The Application of Satellite Radar Altimetry on Ocean and Hydrology

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Background

(a) Pulsed limited satellite radar altimeter principles: radar waveform convolution or retracking examples, retracking using Brown model and threshold retrackers (Appendix). Sample MATLAB scripts attached in the data links for the respective problems.

(b) Radar altimeter mission websites:

TOPEX/POSEIDON, Jason-1/-2/3: https://sealevel.jpl.nasa.gov/missions
Geosat/Geosat-Followon (GFO): https://directory.eoportal.org/web/eoportal/satellite-missions/g/gfo
ERS-1/-2/-3/Envisat/Cryosat-2/Sentinel-3: https://earth.esa.int/web/guest/missions/esa-operational-eo-missions

(c) Radar Altimeter Data System (RADS) – processor for ocean applications only
Website: http://rads.tudelft.nl/rads/rads.shtml
However, this Lab is to extract the data using RADS and to provide it to you for easier processing, so you do not have to run RADS.

(c) Ocean Sea Surface Height Anomaly (SSHA) Processing

Sea Surface Height Anomaly (SSHA) =
altitude of satellite (alt) – corrected altimeter range (range)
– ionospheric correction (iono_cor)
– dry tropospheric correction (dry_tropo_corr)
(d) **Radar altimetry for Hydrologic applications.** Using Google Earth (GE) or GE Pro applications: [https://www.google.com/earth/explore/products/](https://www.google.com/earth/explore/products/)

**PROBLEMS**

(1) **Radar Altimeter Basics and Retracking**

(a) For the TOEPX/POSEIDON (T/P) antenna \( k = 1.31, f = 13.6 \text{GHz}, \gamma = 0.21^\circ \), what is the antenna diameter?

(b) For the T/P antenna, in order to get a 5 km diameter footprint, what is the beamwidth?

(c) How much is the range error if the mis-pointing angle \( \theta = 0.02^\circ \) in the case of the T/P orbital height \( R = 1336 \text{km} \)?

(d) For a pulse-limited radar altimeter, what is the pulse time duration to reach 1 cm range resolution?

(e) For a pulse-limited radar altimeter like T/P, how large is the footprint (in term of diameter) of a 3 ns (nanosecond) pulse?

(f) Use MATLAB code ‘brown.m’ and ‘plot_brown.m’ to plot the waveforms with mis-pointing angle 0.25, 0.5, 0.75 and 1 degree, respectively. What pattern do you find?

(g) Run MATLAB code ‘brown.m’ and ‘plot_brown.m’ to generate the (Brown model convoluted) waveform with SWH values 2, 4, 8, 16 m, respectively. What pattern do you find?

(h) Use MATLAB code ‘threshold_retracker.m’ and data ‘example_waveform.txt’ (generated by #g above) to get the retracked gate and power at threshold level 10%, 20% and 50%, respectively. Plot the waveforms and mark the retracked gates.

Data set and Matlab scripts link:


(2) **Ocean Application:**
The fundamental objective is for the class to be aware of utilities such as RADS is useful in its application for study geodesy and oceanography. The functionality of RADS is only over ocean. Here, RADS is used to generate the data sets directly, so there is no need to learn to process data using RADS. Processed data are available from the data link below.

(a) **Averaged mean sea surface (MSS) model.** The data of the 10-day repeat cycles, namely Cycle 10 and Cycle 100 are provided (cyc10_grd.txt, cyc100_grd.txt), combine the two gridded data sets by averaging, to form a *simple* MSS model globally and plot the result. Compare this model with the packed CLS11 MSS model (cyc100_CLS.txt, MSS values evaluated at the gridded locations of cycle 100, which is a globally covered T/P 10-day repeat cycle), by plotting this model. Explain in words, how is the *simple* model compared with the CLS11 MSS?

(b) **Global surface height anomalies, or SSHA data** have been computed for Cycles 10 and 100, and provided as the given data set (cycl10_SSHA.txt, cycl100_SSHA.txt), using:  

$$\text{SSHA}(t) = \text{SSH}(t) - \text{CLS11MSS}$$

Plot and compare the two SSHA's for the two different cycles.

**Data set and Matlab scripts link:**
https://dl.dropboxusercontent.com/u/42875851/GS8873/Ocean.zip

(3) **Hydrology Application:**

This is an application of retrieving water level over inland water bodies. We will use Enivsat, Jason-2 and SARAL/AltiKa (see readme.txt files for each satellite data, open the .km1 file using Google Earth to see the location of the river height virtual stations, which happen to be at one location on Earth) to retrieve river height anomaly (relative to the EGM08 geoid model) time series over the Brahmaputra River, south Asia.

(a) Use the processed data given (j2_1hz, j2_20hz; n1b_1hz, n1b_18hz; sa_1hz, sa_40hz), plot the 1 Hz and high rate data of the three satellite location. Which satellite performs better over this hydrologic location? Are the data noisy and why? If the data are noisy, what would you do to edit out the ‘bad’ data, use at least 2 methods (statistical method, and by examining $\sigma_0$, #d below).

(b) How does the river height anomaly vary in time? If so, what is the origin of the variations?

(c) What is $\sigma_0$ (sigma o)? How does $\sigma_0$ change over different kinds of surfaces?

(d) Set up a filter to edit data based on $\sigma_0$. Only plot the high rate data which has sigma o value <20 dB. Try to count how many data points you would edit out. Then average the high rate data in each cycle to get 1Hz data. Plot them together. Do the same for sigma $o > 30$dB, sigma $o > 40$dB, sigma $o > 50$dB and sigma $o > 60$dB. Which filter setting is better in your opinion?

**Data set and Matlab scripts link:**
Appendix I: Radar Altimeter Principles

Altimeter Footprint:
1. Large enough to filter out the effects of gravity waves
2. Small enough to resolve the first internal Rossby radius of deformation
3. Small enough that wave filed and wind-induced roughness are homogeneous
4. Footprint with diameter 1-10km satisfies all

Beam-Limited Altimeter:

\[ \gamma = 2 \tan^{-1} \left( \frac{r}{R} \right) \approx 2 \frac{r}{R} \]

Where
- \( \gamma \): antenna beam-width
- \( R \): orbit height
- \( r \): footprint radius

\[ \gamma = k \frac{\lambda}{d} \]

Where
- \( \lambda \): radar wavelength
- \( k \): constant
- \( d \): antenna diameter

Disadvantages:
1. Narrow beams require very large antennae and are impractical in space.
2. Beam-limited altimeter is highly sensitive to mis-pointing.

Pulse-Limited Altimeter:
\[ R^2 + r^2 = (R + l_p)^2 = R^2 + l_p^2 + 2Rl_p \]

Where

\( l_p \): length of the radar pulse \( R \): orbit height \( r \): footprint radius

Because \( l_p^2 \) is very small comparing with \( R^2 \), so we have:

\[ r^2 = \sqrt{2Rl_p} \]

\[ l_p = ct_p \]

Where

\( c \): speed of light \( t_p \): time duration of a pulse

Advantages:
1. Transmitting a very short pulse with a duration of a few nanoseconds-frequency modulated chirp/chirp compression
2. Smaller antenna
3. Wider beamwidth

Delay-Doppler/SAR Altimeter:

\( \) (Credits R.K. Raney, Johns Hopkins University Applied Physics Laboratory)

1. “Can be seen” as beam-limited in the along-track direction
2. Very high pulse rate-18000 per second for Cryosat-2, but uses less power per pulse
3. Coherent pulses are summed to form a longer synthetic aperture
4. Much smaller footprint
Brown Model:
The Brown model describes the average impulse response of a rough surface (ocean) to radar pulse as a convolution of three functions:

\[ P_r(t) = P_{FS}(t) \otimes P_{PT}(t) \otimes P_{Hu}(-z) \]

Where

- \( P_r(t) \): the returned power
- \( P_{FS}(t) \): the flat surface response
- \( P_{PT}(t) \): the point target response
- \( P_{Hu}(-z) \): the PDF of specular points on the sea surface

1. The flat surface impulse response
The flat surface response function is the response get from reflecting the radar pulse from a flat surface:

\[ P_{FS}(t) = U(t) \cdot G(t) \]

Where

\[ U(t) = \begin{cases} 0, & t < 0 \\ 1, & t \geq 0 \end{cases} \] : Heaviside function, \( G(t) \): two way antenna gain pattern

2. The point target impulse response

We approximate this function with a Gaussian function in Brown Model.

[Image: https://earth.esa.int/handbooks/asar/CNTR5-2.html]
3. The vertical distribution of surface scatters
Describe the roughness of the surface.

Rough surface response:

\[
P_r(t) = \eta P_T P_{FS}(0) \sqrt{\frac{\pi}{2}} \sigma_p \left[ 1 + \text{erf} \left( \frac{\tau}{\sqrt{2} \sigma_c} \right) \right] \quad t < 0
\]

\[
P_r(t) = \eta P_T P_{FS}(t) \sqrt{\frac{\pi}{2}} \sigma_p \left[ 1 + \text{erf} \left( \frac{\tau}{\sqrt{2} \sigma_c} \right) \right] \quad t > 0
\]

Flat surface response:

\[
P_{FS}(t) = \frac{G_0^2 \lambda c \sigma_c (\psi_0)}{4(4\pi^2)L_p h^3} \exp \left[ -\frac{4}{\gamma} \sin^2 \xi - \frac{4c}{\gamma h} t \cos 2\xi \right] I_0 \left( \frac{4}{\gamma} \sqrt{\frac{ct}{h}} \sin 2\xi \right)
\]

Where:

\( \eta \): pulse compression ratio,

\( P_T \): peak power

\( \sigma_p \): pulse width

\( \sigma_c = \sqrt{\sigma_p^2 + (2 \sigma_s / c)^2} \quad \sigma_s \): RMS height of the specular points relative to the mean

\( \gamma \): antenna beam width

\( \xi \): mispointing angle

\( I_0 \): Bessel function when \( n = 0 \)

\( G_0 \): on-axis antenna gain

\( \sigma_0(\psi_0) \): surface backscatter coefficient at incidence \( \psi_0 \)

\( L_p \): two way propagation loss
**,Tracker:**
Waveforms are acquired by tracking system on-board the satellite. The purpose of the on-board tracker is to keep the reflected signal from the Earth's surface within the altimeter analysis window. The general principle of an on-board tracker is that it predicts the likely position of the next echo based on information derived from the echoes the receiver has just recorded. This computation happens autonomously on-board the satellite – hence “on-board trackers.” (S. Vignudelli et al., 2011: Coastal Altimetry, DOI: 10.1007/978-3-642-12796-0_4)

**T/P: Second Order \((\alpha, \beta)\) Tracker**
- Jason-1: Split Gate Tracker
- ENVISAT: Model Free Tracker
- Jason-2: DIODE/DEM Tracker

**Retracker:**
Brown ocean retracker
The offset centre of gravity (OCOG) retracker
Threshold Retracker
Maximum Likelihood Estimator (MLE) retracker

**Retracking:**
Fit the waveform with a waveform model, therefore estimate the parameters.
Estimate Parameters:
1. SWH: Significant Wave Height
2. The time of radar signal reach the Earth, furthermore range.
3. The backscatter coefficient
Threshold Retracker:

The threshold retracking algorithm was developed primarily to measure ice sheet elevation change (Davis, 1997). The leading edge position is determined by locating the first waveform sample to exceed the percentage (i.e., threshold level) of the maximum waveform sample amplitude. The pre-leading edge DC level (or thermal noise) is computed by averaging the waveform sample 5 to 7. Davis (1997) suggests the 50% threshold for surface-scattering dominated waveforms, and 10% or 20% threshold level for volume-scattering surface.

\[ A_{\text{max}} = \max(P_i(t)) \]

\[ DC = \frac{1}{3} \sum_{i=5}^{7} P_i(t) \]

\[ TL = DC + T_{\text{COEFF}}(A_{\text{max}} - DC) \]

\[ R_k = (R_k - 1) + \frac{TL - P_{k-1}(t)}{P_k(t) - P_{k-1}(t)} \]

Where

- \( A_{\text{max}} \): maximum waveform amplitude
- \( DC \): thermal noise or DC level
- \( T_{\text{COEFF}} \): threshold level (10%, 20% and 50%)
- \( TL \): power of retracked gate
- \( R_k \): the k-th gate, which k satisfy the power of \( R_k \) is bigger than \( TL \) and power of \( R_{k-1} \) is smaller than \( TL \) (\( P_{k-1} < TL < P_k \)).
$R_g$: retracked gate

(Lee, 2008)