Altimeter Collinear Analysis

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Satellite Altimetry and Gravimetry: Theory and Applications

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- **Orbital Dynamics & Orbit Determinations II (AM) By C.K. Shum**
  - Nonlinear orbit determination & parameter recovery
  - Force, measurement, and Earth orientation models
- **Satellite Altimetry II (AM) By C.K. Shum**
  - Principles of satellite altimetry, mission design, waveforms
  - Geographically correlated orbit errors and POD
  - Instrument, media and geophysical corrections
- **Altimeter Collinear Analysis (PM) By Alexander Braun**
  - Stackfile method for oceanography and marine geophysics
  - Mean sea surface, marine gravity field determinations
  - Models accuracy evaluations and limitations
- **Radar Altimeter Data Processing (PM) By Alexander Braun**
- **Tutorial on iGMT (continued) (PM) By Alexander Braun**
Atmospheric Refraction Corrections
- dry gases
- water vapor
- ionospheric electrons

Sea-State Bias Corrections
- EM bias
- skewness bias

Instrument Corrections
- tracker bias
- waveform sampler gain calibration biases
- antenna gain pattern
- AGC attenuation
- Doppler shift
- range acceleration
- oscillator drift
- pointing angle/sea state

External Geophysical Adjustments
- geoid height $h_g$
- ocean tidal height $h_T$
- atmospheric pressure loading $h_a$

$h = H - R$

$h_d = h - h_g - h_T - h_a$

Sea Surface
Reference Ellipsoid
Bottom Topography

Courtesy: Chelton et al. [2001]
Sea Level Anomalies: Collinear analysis (stackfile):
cross-track and along-track gradient corrections

Credit: C.Y. Kuo, Yuchan Yi, Don Chambers
Underlying Physics

Sea surface slopes at length scales of 12 km to 200 km

Slopes required to one microradian (6 mm in 6 km)
(1 microrad corresponds to ~1 mgal gravity anomaly)

Courtesy: Walter Smith
Gravity anomalies and depth are closely correlated over the ~12 km to 200 km band

(Watts and Talwani, 1975)
Current Bathymetry from Altimetry (E. China Sea)

Observed Gravity Anomalies

Predicted Bathymetry

Courtesy: Walter Smith
Altimeter Sampling

- Although many radar altimeters are flown in a “repeat” ground-track, the ground-track does not repeat exactly.

- Atmospheric drag, and other perturbations, cause the ground-track to drift eastward over time.

- Orbital maintenance maneuvers cause the ground-track to drift back westward, until drag again begins to cause an eastward drift.
Discovery of the Foundation Sea Mounts

Old view

New view
(satellite altimeter data)

Courtesy, Smith and Sandwell (1997)
Altimeter Sampling (cont)

- Additionally, the along-track sea surface height (SSH) measurement is averaged and reported at discrete time intervals, typically ~ 1 sec.

- The time for the satellite to orbit the Earth once is not an integer number of seconds, nor is it exactly constant, because of drag and other perturbing forces.

- This, combined with the cross-track deviations, means that SSH measurements are not repeated at exactly the same location every time, but within a small area, or “bin”.

**Locations of T/P SSH Measurements in a bin. Points were made ~ every 10 days**
Sampling and SSH Variability

- If the mean SSH (or MSS) were flat over the region, variations in SSH could be computed as simple differences from a mean.

- However, the MSS varies significantly from one region to another. Most of this is caused by the geoid.

- Along-track gradients (derivative of MSS relative to distance) of more than 30 m/° of latitude are not uncommon.

- Cross-track gradients can be of similar size.

MSS and along-track MSS gradients from T/P along 1 pass.
MSS Gradients and Error

- The maximum along-track deviation from the center of a bin is about 0.03°. Thus, a 30 m/° gradient implies a maximum change in SSH due only to the MSS of nearly 1 m.

- Even with no temporal changes in SSH, it would that there were changes due to sampling of the MSS.

- If these gradients are not accounted for, they would show up as very large temporal variations in SSH that could be erroneously interpreted as tides or eddies, or obscure smaller, real signals.

Sketch of a MSS model that accounts for gradients (blue solid line) and one that does not (red dotted line) compared to the “true” MSS (thick black line). The SSH is the dashed line.
Collinear Analysis

• The earliest method of correcting for MSS gradients took into account only along-track gradients, and was called collinear analysis [Cheney et al., 1983, Sandwell and Zhang, 1989].

• In this method, along-track SSH profiles were averaged to a regular grid and a MSS gradient from one grid to the next was computed. Then, individual cycle SSH profiles were interpolated to the grid using the computed along-track profiles. Gridding was generally some small fraction of a degree, but not at the smallest resolution possible (~ 0.05°).

• Cross-track deviations were ignored.
Gradient Corrections

- One fundamental assumption in MSS corrections is that with a long enough sample of data in time, real sea level variability will average out and the “mean” SSH can be determined.

- However, this is not the case, as Chambers [2002] demonstrated.

- Real variability (e.g., El Niño as shown in the plots on the right) can alias into non-zero gradients.

- Mesoscale eddies may be worse, since the variability is 3 to 4 times larger than El Niño.

- More research needs to be done to investigate this problem.
Conceptual Stackfile*

*David Sandwell, 1989
Horizontal Locations of T/P Data Points for all Cycles Registered in a Bin
Sea Surface Gradient and Mean Sea Surface Height

\[ h_{ssh} = a + b \cdot dx + c \cdot dy \]

- **a**: the height of the plane at the bin center (this is equivalently the bin’s mean sea surface height, \( \overline{h} \), after correcting for the gradient);
- **b**: the along-track sea surface gradient;
- **c**: the cross-track sea surface gradient;
- **dx**: the along-track displacement from the bin center;
- **dy**: the cross-track displacement from the bin center;
Annual and Semi-Annual Signals

\[ h_{ssh} = g + kt + c \sin(2\pi t) + d \cos(2\pi t) \]
\[ + e \sin(4\pi t) + f \cos(4\pi t) \]

- \( g \): the bias;
- \( k \): the secular rate;
- \( c, e \): the amplitude of the sine term;
- \( d, f \): the amplitude of the cosine term;
- \( t \): time
Iterative scheme to estimate sea surface gradient and mean sea surface

Step 1: Estimation of the offset, secular rate, semi-annual and annual variation, and then removing the secular rate, semi-annual and annual from original measurements. \( h_{ssh,1} = h_{ssh,ori} - h_{ssh,(ann+semi-ann+sec)} \)

Step 2: Estimation of the along-track sea surface gradient and the cross-track sea surface gradient using \( h_{ssh,1} \), and then removing the sea surface gradient from the original measurements.

\( h_{ssh,2} = h_{ssh,ori} - h_{ssh,gra} \)
\( h_{gra} = b \cdot dx + c \cdot dy \)

Step 3: Estimation of the offset, secular rate, trend, semi-annual and annual variation using \( h_{ssh,2} \), and then removing secular rate, semi-annual and annual from original measurements.

\( h_{ssh,3} = h_{ssh,ori} - h_{ssh,(ann+semi-ann+sec)} \)

Step 4: Estimation of the mean sea surface, the along-track sea surface gradient and the cross-track sea surface gradient using \( h_{ssh,3} \).
Ground-Tracks in Global Models

- TOPEX/Poseidon & JASON (10 days)
- ERS-1, ERS-2 & Envisat (35 days)
- ERS-1 (168 days)*
- ERS-1 (3 days)
- GFO, GEOSAT & SEASAT (17 days)
- SEASAT (3 days)
- GEOSAT Geodetic Mission*
- GEOS-3*
Mean Sea Surface from multi-mission altimetry

Sea surface height that a spaceborne altimeter observes: the mean sea surface which mimics the geoid

Courtesy: Ole Andersen and Per Knudsen
MSS (Mean Sea Surface) Height along T/P Ground Tracks
RMS Ocean Variability around MSS along T/P Ground Tracks
Sea Level Variation

\[ \Delta SL_t(\phi, \lambda) = h_{ssh,t}(\phi, \lambda) - \overline{h}_{ssh}(\phi, \lambda) \]

- \( \Delta SL_t(\phi, \lambda) \): the sea level anomaly at time t;
- \( h_{ssh,t}(\phi, \lambda) \): the sea surface height at time t;
- \( \overline{h}_{ssh}(\phi, \lambda) \): the measured mean sea surface of bin center;
- \((\phi, \lambda)\): the latitude and longitude of the bin center;
Ground Tracks of RA Data Used
Gravity Anomaly Estimated from RA Data
Ship Tracks of Surface Gravity Data
Altimetric MSS & Marine Gravity: Limitations

Credit: C.Y. Kuo, Yuchan Yi, Don Chambers
Current Limitations for Determining Mean Sea Surface and Marine Gravity

- Altimeter data outage near coastal regions
- Wave height
- Coastal ocean tide model errors
- Sea ice covered regions
- Active mesoscale variability regions
- ERS specific: less accurate ice mode data but actually measured over ocean areas

Mitigations:
- Improve tides, “correct” for oceanography, retrack altimeter data in shallow seas
Slope error is due mainly to waves.

Higher precision requires an altimeter less prone to random noise induced by ocean surface waves.

Slope RMS variability from Geosat ERM (1 frequency, no radiometer).
Seasonally averaged wave heights, courtesy P. D. Cotton, UK.

Courtesy: Walter Smith
Coastal Tide Model Errors

Estimated ocean tide error in the Indonesian Sea using two current “best” tide models (NAO99.2B and FES95.2.1) displayed spatially (left) and along ERS-2 tracks (right). Although these models only have a spatial resolution of 50 km, there are significant errors up to 5 µrad which (1) affect altimetric slope measurements and therefore need to be corrected to meet secondary objectives, and (2) represent the coastal signal which could be recoverable using altimeter data.