

# **MESOSCALE HEIGHT ANOMALIES CAN BE OBSERVED EQUALLY WELL** FROM REPEAT AND NON-REPEAT ORBITS

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We compare sea surface height anomalies observed by satellite altimeters in exact repeat mission orbits to anomalies observed by altimeters in geodetic or drifting orbits. We find no distinguishable differences. One experiment compares data from the drift of TOPEX between its Tandem and Interleaved missions to repeat-orbit data from Jason-1, ERS-2 and GFO. A second experiment compares data from the ERS-1 non-repeating Geodetic Phases E and F to the repeating TOPEX data. Both studies cover the North Atlantic from 0° to 82°W and 15° to 55°N in order to sample both the Gulf Stream and quieter regions. Height anomalies are obtained along repeat and nonrepeat orbits alike by use of a mean sea surface model. Each experiment is performed twice, once with the EGM2008 and once with the DNSC08 models, showing that the results are model-independent; DNSC08 yields an insignificant 2 mm lower RMS misfit. To compare anomalies between repeat and non-repeat orbits with different spatio-temporal sampling we grid the 1-Hz along-track point data and interpolate the grid to point values. RMS differences between grids and point values are around 4 cm in quiet areas and 6 cm over the entire region, with negligible difference between misfits to repeat and non-repeat data. A grid built solely from ERS-1 geodetic data captures at least 85% of the variance in repeat-track TOPEX point data. Ground tracks of drifting or geodetic orbits can repeat within a mesoscale correlation length at regular intervals. Geosat's geodetic orbit repeated within 50 km every 23 days, and ERS-1's geodetic phases repeat within 82, 66 and 17 km every 17, 20 and 37 days.

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### Mesoscale ocean dynamics observed by satellite altimeters in non-repeat orbits

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We compare sea surface height anomalies observed by satellite altimeters in exact repeat mission orbits to anomalies observed by altimeters in geodetic or drifting orbits. We find no distinguishable differences. One experiment compares data from the drift of TOPEX between its Tandem and Interleaved missions to repeat- 3 mm/km confined to half wavelengths shorter than 10 km [Sandwell orbit data from Jason-1, ERS-2 and GFO. A second experiment and Smith, 2008]). One may now obtain SSHA by subtracting from compares data from the ERS-1 non-repeating Geodetic Phases E the SSH profile a model geoid or mean sea surface (MSS) such as the and F to the repeating TOPEX data. Both studies cover the North Atlantic from 0° to 82°W and 15° to 55°N in order to sample both the Gulf Stream and quieter regions. Height anomalies are obtained so may be closer to the true background SSH than any average of along repeat and non-repeat orbits alike by use of a mean sea sur-profiles from one ERM orbit alone. SSHA referred to a geoid rather face model. Each experiment is performed twice, once with the than a MSS should contain the total dynamic ocean signal. The EGM2008 and once with the DNSC08 models, showing that the results are model-independent; DNSC08 yields an insignificant 2 mm Altimeter measurements of SSH have many applications, but one lower RMS misfit. To compare anomalies between repeat and non- may group these into three broad areas: (1) high spatial resolution repeat orbits with different spatio-temporal sampling we grid the geodesy for inertial navigation and reconnaissance bathymetry; (2) RMS differences between grids and point values are around 4 cm in quiet areas and 6 cm over the entire region, with negligible difor geodetic orbits can repeat within a mesoscale correlation length at regular intervals. Geosat's geodetic orbit repeated within 50 km and 17 km every 17, 20 and 37 days.

We believe this data processing scheme is no longer required for recovery of some SSH signals. Mesoscale SSHAs have much larger amplitudes and spatial scales [Jacobs et al., 2001] than present radial orbit errors (order 2 cm, [Scharroo, 2002; Luthcke et al., 2003]) or the now unknown part of the marine geoid (gradients of 2 to EGM2008 [Pavlis et al., 2008] or DNSC08 [Andersen and Knudsen 2008] models. This approach has several advantages. The model synthesizes results assimilated from many satellite missions, and model can be evaluated at any point so that SSHA can be obtained anywhere, not only along ERM tracks.

1-Hz along-track point data and interpolate the grid to point values. mesoscale dynamic topography for ocean currents and eddies; and (3) larger-scale and long-term variations related to planetary waves and other climate phenomena. The launch of Jason-2/OSTM in June 2008 onto the 10-day ERM track established by TOPEX meets the ference between misfits to repeat and non-repeat data. A grid built climate objective for the next several years. However, that orbit solely from ERS-1 geodetic data captures at least 85% of the vari- is a poor choice for the mesoscale objective [Jacobs et al., 2001] ance in repeat-track TOPEX point data. Ground tracks of drifting and cannot satisfy the geodesy objective. All the other altimeters currently operating are near or beyond their designed life, and it is expected that spatio-temporal resolution of the mesoscale eddy field will decline in the future unless some other satellite mission every 23 days, and ERS-1's geodetic phases repeat within 82, 66 is launched. Envisat may be directed into a drifting orbit, as its fuel is likely to run out before its instruments fail. In this paper, we demonstrate that an altimeter in a drifting or geodetic orbit can observe the mesoscale SSHA field.

are the "TOPEX Drift" (July to October, 2002) and "ERS-1 Geode-

tic Phase" (April 1994 to March 1995) analyses described below.

#### 1. Introduction

The Geosat, ERS-1, TOPEX/Poseidon, ERS-2, GFO, Jason-1, Envisat and Jason-2/OSTM radar altimeter missions together have collected more than 63 satellite-years of sea surface height (SSH) observations, all but 2.4 of them in exact repeat and frozen orbits that repeatedly overfly the same set of ground tracks within ±1 km. At the time when the first exact repeat mission (ERM) was designed [Born et al., 1987], little was known of the marine geoid and large eographically correlated radial orbit errors were common in satelte ephemerides. These conditions necessitated the altimeter data

2. Data Analysis One cannot compare the SSHA recovered from a non-ERM path to what would have been obtained if the same observing system had been on an ERM path at the same time. Instead we must compare SSHA from an altimeter on a non-ERM path to SSHA obtained over the same time interval by another altimeter on an ERM path. Two opportunities to do this have occurred, and we examine both; these

cover the same large area of the North Atlantic

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sampling and aliasing of SSH signals, with no one of them adequate track so that it could drift towards a new 10-day ERM ground track to fully sample all the mesoscale SSH variability [Jacobs et al., spatially interleaved with the original 10-day ERM track. The drift-2001]. In particular, the gaps between adjacent ground tracks in ing was begun on 15 August and completed on 16 September 2002. the TOPEX and Jason-1 orbits are much larger than the typical size After reaching the new ground track, TOPEX was maneuvered to of mesoscale eddies, and so one must expect that during the Drift keep operating as a 10-day ERM on the newly achieved ground and Interleaved periods TOPEX sampled eddy SSHA not sampled by Jason-1, and vice-versa. To control for this and obtain the most

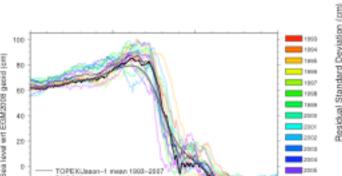
appropriate comparisons, we first build a space-time grid of SSHA data from those satellites whose space-time sampling is closest to polate the grid to the along-track sample points of all the satellites Jason-1 was also operating throughout this time on the 10-day ERM and examine the SSHA differences between observed point data and track originated by TOPEX, one can compare the performance of interpolated and gridded data. This allows one to compare height TOPEX against Jason-1 in all three (Tandem, Drift, and Interleaved) differences due to drifting or ERM orbits against height differences periods, to rule out anomalies in TOPEX's performance during these

In both experiments our grids have steps of 0.25° in latitude and longitude and 3 days in time, covering the North Atlantic from 0° to 82°W and 15° to 55°N. For the TOPEX Drift experiment the grid is built using only ERS-2 35-day and GFO 17-day ERM data in the interval from 2 July to 30 October 2002. In the ERS-1 Geodetic Phases experiment the grid is built using only drifting ERS-1 geodetic orbit data, in the interval from 17 April 1994 to 10 March 1995. In each case the grid values are initialized by a simple weighted average of the along-track point SSHA data, using weights that are Gaussian functions of space and time with e-folding scales of 7 days and 1° of spherical angle. After initialization the residuals (difference of the point data and the initialized grid) are formed and weighted with e-folding scales of 7 days and 0.5° of distance, and the weighted residual is added to each grid point. This simple gridding method is fast to compute and may approximate objective interpolation using Gaussian covariance functions for the mesoscale [Jacobs et al., 2001] if slow westward advection of eddies is ignored.

#### 2.1. TOPEX Drift Period

due merely to smoothing and gridding.

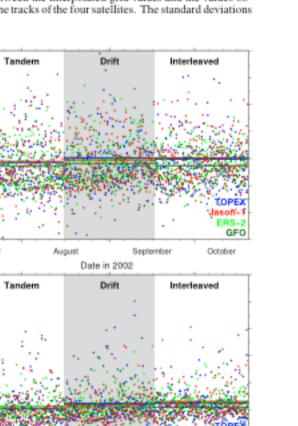
TOPEX/Poseidon was launched in 1992 into a 10-day ERM orbit selected for its crossing angles and tidal aliasing properties [Fu et al., 1991]. Later, Jason-1 (2001) and Jason-2/OSTM (2008) were launched to follow the same ERM track established by TOPEX. In the first 6.5 months after the launch of Jason-1, TOPEX and Jason-1 made SSH observations one minute apart along the same ground track in a Tandem Mission. After completion of the tandem mission TOPEX was maneuvered off of the established 10-day ground



track. This Interleaved Mission lasted until the end of the TOPEX This sequence of events allows one to compare SSHA signals observed by TOPEX in a 10-day ERM (the Tandem or Interleaved missions) with those it observed during the Drift period, when its optimal according to Plate 9 in Jacobs et al. [2001]. We then inter-

periods. Both TOPEX and Jason-1 are dual-frequency altimeters with ancillary water vapor radiometers, and these systems are considered the "gold standard" in physical oceanography

We interpolated the ERS-2+GFO SSHA grids to the 1-Hz alongtrack sample points of ERS-2, GFO, TOPEX and Jason-1 by linear interpolation in latitude, longitude and time, and then formed the differences between the interpolated grid values and the values observed along the tracks of the four satellites. The standard deviations



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of these height differences on each pass are plotted in Figure 2, for tenths of a millimeter from one interval to another, but there is no both the entire area analyzed and also a sub-area restricted to the obvious increase due to the drifting orbit. The results do not depend southern half of the grid (15° to 35°N only); the southern portion on the mean sea surface model used. DNSC08 gives lower RMS samples a quiet area of the ocean and excludes the energetic eddies values than EGM2008, but only by an insignificant 2 mm or so. We of the Gulf Stream. We also formed the root sum of squares of the find no essential difference between the ERM and non-ERM SSHA individual pass standard deviations in order to form an overall root observations of TOPEX. mean square magnitude of the residual height for each satellite dur-

#### ing the Tandem, Drift and Interleaved periods; these are shown as 2.2. ERS-1 Geodetic phases

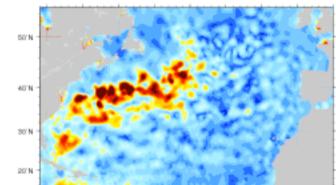
horizontal lines in Figure 2 with numerical values given in Table 1. The TOPEX standard deviations and overall rms appear essendem, Drift, and Interleaved. The overall rms values change by a few

Table 1. RMS along-track SSHA residual with respect to the ERS-2 + GFO grid before ("Tandem"), during ("Drift"), and after ("Interleaved") the TOPEX drift phase in 2002, in centimeters. Values before / after the slash are obtained with the EGM2008 / DNSC08 mean sea surfaces, respectively.

Altimeter Tandem Drift Interleaved All North Atlantic TOPEX 5.88/5.70 6.06/6.06 6.00/5.95 Jason-1 5.94/5.78 6.04/5.89 6.25/6.04 5.91/5.77 6.03/5.90 6.23/6.07 5.35/5.43 5.56/5.62 5.45/5.48 North Atlantic south of Gulf Stream TOPEX 4.30/4.04 4.60/4.46 4.57/4.44 4.37/4.12 4.57/4.36 4.82/4.56 4.39/4.24 4.56/4.48 4.74/4.61 3.92/4.05 4.12/4.21 4.13/4.17

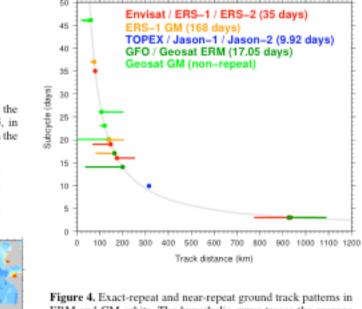
Table 2. RMS along-track SSHA residual with respect to the ERS-1 grid during the ERS-1 Geodetic Mission of 1994-5, in centimeters. Values before / after the slash are obtained with the EGM2008 / DNSC08 mean sea surfaces, respectively.

All North Atlantic South of Gulf Stream TOPEX/Poseidon 6.55/6.38 4.94/4.73 5.28 / 5.21 4.07/4.07



From April 1994 to March 1995 the ERS-1 altimeter was moved tially the same as those of Jason-1, in all three time intervals, Tan- off of its usual 35-day ERM track into a geodetic orbit. ERS-1 geodetic Phases E and F were described as two interleaved exact repeats of 168 days each but were effectively non-repeat orbits by oceanographic standards. At the same time, TOPEX remained in its 10-day ERM orbit. During ERS-1's geodetic phases its nodal period differed from the 35-day ERM period by less than 3 parts per housand, and so the space-time sampling of the geodetic phases was also nearly ideal for mesoscale sampling by a single altimeter [Jacobs et al., 2001].

We interpolated the SSHA grids built from the ERS-1 geodec phase data to the 1-Hz along-track sample points of ERS-1 and TOPEX, and compared the differences as in the TOPEX Drift experiment above. The standard deviations of the differences are shown



ERM and GM orbits. The hyperbolic curve traces the average Equatorial spacing between ascending tracks as a function of the repeat cycle time for an 800 km altitude orbit. Colored dots without horizontal bars indicate ERM orbits. Dots with horizontal bars indicate near-repeat sub-cycles in 800 km orbits. The bar's extent to the left (respectively, right) indicates the westward (respectively, eastward) drift of the ground track pattern during each sub-cycle.

may be quite arbitrary, due to inter-annual variations in SSH (Figure 1. Sea surface height in cm above the EGM2008 geoid ure 1). Figure 1. Sea surface height in cm above the EGM2008 geoid along TOPEX and Jason-1 ascending ground track #217 cross-   figure 1. Sea surface height in the Radar Altimeter Database System, with all corrections Figure 1. Sea surface height in cm above the EGM2008 geoid along TOPEX and Jason-1 ascending ground track #217 cross-			
may be quite arbitrary, due to inter-annual variations in SSH (Fig- ure 1). Figure 1. Sea surface height in cm above the EGM2008 geoid along TOPEX and Jason-1 ascending ground track #217 cross-	at time Equatorial East(+) or W	éest(-) # of revs	
surface models removed. measured by TOPEX (1993-2007): the each of the three periods Tandem. Drift or Interleaved, as given gridded ERS-1 SSHA over the 11 months of the ERS-1 sequence 37.000	(days)   spacing (km)   step (     2.996   926.760   149     17.002   164.274   -82     19.998   139.142   66     37.000   75.361   -16     74.001   37.696   -33     31.000   21.268   16	(km)   per sub-cycle     9.316   43     2.953   244     6.363   287     6.591   531     3.181   1062     6.591   1880     0.000   2411	

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in Table 2. The root-sum-of-squares amplitude of these differences row of Table 3, were it not for the fact that the satellite was then between TOPEX 10-day ERM and ERS-1 Geodetic Phase are only moved to an interleaving track with the same repeat period. slightly higher than those obtained for ERS-2+GFO versus TOPEX Geodetic orbits differ from traditional oceanographic exact reor Jason-1, despite the fact that, in this case, the grid was built from peat orbits by only a few parts per thousand in the nodal period. one satellite in a GM orbit rather than two satellites in ERM orbits, ERS-1 operated conventional ERMs of 43 revolutions in 3 days and ERS-1 was a one-frequency altimeter and had a different ancil- and 501 revolutions in 35 days; 43/3 and 501/35 differ by 0.13%, lary radiometer, and some oceanographers would consider its data 2411/168 and 43/3 differ by 0.12%, and 2411/168 and 501/35 differ to be inferior to those of TOPEX. by 0.25%. Any spacecraft having the propulsion system to maintain an ERM orbit can easily maneuver between an ERM and a geodetic orbit. It should be possible to design a geodetic orbit which is rich

#### 3. Discussion

We have compared ERM and non-ERM SSHA recovery by smoothing some of the data onto grids and then interpolating the GFO in Table 1 and ERS-1 in Table 2 compare the smoothed and were built, while the values for TOPEX and Jason-1 in those Tables smoothing by weighted averaging onto the grid, the error in inter- enough for new geodesy while repeating closely enough for mesoscale obtide models, and path delay and sea state corrections applied to the of NOAA or the U.S. Government. raw altimeter data. Since we have not applied any arc adjustment to the individual passes, at least 2 cm of these differences must be due to orbit error. We have also lumped on-board tracked data (TOPEX References and GFO) with retracked data (ERS-1, ERS-2, Jason-1). These numbers should be compared to the 3.5 to 3.7 cm RMS error ex- Andersen, O. B., and P. Knudsen, The DNSC08MSS global mean pected for 1-Hz samples of on-board tracked TOPEX and retracked

Jason-1 SSH [Chambers et al., 2003]. One may also compare the RMS mesoscale signal amplitude in Born, G. H., J. L. Mitchell, and G. A. Heyler, Geosat-ERM mission design, along-track data to that obtained by averaging the grids. The more interesting case is the ERS-1 Geodetic Phase experiment, where the grid is built from geodetic orbit tracks; the overall RMS amplitude of the grid is 9.9 cm, while the RMS amplitude of the SSHA along Fu, L.-L., E. Christensen, and M. Lefebvre, TOPEX/Poseidon: Observing the TOPEX ERM tracks is 11.3 cm over the same area and interval. If we subtract (3.6 cm)<sup>2</sup> from the along track variance to account for SSHA signal is estimated to be 10.7 cm. Since (9.9/10.7)2 is slightly more than 85%, our gridding of non-ERM SSHA seems to capture Luthcke, S. B., N. P. Zelensky, D. D. Rowlands, and F. G. Lemoine, The 1around 85% of the variance in the along-track TOPEX SSHA data, despite the facts that the two satellites have different space-time sampling of SSH, our gridding was sub-optimal for mesoscale signals and was not designed to interpolate signals with other correlation scales, and our grid was built from a non-ERM orbit. Since the mesoscale signal is much larger (>30 cm) in energetic areas (Fig-Monaldo, F. M., and D. L. Porter, On combining bathymetric and ocean ure 3), the gridding of the non-ERM ERS-1 data has surely captured much more than 85% of the mesoscale energy.

Drifting or geodetic orbits can repeat within a mesoscale eddy correlation distance at regular intervals (Figure 4). The Geosat GM, for example, repeated within 50 km every 23 days, and the ERS-1 GM had several near repeats (Table 3), with the 20-, 17- and 37day near repeats being the most useful for mesoscale studies. The Equatorial track spacing in Table 3 is the average distance between ascending tracks at the Equator, and is simply the circumference of the Equator divided by the number of orbits in an exact-repeat or near repeat sub-cycle lays down a fixed network of tracks, but with each sub-cycle the network drifts east or west by some km, rather than repeating exactly. For example, one row of the Table shows Sandwell, D. T., and W. H. F. Smith, Global marine gravity from retracked that after 244 revolutions, taking 17.002 days, the ERS-1 geode-

Acknowledgments. This work builds on earlier unpublished studies comparing gridded Gulf Stream eddy SSHA fields obtained from smooth grids to point data. The RMS residuals from ERS-2 and TOPEX and ERS-1 during the latter's Geodetic Phases. Our animation comparing the fields replaced the ERS-1 radiometer's wet path deinterpolated gridded values to the point data from which the grids ABySS-Lite mission's lack of a radiometer, and was shown at two meetlay correction with a model in order to simulate the proposed ABySS or ings [Raney et al., 2003, 2004] and in an NRC Decadal Survey concept compare the grids to point data not used to build the grids. The RMS [http://topex.ucsd.edu/concept/mesoscale.html]. Later Monaldo and Porter differences in Table 1 are 5.35 to 6.25 cm overall, and 3.92 to 4.82 [2005, 2006] independently obtained similar results. R. G. Trimmer sugoutside the Gulf Stream region. These numbers lump together the gested to the U.S. Navy that a future mission could have an orbit drifting polation of the grid to the sample points, signals in the along-track servation. The contents of this paper are solely the opinions of the author(s) altimeter SSHA not captured by the grid, and errors in the orbits, and do not constitute a statement of policy, decision, or position on behalf

enough in "near repeats" to meet mesoscale sampling requirements.

DNSC08MSS.pdf, 2008.

Chambers, D. P., J. C. Ries, and T. J. Urban, Calibration and verification of Jason-1 using global along-track residuals with TOPEX, Max. Geod.,

ocean circulation from space, in OCEANS '91. 'Ocean Technologies and Opportunities in the Pacific for the 90's', pp. 1262-1267, 1991. the expected error in the along-track data, then the RMS along-track Jacobs, G. A., C. N. Barron, and R. C. Rhodes, Mesoscale characteristics,

> centimeter orbit: Jason-1 precision orbit determination using GPS, SLR, DORIS, and altimeter data, Mar. Geod., 26, 399-421, 2003.

designed for bathymetry for monitoring ocean mesoscale variability, in OCEANS 2005, Proceedings of the MTS/IEEE Oceans 2005 Meeting, vol. 2, pp. 1906-1910, 2003

circulation altimeter missions, in Proc. of the Symposium on 15 Years of Progress in Radar Altimetry, Venice, 13-18 March 2006, Eur. Space Agency Spec. Publ., ESA SP-614, edited by D. Danesy, 2006.

tational model to degree 2160: EGM2008, presented at the 2008 General Assembly of the European Geosciences Union, Vienna, Austria, April 13-18, 2008.

and E. Reynolds, Abyss-Lite: improved bathymetry from a dedicated small satellite delay-Doppler altimeter, in Geoscience and Remote Sensing Symposium, 2003, Proceedings, vol. 2, pp. 1083-1085, IEEE, 2003. near-repeat cycle or sub-cycle (right hand column of Table 3). A Raney, R. K., W. H. F. Smith, and D. T. Sandwell, Abyss-Lite: A high-

Raney, R. K., W. H. F. Smith, D. T. Sandwell, J. R. Jensen, D. L. Porter,

sea surface, ftp://ftp.spacecenter.dk/pub/DNSC08/DOCUMENTS/ J. Astron. Sci., 35(2), 119-134, 1987.

26(3&4), 305-317, doi:10.1080/714044523, 200

J. Geophys. Res., 106(C9), 19,581–19,595, 2001.

Monaldo, F. M., and D. L. Porter, On the question of using an altimeter

Pavlis, N. K., S. A. Holmes, S. C. Kenyon, and J. K. Factor, An Earth gravi-

resolution gravimetric and bathymetric mission, in Proceedings Space 2004, pp. AIAA-2004-6006, AIAA, San Diego, Calif., 2004.

Geosat and ERS-1 altimetry: ridge segmentation versus spreading rate,

tic orbit had laid down a network with an average track spacing Scharroo, R., A Decade of ERS Satellite Orbits and Altimetry, Delft Univerof 164 km. This resembles the Geosat ERM of 244 revolutions in sity Press, The Netherlands, 2002. 17.0505 days, except that ERS-1 did not exactly repeat; rather, its network of ground tracks then retraced its pattern 83 km west of Walter H. F. Smith, National Oceanic and Admospheric Administration where it had been in the previous cycle. After 20 days, a network Laboratory for Satellite Altimetry, E/RA31, 1335 East-West Highway, Silver with an average spacing of 139 km was built and drifted 66 km east- Spring, MD 20910, USA. (walter.hf.smith@noaa.gov) ward, and so on. Only after 2411 revolutions and 168 days would Remko Scharroo, Altimetrics LLC, 330a Parsonage Road, Cornish, NH the ERS-1 geodetic phase orbit repeat exactly, as shown in the last 03745, USA. (remko@altimetrics.com)