SATELLITE ALTIMETRY OVER LAND

Shard Chander
Space Applications Centre

schander@sac.isro.gov.in

Wednesday, 16 August 2017
Outline of Presentation

- Introduction
- Basics of Altimetry
- Applications: Geodesy, Oceanography, Ice sheet, Hydrology
- Altimetry over Land (Limitation and Solution)
- Water Level Retrieval
- Validation with *in-situ* gauge measurements & GPS survey

- Water Level product dissemination over major Indian inland water bodies through VEDAS
- Future scope of Radar altimetry
**Introduction**

**Hydrosphere:** the combined mass of water found on, under, and over the surface of the Earth. The Earth’s liquid water constitutes the **hydrosphere**.

The components of the hydrosphere, as well as the **cryosphere** (frozen water), the atmosphere, and the **biosphere**, participate in the global **water cycle**.

(Merritts et al., 1998)
**Hydrosphere residence times**

- Oceans = 3,100 years
- Atmosphere = 9 days
- Continents = 403 years
- Rivers 12 - 20 days

---

**Water Cycle**

![Water Cycle Diagram](http://ga.water.usgs.gov/edu/watercycle.html)
The vast majority of Earth’s water is in the oceans (salt water), with smaller, but geologically important, quantities of fresh water in lakes, rivers, and ground water.

- Most of the world’s water is in the ocean basins (~ 97%)
- A much smaller amount (~ 3%) is freshwater
- Only 1% of the freshwater is easily accessible

"If the wars of this century were fought over oil, the wars of the next century will be fought over water." - World Bank vice president (Ismail Serageldin), 1995
Remote sensing is the collection of information about the surface of the Earth and its atmosphere by detecting reflected or emitted electromagnetic radiation from sensors aboard airplanes and satellites.

- **Water surface height**  (SARAL-single/dual frequency altimeters)
- Water color/quality  (optical multispectral/hyperspectral)
- Water surface temperature (INSAT 3D– thermal infrared)
- Ice-sheet monitoring  (SARAL- single/dual frequency altimeters)
- Ground water  (GRACE-gravity mission)
- Atmospheric water vapor  (MADRAS microwave imager/SARAL)
Altimetry...Active microwave instrument

- Scatterometer (scattering from surface roughness)
  - ocean vector winds

- Synthetic Aperture Radar (SAR)
  - sea ice
  - high resolution wind speed over water
  - land mapping: surface roughness and 3-D terrain
  - surface currents and swell

- Altimeters (nadir pointing radar)
  - sea surface height (long wavelengths ~50 km)
  - significant wave height
  - wind speed
  - gravity and bathymetry
  - ice sheets
  - Inland waters

\[ R = \frac{1}{2} ct \]

- \( c = 3 \times 10^8 \text{ m/s} \)
- satellite altitude \( \sim 800 \text{ km} \)
- \( t = 2R/c = 0.005 \text{ s} \)
  \( = 5 \text{ milliseconds} \)
- SARAL uses 4000 pulses per second
Microwave energy is largely unaffected by the atmosphere: It has almost 100% transmission
Altimeter Mission Component

- **Dual-frequency radiometer**
  
  (23.8 GHz +/- 200 MHz & 37 GHz +/- 500 MHz)
  
  - Required for wet troposphere correction on altimeter measurements

- **Laser Retro-reflector Array**
  
  - POD system calibration and guarantees minimum orbitography

- **DORIS**
  
  - required for achieving high accuracy orbitography performances on low earth orbit in a precisely monitored reference frame (mean sea level analysis)
  
  - required for coastal/inland applications due to real-time coupling with altimeter

---

- **Key components of an altimetric mission:**
  
  - precise radar altimeters (generally dual frequency for ionospheric delay correction)
  
  - precise orbit determination systems
  
  - additional systems (mainly radiometer for tropospheric delay correction)

- **Products:**
  
  - Dynamic Topography through Sea Surface Height (few-cm accuracy)
  
  - Sea Surface Wave Height
  
  - Sea Surface Wind Speed
Basic Principles of Altimetry
Evolution of Altimetry

Skylab 1973-1979
Seasat 1978 (100 days)
Geosat 1985-1990
GFO 1998 -2008
ERS-1 1991-2000

Topex/Poseidon 1992 –2006
ERS-2 1995 - 2011
Jason-1 2001 – 2013
Envisat 2002 - 2011
OSTM/Jason-2 2008 -

Cryosat-2 2010 -
SARAL 2013-
Jason-3 2016 -
Sentinel-3 2016 -

Jason-CS
SWOT
Evolution of Altimetry

Table- 1.1: Satellite mission and operating characteristics of altimeter

<table>
<thead>
<tr>
<th>Altimeter</th>
<th>Period</th>
<th>Temporal Resolution (days)</th>
<th>Height (km)</th>
<th>Inclination</th>
<th>Band</th>
<th>Radar Frequency (GHz)</th>
<th>Pulse Repetition Frequency (PRF) (Hz)</th>
<th>Gate Width (ns)</th>
<th>Waveform Averaging (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skylab</td>
<td>May 1973-1976</td>
<td>17</td>
<td>435</td>
<td>50°</td>
<td>Ku</td>
<td>13.9</td>
<td>350</td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td>GEOS-3</td>
<td>Apr 1975-Dec 1978</td>
<td>17</td>
<td>845</td>
<td>115°</td>
<td>Ku</td>
<td>13.9</td>
<td>100</td>
<td>15</td>
<td>-</td>
</tr>
<tr>
<td>Geosat</td>
<td>12 Mar 1985-Jan 1990</td>
<td>17</td>
<td>800</td>
<td>108°</td>
<td>Ku</td>
<td>13.5</td>
<td>1020</td>
<td>3.125</td>
<td>10</td>
</tr>
<tr>
<td>ERS-1</td>
<td>17 Jul 1991-10 Mar 2000</td>
<td>35</td>
<td>784</td>
<td>98.55°</td>
<td>Ku</td>
<td>13.8</td>
<td>1020</td>
<td>3.03</td>
<td>20</td>
</tr>
<tr>
<td>ERS-2</td>
<td>21 Apr 1995-Jul 2011</td>
<td>35</td>
<td>784</td>
<td>98.55°</td>
<td>Ku</td>
<td>13.8</td>
<td>1020</td>
<td>3.03</td>
<td>20</td>
</tr>
<tr>
<td>GFO</td>
<td>10 Feb 1998-25 Sep 2008</td>
<td>17</td>
<td>880</td>
<td>108°</td>
<td>Ku</td>
<td>13.5</td>
<td>1020</td>
<td>3.125</td>
<td>10</td>
</tr>
<tr>
<td>Jason-1</td>
<td>7 Dec 2001-Jul 2013</td>
<td>10</td>
<td>1336</td>
<td>66°</td>
<td>Ku</td>
<td>13.6</td>
<td>1800</td>
<td>3.125</td>
<td>20</td>
</tr>
<tr>
<td>Envisat</td>
<td>1 Mar 2002-Jan 2011</td>
<td>35</td>
<td>784</td>
<td>98.55°</td>
<td>Ku</td>
<td>13.6</td>
<td>1800</td>
<td>3.125</td>
<td>18</td>
</tr>
<tr>
<td>Jason-2</td>
<td>20 Jun 2008-present</td>
<td>10</td>
<td>1336</td>
<td>66°</td>
<td>Ku</td>
<td>13.6</td>
<td>1800</td>
<td>3.125</td>
<td>20</td>
</tr>
<tr>
<td>SARAL</td>
<td>25 Feb 2013-present</td>
<td>35</td>
<td>784</td>
<td>98.55°</td>
<td>Ku</td>
<td>35.75</td>
<td>4000</td>
<td>2</td>
<td>40</td>
</tr>
</tbody>
</table>
Altimetry over Land

T/P, Jason- 1/2/3 track (10 days repeatability)

ERS-1/2, Envisat, SARAL track (35 days repeatability)
Data Products Levels

LEVEL 0 Raw data as acquired by satellite

LEVEL 1 A Data in engineering units first order correction i.e. known sensor variations, calibration bias, orbit related corrections, status flag etc.

LEVEL 1 B Waveform data

LEVEL 2 A Waveform based parameters: SWH, Wind Speed, Back Scattering Coefficient

LEVEL 2 B Geophysical Parameters Retrieval: Sea Surface Height, dynamic sea surface topography...

- Near Real Time (NRT) data products (Level 0,1)
  - Operational Geophysical Data Records (OGDR) ~ 3 hours

- Offline Data Products (Level 2)
  - Interim Geophysical Data Record (IGDR) ~ 3 days
  - Geophysical Data Record (GDR) ~ 30 days
  - Sensor Geophysical Data Record (SGDR) ~ 30 days (GDR+ Level 0+ Level 1 b)

NetCDF format

Matlab, IDL, C, fortran, BRAT (Basic Radar Altimeter toolbox)
Applications of Altimetry

- Hydrology: time series water level over reservoir
- Sea Level Rise
- Greenland ice sheet monitoring
For a narrow-beam antenna, the antenna beam-width ($\gamma$) is given by

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

where $R$ is the orbital height and $r$ is the footprint radius.

$$\gamma = k \frac{\lambda}{D}$$

where $k$ is the antenna constant, $\lambda$ is the wavelength and $D$ is the antenna diameter.

Table 2.1: Antenna Diameter for Beam-limited Altimeter footprint of 2.5 km

<table>
<thead>
<tr>
<th>Altimeter</th>
<th>Frequency (GHz)</th>
<th>Altitude (km)</th>
<th>$\gamma$ (°)</th>
<th>Antenna Diameter (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jason-1/2</td>
<td>13.5</td>
<td>1336</td>
<td>0.21</td>
<td>7.7</td>
</tr>
<tr>
<td>Envisat</td>
<td>13.5</td>
<td>800</td>
<td>0.21</td>
<td>4.6</td>
</tr>
<tr>
<td>SARAL</td>
<td>36.5</td>
<td>800</td>
<td>0.36</td>
<td>1.7</td>
</tr>
</tbody>
</table>
Pulse Limited Altimetry

\[ A_1(H_w) = \pi r_1^2 = \frac{\pi c \Delta t_1 R_0}{1 + R_0 / R_e} = \frac{\pi (c \tau + 2H_w) R_0}{1 + R_0 / R_e} \]
Waveform

(a) \[ R_0 = R - \frac{H_w}{2} \]

(b) \[ R_{out} = R_0 + H_w + \frac{ct}{4} \]

(c) \[ R_{out} = R_0 + H_w + \frac{ct}{2} \]

(d) \[ R_{out} = R_0 + H_w + ct \]

\[ t' = t_0 + \frac{H_w}{c} + \frac{ct}{4} \]

\[ t' = t_0 + \frac{H_w}{c} + \frac{ct}{2} \]

\[ t' = t_0 + \frac{H_w}{c} + ct \]

\[ t' = t_0 + \frac{H_w}{c} + \frac{3ct}{2} \]
Inland water bodies (Ukai Reservoir, Gujarat, India)

The floods of August 2006 are among the worst Gujarat’s Surat city has experienced in recent times. The sudden release of a huge amount of water from the Ukai dam led to over 80 per cent of Surat going under water. More than 2 million people were incommunicado—trapped for four days and four nights.
Waveforms acquired by SARAL altimeter over first 4 cycles
Waveform Classification

- Maximum value of the echo (MAX),
- Mean value of the echo (MEAN),
- Peakiness defined as MAX/MEAN,
- Variance of the echo,
- Skewness of the echo,
- Kurtosis of the echo,
- Ramp (slope of the echo between samples and 60),
- Attitude (slope of the echo between samples 40 and 104),
- First Order Derivative of the Waveform
- Parameters derived from OCOG algorithm
Waveform Classification...cont...
Waveform classification over Brahmaputra River Basin

<table>
<thead>
<tr>
<th>Type</th>
<th>No of waveforms</th>
<th>Percentage of total waveforms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brown like</td>
<td>1900</td>
<td>27%</td>
</tr>
<tr>
<td>Multi-peak</td>
<td>1570</td>
<td>22%</td>
</tr>
<tr>
<td>Specular</td>
<td>3000</td>
<td>43%</td>
</tr>
<tr>
<td>Rectangular</td>
<td>533</td>
<td>7.5%</td>
</tr>
</tbody>
</table>
Waveform Retracking

- Altimeter can only measure within a narrow range window vertically, called “Analysis window”.
- “On-board tracker”, a predictive device that minimize the risk of the altimeter losing track of the surface.
- In order to achieve very high accuracy in range the waveforms acquired are down linked to earth where they are retracked manually to improve the range estimates. This is called “Waveform Retracking”.

![Diagram of waveforms with annotations for LEW, Trailing edge slope, Leading edge position, noise, gate counts, and bins.](image)
This retracker was first proposed by Martin et al. (1983). It is a five parameter functional model designed to derive geophysical parameters for Brown like waveforms obtained over ocean.

The aim of the Ice-2 retracker is to make the measured waveform coincide with a power model which is a slight modification of the Brown model and developed for retracking waveforms over continental ice sheets. This is a special case of retracker with zero trailing edge, that generally happens over ice surfaces, with high specular return.

The power model is as follows (Legresy et al. (2005)):

\[
y(t) = \beta_1 + 0.5\beta_2 \exp(-\beta_3(t - \beta_4)) (1 + \text{erf}(t - \beta_3/\beta_4)) \tag{2.24}
\]

where \( \text{erf} \) is the error function.
Waveform Retracking...OCOG/Threshold Retracker

This retracker was first developed by Wingham et al. (1986). The OCOG retracker is normally used for rectangular type waveforms where no model can be fitted. It attempts to find the Centre of Gravity (COG), Amplitude (A) and Width (W) of the waveform

\[ A = \sqrt{\frac{\sum_{i=1+n}^{N-n} P_i^4(t)}{\sum_{i=1+n}^{N-n} P_i^2(t)}} \]

\[ W = \frac{\left( \sum_{i=1+n}^{N-n} P_i^2(t) \right)^2}{\sum_{i=1+n}^{N-n} P_i^4(t)} \]

\[ COG = \frac{\sum_{i=1+n}^{N-n} iP_i^2(t)}{\sum_{i=1+n}^{N-n} P_i^2(t)} \]

\[ LEP = COG - \frac{W}{2} \]

The threshold retracker was first developed by Davis (1997). The amplitude of the waveform is determined as the OCOG retracker. Then the leading edge is determined by computing the gate corresponding to threshold of the amplitude after taking care of the thermal noise component.

\[ P_N = \sum_{i=1}^{5} P_i / 5 \]

\[ T_l = (A - P_N)Th + P_N \]

\[ G_r = G_k - 1 + (T_l - P_{k-1}) / (P_k - P_{k-1}) \]
A modified subwaveform based retracker was also developed especially for inland water bodies. This method yields several subwaveforms in a multipeak waveform and thus several retracted ranges. Two Differences namely first difference (d1), which is the power difference between consecutive gates and second difference (d2), which is power difference between every alternate gate is computed.
Waveform Retracking...Modified Subwaveform Retracker
If the Atmosphere were a perfect vacuum

Wave Distribution of the ocean had a well-known distribution

\[ R = \frac{ct}{2} \]

The excess propagation path, also called path delay, induced by the neutral gases of the atmosphere between the backscattering surface and the satellite is given by:

\[ \delta h = \int_{H_{surf}}^{H_{sat}} (n(z) - 1) \, dz \]

\[ 10^{-6} N(z) = n(z) - 1 \]

\[ N(z) = 77.6 \frac{P_d}{T} + 72 \frac{e}{T} + 3.75 \times 10^5 \frac{e}{T^2} \]

\[ N(z) \text{ is given (Smith and Weintraub (1953))} \]
The excess propagation path, also called path delay, induced by the neutral gases of the atmosphere is known as Dry Tropospheric correction.

\[ DTC = \frac{0.0022768 P_0}{1 - 0.00266 \cos 2\phi} \]

Saastamoinen (1972)

where \( P_0 \) is the surface pressure in hPa, \( \phi \) is the latitude and \( h_s \) is the surface height.
Geophysical Range corrections....Dry Tropospheric Correction
The path delay due to the presence of water vapor in the atmosphere, the wet tropospheric correction (WTC), is one of the major error sources in satellite altimetry.

On-board microwave radiometers are used to estimate this correction over Ocean.

- Brightness Temperature 23.8 GHz channel measures atmospheric water vapor emission
- Brightness Temperature 36.5 GHz Channel corrects for non raining clouds

Alternatively, the vertically integrated water vapor required for the wet tropospheric range correction could be obtained from meteorological model analyses.

\[
WTC = a_0 + a_1 \times \log(280 - BT_{23.8}) + a_2 \times \log(280 - BT_{36.5}) + a_3 \times \frac{1}{(\sigma_3^2)}
\]

Bevis et. al. 1994

\[
WTC = -\left(0.101995 + \frac{1725.55}{50.440 + 0.789T_0}\right) \frac{TCWV}{1000} \tag{2}
\]

where \(T_0\) is the near-surface air temperature (two-meter temperature) and \(TCWV\) is the total column water vapor.

- ECMWF operational model (0.125 degree grid)
- ERA reanalysis (0.75 degree grid)
Radiometer Water Vapor
Atmospheric refraction from free electrons and ions in the upper atmosphere is related to the dielectric properties of the ionosphere. This columnar electron density can be approximated by the Total Electron Content (TEC).

\[
\Delta h_{ion} = 10^{-6} \int_{0}^{h} N_{ion}(z)dz = \frac{40.3 \times 10^6}{f^2} \int_{0}^{h} E(z)dz
\]

\[
IC = -40.3 \frac{TEC}{f_{K_a}^2}
\]

Picot et. al. 2003
Geophysical Range corrections....Ionospheric Correction
- **Solid earth tides**
  - The solid earth tide is the periodic movement of the Earth’s crust caused by gravitational attraction of the Sun, Moon and Earth.
  - Order of magnitude: 50 cm.

- **Pole tides**
  - This tide results from polar motion has component periods mainly of 12 months & 14 months.
  - Order of magnitude: 2 cm.

<table>
<thead>
<tr>
<th>Component</th>
<th>Magnitude</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ocean tide (open ocean)</td>
<td>±50 cm</td>
<td>±10 cm</td>
</tr>
<tr>
<td>Ocean tide (coasts)</td>
<td>±2 m</td>
<td>±10 cm</td>
</tr>
<tr>
<td>Ocean tide (ice shelves)</td>
<td>±1 m*</td>
<td>±40 cm*</td>
</tr>
<tr>
<td>Long period ocean tide</td>
<td>±1 m (with long period)</td>
<td>few cm</td>
</tr>
<tr>
<td>Pole tide</td>
<td>&lt; 2 cm</td>
<td>few mm</td>
</tr>
<tr>
<td>Ocean-loading tide</td>
<td>±10 cm</td>
<td>&lt; 0.5 cm</td>
</tr>
<tr>
<td>Solid Earth tide</td>
<td>±30 cm</td>
<td>±0.5 cm</td>
</tr>
</tbody>
</table>
Geophysical Range corrections variability
Water Level Retrieval

Water body extent
- Microwave Satellite Imagery (Monsoon)
- Optical Satellite Imagery (Non-monsoon)

Waveform Classification
- Brown (Class-1)
- Specular (Class-2)
- Rectangular (Class-3)
- Triangular (Class-4)
- Linear-rise (Class-5)

Waveform Retrackers
- Brown / ICE-2 / OCOG
- Threshold / Beta-6
- New Improved

Geophysical Range Corrections
- Dry Tropospheric Correction
- ECMWF pressure, Latitude, in-situ height
- Wet Tropospheric Correction
- Total Column Water Vapor, Temperature at 2m, in-situ height
- Ionospheric Correction
- GIM Total Electron Content maps

Satellite Altimetry Sensor Dataset (SGDR)

40 Hz Waveforms selection within reservoir

Linear Discriminant analysis, Maximum likelihood

Select next class

Select Class-1 Waveforms

Non-linear least square fitting

Sub waveform extraction

Estimate Range using retrackers and convert into water level

Remove outlier
- Standard deviation (3 o)
- Select maximum backscatter

Inland waters

Minimum Reservoir Level
- < Water Level < Full Reservoir Level

Water Level = Altitude-Range-Dry Tropospheric Correction- Wet Tropospheric Correction - Ionospheric Correction - Load Tide - Solid Earth Tide
Water level over Inland water bodies selected using Satellite Altimetry
A Landsat-8 image showing Ukai reservoir in Gujarat and plot showing the time series of water level height obtained using Envisat (red) v/s the in-situ (blue) tide gauge measurement.

In-situ data was provided by, Flood Cell, Ukai division, Tapi, Gujarat
<table>
<thead>
<tr>
<th>Date</th>
<th>In-situ gauge (m)</th>
<th>Altimeter Water level (m)</th>
<th>GPS Water level (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>17&lt;sup&gt;th&lt;/sup&gt; January 2014 (Cycle 9)</td>
<td>103.20</td>
<td>103.18</td>
<td>103.14</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(Std=3.4 cm, 7708 points)</td>
</tr>
<tr>
<td>2&lt;sup&gt;nd&lt;/sup&gt; January 2015 (Cycle 19)</td>
<td>100.67</td>
<td>100.24</td>
<td>100.226</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(Std=3 cm, 11109 points)</td>
</tr>
</tbody>
</table>
Inland water bodies selected

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Water Body</th>
<th>Sr. No.</th>
<th>Water Body</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bansagar</td>
<td>26</td>
<td>Dhora reservoir</td>
</tr>
<tr>
<td>2</td>
<td>Gandhi sagar</td>
<td>27</td>
<td>Maithon reservoir</td>
</tr>
<tr>
<td>3</td>
<td>Maharana pratap</td>
<td>28</td>
<td>Pangong lake</td>
</tr>
<tr>
<td>4</td>
<td>Mansarover</td>
<td>29</td>
<td>Panchat reservoir</td>
</tr>
<tr>
<td>5</td>
<td>Nizamsagar</td>
<td>30</td>
<td>Masanjor reservoir</td>
</tr>
<tr>
<td>6</td>
<td>Rakshatal</td>
<td>31</td>
<td>Indravati reservoir</td>
</tr>
<tr>
<td>7</td>
<td>Rana pratap sagar</td>
<td>32</td>
<td>Narayana pura reservoir</td>
</tr>
<tr>
<td>8</td>
<td>Sambhar</td>
<td>33</td>
<td>Priyadarshini reservoir</td>
</tr>
<tr>
<td>9</td>
<td>Ukai</td>
<td>34</td>
<td>Malaprabha reservoir</td>
</tr>
<tr>
<td>10</td>
<td>Bara talao</td>
<td>35</td>
<td>Almatti reservoir</td>
</tr>
<tr>
<td>11</td>
<td>Wular lake</td>
<td>36</td>
<td>Ujjani reservoir</td>
</tr>
<tr>
<td>12</td>
<td>Rihand dam</td>
<td>37</td>
<td>Mahi bajaj reservoir</td>
</tr>
<tr>
<td>13</td>
<td>Karanja reservoir</td>
<td>38</td>
<td>Itiadih reservoir</td>
</tr>
<tr>
<td>14</td>
<td>Rangwan reservoir</td>
<td>39</td>
<td>Tungabhadra reservoir</td>
</tr>
<tr>
<td>15</td>
<td>Dukwan reservoir</td>
<td>40</td>
<td>Nagarjuna sagar reservoir</td>
</tr>
<tr>
<td>16</td>
<td>Kandaleru reservoir</td>
<td>41</td>
<td>Koyana reservoir</td>
</tr>
<tr>
<td>17</td>
<td>Ranjit sagar dam</td>
<td>42</td>
<td>Bisalpur reservoir</td>
</tr>
<tr>
<td>18</td>
<td>Srisailam reservoir</td>
<td>43</td>
<td>Jai samand reservoir</td>
</tr>
<tr>
<td>19</td>
<td>Shanthi sagara</td>
<td>44</td>
<td>Sabarmati reservoir</td>
</tr>
<tr>
<td>20</td>
<td>Thokarwadi reservoir</td>
<td>45</td>
<td>Kadana reservoir</td>
</tr>
<tr>
<td>21</td>
<td>Ramtek reservoir</td>
<td>46</td>
<td>Bargi reservoir</td>
</tr>
<tr>
<td>22</td>
<td>Pujaritola reservoir</td>
<td>47</td>
<td>Tilaiya reservoir</td>
</tr>
<tr>
<td>23</td>
<td>Gudha reservoir</td>
<td>48</td>
<td>Balimela reservoir</td>
</tr>
<tr>
<td>24</td>
<td>Ekruk lake</td>
<td>49</td>
<td>Kolab reservoir</td>
</tr>
<tr>
<td>25</td>
<td>Yellareddy reservoir</td>
<td>50</td>
<td>Linganamakki reservoir</td>
</tr>
</tbody>
</table>
Water level product from VEDAS web-portal
**Satellite Altimetry over Ice-sheets**

<table>
<thead>
<tr>
<th>ROI</th>
<th>Longitude (° W)</th>
<th>Latitude (° N)</th>
<th>Accumulation Zones</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>49.5-50</td>
<td>67-68</td>
<td>Ablation Zone</td>
</tr>
<tr>
<td>B</td>
<td>43.5-44</td>
<td>64-65</td>
<td>Percolation Zone</td>
</tr>
<tr>
<td>C</td>
<td>49.5-50</td>
<td>63-64</td>
<td>Ablation Zone</td>
</tr>
<tr>
<td>D</td>
<td>33.5-34</td>
<td>77-78</td>
<td>Percolation Zone</td>
</tr>
<tr>
<td>E</td>
<td>54.5-55</td>
<td>77-78</td>
<td>Dry Snow Zone</td>
</tr>
<tr>
<td>F</td>
<td>24.5-25</td>
<td>73-74</td>
<td>Wet Snow Zone</td>
</tr>
<tr>
<td>G</td>
<td>51.5-52</td>
<td>73-74</td>
<td>Wet Snow Zone</td>
</tr>
<tr>
<td>H</td>
<td>30.5-31</td>
<td>71-72</td>
<td>Ablation Zone</td>
</tr>
<tr>
<td>I</td>
<td>49.5-50</td>
<td>77-78</td>
<td>Dry Snow Zone</td>
</tr>
<tr>
<td>J</td>
<td>46.5-47</td>
<td>62-63</td>
<td>Wet Snow Zone</td>
</tr>
<tr>
<td>K</td>
<td>37.5-38</td>
<td>76-77</td>
<td>Dry Snow Zone</td>
</tr>
<tr>
<td>L</td>
<td>42.5-43</td>
<td>73-74</td>
<td>Dry Snow Zone</td>
</tr>
<tr>
<td>M</td>
<td>36.5-37</td>
<td>67-68</td>
<td>Wet Snow Zone</td>
</tr>
<tr>
<td>N</td>
<td>30.5-31</td>
<td>80-81</td>
<td>Percolation Zone</td>
</tr>
</tbody>
</table>

**Diagram:**

- **ALTITUDE**
  - Ice Height = ALTITUDE – RANGE
  - WTC – DTC – IC – Solid Earth Tide – Pole Tide – GEOID
- **RANGE**
  - Ice Height datum conversion from TOPEX ellipsoid to WGS84
- **Correction**
  - Dry Troposphere
  - Wet Troposphere
  - Inosphere
  - Solid Earth Tide
  - Pole Tide
- **Selection Criteria**
  - 3s for retracker selection and Height estimation
- **Ocean retracker**
- **ICE-1 Retracker**
- **Ice height over Greenland ice sheet** (Polar Stereographic)
Ice Height estimation over Greenland Ice sheet using SARAL

Cycle 5
Aug 2013

ICESAT/GLAS DEM Slope map
• Almost 98% of Antarctic continent is covered with ice, which when melted will rise global sea level by ~56 m.
Future scope of Radar altimetry

Wide-Swath Altimetric Measurement of Ocean Surface Topography

Report of the Wide Swath Ocean Altimeter Science Working Group

Edited by Lee Liang Fu

KaRIN: Ka-band Radar Interferometer

The Problem Altimeters miss considerable dataset
All altimeter dataset is free, we should utilize as per the requirement
(ftp://avisoftp.cnes.fr/AVISO/pub/)

Further reading
(https://www.aviso.altimetry.fr/)

Thanks

schander@sac.isro.gov.in