Remote Sensing:

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Active microwave systems
(2) Satellite Altimetry
* range data processing
* applications
Satellite Altimeters

- nadir-pointing satellite-based radars measures the range from satellite to surface of the Earth

- radar pulse is reflected from the Earth’s surface

- measure the round-trip travel time

- range from satellite to surface is $R = \frac{1}{2} ct$
  where $c =$ speed of light

- Precision Orbit Determination (POD) systems measure the altitude of the satellite above a reference ellipsoid

- several corrections must be made for atmosphere and sea state effects on range calculation
• Altimeters (nadir pointing radar)
  – *sea surface height* (long wavelengths ~50 km)
    • mesoscale currents, eddies, fronts
    • thermal expansion
  – significant wave height
  – wind speed
  – gravity and bathymetry
  – ice sheets

ERS-1 flew on three different orbits:
  - a 3-day period for calibration and ice-sea observation
  - a 35-day period for multi-disciplinary ocean observations
  - a 168-day period for geodetic applications

ERS-2, the follow-on from ERS-1, it was used in tandem with it from August 1995 to June 1996, their identical orbits (35 days) having a one-day shift.
Sea surface HEIGHT (SSH)

- **Sea Surface Height is satellite** *altitude* **minus** *range*

- **It comprises two contributions:** *geoid* and *dynamic topography*

- **Geoid:**
  - The sea surface height that would exist without any motion. This surface is due to gravity variations around the planet due to mass and density differences on the seafloor
  - Major bathymetric features deform sea level by tens of meters and are visible as a hill on the geoid

- **Dynamic topography**
  - The ocean circulation comprises a permanent mean component linked to Earth's rotation, mean winds, and density patterns…
  - …and a highly variable component (wind variability, tides, seasonal heating, eddies)
Sea Surface Height

\[ SSH = \text{altitude} - \text{range} \]
\[ = \text{Geoid} + \text{dyn. topography} \]

To get dynamic topography the easiest way would be to subtract the geoid from SSH

\[ D = SSH - G \]

The geoid is not yet known accurately enough for all oceanographic applications, but this is changing due to the GRACE mission.
Jason satellite

AVISO Web site

Jason launch movies

Precision Orbit Determination

The Jason satellite is tracked in 3 ways

1. Turbo-Rogue Space Receiver (TRSR)
   - continuously tracks up to 16 GPS satellites
   - measures phase of carrier signals and pseudo-range (time) to
   - estimates position to better than 20 m and time to 100 nanoseconds

2. Laser Retroflector Array (LRA)
   - an array of mirrors on the satellite that provide a target for laser-tracking measurements from ground stations
   - round-trip time of the laser is another range measurement
   - accuracy is a few mm, but only 10 to 15 stations are in operation

3. DORIS
   - receivers on the satellite measure Doppler shift of signal from ground-station beacons (2 frequencies)
   - gives satellite velocity
   - a dynamic orbit model integrates the velocity and position data, drag, solar forces on satellite, to continuously compute the satellite trajectory

Where is Jason now?
GRACE: Gravity Recovery and Climate Experiment

Dedicated mission for observing the mean gravity field (geoid) and gravity changes due to the hydrologic cycle.
GRACE: Gravity Recovery and Climate Experiment

**Science Goals**
High resolution, mean & time variable gravity field mapping for Earth System Science applications.

**Mission Systems**
- **Instruments**
  - KBR (JPL/SSL)
  - ACC (ONERA)
  - SCA (DTU)
  - GPS (JPL)
- **Satellite** (JPL/DSS)
- **Launcher** (DLR/Eurockot)
- **Operations** (DLR/GSOC)
- **Science** (CSR/JPL/GFZ)

**Orbit**
- Launch: March 2002
- Altitude: 485 km
- Inclination: 89 deg
- Eccentricity: ~0.001
- Lifetime: 5 years
- Non-Repeat Ground Track
- Earth Pointed, 3-Axis Stable
GRACE: Gravity Recovery and Climate Experiment

http://www.csr.utexas.edu/grace/gallery/animations/measurement/measurement_qt.html
Gravity anomalies from 363 days of GRACE data (GGM02S)
(a) Circulation at 1000 m depth obtained from the GRACE geoid combined with satellite altimetry and ship measurements. Note that the flow direction in the Gulf Stream extension matches that measured by ship-deployed floats in (b)

(b) Ocean currents from direct measurement by floats deployed from ships. This can be compared to the panels above and below.

(c) Same as (a) except that the best gravity model *prior* to GRACE was used. In many areas the implied currents are flowing in the wrong direction.
• Topex/Poseidon and Jason satellites (same orbit)

  – altitude 1336 km
    • relatively high: less drag and more stable orbit

  – inclination of 66° to Earth's polar axis
    • it can "see" only up to 66° North and South

  – the satellite repeats the same ground track every 9.9156 days

  – the ground-tracks are 315 km apart at the equator
    • track repeat precision is about 1km

  – ground scanning velocity is 5.8 km/s, orbit velocity 7.2 km/s
Where is Jason now?  Where is Topex now?
http://www.heavens-above.com/orbitdisplay.asp?lat=34.148&lng=-118.144&alt=0&loc=Pasadena&TZ=PST&SatID=26997
Tidal aliasing considerations

\[ \Delta \phi_{tide}(j) = \frac{2\pi P_{orb}}{T_{tide}(j)} \]

- Orbital parameters (inclination, altitude and precession rate which set orbital period) should be chosen so that the alias period of energetic tidal harmonic constituents is at least resolved by the duration of the altimeter mission, and preferably to frequencies of less than 2 cycles per year.

- Aliased tide variations (which appear to be low frequency signals) are phase shifted on adjacent ground-tracks by several days, and can appear to propagate westward or eastward
TABLE 8. Tidal Periods for the Six Major Tidal Constituents, Along with the Alias Period and the Three Longest Zonal Alias Wavelengths for Altimeter Measurements in the 10-Day Repeat T/P Orbit Configuration

<table>
<thead>
<tr>
<th>Tide</th>
<th>Period (hr)</th>
<th>$T_{alias}$ (days)</th>
<th>$\lambda_{-1}$ (degrees)</th>
<th>$\lambda_0$ (degrees)</th>
<th>$\lambda_1$ (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_2$</td>
<td>12.4200601</td>
<td>62.11</td>
<td>2.16 E</td>
<td>9.01 E</td>
<td>4.14 W</td>
</tr>
<tr>
<td>$S_2$</td>
<td>12.000000</td>
<td>58.74</td>
<td>2.79 W</td>
<td>183.01 W</td>
<td>2.88 E</td>
</tr>
<tr>
<td>$N_2$</td>
<td>12.658348</td>
<td>49.53</td>
<td>2.16 W</td>
<td>9.01 W</td>
<td>4.14 E</td>
</tr>
<tr>
<td>$K_1$</td>
<td>23.93447</td>
<td>173.19</td>
<td>7.81 W</td>
<td>366.03 W</td>
<td>2.86 E</td>
</tr>
<tr>
<td>$O_1$</td>
<td>25.819342</td>
<td>45.71</td>
<td>2.17 E</td>
<td>9.24 E</td>
<td>4.09 W</td>
</tr>
<tr>
<td>$P_1$</td>
<td>24.06589</td>
<td>88.89</td>
<td>2.81 W</td>
<td>366.03 W</td>
<td>2.86 E</td>
</tr>
</tbody>
</table>

Note: Generally, the longest wavelength is the one that is most apparent in time-longitude plots of sea surface height variability (see Schlax and Chelton, 1994b, 1996). The direction of propagation for each alias is denoted as E for eastward and W for westward.

TABLE 9. The Same as Table 8, Except for the 35-Day Repeat ERS Orbit Configuration

<table>
<thead>
<tr>
<th>Tide</th>
<th>$T_{alias}$ (days)</th>
<th>$\lambda_{-1}$ (degrees)</th>
<th>$\lambda_0$ (degrees)</th>
<th>$\lambda_1$ (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_2$</td>
<td>94.49</td>
<td>0.78 W</td>
<td>8.79 E</td>
<td>0.67 E</td>
</tr>
<tr>
<td>$S_2$</td>
<td>$\infty$</td>
<td>0.72</td>
<td>179.76</td>
<td>0.72</td>
</tr>
<tr>
<td>$N_2$</td>
<td>97.39</td>
<td>0.86 E</td>
<td>4.29 W</td>
<td>0.62 W</td>
</tr>
<tr>
<td>$K_1$</td>
<td>365.25</td>
<td>0.72 E</td>
<td>359.70 E</td>
<td>0.72 W</td>
</tr>
<tr>
<td>$O_1$</td>
<td>35.07</td>
<td>0.79 W</td>
<td>8.58 E</td>
<td>0.66 E</td>
</tr>
<tr>
<td>$P_1$</td>
<td>365.25</td>
<td>0.72 W</td>
<td>359.52 W</td>
<td>0.72 E</td>
</tr>
</tbody>
</table>

TABLE 10. The Same as Table 8, Except for the 17-Day Repeat Geosat Orbit Configuration

<table>
<thead>
<tr>
<th>Tide</th>
<th>$T_{alias}$ (days)</th>
<th>$\lambda_{-1}$ (degrees)</th>
<th>$\lambda_0$ (degrees)</th>
<th>$\lambda_1$ (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_2$</td>
<td>317.13</td>
<td>1.25 W</td>
<td>8.00 W</td>
<td>1.81 E</td>
</tr>
<tr>
<td>$S_2$</td>
<td>168.81</td>
<td>1.46 E</td>
<td>179.89 E</td>
<td>1.49 W</td>
</tr>
<tr>
<td>$N_2$</td>
<td>52.07</td>
<td>1.08 E</td>
<td>4.09 E</td>
<td>2.31 W</td>
</tr>
<tr>
<td>$K_1$</td>
<td>175.45</td>
<td>1.47 E</td>
<td>359.79 E</td>
<td>1.48 W</td>
</tr>
<tr>
<td>$O_1$</td>
<td>112.95</td>
<td>1.25 W</td>
<td>8.18 W</td>
<td>1.80 E</td>
</tr>
<tr>
<td>$P_1$</td>
<td>4465.22</td>
<td>1.47 E</td>
<td>359.78 E</td>
<td>1.48 W</td>
</tr>
</tbody>
</table>
Altimetry: How it works

For altimeter observations to be useful for oceanography, range accuracy of order 2 cm is required.

Where is Jason now?
Figure 14.3 The length of the altimeter pulses plus the height of the waves on the sea surface determine the surface area observed by an altimeter. Two extremes are illustrated. The top and middle show a time sequence for a rectangular pulse incident on a sea surface whose wave height is very small compared with the pulse width. The bottom shows a 3 ns pulse incident from an altitude of 843 km on a sea surface with 10 m waves and 300 m dominant wavelength (the vertical scale is magnified by a factor of 100). (From Walsh, Uliana and Yaplee, 1978.)
Pulse-limited altimetry

Foot-print size on the sea surface:
- large enough to filter out surface gravity waves
- small enough to resolve Rossby radius ~ 30 to 75 km
- wave field and roughness (radar cross-section) are homogeneous
- 1 – 10 km satisfies these criteria

Antenna beam width depends on:
- range and foot-print size => \(0.21^\circ\) for T/P

Antenna diameter depends on:
- EM wavelength and beam width => \(d = 7.7\) m

Too big to fly, and beam-limited design is sensitive to pointing errors
Pulse-limited altimetry

FIGURE 7 The measurement geometry for (a) a very narrow beamwidth-limited altimeter, and (b) a pulse-limited altimeter with a relatively large antenna beamwidth γ. In both cases, the boresight of the antenna views the sea surface at off-nadir angle θ from a height R above the sea surface.

FIGURE 8 A schematic geometrical description of a pulse of duration τ and width cτ incident on a monochromatic wave surface with crest-to-trough wave height Hw. One-way travel times τ' are labelled relative to the time t'_0 = R0/c when the leading edge of the pulse intersects the planar surface of wave crests at nadir. The angle θ_out corresponds to the angle from which radar returns arrive at the satellite at twice the one-way travel times displayed on each panel. As described in the text, the reflection of the midpoint of the pulse from wave crests at one-way travel time τ' and angle θ_out arrives at the satellite simultaneously with the trailing edge of the pulse reflected from wave troughs at the same one-way travel time τ'. The bounds of the pulse-limited footprint area contributing to the radar return at two-way travel time 2τ' are shown in the lower panels.
Sea state affects the radar reflection

Figure 14.2 In order to determine the arrival time of the altimeter pulses to within a fraction of a nanosecond, and to determine significant wave height (SWH), a smooth curve is fitted through the averaged shape of many altimeter pulses (from Walsh, Uliana and Yaplee, 1978).
FIGURE 12  Plan views of the fractional illumination patterns at two-way travel time intervals of 5 nsec for a pulse of duration 3.125 nsec and significant wave heights of $H_{1/3} = 1, 5, \text{and } 10 \text{ m}. \text{ The circles in each panel represent the perimeters where the fractional illumination is 1\%}.$
FIGURE 13 The evolution of (a) the footprint area; and (b) the associated radii that define the outer and inner perimeters of the footprint annulus contributing to the radar return as a function of two-way travel time for Gaussian sea surface height distributions with $H_{1/3} = 1, 5,$ and $10$ m (dashed, solid, and dotted lines, respectively). The radii and areas are defined probabilistically by the 1% thresholds of fractional illumination as described in the text.
The onboard Adaptive Tracking Unit analyzes the returned pulses to estimate two-way travel time, wave height and radar cross-section.
Corrections that must be applied in the range calculation:

(1) Sea state bias

- Electromagnetic bias
  - ocean troughs have a larger radius of curvature than wave crests
  - greater reflection from wave troughs than wave crests induces an EM sea level bias toward wave troughs
  - scatter at crests due to small scale roughness increases the effect
  - difference between height of mean sea level and mean scattering surface

- Skewness bias
  - non-Gaussian distribution of the sea shifts the median from the mean sea level troughs adding to the EM bias toward wave troughs

- Combined sea-state bias depends on significant wave height, but also stage of development of the sea:
  - fetch limited vs duration limited
  - presence of swell (has less bias)
  - these cannot be determined from the altimeter pulse waveform

Where is Jason now?
FIGURE 35 The sea-state bias coefficient $b$ estimated by the nonparametric model of Gaspar and Florens (1998) as a function of significant wave height and wind speed (upper panel). Lower panel shows binned values of the percentage of total observations for a bin size of 0.25 m in $H_{1/3}$ by 0.5 m sec$^{-1}$ in wind speed. The shading in the upper panel indicates regions where the bins contain less than 0.1% of the observations (see lower panel), which is too small to obtain reliable estimates of $b$. (Data provided courtesy of P. Gaspar.)
Corrections that must be applied in the range calculation:

(2) Index of refraction (speed of light through atmosphere)

- Ionospheric correction
  - variation in the number of free electrons present in the sub-satellite ionosphere
  - electron content varies from day to night (fewer free electrons at night), from summer to winter (fewer during summer), and as a function of the solar cycle (fewer during the solar minimum)
  - effect is inversely proportional to transmitter frequency
  - Poseidon is a dual-frequency altimeter so differential response provides information on range correction
  - Atmospheric modeling and GPS (also dual frequency) can be used to map ionosphere electron density
Figure 29: Global maps of the vertically integrated ionospheric electron content estimated from GPS data at 1500 local time along 160°W (0140 UTC) on July 16, 1998 (top) during a period of low electron content and on November 16, 1999 (bottom) during a period of high electron content. Contour interval is 10 TECU with additional contours shown as dashed lines for 5 and 15 TECU. (Data are from the Global Ionospheric Maps produced at the Jet Propulsion Laboratory, with sponsorship from the U.S. Naval Oceanographic Office and the National Aeronautics and Space Administration.)
Corrections that must be applied in the range calculation:
(2) Index of refraction (speed of light through atmosphere)

- **Dry tropospheric correction**
  - by far the most significant adjustment to 2-way travel time
  - gases present in the sub-satellite troposphere
  - correction involves vertical integral of the air density and is thus proportional to mean sea level pressure (MSLP)
  - MSLP analysis fields from ECMWF used in Jason processing
  - the dry correction includes the weight of the water molecules

- **Wet troposphere correction**
  - accounts for water vapor influence on the index of refraction
  - vertical integral of water vapor determined from an onboard radiometer
The challenges to achieving 2 cm accuracy are:

- computing the satellite position accurately
- range corrections for the atmosphere
  - density of atmosphere, water vapor
- range corrections for sea state
- accounting for the aliasing of tides
- knowing the shape of a reference gravitational potential surface, or “geoid”, that defines a surface along which gravity is constant (and therefore dynamically “level”)
Where is Jason now?
Climate Research: By modeling changes in the distribution of heat in the ocean, scientists can study the evolution of weather patterns from the ocean system.

El Niño & La Niña Forecasting: Understanding the pattern and effects of climate cycles such as El Niño helps predict the disastrous effects of floods and drought.

Hurricane Forecasting: Altimeter and scatterometer data are incorporated into atmospheric models for hurricane season forecasting and individual storm severity.

Ship Routing: Maps of currents, eddies, and vector winds are used in commercial shipping and recreational yachting to optimize routes.

Offshore Industries: Cable-laying vessels and offshore oil operations require accurate knowledge of ocean circulation patterns to minimize impacts from strong currents.

Marine Mammal Research: Sperm whales, fur seals, and other marine mammals can be tracked, and therefore studied, around ocean eddies where nutrients and plankton are abundant.

Fisheries Management: Satellite data identify ocean eddies which bring an increase in organisms that comprise the marine food web, attracting fish and fishermen.

Lobster Larvae Survival Studies: The study shows that altimeter derived geostrophic currents may be of use in predicting natural repopulation success. Repopulation is a topic of growing interest as over fishing occurs and efforts are made to replenish stock.

Coral Reef Research: Remotely sensed data are used to monitor and assess coral reef ecosystems, which are sensitive to changes in ocean temperature.

Ocean Debris Tracking: Floating and partially submerged material consisting of nets, timber and ship debris is increasing with human population and increasing contact with the sea. This material is capable of physically destroying coral and entangling animals.

Long internal waves studies with applications to large-scale ocean transport and improvement of altimeter measurements
R. Glazman

Low-frequency sea level variability in the Atlantic, Indian and Southern Oceans
R. Morrow, G. Reverdin

Low-frequency variability in the southeastern Pacific
R. Abarca, A. Velez, Y. Du Penhoat, B. Dewitte, G. Pizarro

Mass, heat and salt transports in the western North Pacific

MERGATOR, forecasting global ocean

Merging altimetry and thermal imagery to estimate velocity in ocean boundary currents
W. Emery, J. Wilkin, M. Bowen.

Altimetric Studies of Ocean Tidal Dynamics

Altimetry research with Jason-1 at SOC
P. Challenger, P. Cipollini, D. Cromwell, C. Oemmeringer, O. Quarty, H. Snaith, M. Stokosz, D. Woolf

Application of altimetry measurements to observational and modeling studies of low-frequency upper ocean mass and heat circulation in the tropical Pacific

The application of Jason-1 measurements to estimate the global near-surface ocean circulation for climate research
C.J. Koblinsky, B.D. Beckley, P.P. Niiler, B. Cornuelle, N. Barth.


SCIENCE - Scientific Investigations

Merging altimetry and thermal imagery to estimate velocity in ocean boundary currents

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Applications

Large-scale ocean circulation

CHAPTER 2, FIGURE 12  Time-longitude plots of SSH along 24° latitude in each of the five ocean basins. The raw SSH data were smoothed as in Figure 11 and zonally high-pass filtered to attenuate wavelengths longer than about 8000 km.
Fig. 1. Latitudinal variation of the time required for baroclinic Rossby waves to cross an ocean basin with the geometry of the North Pacific. These transit times are based on the phase speeds predicted by the standard theory for freely propagating, non-dispersive, linear, first-mode baroclinic Rossby

Fig. 2. Time-longitude sections of filtered sea level (22) in the Pacific Ocean along 39°, 32°, and 21°N. These examples are representative of extratropical latitudes throughout the world.
FIGURE 14 The westward phase speeds estimated from 7 years of T/P data (left) and 3 years of Run 11 of the POP model (right) along the respective sections shown in Figure 13. The solid circles correspond to estimates from the Pacific Ocean and the open circles correspond to estimates from the Atlantic and Indian oceans. The solid lines in the upper panels indicate the global zonally averaged latitudinal variation of the phase speeds predicted by the standard theory for extratropical freely propagating, nondispersive Rossby waves in the absence of any background mean flow based on the eigenvalue solutions obtained from climatological hydrographic data by Chelton et al. (1998) (left panel) and from the hydrography of the POP model (right panel). The pointwise ratios of each observed phase speed to the phase speeds predicted at the same locations as the observations based on the standard theory and the extended theory that includes the baroclinic background mean flow are shown in the middle and bottom panels, respectively.
Applications: ENSO observation
Applications

Meso-scale vectors currents from ground-track cross-over points

CHAPTER 3, FIGURE 9. Velocity variance ellipses in the East Australian Current from Geosat observations at crossover points and long-term surface drifter data, plotted over bathymetry (From Wilkin, J. and Morrow, R.A. 1994. With permission)
Applications

Sea-level rise

FIGURE 8  Same as Figure 4, but after correcting for instrument effects using the tide gauge calibration time series (lower panel, Figure 7) and removing annual and semi-annual variations.
Applications

Tidal dissipation

FIGURE 11  (a) rate of dissipation per unit of area by tidal bottom friction for $M_2$, computed from the hydrodynamic model FES94.1. Units are in KW/km$^2$. (b) Energy fluxes for the $M_2$ tide, estimated from FES94.1. Units are in KW/km.
Applications

Tidal energy flux

FIGURE 11  (a) rate of dissipation per unit of area by tidal bottom friction for $M_2$, computed from the hydrodynamic model FES94.1. Units are in KW/km$^2$. (b) Energy fluxes for the $M_2$ tide, estimated from FES94.1. Units are in KW/km.
Applications

Ice-sheet dynamics

CHAPTER 9, FIGURE 10 Basal shear stresses for Greenland derived from surface topography from satellite altimetry and bottom topography from airborne radar sounding. Minimum stresses occur at ice divides.
Applications

Where is Jason now?
On the 13th November 2002 the oil tanker, Prestige, suffered a breakdown off the coast of Cape Finisterre (Spain). On the 19th November it sank off the coast of Galicia to a depth of 3500 metres, with from 50 to 60,000 tonnes of heavy fuel oil in its tanks.
Future of Altimetry

- Cryosat (ESA)
  - Altimeter dedicated to polar observation
  - High inclination orbit 92°, 710 km altitude
  - 3½-year mission to determine variations in the thickness of the continental ice sheets and marine ice cover
  - Test the predictions of thinning arctic ice due to global warming
  - Low resolution nadir altimeter
    - can operate in SAR mode
  - Launch 8 October 2005 (oops!)
Future of Altimetry

The Ocean Surface Topography Mission (OSTM) will be a follow-on to the Jason mission. It is scheduled to launch in June of 2008.
Future of Altimetry

- **WSOA: the Wide Swath Ocean Altimeter**
  - An altimeter/interferometer project

- Several altimeters mounted on masts will acquire measurements simultaneously, providing continuous wide-area coverage.

- WSOA is based on a technique combining altimeter and interferometer measurements. It is a wide-field radar altimeter able to measure sea-surface height across a swath centered on the satellite ground track.

- The satellite payload will include:
  - dual-frequency, nadir-looking radar altimeter in Ku and C bands
  - to provide ionospheric corrections
  - acquire measurements as accurate as Topex and the Jason
  - A three-channel radiometer
  - GPS, Doris and laser reflector precise orbit determination
  - WSOA, comprising two interferometers mounted on a mast, with a baseline of 6.4 m each covering a swath of 15 to 100 km
WSOA on “Jason-2”

Three factors underlying measurement uncertainty:

- Measurement noise, which depends on the antenna baseline (longer baseline = less noise). With an antenna baseline of 6.4 m the raw noise is 5.2 cm
- Ionospheric, tropospheric and sea-state bias effects (estimated at 1 to 2 cm)
- Errors from satellite roll and pitch steering which impact measurement geometry
Comparison of T/P+Jason-1 measurements and simulated WSOA data (with Topex/Poseidon shifted into an orbit parallel to Jason-1).

This mosaic offers a huge advantage in terms of describing the dynamic topography at high resolution:
• It allows a measure of sea surface gradient between pixels and, therefore, geostrophic velocity
• Simulations based on realistic model data yield an error of 4.7 cm/s rms on the zonal velocity and 5.9 cm/s on meridional velocity.