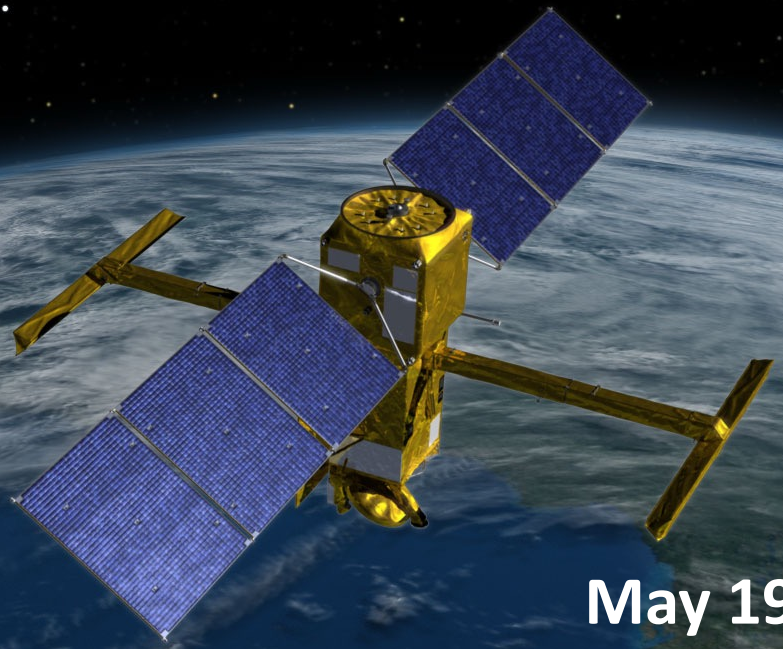
National Aeronautics and Space Administration

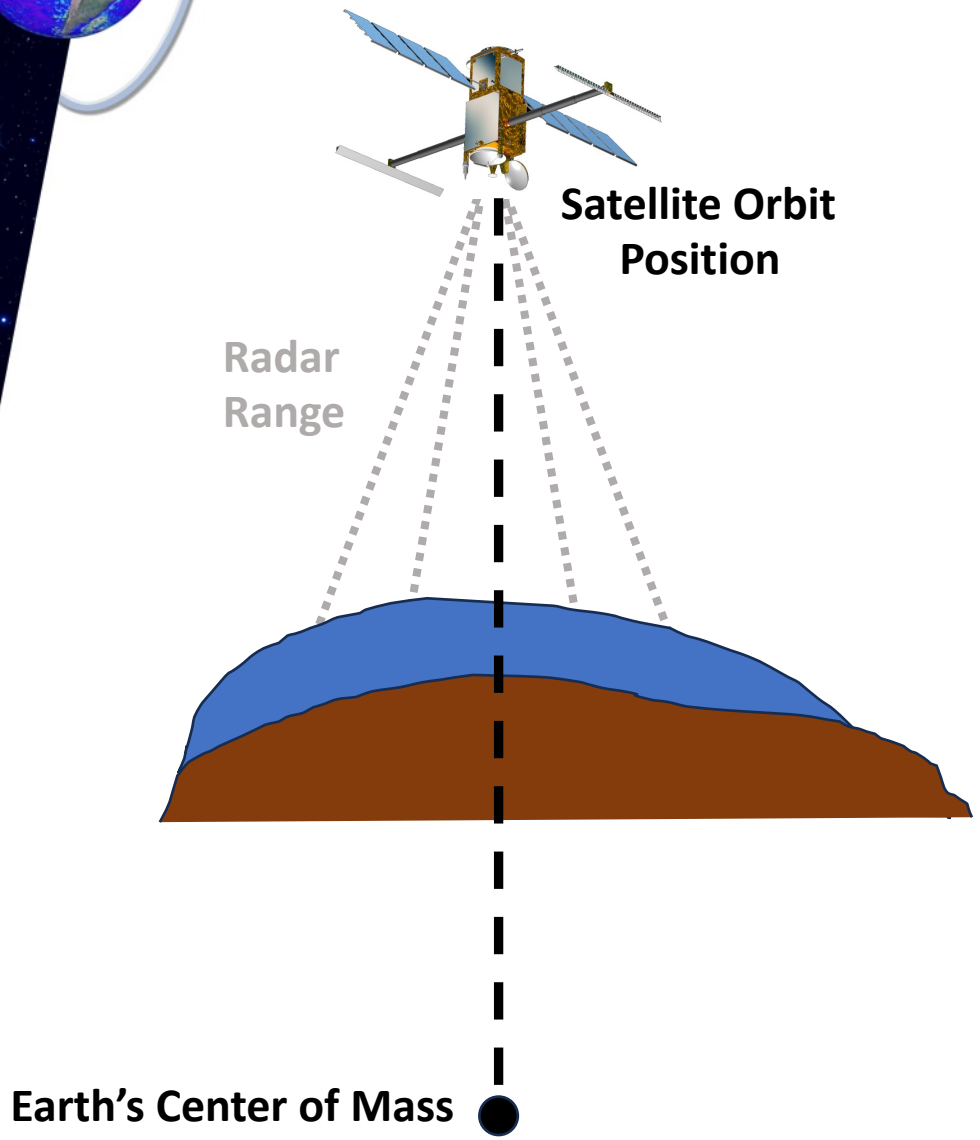
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

SWOT Reference Frame, Geodetic Coordinates, Reference Surfaces, and Tides



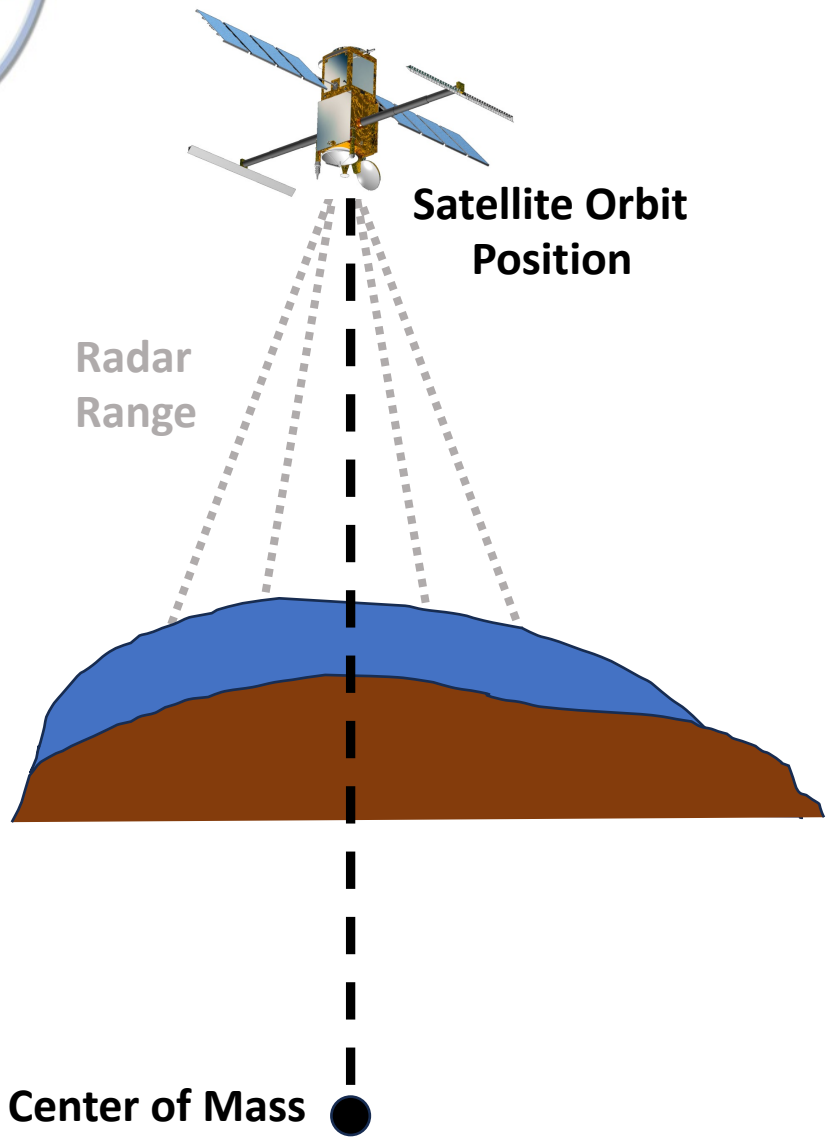
May 19, 2025

Motivation



- **SWOT measures height of surface water with respect to the instantaneous center of mass of the Earth system.**
  - Inherently measures motion of crust and water with respect to instantaneous center of mass of Earth.
- Geometric difference between:
  - Satellite orbit position with respect to Earth's instantaneous center of mass.
    - Satellite motion is about the Earth's center of mass.
  - Radar range to surface water.
- SWOT products use various models to facilitate representation of measurements in a form more analogous to height of water with respect to moving Earth's crust.
  - For example, as might be reported by a tide gauge fixed to the Earth's crust, or bottom pressure gauge.

Relevant Models



- **Reference Frame:** Defines the coordinate system for the measurements.
  - Source of reference frame is the coordinate system used to represent the satellite orbit position.
- **Static Reference Surfaces:** Defines the static reference level of the height of the water surface reported on products.
  - **Reference Ellipsoid**: Simple oblate spheroid to represent shape of Earth.
  - **Geoid**: Equipotential surface representing shape of the Earth.
    - Follows shape of mean sea surface over oceans.
  - **Mean Sea Surface**: Long-term average of the height of the ocean surface.
- **Tides:** Predictable contributors to measurements of geocentric height of surface water.
  - **Solid Earth Tide, Ocean Tide, Load Tide, Pole Tide, Dynamic Atmosphere Correction (DAC).**

Reference Frame versus Reference Ellipsoid

- SWOT reference frame and reference ellipsoid are not intrinsically tied to each other.
  - **Reference frame:**
    - Earth-centered, Earth-fixed cartesian (XYZ) coordinate system.
    - Origin is at instantaneous center of mass (CM) of the entire Earth system, as realized by satellite geodesy.
    - High-accuracy estimates of SWOT spacecraft position and velocity are computed in the adopted reference frame.
    - Spacecraft cartesian position estimates transfer adopted reference frame to SWOT measurements.
  - **Reference ellipsoid:**
    - Captures the approximate oblate spheroid shape of the Earth in two parameters: semi-major axis and flattening.
    - Facilitates expression of SWOT measurements in geodetic coordinates of latitude, longitude, height.

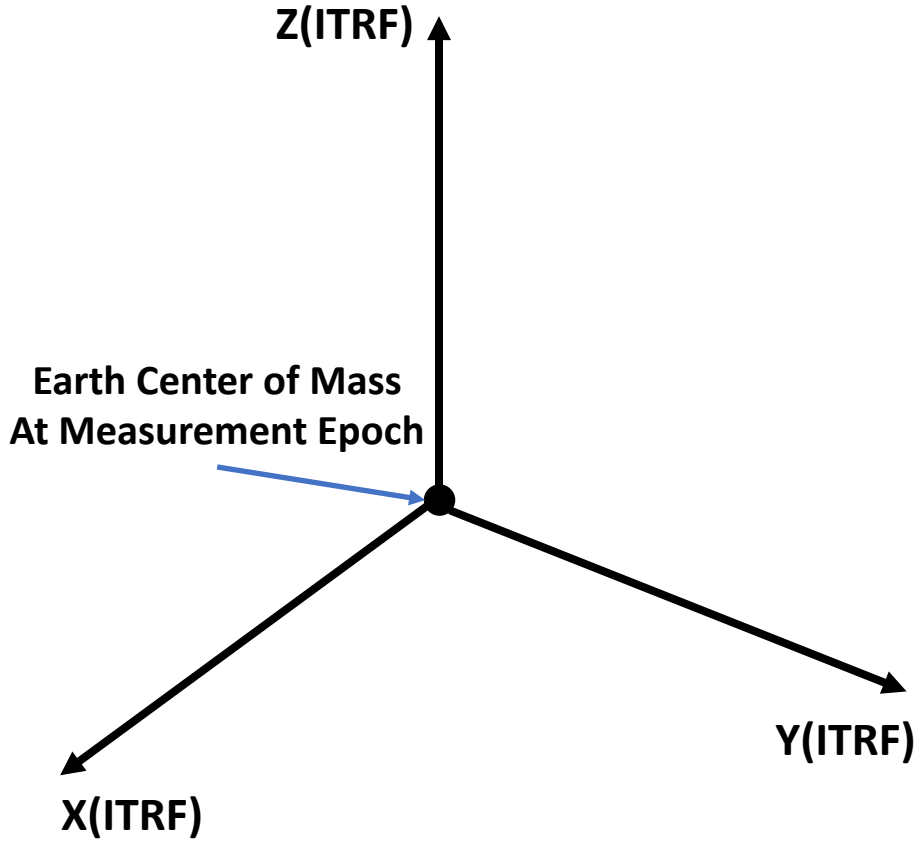
- **Reported geodetic coordinates (latitude, longitude, height) of SWOT measurements are consistent with the adopted reference frame and ellipsoid.**
  - Center of reference ellipsoid is the adopted reference frame.
  - Geodetic coordinates computed from cartesian XYZ coordinates in adopted reference frame using shape of adopted referenced ellipsoid.
    - Height is with respect to shape of ellipsoid and not local gravimetric deflection.

- SWOT approach leverages significant heritage from over 30 years of nadir altimetry.
  - SWOT products through Version D adopt the same reference frame (ITRF14) and reference ellipsoid (WGS84) as used by nadir altimetry version F product standards.

SWOT Reference Frame

- SWOT products adopt the International Terrestrial Reference Frame (ITRF).
  - ITRF long-term origin aims to represent the center of mass of the Earth system.
  - ITRF2014 used through Version D products.
  - **See section 3.3.2 of User Handbook.**

- **Reference frame of SWOT measurements is as realized by adopted ITRF at the time of the measurements.**
  - Centered on instantaneous center of mass of the Earth system at time of SWOT measurements.
  - Not at the reference epoch used by the ITRF to align the various geodetic techniques or, for example, 2010.0 epoch.

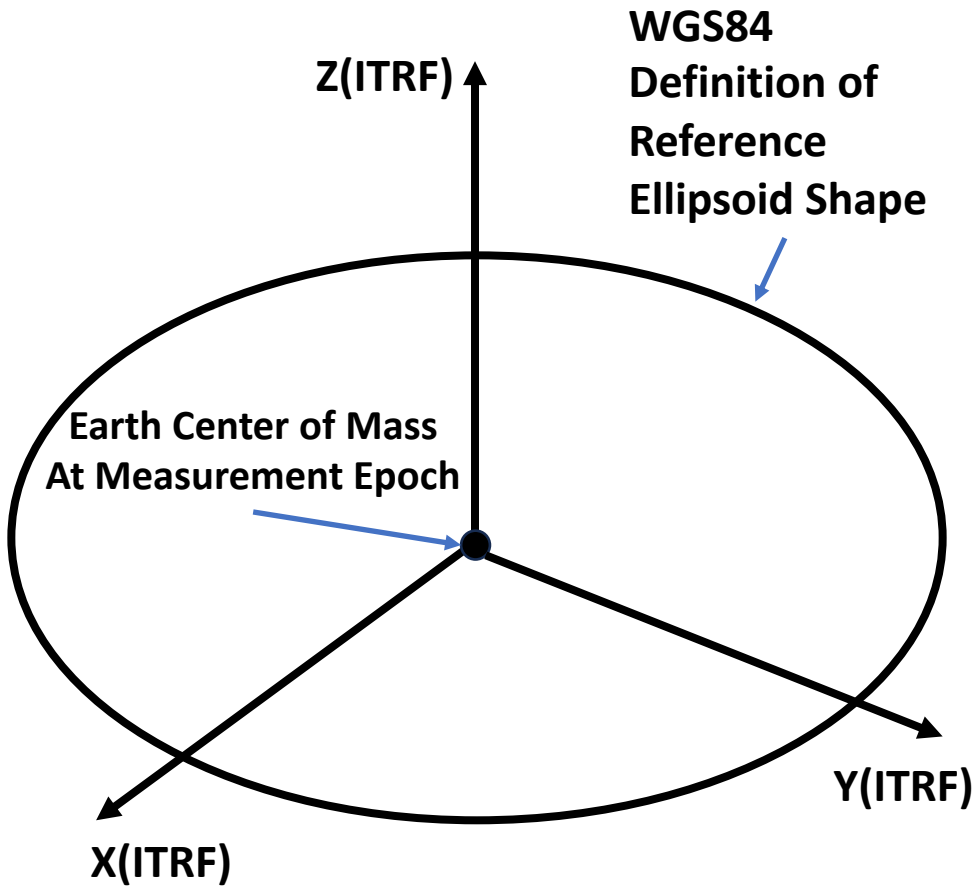


SWOT Reference Ellipsoid and Geodetic Coordinates

- SWOT products adopt the WGS84 definition of the reference ellipsoid through Version D SWOT products.
  - Semi-major axis: 6378137 m
  - Flattening: 1/298.257223563
  - **See Section 3.3.3 of User Handbook.**

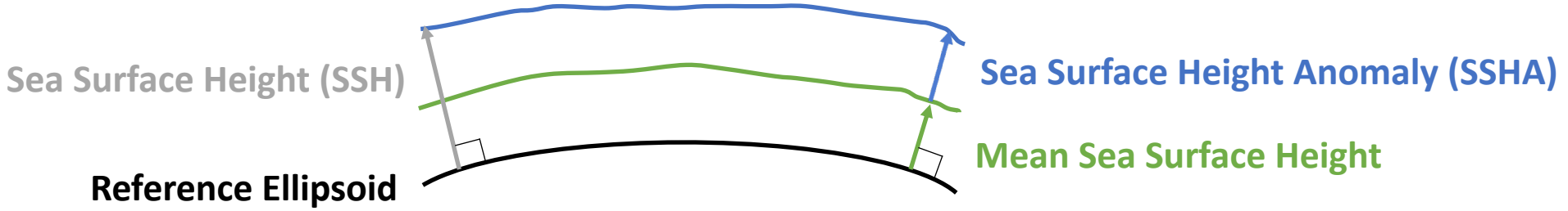
- Center of the reference ellipsoid is instantaneous center of mass of Earth system at measurement time.
  - As realized by ITRF at the measurement time.

- **SWOT uses the term "WGS84" to refer to the shape of the reference ellipsoid ONLY.**
  - **Does not refer to any of the WGS84 terrestrial reference frames.**



Static Reference Surfaces for Measurements and Models: SWOT LR (Ocean) Products

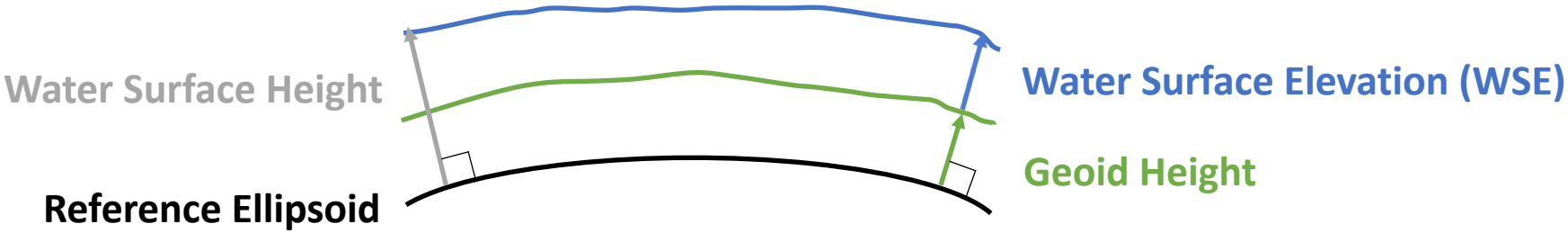
Measurement or Model	Reference Static Surface	SWOT Product
Geoid Height	Reference Ellipsoid	KaRIn L2_LR_SSH, Nadir Altimeter
Mean Sea Surface Height	Reference Ellipsoid	KaRIn L2_LR_SSH, Nadir Altimeter
Sea Surface Height (SSH)	Reference Ellipsoid	KaRIn L2_LR_SSH
Sea Surface Height Anomaly (SSHA)	Mean Sea Surface (Mean-Tide)	KaRIn L2_LR_SSH, Nadir Altimeter



- **See Sections 3.1.23 3.1.24, and 6.9 of User Handbook.**
  - **Users must explicitly apply reported crossover calibration correction to reported KaRIn SSH and SSHA.**
  - Reported SSH **does not use models** to subtract effects of tides and dynamic atmosphere correction.
    - Users should explicitly apply provided corrections for tides and dynamic atmosphere correction as they choose.
  - Reported SSHA **is after using models** to subtract effects of tides and dynamic atmosphere correction.

Static Reference Surfaces for Measurements and Models: SWOT HR (Hydrology) Products

Measurement or Model	Reference Static Surface	Product
Geoid Height	Reference Ellipsoid	All Level 2 SWOT HR Products
Water Surface Height	Reference Ellipsoid	KaRIn L2_HR_PIXC
Water Surface Elevation (WSE)	Geoid (Mean-Tide)	KaRIn L2_HR_RiverSP/Avg, L2_HR_LakeSP/Avg, and L2_HR_Raster



- **See Sections 3.1.23 and 3.1.25 of User Handbook.**
  - **Reported Water Surface Height and WSE are after applying reported crossover calibration correction.**
  - Reported Water Surface Height **does not use** models to subtract effects of tides.
    - Users should explicitly apply provided corrections for tides as they choose.
  - Reported Water Surface Elevation (WSE) **is after using models** to subtract effects of solid-Earth, load, and pole tides that affect the Earth crust.

Applied Tide Corrections on LR (for SSHA) and HR (for WSE) Products

Tide Component	Description
Solid Earth (Body) Tide Height	Direct response of solid Earth crust to luni-solar tide-generating forces.
Ocean Tide Height	Direct barotropic response of the oceans to luni-solar tide-generating forces.
Load Tide Height	Indirect response of the solid Earth crust to load of ocean tide mass. Computed with respect to center of mass of Earth.
Internal (Ocean) Tide Height	Indirect baroclinic response of the oceans to the barotropic ocean tide. SWOT model only includes coherent internal ocean tide.
Pole Tide Height	Response of the solid Earth crust and oceans to centrifugal potential force resulting from polar motion. Includes solid Earth, ocean, and load pole tides. Ocean pole tide = 0 over land.

LR Products

SSHA = (SSH
- mean_sea_surface_height
- solid_earth_tide_height
- ocean_tide_height
- load_tide_height
- internal_tide_height
- pole_tide_height
- dynamic_atmosphere_correction). (3.4)

From Section 3.1.24 of User Handbook

HR Products

WSE = (*H*
- geoid_height
- solid_earth_tide_height
- load_tide_height
- pole_tide_height). (3.5)

From Section 3.1.25 of User Handbook

Reported Geoid Height on SWOT Products is in Mean-Tide System

- **Mean-Tide Geoid height is always used on SWOT products.**
  - Includes both reported and applied values.
  - SWOT adopts Mean-Tide EGM2008 through Version D products.
  - Follows convention adopted by altimetry products.
  - **See Section 11.3.1 of User Handbook.**

- SWOT approach for Mean-Tide Geoid Height.
  - **Mean-Tide Geoid Height = Tide-Free Geoid Height + Δh**
  - Tide-Free EGM2008 distributed by National Geospatial-Intelligence Agency (NGA).
    - In geodetic coordinates with respect to WGS84 ellipsoid [Pavlis et al., 2012].
  - $\Delta h = (1.0 + k_2)*H_{perm}*\mathrm{sqrt}(5/(4*\pi))*(1.5*\sin(\theta)*\sin(\theta) - 0.5)$
    - H_{perm} = -0.31460 m, k_2 = 0.3, θ = geocentric latitude.
    - NOTE: Has been applied using geodetic latitude in SWOT products through Version D, which results with < 1.3 mm error.

Difference Between Mean-Tide and Tide-Free Geoid Height

- At equator:
  - Mean-Tide Geoid height larger than Tide-Free Geoid height by 12.9 cm.
  - Water surface elevation relative to mean-tide geoid smaller than relative to tide-free geoid.

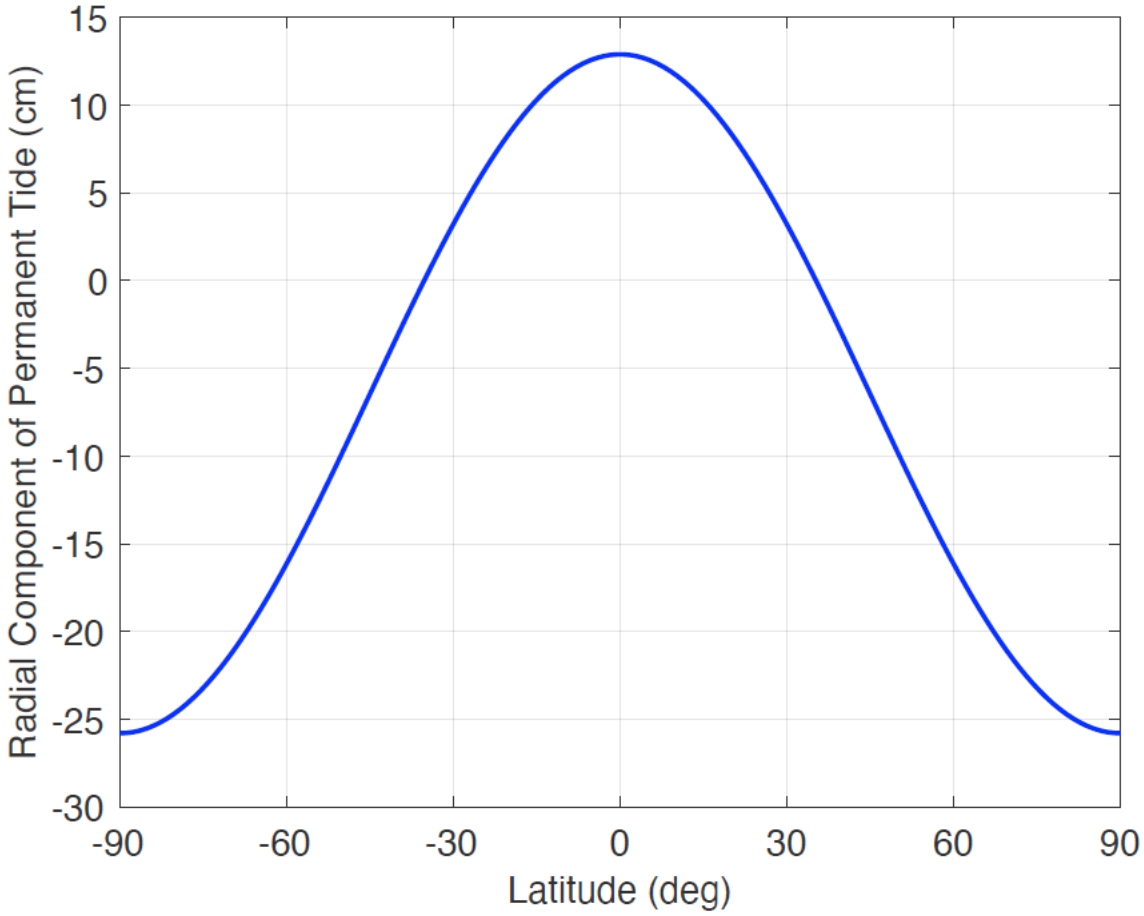


Figure 11.2: Difference Δh between mean-tide and tide-free geoid heights.

From Section 11.3.1 of User Handbook

Solid Earth (Body) and Ocean Tide Heights on SWOT Products Do Not Include Contribution from Permanent Tide

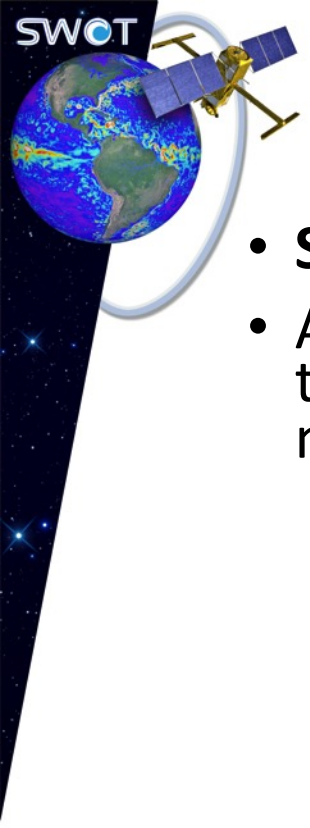
- **Models for solid Earth and ocean tide heights on SWOT products do not include contribution from the permanent tide.**
  - Reported solid Earth and ocean tide heights on SWOT products have zero mean over time at a particular position.
    - Permanent tide represents the Earth's response to the time-independent (zero-frequency) component of the luni-solar tide-generating forces.
  - Follows convention adopted by altimetry products.
  - **See Section 11.3.4 of User Handbook.**

- Mean sea surface height models generated from historical altimetry data include displacement from permanent tide.
  - Natural consequence of historical altimetry data not including permanent tide height in adopted models of solid Earth and ocean tide heights.

Comparing SWOT Measurements to Independent Data: Use the Same Reference Frame

- **SWOT measurements are referenced to the instantaneous center of mass of the Earth system at the measurement time.**
  - As realized by the ITRF at the measurement time.
  - SWOT products through Version D adopt ITRF14.
    - ITRF14 and ITRF20 are very close (see Altamimi et al., 2023).

- If necessary, transform coordinates of independent data to ITRF at measurement time.
  - Best to use ITRF14, but ITRF20 is very close (likely < 1 cm).



Relationship Between ITRF and WGS84 Reference Frames

- **SWOT does not use the WGS84 terrestrial reference frame**.
- According to documentation from National Geospatial-Intelligence Agency (NGA), the three most recent WGS84 terrestrial reference frames are aligned with the three most recent ITRFs:
  - WGS84(G2296) Terrestrial Reference Frame: "***This new WGS 84 frame realization is aligned to both the ITRF2020****, the most recent ITRF realization, and the IGS20, the frame used by the International GNSS Service (IGS).*"
    - https://earth-info.nga.mil/php/download.php?file=WGS%2084(G2296).pdf
  - WGS84(G2139) Terrestrial Reference Frame: *"**WGS 84(G2139) is coincident with ITRF14(IGb14)** for the purposes of positioning and navigation*."
    - https://earth-info.nga.mil/php/download.php?file=(U)WGS%2084(G2139).pdf
  - WGS84(G1762) Terrestrial Reference Frame: "*World Geodetic System 1984* ***(WGS 84) G1762, bringing WGS 84 into further alignment with ITRF08 and IGb08***."
    - https://gpsworld.com/wp-content/uploads/2014/08/WGS-84-G1762.pdf
- WGS84(G2139), WGS84(G2296), ITRF2014, and ITRF2020 are all linear frames defined by position and velocity of globally distributed ground stations.
  - **All should be evaluated at the SWOT measurement times when comparing to measurements on SWOT products.**
    - Should not be evaluated at any specific reference epoch, for example, at 2010.0 epoch.

Comparing SWOT Measurements to Independent Data: Use the Same Reference Static Surface

- SWOT adopts models of the mean-tide geoid and a mean sea surface that include contribution from permanent tide.
  - Reported WSE on SWOT products through Version D referenced to mean-tide EGM08 geoid.
  - Reported SSHA on SWOT products referenced to:
    - CNES/CLS 2022 mean sea surface on Version C.
    - CNES/CLS/SIO/DTU Hybrid 2023 mean sea surface on Version D.

- If necessary, adjust independent data to use consistent reference static surface.
  - Including reference ellipsoid, geoid, and mean sea surface.
  - **See Sections 3.1.24 and 3.1.25 of User Handbook for SWOT approach** (also on slide 9).

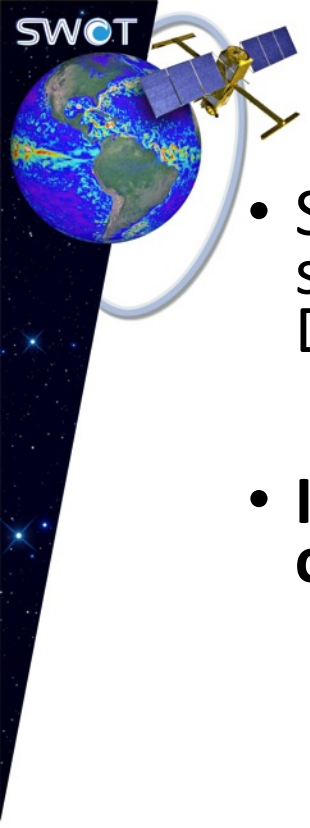
- Examples:
  - If independent WSE data referenced to GeoidX, say WSE(GeoidX):
    - WSE (mean-tide EGM08 geoid) = WSE (GeoidX) + GeoidX – Mean-Tide-EGM08

  - If independent WSE data referenced to Tide-Free EGM2008:
    - WSE (mean-tide EGM08 geoid) = WSE (tide-free EGM08 geoid) - Δh
      - Where Δh is as shown on slide 10. **See section 11.3.1 of User Handbook.**

Comparing SWOT Measurements to Independent Data: Use Consistent Treatment of Tides in Solid Earth

- SWOT products aim to report SSHA and WSE measurements with respect to the moving crust of the solid Earth.
  - As would be observed by a tide-gauge fixed to the crust or bottom pressure gauge.
  - SWOT radars observe surface height, **including displacement of crust and surface water**, relative to the center of the Earth.
  - Models are used to subtract contribution of crustal displacements that result from the solid Earth, load, and pole tides from observed surface height.
    - Largest, and most predictable, contributors to crustal motion.
    - NOTE: SWOT products report load tide with respect to center of mass of Earth.

- If necessary, adjust independent data to use consistent treatment of tides in solid Earth.
  - **See Sections 3.1.24 and 3.1.25 of User Handbook for SWOT approach** (also on slide 9).
  - Alternatively, use the adopted models for effects of solid Earth tides provided on SWOT products to adjust the SWOT measurements to approach used by independent data.
    - Less optimal since, for example, SWOT WSE is generated from aggregate of point (pixel cloud) measurements.



IERS Solid Earth Tide Model Includes Permanent Tide Height

- Solid Earth Tide model from the International Earth Rotation Service (IERS) standards is typically used by the four geodetic positioning services (GNSS, DORIS, SLR, VLBI) and related precise geodetic processing software.

- **IERS solid Earth tide model includes contribution from the time-independent component (i.e., permanent tide), unlike model used in SWOT products.**
  - Solid Earth tide heights from IERS model do not have zero mean over time at a particular position.
  - Coordinates computed after using the IERS model to subtract effects of solid Earth tide are referred to as “conventional tide free” values.

- IERS Conventions (Section 7.1.1.2) refers to this (permanent tide) component as the “permanent deformation”, Δh_{pd}.
  - $\Delta h_{pd} = h_2 * H_{perm} * \mathrm{sqrt}(5/(4*\pi)) * (1.5*\sin(\theta)*\sin(\theta) - 0.5)$
    - H_{perm} = -0.31460 m, h_2 = 0.6078, θ = geocentric latitude.
    - NOTE: Using geodetic latitude results with < 0.6 mm error.
  - **See Section 11.3.4.1 of User Handbook.**

Permanent Deformation Component of IERS Solid Earth Tide Model

- Differences of -12 to + 6 cm will exist when SWOT data are compared to independent data that have used the IERS model to subtract effects of solid Earth tide.
  - Depends on latitude.

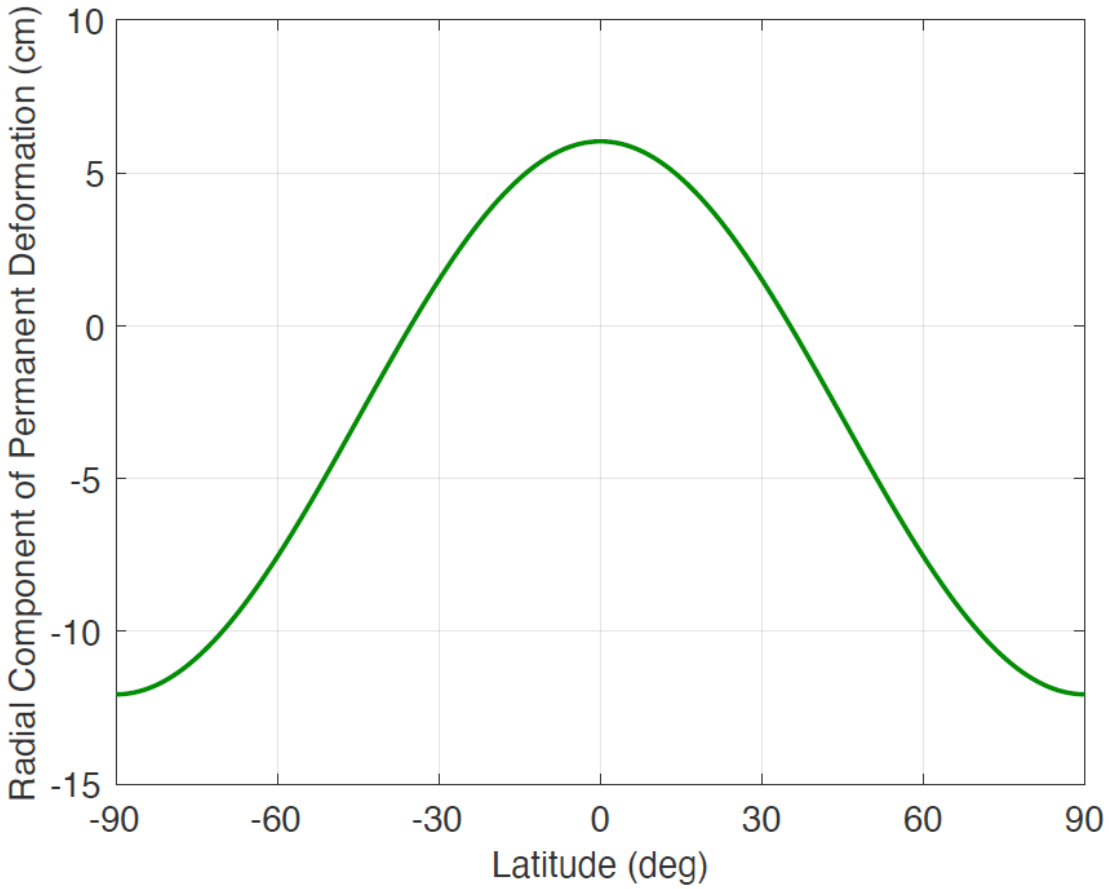


Figure 11.4: Permanent deformation Δh_{pd} to add to conventional tide-free coordinates.

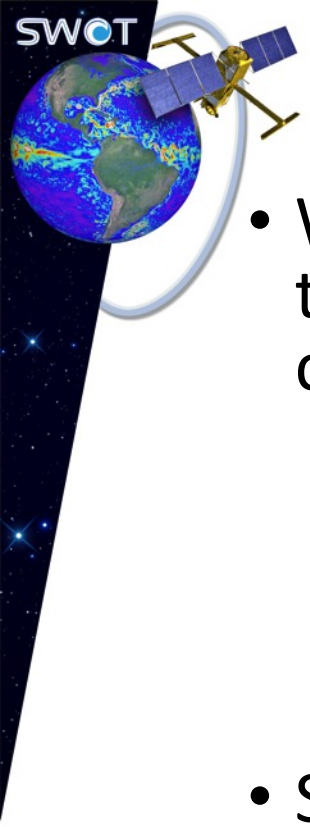
From Section 11.3.4.1 of User Handbook

Comparing SWOT Measurements to Independent Data:
Example to Adjust For Difference Between SWOT and IERS Solid Earth Tide Model

- If independent data subtract effects of solid Earth tides using the IERS model, they must be adjusted for different treatment of permanent deformation in the SWOT model, e.g.,
  - If independent WSE data use IERS solid Earth tide model, say WSE (IERS):
    - WSE (SWOT) = WSE (IERS) + Δh_{pd}
    - Where Δh_{pd} is as shown on slide 17.
    - See also **Section 11.3.4.1 of User Handbook** and Section 7.1.1.2 of IERS Conventions.

Comparing SWOT Measurements to Independent Data:
Use Consistent Treatment of Load Tide

- Load tide on SWOT products is with respect to center of mass of Earth, consistent with the measurements.
- Many geodetic positioning software packages allow users to choose between modeling the load tide with respect to Earth's center of mass or center of figure.
  - For GNSS positioning, use the option that is consistent with the provider's representation of the GNSS satellite orbit positions and clocks.
  - Otherwise, typically, choose option for load tide with respect to Earth's center of mass.



Conclusions

- When comparing SWOT data to independent data, user must take care to ensure that the two data sets use a common set of representation conventions.
  - User may need to convert or transform one or both data sets to reach this common representation.
  - The fine measurement precision and global coverage of SWOT products means that users must be cognizant of the details of the representation conventions when making these comparisons.
- SWOT representation conventions are documented in the SWOT User Handbook
  - https://podaac.jpl.nasa.gov/SWOT?tab=datasets-information&sections=about
- Users are responsible for determining the representations of their independent data to which SWOT is compared.
  - May also need to be familiar with assumptions that are embedded in conversion or transformation software, as well as positioning software.