Could Satellite Altimetry have Improved Early Detection and Warning of the 2011 Tohoku Tsunami?

Ben Hamlington[1], Robert Leben[1], Oleg Godin[2], Edison Gica[3], Vasily Titov[3], Bruce Haines[4], Shailen Desai[4]

1. Colorado Center for Astrodynamics Research
2. NOAA/Earth System Research Laboratory
3. NOAA Center for Tsunami Research
4. Jet Propulsion Laboratory

Early Warning and Detection of Tsunami

- Early warning of an impending tsunami is heavily dependent on the detection of the tsunami away from the shore.
  - Wave amplitude in the open ocean is small (generally < 1 meter).
  - Difficult to distinguish tsunami signal from other ocean variability until tsunami approaches the shore.
  - Detection must occur with enough lead-time to allow coastal populations to move to safety.
- Models have generally been used to provide early assessment of an impending tsunami threat.
  - Without actual observations in the open ocean, it is difficult to definitively determine the presence of a tsunami in the ocean.
  - Open ocean observations could also be used to hone model predictions and improve representation of the earthquake source (Geist et al. 2007; Yamakazi et al. 2011).

Detection of Tsunami by Satellite Altimetry

- In recent years, tsunami detection has been demonstrated in the open ocean using measurements from satellite altimeters.
  - Detection using sea surface height measurements:
    - **1992 Nicaragua Tsunami** (Okal et al. 1999)
    - **1995 Chile Tsunami** (Okal et al. 1999)
    - **2004 Sumatra-Andaman Tsunami** (e.g. Smith et al., 2005; Song et al., 2005; Ablain et al., 2006; Hirata et al., 2006; Geist et al., 2007; Gower, 2007; Hayashi, 2008; Hoechner et al., 2008)
    - **2010 Chile Tsunami** (Hamlington et al. 2010)
  - Detection using sea surface roughness measurements
    - **2004 Sumatra-Andaman Tsunami** (Godin et al. 2004)
    - **2010 Chile Tsunami** (Hamlington et al. 2010)

Can Satellite Altimeters Help With Early Warning and Detection of Tsunamis?

"Unfortunately, satellite altimetry bears little promise of useful contribution to future tsunami warning systems, as it requires intensive and time- consuming data processing, and above all, the presence of a satellite at the right place at the right time." (Okal, 2011).

- Statement has frequently been made that there is only a small chance of observing a tsunami with along-track measurement system of satellite altimetry.
  - May be true for smaller-scale events, but does not hold true for larger events.
- Relevant questions:

1. Not if, but how soon after the tsunamigenic event will a satellite altimeter sample the tsunami?
2. How can satellite altimeter measurements be used for improving tsunami early warning and detection?

To better answer these questions, we study the 2011 Tohoku tsunami (Note: This study was done assuming Envisat 35-day repeat orbit and Jason-1 in interleaved 10-day repeat orbit).

2011 Tohoku Tsunami

- Tohoku tsunami generated by Mw 9.0 earthquake at 5:46 UTC on March 10th, 2011, approximately 130 km east of Sendai, Honshu, Japan.
  - Caused over 19,000 casualties in northeastern Japan and affected more than 57 cities (Ando et al. 2011).
- **Important to emphasize that we do not suggest that satellite altimetry could have helped for the warning of coastal populations of Japan.**
  - Time between earthquake and arrival of tsunami was measured in minutes rather than hours.
  - Quickest and best warning for coastal populations in such close proximity to the location where the tsunami was the earthquake itself.
  - Here, we focus on improving far-field tsunami detection and warning (time-lag between tsunami generation and arrival on the order of hours).

Satellite Altimeter Coverage of 2011 Tohoku Tsunami

Envisat:

Pass 419 of cycle 100 (5.5 hours)

Pass 428 of cycle 100 (13 hours)

Pass 439 of cycle 100 (22 hours)

Jason-1:

Pass 147 of cycle 338 (7.5 hours)

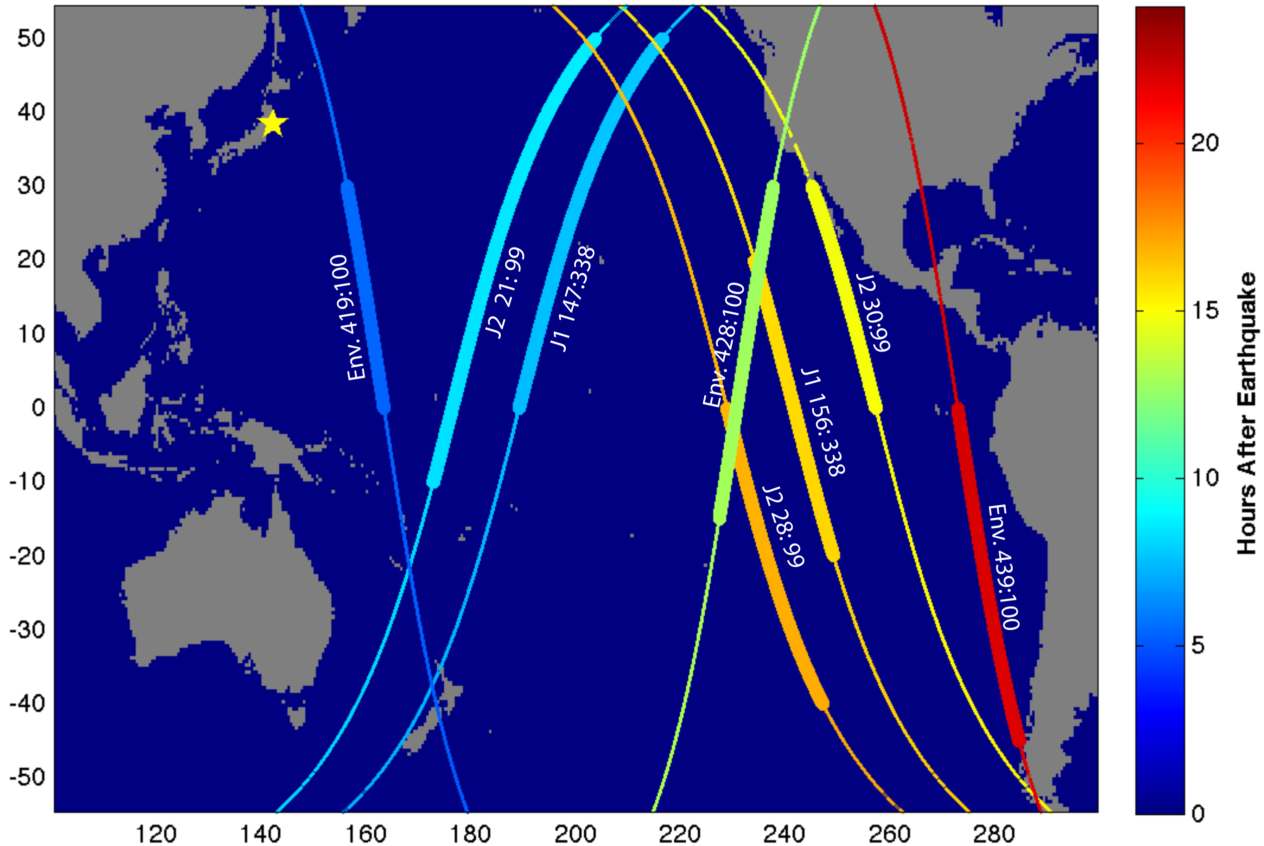
Pass 156 of cycle 338 (16 hours)

Jason-2:

Pass 21 of cycle 99 (8.5 hours)

Pass 28 of cycle 99 (15 hours)

Pass 30 of cycle 99 (17 hours)



Satellite Altimeter Coverage of 2011 Tohoku Tsunami

Envisat:

Pass 419 of cycle 100 (5.5 hours)

Pass 428 of cycle 100 (13 hours)

Pass 439 of cycle 100 (22 hours)

Jason-1:

Pass 147 of cycle 338 (7.5 hours)

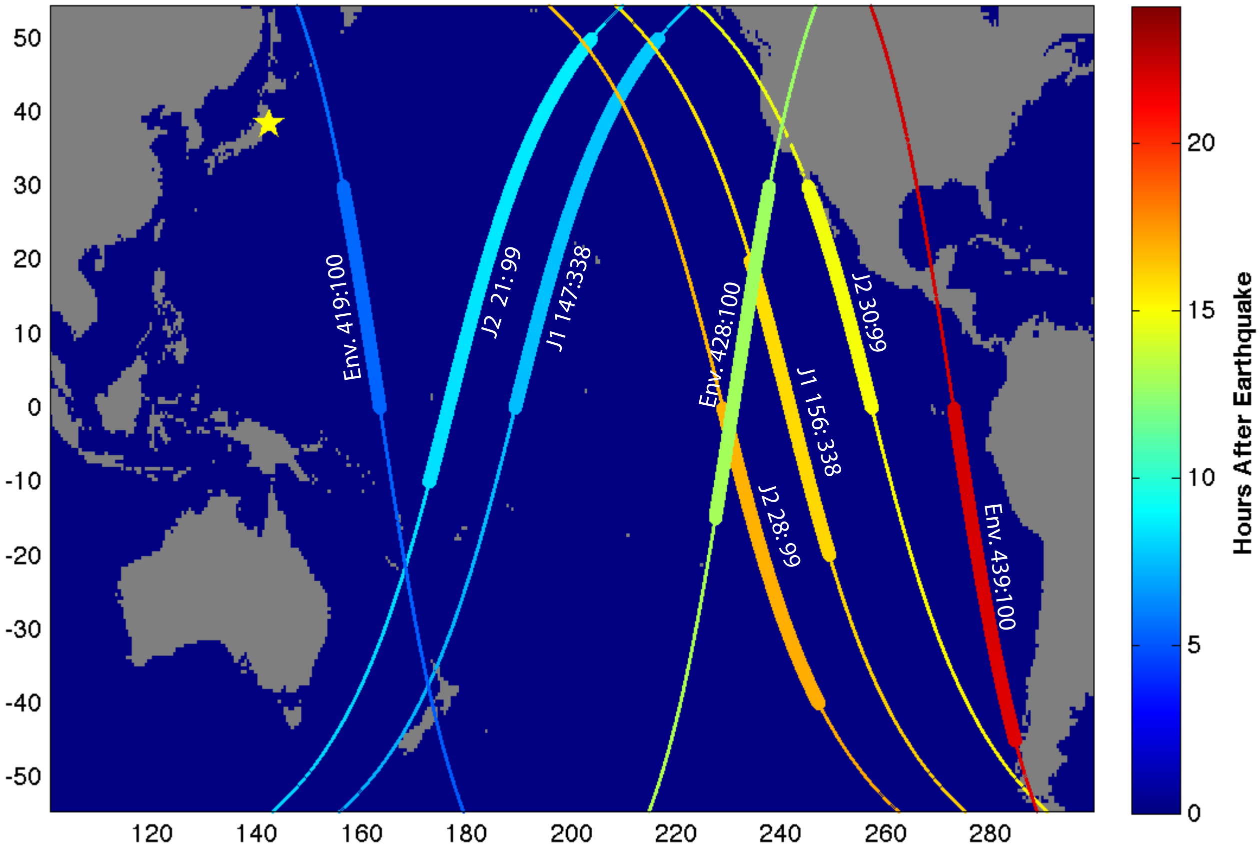
Pass 156 of cycle 338 (16 hours)

Jason-2:

Pass 21 of cycle 99 (8.5 hours)

Pass 28 of cycle 99 (15 hours)

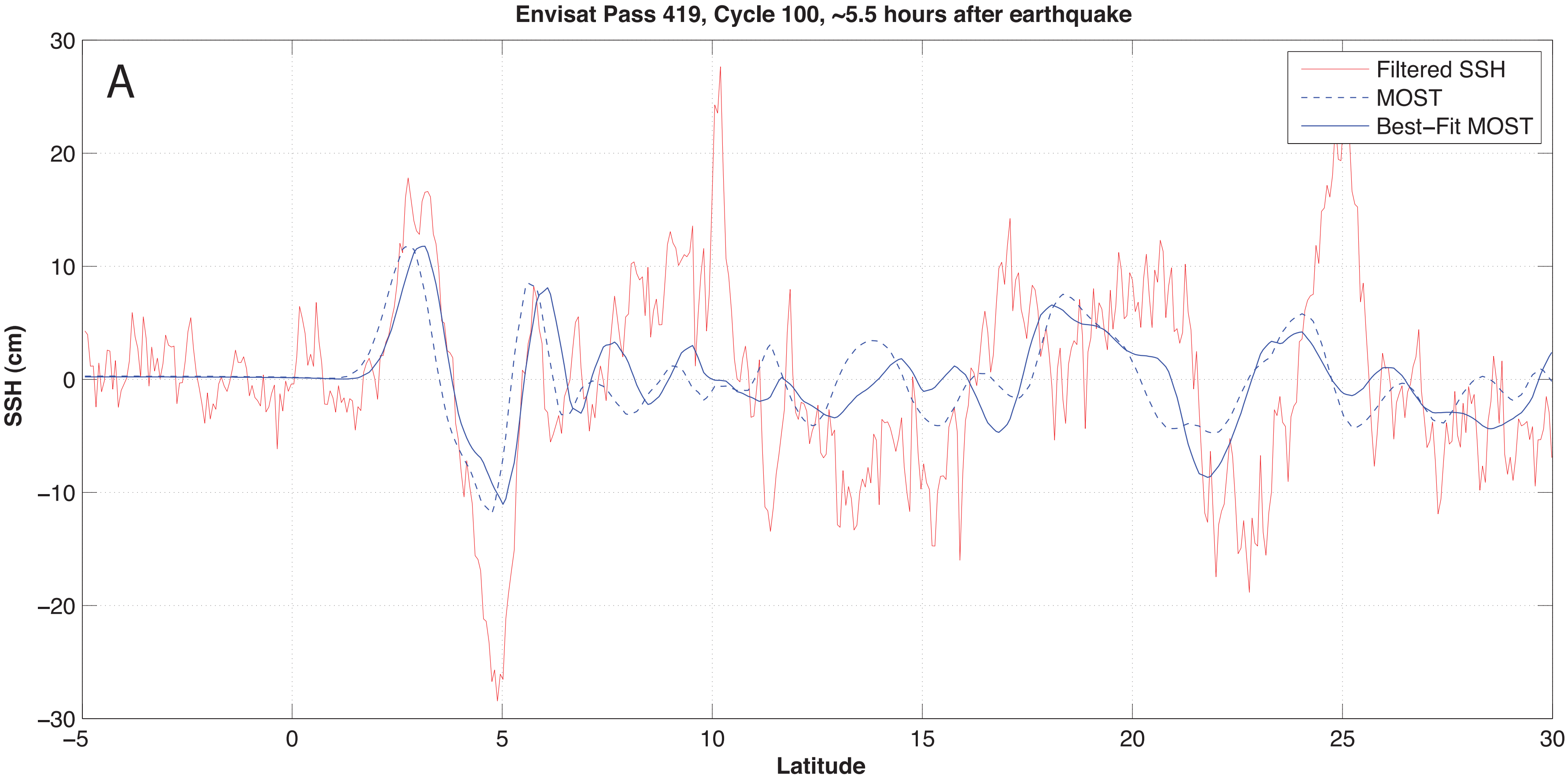
Pass 30 of cycle 99 (17 hours)



Data

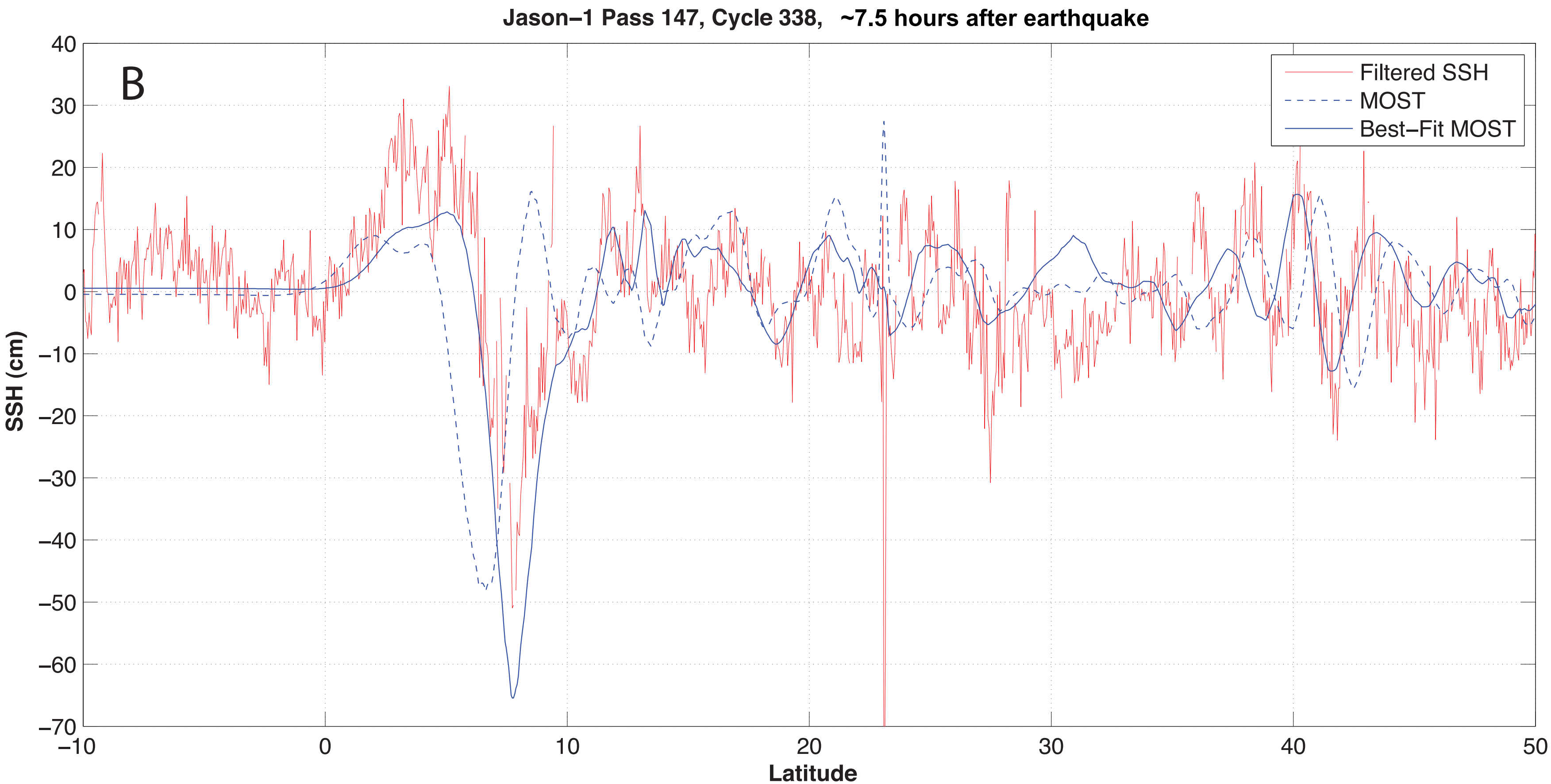
- Jason-1 and Jason-2 Near Real Time SSH anomaly data was obtained from the Physical Oceanography Distributed Archive Center (PO.DAAC) at NASA JPL.
  - For Envisat and for historical Jason-1 data used in randomization tests, SSH measurements were obtained from the Radar Altimeter Database System (RADS).
  - At time of study, Jason-1 and Envisat NRT SSH data had average latency of roughly 7 hours, with Jason-2 having latency closer to 4 hours.
  - Data is filtered by removing smoothed average of previous two cycles along same pass (Gower 2007; Hamlington et al. 2011).
- For comparison and to verify time and location of tsunami leading edge, we used the Method of Splitting Tsunami (MOST) model SSH data produced by NOAA Center for Tsunami Research (Titov et al. 2005).
  - 2-D SSH data from MOST were interpolated at times and locations of each altimeter ground-track and compared to NRT SSH data.

Model vs. NRT Data: Envisat

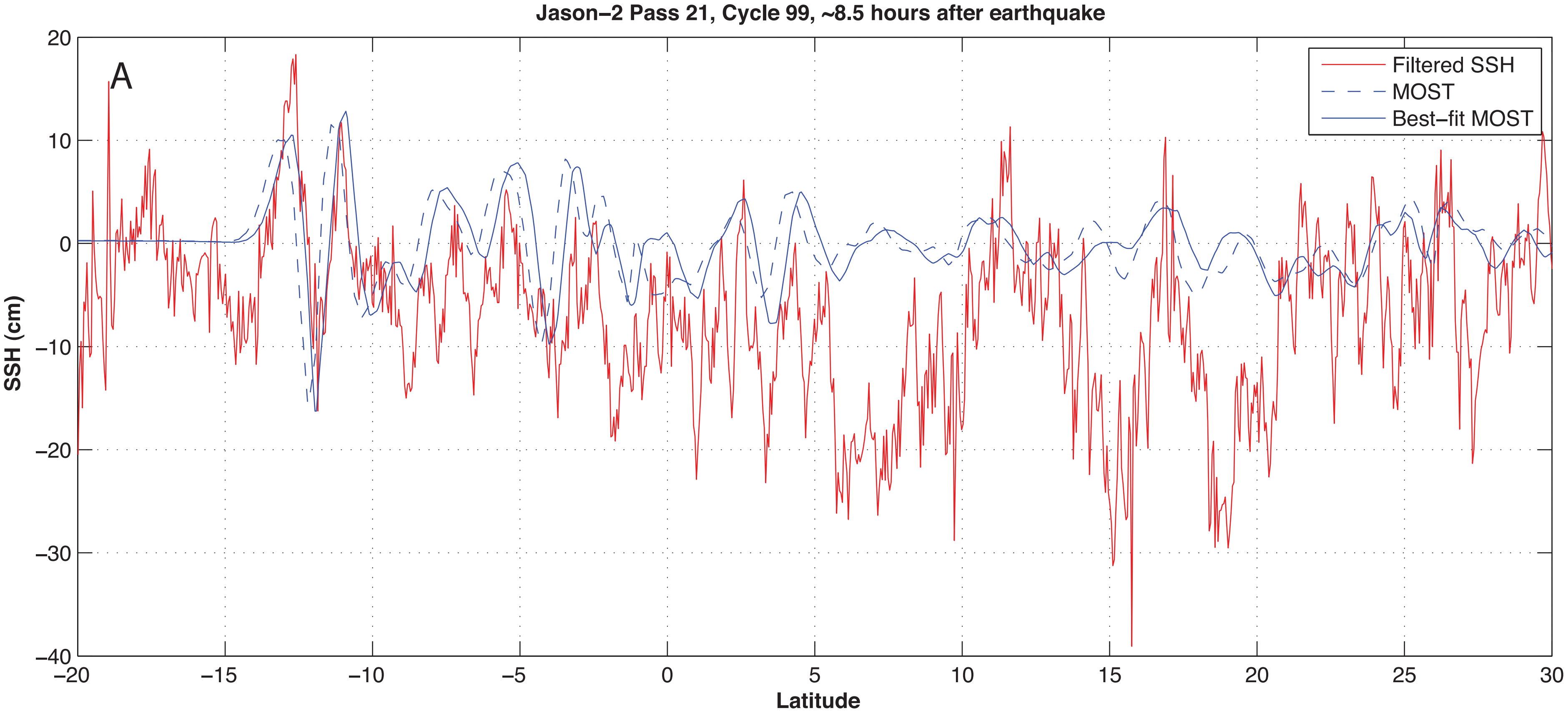


Model vs. NRT Data: Jason-1

•



Model vs. NRT Data: Jason-2



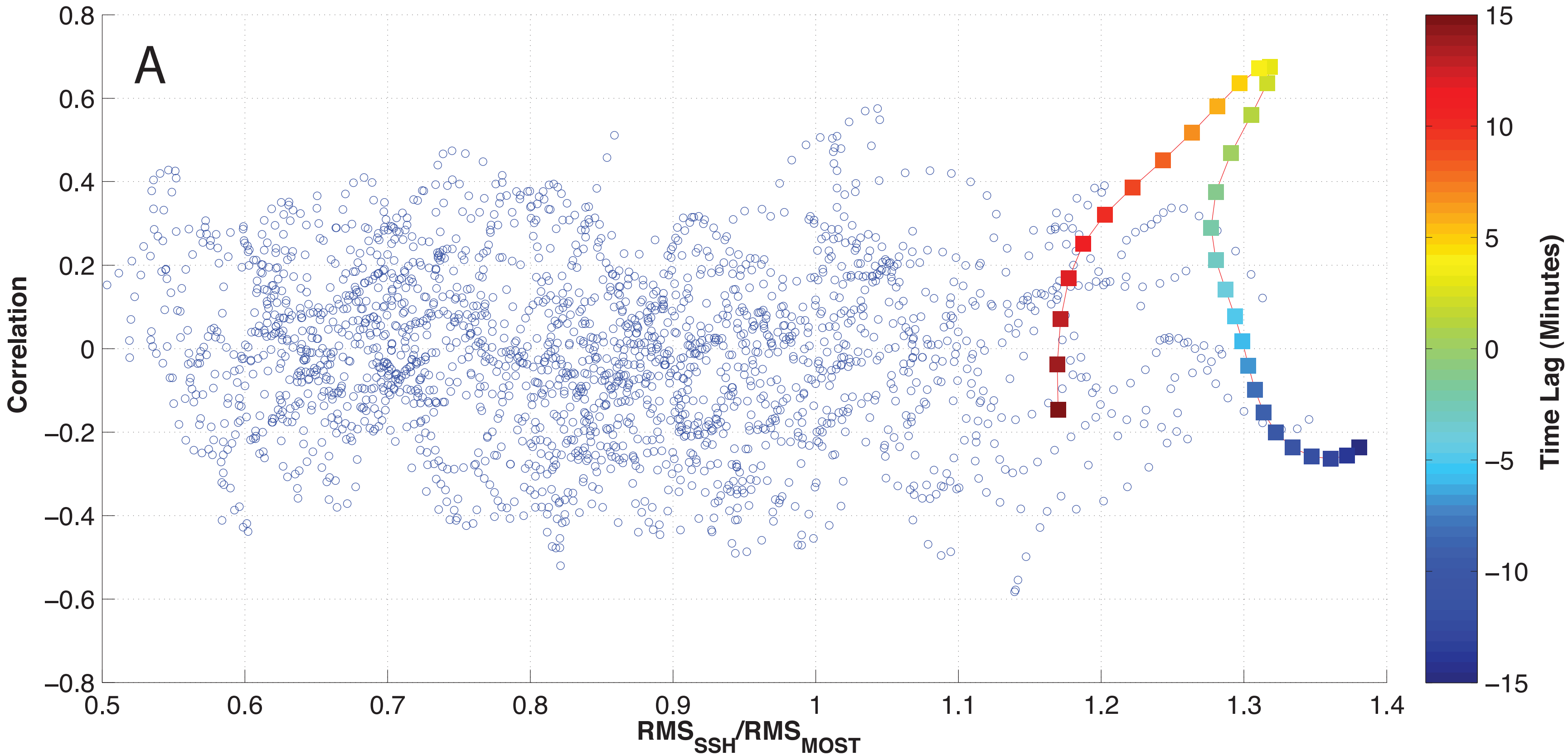
Historical Randomization Tests

- Using historical data, it is possible to determine if the correlation and amplitude between observations and model data for a given pass are exceptional (containing tsunami signal).
  - Using the Envisat pass as an example the test is completed as follows:

1. Pass 419 (tsunami pass) from every previous Envisat cycle is collected using RADS, and the correlation and RMS amplitude ratio between the MOST model and filtered SSH data is computed.
2. MOST model is adjusted +/- 15 minutes, leading to 31 data points for each cycle.
3. Locations with high correlation, and RMS amplitude ratio of ~1, suggest the presence of a tsunami.

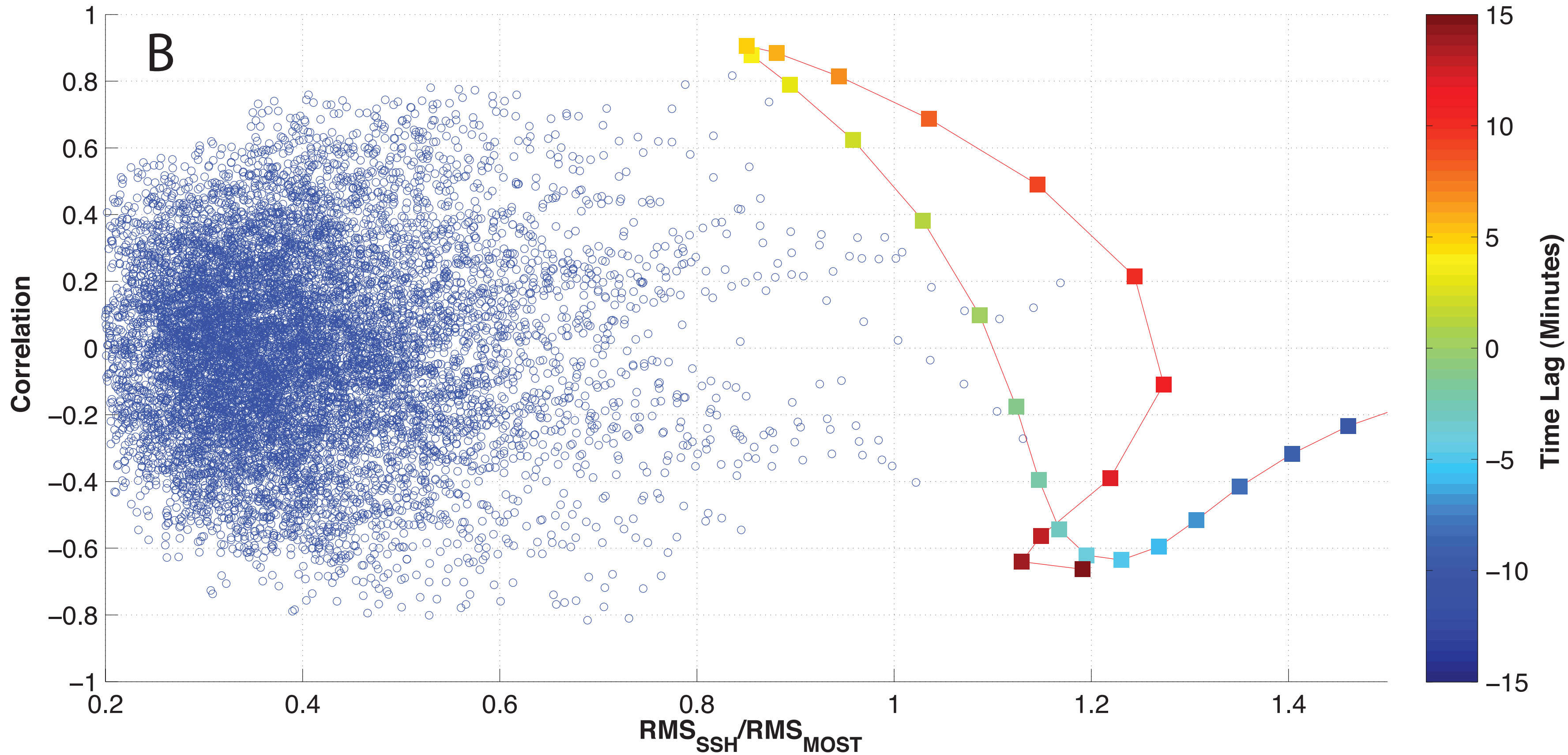
Historical Randomization Tests: Envisat

•

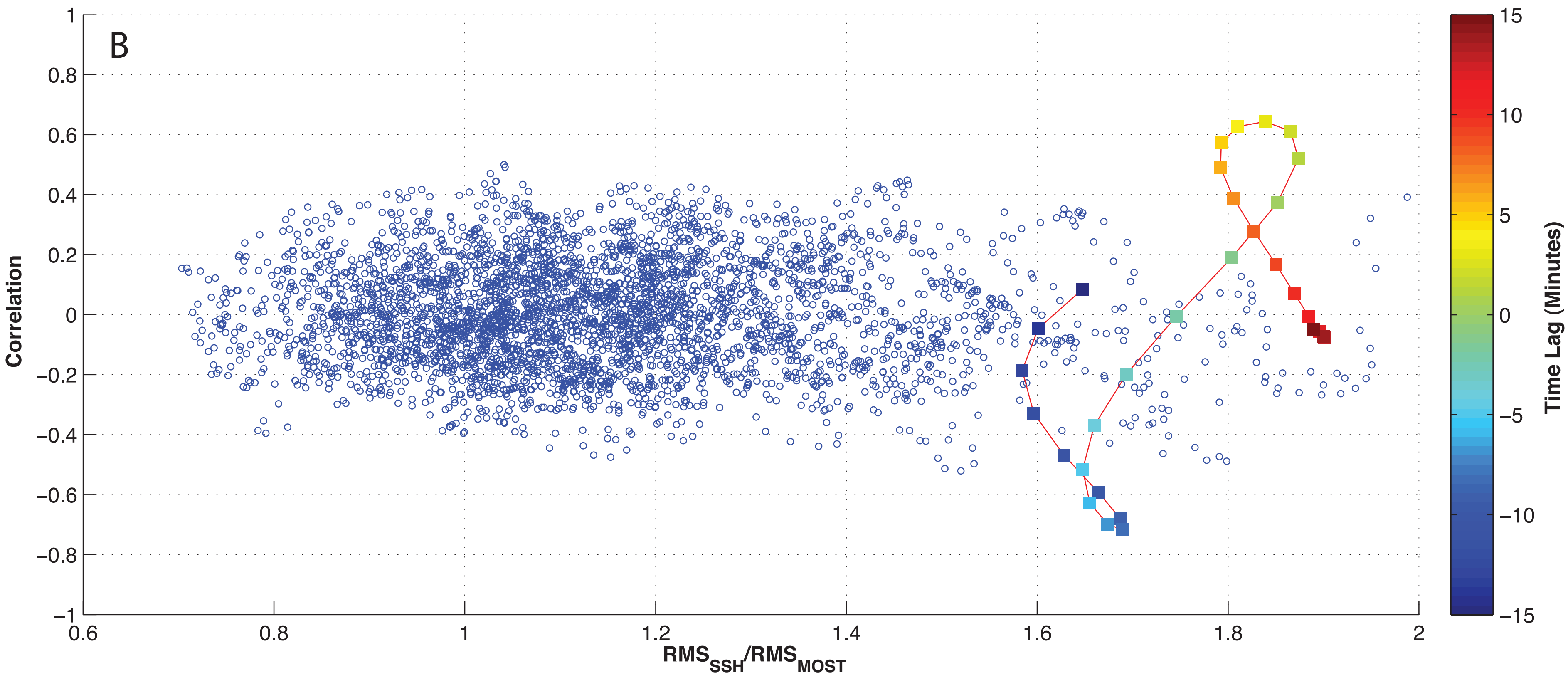


Historical Randomization Tests: Jason-1

•



Historical Randomization Tests: Jason-2

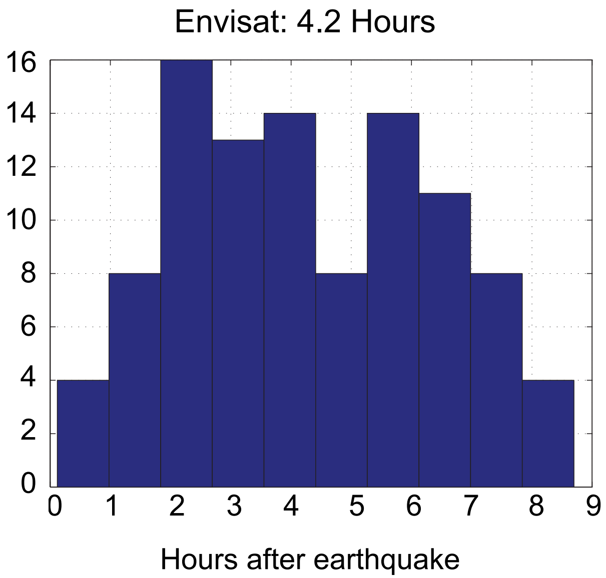


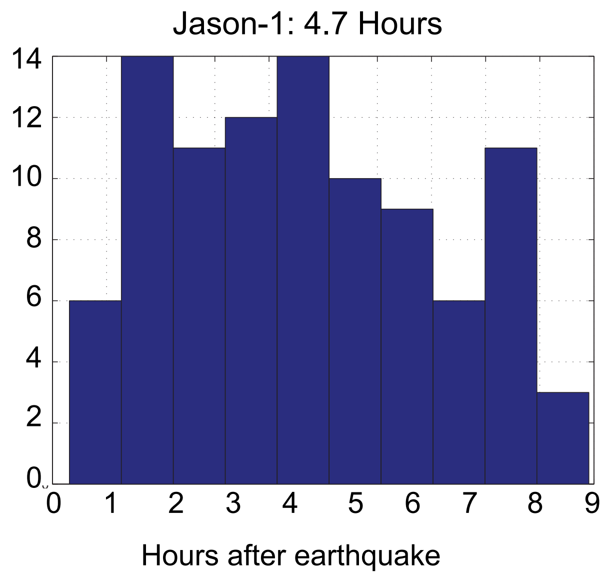
NRT Tsunami Monitoring Using Satellite Altimetry

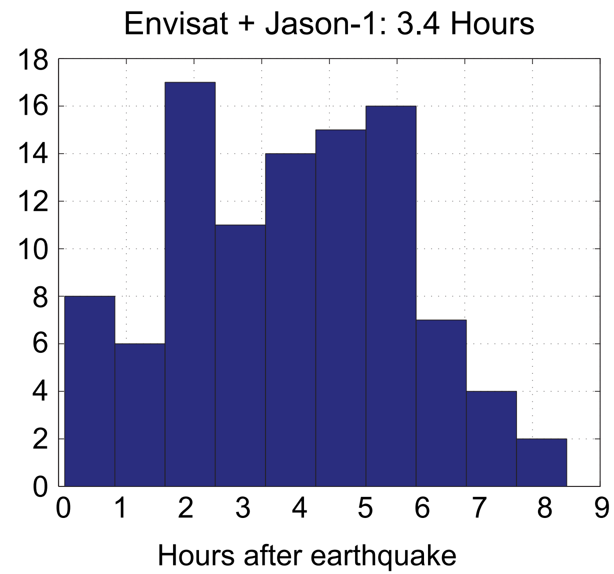
- Deep-Ocean Assessment and Report of Tsunamis (DART) buoys are generally used to detect tsunamis shortly after generation.
  - Located primarily around coastlines, only a couple in interior of Pacific Ocean.
- Recent advances in processing of altimeter data have opened up the possibility of using satellite altimeters to improve assessments of the propagating tsunami.
  - Latencies could be reduced further by using less accurate orbit altitude estimates or the addition of ground terminals for reception of telemetry from satellites.
- For Tohoku tsunami:
  - Envisat first measured tsunami 5.5 hours after earthquake → with current latencies, could have improved warnings and predictions in Central and South America.
  - A Jason-2 pass within 5.5 hours of earthquake → with current latencies, could have improved warnings and predictions for Hawaii.

How soon after tsunami should we expect satellite altimeter sampling?

- Using a simple randomization test and setting the start time of the Tohoku tsunami at random times in the past, we can determine the expected time for a satellite altimeter overflight.







Could satellite altimetry have improved early warning and detection of the 2011 Tohoku Tsunami?

1. MOST model results are computed very quickly from a set of pre-computed runs for locations where tsunamis have occurred in the past.
   - Model is adjusted with DART buoy data, which is primarily located near coastlines.
   - No observations in the open ocean are currently used to improve the model estimate.
2. Comparison between NRT altimetry data and initial MOST model can be made and altimetry passes coincident with the tsunami signal could be identified.
3. NRT satellite altimetry data containing the tsunami signal would then be used to refine and improve model estimates.
4. Additionally, satellite altimetry data could be used directly to confirm the presence and size of a tsunami in the open ocean.

We now have a software system in place at CCAR to retrieve and analyze JPL/PO.DAAC NRT Jason-2 altimeter data as soon as a potential tsunamigenic earthquake occurs.

Summary and Conclusions

- Satellite altimetry cannot provide improved warning for locations in the near-field of the tsunami.
  - Far-field events can still be large and result in significant damage to property and potential loss of life.
- Satellite altimetry should not be dismissed when considering the early warning and detection of tsunamis.
  - Open ocean observations of the tsunami provide the opportunity for additional model refinement.
  - Satellite altimeters cover areas of the ocean where no DART buoy is present.
  - Along-track measurements provide a larger, cross-sectional view of a propagating tsunami giving information that cannot be obtained from DART buoys.
  - Results depend heavily on data latencies and satellite altimeter availability at the time of the tsunami.
  - SWOT has the potential to make detection of a tsunami far easier.

Questions?

Additional details and analysis can be found in "Could Satellite Altimetry have Improved Early Detection and Warning of the 2011 Tohoku Tsunami?" Hamlington et al., GRL, 2012.