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

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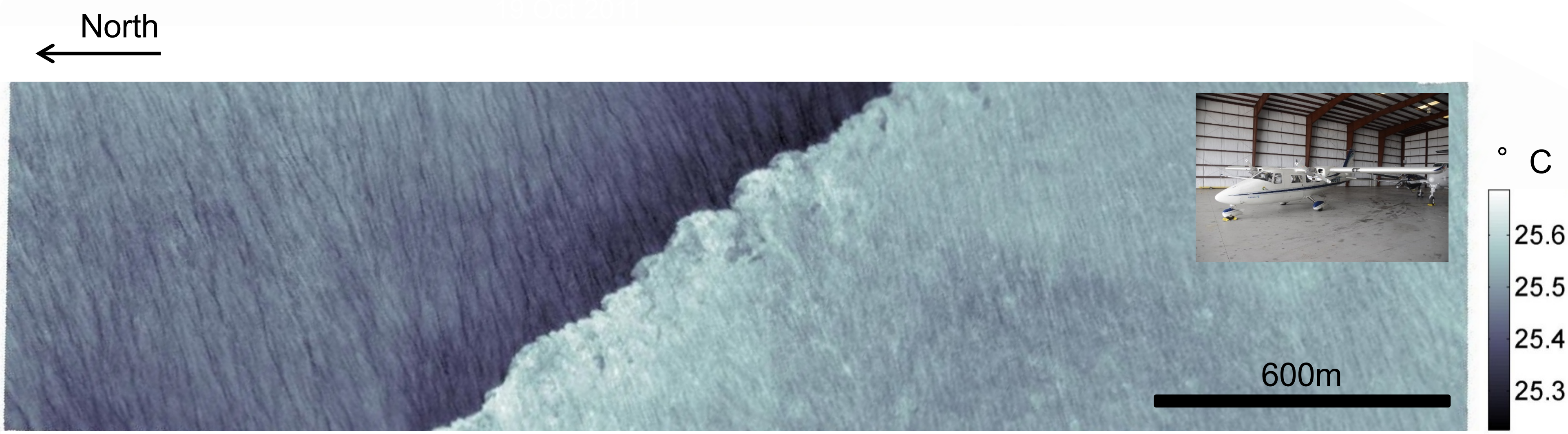
Scripps Institution of Oceanography

SWOT Calval Workshop

Montreal, June 29 2018



Airborne infrared imagery showing a temperature front at the northern boundary of the Loop Current

SIO Modular Aerial Sensing System (MASS)

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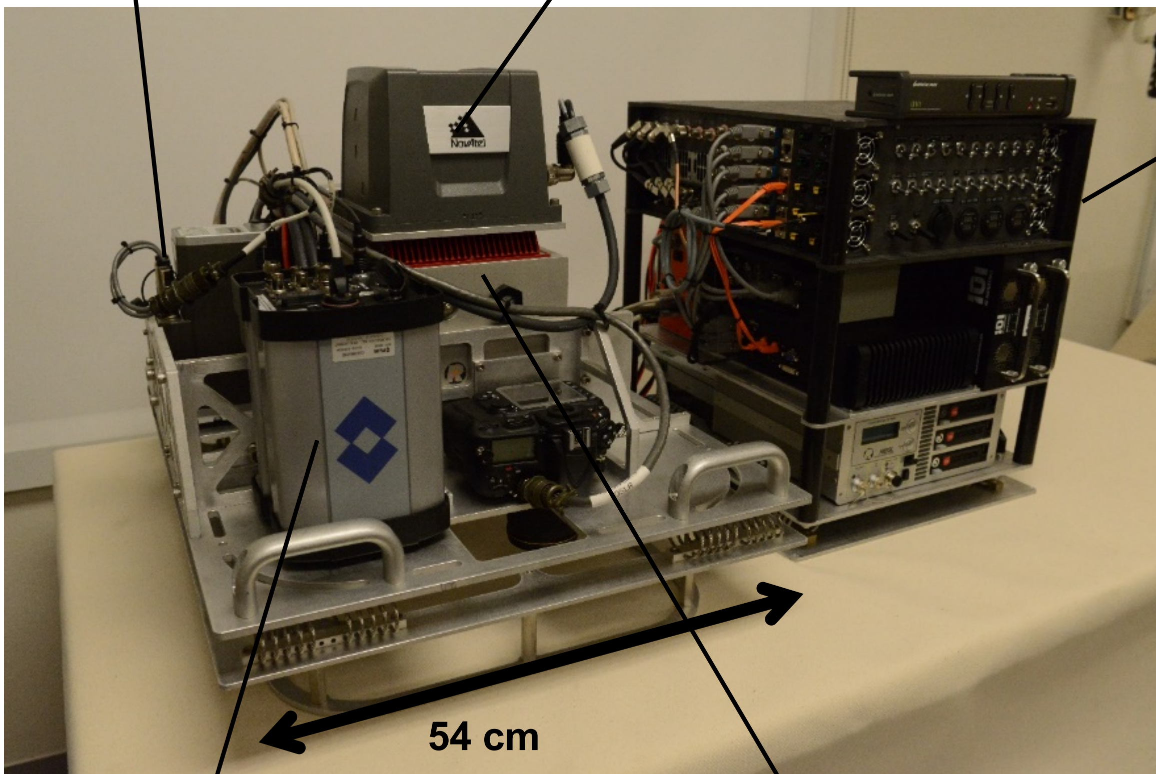
Hyperspectral (Specim Kestrel)

GPS/IMU (NovAtel LN200 SPAN)



Power distribution, synchronization, data acquisition

Currently operating two complete MASS systems

Scanning waveform lidar (RIEGL Q680i)

Long Wave IR Camera (FLIR SC6700 LWIR)

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

SIO Modular Aerial Sensing System (MASS)

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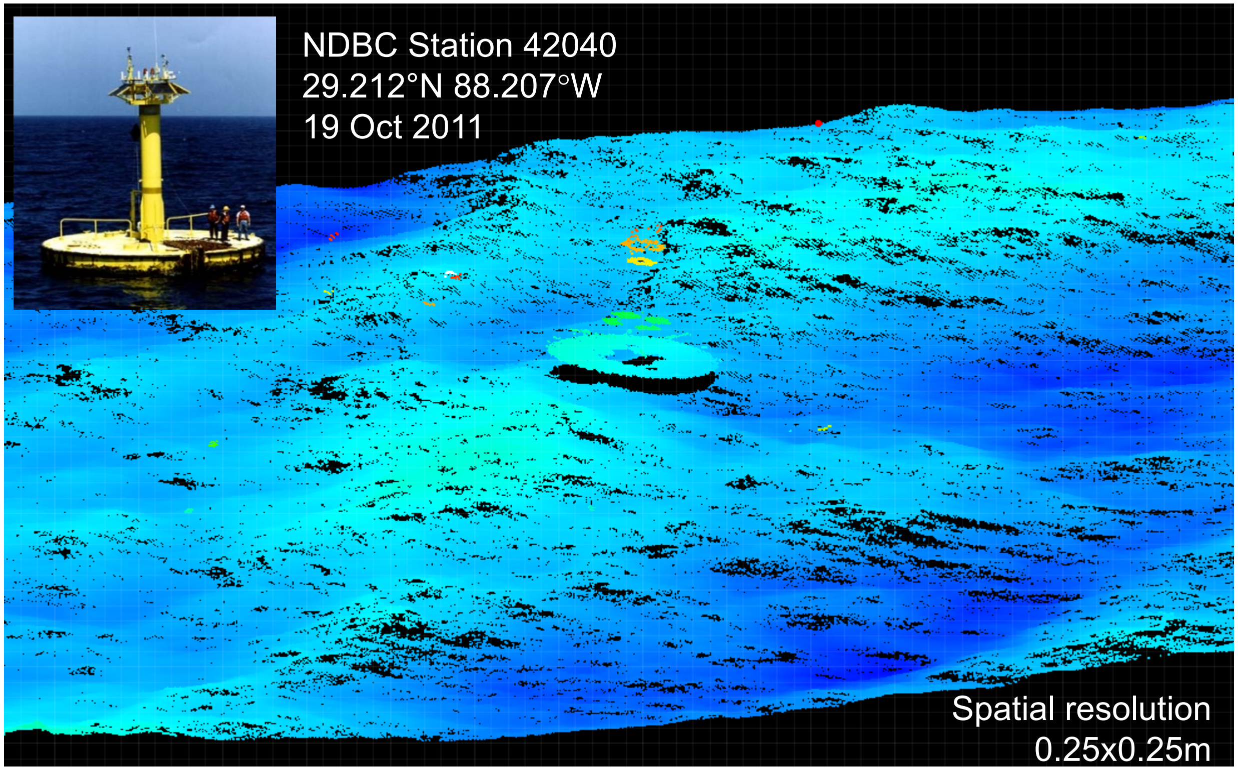
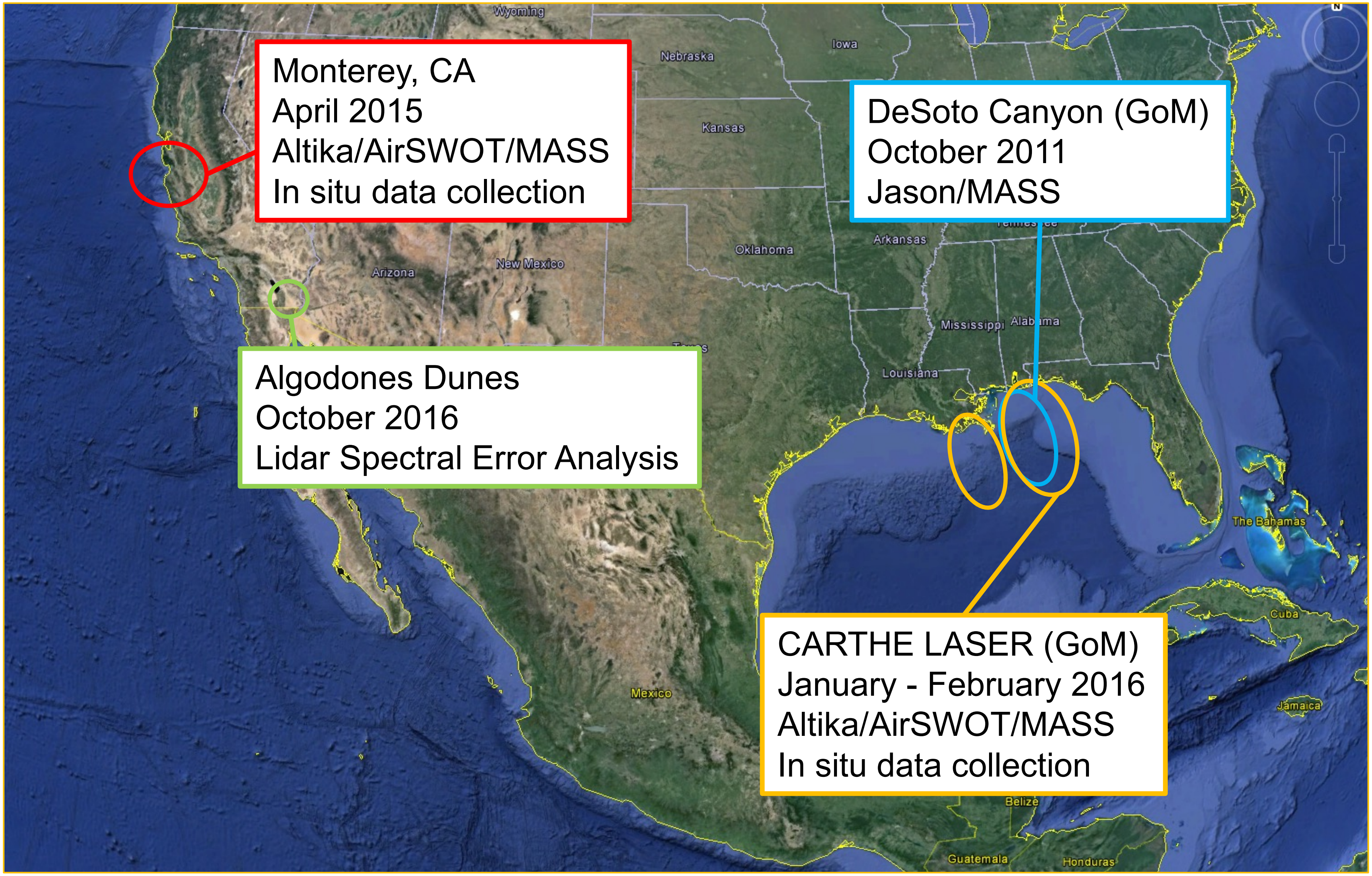


Example of surface elevation as measured from the MASS during a 2011 experiment in the Gulf of Mexico, flying above NDBC buoy #42040. (wind~12m/s, Hs = 3.1m, aircraft altitude = 500m AMSL)

Lidar has exquisite height precision and resolution

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 & Cal/Val Campaigns - Overview



MASS validation and maturation have encompassed several sites over several years

High-Resolution SSHA from Airborne Altimetry

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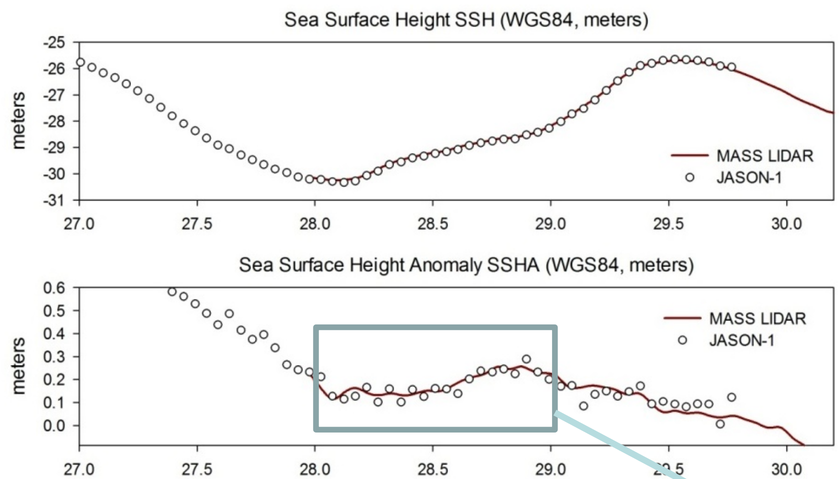
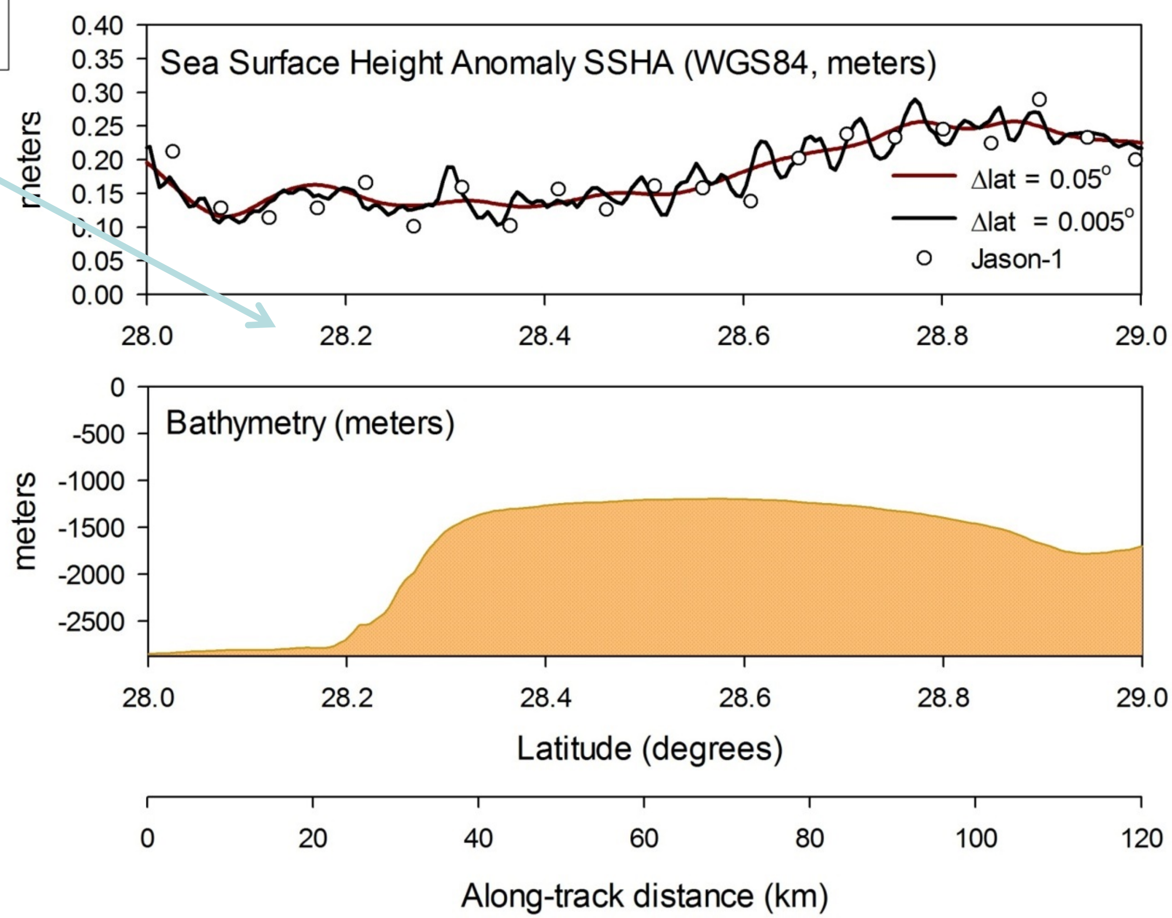
DeSoto Canyon, Gulf of Mexico 2011 Experiment (from Melville et al. 2016 JTECH publication).





Lidar is capturing real phenomena at wavelengths shorter than observed by existing radar altimeters; SWOT will explore these effects, so Cal/Val at these scales is critical.

Reciprocal Passes Across the Loop Current

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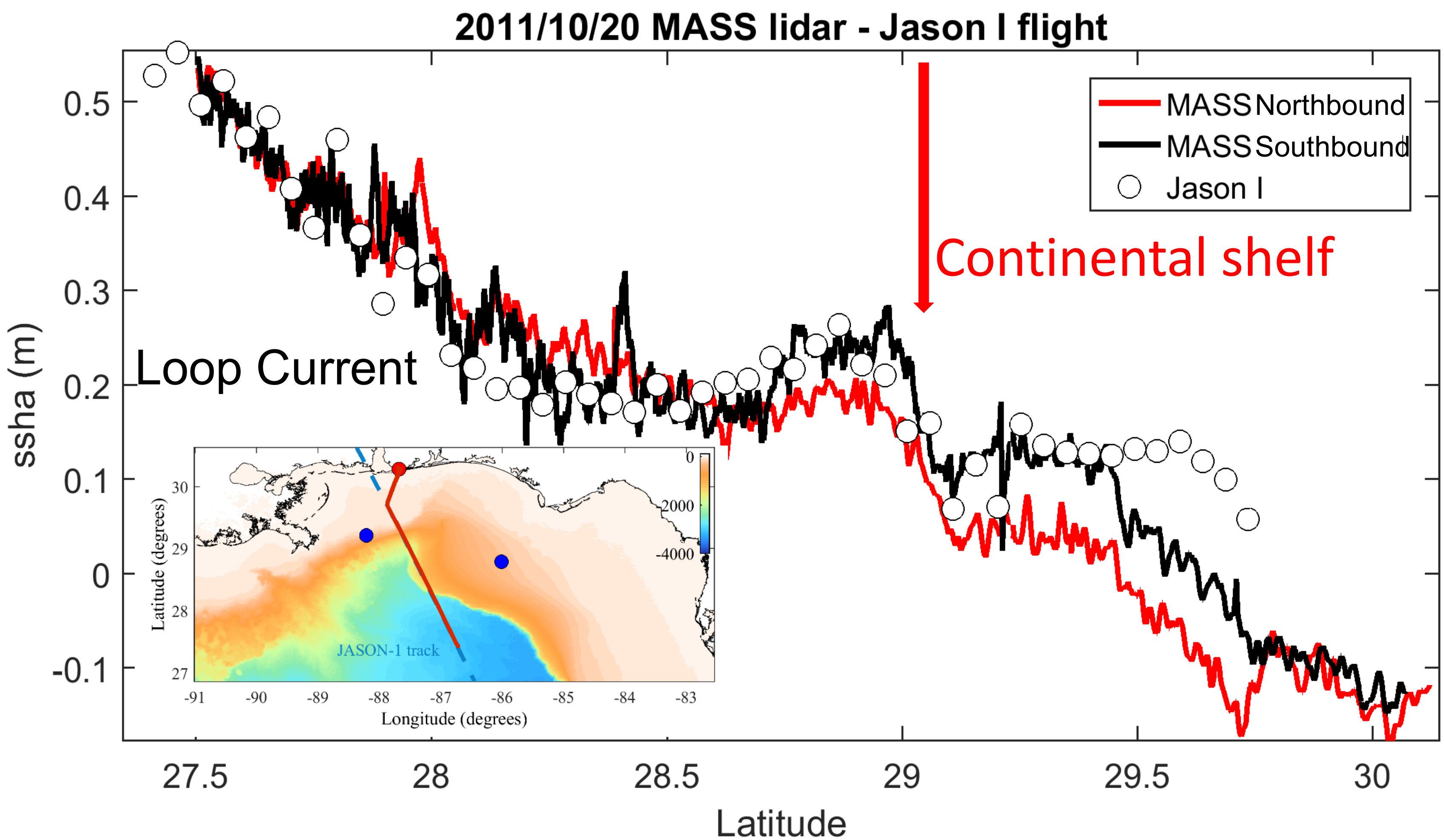


Fig. 6: SSHA estimated from two MASS lidar passes (“northbound” and “southbound”) over the same Jason-I track (see insert). Note that the satellite pass occurred in the middle of the southbound lidar pass (black).

Reciprocal Passes Across the Loop Current

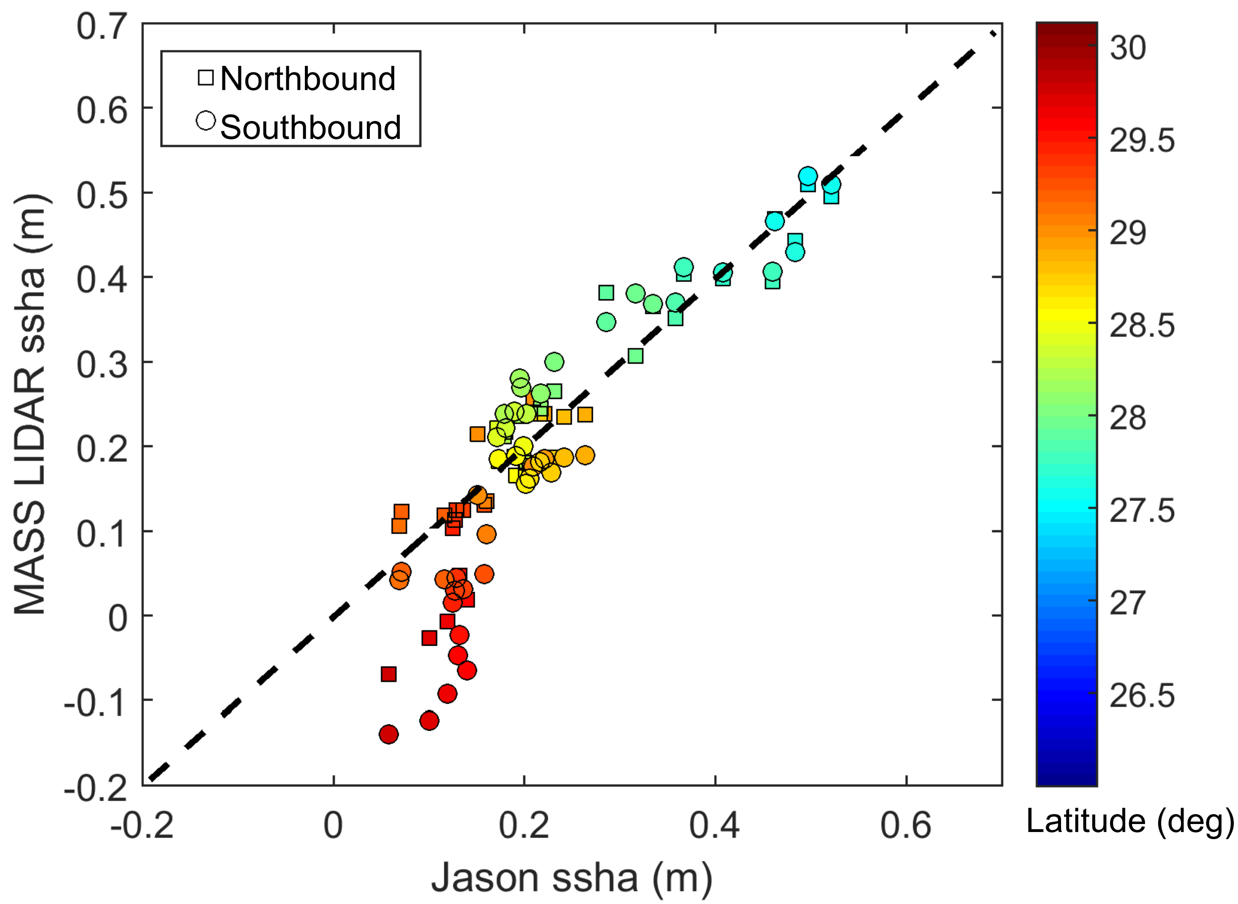
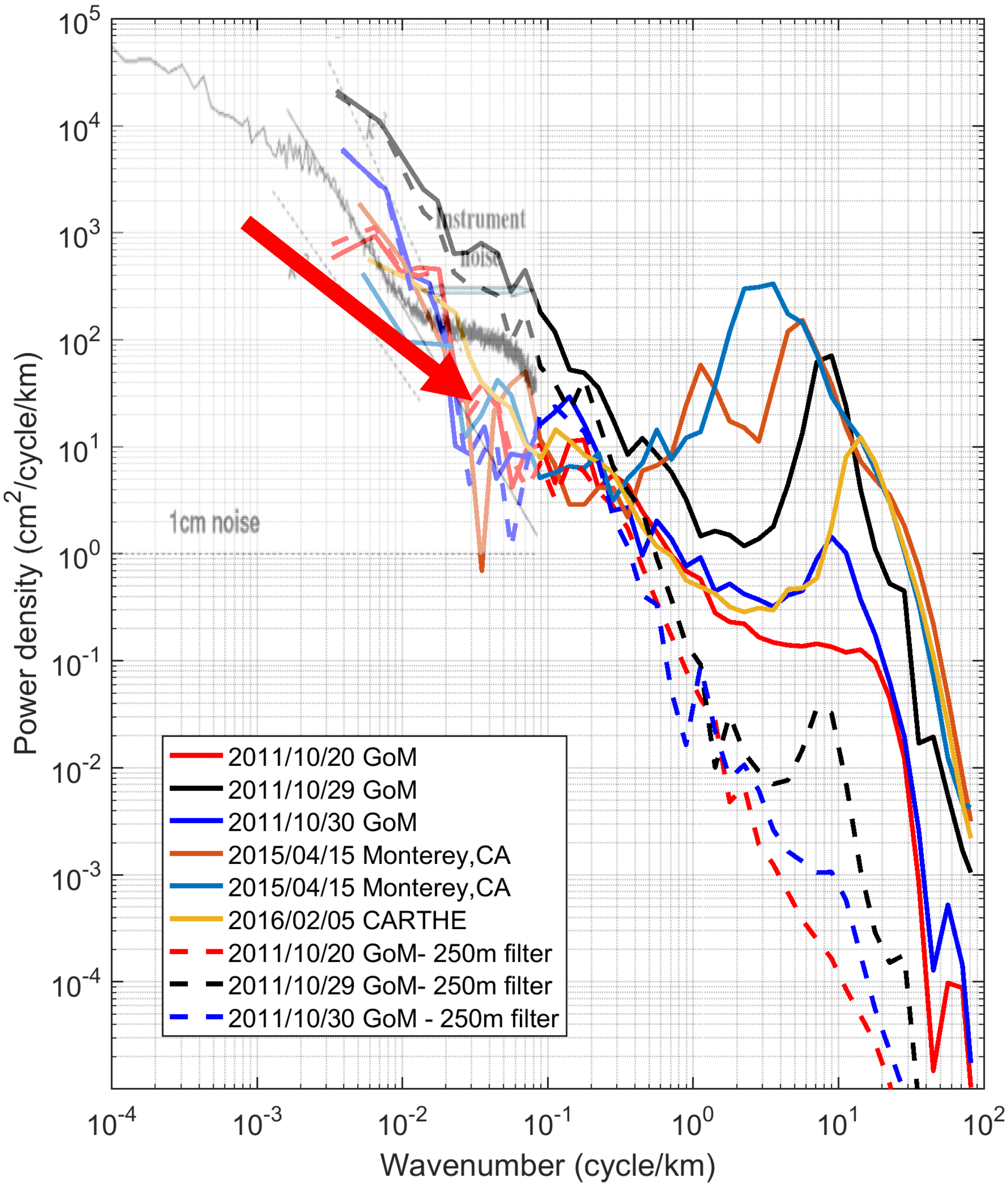


Fig. 7: Scatterplot of the SSHA measured by Jason-I and the MASS lidar averaged over the along-track spatial resolution of the satellite for the latter. Note the divergence for the northern part of the track, as we get close to the continental shelf.

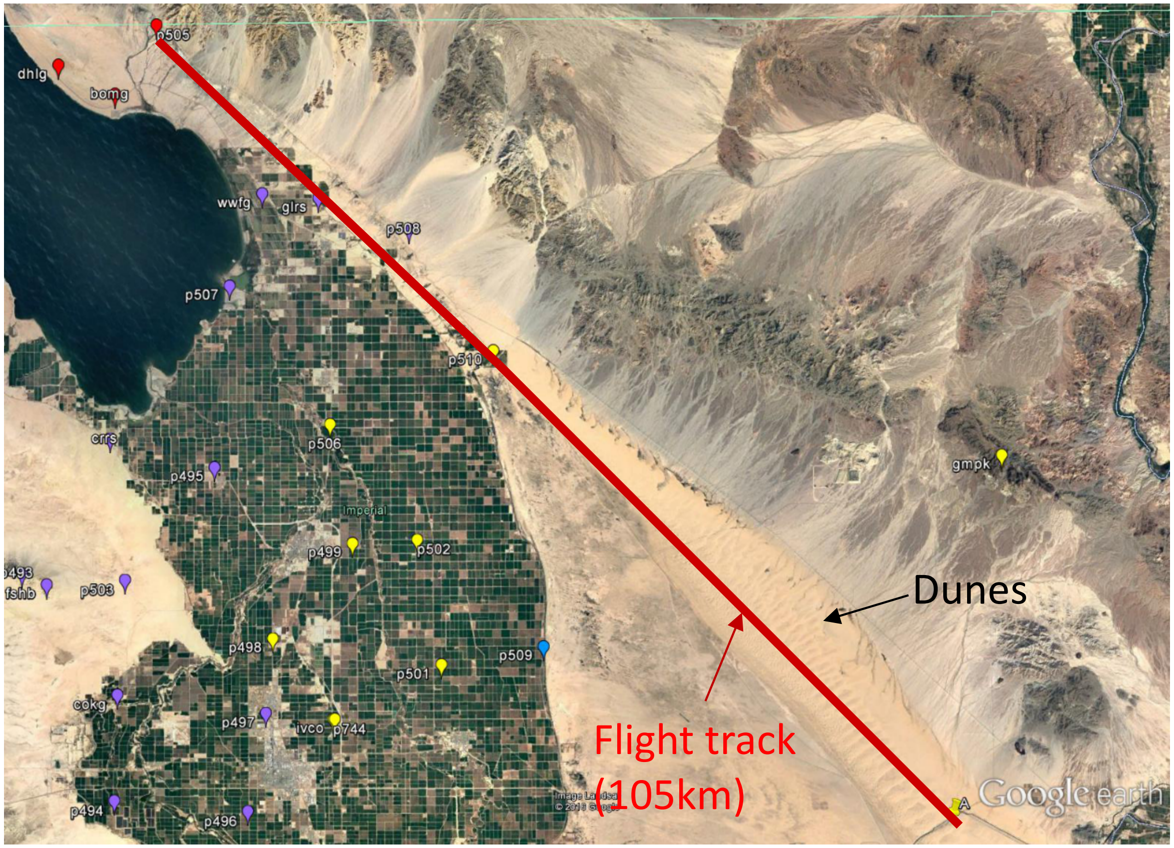
SSHA Spectra

SSHA spectra measured by the MASS scanning lidar for the flights conducted during the three experiments shown in slide 4. The data are plotted over satellite altimeter data from Figure 1 of Fu & Ferrari (2008), noting the O(100)km resolution of the traditional satellite altimeters. Note the differences between 250 m filtered data (dashed) and original data (solid).

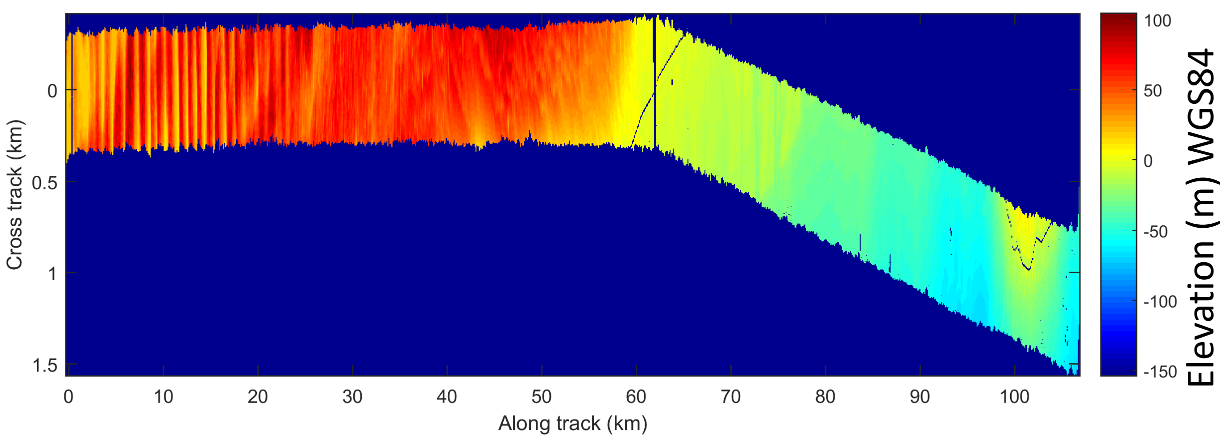
Note that these plots show SSHA spectra, not SSH error spectra as in SWOT requirements. We cannot determine SSH error because there is not independent source of SSH truth, which is why we need SWOT and why SWOT Cal/Val at these wavelengths is critical



Algodones Dunes Campaign – October 17-19 2016



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

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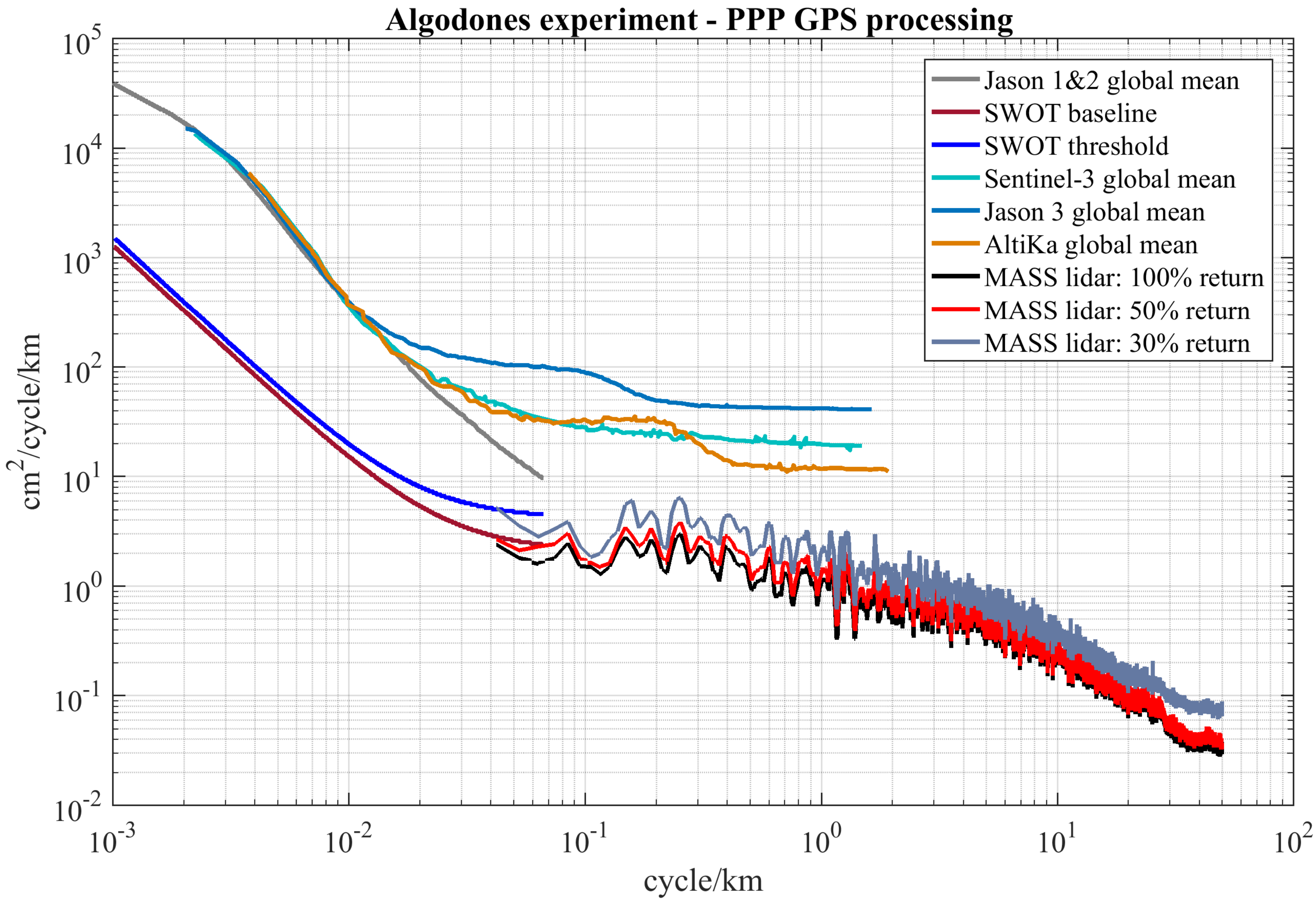
Lidar random noise floor is lower than anything else; lidar errors include apparent height errors due to horizontal errors over steep dunes



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

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

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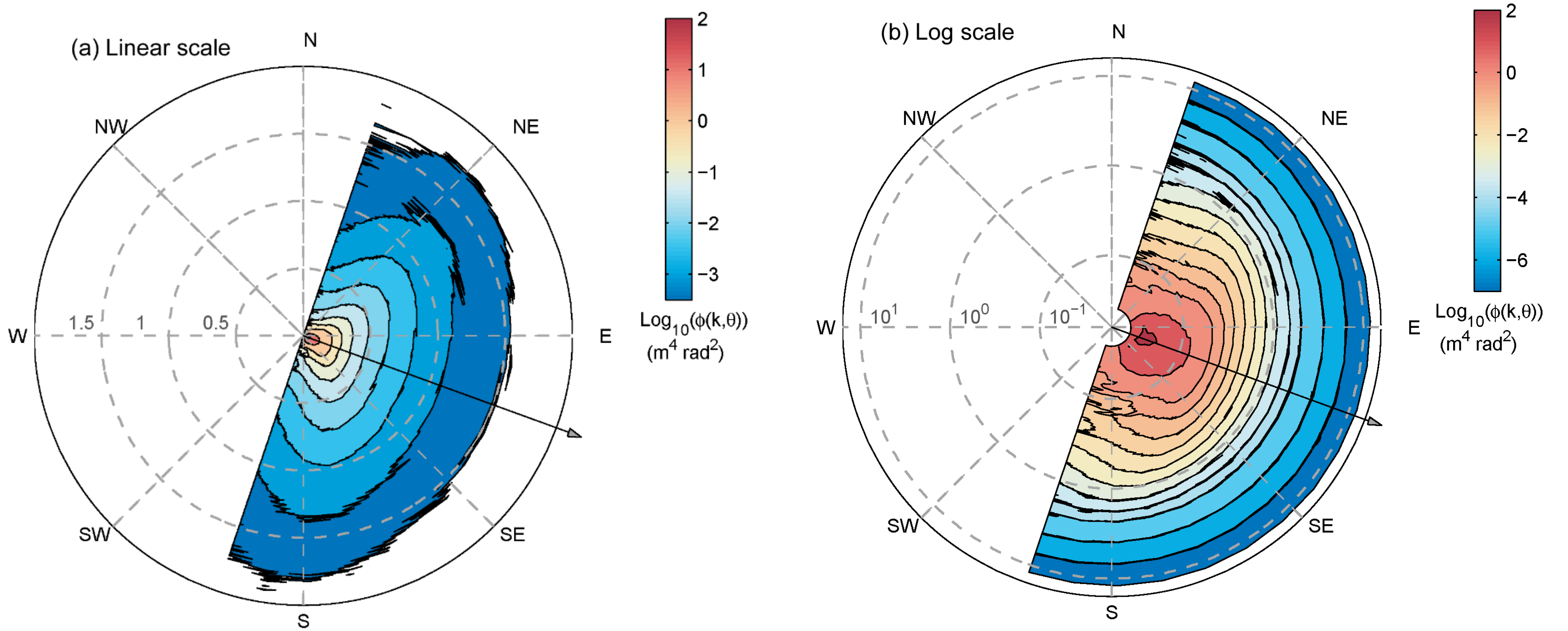
Lidar also provides directional wave spectra, which may be very useful for SWOT troubleshooting and surface wave phenomena like sea-state bias



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.*, **0**, https://doi.org/10.1175/JPO-D-17-0017.1

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

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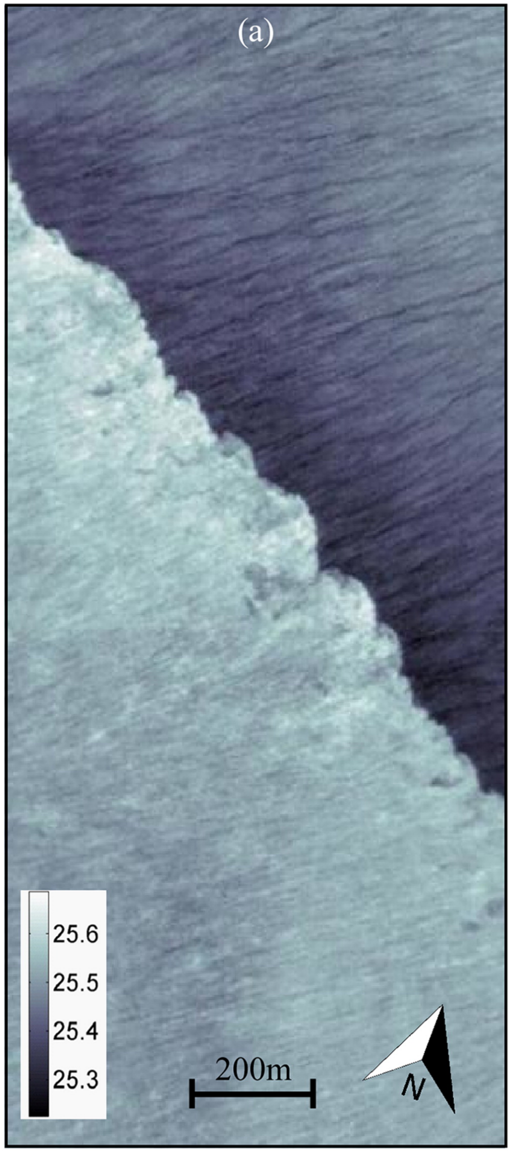

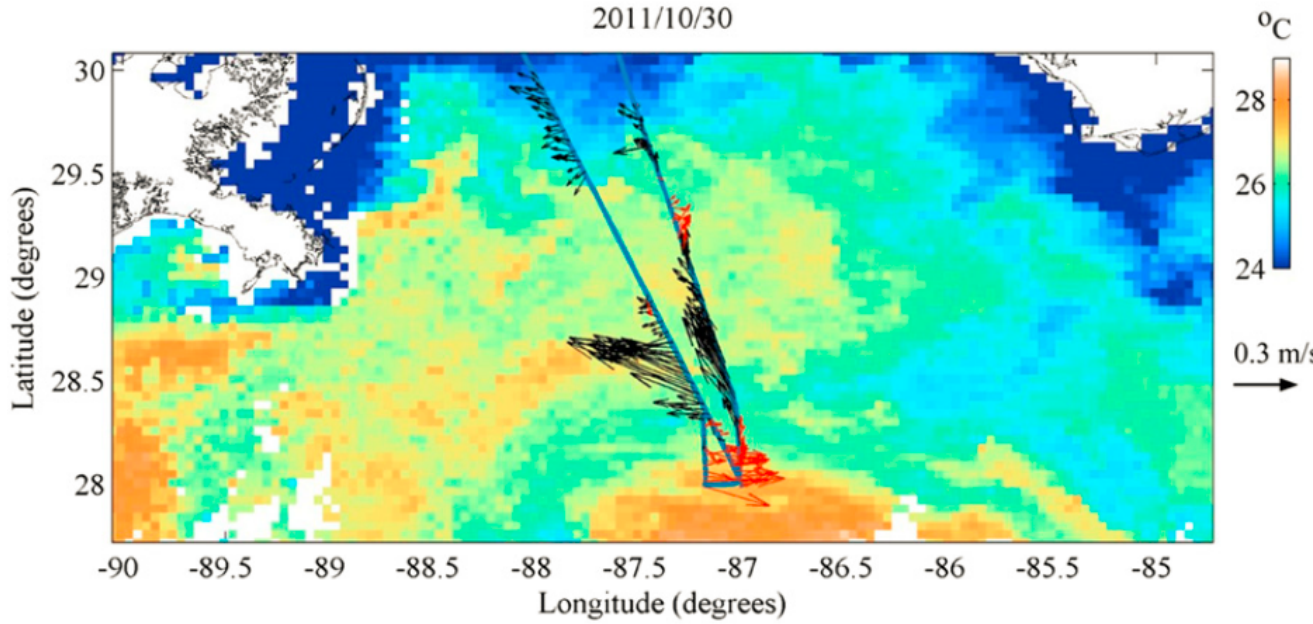

FIG. 7. SST estimated from *Terra* level 3 daily product (°C) on 30 Oct 2011, 10 h prior to the airborne survey conducted the same day. The flight track is shown in blue. The average surface velocities derived from the thermal imagery are shown as vectors along the flight track (red, positive easterly 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

Aircraft Transition

- Need greater range and speed, so plan is to switch platform
  - Gives greater flexibility in Cal/Val site location and flight patterns
  - Reduces time between aircraft flight lines and SWOT overflights to minimize temporal change in ocean state
- Scheduling challenges with the NASA P-3 (oversubscribed)
- NRL P-3 available but too expensive
- Now focusing on the NASA Gulfstream-V (JSC G-V), 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 m*easurements, both in the atmosphere and in the water and radiometric data (e.g. AXBT, etc)

NASA JSC Gulfstream-V

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Aircraft nominal performance:

Duration:
15 hours
(payload and weather dependent)

Useful Payload:
8,000 lbs

Gross Take-off Weight:
91,000 lbs

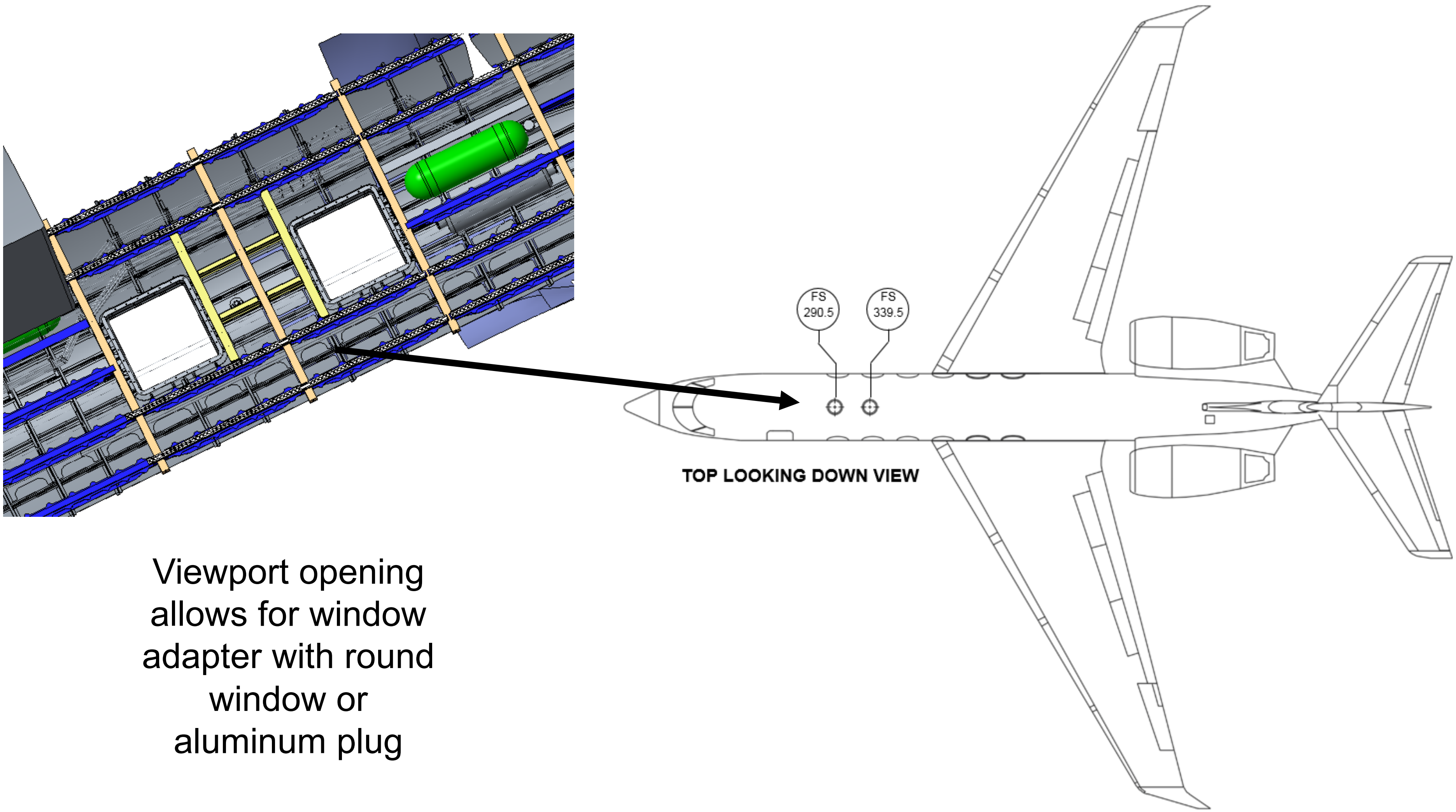
Max Altitude:
51000'

Air Speed:
Up to 500 knots

Range:
5,500 Nmi

MASS integration into the G-V

- Proposed concept validated by JSC, now proceeding with System Requirement Review (SRR)
- Using two 17.4” diameter optical viewports to be installed in Fall 2018

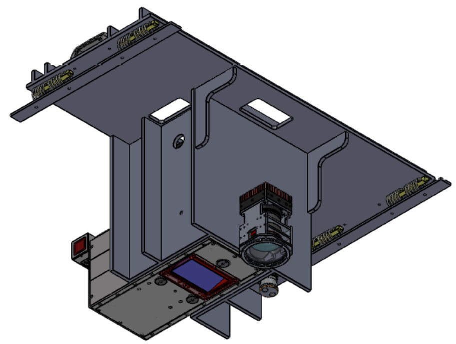


Viewport opening allows for window adapter with round window or aluminum plug

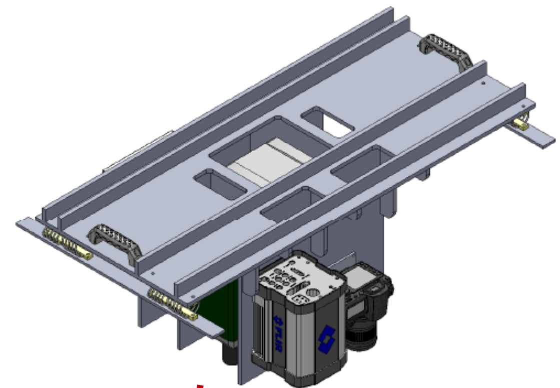
MASS integration into the G-V

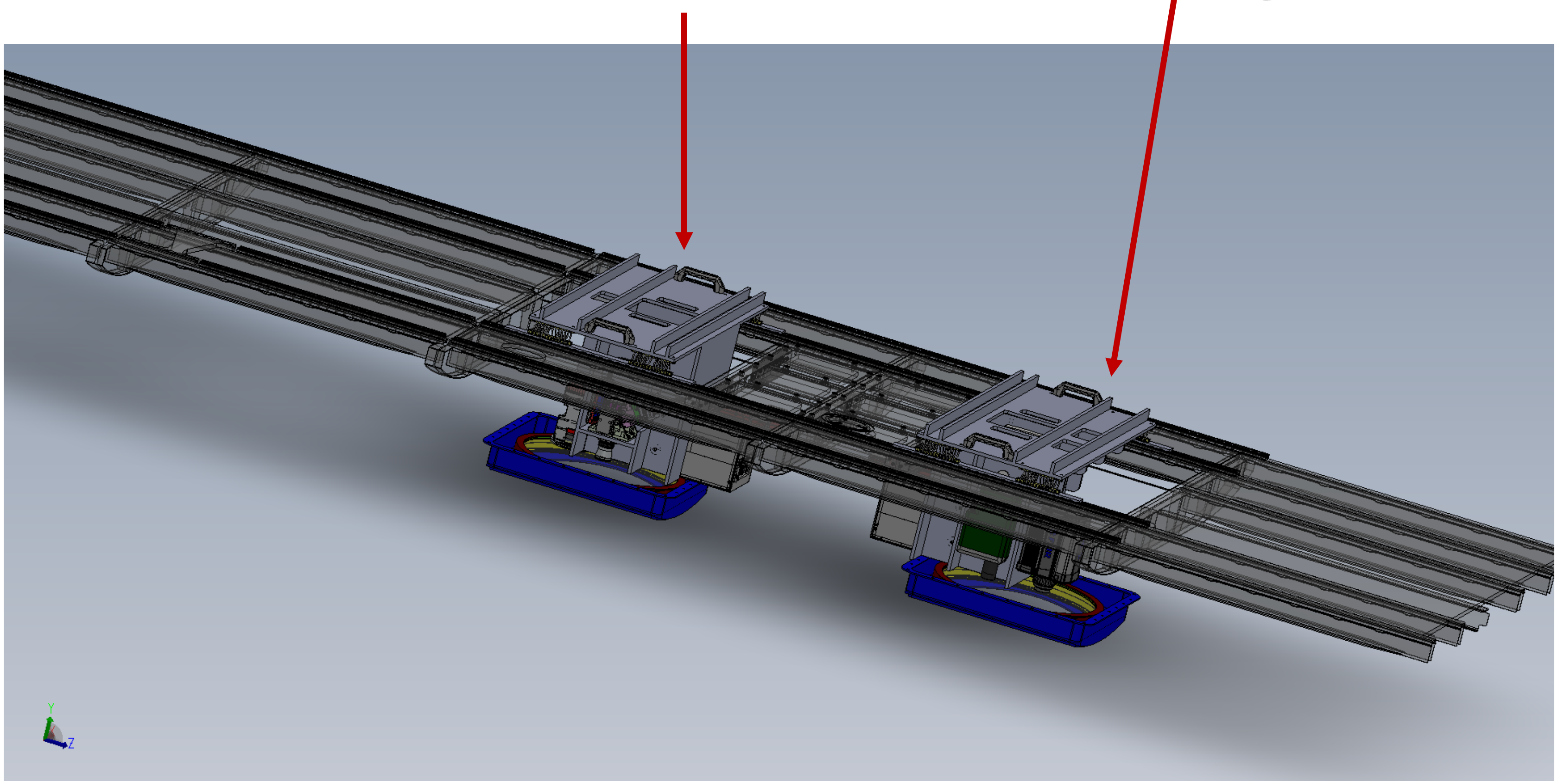
- Two topographic scanning lidars (2x400kHz)
- Visible cameras
- Infrared camera
- Hyperspectral

Back assembly



Front assembly





MASS integration into the G-V

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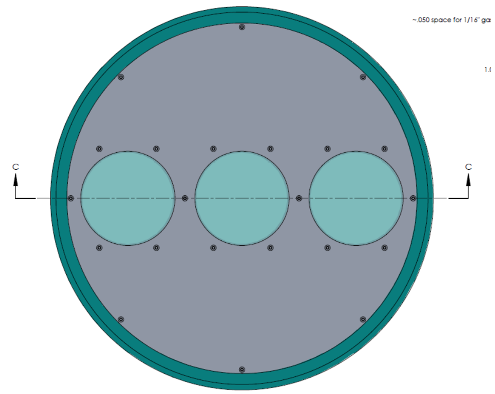
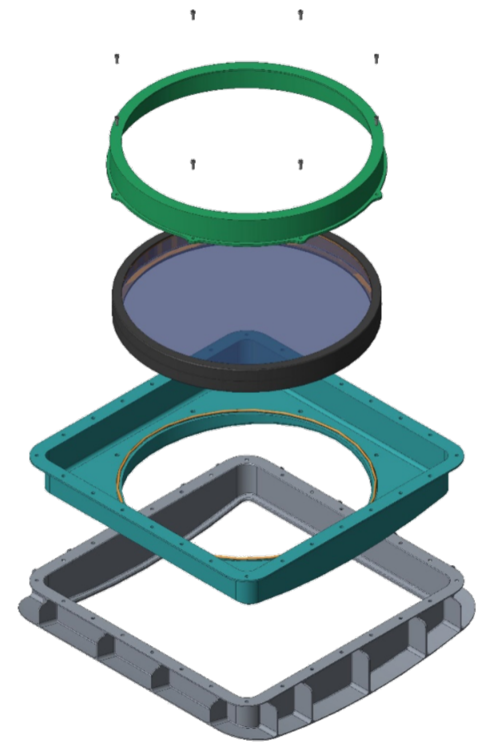
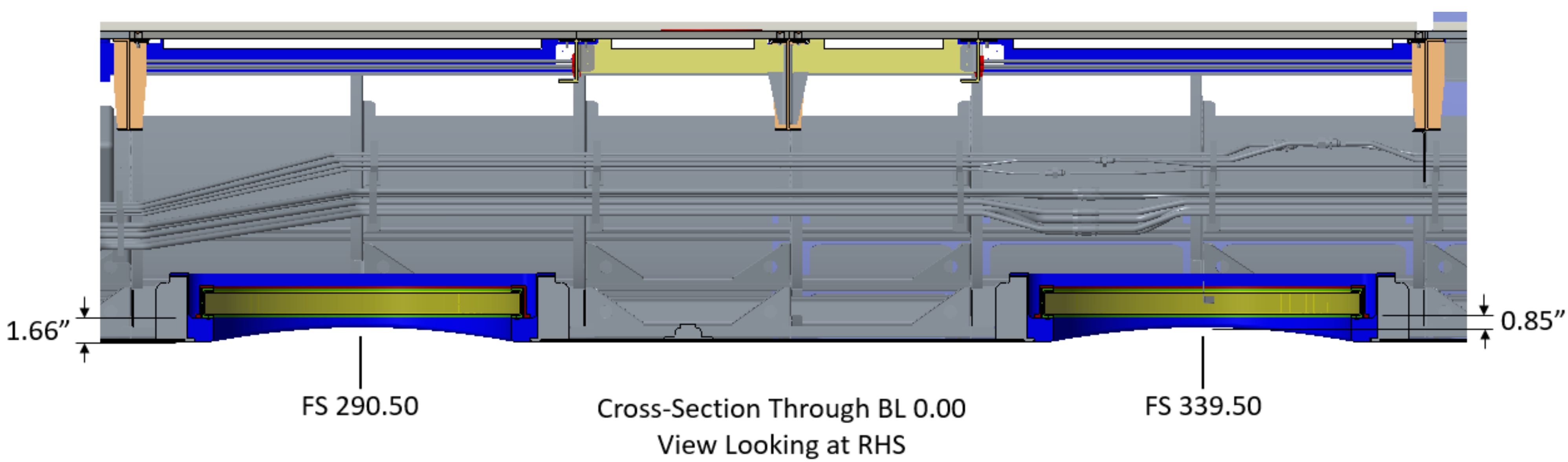
Need to design appropriate viewport window to accommodate all instrument wavelength requirements and ensure proper aircraft pressurization.

Two types of glass selected:
- BK7 (lidar and hyperspectral) with surface flatness $\leq 2\lambda$
- ZnSe (long-wave IR)

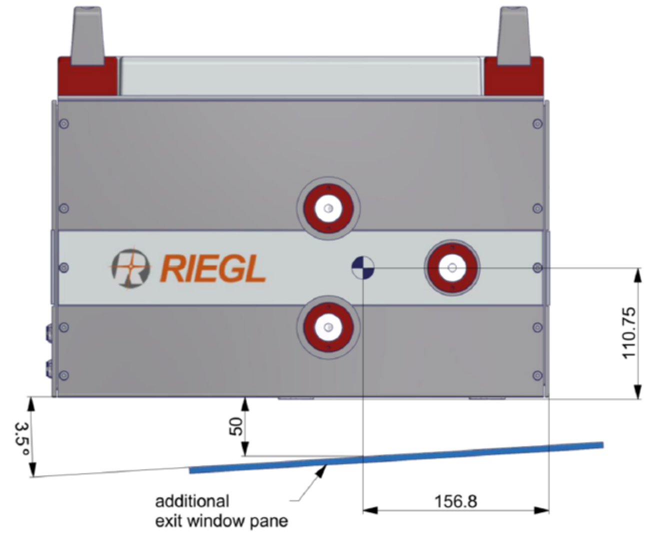


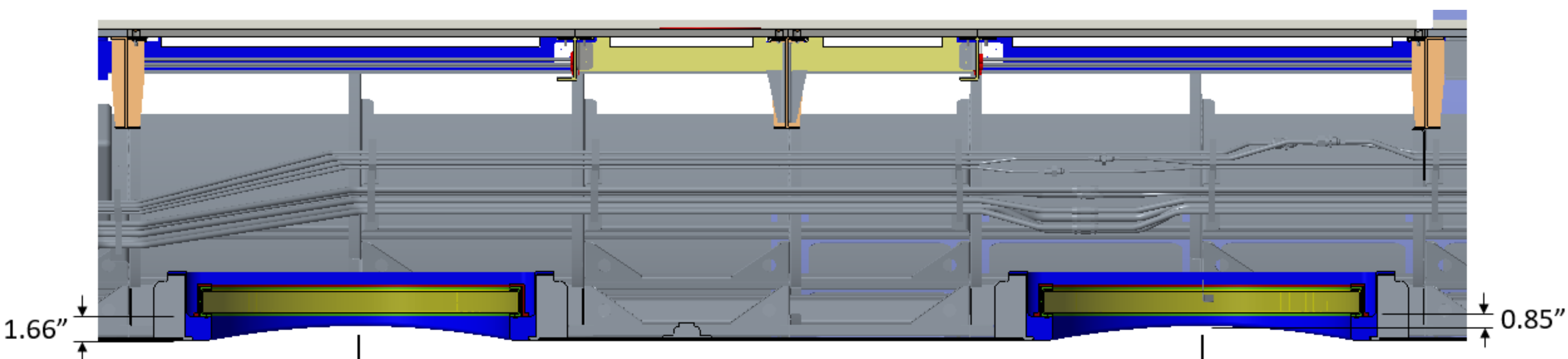




Need to design appropriate viewport window to accommodate all instrument wavelength requirements and ensure proper aircraft pressurization.

Angular requirements between laser beam and viewport window:
Window must be at 1.5º to 20º angle with respect to the scanner, 3.5º typical angle.

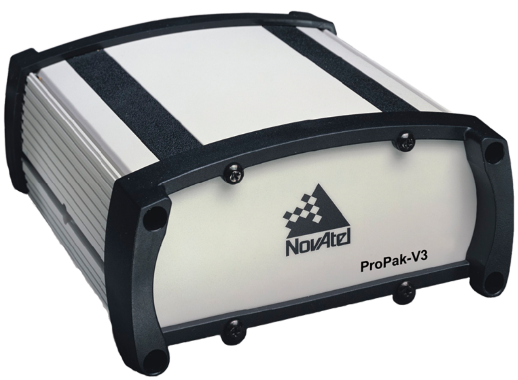




Cross-Section Through BL 0.00
View Looking at RHS

Upgrade to MASS GPS receiver (coupled with IMU)

Novatel Propak-3
GPS network L1/L2
Single antenna



Novatel PW7720-FDD-RZN-TBN-S3
PwrPak7D dual antenna
GPS+GLO+GAL+BDS,
L1/L2/E1/E5B/B1/B2,
Dual Antenna

New GPS receiver evaluation planned for September 2018 during airborne experiment near the OOI Pioneer Array (East Coast), possibly along tandem Sentinels flight track (?)

Proposed schedule

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- Error budget and analysis with JPL support for GPS processing based on the Algodones Flights
- Reprocessing of existing lidar flights with JPL support.

- Working with NASA Johnson Space Center (JSC), developing a plan to integrate the MASS instrument in the NASA G-V:
  - System Requirements Review (07/24/2019 SIO)
  - Preliminary Design Review (August 2018 – SIO)
  - Critical Design Review (October 2018 – JSC)
  - Airworthiness Review (February 2019 – JSC)
  - Operational Readiness Review (February 2019 – JSC)

Pilot Cal/Val MASS G-V flight (March-April 2019, 2 weeks, West Coast Cal/Val site):

- Validate MASS integration in new aircraft over terrestrial and ocean targets
- Characterize **spatio-temporal decorrelation scales of submesoscale variability** and **validate proposed SWOT Cal/Val flight profiles**
- Altika/Jason satellite overflights

Analysis & preparation for Ocean Cal/Val (e.g. flight profile optimization, numerical model framework)

2017 | 2018 | 2019 | 2020 | 2021

Proposed schedule

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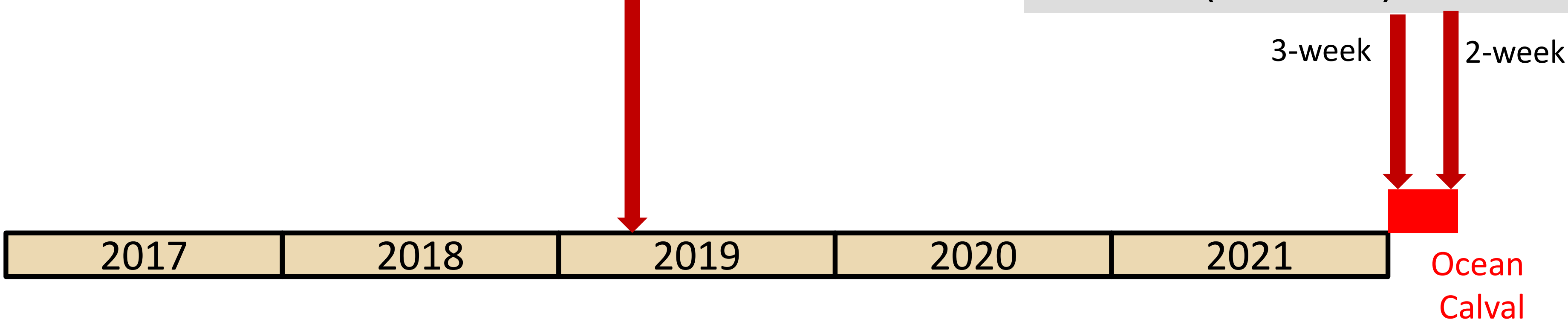
Pilot Cal/Val MASS GV flight (March-April 2019, 2 weeks, West Coast Cal/Val site):

- Validate MASS integration in new aircraft over terrestrial and ocean targets
- Characterize spatio-temporal decorrelation scales of submesoscale variability and validate proposed SWOT Cal/Val flight profiles
- Altika/Jason satellite overflights

Analysis & preparation for Ocean Cal/Val (e.g. flight profile optimization, numerical model framework)

SWOT Cal/Val MASS GV flights (3+2 weeks)



Pre-launch flight profiles (SWOT CAL/VAL site, West coast of California)

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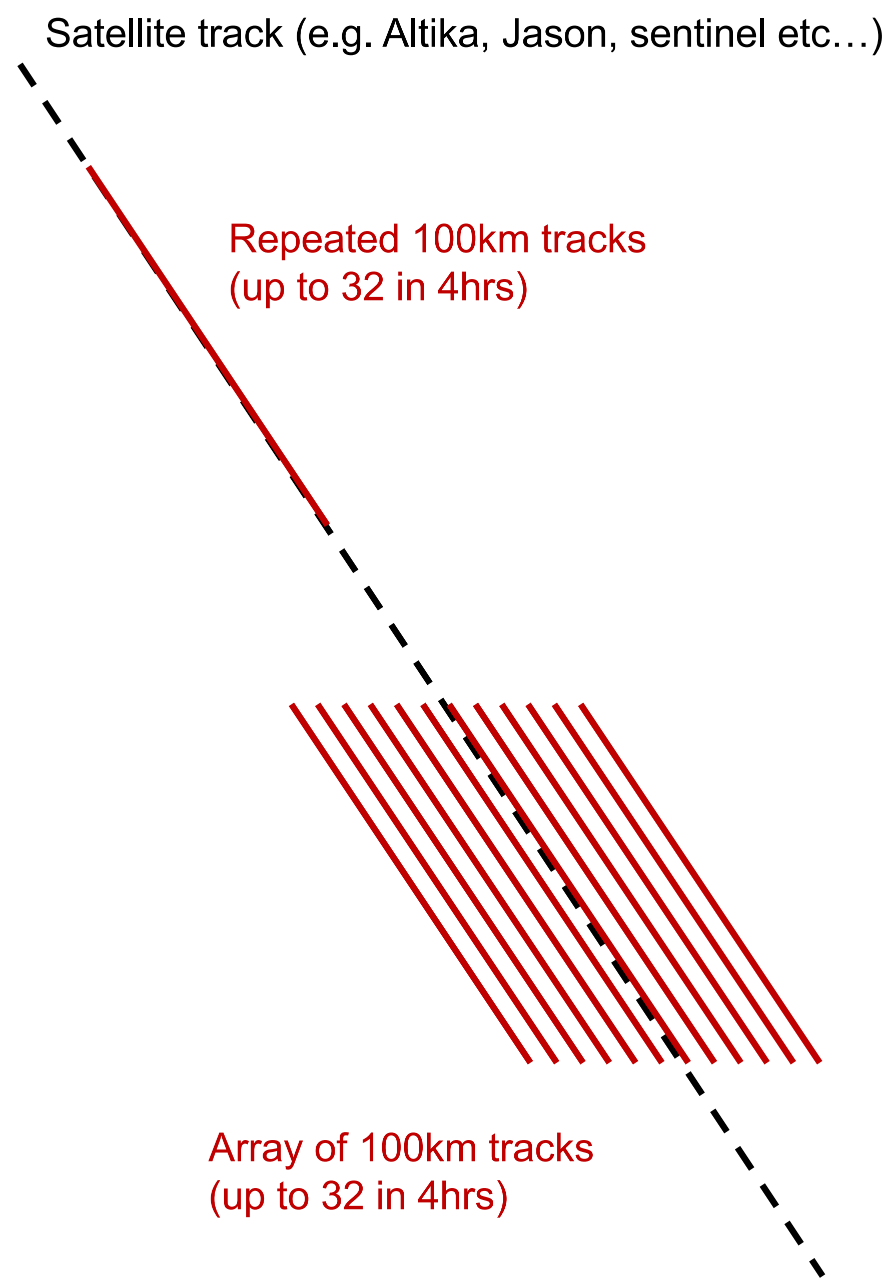
- **Validate MASS integration in new aircraft over terrestrial and ocean targets**
- Similar approach to Algodones flights presented earlier
- Repeat short passes(<40km) over ocean track.

- **Characterize spatio-temporal decorrelation scales of submesoscale variability and validate proposed SWOT Cal/Val flight profiles**

- Repeat 40-100km tracks (<8min/track) at various heading relative to wind/wave direction

- Array of 100km tracks separate by 1-5km (~100x6-40km area over one hour)

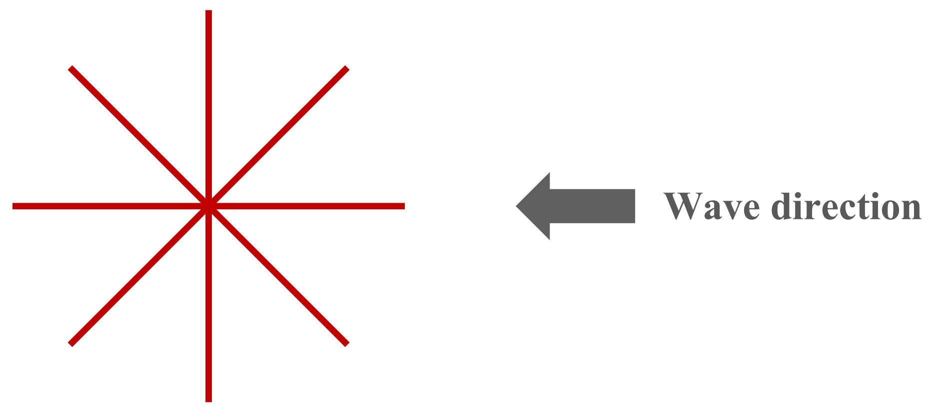
- **Altika/Jason satellite overflights to characterize lower wavenumber performance (e.g. 600km flight in <1hr)**

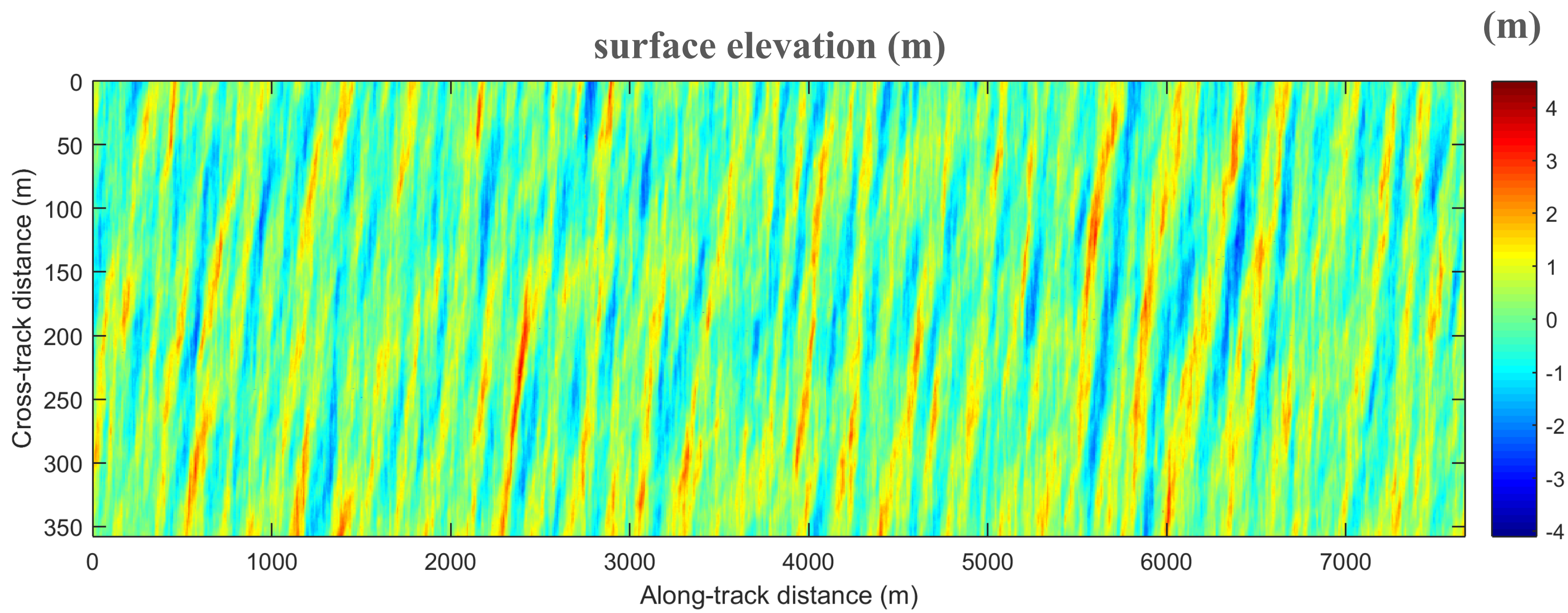


Airborne lidar cross-track averaging

MASS lidar has a much smaller swath width than SWOT (~1km). Plan is to adjust the flight track depending on wave direction and wave period to avoid aliasing errors.

We plan to test cross-track wave averaging using a star shape flight profile during the pilot program





Post-launch flight profiles (SWOT CAL/VAL site, West coast of California)

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Flight profiles adjusted depending on objectives:

- **Cross-track variability sampling and phase screen evaluation (not characterized by in-situ array)**

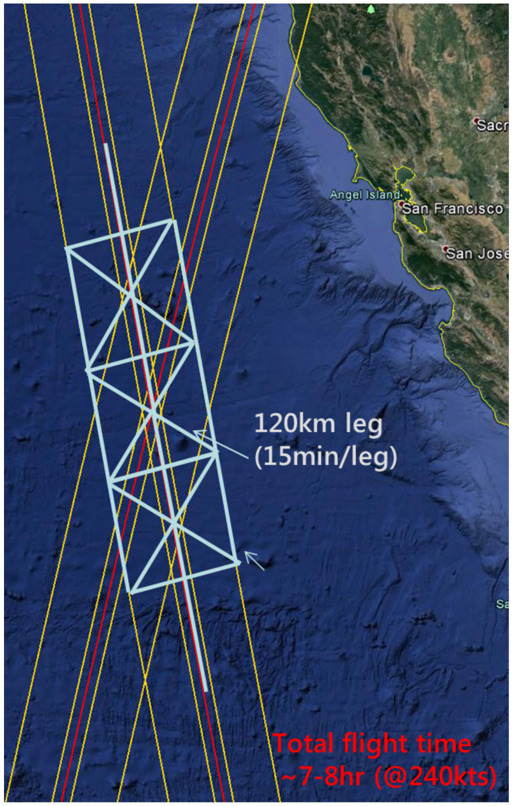
- **Spectral comparison with long, reciprocal, along track passes and few cross tracks**

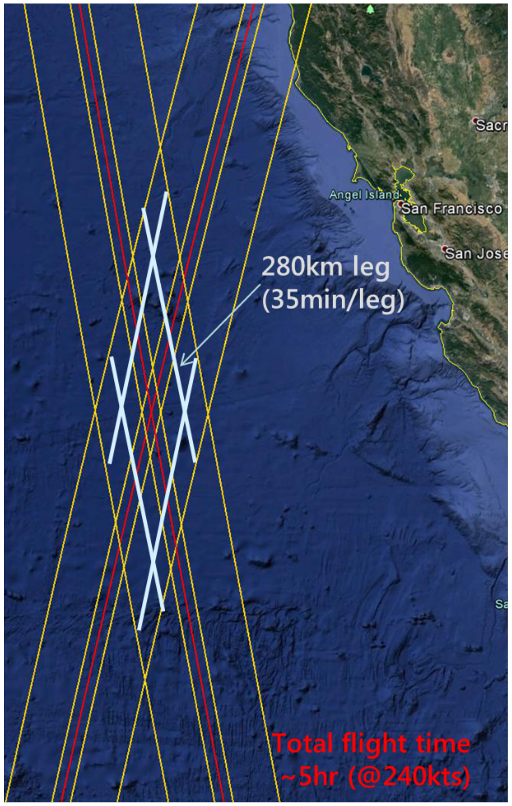
- **Decorrelation length and time scale using repeated "short" 100km legs (up to ten 100-km legs in one hour) in along and cross SWOT track direction**

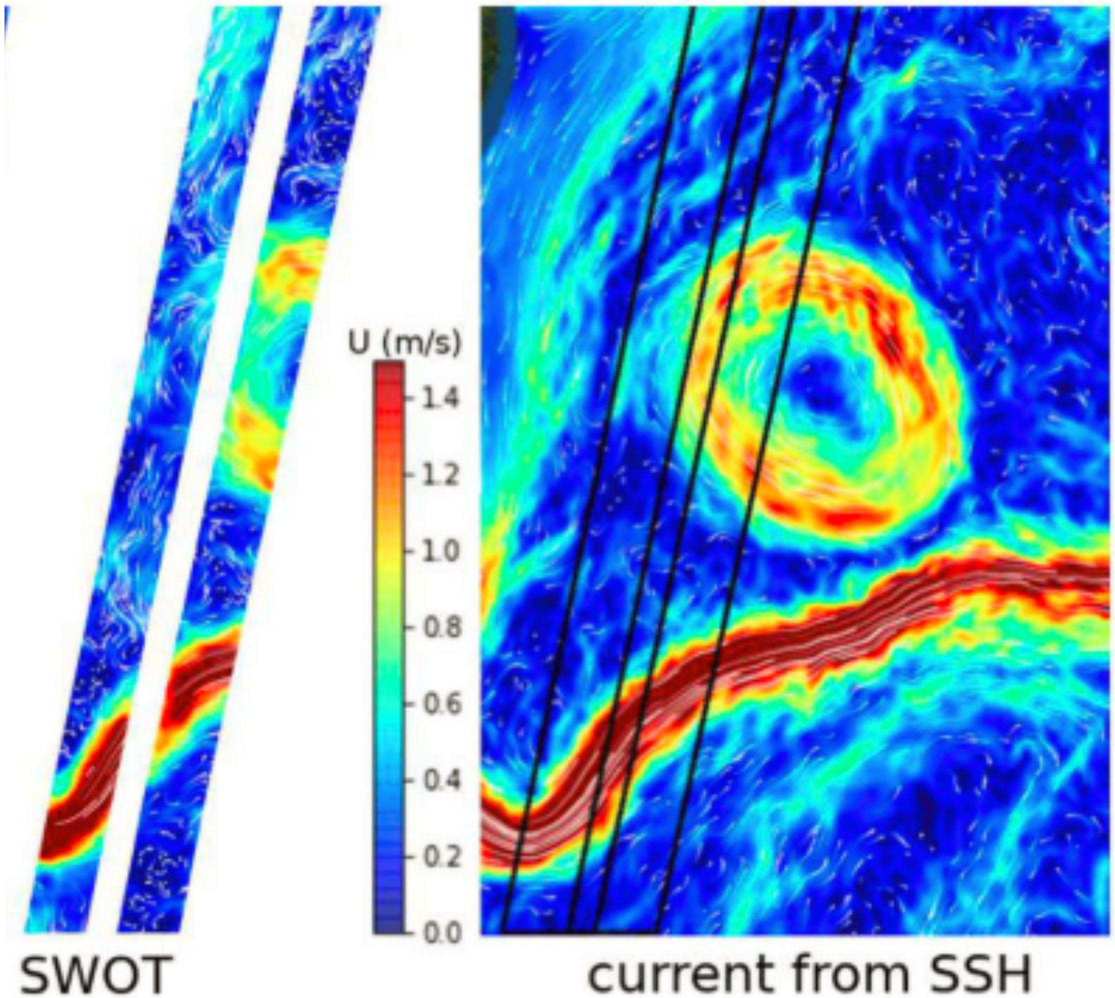
- **Directional wave properties map (Hs directional spectra, steepness etc…)**

- All cross tracks are reciprocal to reduce SSH errors and compute surface current from IR imagery

(assuming there is enough temperature structure at the surface)







From Ubelmann et al., 2017 SWOT ST meeting

Ability to adjust flight track to target features of interest in the SWOT CalVal area away from any in-situ data collection to help understanding measured SSH from SWOT

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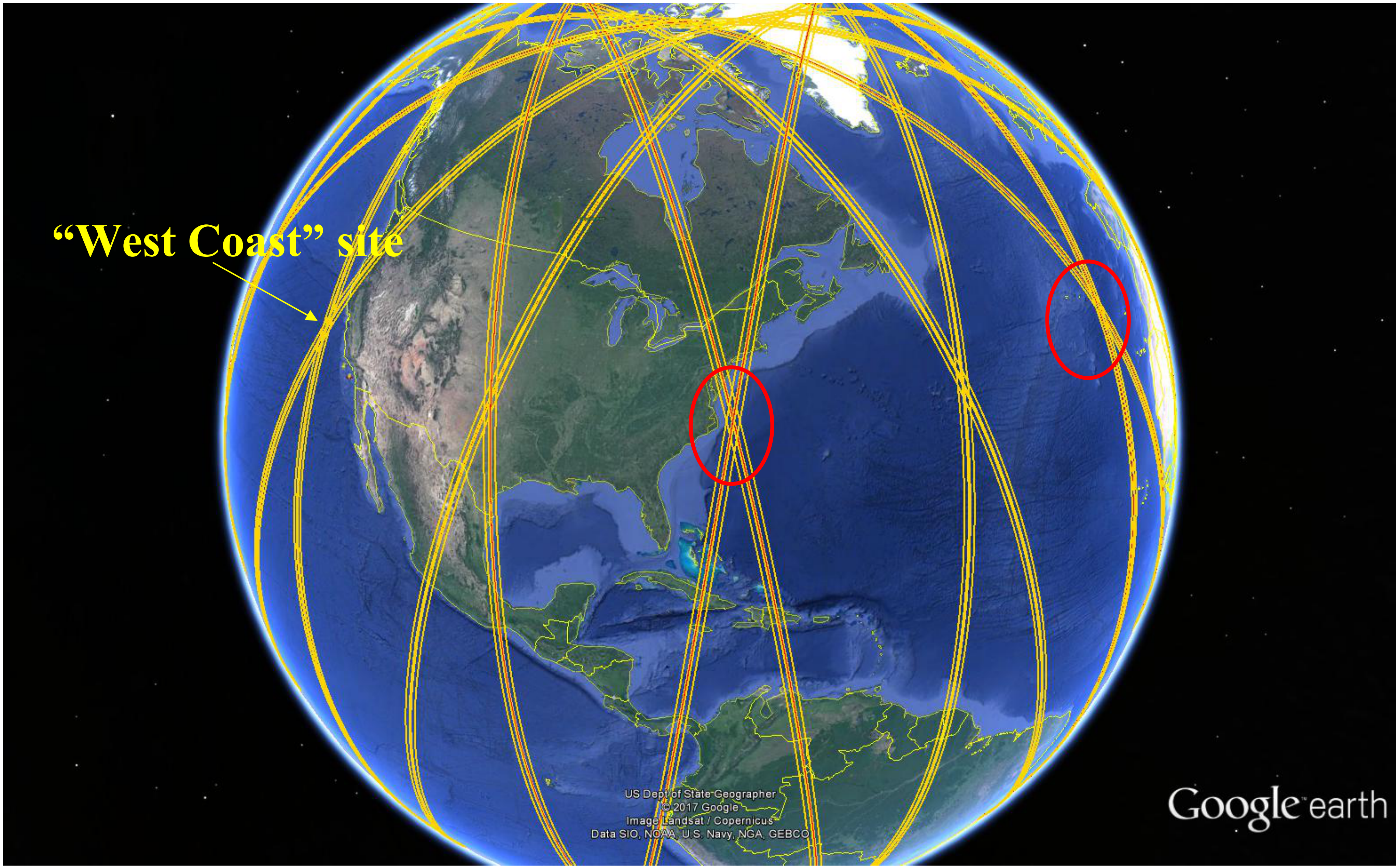
Proposed aircraft is not site dependent and can conduct deployment at multiple locations



Conclusions

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- Current MASS can measure 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 traditional altimetry appear to be good except on continental shelves.
- Spectral studies of MASS noise levels have been made over the California desert showing compliance with SWOT requirements for reciprocal airborne tracks.
- The MASS provides additional measurements for the validation of SWOT performance:
  - directional wave spectra
  - Sea surface temperature and hyperspectral imagery (used to identify submesoscale features such as fronts and filaments)
  - Surface velocity (from IR imagery)

Conclusions

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- Currently preparing a pilot Cal/Val field program in March/April 2019 at the West coast crossover site using the NASA G-V.
- Flight requests have been submitted to use the G-V for both pilot and post launch SWOT Cal/Val experiments.