Satellite Altimetry and Gravimetry: Theory and Applications

C.K. Shum$^{1,2}$, Alexander Bruan$^{2,1}$

$^{1,2}$Laboratory for Space Geodesy & Remote Sensing
$^2$Byrd Polar Research Center

The Ohio State University
Columbus, Ohio, USA

ckshum@osu.edu, braun.118@osu.edu
http://geodesy.eng.ohio-state.edu

Norwegian Univ. of Science and Technology
Trondheim, Norway

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Space Geodesy: An Interdisciplinary Science in the 21st Century

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Wednesday, 23 June 2004

• **Space Geodesy: An Interdisciplinary Science** (AM) C.K. Shum

• **20th Century Sea Level Rise** (AM) C.K. Shum

• **Determination of Vertical Motion Using Satellite Altimetry and Tide Gauges** (PM) Alexander Braun
Space Geodesy: An Interdisciplinary Science in the 21st Century

- What is Geodesy?
- Earth science applications using Space Geodesy
  - **GPS** (atmosphere, climate, ionosphere, geodynamics, navigation, water level, GPS altimetry, positioning, etc)
  - **Synthetic Aperture Radar Interferometry** (tectonics, DEMs, volcano, ice velocity/mass balance, subsidence, current/wave)
  - **Satellite altimetry** (circulation, gravity, tides, sea level, hydrology, ionosphere, ice mass balance, sea ice, bathymetry, vertical motion)
  - **Space gravimetry** (hydrology, oceanography, ice sheet mass balance, glaciology, geodynamics, postglacial rebound)

- Conclusions
What Is Space Geodesy?

A science discipline to determine the size (gravity), shape (volume), and their changes of the Earth (and planets); and positions and motions of a point anywhere on the surface or in space.
Credit: Cartoon modified from a figure by K. Lambeck
GPS Buoy Water Level
GPS Buoy System

• Equip GPS capability to the buoy/vessel to survey the water level.
• Buoy position and water level is processed with DGPS in kinematic mode
• Buoy design and implementation vary from one application to another
• Coastal applications (within 100 km off shore for a few cm–decimeter accuracy in water height): geocentric water surface height measurements and radar altimeter calibrations
Some GPS Buoy Designs

ETH Zurich (GGL) buoy

UTas buoy

GFZ Ruggedized buoy
NOAA/NGS Autonomous Buoy

Credit: G. Mader
OSU Waverider GPS Buoy

- Life-saver type buoy.
- Choke Ring GPS antenna.
- Tethered to a ship or on shore where receiver and battery reside.
- Plastic radome prevents water from entering the center compartment.
OSU Waverider GPS Buoy

- Marks on 4 sides.
- Offsets from the marks to ARP are measured in the laboratory.
- Observing water line with marks during each deployment in order to get the height of ARP above the water line.
Waverider GPS Buoy Deployment
Antenna Reference Point Height

L1 phase center

offset from ant_info.002

up component from user

xyz from user

antenna reference point (ARP)
KARS Height Solution (an example)

1-Sec Buoy Height Solutions of P1 with Different Ref. Stations (Lake Erie)

\[ h_{G321} = 138.311 \text{ m} \pm 2 \text{ mm} \]
\[ h_{GARF} = 138.320 \text{ m} \pm 2 \text{ mm} \]
\[ h_{GUST} = 138.283 \text{ m} \pm 2 \text{ mm} \]
Equipments

- Bottom pressure gauge
- GPS buoy
- NOAA acoustic tide gauge
Lake Erie Calibration Sites (Marblehead and Cleveland)
GPS buoy campaign for Marblehead Site

- 3 TP/Jason nominal footprints (call Bin) on Pass 76 were surveyed with GPS buoy.
- GPS occupation: 1 hr of 1Hz GPS data at each location.
- Mean lake surface gradient estimate: ~20 cm over 18.4 km from Marblehead to Bin B with formal error <1cm.
- Geoid height at TG: -35.293 m with formal error < 1 cm. (8 hr of 1Hz GPS data).
GPS buoy data processing with TGO - Trimble Geomatics Office KARS – Kinematic And Rapid Static (Mader, 1986).
GPS buoy solution at a tide gauge

GPS Buoy SSH (KARS) Solution and Marblehead TG (2001/10/20)

Ellipsoidal height (m)

UTC (hours)

- GPS Buoy
- Marblehead Gauge (6-min)
GPS Occultation:
- Precision orbit determination <0.1 mm/yr near-real time 3-D velocity
- Global pressure improvement
GPS Occultation

- POD (0.1 mm/sec 3-D velocity accuracy)
- Potential pressure field improvement
GPS OCCULTATION MISSIONS

Micro-Lab (GPS-Met), 1995

Orsted, 1999

Sunsat, 1999

SAC-C, June 2000

CHAMP, launched July 15, 2000

GRACE, launched 16 March 2002

COSMIC, 78°-85° inclination, 6 satellite-constellation with nodal planes separated by ~30°, 2005 launch, 5 yr mission

ACE+, 2007 (proposed) 4 satellites
6-hour (May 2001) NCEP-ECMWF surface pressure differences using NCEP topography (up to >8 hPa in the S. Ocean and -6 to -7 hPa over Antarctica)
Effect of Atmospheric Aliasing on Monthly GRACE Gravity Field Recovery

Geoid and height anomalies (mm) at altitude shown

Simulated aliasing as 6 hr. - 3 day NCEP mean pressure (scaled, 30x30 model). Monthly averaged atmospheric load error (height anomalies at altitude) has high-frequency component in S. Ocean and Antarctica)
GLOBAL COMPARISONS OF ECMWF AND CHAMP OCCULATION PROFILE

Include profiles penetrate within 1 km about MSL

- CHAMP data (source: UCAR) period: Jan – March 2003 (except 4 days)
- Data interpolated/extrapolated for 0-30 km (above MSL) at 1-km intervals
Lowest occultation altitude – ECMWF topography

Radar penetration better over polar regions and S. Ocean
SAR Interferometry

- Digital Elevation Models
- Earthquake deformation
- Land subsidence
- Ice stream velocity
- Ocean tides over sea-ice covered oceans
This image was generated using topographic data from the SRTM and shows the largest island in the Fiji Island group (10,429 sq km).

Colors show the elevation as measured by SRTM. Colors range from green at the lowest elevations to pink at the highest elevations. Water is black.

Suva, the capital city, lies on the southeast shore. The Nakauvadra, the rugged mountain range running from north to south, has several peaks rising above 900 meters. Mount Tomanivi, in the upper center, is the highest peak at 3854 meters. 142 km

Location: 17.8° S, 178.0° E
Orientation: North at top
Original Data Resolution: 30 meters
Date Acquired: 19 Feb 00
Date Released to Media: 21 Feb 00
Shuttle Radar Topography Mission Derived Topography Using X-SAR

Courtesy: DLR
Interferogram = phase difference between $S_1$-C and $S_2$-C.

B : Baseline
$B_n$ : Perpendicular baseline
$B_p$ : Parallel baseline
$\phi$ : Incidence angle

Image swath $\sim 100$ km
Horizontal Velocity Field:
Nivlisen Ice Shelf, Dronning Maud Land

Max. displacement of the Potsdam Glacier ~120 m/yr; close to the grounding zone. Grounding zone location is confirmed to be significantly affected by ocean tides.

Bäßler, Detrich, Shum [2003]
Study Area: Sulzberger Ice Shelf

Sulzberger ice shelf:
76.5 S ~ 77.5 S
153 W ~ 156 W
**Interferogram (I) : Track 424**

(a) Interferogram between ERS1 23959 & ERS2 4286
\[ B_n = -121 \text{ m} \]

(b) Interferogram between ERS1 24875 & ERS2 5202
\[ B_n = -6.2 \text{ m} \]

(c) Differential interferogram before baseline scaling
(d) Differential interferogram after baseline scaling
\[ = (a) - 19 \times (b) \]

*19 is the baseline ratio (to remove topography effects*
Geocoded Interferometric DEM

1. Find coast line using scaled differential interferogram (d)
2. Mask out sea and ice tongue from unscaled differential interferogram (c)
3. Baseline estimation & phase unwrapping
4. DEM generation over the land (grounded ice)
Elevation Comparison:
Interferometric DEM height & ICESat laser altimeter profile (C-D)

- Mean bias: 12.46 m
- 8 yr difference
- Ellipsoidal height vs. approximated height
Relative Height

Standard deviation (in the middle) = 1.34 m

Standard deviation (for all the profile) = 5.12 m

Standard deviation (in the middle) = 1.34 m

Mean bias (12.46 m) removed
(Left) Differential interferogram for track 381
(Right) Classification for land glacier (LG), ice tongue (IT), grounding zone (GZ), ice stream (IS), and sea ice (SI)
Deformation Change Measurement

\[ \Delta z = \frac{\Delta r}{\cos \alpha} \]

Where

\( \Delta z \): Surface elevation change

\( \Delta r \): Slant range difference

\( \alpha \): Incidence angle \((= 23 ^\circ)\)

\[
\frac{\Delta z \times 5.6cm}{2 \times \frac{2\pi}{2\pi}} = 16.7cm
\]

- Deformation from InSAR = Tide + Atmosphere + Other
## Predicted Ocean Tides by Model

<table>
<thead>
<tr>
<th>Date</th>
<th>NAO99</th>
<th>TPXO</th>
<th>CATS</th>
<th>GOT</th>
<th>Solid Earth Tide (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996-2-10</td>
<td>-15.8</td>
<td>-13.1</td>
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<td>1996-2-13</td>
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<tr>
<td>1996-2-14</td>
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<td>1996-3-13</td>
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<td>1996-4-18</td>
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<td>4.2</td>
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</tbody>
</table>
## Tide Change Prediction by Model

<table>
<thead>
<tr>
<th>Model</th>
<th>Predicted Tidal difference (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAO</td>
<td>$$-((-15.779-0.7)-(-21.504-0.3))+((-9.822-5.8)-(-0.809-6.2)) = -13.9$$</td>
</tr>
<tr>
<td>TPXO</td>
<td>$$-((-13.141-0.7)-(-21.124-0.3))+((2.944-5.8)-(12.483-6.2)) = -16.7$$</td>
</tr>
<tr>
<td>CATS</td>
<td>$$-((-12.268-0.7)-(-20.086-0.3))+((1.643-5.8)-(10.768-6.2)) = -16.1$$</td>
</tr>
<tr>
<td>GOT</td>
<td>$$-((-7.362-0.7)-(-15.623-0.3))+((-8.648-5.8)-(-3.027-6.2)) = -13.1$$</td>
</tr>
</tbody>
</table>

- Deformation change obtained by SAR: -16.7 cm
  (Atmospheric effect or inverse barometric correction ignored)
TOPEXPOSEIDON and JASON
Global Mean Sea Level and El Nino and La Nina Monitoring
RMS Ocean Variability around MSS along T/P Ground Tracks
Current Bathymetry from Altimetry

Observed Gravity Anomalies  Predicted Bathymetry
Bathymetry from Satellite Altimetry

http://ibis.grdl.noaa.gov/SAT/Bathy.intro.html

Courtesy: Walter Smith
20-km-scale Bathymetry Steers Ocean Currents

Forecast models require correct global bathymetry

A single feature as small as 20 km across can steer a major current (Kuroshio mean flow in U.S. Navy model at 1/16° [Metzger & Hurlburt, 2001]