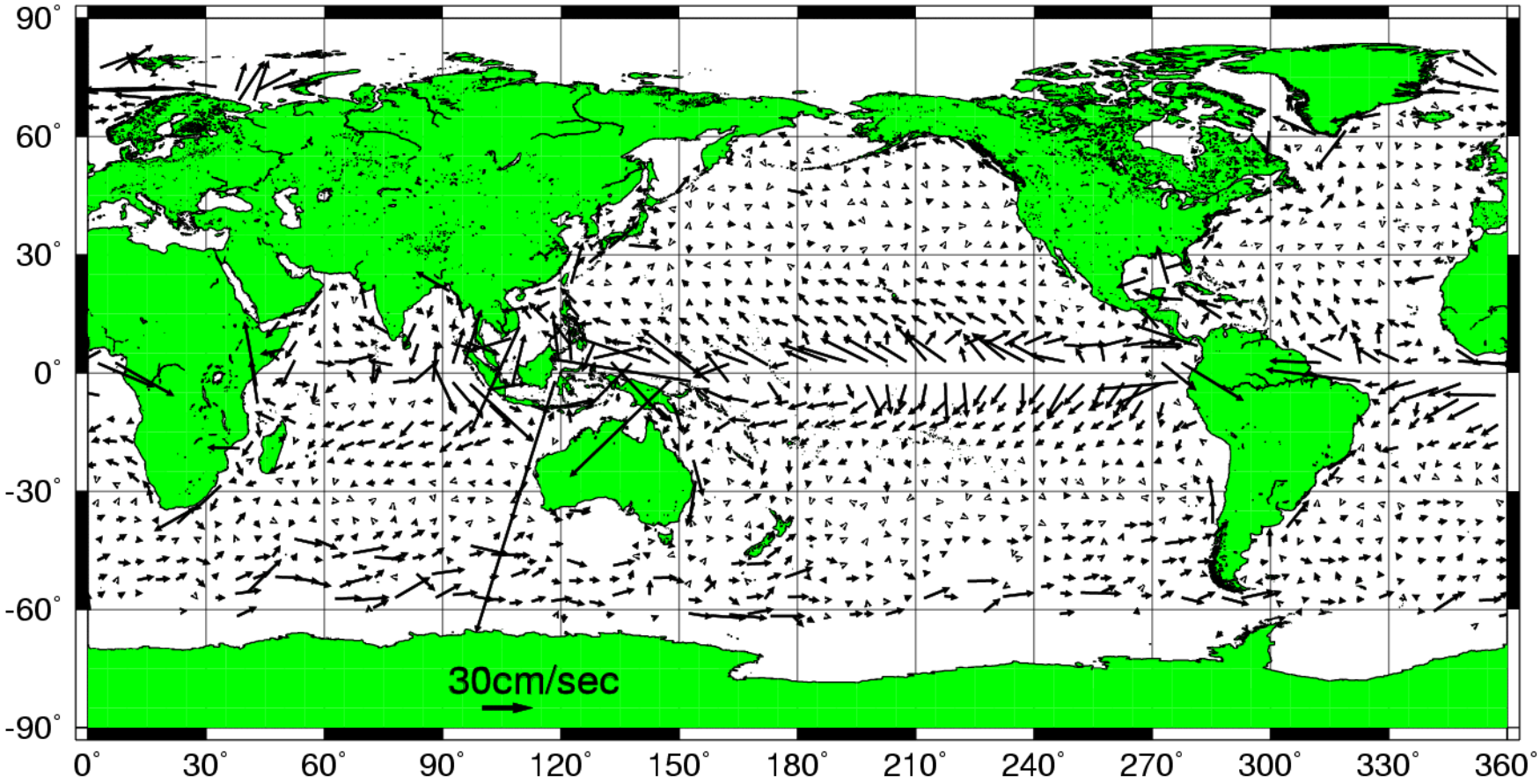
Total Velocity Diff. Buoys - GRIM5-C1 DOT to Nmax=20



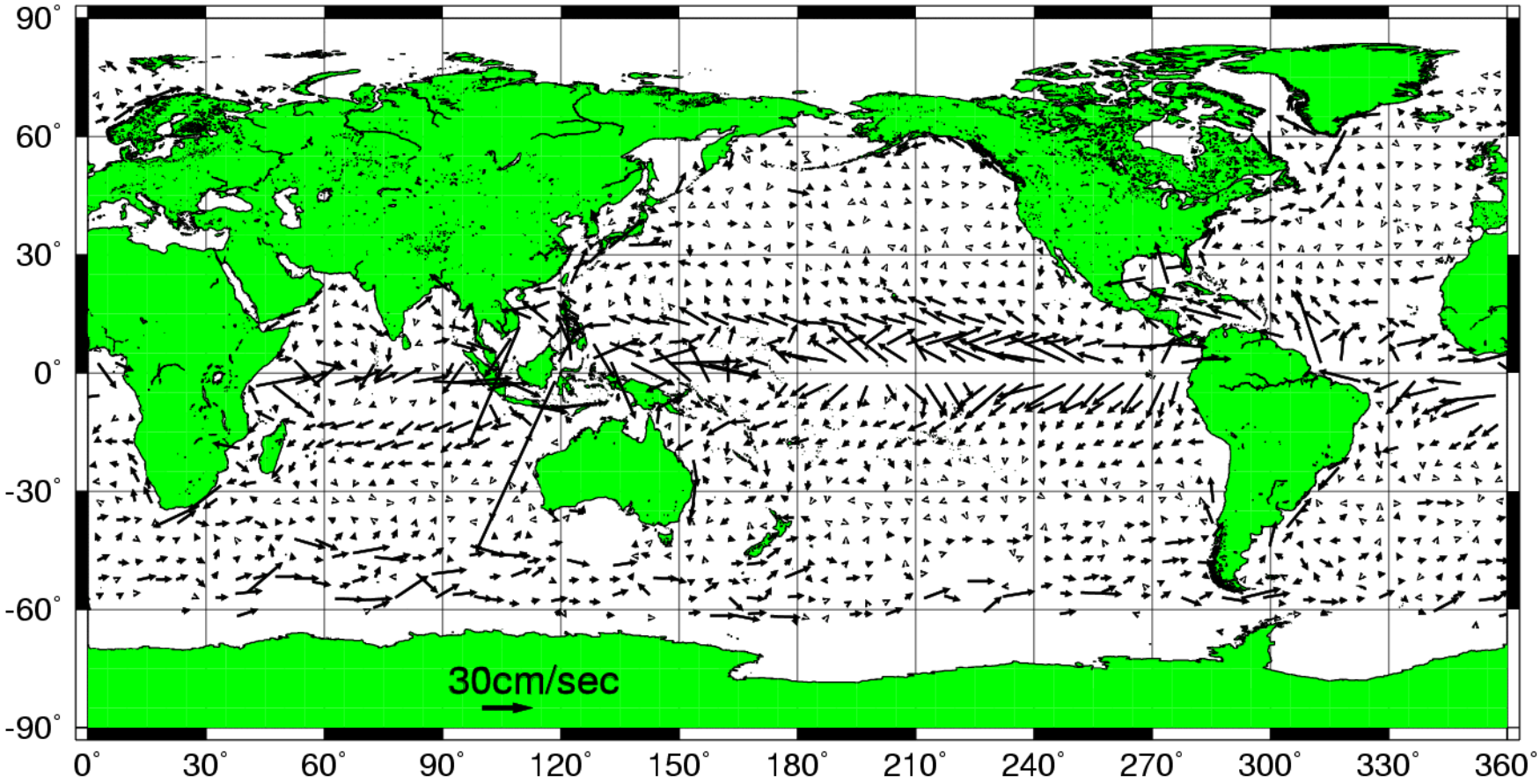
Total Velocity Diff. Buoys - TEG-3 DOT to Nmax=20



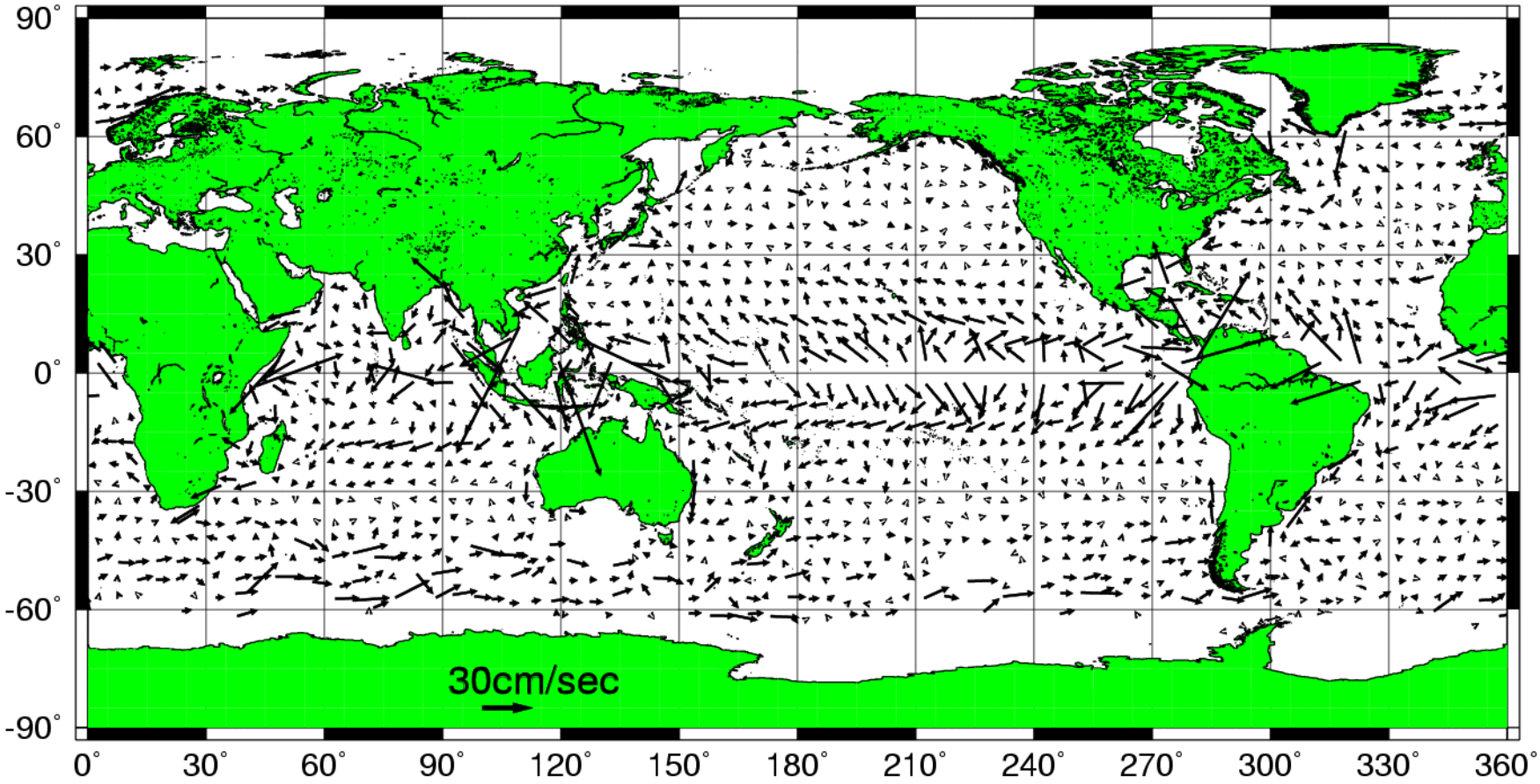
Total Velocity Diff. Buoys - TEG-4 DOT to Nmax=36



Total Velocity Diff. Buoys - EGM96 DOT to Nmax=20



Total Velocity Diff. Buoys - PGM2000A DOT to Nmax=30



Comparison With a 6-Year Mean TOPEX Track

$$\Delta = SSH - \zeta_{POCM\_4B} - N_{Model}$$

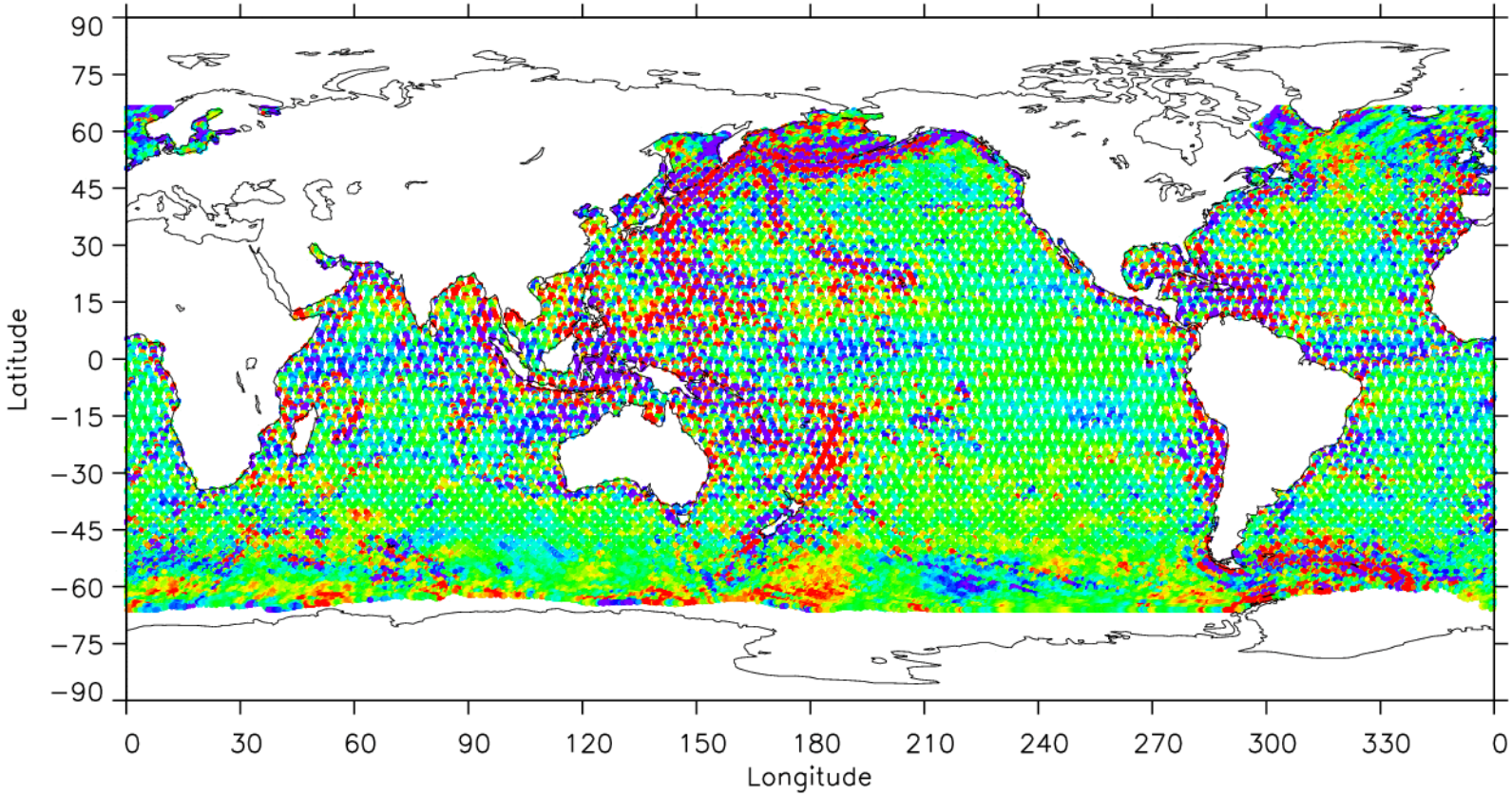
ζ_{POCM_4B} is computed from a SH model to N_{max}=30.

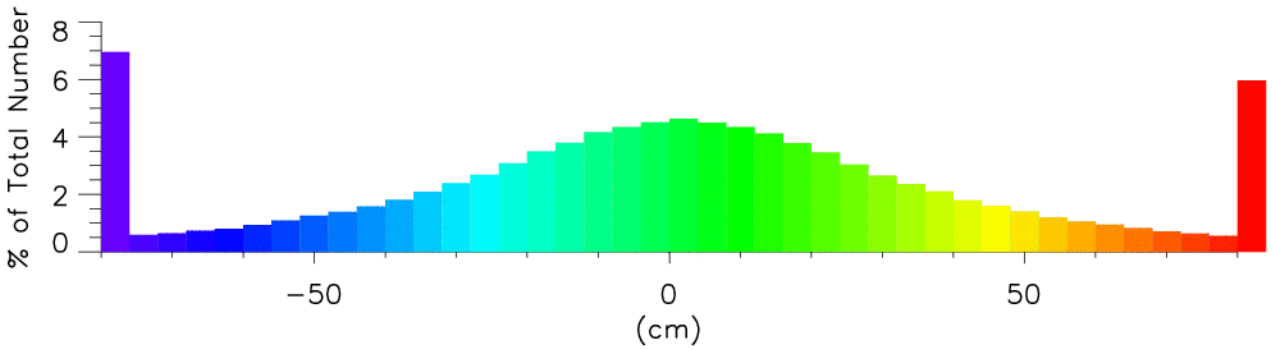
N_{Model} is computed from each SH model to a specific N_{max}.

Units are cm.

Model (Nmax)	Min.	Max.	S.Dev.
GRIM5-C1 (120)	-766	1140	69.2
GRIM5-C1/EGM96 (360)	-549	426	**34.1**
TEG-4 (180)	-497	513	43.7
TEG-4/EGM96 (360)	-348	323	26.6
EGM96 (360)	-395	296	23.1
PGM2000A (360)	-393	294	**22.4**

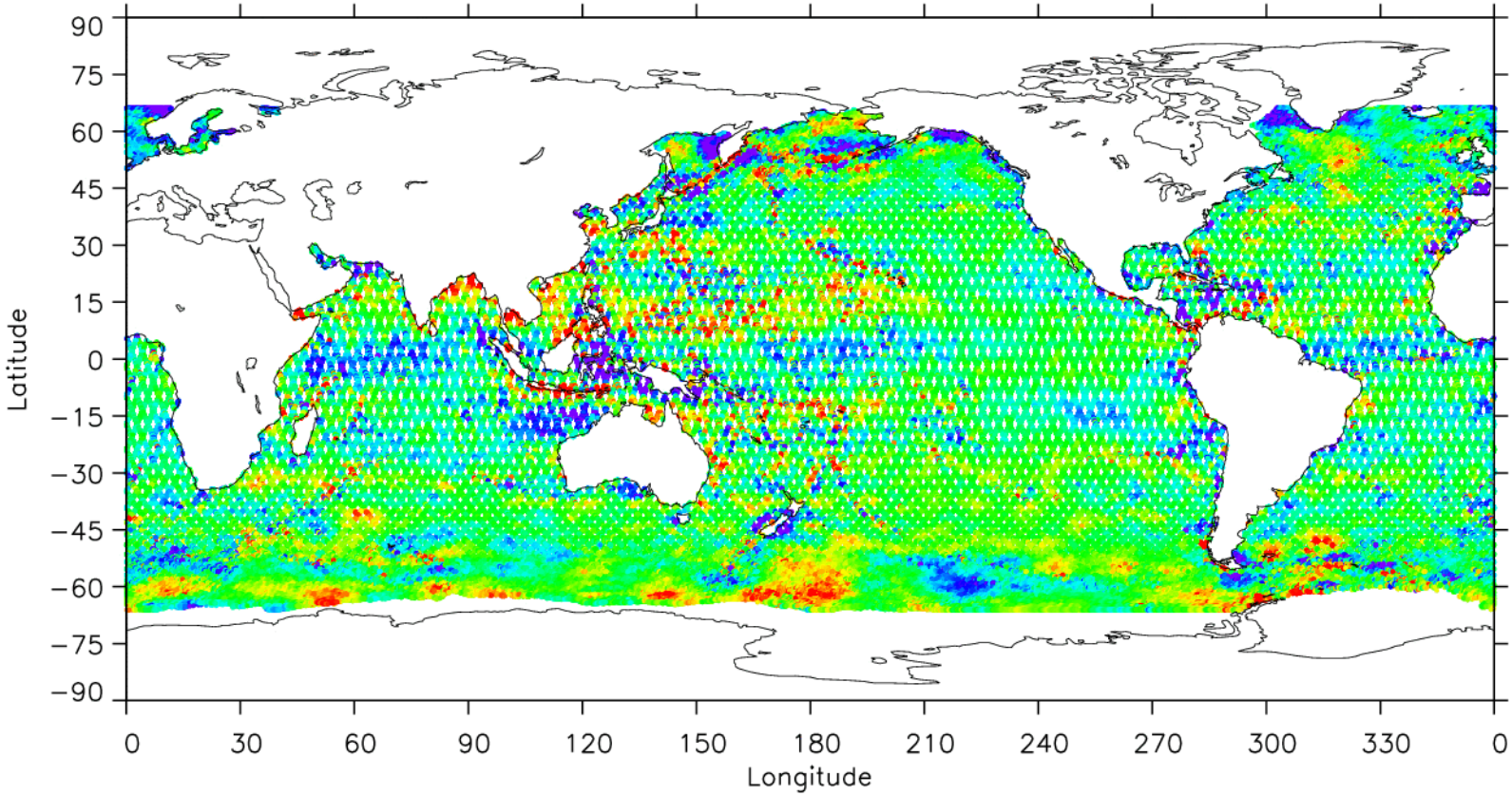
1 Hz Resid. SSH: T/P 6-Year Mean Minus GRIM5-C1 (Nmax=120)

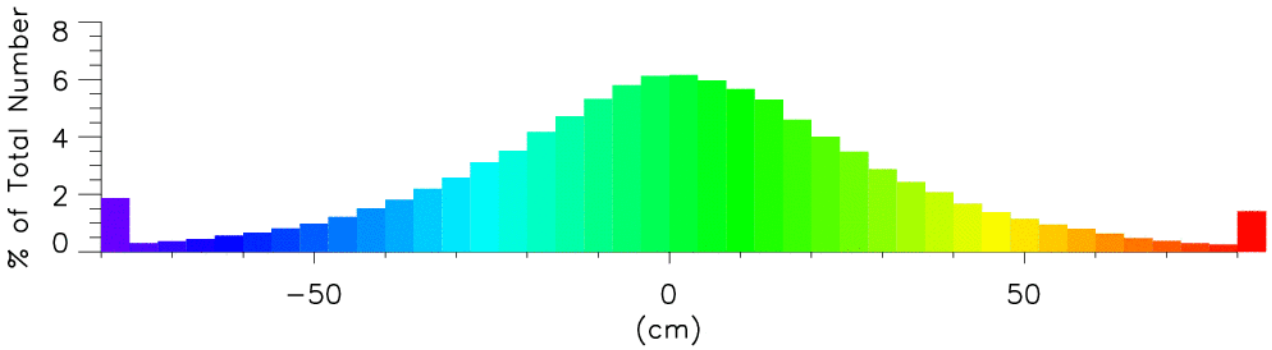




RMS : 69.1704 Mean : 0.0529905 Number of Points : 541277 Data Range (−766.257 , 1139.91) Color Range : (−80.000000 , 80.000000)
topex.6ymean.rssh_grim5c1.to120.ps

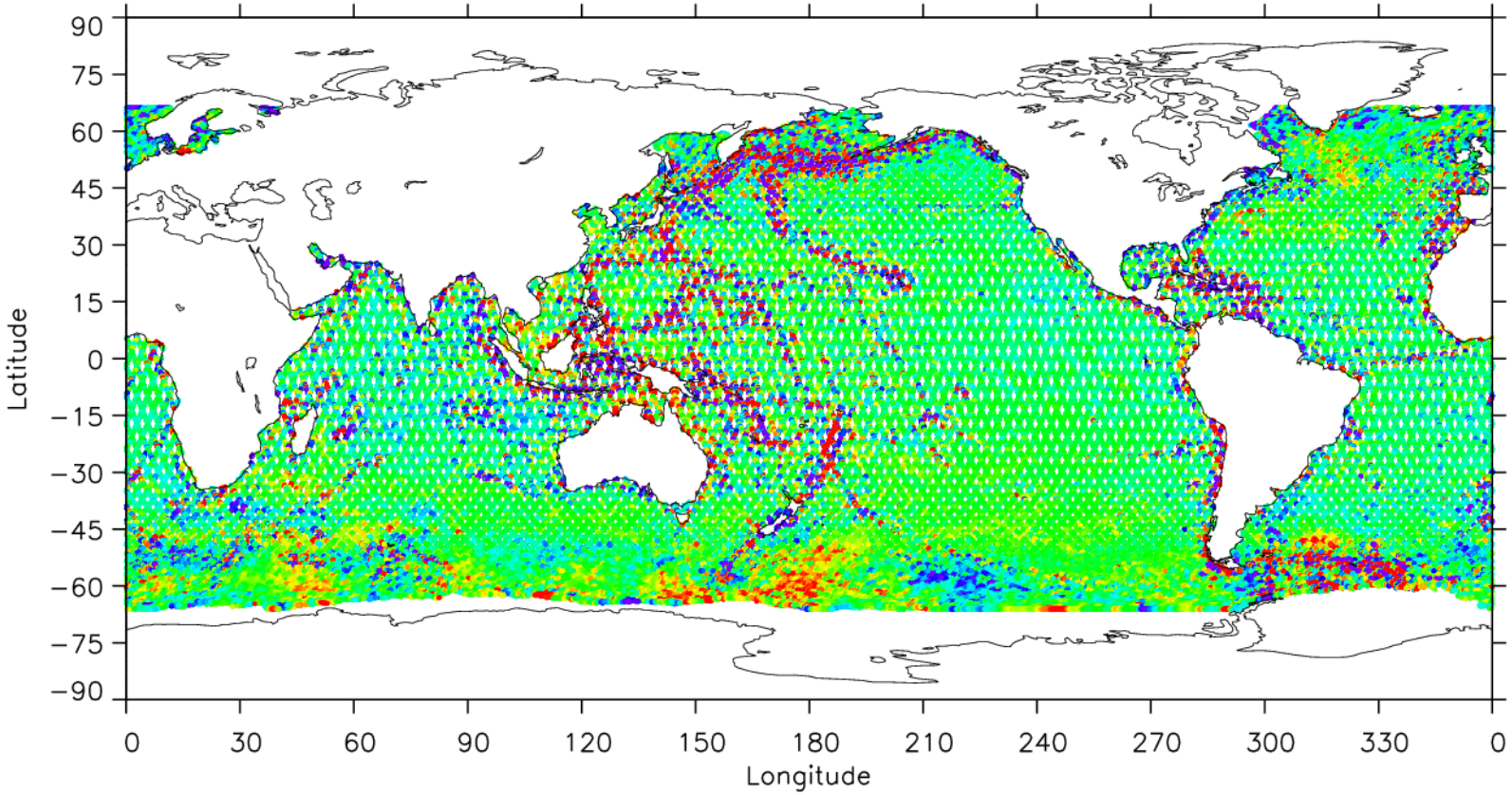
1 Hz Resid. SSH: T/P 6-Year Mean - GRIM5C1/EGM96 (Nmax=360)

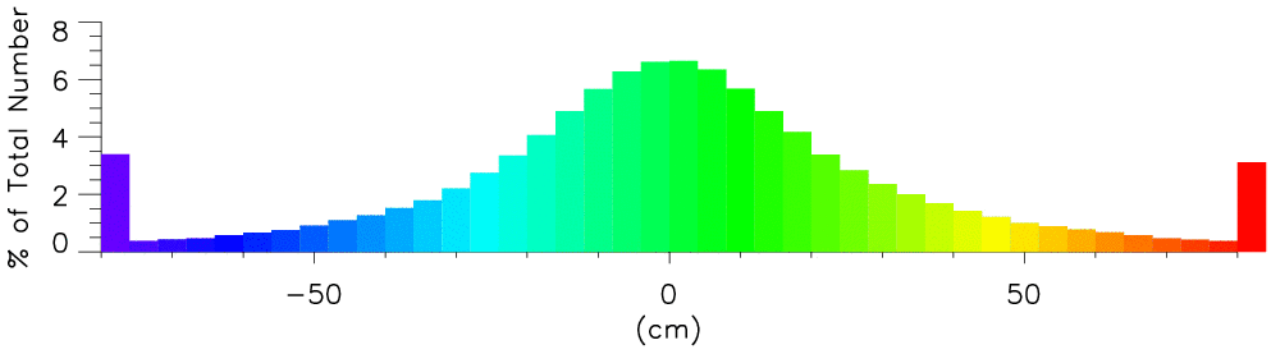




RMS : 34.0763 Mean : 0.885103 Number of Points : 541277 Data Range (-548.695 , 425.772) Color Range : (-80.000000 , 80.000000)
topex.6ymean.rssh_grim5c1egm96.to360.ps

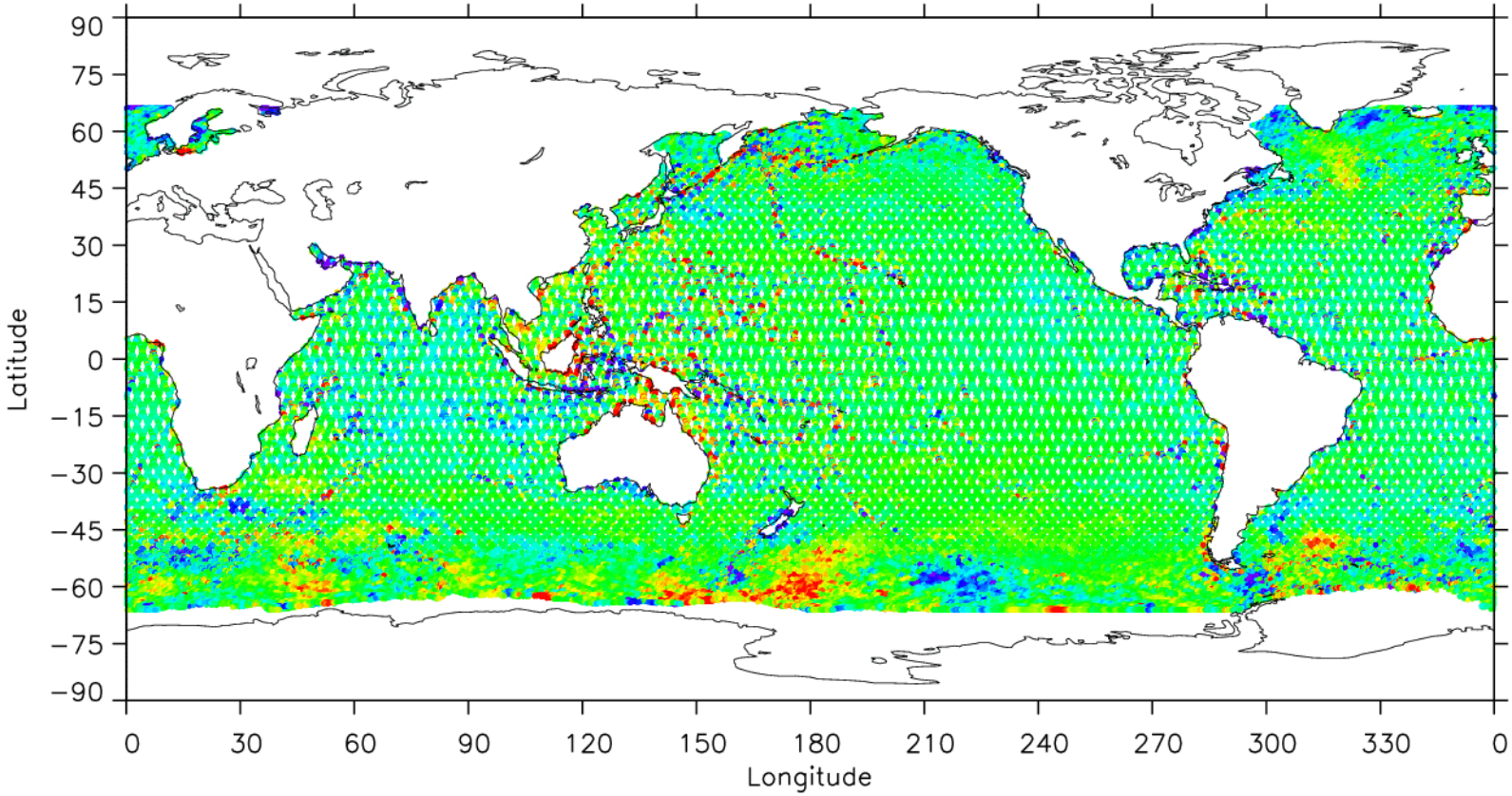
1 Hz Resid. SSH: T/P 6-Year Mean Minus TEG-4 (Nmax=180)

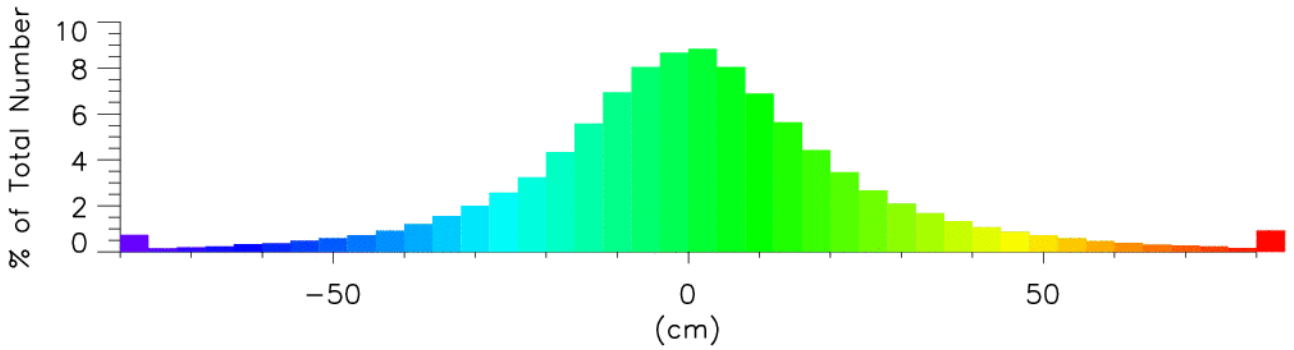




RMS : 43.7118 Mean : 0.948735 Number of Points : 541277 Data Range (−497.242 , 512.560) Color Range : (−80.000000 , 80.000000)
topex.6ymean.rssh_teg4.to180.ps

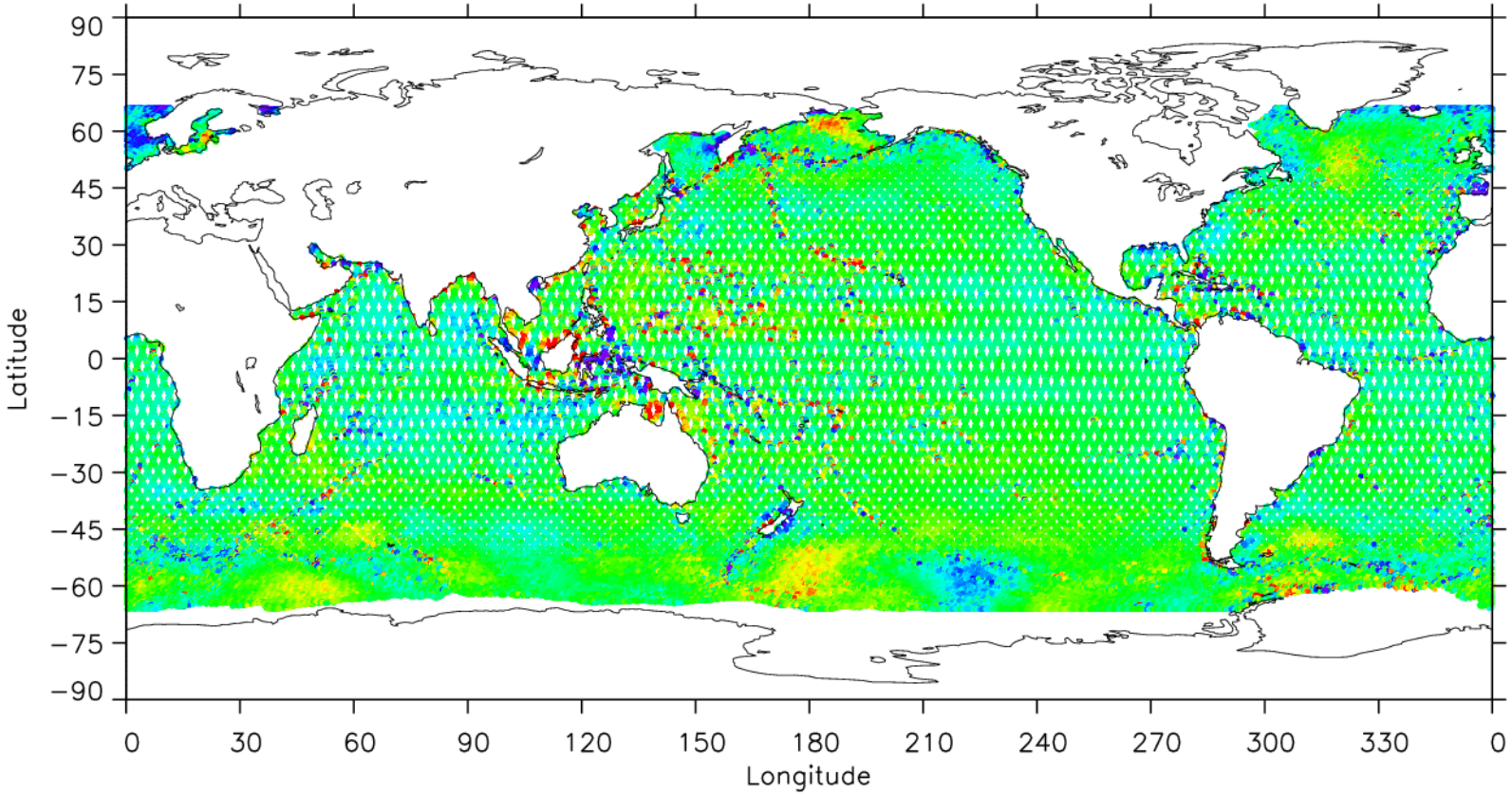
1 Hz Resid. SSH: T/P 6-Year Mean - TEG-4/EGM96 (Nmax=360)

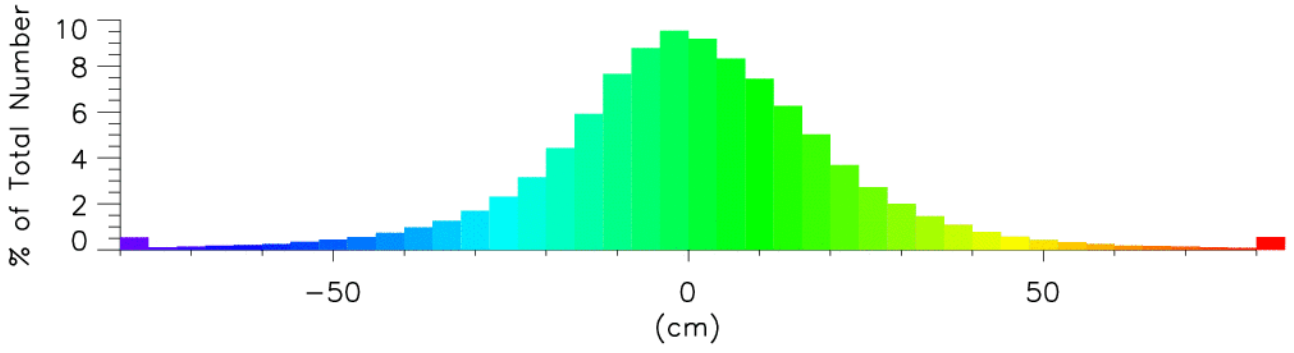




RMS : 26.5736 Mean : 1.12823 Number of Points : 541277 Data Range (-347.532 , 322.775) Color Range : (-80.000000 , 80.000000)
topex.6ymean.rssh_teg4egm96.to360.ps

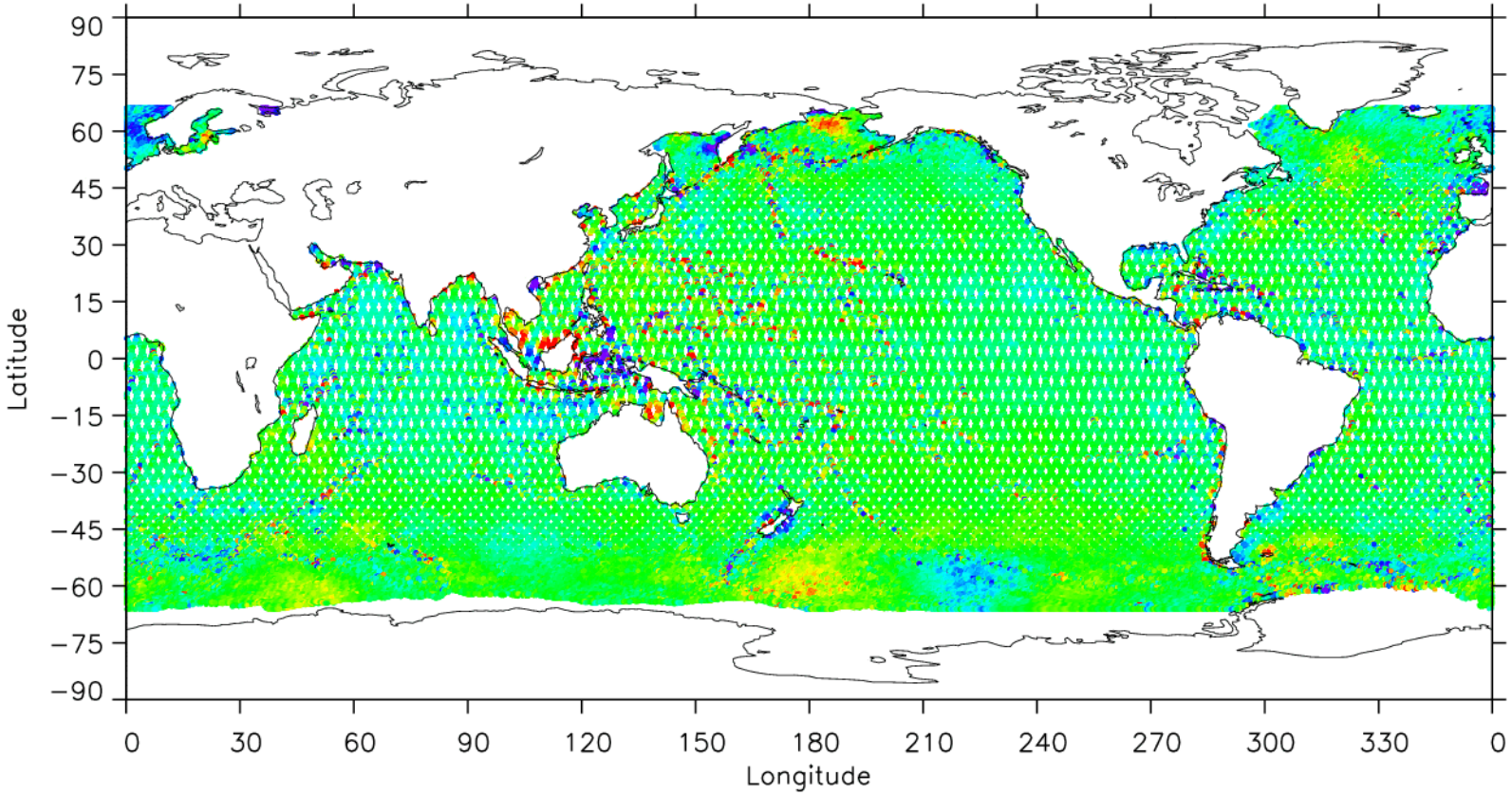
1 Hz Resid. SSH: T/P 6-Year Mean Minus EGM96 (Nmax=360)

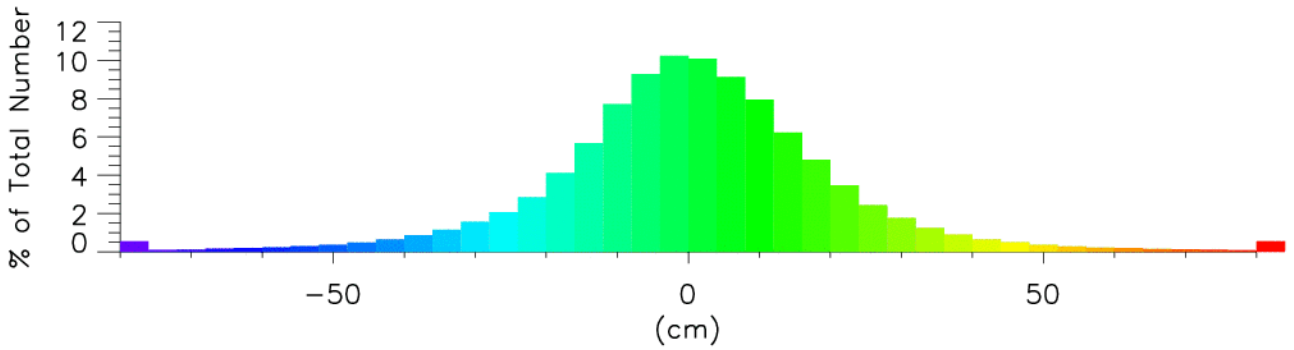




RMS : 23.1393 Mean : 0.645307 Number of Points : 541277 Data Range (−394.869 , 296.000) Color Range : (−80.000000 , 80.000000)
topex.6ymean.rssh_egm96.to360.ps

1 Hz Resid. SSH: T/P 6-Year Mean Minus PGM2000A (Nmax=360)





RMS : 22.3816 Mean : 0.638712 Number of Points : 541277 Data Range (−393.053 , 294.263) Color Range : (−80.000000 , 80.000000)
topex.6ymean.rssh_pgm2000a.to360.ps

Orbit Test Summary

All tests use daily IERS pole series and ITRF96 station locations.
No global parameters are estimated, and the data complement remains consistent for all gravity/tide model combinations (i.e. no ***n*-σ** editting is performed).

Satellite	Arcs	Arc Parameters Adjusted
LAGEOS	Three monthly arcs: 880331, 880430, 880530 10145 SLR observations	state vectors C_R/arc along-track constant EA/15 days **along-track 1-CPR EA/15 days** measurement bias per station per arc
LAGEOS–2	Five 10-day arcs: 951117, 960115, 960423, 960612, 960801 4974 SLR observations	state vectors along-track constant EA/5 days measurement bias per station per arc
Starlette	Eight 10-day arcs: 960702, 960712, 960811, 960830, 960919, 961009, 961029, 961118 10161 SLR observations	state vectors C_R/arc C_D /day
Ajisai	Eight 5-day arcs: 890404, 890409, 890414, 890419, 890424, 890429, 890504, 890509 4801 SLR observations	state vectors C_R/arc C_D /day measurement bias per station per arc
Stella	Five 10-day arcs: 951117, 960115, 960423, 960612, 960801 2953 SLR observations	state vectors C_D/day measurement bias per station per arc
Westpac	Three 10-day arcs: 980903, 980923, 981023 1008 SLR observations	state vectors C_D/day C_R/arc measurement bias for stations 1884, 1893, 7090 per arc Above plus: **along-track 1-CPR EA/5 days**
GFZ–1	One 24-day arc: 960804 Uses new low-altitude drag model 3372 SLR observations	state vector drag scale factor every 8 revs C_R 1 measurement bias per arc Above plus: **along-track 1-CPR EA/arc**
TRMM	Three arcs: 971219 (10 days), 980101 (7 days), 980118 (6 days) Uses new low-altitude drag model 24396 TDRSS Range observations 24731 TDRSS Range-Rate observations	state vectors drag scale factor every 4 revs cross-track C_L per arc range and range-rate biases per pass

Key 1-CPR: 1-cycle-per-revolution EA: empirical acceleration

ORBIT FIT RESULTS

EGM96 tides used in all cases.
RMS of fit in (cm) for range (r), and (mm/s) for range-rate (r-r).

Tracking data residuals from tests estimating 1-CPR accelerations.

	JGM-3	TEG-3	EGM96	PGM2000A	GRIM5-C1	TEG-4
LAGEOS	3.72	3.69	3.46	**3.42**	3.55	**4.24**
LAGEOS-2	3.05	**3.03**	3.05	3.05	3.15	**4.08**
Stella	**12.36**	11.24	6.99	7.34	**5.58**	6.20
Westpac	**10.24**	**6.54**	6.91	7.00	7.42	6.72
GFZ-1	138.01	**274.19**	96.00	89.01	**86.92**	91.73
Starlette	**7.48**	7.14	7.17	7.07	**6.65**	7.31
ERS-1 (SLR)	9.56	**13.21**	6.21	6.82	6.97	**6.18**
ERS-1 (Alt.)	22.11	20.49	**14.28**	15.84	**25.29**	19.65

RED: Worst **BLUE**: Best

ORBIT FIT RESULTS

EGM96 tides used in all cases.
RMS of fit in (cm) for range (r), and (mm/s) for range-rate (r-r).

Tracking data residuals from tests ***NOT*** estimating 1-CPR accelerations.

	JGM-3	TEG-3	EGM96	PGM2000A	GRIM5-C1	TEG-4
LAGEOS	4.81	4.94	4.36	**4.30**	**8.38**	5.28
LAGEOS-2	3.87	3.87	3.89	**3.86**	**5.26**	4.68
Stella	**18.14**	16.03	9.42	9.34	**8.94**	9.03
Westpac	**12.92**	9.35	11.48	9.84	**8.19**	10.39
GFZ-1	160.56	**340.09**	**100.45**	109.84	127.74	138.72
Starlette	**11.26**	10.13	9.96	9.93	**8.99**	10.09
Ajisai	5.37	**5.42**	**5.08**	5.11	5.26	5.13
TRMM (r)	303.16	**360.73**	177.71	**173.20**	243.66	176.36
TRMM (r-r)	6.23	**7.30**	3.91	**3.77**	5.21	3.83

RED: Worst **BLUE**: Best

TOPEX/POSEIDON Orbit Comparisons With JPL Reduced-Dynamic Solutions

With 1-Cycle Per Revolution Empirical Accelerations

Model	SLR RMS (cm)	DORIS RMS (cm/s)	RMS Difference wrt JPL Reduced Dynamic (cm)			
			Radial	Cross	Along	Total
JGM3	3.42	0.0552	2.4	4.1	6.3	8.0
TEG3	3.44	0.0551	2.5	4.3	6.4	8.2
EGM96	3.49	0.0552	2.5	4.7	6.6	8.5
PGM2000A	3.38	0.0552	2.5	4.3	6.6	8.4
GRIM5C1	3.30	0.0552	2.5	4.2	6.7	8.3
TEG4	3.39	0.0552	2.6	4.4	7.2	8.9

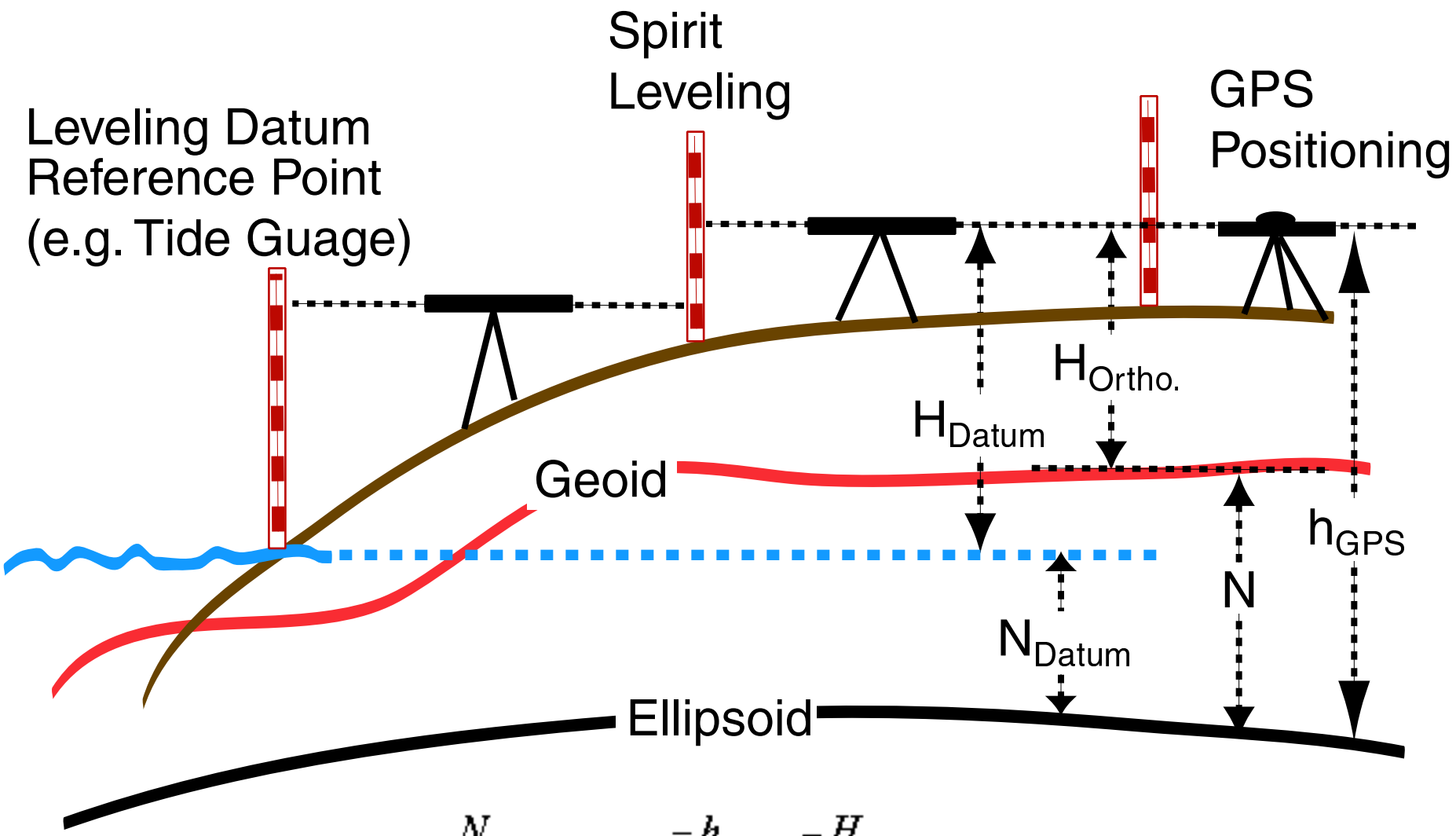
Average result for T/P cycles 10, 19, 21, 46, weighted by number of observations per solution

TOPEX/POSEIDON Orbit Comparisons With JPL Reduced-Dynamic Solutions

Without 1-Cycle Per Revolution Empirical Accelerations

Model	SLR RMS (cm)	DORIS RMS (cm/s)	RMS Difference wrt JPL Reduced Dynamic (cm)			
			Radial	Cross	Along	Total
JGM3	33.5	0.0759	18.4	67.2	46.2	84.4
TEG3	25.0	0.0652	11.0	54.8	33.2	65.7
EGM96	9.6	0.0583	7.0	14.5	19.5	25.8
PGM2000A	11.5	0.0615	9.8	14.4	25.2	30.9
GRIM5C1	34.6	0.1205	38.8	23.3	98.2	108.7
TEG4	15.8	0.0593	7.1	30.3	21.2	39.4

Average result for T/P cycles 10, 19, 21, 46, weighted by number of observations per solution



$$N_{Geometric} = h_{GPS} - H_{Datum}$$

Comparison With GPS/Leveling Geoid Undulations

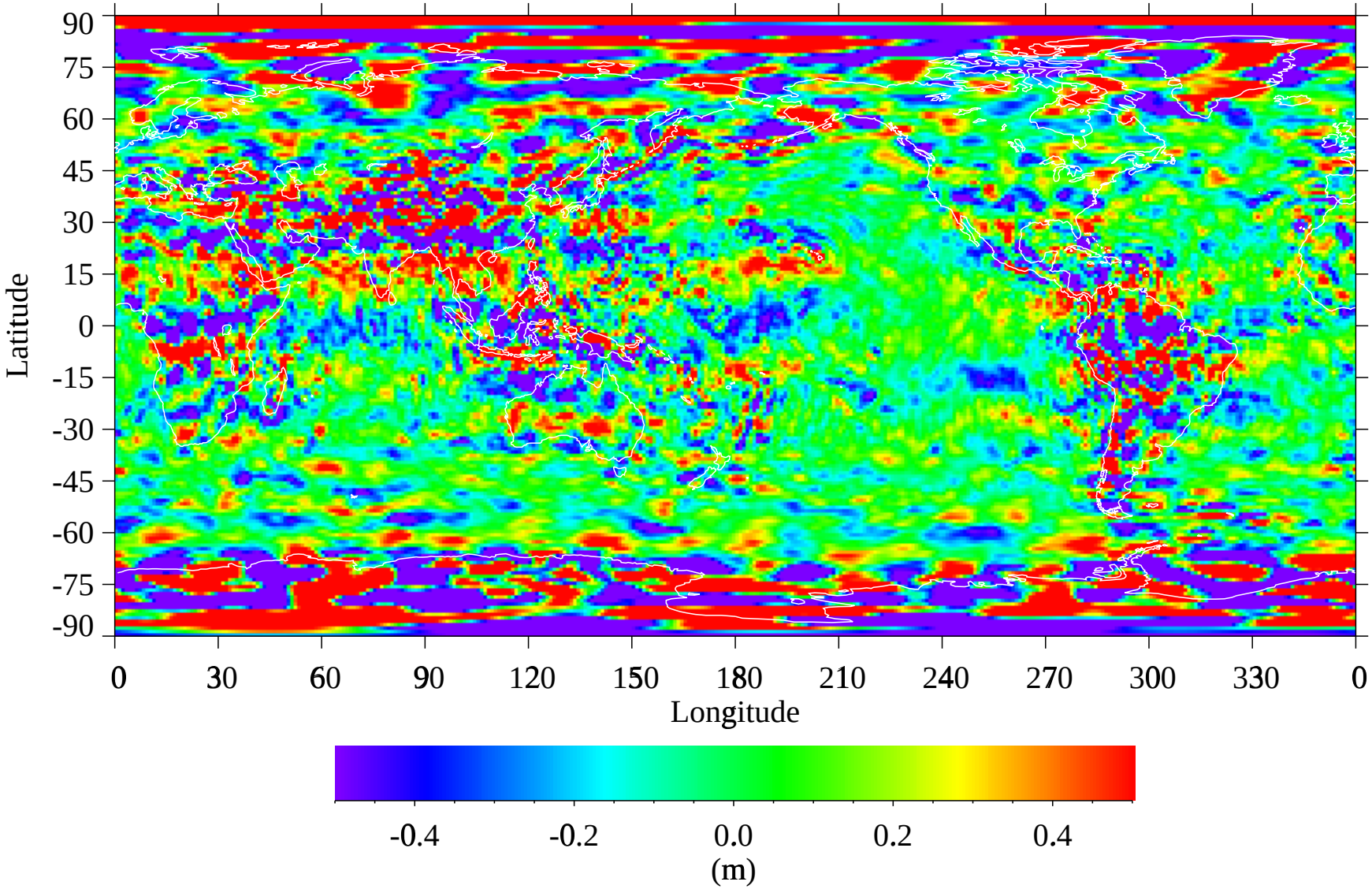
$$\Delta = N_{Geometric} - N_{Model}$$

N_{Model} is computed from each SH model to a specific N_{max}.

S.Dev. is the weighted (by number of points per region) mean standard deviation of Δ, after removing a bias per region.

Model (Nmax)	S.Dev. (cm)
GRIM5-C1 (120)	69.4
GRIM5-C1/EGM96 (360)	40.8
TEG-4 (180)	68.9
TEG-4/EGM96 (360)	**61.2**
EGM96 (360)	**37.2**
PGM2000A (360)	37.7

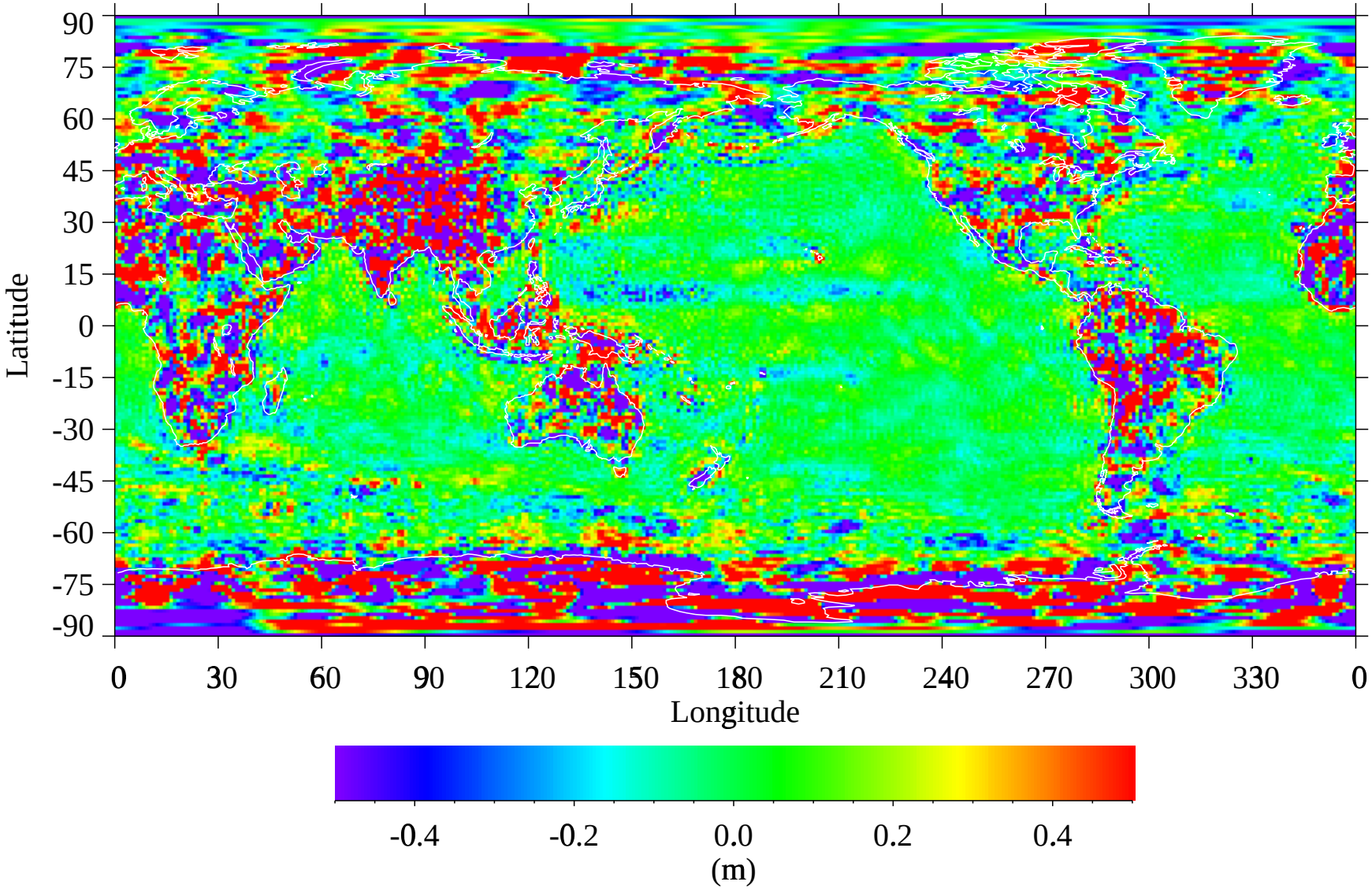
Geoid Undulation Difference: EGM96 - GRIM5-C1 (Nmax=120)



Data Range : (-8.12104 , 5.18864) Color/Contour Range : (-0.500000 , 0.500000) Contour Interval: 0.0800000 Number of Valid Points : 64800 Number of Excluded Points : 0

iundm60.f002t120.egm96-grim5c1.ps1

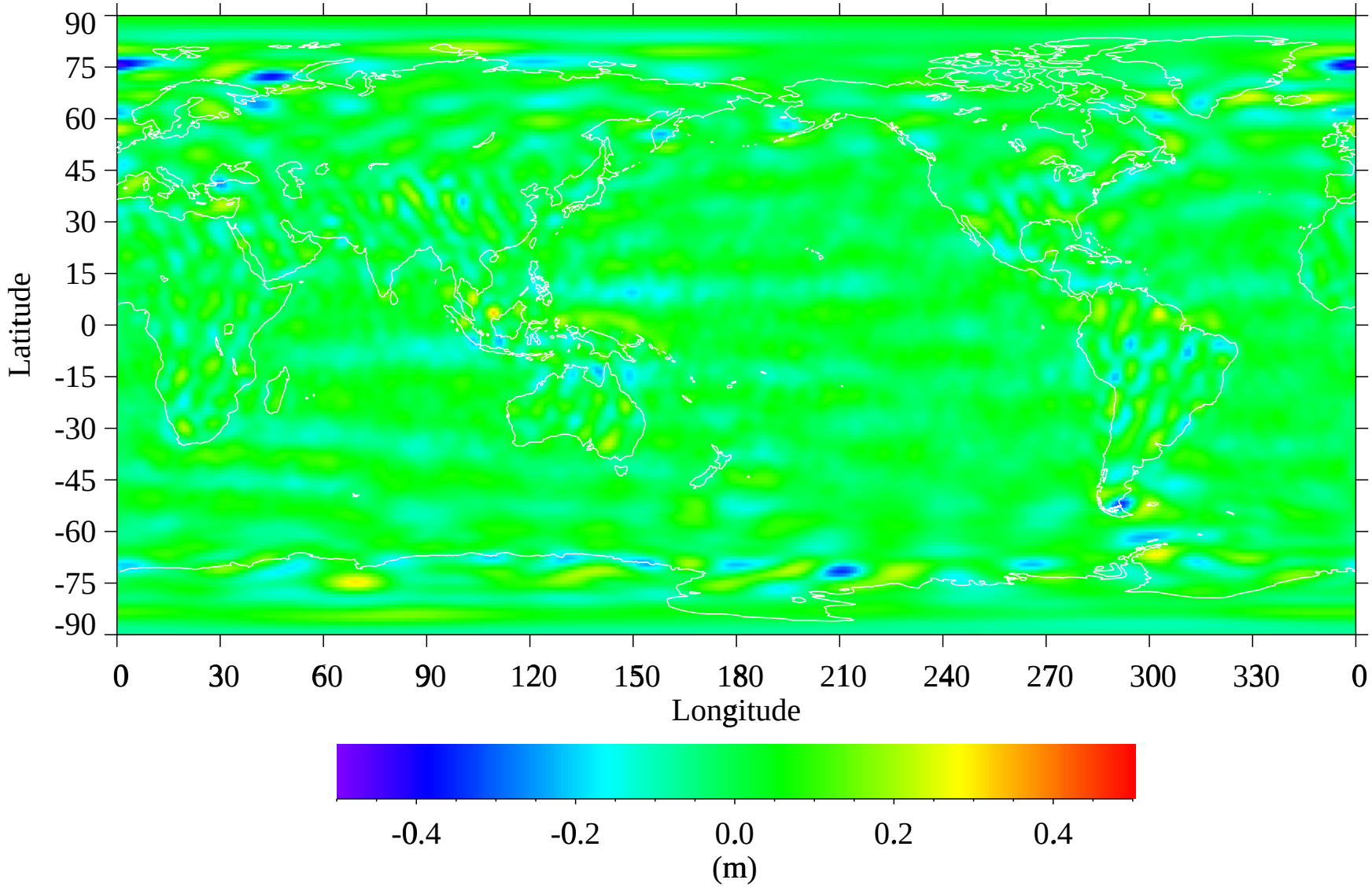
Geoid Undulation Difference: EGM96 - TEG-4 (Nmax=180)



Data Range : (-11.0682 , 11.7240) Color/Contour Range : (-0.500000 , 0.500000) Contour Interval: 0.0800000 Number of Valid Points : 64800 Number of Excluded Points : 0

iundm60.f002t180.egm96-teg4.ps1

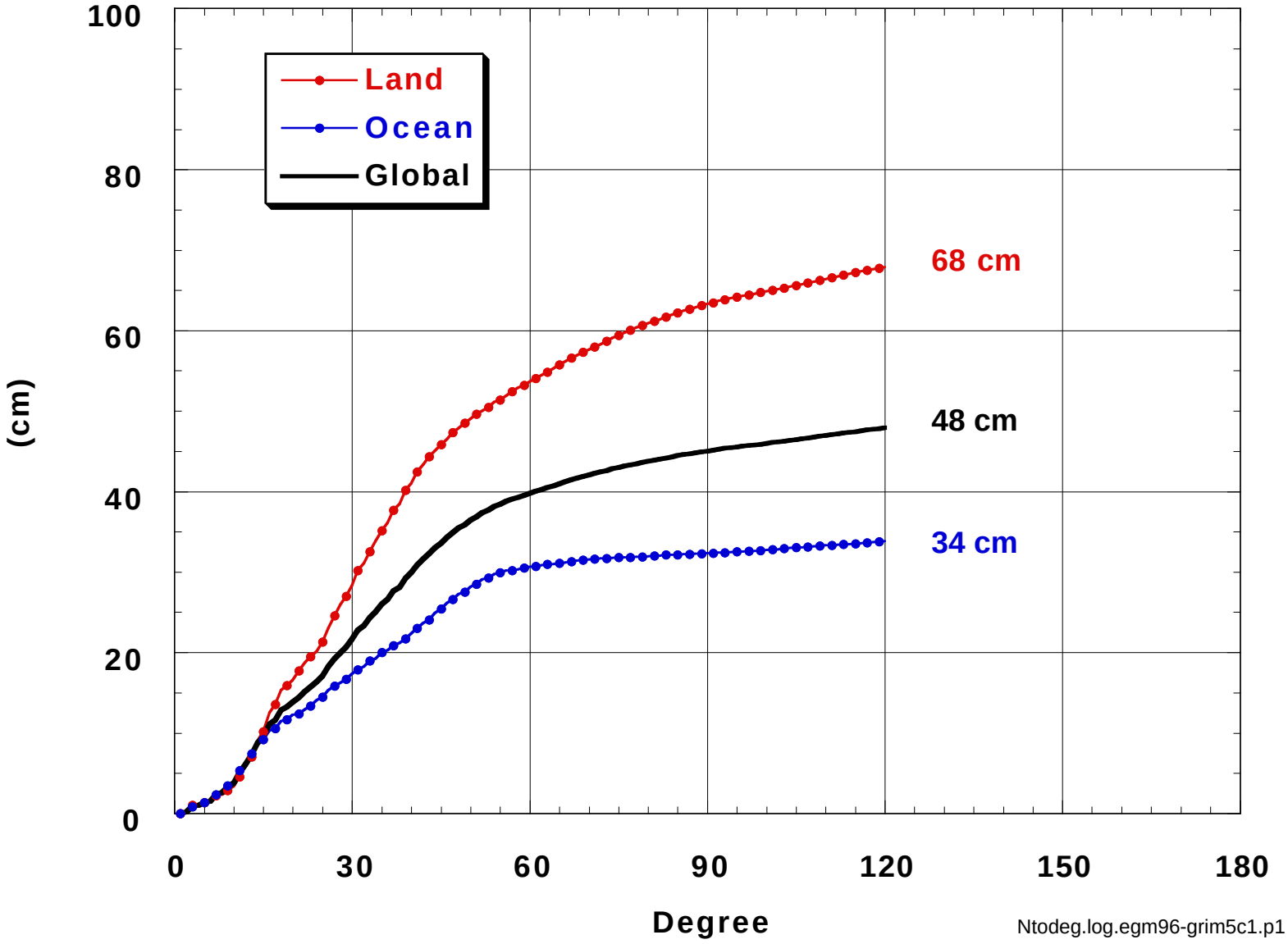
Geoid Undulation Difference: EGM96 - PGM2000A (Nmax=180)



Data Range : (-0.454935 , 0.323812) Color/Contour Range : (-0.500000 , 0.500000) Contour Interval: 0.0800000 Number of Valid Points : 64800 Number of Excluded Points : 0

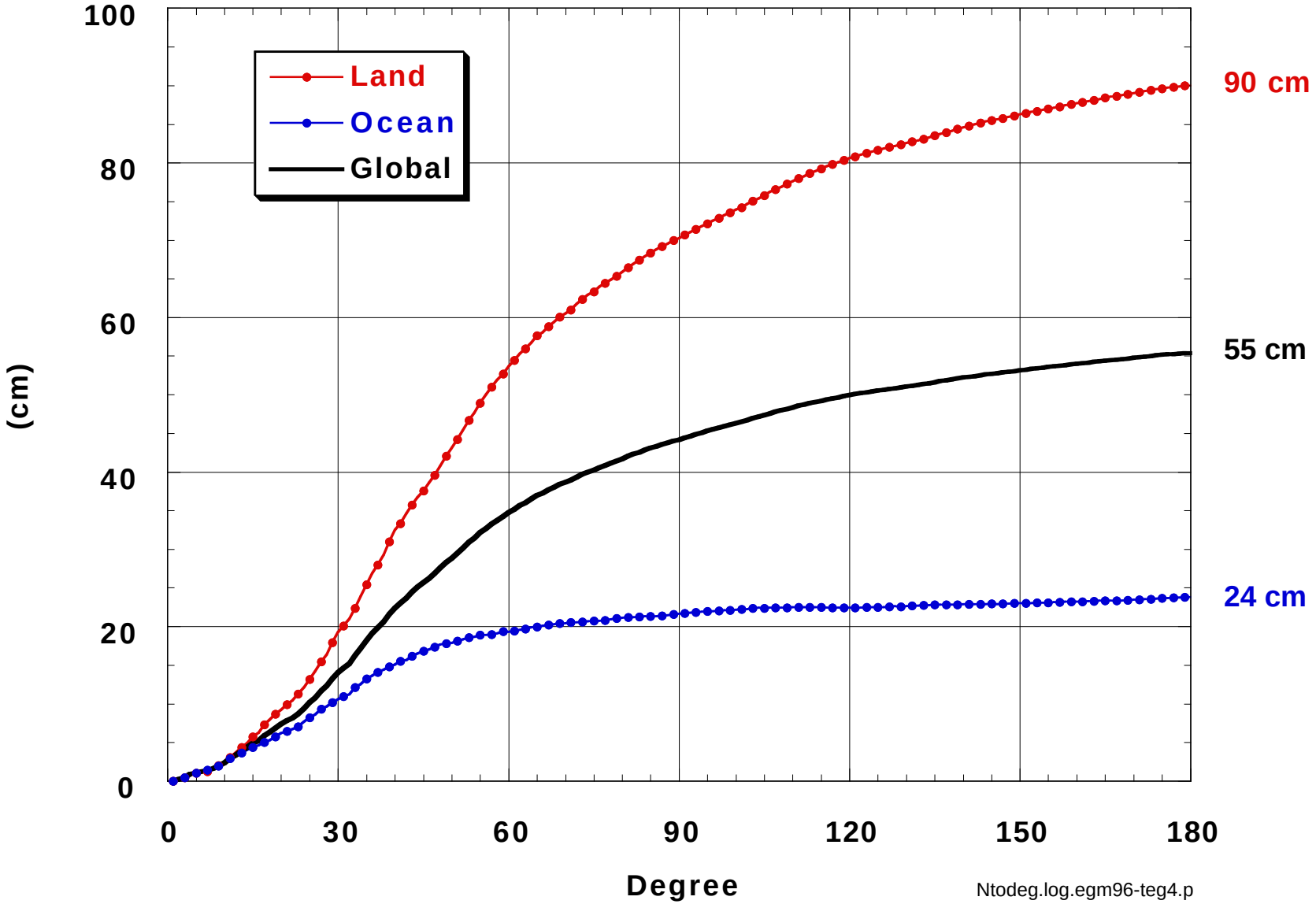
iundm60.f002t180.egm96-n23.ps1

EGM96 - GRIM5-C1
Standard Deviation of Geoid Undulation Differences
(Computed cumulatively)

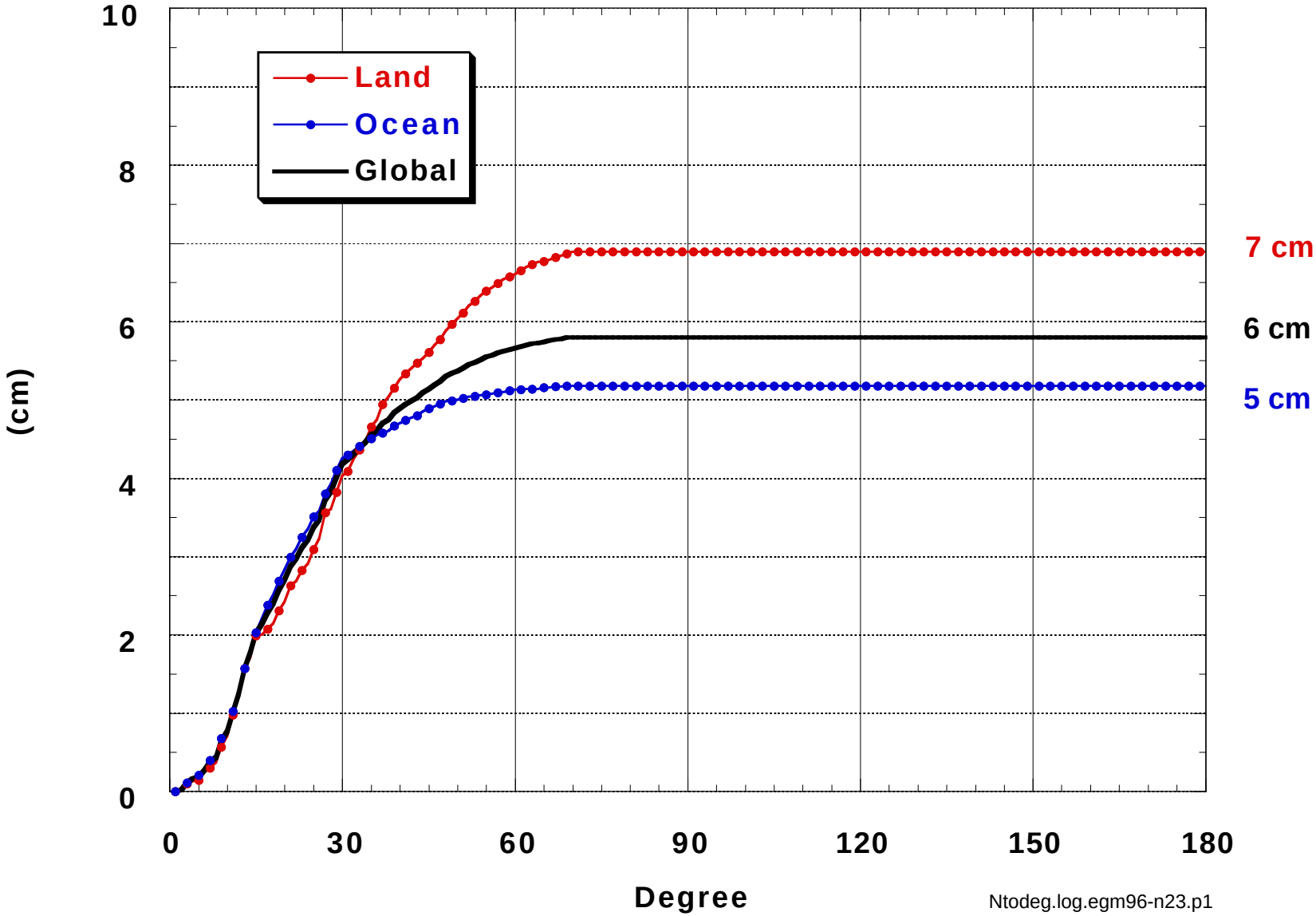


Ntodeg.log.egm96-grim5c1.p1

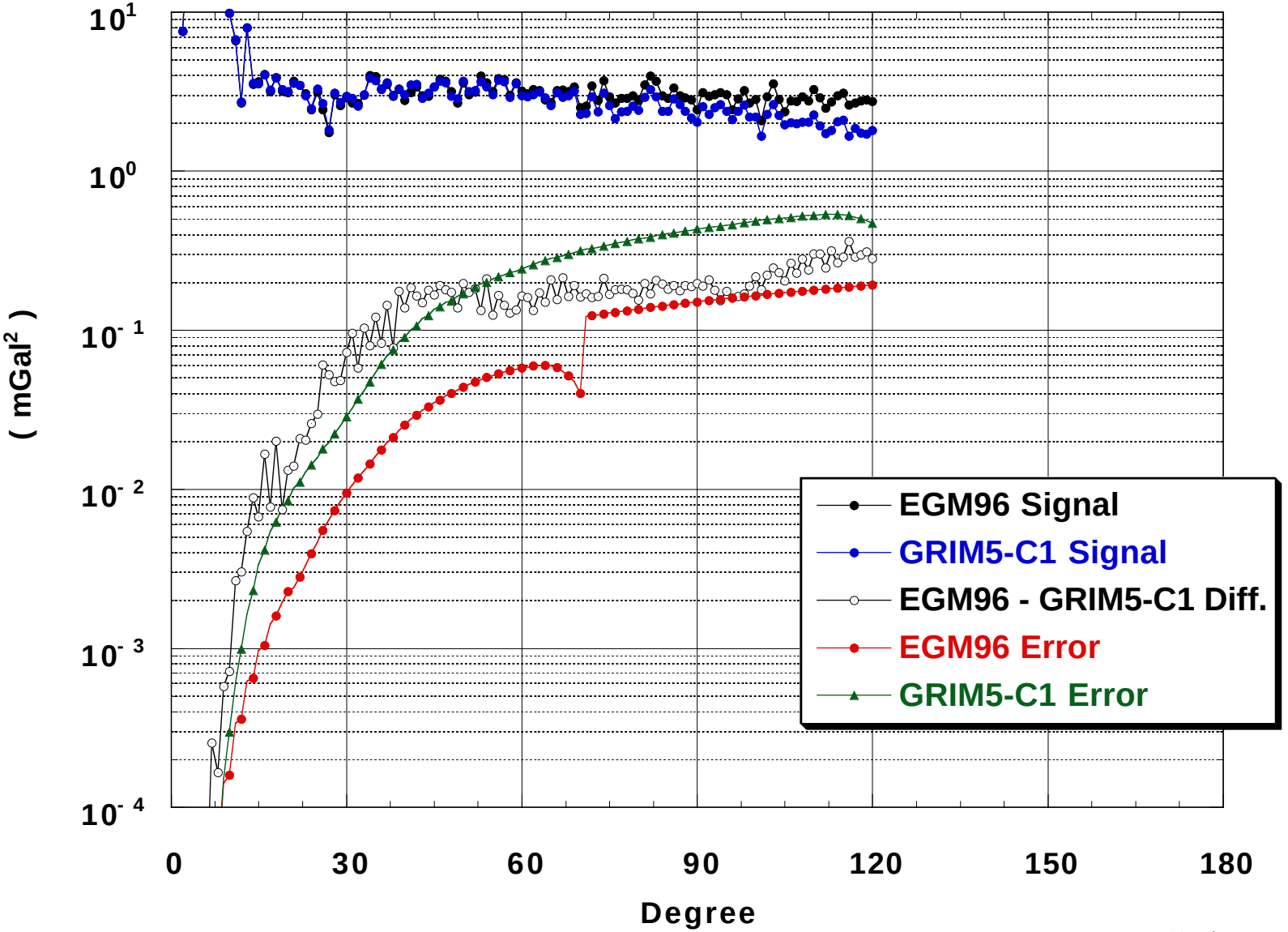
EGM96 - TEG-4
Standard Deviation of Geoid Undulation Differences
(Computed cumulatively)



EGM96 - PGM2000A
Standard Deviation of Geoid Undulation Differences
(Computed cumulatively)

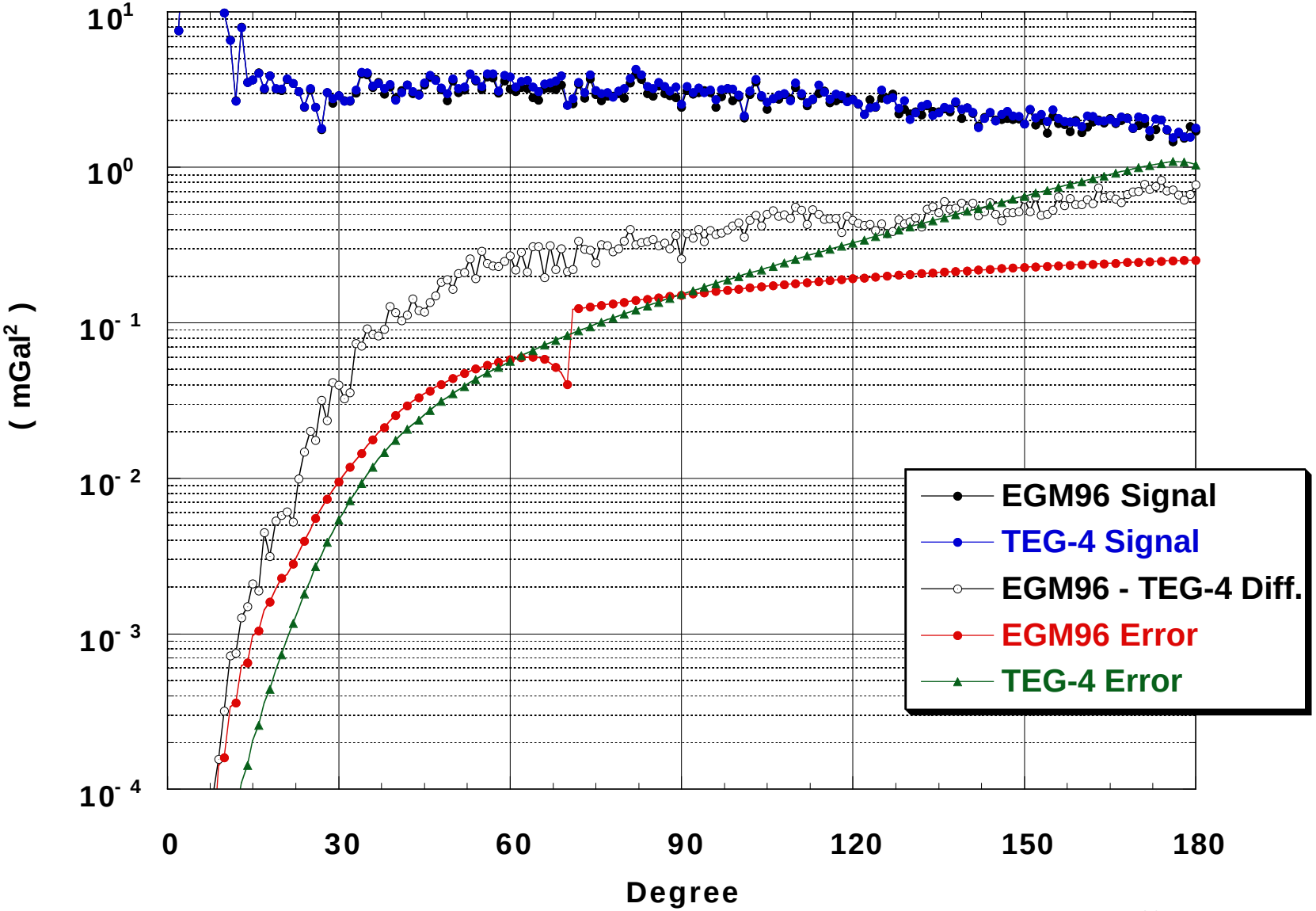


Gravity Anomaly Degree Variances



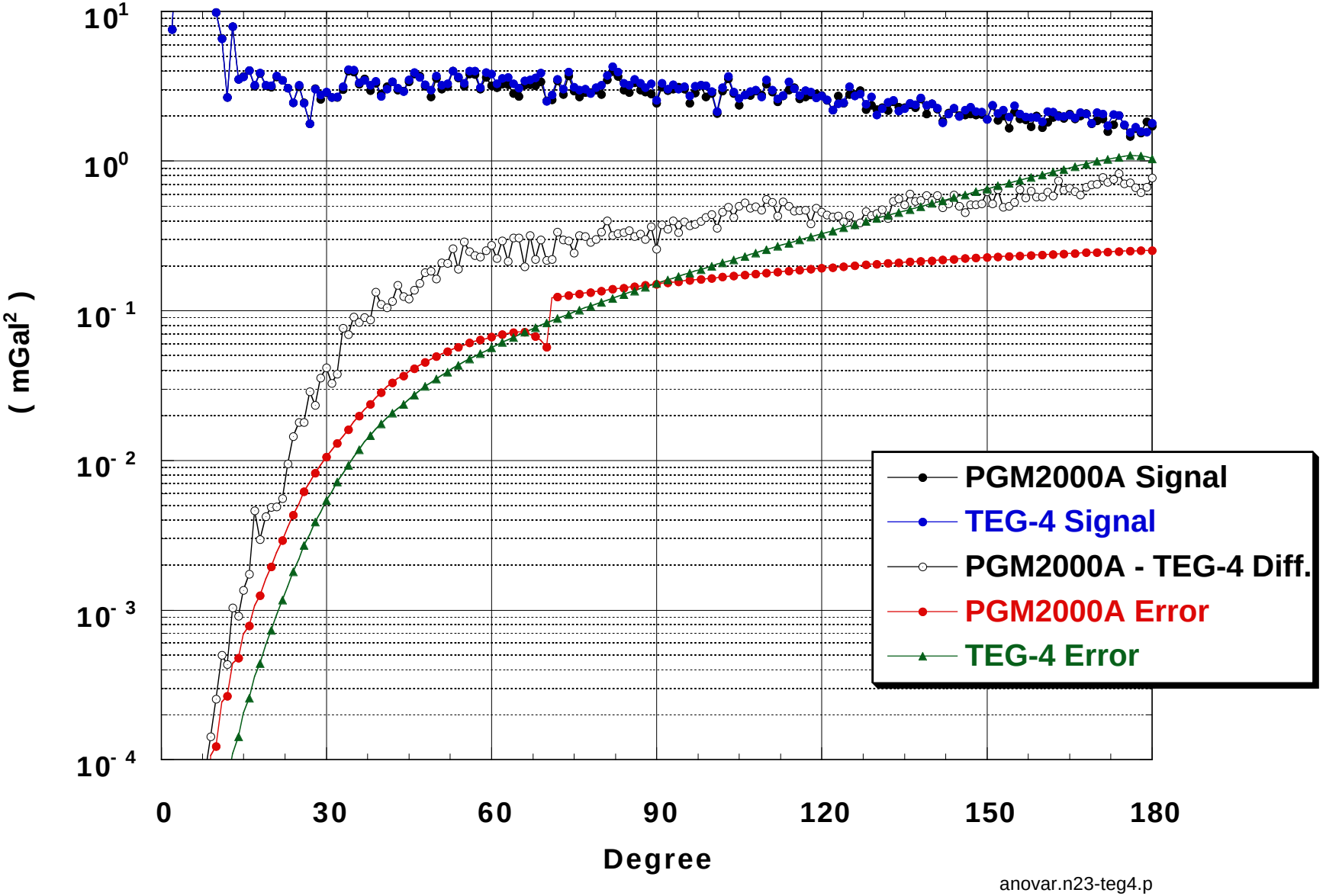
anovar.egm96-grim5c1.p1

Gravity Anomaly Degree Variances



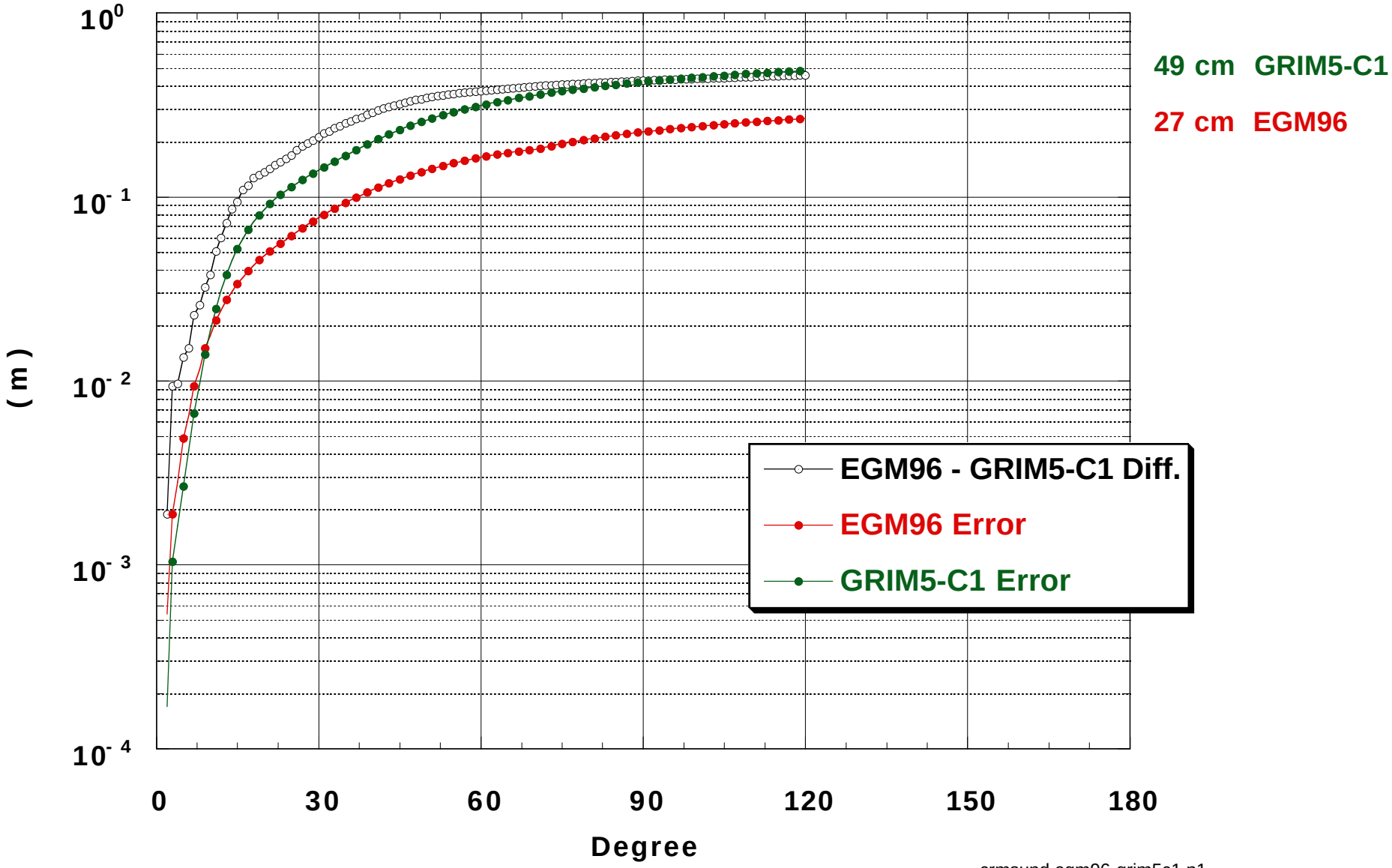
anovar.egm96-teg4.p

Gravity Anomaly Degree Variances



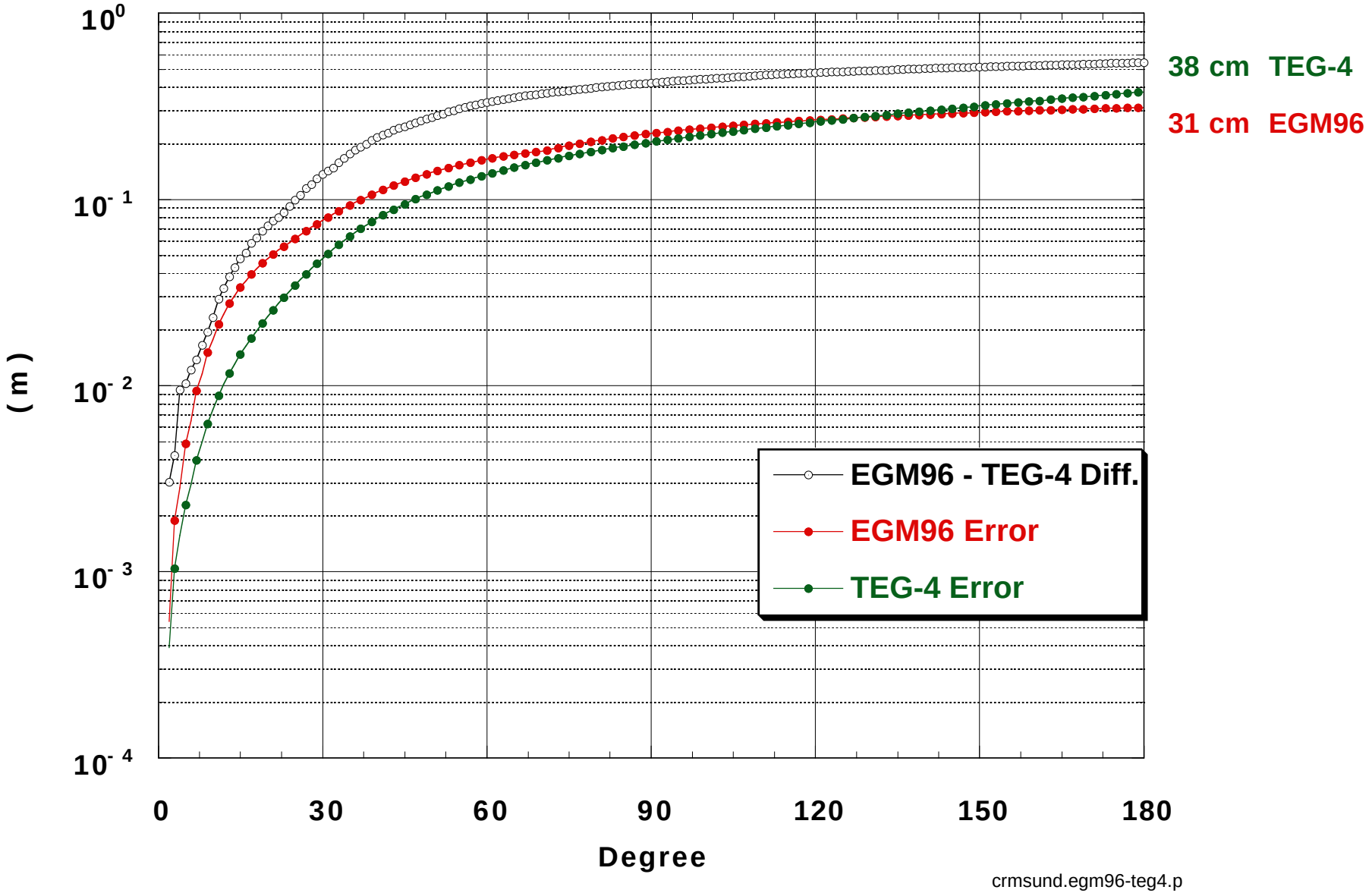
anovar.n23-teg4.p

RMS Geoid Undulation Errors and Differences (Computed cumulatively)



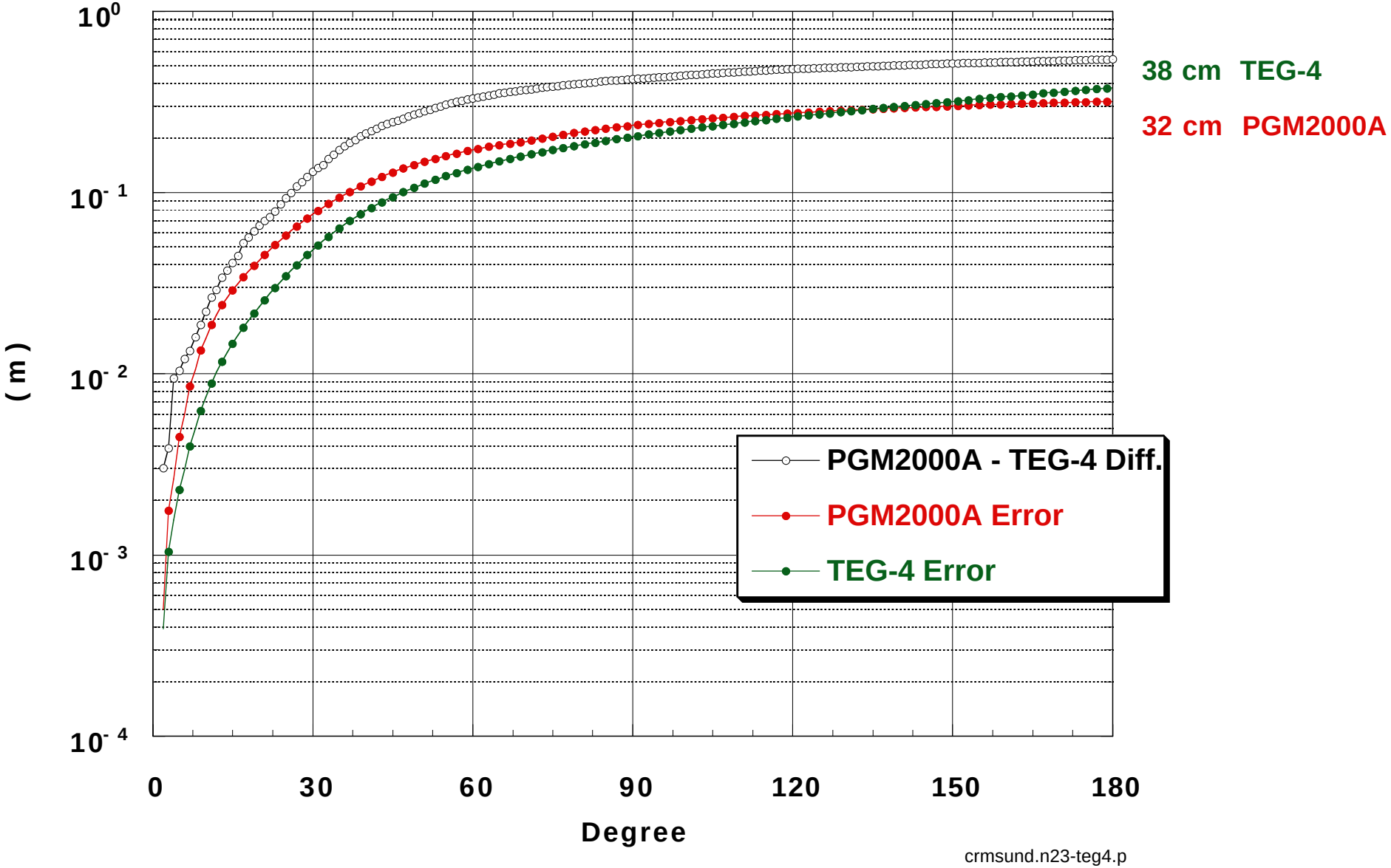
crmsund.egm96-grim5c1.p1

RMS Geoid Undulation Errors and Differences (Computed cumulatively)



crmsund.egm96-teg4.p

RMS Geoid Undulation Errors and Differences (Computed cumulatively)



crmsund.n23-teg4.p

Summary

- Of the gravitational models considered here, EGM96 and PGM2000A support the best overall (marine and land) geoid modeling capability, *at the highest globally available resolution*.
- EGM96 and PGM2000A have comparable orbit modeling capabilities with the other models considered here.
- GRIM5-C1 and TEG-4 result in track pattern artifacts when subtracted from the GSFC00.1 Mean Sea Surface. These artifacts disappear when the TEG-3, EGM96, and PGM2000A geoid models are used.
- GRIM5-C1 and especially TEG-4 perform very poorly in geoid determination over land.
- The error spectrum of TEG-4 makes little (if any) sense.
- *At present, we recommend the **PGM2000A** geoid model, to N_{max}=360, to be used for the Jason-1 GDR preparation.*