Broad range airborne ocean topography measurements: Modular Aerial Sensing System (MASS) in support of SWOT Calval

Luc Lenain, Ken Melville, Nick Statom & Laurent Grare
Scripps Institution of Oceanography

SWOT CalVal meeting
June 17 2019 (Bordeaux, France)

Jet Propulsion Laboratory
California Institute of Technology

With support from:
NASA Johnson Space Center (JSC)
Derek Rutovic, Charlie Marshik, Mike Stevens and the GV team

CNES/CLS
Nicolas Picot, Matthias Raynal, Marie-isabelle Pujol,
& Gerald Dibarboure

Objectives

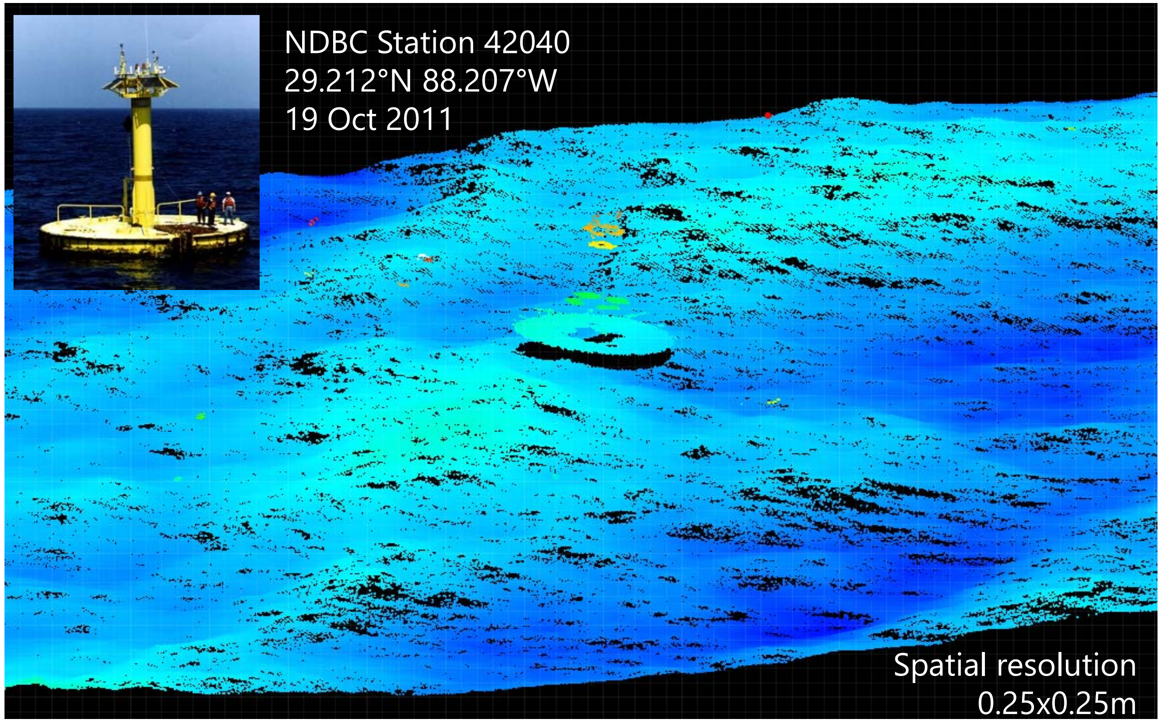
The objective of the prelaunch MASS program is to validate the integration and performance of the SIO Modular Aerial Sensing System (MASS) in a new aircraft, the NASA JSC Gulfstream V (G-V), over oceanic and terrestrial targets in support of the SWOT CalVal.

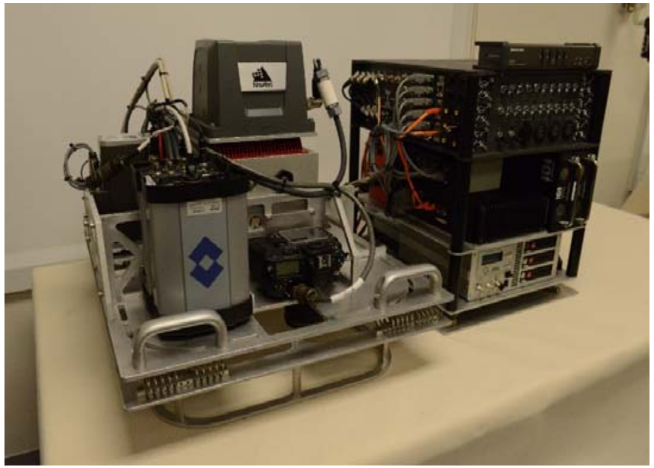
- MASS integration into the NASA G-V aircraft
- Engineering flights at the SWOT CA crossover site during a prelaunch experiment
- Data collection enabling detailed analysis and flight planning necessary for SWOT post-launch CalVal with the MASS suite
- Detailed processing and analysis of the obtained MASS data

Outline

- Modular Aerial Sensing System integration onto the NASA JSC G-V (“NASA5”)
- Prelaunch experiment overview & flight planning rationale
- Preliminary analysis and results from the mission at the CA SWOT crossover
- Lessons learnt, upcoming analysis & flight planning considerations for post-launch mission

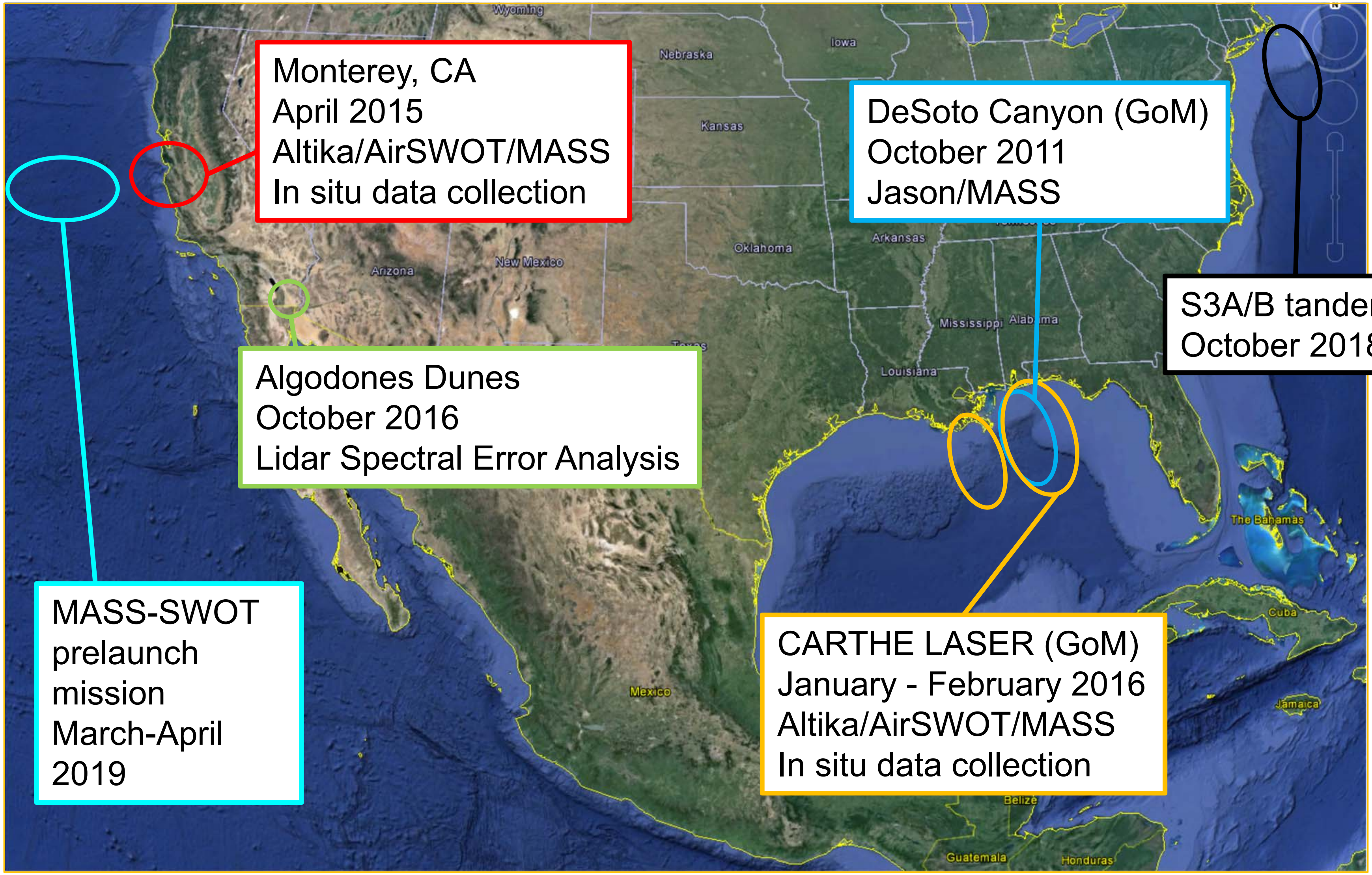
SIO Modular Aerial Sensing System (MASS)





Instrumentation		**Measurement**
Scanning Waveform Lidar	Riegl Q680i	Surface wave, surface slope, directional wave spectra (vert. accuracy ~2-3cm)
Long-wave IR Camera	FLIR SC6000 (QWIP)	Ocean surface processes, wave kinematics and breaking, frontal processes
High-Resolution Video	JaiPulnix AB-800CL	Ocean surface processes, wave kinematics and breaking, frontal processes
Hyperspectral Camera	Specim EagleAISA	Ocean surface and biogeochemical processes
GPS/IMU	Novatel SPAN-LN200	Georeferencing, trajectory

Ocean Topography & CalVal Campaigns - Overview



Monterey, CA
April 2015
Altika/AirSWOT/MASS
In situ data collection

DeSoto Canyon (GoM)
October 2011
Jason/MASS

S3A/B tandem
October 2018

Algodones Dunes
October 2016
Lidar Spectral Error Analysis

MASS-SWOT prelaunch mission
March-April 2019

CARTHE LASER (GoM)
January - February 2016
Altika/AirSWOT/MASS
In situ data collection

MASS validation and maturation have encompassed several sites over several years

Reciprocal Passes Across the Loop Current

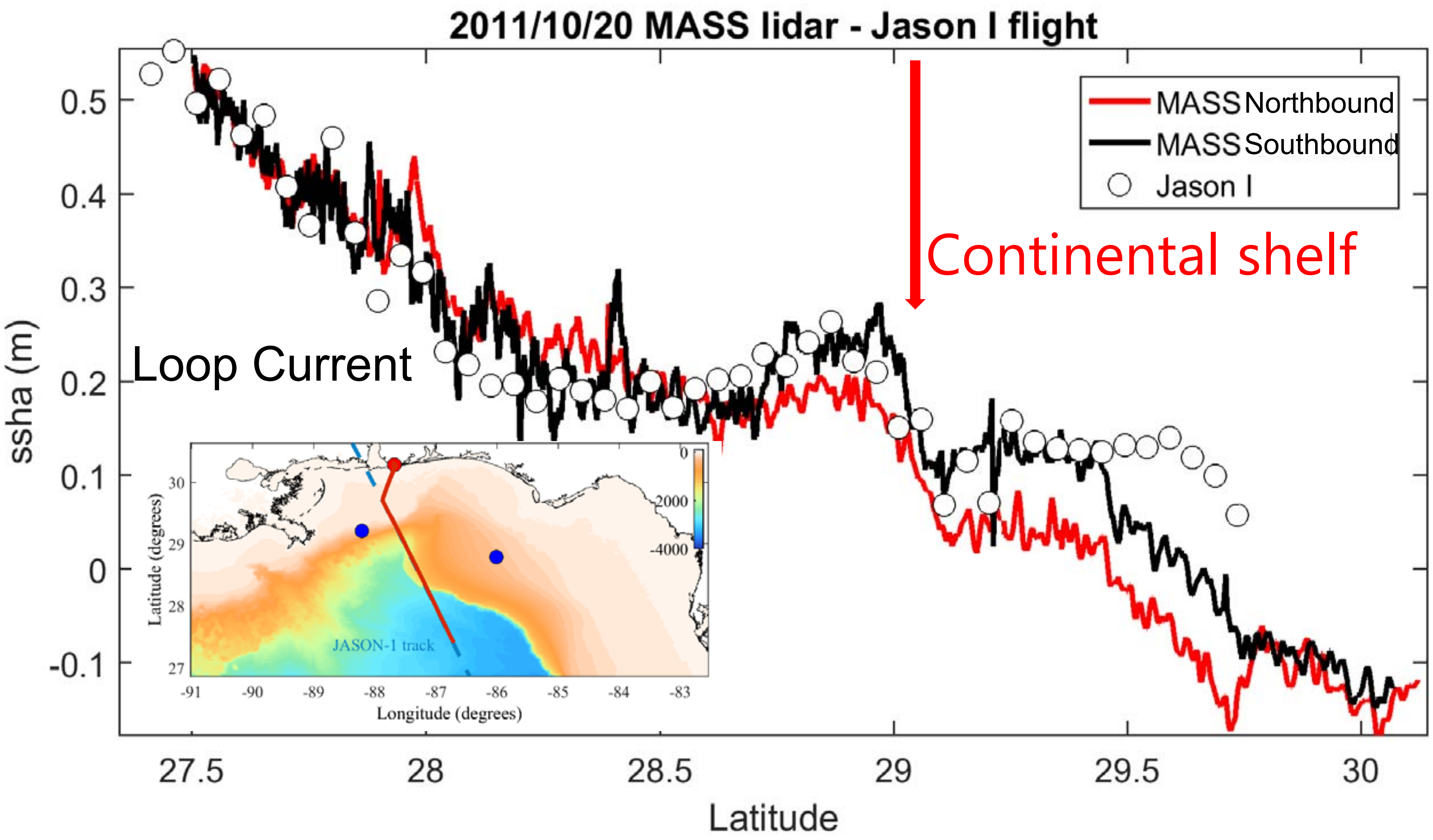
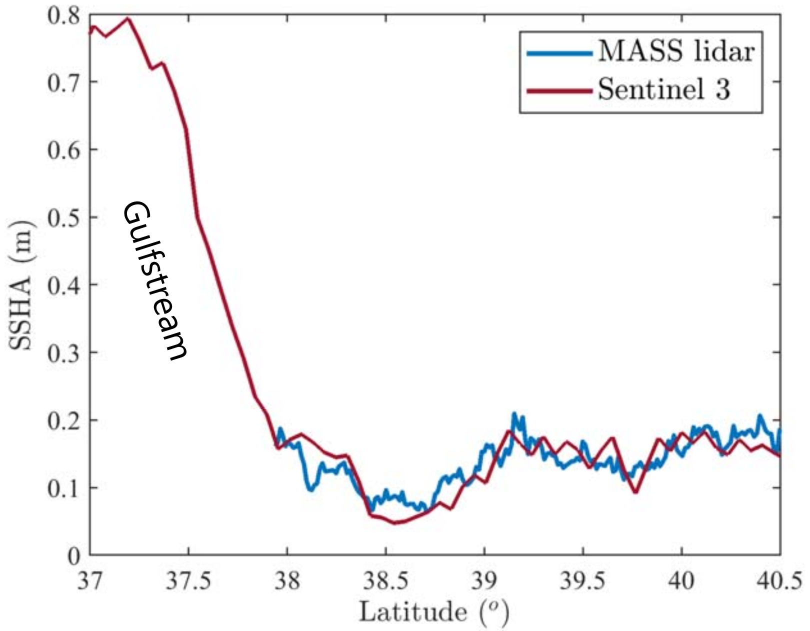


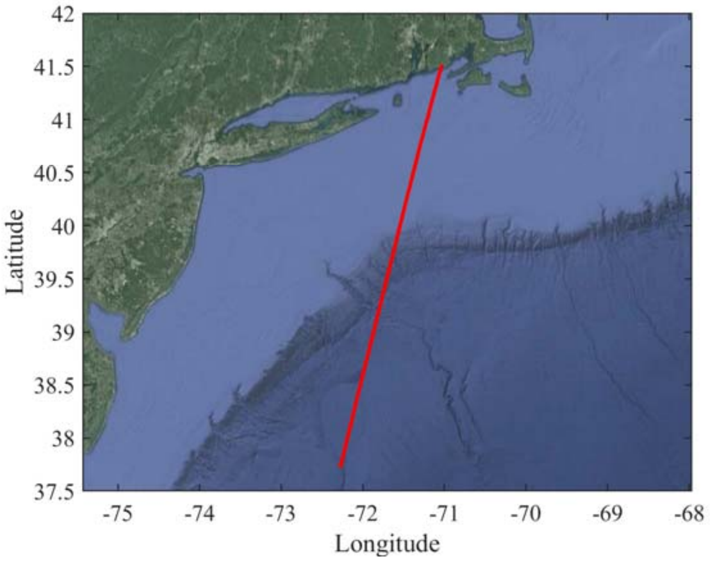
Fig. 6: SSHA estimated from two MASS lidar passes ("northbound" and "southbound") over the same Jason-I track (see insert). Note that the satellite pass occurred in the middle of the southbound lidar pass (black).

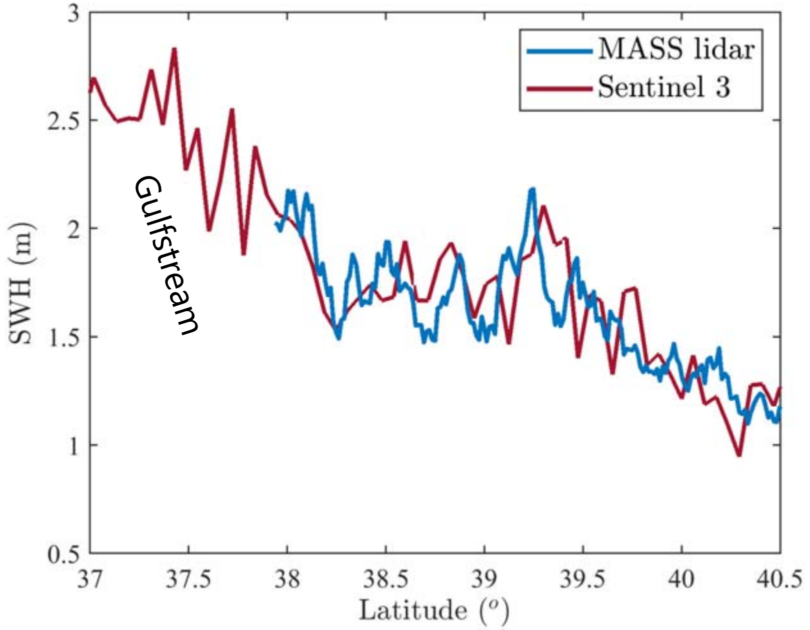
Sentinel 3 – MASS overflight

Sentinel 3 #364 pass on September 29 2018.

- Spatially collocated measurements, 1-2hr apart due to weather (late take-off)
- MASS lidar derived ssha corrected for tide using the same models used for S3 products (recomputed by CNES for aircraft trajectory) and using S3 MSL model.
- First look at the data is promising. More work is needed.

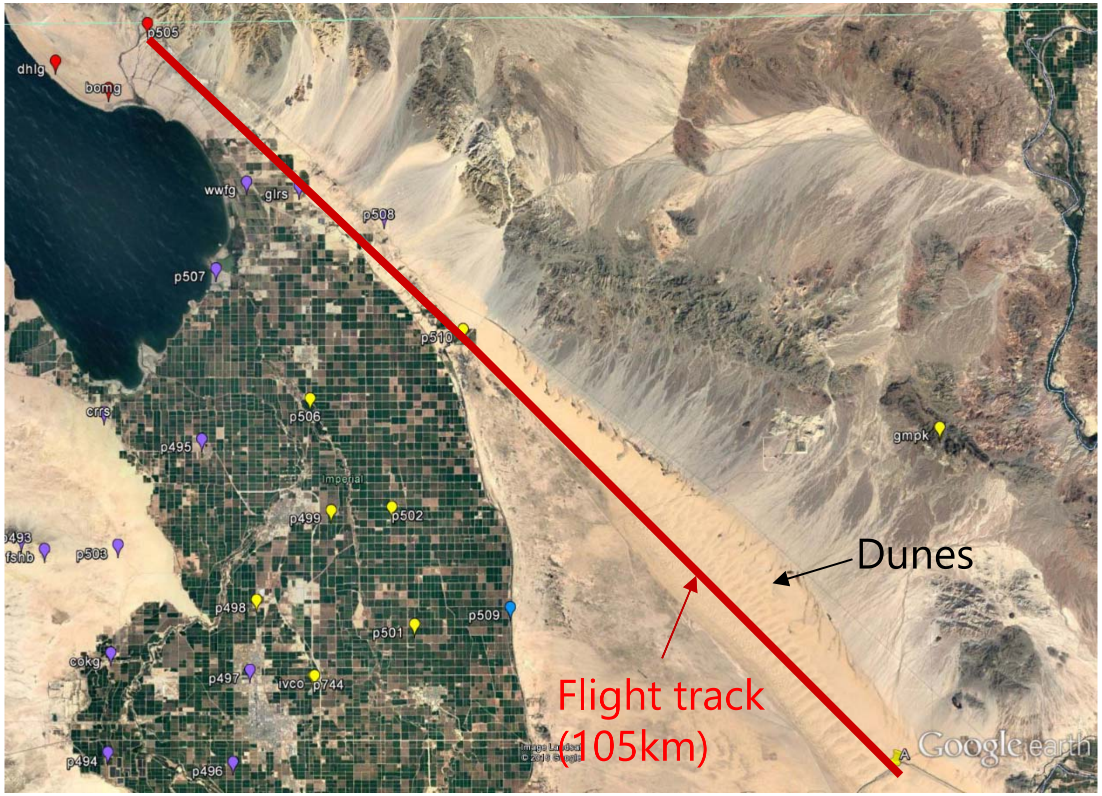




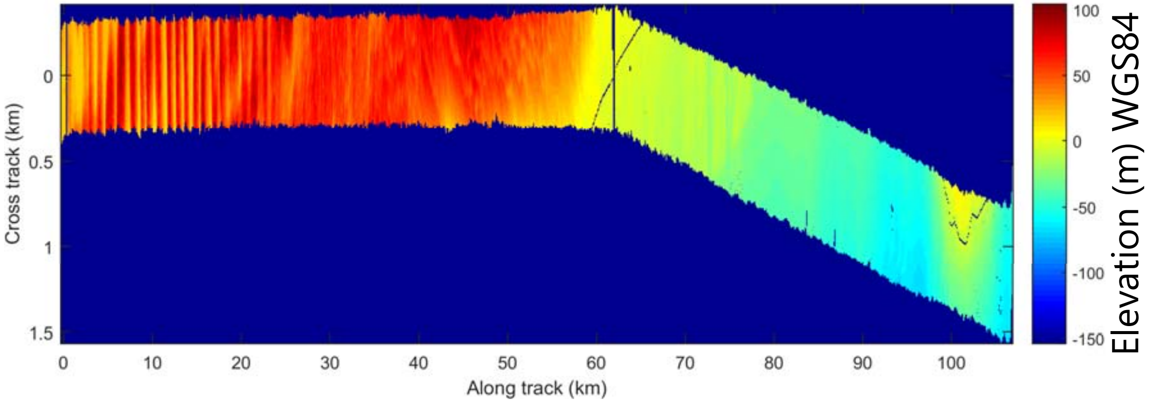


Algodones Dunes Campaign – October 17-19 2016

SCRIPPS INSTITUTION OF OCEANOGRAPHY UC San Diego



Lack of reliable truth over ocean motivates validation over land, where target does not change over experiment time



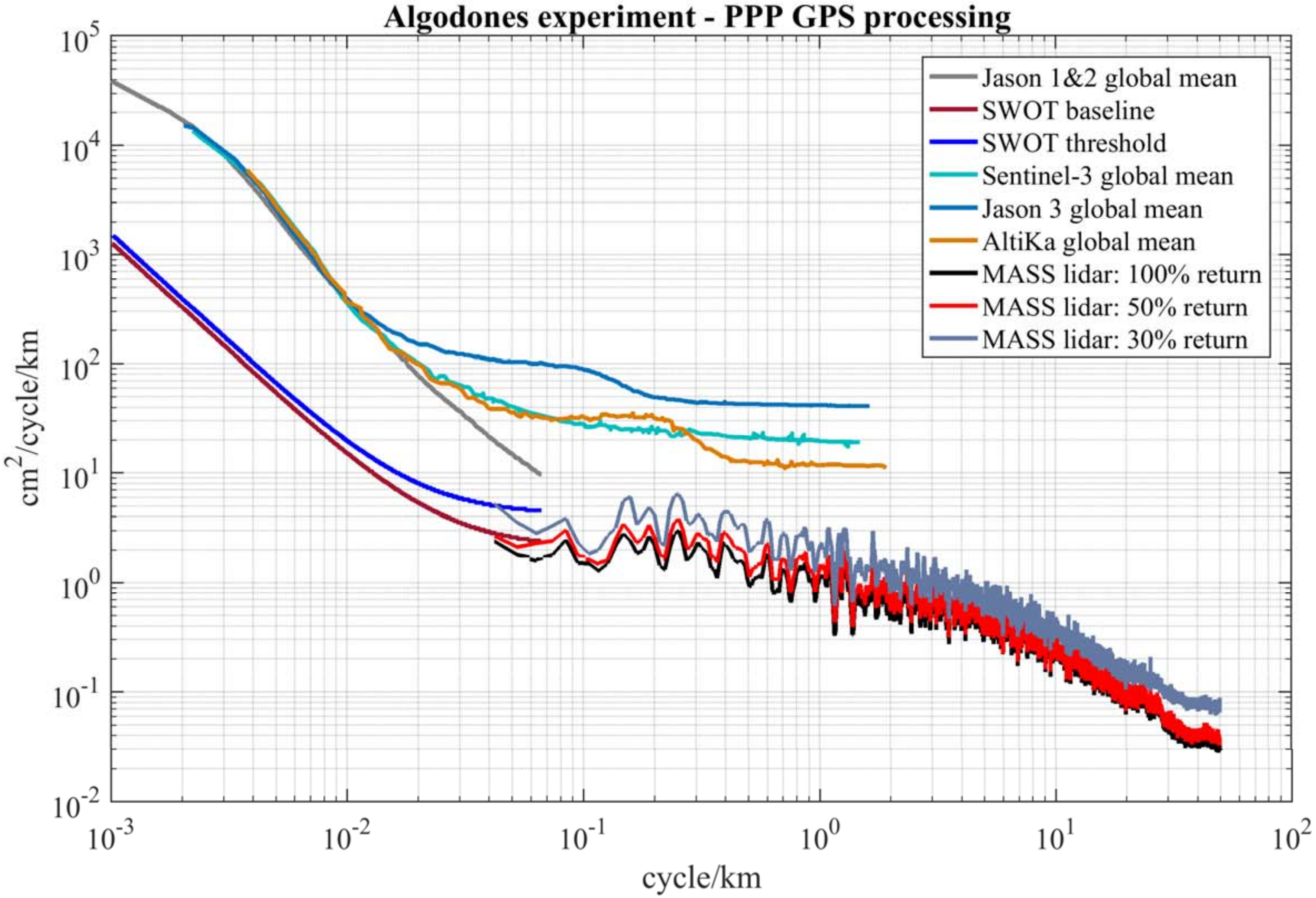
Measure MASS lidar noise spectra and compare with SWOT requirements.

Chose desert area east of San Diego.

Two flights, total of 11 passes over the same track
(~2000’ AGL flight altitude)

Characterization of MASS lidar noise spectrum

Lidar random noise floor is lower than other measurement techniques; lidar errors include apparent height errors due to horizontal errors over steep dunes



Here the residual spectra are computed using an average over two passes (reciprocal)

Aircraft Transition

- Need greater range and speed, so platform switch was needed for SWOT
  - Gives greater flexibility in flight patterns and sampling over the entire SWOT swath
  - Reduces time between aircraft flight lines and SWOT overflights to minimize temporal change in ocean
- Selected aircraft: NASA Gulfstream-V (JSC G-V, “NASA5”), recently added to the NASA fleet of research aircraft.

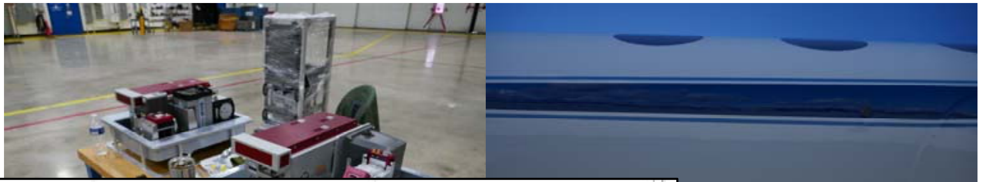
Additional value besides direct wave, ssh, and sst measurements:
Could also potentially provide the ability to collect coincident *in situ* measurements, both in the atmosphere and in the water and radiometric data (e.g. AXBT, etc)

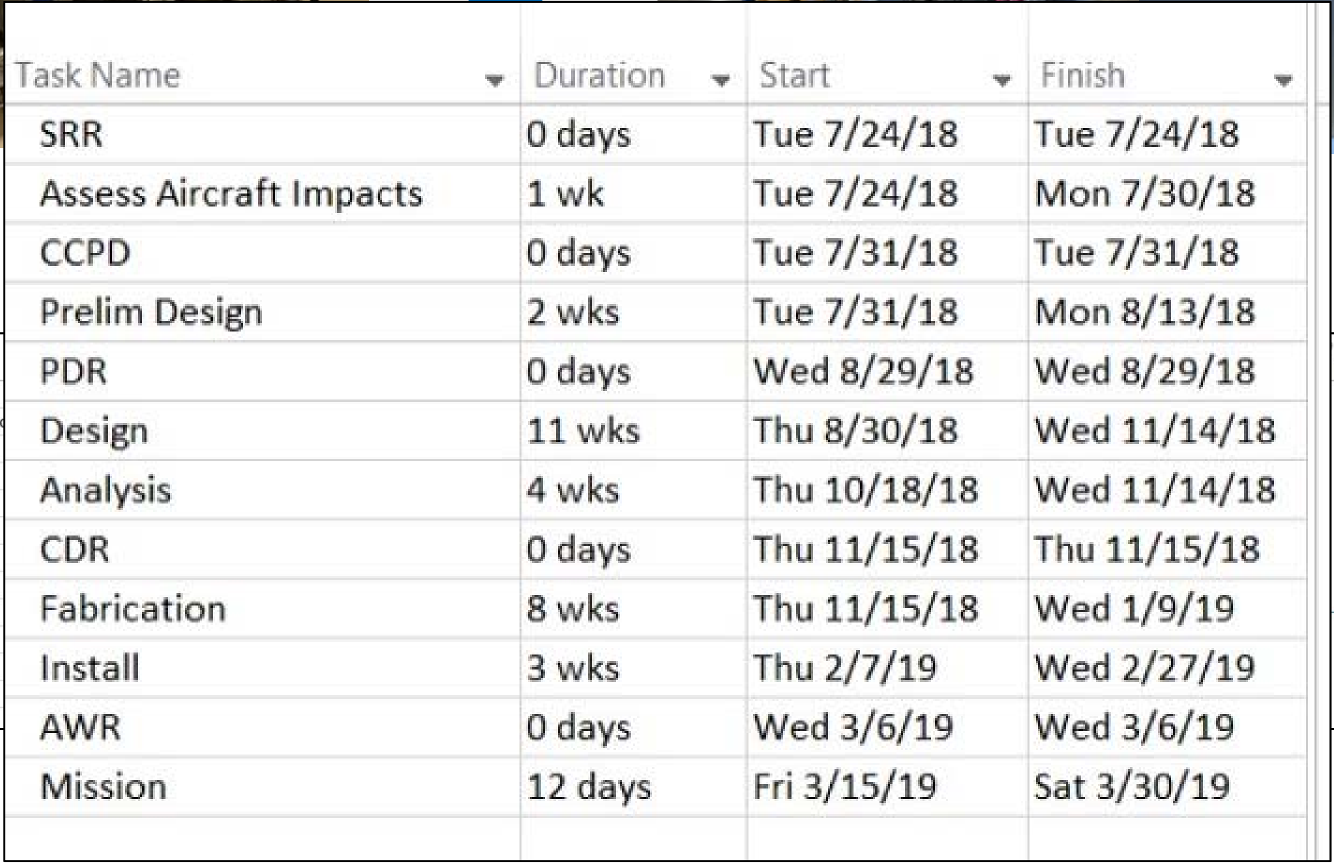
NASA JSC Gulfstream-V

Aircraft nominal performance:
Duration:
15 hours
(payload and weather dependent)
Useful Payload:
8,000 lbs
Gross Take-off Weight:
91,000 lbs
Max Altitude:
51000’
Air Speed:
Up to 500 knots
Range:
5,500 Nmi

Integrating the MASS into the G-V

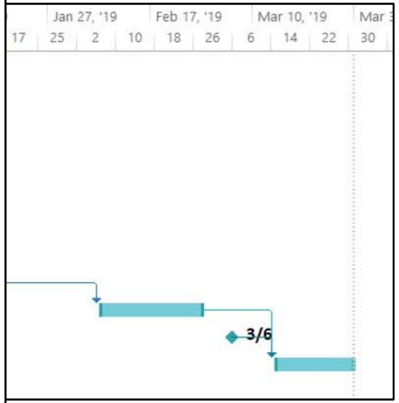
Transitioning from a relatively simple twin aircraft MASS installation to a complex NASA G-V jet with two MASS instruments.



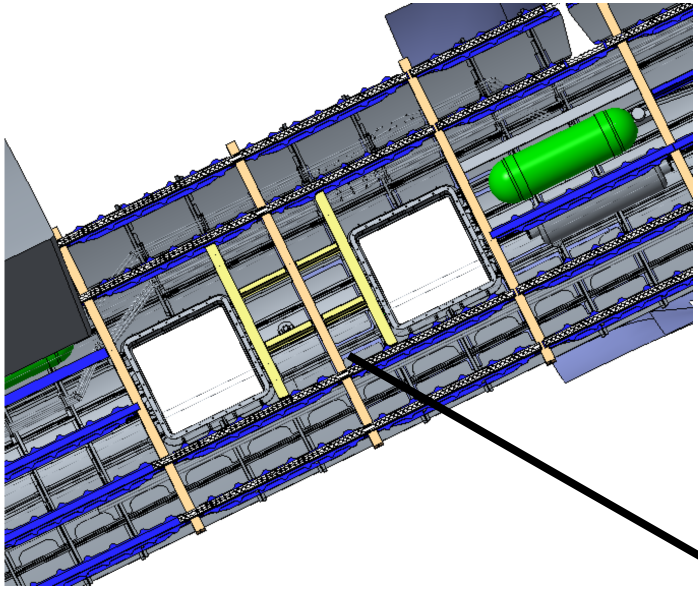


Task Name	Duration	Start	Finish
SRR	0 days	Tue 7/24/18	Tue 7/24/18
Assess Aircraft Impacts	1 wk	Tue 7/24/18	Mon 7/30/18
CCPD	0 days	Tue 7/31/18	Tue 7/31/18
Prelim Design	2 wks	Tue 7/31/18	Mon 8/13/18
PDR	0 days	Wed 8/29/18	Wed 8/29/18
Design	11 wks	Thu 8/30/18	Wed 11/14/18
Analysis	4 wks	Thu 10/18/18	Wed 11/14/18
CDR	0 days	Thu 11/15/18	Thu 11/15/18
Fabrication	8 wks	Thu 11/15/18	Wed 1/9/19
Install	3 wks	Thu 2/7/19	Wed 2/27/19
AWR	0 days	Wed 3/6/19	Wed 3/6/19
Mission	12 days	Fri 3/15/19	Sat 3/30/19

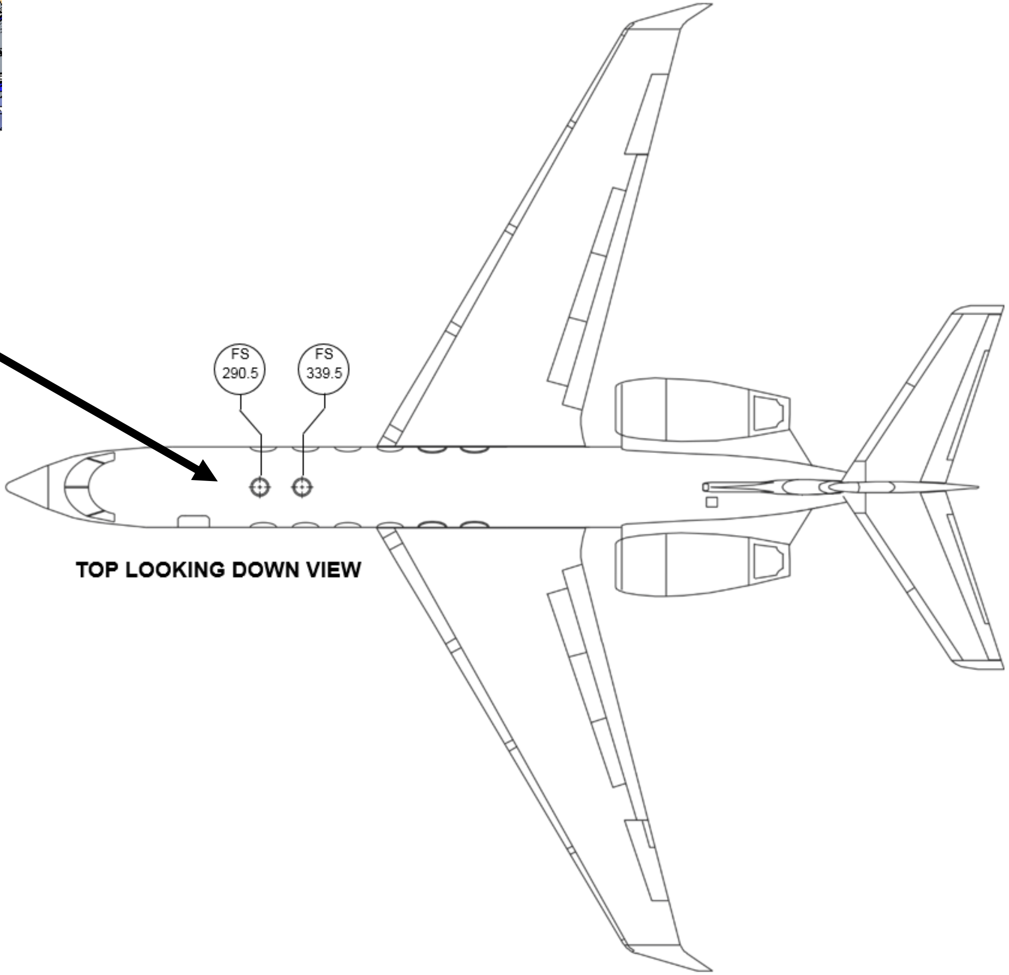
Task Name
SRR
Assess Aircraft Impac
CCPD
Prelim Design
PDR
Design
Analysis
CDR
Fabrication
Install
AWR
Mission



NASA G-V viewports



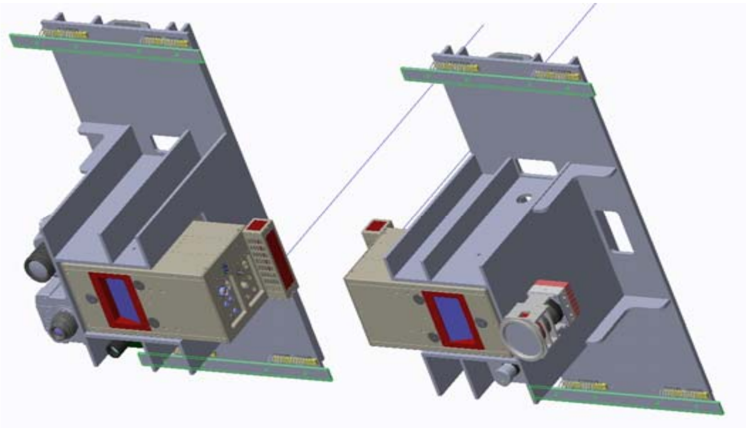
Viewport opening
allows for window
adapter with round
window or
aluminum plug

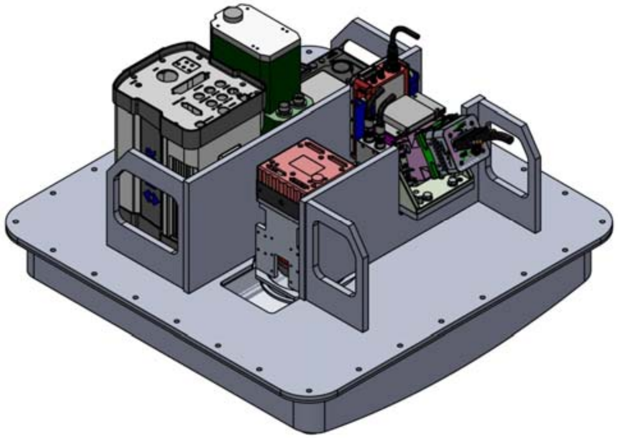


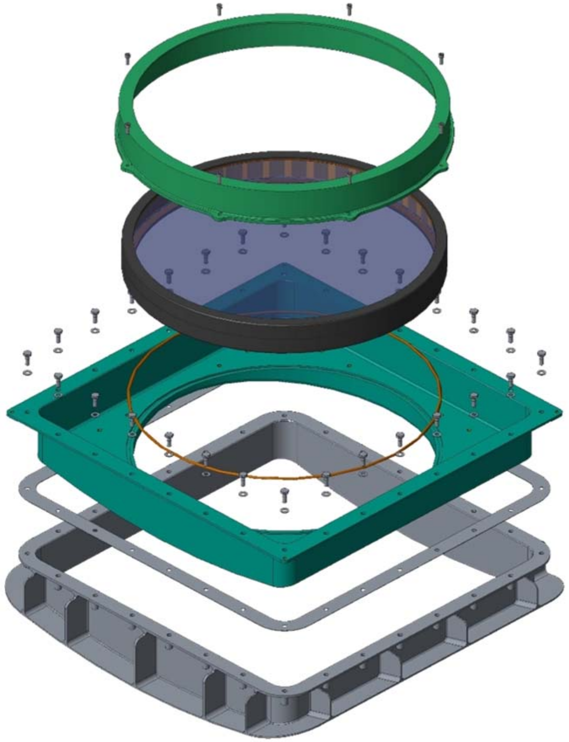
Many (!!) design iterations

Initial plan: Install the MASS in a **pressurized space**, looking through a window viewport (standard sensor install in research aircraft)

This poses installation challenges and could have potentially impacted the quality of the lidar measurements (signal attenuation through viewport window, and uncharacterized refraction)



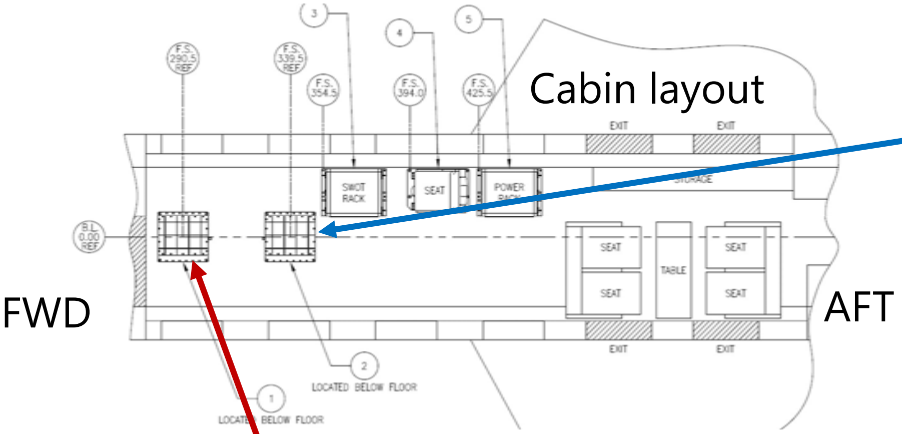


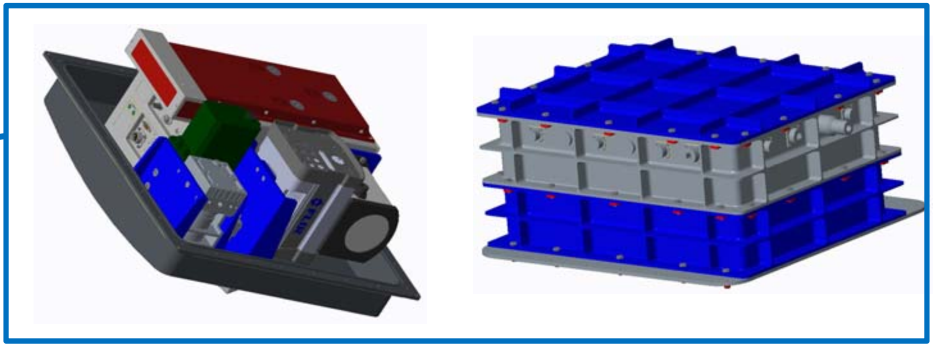


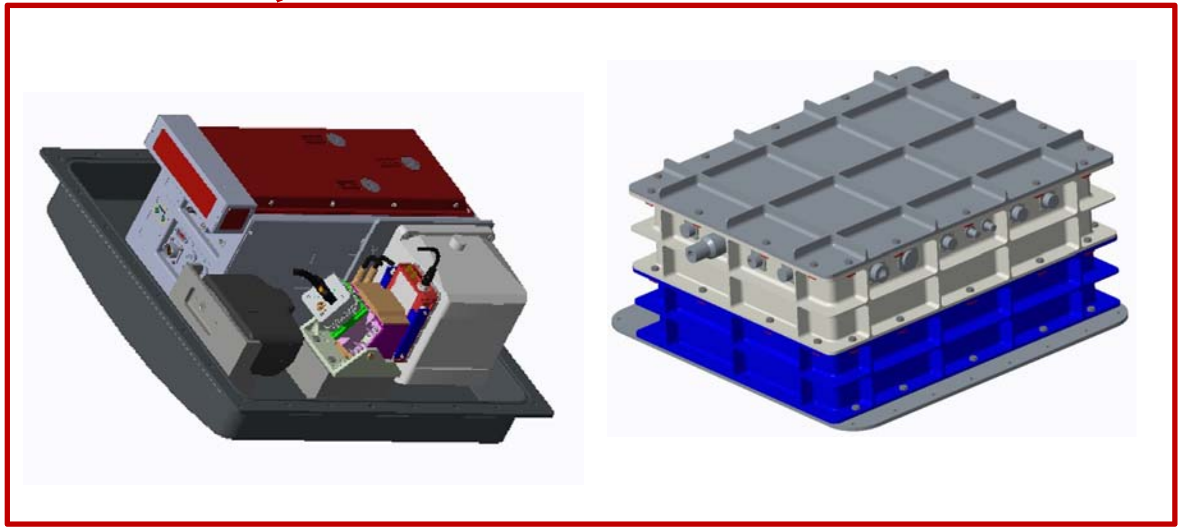
Final design

Ultimately, to ensure best instrument performance, the “MASS-GV” was installed in an **unpressurized** section of the aircraft, enclosed in pressurized “doghouse”.

Constraint: Maximum allowable flight altitude of 15,000 AMSL (to avoid sensor damage), including for transit between JSC and Monterey, CA.







- The two “Doghouses” were fabricated by NCAR.
- System integration was conducted at NASA JSC by SIO & NASA JSC engineering teams

First science mission for the NASA G-V

Airborne Science Newsletter

Spring 2019

NASA JSC G-V Completes First Science Mission in preparation for SWOT

Welcome NASA's new G-V to Airborne Science! After a 5-month modification period, the G-V (N95NA) was ready for science on February 14, 2019 with two, large nadir portals (22-inch x 22-inch) installed in the forward fuselage area. This was the final modification effort required for the G-V to meet initial operations capability for the Earth science community, and the aircraft was immediately pressed into service. The Modular Aerial Sensing System (MASS) instrument was installed over both portals enclosed inside a pressure "dog house" structure in the plane. The MASS instrument, a waveform scanning lidar, is provided by the Scripps Institution of Oceanography to measure sea surface altimetry. The goal of this first mission was to validate the instrument's performance on the G-V in a geographic location over the Pacific Ocean under the track of the future SWOT satellite mission.

After a smooth integration of the MASS instrument onto the G-V, the airborne campaign was carried out in the vicinity of JSC and then from the Monterey, California Regional Airport over the identified SWOT cal/val site just off-shore. With 37.1 science flight hours, the mission finished on schedule, achieving all science objectives. According to Scripps Principal Investigator Luc Lenain, "The G-V platform has demonstrated to be an ideal platform for this work, meeting the speed, endurance and flight altitude required for this project."

The G-V team will next begin integration of the Land, Vegetation and Ice Sensor (LVIS) on the aircraft. LVIS, a wide-swatch imaging laser altimeter, will be flown in May to provide calibration and validation of measurements generated by the GEDI Ecosystem Lidar on the International Space Station.

Contact Derek Rutovic (mihailo.rutovic-1@nasa.gov) with questions to pertaining to payload installation on the G-V.

Contributed by Derek Rutovic, JSC

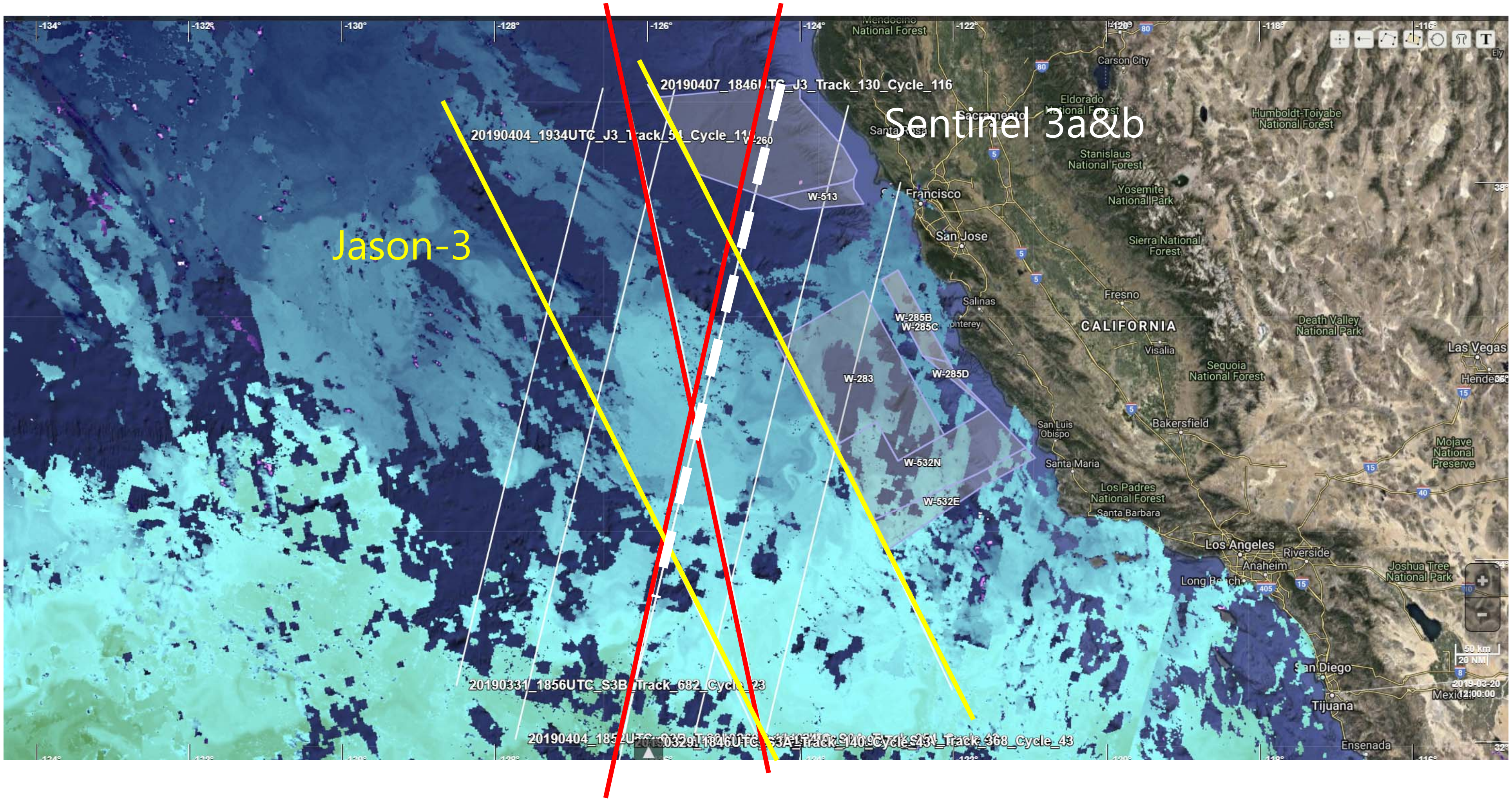
The MASS instrument was installed to make use of G-V nadir portals.

JSC Gulfstream team in Houston following first G-V science flight

Experiment March 27 – April 12 2019 (Monterey CA)

Experiment March 27 – April 12 2019 (Monterey CA)

- SST image from OceanDataLab along with SWOT crossover tracks, airspace warning areas and Jason III/S3ab tracks during the experiment period.



SWOT crossover

Flight profiles

- Boresight calibration flight @JSC (grid pattern over residential area)
- Terrestrial repeated paths (similar to Algodones flights) over El Paso (in transit) & central California
- Up & crosswind/waves repeated reciprocal legs – Two flights
- Sentinel 3A overflights (March 29 2019) – one flight
- Grid pattern, reciprocal legs – Two flights

- 1500ft AMSL flights, right under the clouds, @290kts.
- Experienced a range of surface waves/ wind conditions (low to strong wind speeds, with and without wave breaking)

- Note: Weather/wave forecasts at the site were generally wrong, and no in-situ measurements were available for flight planning.

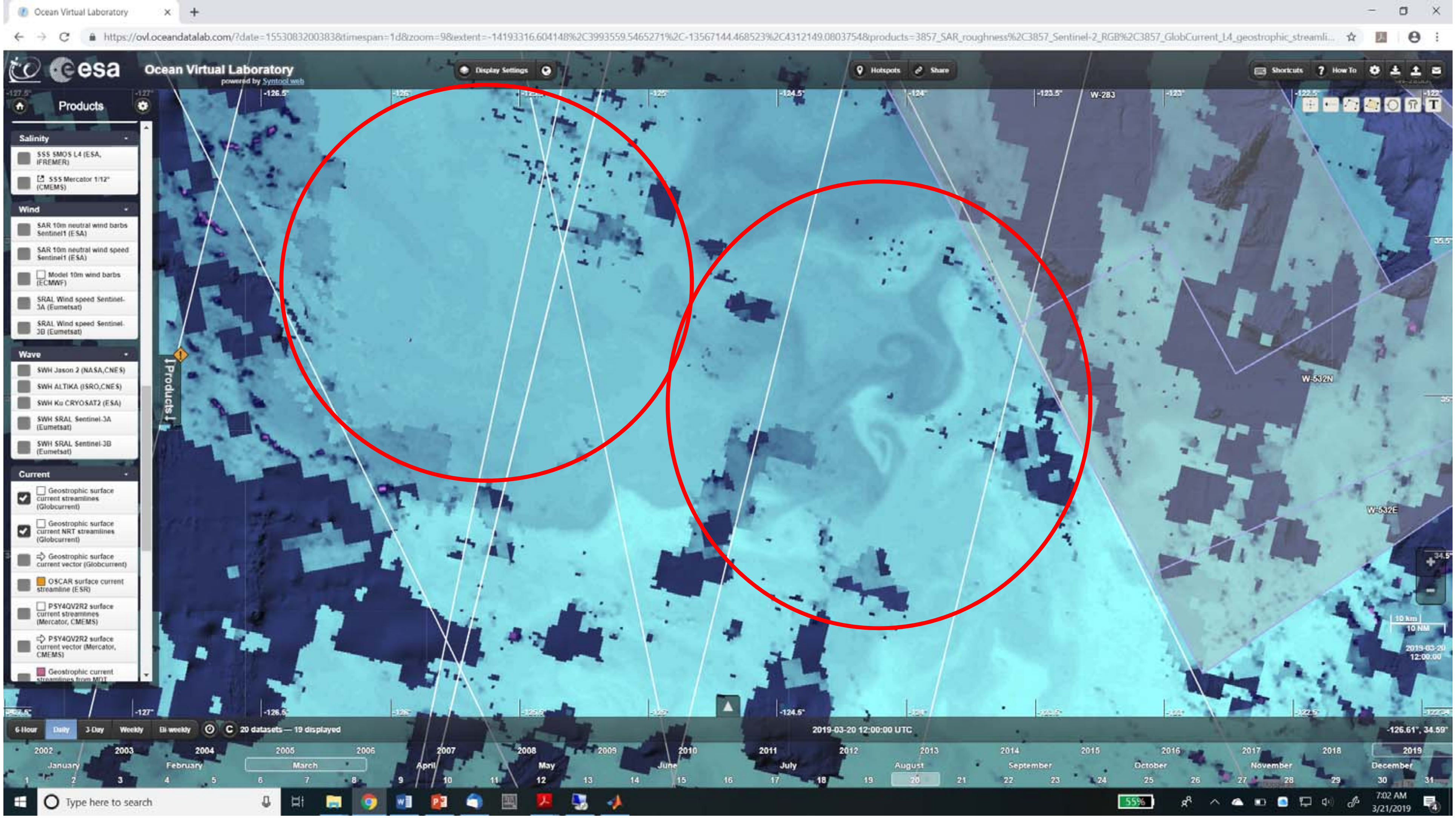
- Wind speed and momentum flux estimate under the flight track will be available (Lenain et al. 2019, JPO subjudice)

In flight (clouds!!)

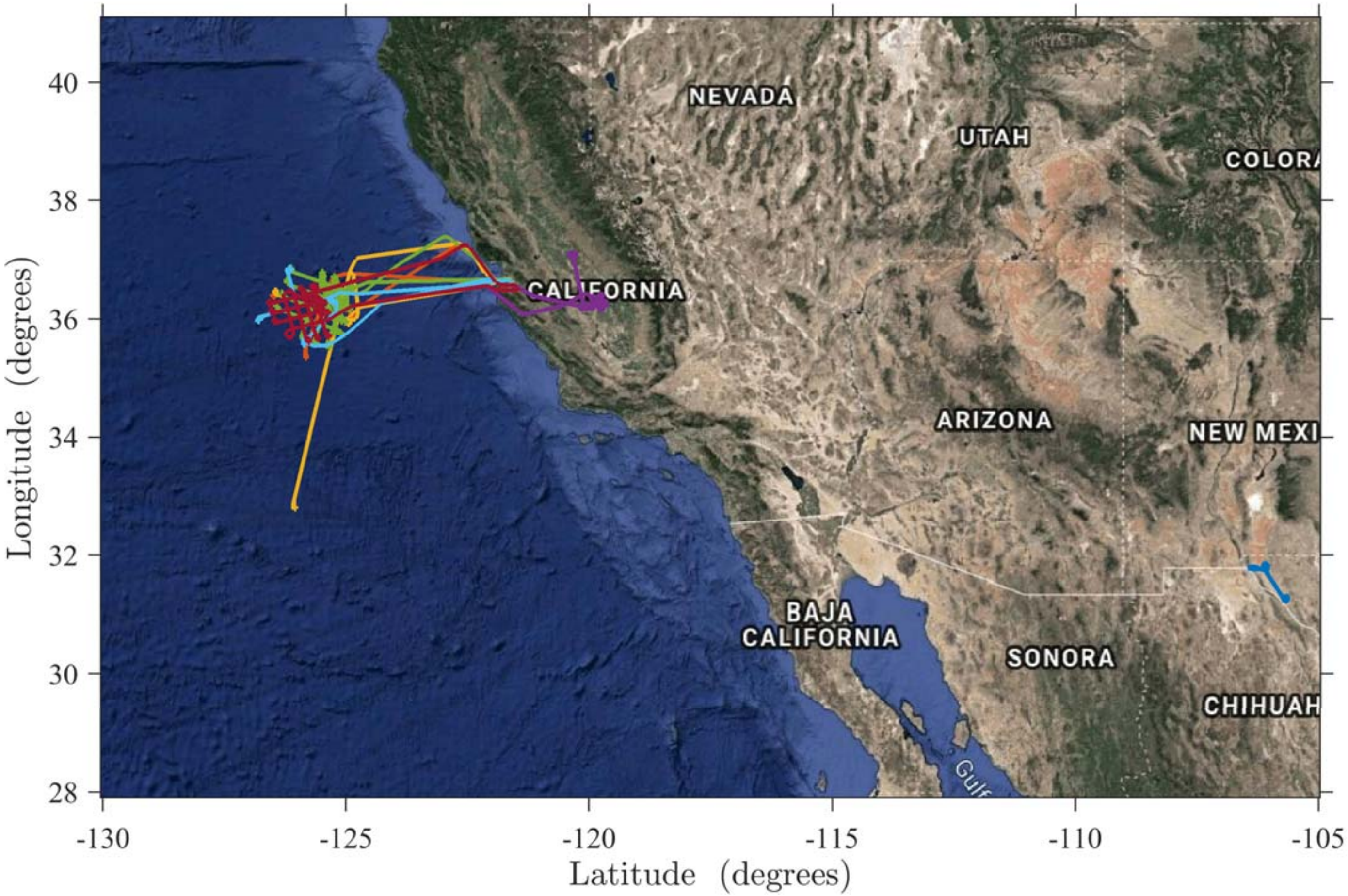
Incredible value of being physically "on-site", e.g. to better understand features identified by the spatially limited array of in-situ measurements

Flight profiles

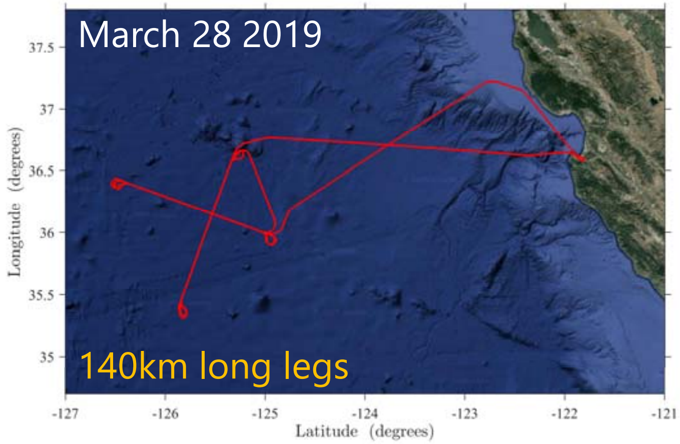
- Initial goal was to target areas with 1/minimal and 2/significant submesoscale activity (SST from S3, March 20 2019)



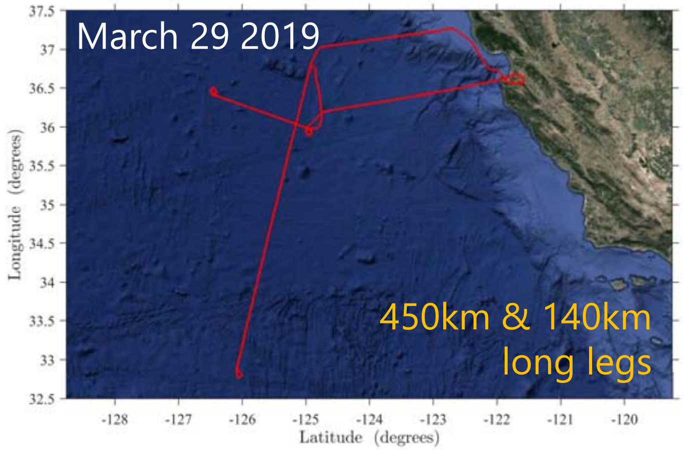
Flight tracks



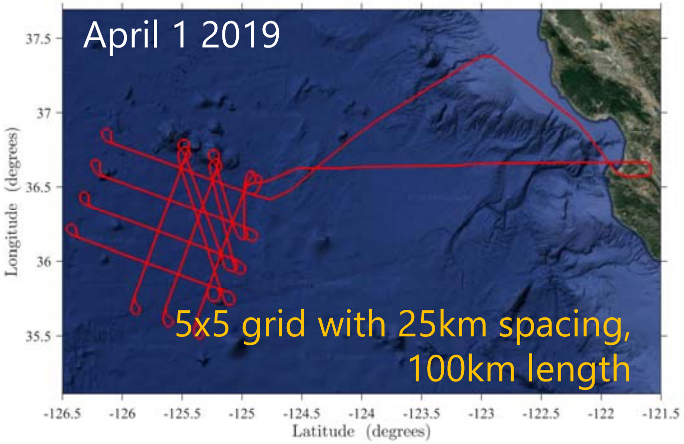
Flight tracks


March 28 2019

140km long legs


March 29 2019

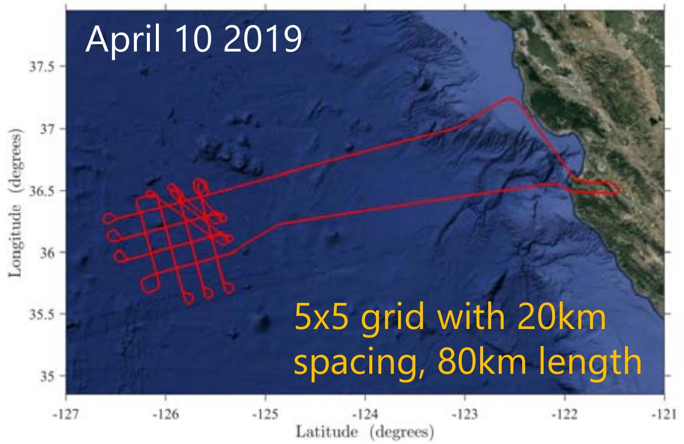
450km & 140km long legs


April 1 2019

5x5 grid with 25km spacing, 100km length


April 9 2019

125km long legs

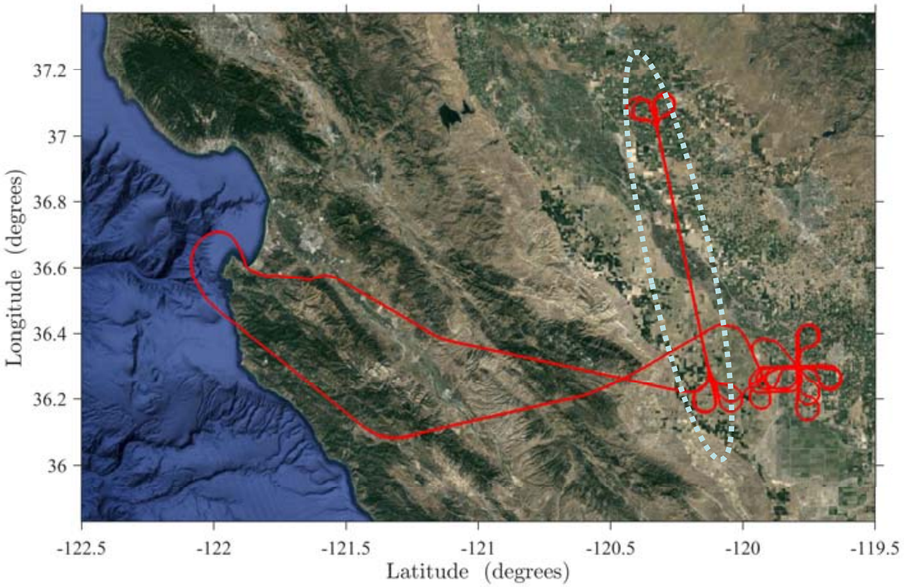

April 10 2019

5x5 grid with 20km spacing, 80km length

April 2-8 2019: no flights due to weather and G-V mechanical failure (down April 5-8 2019)

Characterization of MASS lidar noise spectrum

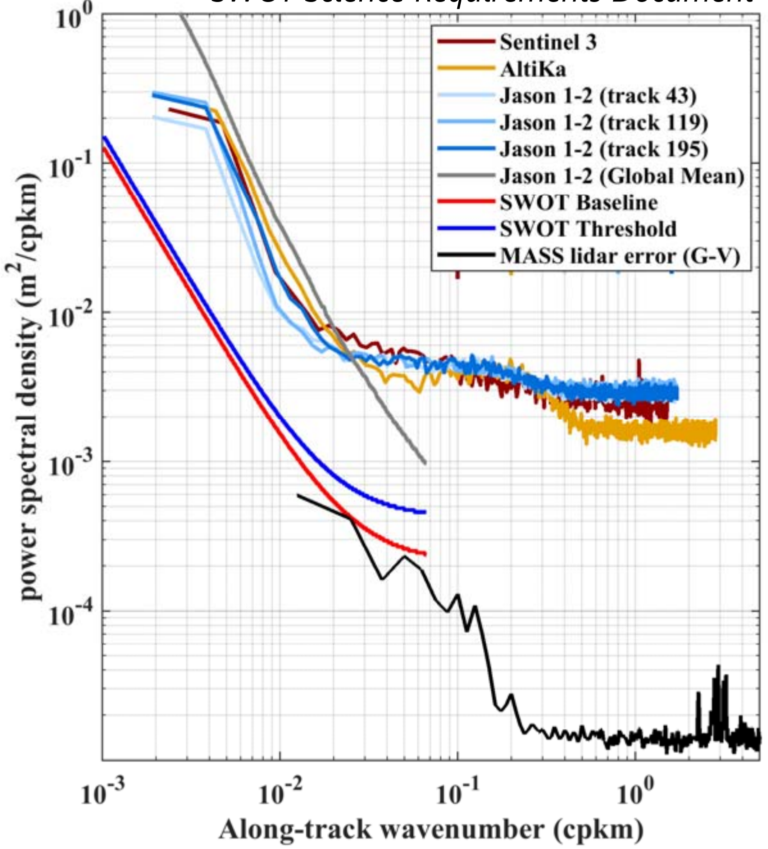
Terrestrial flight over Central Valley & El Paso, TX region (not processed yet). El Paso flight legs shorter (45km vs. 90km) due to terrain and airspace constraints.



Not an ideal location, some vegetation, small rivers, buildings etc., but was our best option. Challenge to plan low level (1800' AGL) repeated passes (requires law enforcement & fire department coordination to mitigate "concerns" from local residents)

This expands the earlier results to lower wavenumbers, demonstrating that the MASS lidar complies with the SWOT spectral errors requirements

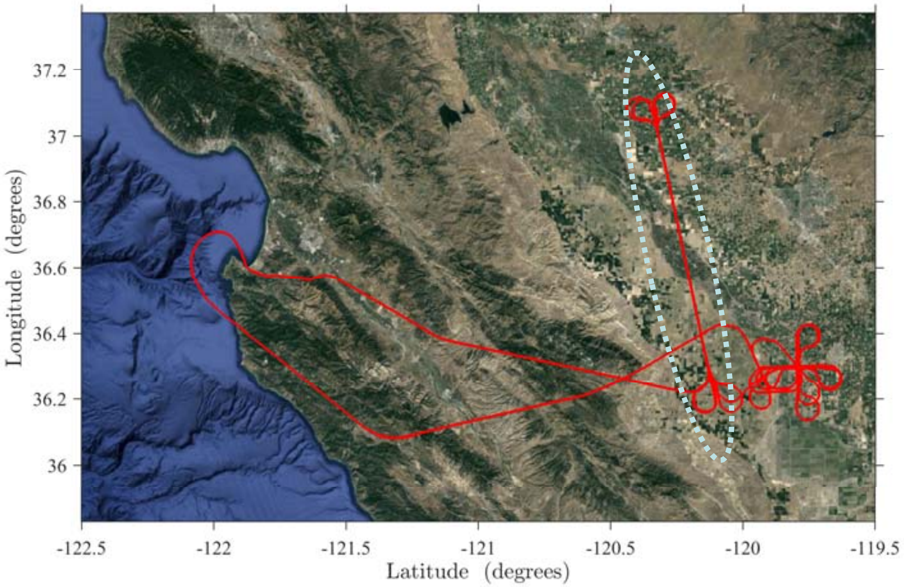
Chereskin et al. 2019
SWOT Science Requirements Document



Here the residual spectra are computed using an average over two passes (reciprocal)

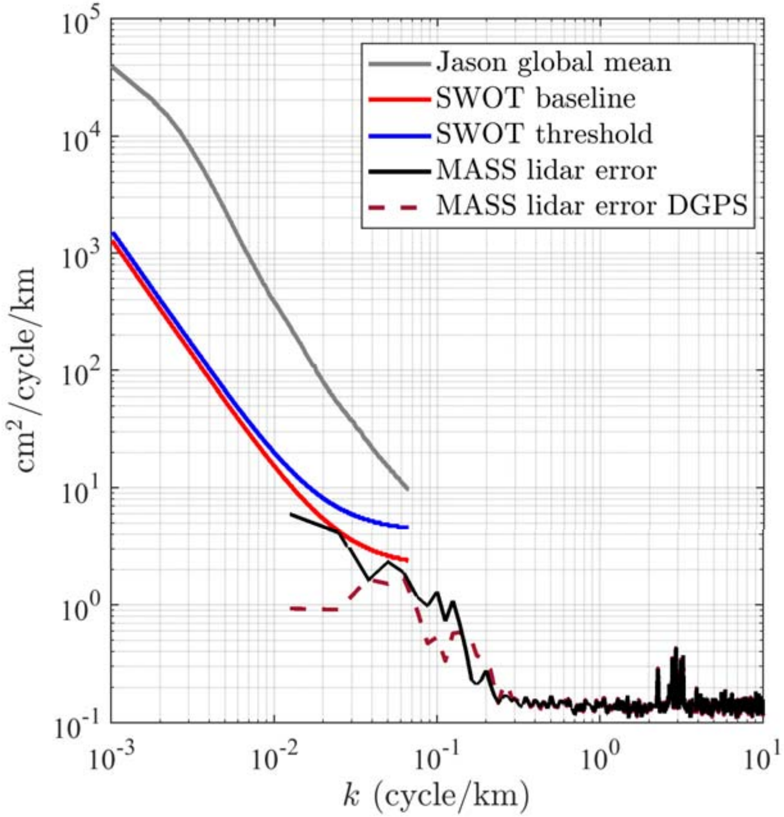
Characterization of MASS lidar noise spectrum

Terrestrial flight over Central Valley & El Paso, TX region (not processed yet). El Paso flight legs shorter (45km vs. 90km) due to terrain and airspace constraints.



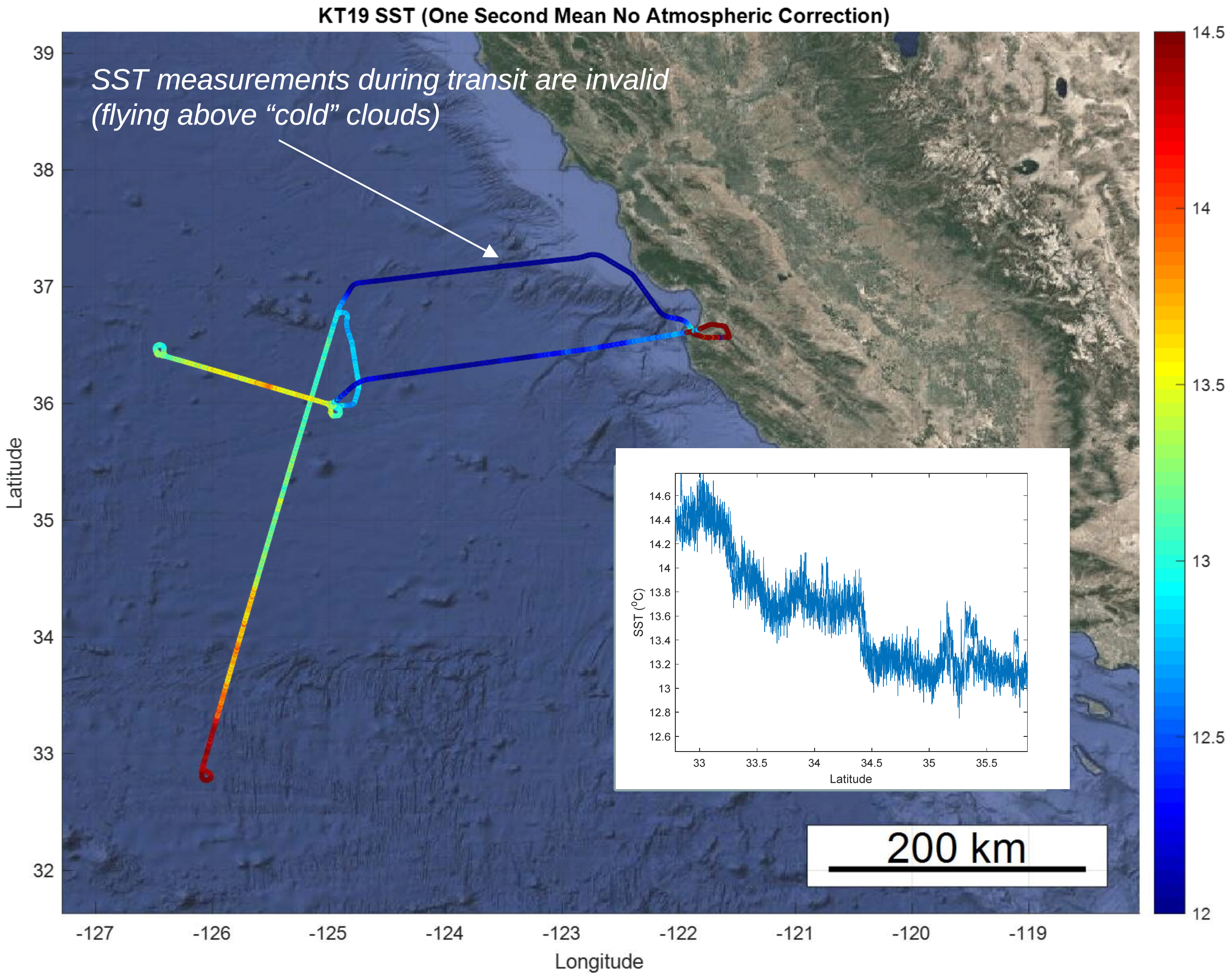
Trajectory computed using PPP processing – JPL solutions expected over the summer (JPL reprocessing)

Lower noise level with PP (i.e. Differential GPS) solution, as expected.



Here the residual spectra are computed using an average over two passes (reciprocal)

Preliminary results - S3 overflight March 28 2019



KT19 SST (One Second Mean No Atmospheric Correction)

SST measurements during transit are invalid (flying above “cold” clouds)

Flight planning and tide computation supported by CNES/CLS (thank you!).

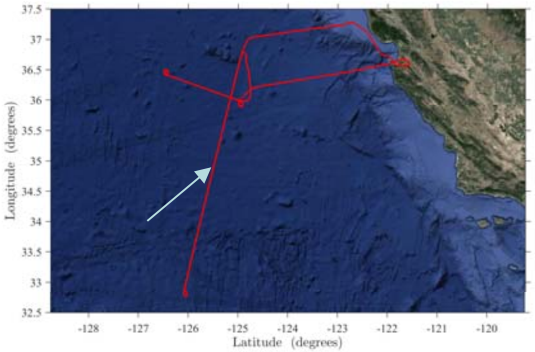
Preliminary results - S3 overflight March 28 2019

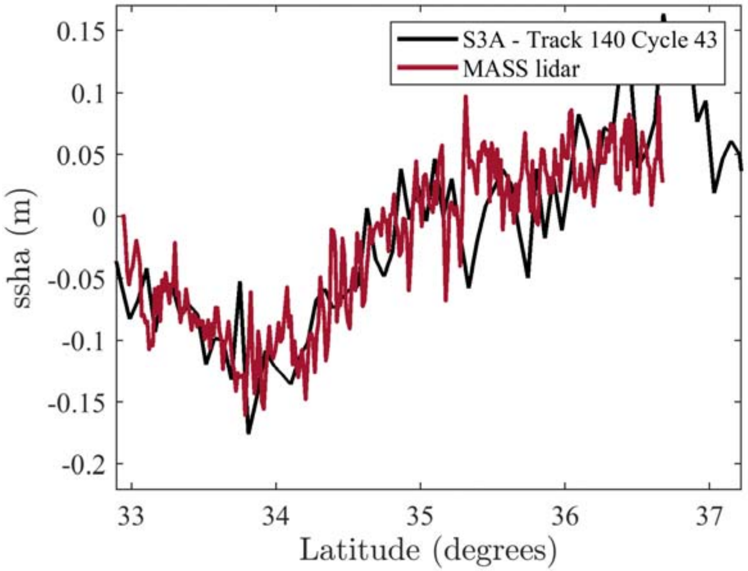
Sea surface height anomaly, ssha, corrected for tides (Ocean FES2014, Solid Earth, Pole Desai) and CLS 2015 MSS model, computed along the aircraft track (space & time) by CNES/CLS.

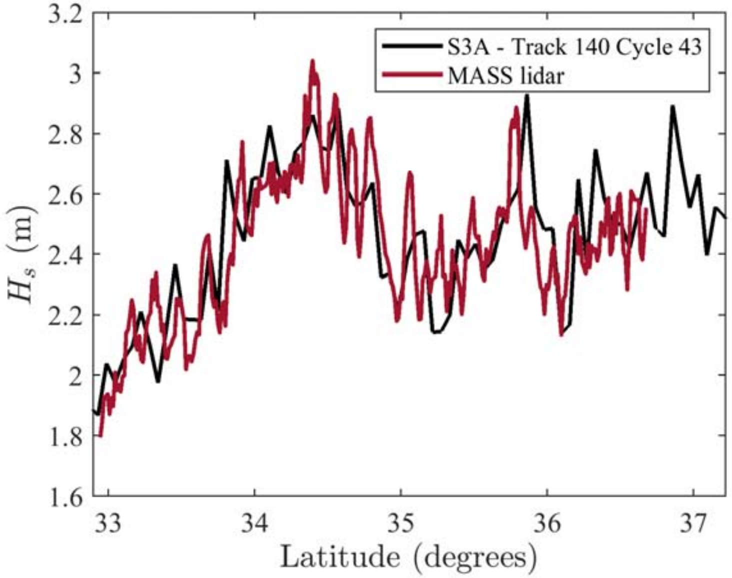
S3A ssha product considered here is from the Ku-band sensor.

Note the correlation between S3A and the MASS lidar products in the spikes of significant wave height.

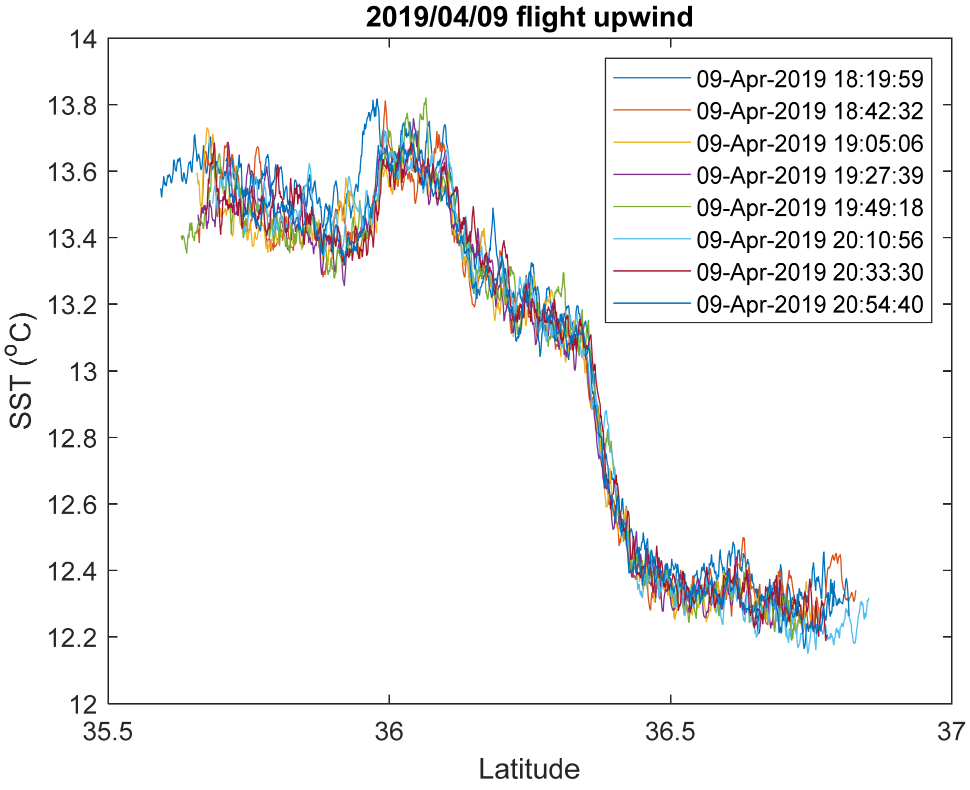
A 15cm constant offset has been applied, yet to be explained but likely caused by reference frame error in arm level (GPS/IMU) computation.

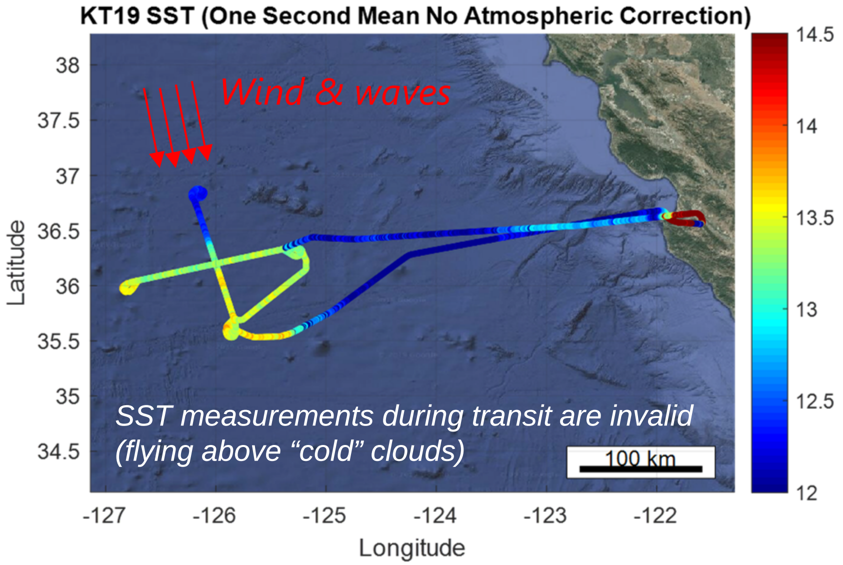






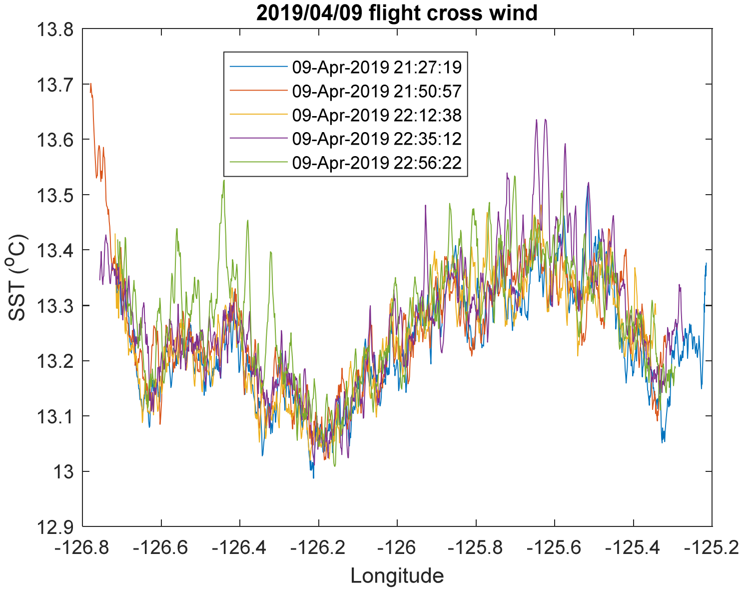
Preliminary results – April 9 2019


2019/04/09 flight upwind


KT19 SST (One Second Mean No Atmospheric Correction)

Wind & waves

SST measurements during transit are invalid (flying above “cold” clouds)


2019/04/09 flight cross wind

Preliminary results – April 9 2019

CLS 2015 MSS model

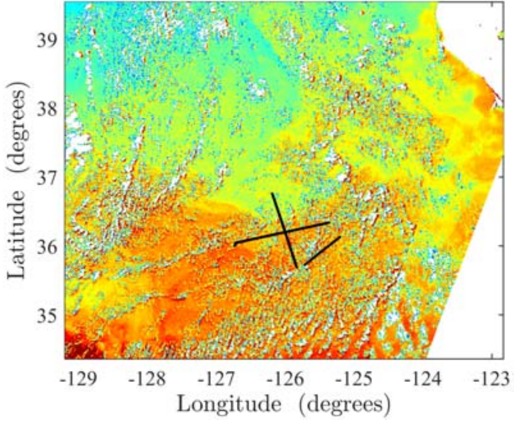
125km long legs – 8 legs up & down wind, 6 crosswind over 2.5hr

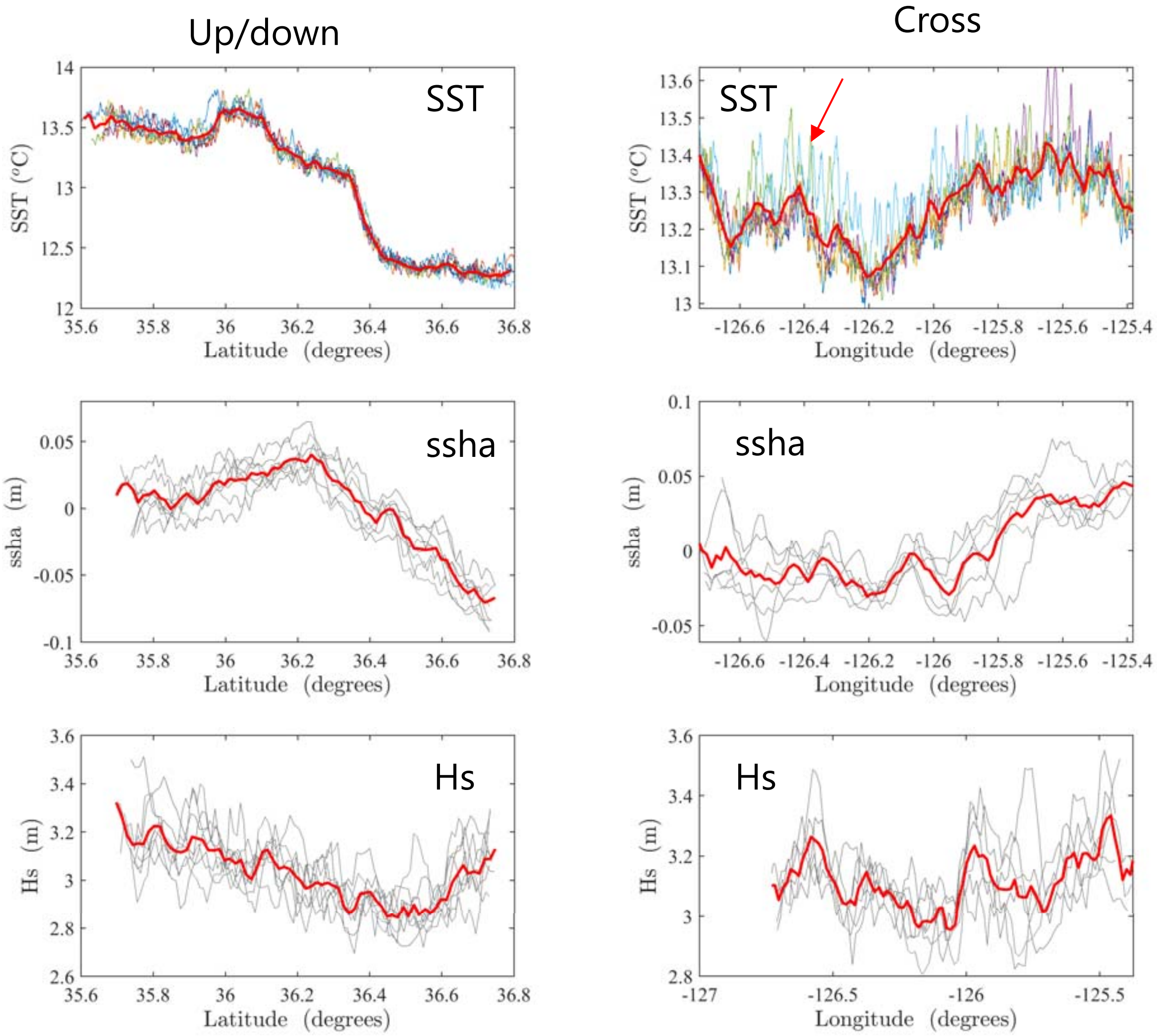
Cloud contamination (more processing needed using IR/Visible cameras to identify cloud corrupt data)

Not much variability over 2.5 hrs.

Red line are bin-averages

S3A SST image





Preliminary results – April 9 2019

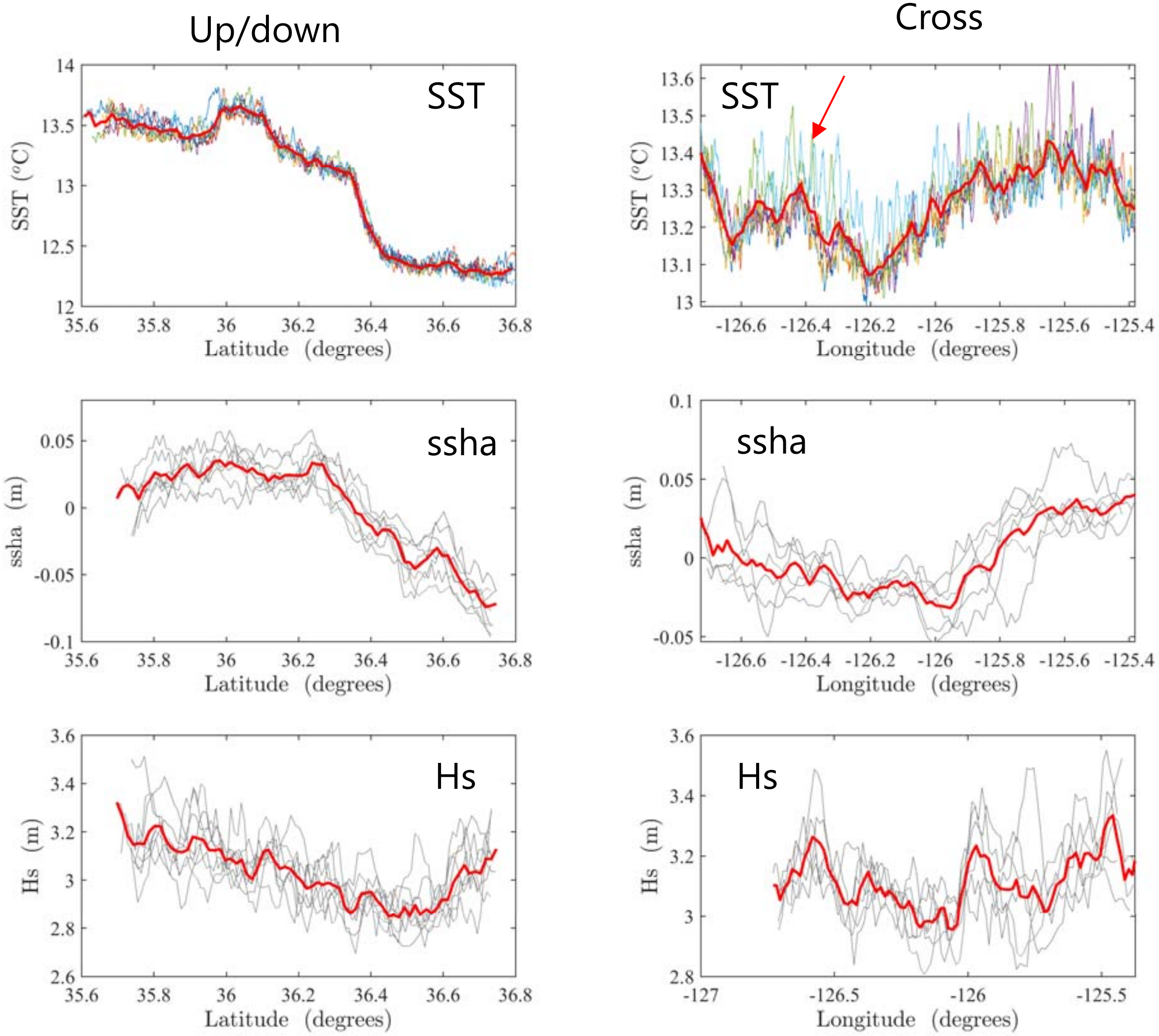
EGM2008 MSS model

125km long legs – 8 legs up & down wind, 6 crosswind over 2.5hr

ssha variability caused by ageostrophic motion? Surface processes? **Geoid?**

Using two other versions of Geoid model (provided by D. Sandwell):

- **EGM2018**
- **CLS "updated" with in-situ products**



Preliminary results – April 9 2019

125km long legs – 8 legs up & down wind, 6 crosswind over 2.5hr

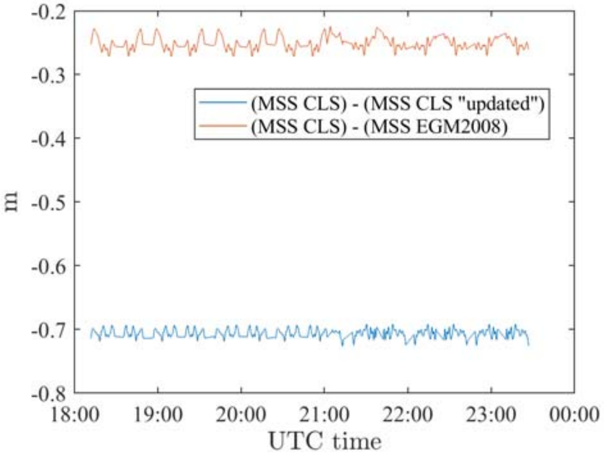
CLS "updated" MSS model

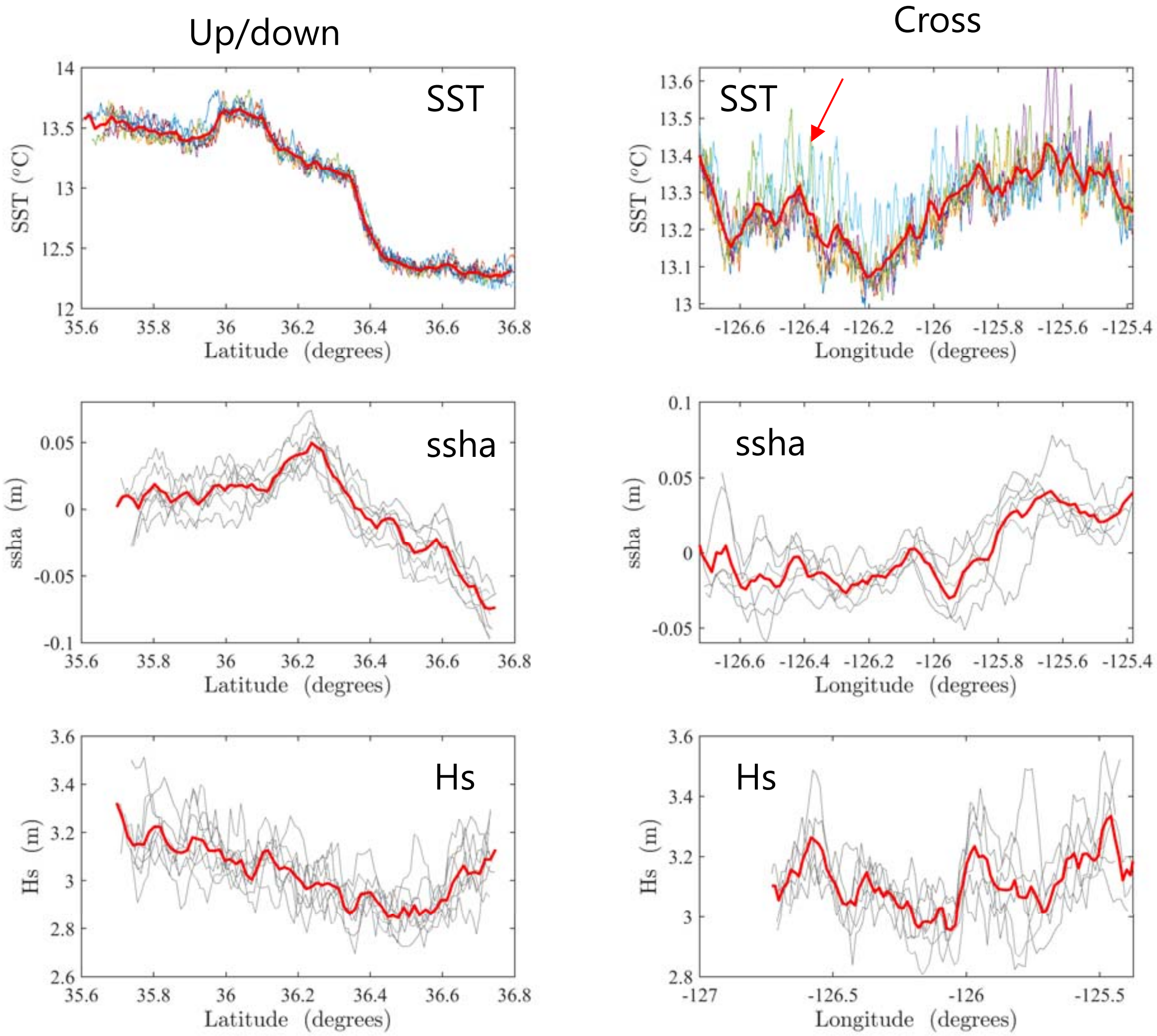
ssha variability caused by ageostrophic motion? Surface processes? **Geoid?**

Using two other versions of Geoid model (provided by D. Sandwell):

- **EGM2018**
- **CLS "updated" with in-situ products**

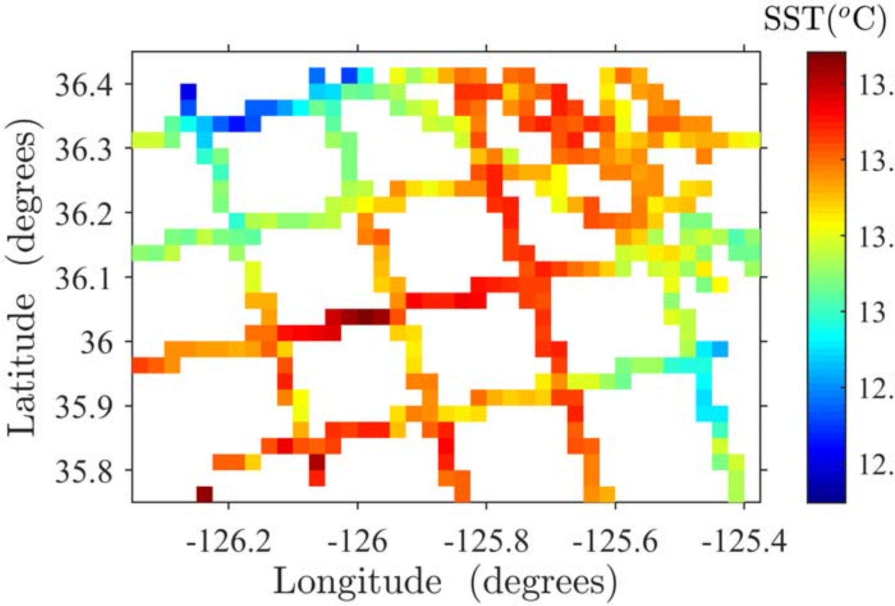
Note: offsets between MSS products

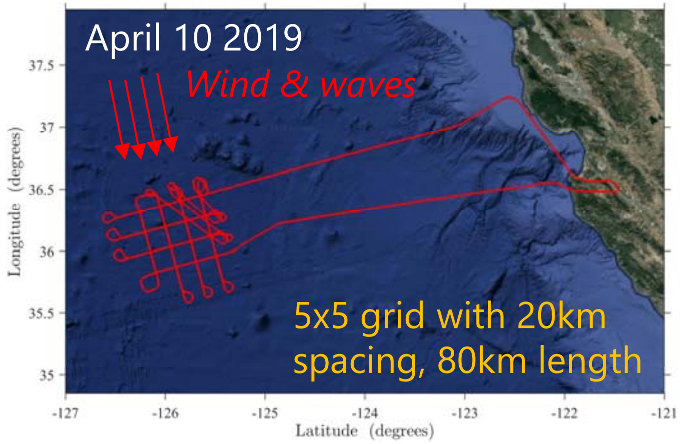




Preliminary results – April 10 2019 - SST

5x5 grid with 20km spacing, 80km length (reciprocal legs)
5hrs on station

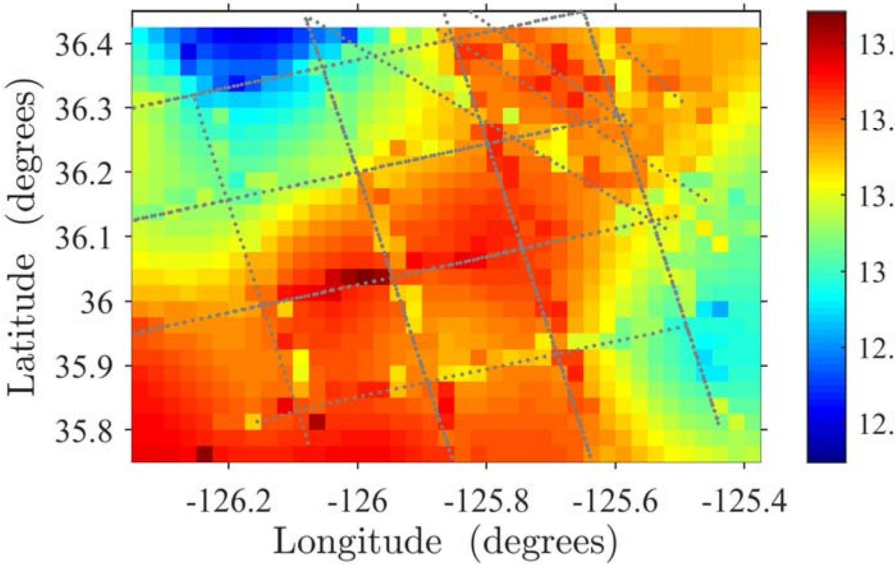



April 10 2019

Wind & waves

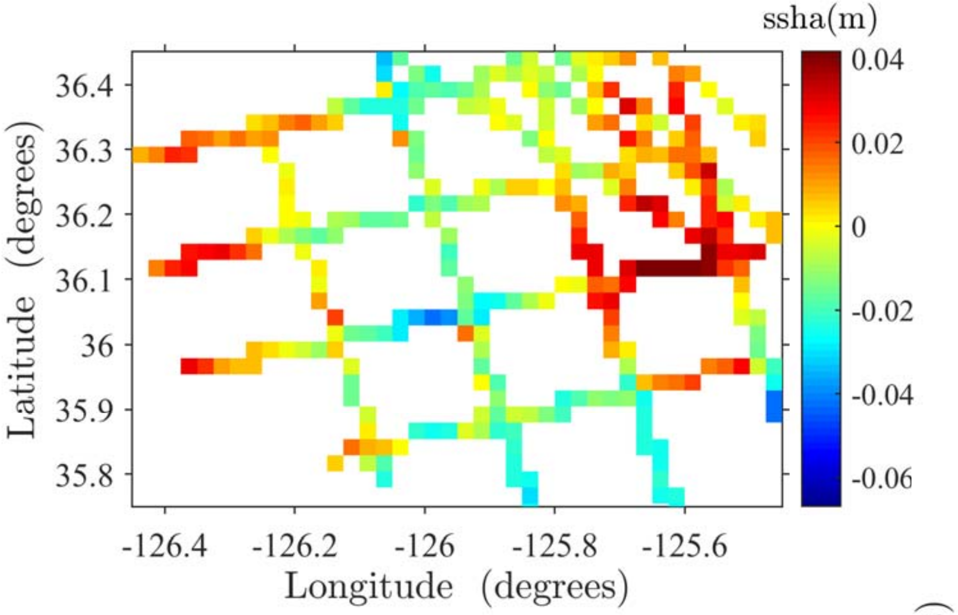
5x5 grid with 20km spacing, 80km length

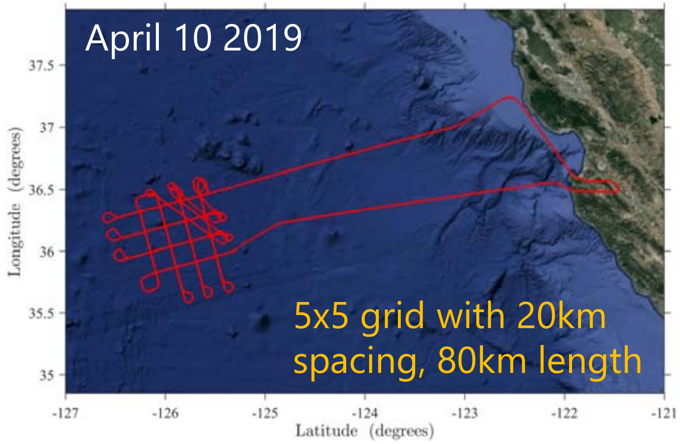
Objective mapping (Lx = Ly =0.2º)



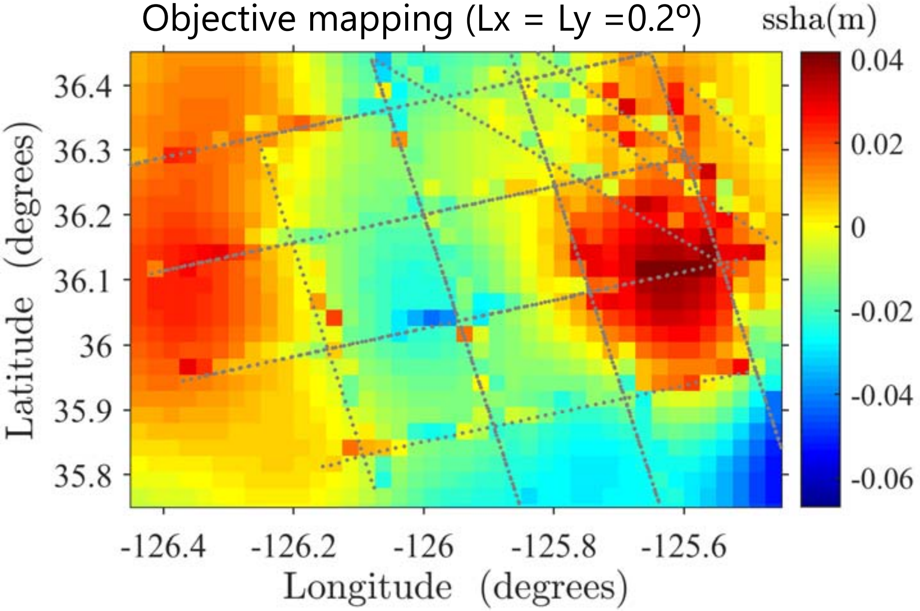
Preliminary results – April 10 2019 - ssha

5x5 grid with 20km spacing, 80km length (reciprocal legs)
5hrs on station



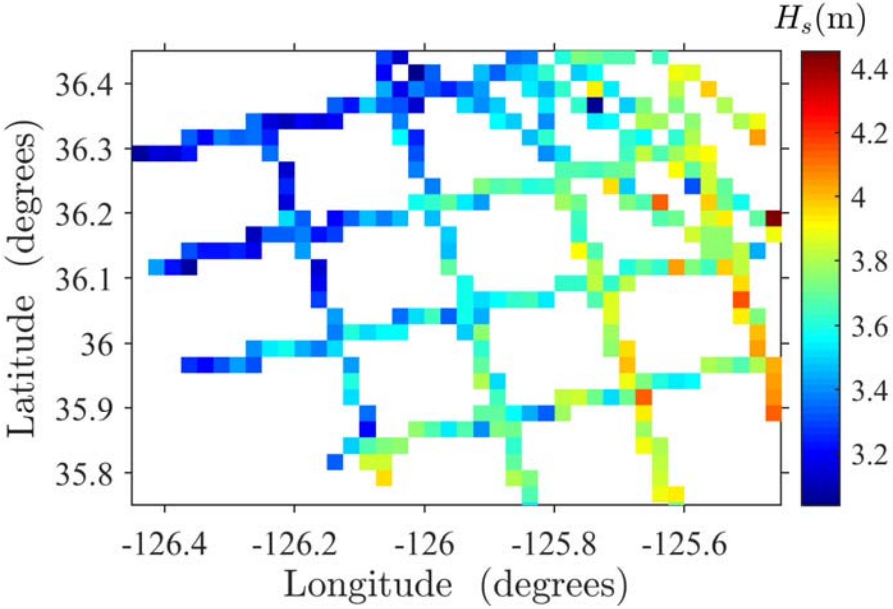


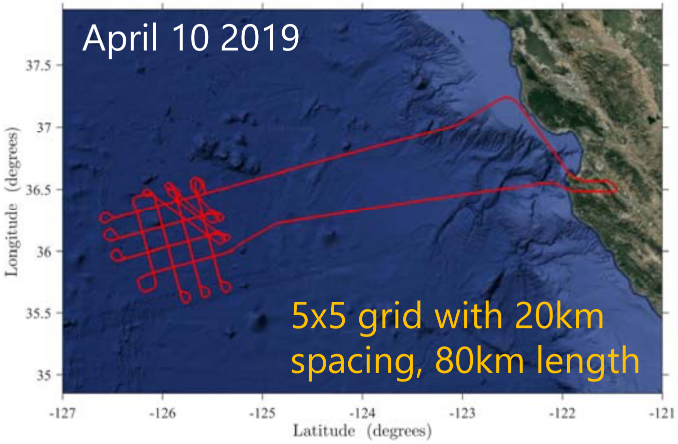
Objective mapping (Lx = Ly =0.2º)



Preliminary results – April 10 2019 - Hs

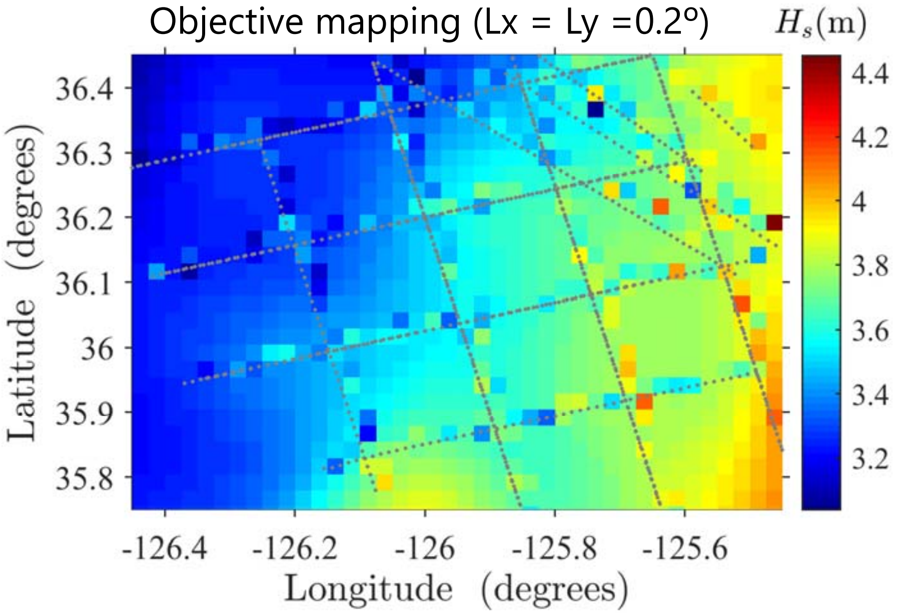
5x5 grid with 20km spacing, 80km length (reciprocal legs)
5hrs on station




April 10 2019

5x5 grid with 20km spacing, 80km length

Objective mapping (Lx = Ly =0.2°)



Lessons learnt (so far!) and on-going analysis

- Low level cloud density was significant but manageable (we could fly below). This will likely have an impact on satellite imagery at the crossover site as well (e.g. SST, visible), importance to better understand submesoscale variability during the post-launch SWOT CalVal.

- Lack of in-situ atmospheric and oceanographic measurements combined with unreliable weather and marine forecasts is not ideal for flight planning.

- We found significant spatial variability in ssha, Hs, SST that will need to be characterized for SWOT CalVal since the spectral requirement is defined for a cross-track average.

- NASA G-V is the ideal platform to support the SWOT CalVal with the MASS. Monterey airport was a good base of operations.

- Support from JSC G-V team was absolutely outstanding.

- We should consider increasing the flight windows for the pre-launch mission to account for mechanical failures and weather days (without increasing number of flight hours).

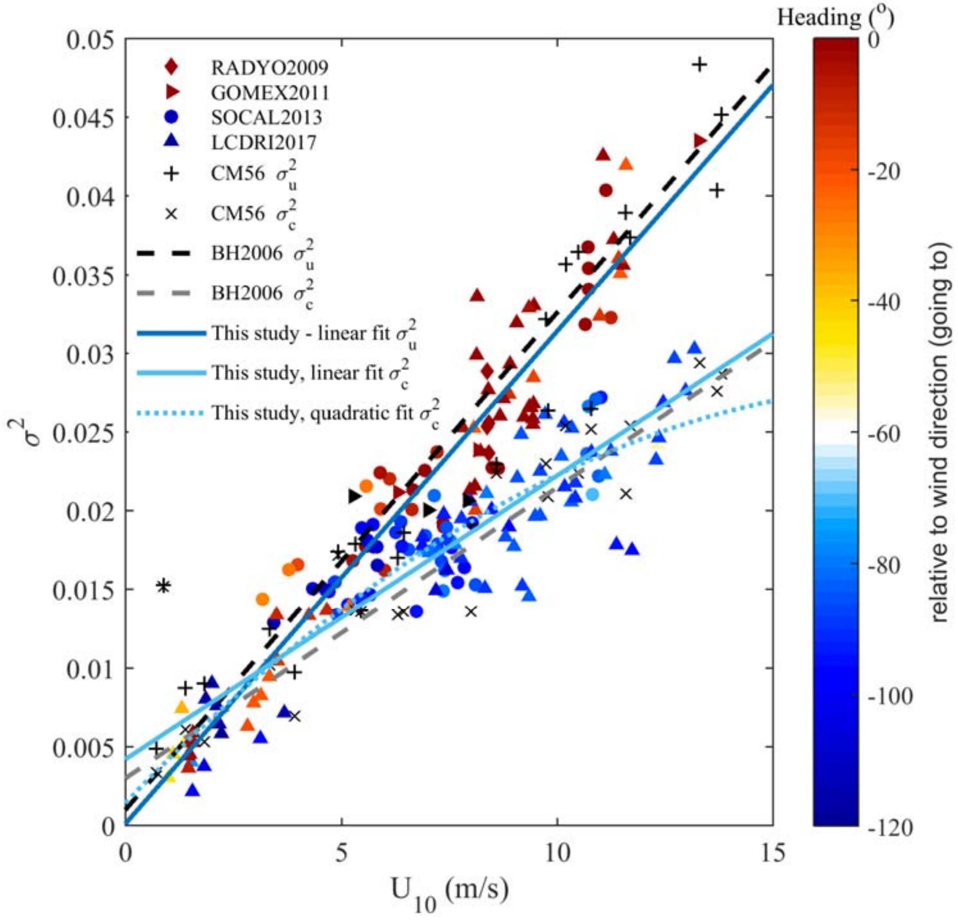
Lessons learnt (so far!) and on-going analysis

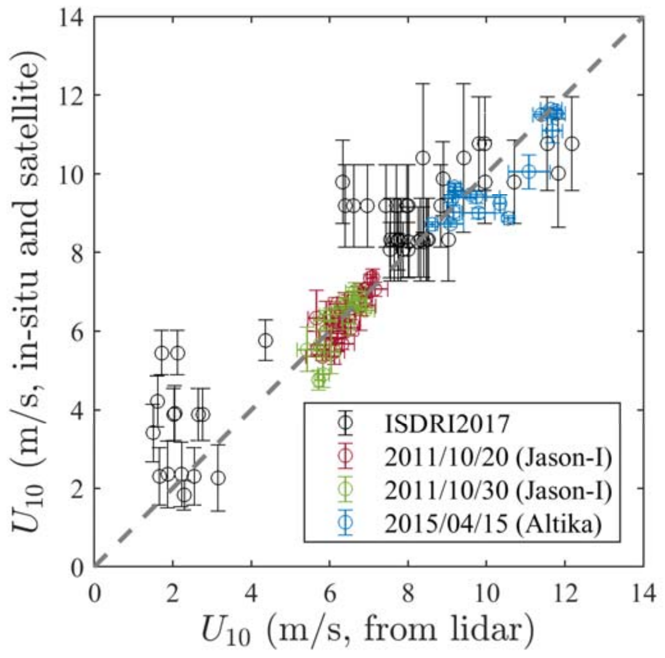
- On-going and future analysis

- Compare GPS solutions from various sources (PPP, JPL reprocessing) and trajectory/attitude measurements from the two GPS/IMU installed on the aircraft
- Process ssha and other lidar products based on these solutions to evaluate best GPS processing approach
- Compute ssha, Hs wavenumber spectra (along–track), and PSD of ssha measured from reciprocal passes
- Process imagery data to identify very low level clouds that could contaminate ssh and sst measurements
- Compute surface winds and momentum flux (Lenain et al, 2019 JPO subjudice)
- Compute directional spectra along the flight track (3km along track resolution)
- Compute surface velocity from IR imagery
- Continue detailed analysis of S3A and MASS lidar products using 20Hz and other more experimental S3 products.
- Characterize decorrelation time and length scales of ssha, significant wave height, sst for repeated passes.

Lidar measurements of surface wind and slope statistics over the ocean

estimating surface slope statistics and wind speed and momentum flux remotely
Novel lidar based technique, following the seminal work of Cox & Munk 1956.



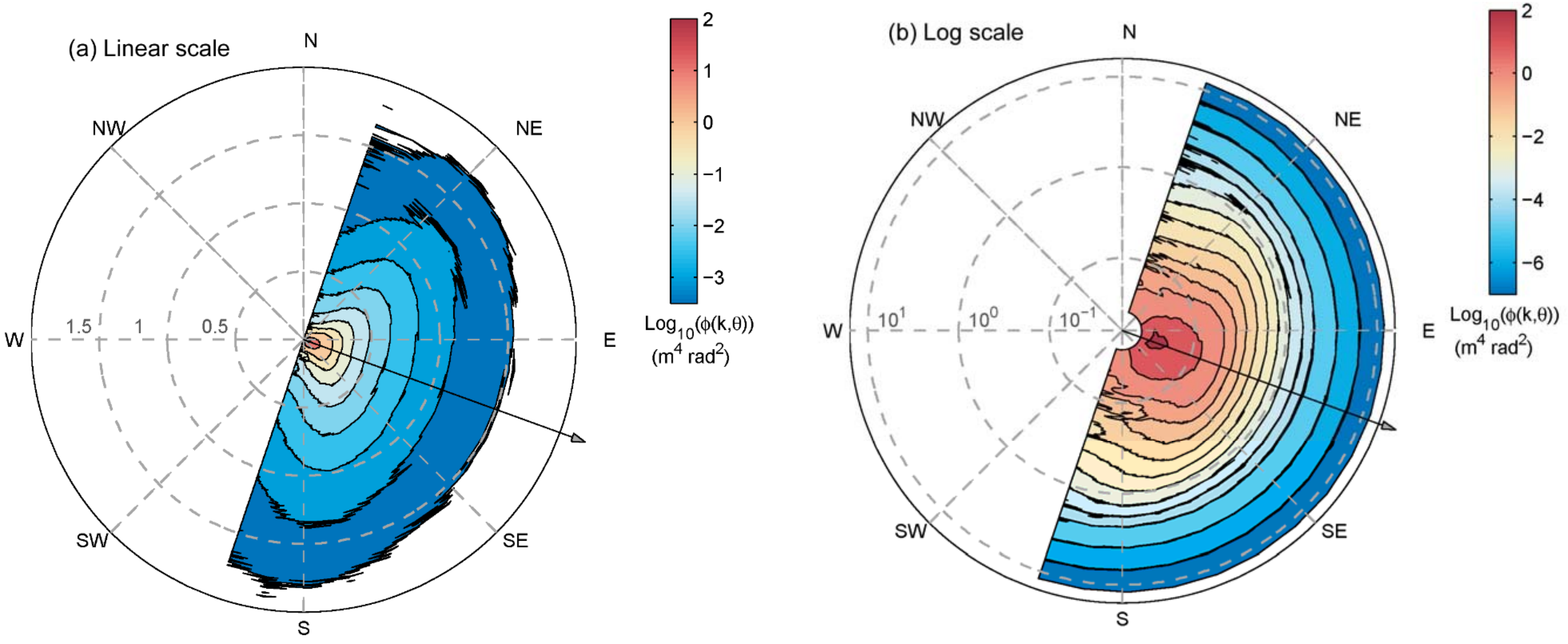


Manuscript submitted to JPO (Lenain, Statom & Melville)

Additional MASS measurements relevant to SWOT: Directional Wave Measurements Down to Sub-Meter Scales

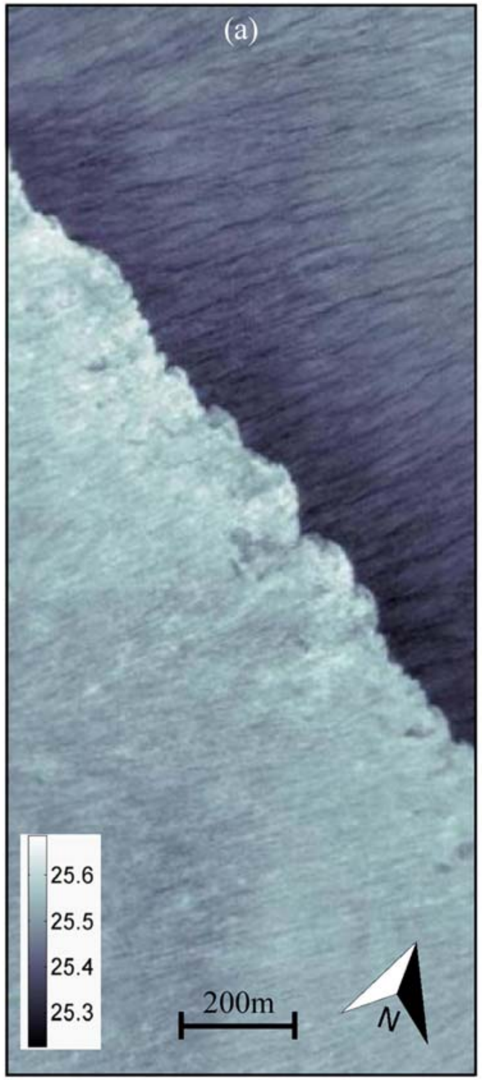
SCRIPPS INSTITUTION OF OCEANOGRAPHY UC San Diego

Lidar also provides directional wave spectra, which may be very useful for SWOT troubleshooting



Lenain, L. and W.K. Melville, 2017: Measurements of the directional spectrum across the equilibrium-saturation ranges of wind-generated surface waves. *J. Phys. Oceanogr.*, https://doi.org/10.1175/JPO-D-17-0017.1

Beyond MASS ssh lidar measurements: Using IR imagery to infer surface velocity



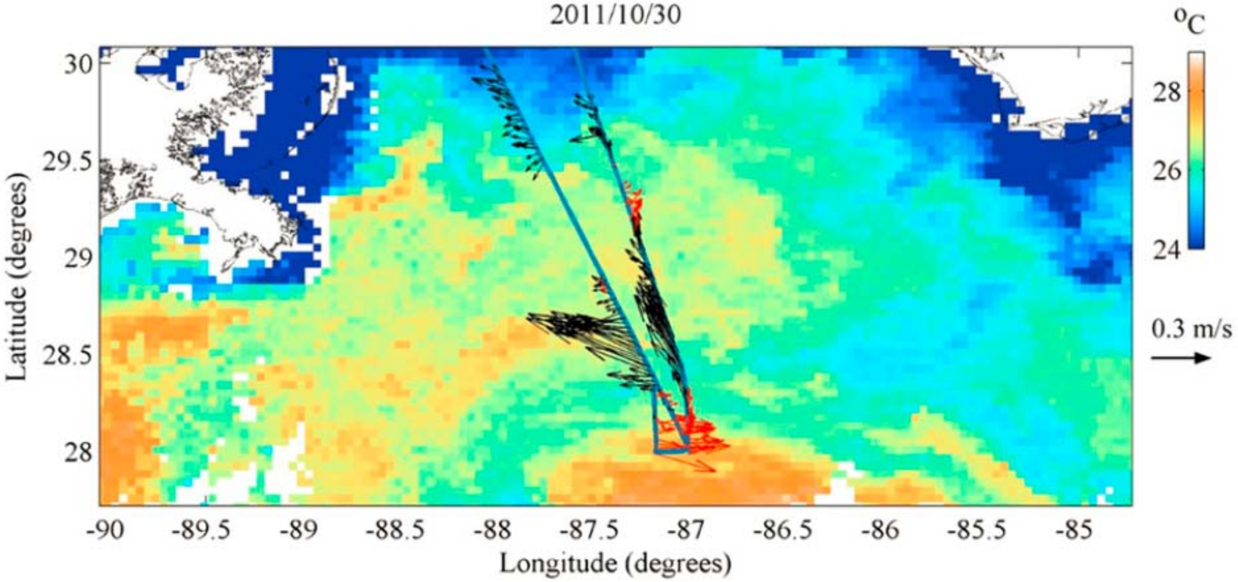


FIG. 7. SST estimated from *Terra* level 3 daily product (°C) on 30 Oct 2011, 10 h prior to the airborne survey conducted the same day. The flight track is shown in blue. The average surface velocities derived from the thermal imagery are shown as vectors along the flight track (red, positive easterly velocity; black, negative easterly velocity). Note the sharp change in surface velocities as the aircraft went across the Loop Current front.

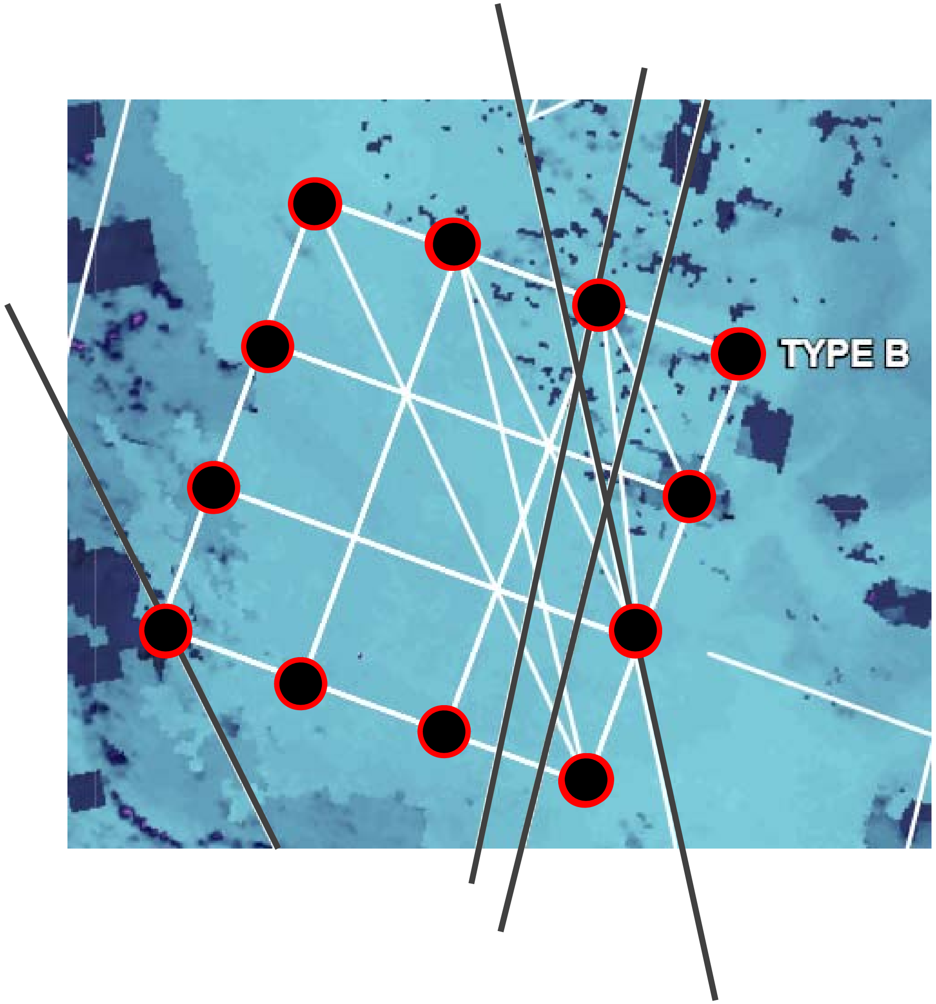
Surface velocity computed from feature tracking of the MASS SST imagery, then averaged to remove orbital wave motion

Conclusions

- MASS successfully integrated in the NASA G-V, and is capable of measuring surface waves and SSHA typically with O(100) m – 1 km swath width and sub-meter along- and cross-track resolution.
- Comparisons of SSHA with Sentinel 3 altimetry appear to be very good.
- Spectral studies of MASS noise levels have been made over central California showing compliance with SWOT requirements for reciprocal airborne tracks.
- The next 6 months will be dedicated to detailed analysis of the data collected during the prelaunch MASS-SWOT mission.
- Note that the MASS provides additional measurements for the validation of SWOT performances
    - ➢directional wave spectra
    - ➢Sea surface temperature and hyperspectral imagery (used to identify submesoscale features such as fronts and filaments)
    - ➢Surface velocity (from IR imagery)
    - ➢Surface winds and momentum flux

Flight profiles

- Type B: 100km reciprocal legs grid pattern

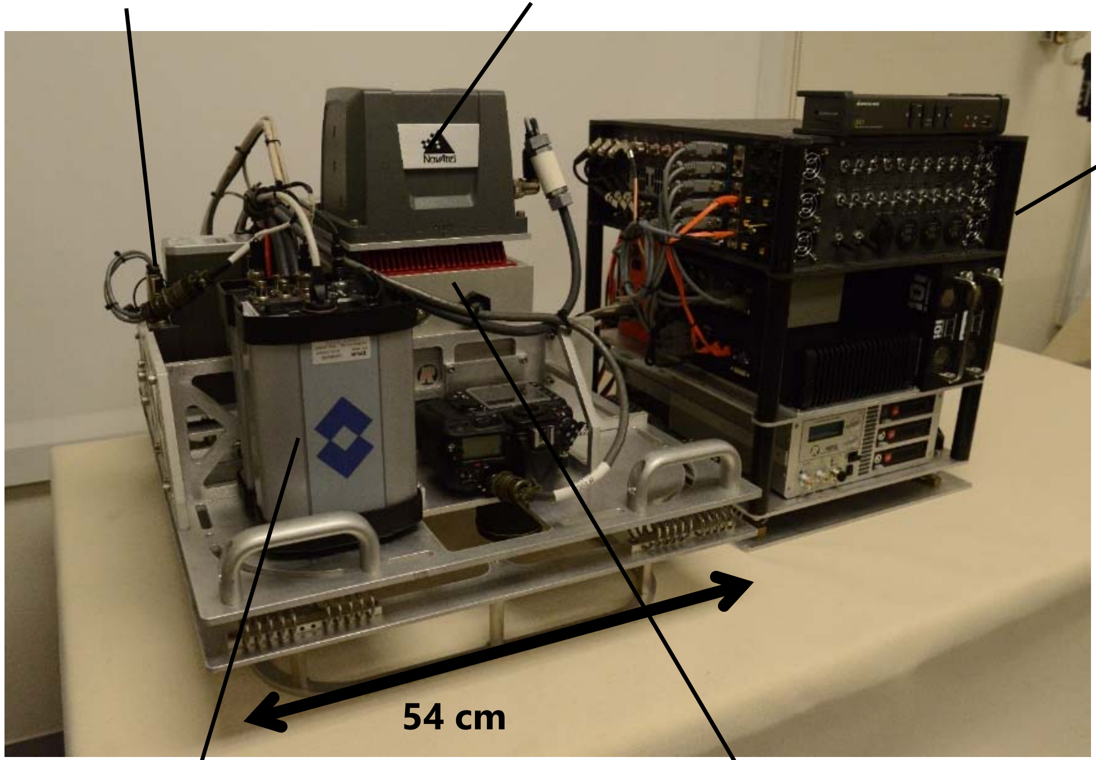


SIO Modular Aerial Sensing System (MASS)

Hyperspectral (Specim Kestrel)

GPS/IMU (NovAtel LN200 SPAN)

Power distribution, synchronization, data acquisition



Long Wave IR Camera (FLIR SC6700 LWIR)

Scanning waveform lidar (RIEGL Q680i)

System had mostly flown on Partenavia P68 to date, but MASS is quite portable; P68 has limited speed and range

Technical description in Melville et al. 2016