GOES-R Near Surface UAS Feasibility Demonstration Study

Supports: NESDIS Post-Launch Satellite Sensor Product Calibration & Validation
Funded by: GOES-R Program Office

Supporting Publications:

Francis Padula; Aaron J. Pearlman; Changyong Cao; Steve Goodman, "Towards post-launch validation of GOES-R ABI SI traceability with high-altitude aircraft, small near surface UAS, and satellite reference measurements," Proc. SPIE 9972, Earth Observing Systems XXI, 99720V (19 September 2016). (link)

Aaron J. Pearlman; Francis Padula; Xi Shao; Changyong Cao; Steven J. Goodman, "Initial design and performance of the near surface unmanned aircraft system sensor suite in support of the GOES-R field campaign," Proc. SPIE 9972, Earth Observing Systems XXI, 99720U (19 September 2016). (link)

Francis Padula, Aaron Pearlman, Xi Shao, Changyong Cao, Steve Goodman

NOAA NESDIS

March 2017

GOES-R Field Campaign Overview

The purpose of the GOES-R field campaign is to support post-launch validation of L1b & L2+ products:

- **Advanced Baseline Imager (ABI) & Geostationary Lighting Mapper (GLM):**
  - Planning ~6 week field campaign (~100 flight hours) with the high-altitude NASA ER-2 platform coordinated with ground based and near surface observations over several Earth targets
  - Time-Frame :
    - March – May 2017
  - An open access data portal will provide all validation datasets acquired during the campaign

[Padula et al. SPIE 2016]

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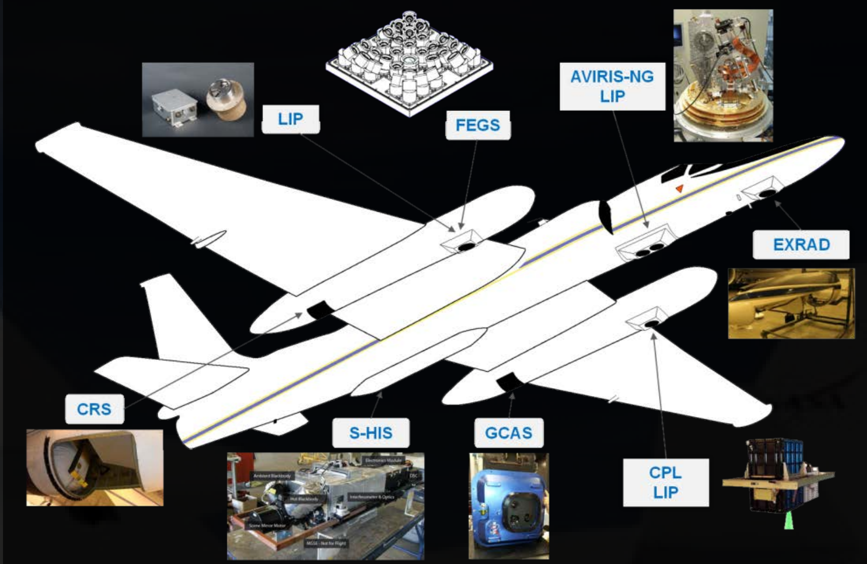
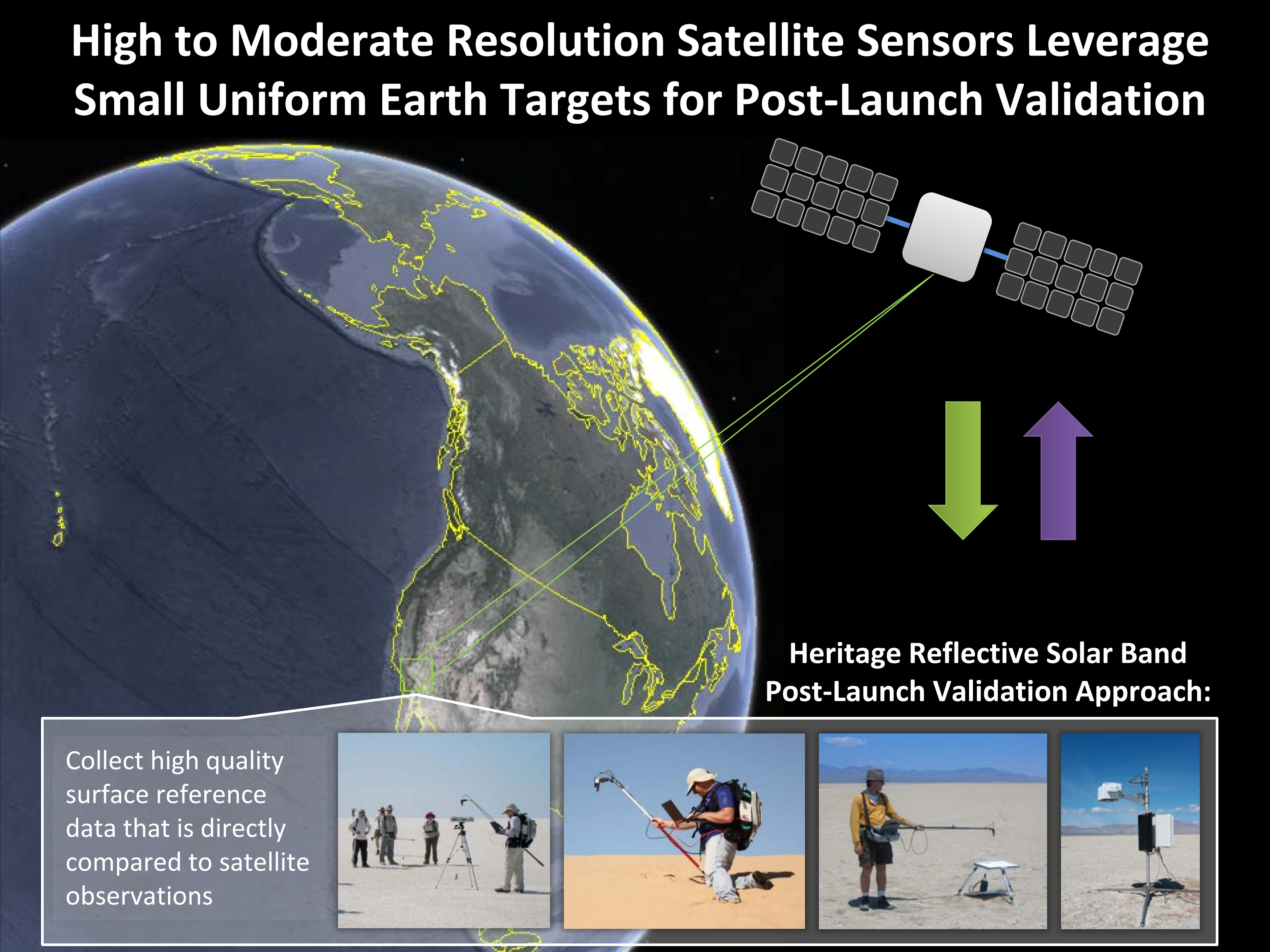
GOES-R Field Campaign ER-2 Based Instruments

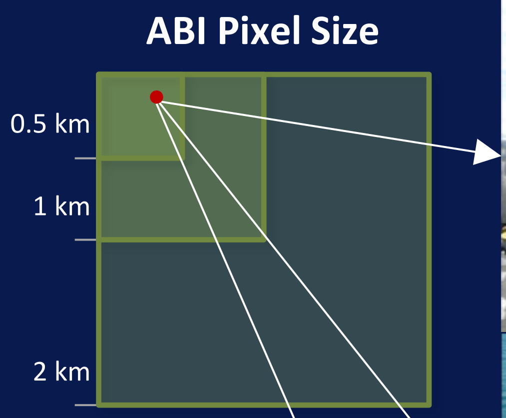


[Padula et al. SPIE 2016]


High to Moderate Resolution Satellite Sensors Leverage Small Uniform Earth Targets for Post-Launch Validation
Heritage Reflective Solar Band Post-Launch Validation Approach:
Collect high quality surface reference data that is directly compared to satellite observations

Post-Launch Validation Challenges & Gaps for Low Resolution Environmental Satellite Sensors

- **Challenging to provide high quality data that can be directly compared to satellite observations without gross assumptions (i.e. uniformity):**
  - Ground validation measurements are typically point-based measurements
  - Often need to disturb the collection environment to make the measurements
  - Labor intensive
  - Costly (typically involves a large team)
  - Repeatability can be challenging
  - Limited collection geometry



- **Currently no operational capability to measure goniometric observations over regions comparable to environmental satellite observations**
- **Difficult to collect observations of extended regions**

Development of Advanced Post-Launch Validation Capabilities: Near Surface UAS Measurements

GOES-R Funded: "GOES-R Near Surface UAS Feasibility Demonstration Study" - NOAA Cooperative Institute Partnership with the University of Maryland (UMD) in collaboration with the NOAA UAS Program

Scope: Develop prototype UAS & assess the feasibility of near surface validation reference measurement capabilities in support of GOES-R Field Campaign validation efforts (L1b/L2+)

Phase 1: Procurement/Development & Integration of Prototype Systems:

Rotary UAS

Phoenix ACE XL Specifications
Endurance: 30 minutes
Fully autonomous system
Take-off weight: 10 lbs.

Customized electronic enclosure and autonomous 2 axis gimbal

Fixed-Wing UAS

Talon120 Specifications
Length: 6' Wingspan: 12.5' MGTOW: 20 lbs.
Payload capacity: 2.5 lbs.
Range: 8 miles LOS
Endurance: 2.0 – 2.5 hours
Fully autonomous system
Typical operating alt.: 50-500 ft. AGL; MSL up to 10,000 ft

Customized nose cone for high resolution georeferenced imagery

Collection Reference Data:

1) **Rotary UAS -** Goniometric observations & area collection

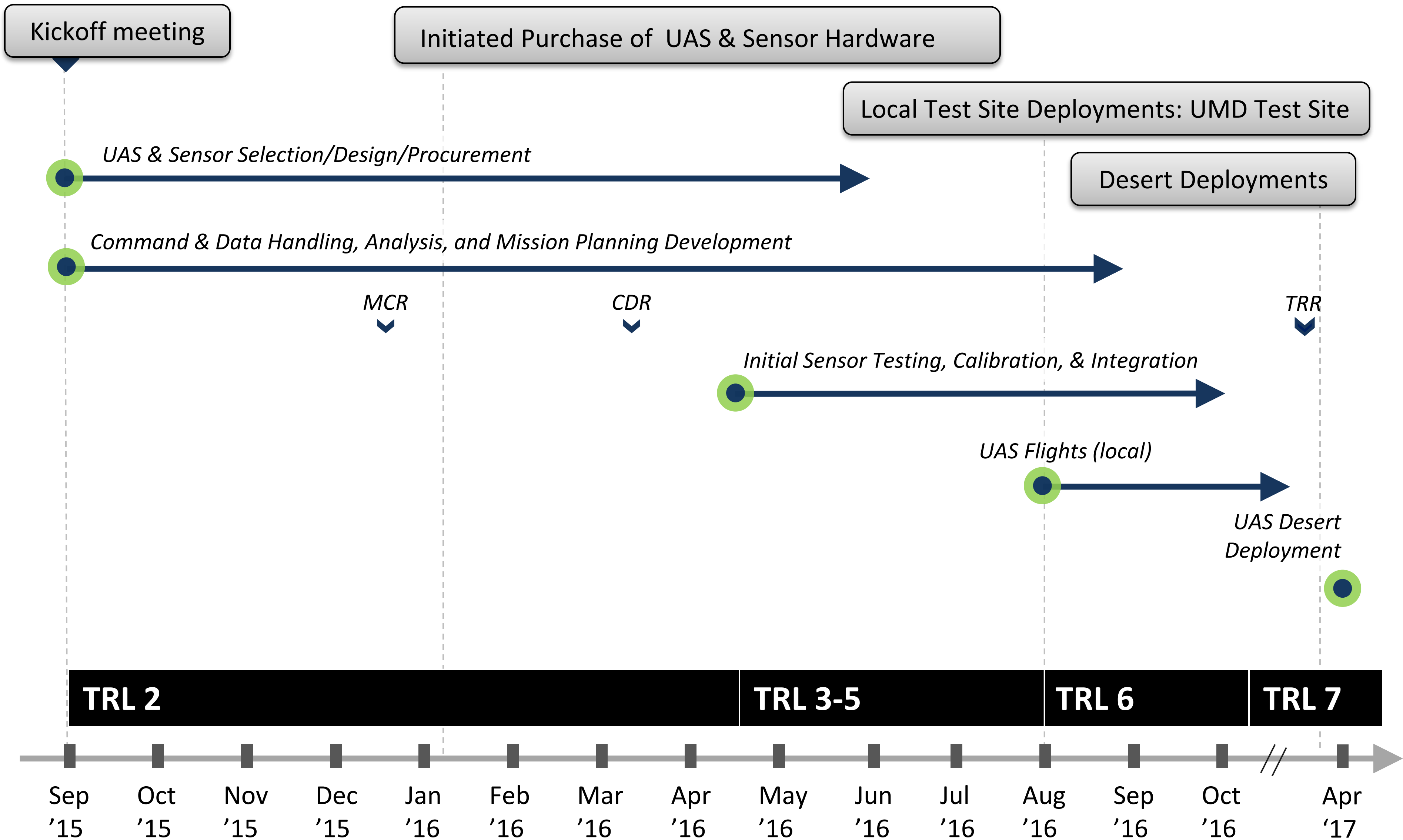
2) **Fixed-Wing UAS** – area collection

Phase 2: Capability & CONOPS Optimization

Current Phase → Phase 3: Field Campaign Deployment

GOES-R UAS Feasibility Demonstration Study Milestones & Schedule

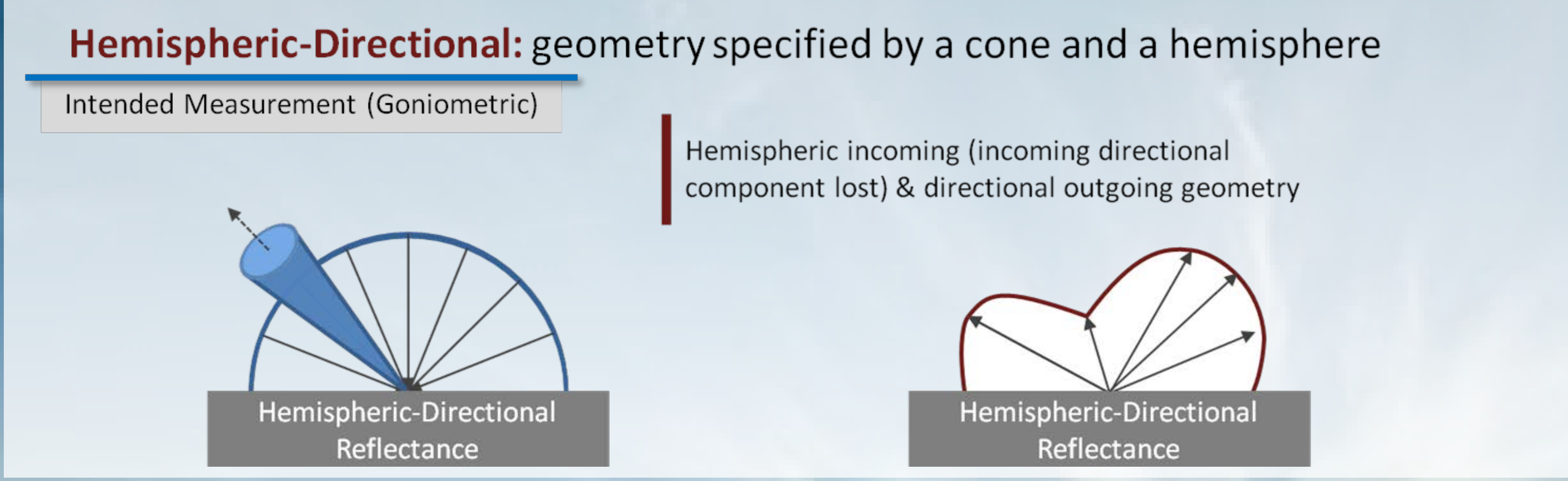
Drafted & Submitted an initial set of near surface UAS science requirements to the NOAA Unmanned Aircraft Systems Program in January of 2015



GOES-R Near Surface UAS Capability Priorities

1) Hyperspectral (0.35 – 2.5 µm) Reflective Solar Band (RSB) measurements are of highest priority

- **Downward Observation (surface)**
  Ability to autonomously control the view geometry of the sensor payload(s) for oblique angle data collection of a fixed earth target: Range: 0° (nadir) to 90° (horizon) with a step size of 1° or less
  - » Near surface ~10 m above ground level (i.e. assume atmosphere is negligible)



2) Broadband IR (8 – 14 µm) measurements

- **Directional Surface Observations (ideally filtered to match ABI spectral bands, primary focus ABI Bands 14-15)**

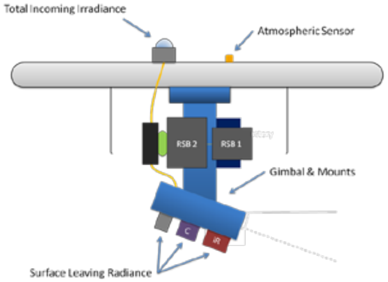
2) High resolution georeferenced imagery (NADIR & Oblique)

- **Context imagery of calibration/validation targets & Digital Elevation Model (DEM) generation**

Common Requirements for Both Systems

- All sensor measurements have documented SI traceable paths
- All sensor measurement uncertainties are documented and reviewed
- System design shall be flexible to integrate on multiple UAS
- UAS capable of autonomous flight through pre-programmed flight planning
- Meta data to be collected & stored (image acquisition times, sensor look angles, GPS data)

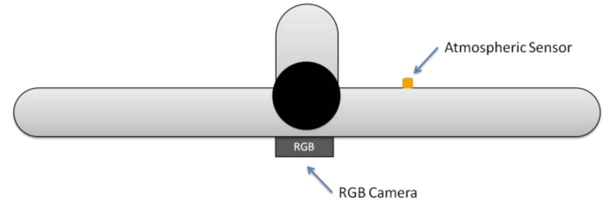
Baseline: Near Surface UAS Systems & Products



Baseline Capabilities:

- Observations over extended regions matching satellite view geometry
- Goniometric observations over a given target (directional hemispheric)

RSB 1 = Compact Hyperspectral (VNIR) Spectrometer
RSB 2 = Compact Hyperspectral (SWIR) Spectrometer
IR = LWIR Radiometer(s)
C = RGB HD Video (Context Imager)

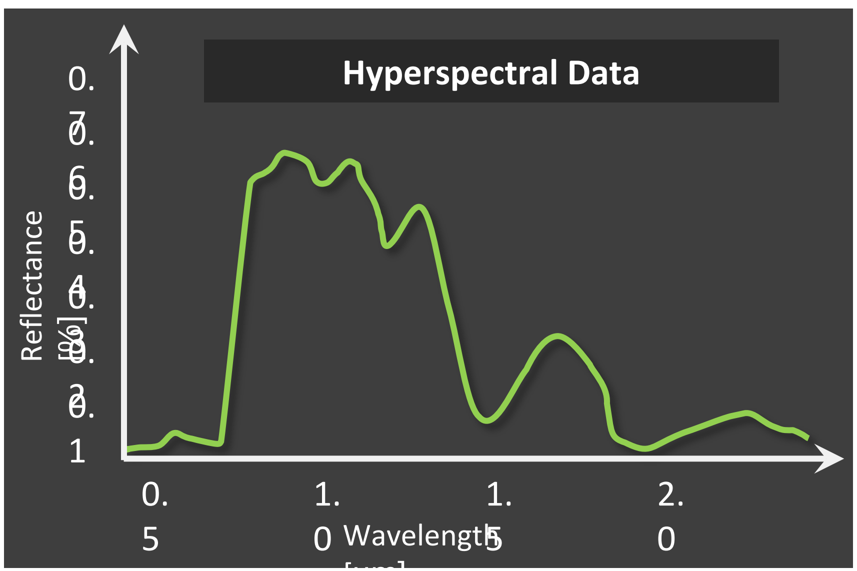


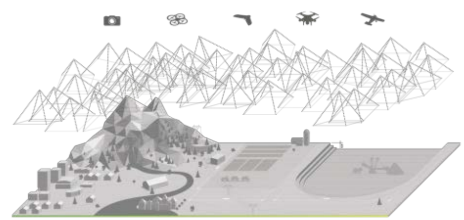
Primary Payload: RSB Hyperspectral (0.35 to 2.5 µm)
- non-imaging

Filtered IR radiometers
Atmospheric profile (near surface)

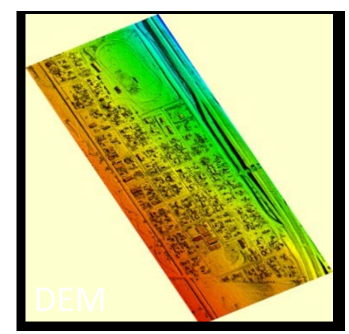
Primary System

- 2D high resolution georeferenced and orthorectified mosaics
- Digital Elevation Model (± 1-5 m)
- Atmospheric profiles to maximum collection alt. (~400 ft or 121.9 m)



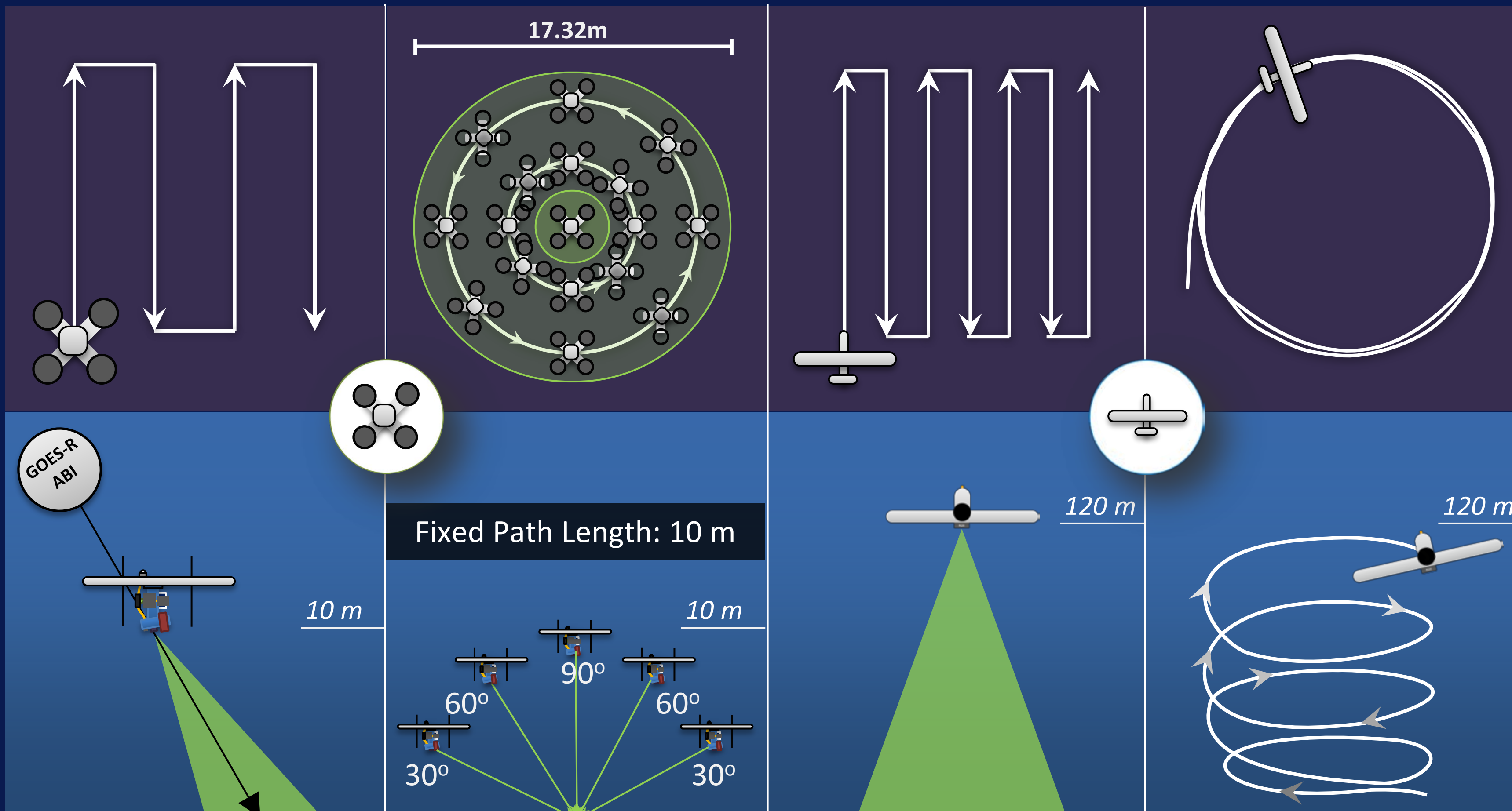


Pix4D Software



Images Courtesy: www.falconunmanned.com/falcon-uav-news/

Four UAS Baseline Collection Types



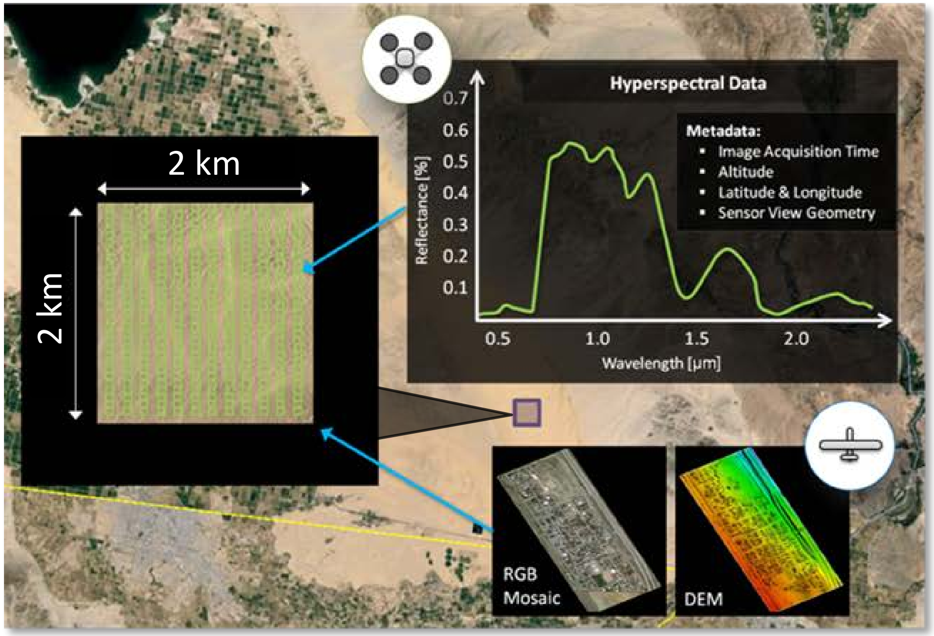
Fixed View Geometry Matching ABI (L1b)

Goniometric Target Collection (L2+/L1b)

NADIR & Oblique Area Collection (L1b/L2+)

Spiraling Ramp Collection (L1b/L2+)

Near Surface UAS Measurements Provide Improved Validation Capabilities:
Validation of Satellite Data



UAS Capability Can Enhance GOES-R ABI Post-launch Validation Capabilities:

- Provides a pathway to validate radiometric performance post-launch (Reflective Solar Bands & Thermal Emissive Bands surface channels) and product performance uncertainties
- UAS deployments can support long-term monitoring of satellite sensor performance
- Enduring capability for Cal/Val scientist:
  - Near surface UAS campaigns can be replicated numerous times throughout the year at significantly reduced costs in comparison to heritage approaches
  - UAS deployments can support characterization of the degree of uniformity within the given satellite footprint (Ideally, for all reference Cal/Val sites (i.e. fixed ground instruments) in different seasons
- Goniometric surface measurements can be used to check components of model values used in retrieval algorithms

UNIVERSITY OF MARYLAND
UAS TEST SITE
A. JAMES CLARK SCHOOL *of* ENGINEERING



35+ UAS (fixed & rotor wing, 3 lbs to 160 lbs)

- *1 x UAVS Talon 240G*
- *3 x UAVS Talon 120LE*
- *3 x AV Wasp*
- *3 x AV Raven*
- *3 x AV Dragon Eye*
- *1 x "Dragon Pi"*
- *3 x Apprentice S15e*
- *1 x FireFLY 6 hybrid*
- *1 x DJI S-1000*
- *2 x DJI S-900*
- *1 x UAVS Phoenix 60*
- *1 x UAVS Phoenix ACE LE*
- *1 x UAVS Phoenix ACE XL*
- *6 x 3DR Iris*
- *1 x 3DR Solo*
- *5 x DJI Phantom 3*
- *1 x DJI Inspire*

Payloads/Sensors specific to mission requirements

- Established Aug 2014 as one of six FAA UAS Test Sites
  - Partnered with Virginia & New Jersey
  - Located in Southern MD near Patuxent River NAS (Navy UAS test & eval)
- Govt/Academia/Industry research customers – focus on integrating UAS into National Airspace System & civil/commercial applications of UAS
- Robust airworthiness process; reachback to expertise at College Park
- Flight ops under public COAs, FAA Part 107, or foreign/international rules; airspace access nationwide including segregated airspace
- Major Research Projects
  - FAA, DHS: Airspace Intrusion Detection (1st *legal* UAS flight in Class C)
  - 1st civil UAS cargo flight across Chesapeake Bay (simulated medical supplies)
  - NOAA: GOES-R satellite cal/val & NERR mapping
  - GWU, USNA: Ship Air Wake Analysis (flown from YP boat in Chesapeake Bay)
  - US Navy: Open source autopilot (analysis of alternatives)
  - NASA: UAS Traffic Management (air traffic control for UAS)
  - Public Safety Agencies: life preserver drop, missing person search, comms relay, accident scene reconstruction, emergency vehicle support, radiation detection
  - Agriculture/Aquaculture/Anthropology/Geology: Aerial Surveys & 3D Mapping
  - AQWUA: A Quad with Underwater Abilities (fly/swim)
  - BVLOS/BLOS Ops (current requirement is visual LOS only)
  - Collaborative Control (UAS swarming)

Prototype Fixed-Wing System: UAS + Payloads

1. **High Resolution Camera:**
   – High resolution RGB camera
2. **Atmospheric Sensor:**
   – T, RH, & Px profiles

Baseline Capabilities:

- 2D high resolution georeferenced and orthorectified mosaics (NADIR & Oblique)
- Digital Surface Model (± 1-5 m)
- Atmospheric profiles to maximum collection alt. (~400 ft or 121.9 m)

Secondary System (TRL 9)

Fixed-Wing UAS

Talon120 Specifications

Length: 6’ Wingspan: 12.5’

Endurance: 2.0 -2.5 hours

Range: 8 mile LOS

Fully autonomous system

Payload Capacity: 2.5 lbs

Fixed-Wing UAS Payloads

baseline

Cannon S100
(RGB)

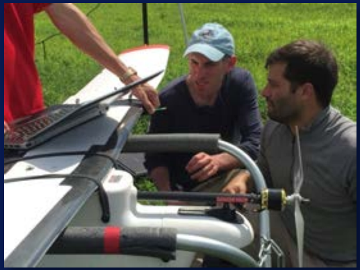
Imaging

Cannon
TRL 9

Atmospheric Sensor
(T, Px, RH)

Non-Imaging

InterMet Systems
TRL 7



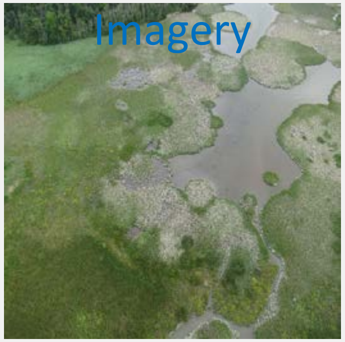
GOES-R UAS Feasibility Demonstration Study:
Successful Fixed-Wing UAS functional & operational performance demonstrations

Completed successful test flights at the:

- University of Maryland (UMD) UAS test site in Bushwood, MD on August 3, 2016
- NOAA National Estuary Research Reserve (NERR) in Jug Bay, MD on August 8, 2016 – UAS test data provided to NOAA NERR as operational data
- Resulting products: 2D & 3D geo-referenced maps

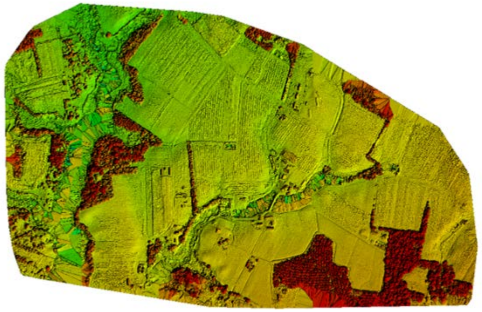
NADIR

Oblique Imagery



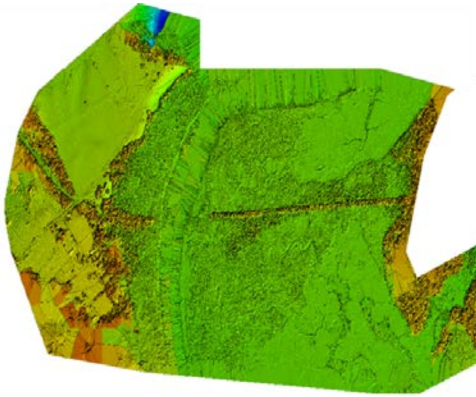
2D Geo-Referenced Orthomosaic

3D Digital Surface Model



2D Geo-Referenced Orthomosaic

3D Digital Surface



UMD UAS Test Site – Bushwood, MD

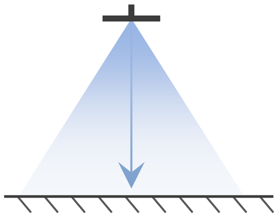
NOAA NERR – Jug Bay, MD

Fixed-Wing UAS Sample data

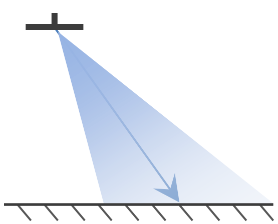
2D Georeferenced Imagery Mosaic - Flight Altitude of 700 ft

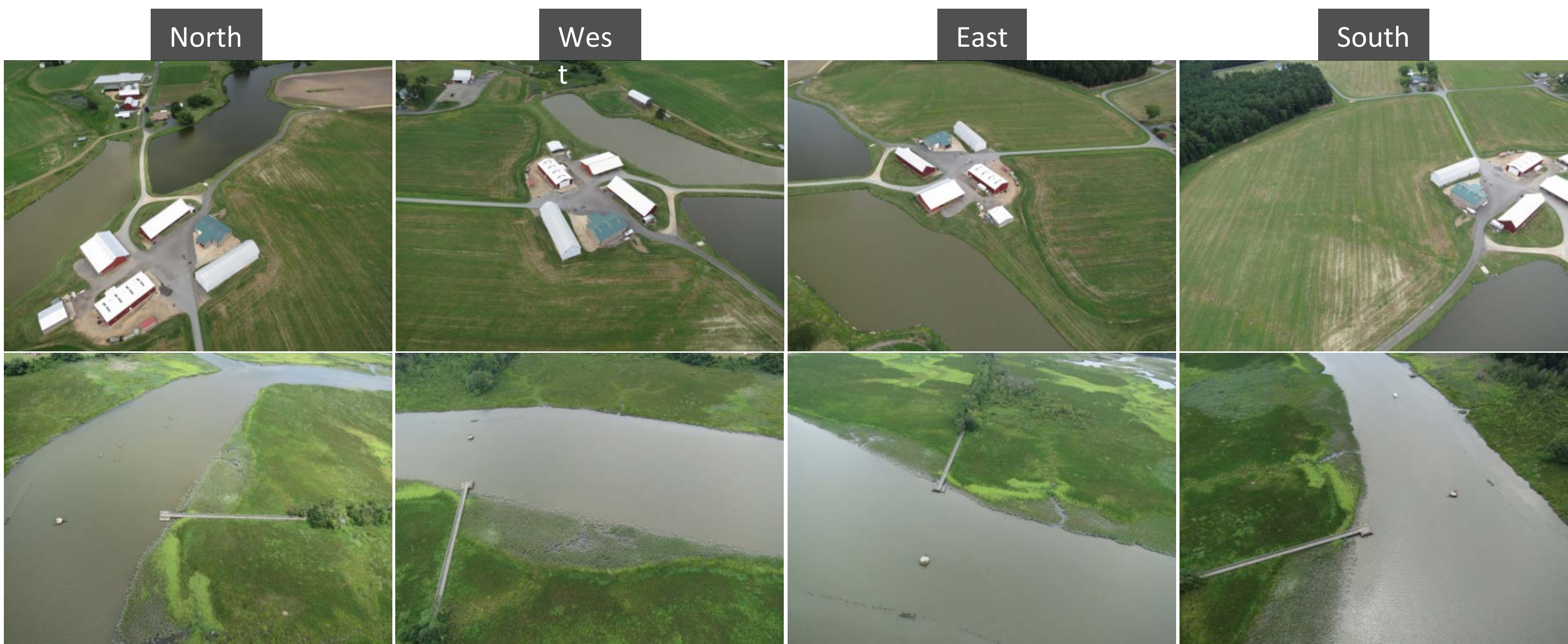
Fixed-Wing UAS Collection (NADIR to 45º)

NADIR Collection:



Oblique Collection (~45º)





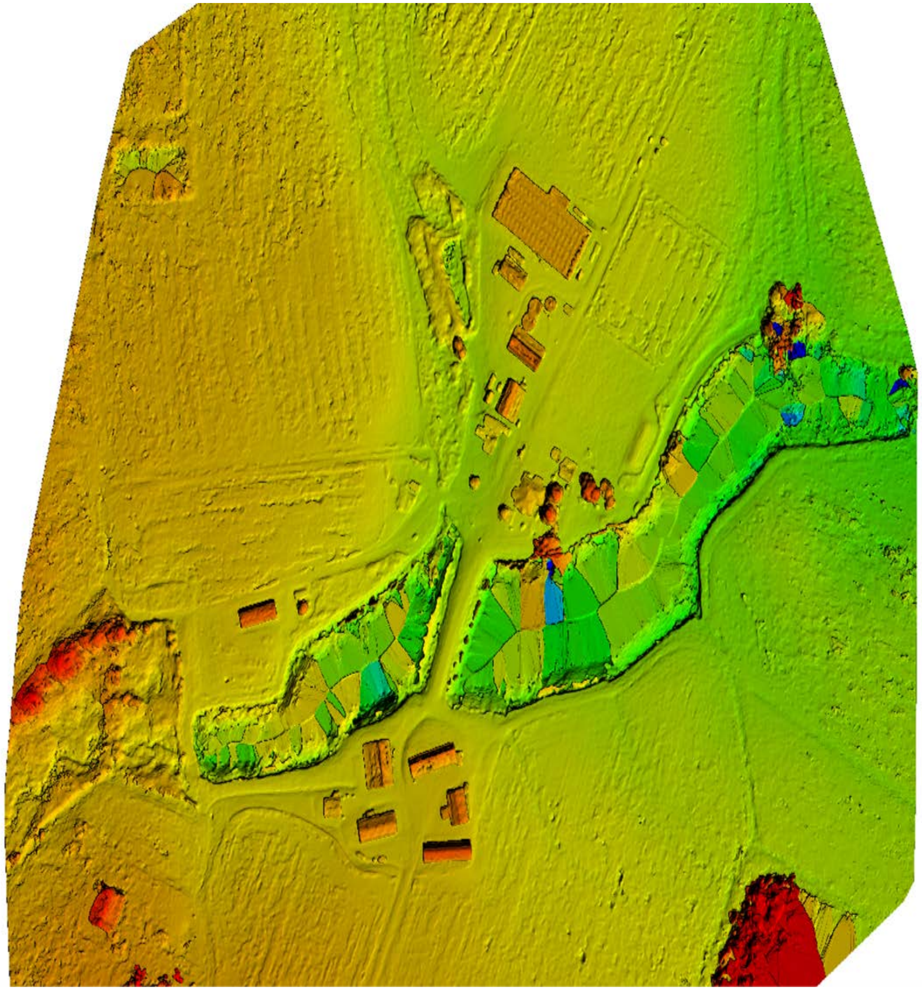
2D Georeferenced Orthomosaics Products NADIR + Oblique Imagery vs Nadir Only Imagery

NADIR + Oblique

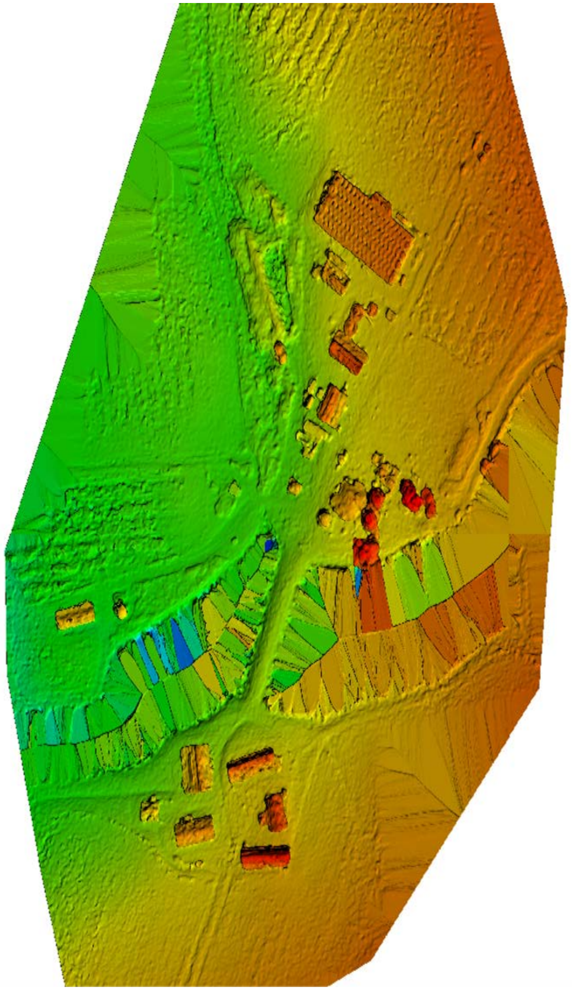
NADIR Only

3D Georeferenced Digital Surface Model (DSM) Products NADIR + Oblique Imagery & Nadir Only Imagery

NADIR + Oblique

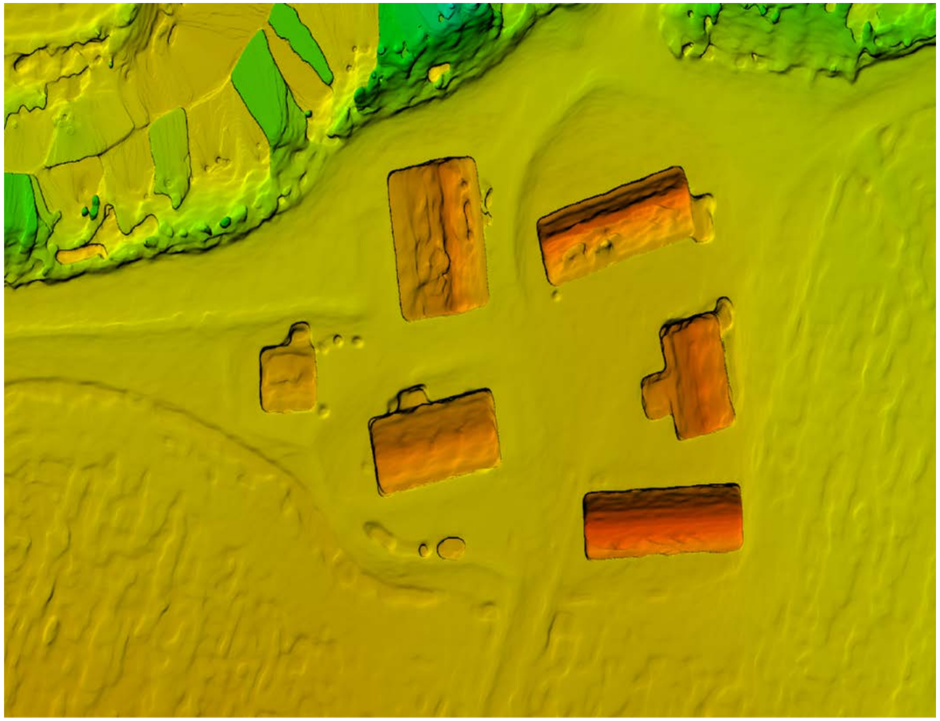


NADIR Only

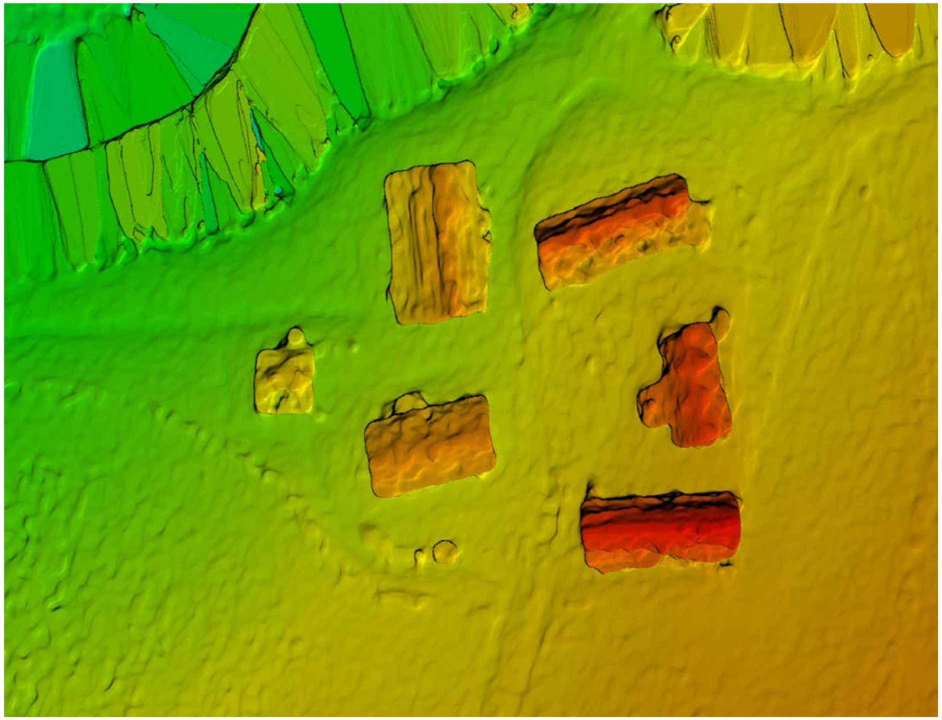


3D Georeferenced Digital Surface Model (DSM) Products NADIR + Oblique Imagery & Nadir Only Imagery -- Zoom In --

NADIR + Oblique



NADIR Only



- NADIR + Oblique imagery dataset produced an enhanced DSM (better defined structure) vs the NADIR only dataset

3D Georeferenced Digital Surface Model (DSM) Products NADIR + Oblique Imagery & Nadir Only Imagery
-- Zoom In --

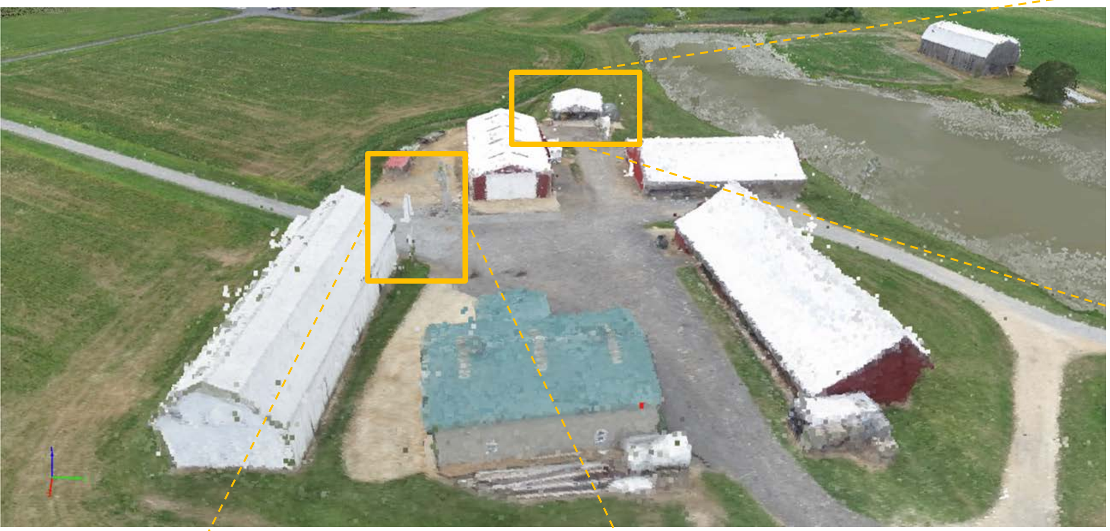
NADIR Only

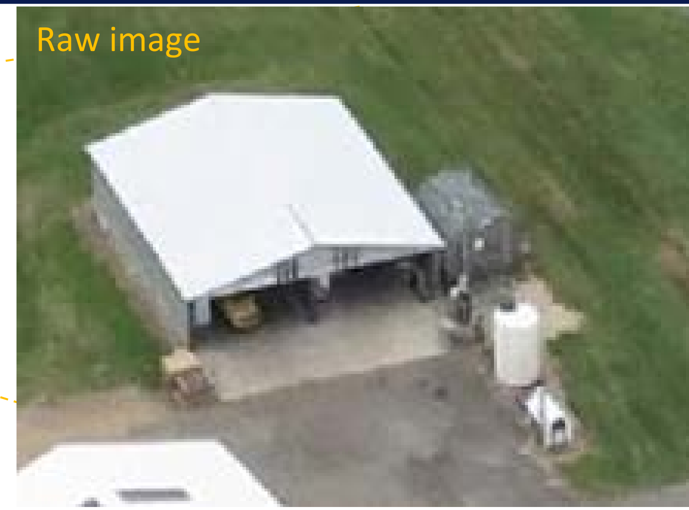
3D Georeferenced Digital Surface Model (DSM) Products NADIR + Oblique Imagery & Nadir Only Imagery
-- Zoom In --

NADIR + Oblique

3D Georeferenced Digital Surface Model (DSM) Products NADIR + Oblique Imagery & Nadir Only Imagery -- Zoom In --

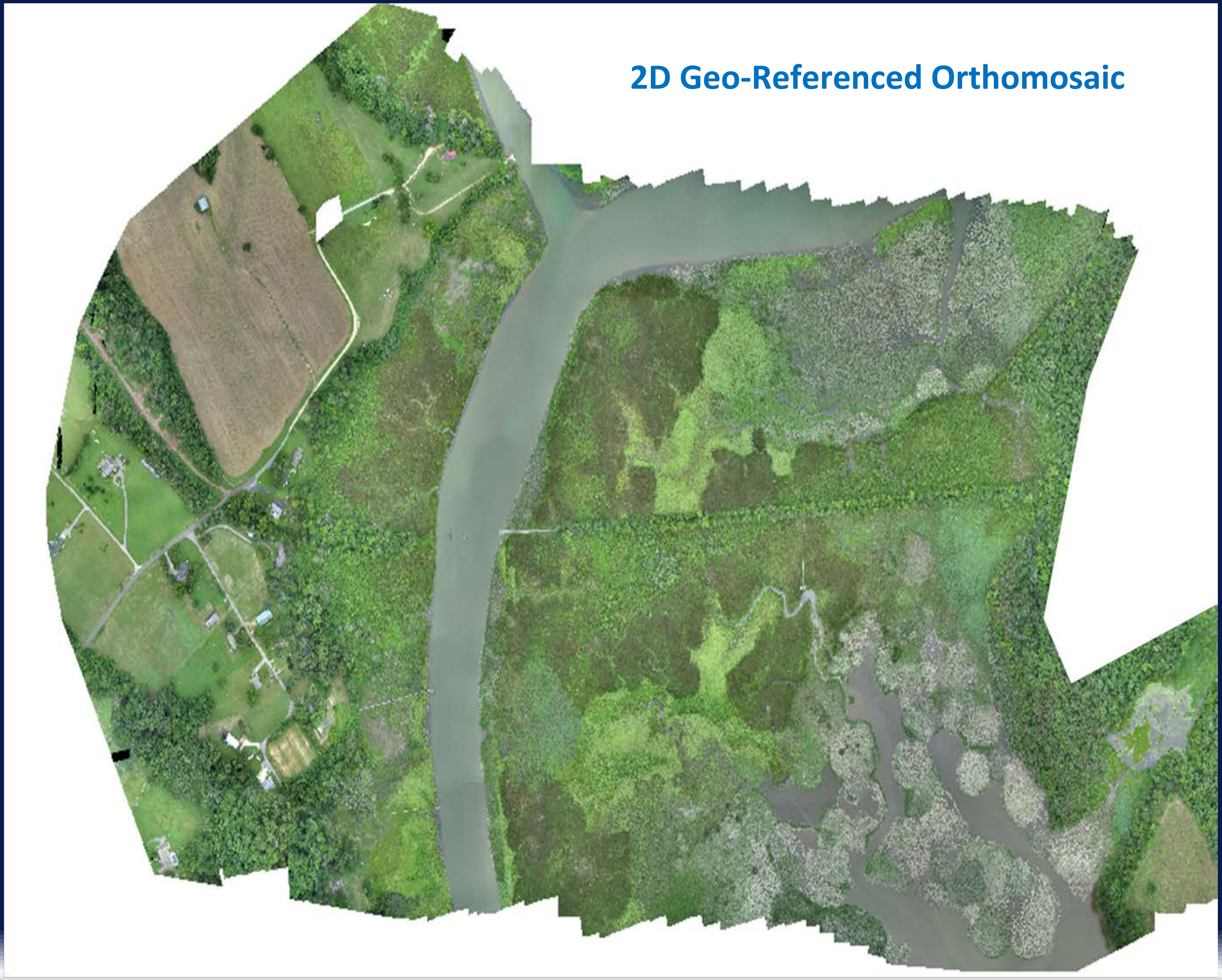
NADIR + Oblique





NADIR Only

NOAA National Estuary Research Reserve (NERR) Jug Bay, MD – August 8, 2016



NOAA National Estuary Research Reserve (NERR) Jug Bay, MD – August 8, 2016

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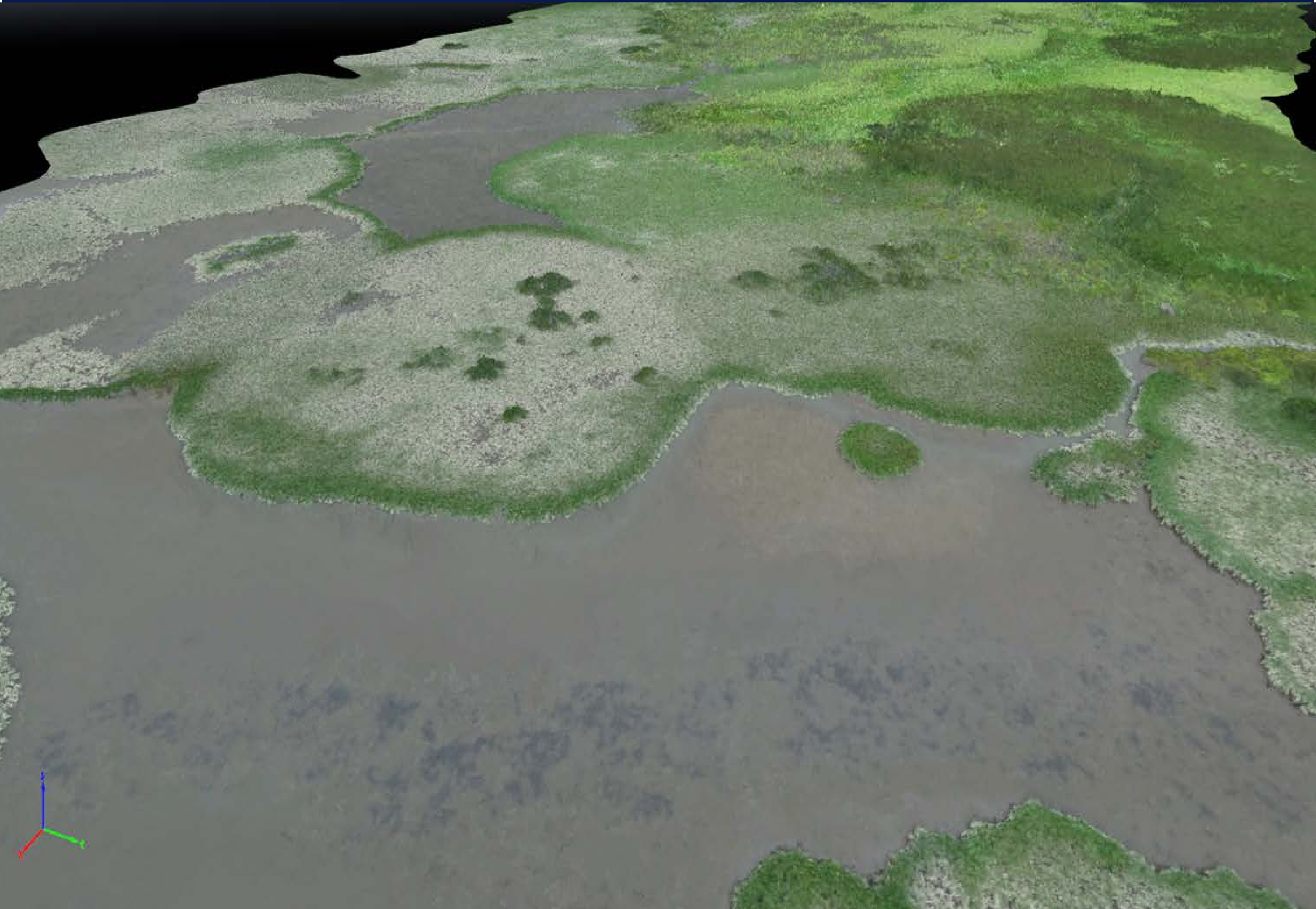
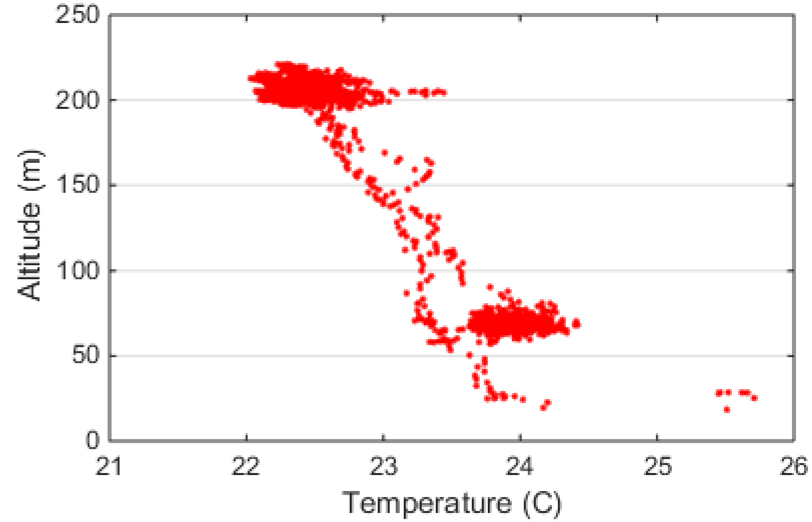
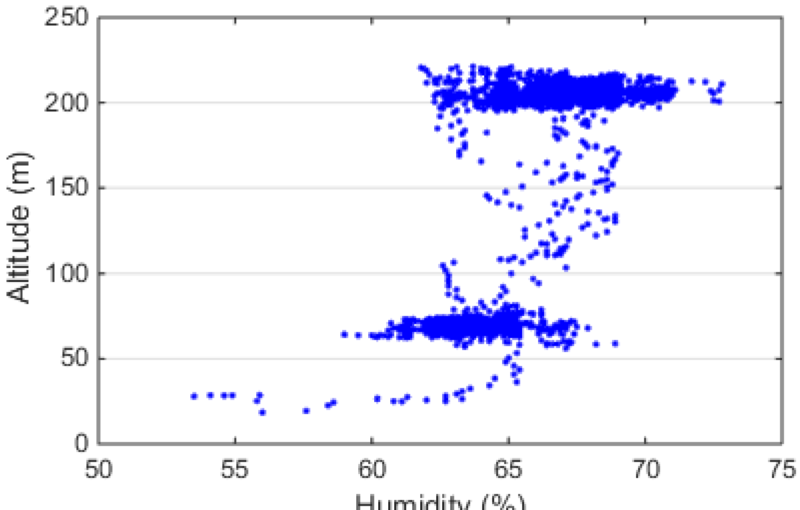
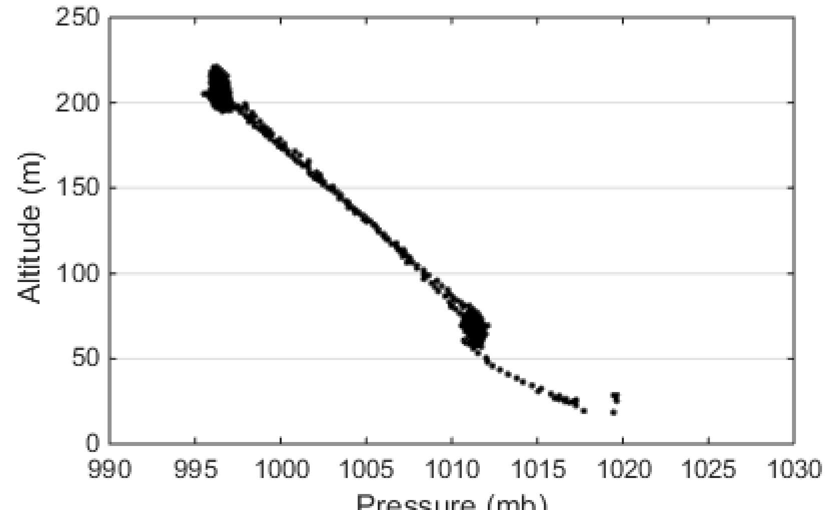


Atmospheric Sensor: Functional Performance Testing

University of Maryland (UMD) UAS test site in Bushwood, MD on August 3, 2016







Prototype Rotary System: UAS + Payloads

1. Reflective Solar Band (RSB) Sensor Suite:
- Hyperspectral coverage from 0.35 to 2.5 µm
  - Downward (directional)

2. IR Radiometer:
- Broadband IR – 8-14 µm/potentially filtered to match the ABI channels

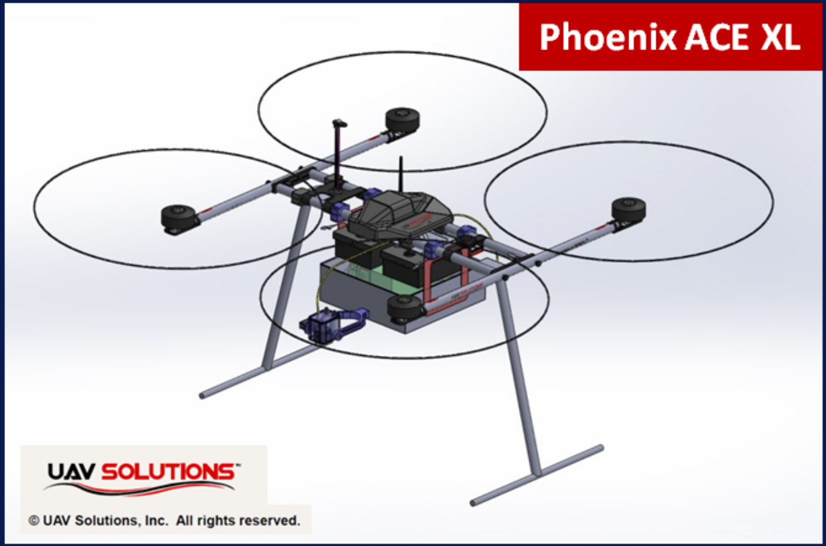
3. Context Imager:
- RGB HD video - context imager

4. Atmospheric Sensor:
- T, RH, and Px profiles

Baseline Capabilities:
- Observations over extended regions matching ABI view geometry
- Goniometric observations over a given target (directional hemispheric)

Primary System (TRL 7)

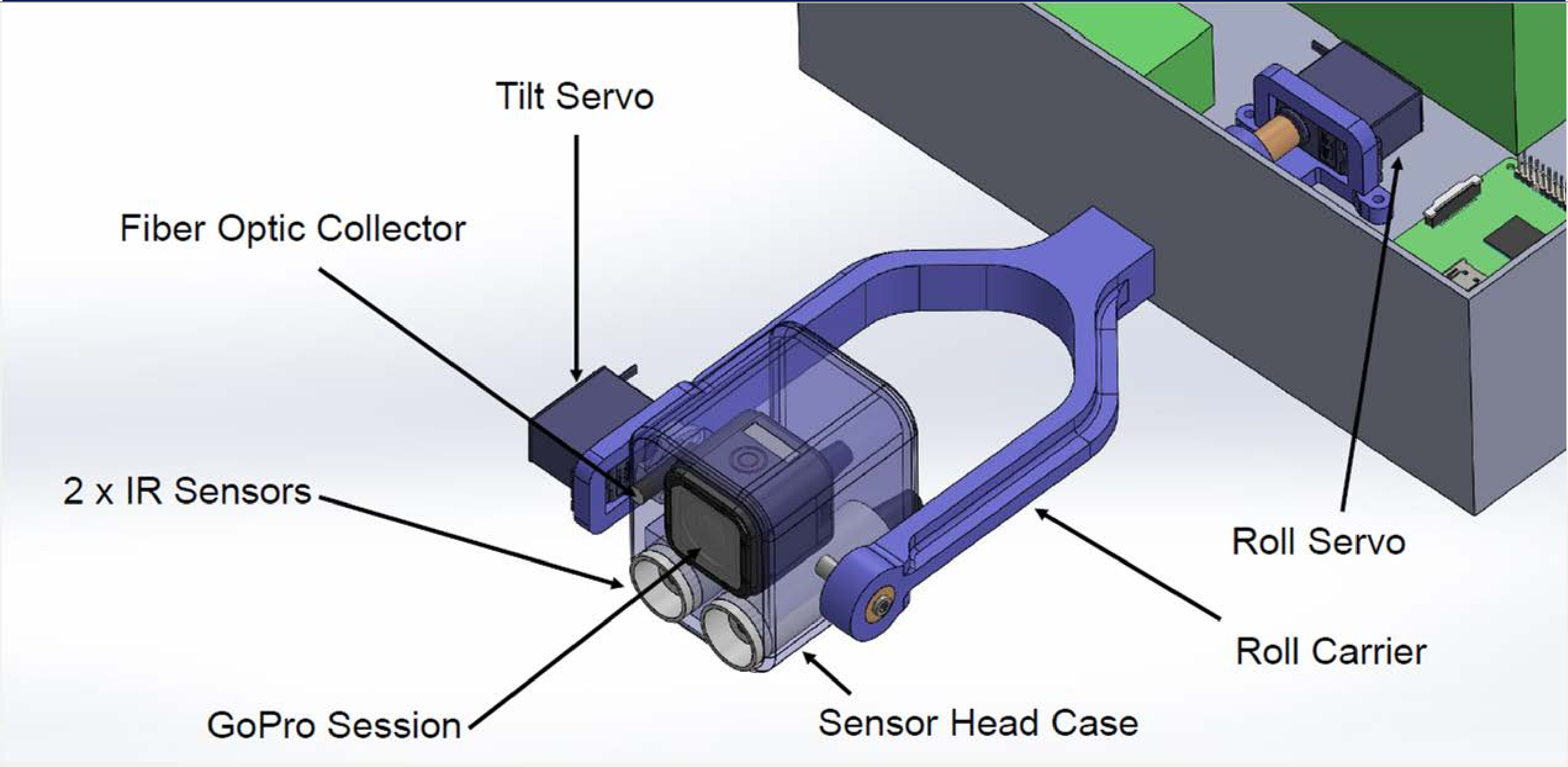
Rotary UAS



Phoenix ACE XL Specifications
Endurance: 30 minutes of collection
Fully autonomous system
Payload Capacity: 10-12 lbs

Customized electronic enclosure and autonomous 2 axis gimbal

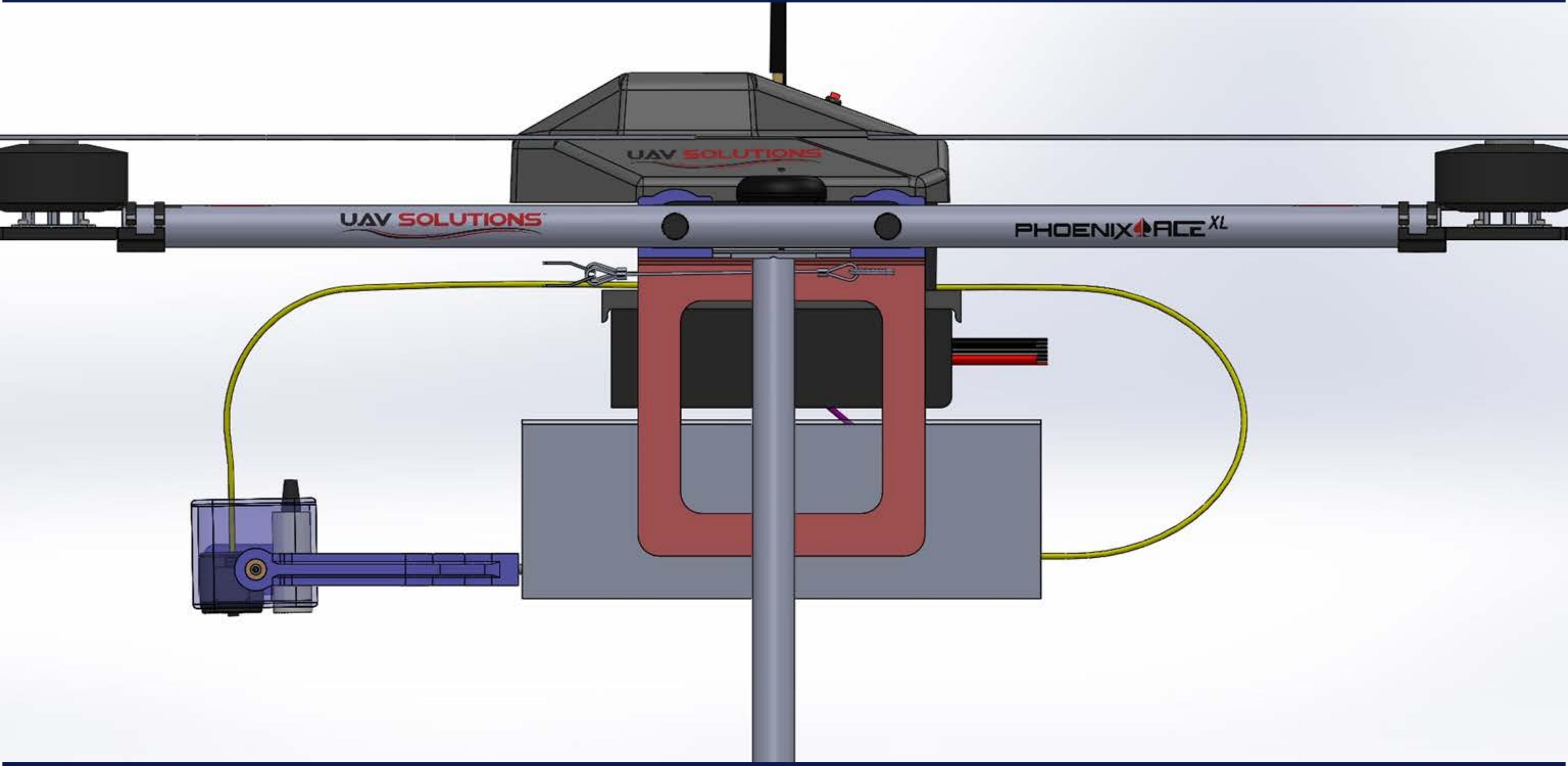
GOES-R Prototype Rotary UAS: Downward Observations



GOES-R Prototype Rotary UAS:

Gimbal & Fiber Motion

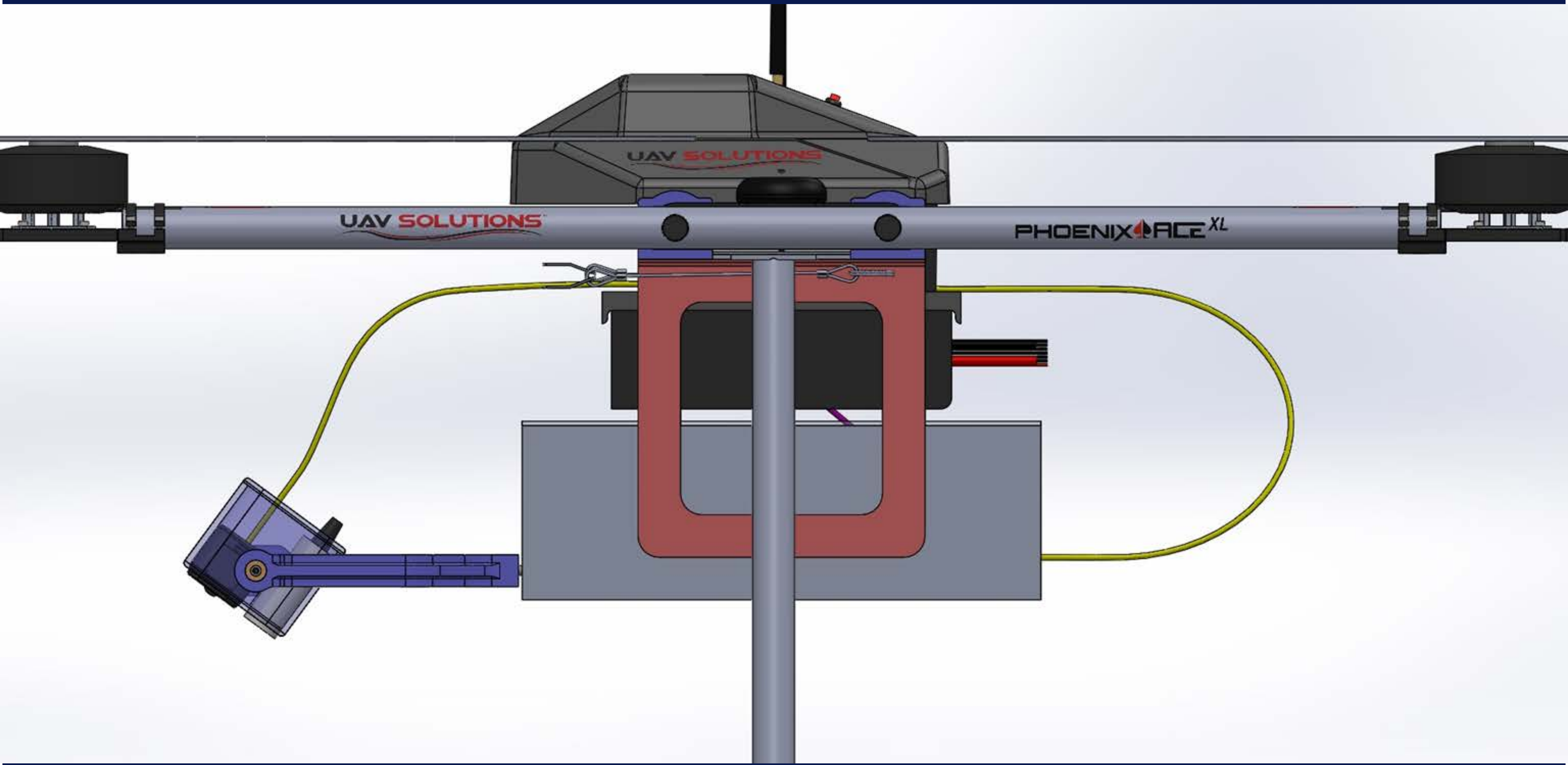
0º NADIR Viewing



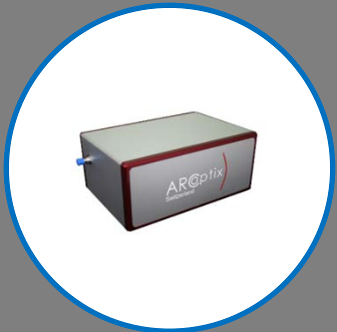
GOES-R Prototype Rotary UAS:

Gimbal & Fiber Motion

45º NADIR Viewing



Rotary UAS Payloads



RSB Sensor Suite

IR Radiometer

Context Imager

Atmospheric Sensor

VNIR Spectrometer
(0.35 – 1.1 µm)

Non-Imaging

Ocean Optics
TRL 9

SWIR Spectrometer
(0.9 – 2.6 µm)

Non-Imaging

ARCoptix
TRL 7

Broadband IR
(8.0 – 14 µm)

Non-Imaging

Apogee Instruments
TRL 9

Context HD Video
(RGB)

Imaging

GoPro
TRL 9

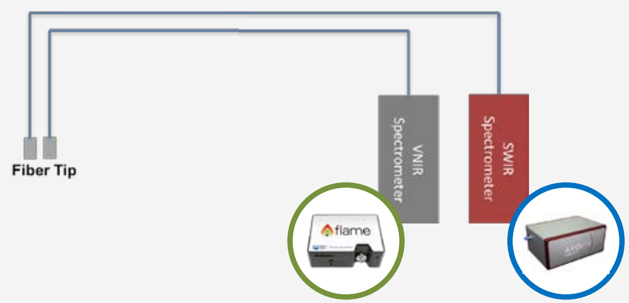
Atmospheric Sensor
(T, Px, RH)

Non-Imaging

InterMet Systems
TRL 7

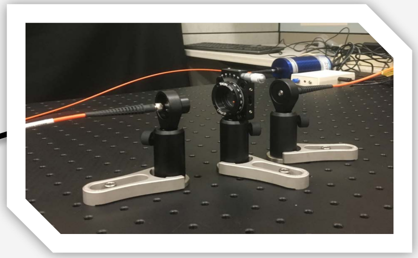
Radiometric/Geometric Calibration & Characterization

NOAA Calibration Center laboratory developed for UAS payload calibration & characterization to ensure data quality



Reflective Solar Band Sensor Suite

Polarization Sensitivity



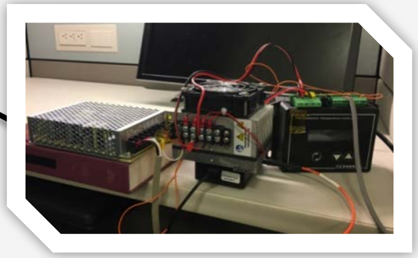
Calibration

Temperature Effects

Wavelength

Dark counts

Responsivity



[Pearlman et al. SPIE 2016]

Camera Calibration

To enable overlaying of sensor footprints in context imagery

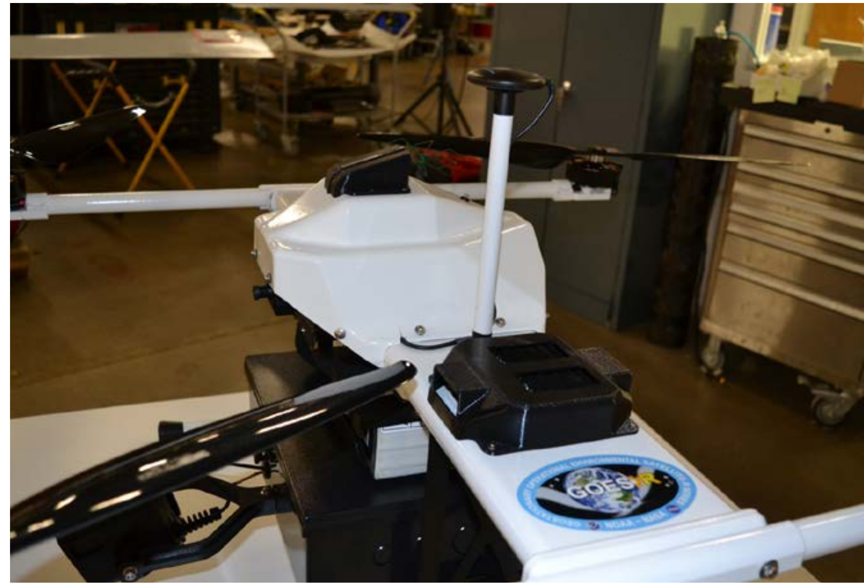
Distorted

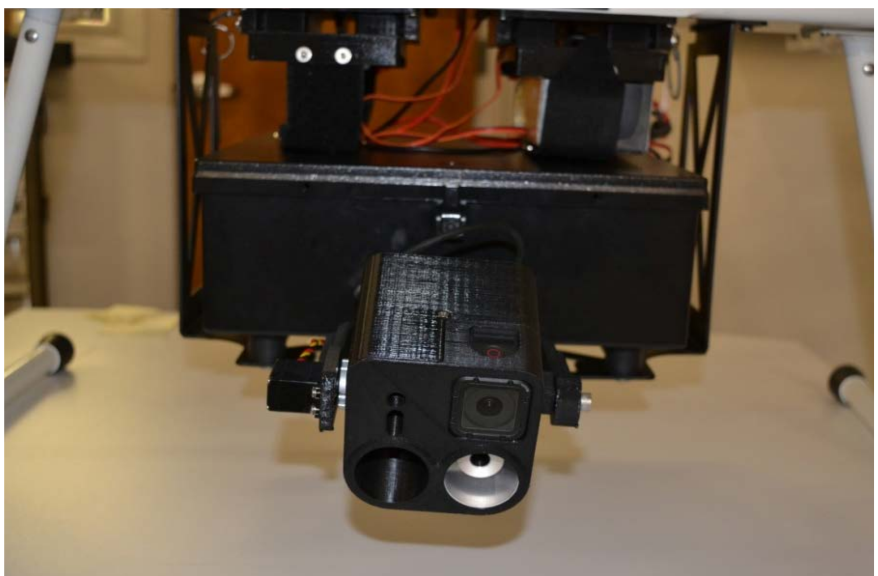
Corrected

[www.OpenCV.org]

Prototype Rotary UAS Developed

Flight Testing Without Payloads

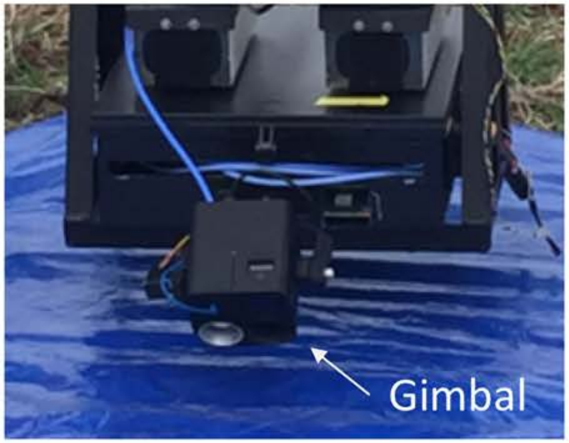


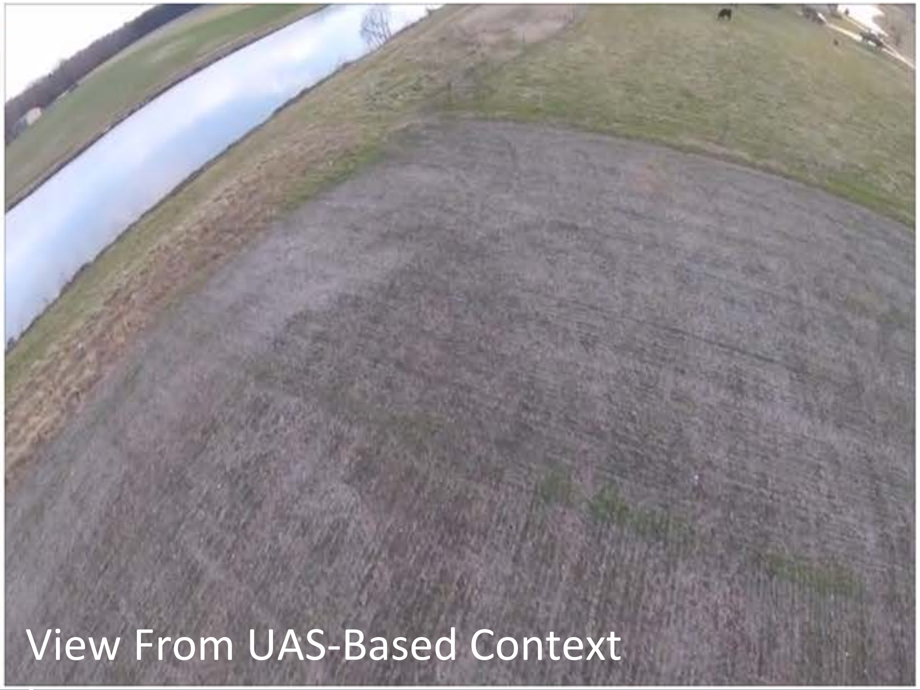


Flight Testing With Payloads

Prototype Rotary UAS Developed (TRL 7):

- Autonomous Mission Planning
- 2-axis stabilized gimbal (pointing capability)
- Hyperspectral VNIR/SWIR & thermal IR broadband sensors
- Context imager



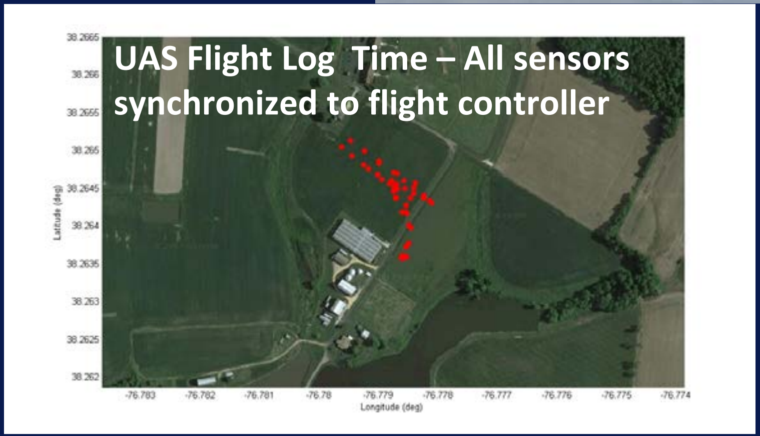


View From UAS-Based Context Imager

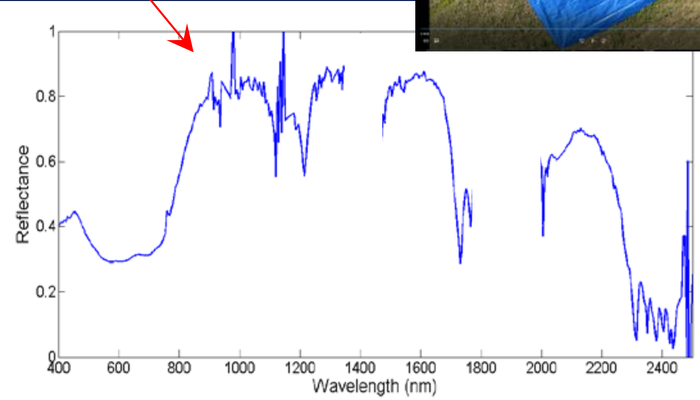
GOES-R UAS Feasibility Demonstration Study:
Successful Rotary UAS functional performance demonstrations

Completed successful functional test flights:

- NOAA National Estuary Research Reserve (NERR) in Jug Bay, MD on November 11, 2016
- University of Maryland (UMD) UAS test site in Bushwood, MD on January 13, 2017
- Demonstrated functional performance of prototype UAS & payloads:
  - Hyperspectral & thermal IR geo-referenced products



Blue Tarp:
1) In-Flight Photo
2) Hyperspectral Spectra



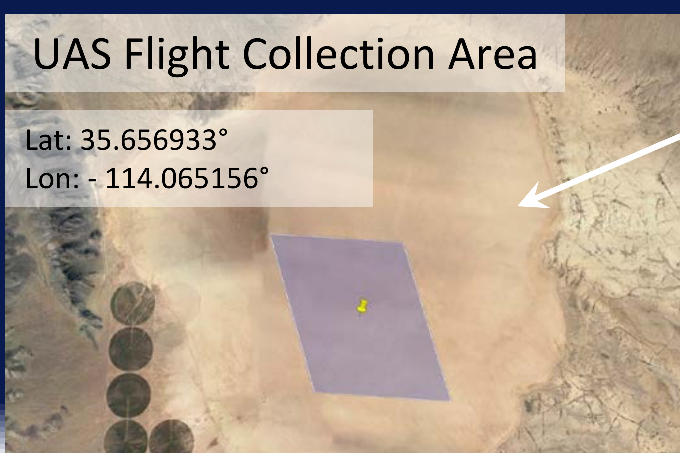
Operational Environment Testing: GOES-R Field Campaign April 3-7, 2017

GOES-R near surface UAS feasibility demonstration study concludes with an operational environmental test in Red Lake, AZ during the GOES-R field campaign:

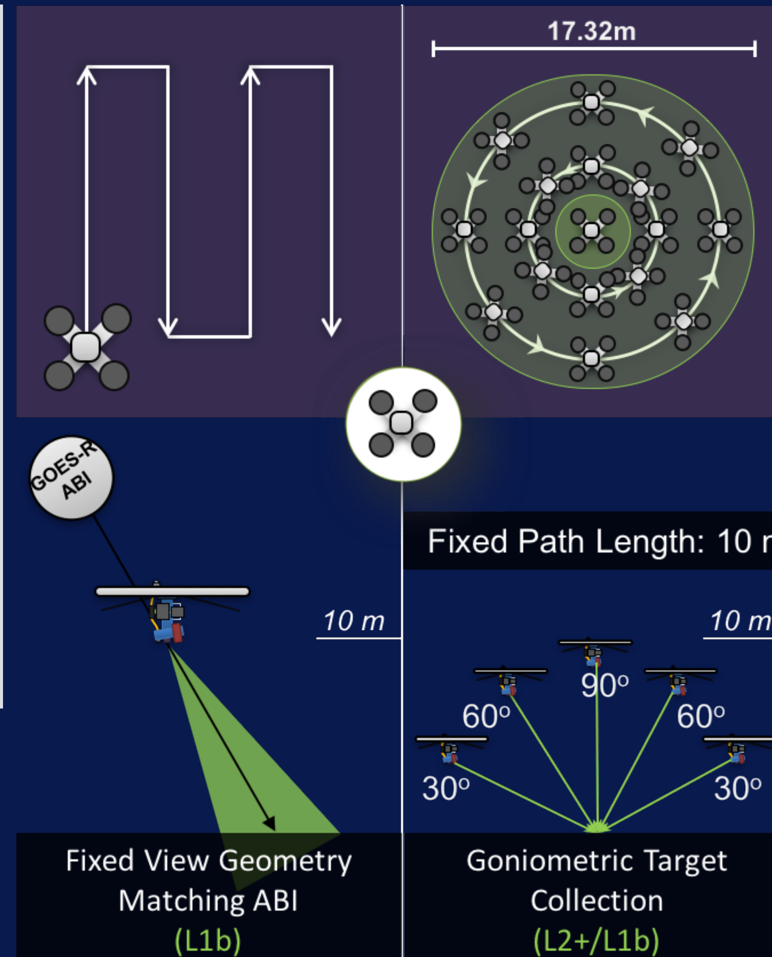
- Test data will provide reference data in support of GOES-R ABI post-launch validation efforts

Reference Measurements to be collected:

- UAS rotary geo-referenced products:
    - » Hyperspectral surface reflectance
    - » Surface effective temperature
- Mobile SURFRAD station:
    - » Automated surface & atmospheric measurements



Red Lake, AZ



Pre-Deployment Site Survey Completed February 7-8, 2017

Challenges Addressed

- **Open Source Flight Controller**
  - Enables access to the UAS metadata (Pixhawk)
- **Autonomously Controlled Payload Gimbal**
  - Customized 2-axis servo to ensure the UAS based sensors match the view geometry of the satellite sensor
  - Mission Planner & flight controller (Pixhawk) – capability improvements identified
- **Payload Command and Data Handling**
  - Developed a multi-sensor architecture using two single board computers (Raspberry PI) in parallel
- **Time Synchronization of the UAS System**
  - Ensures proper metadata tagging between sensor payloads and UAS flight controller and improved sensor product navigation
- **Near Surface Flight Operations: ~10 m**
  - Radiative transfer simulations validated the approach
- **Oblique Image Capability Added**
  - Enables enhanced image analysis & 3D geo-referenced imagery products via structure from motion techniques

Summary

- Developed & demonstrated a rotary & a fixed-wing UAS capabilities in support of advanced capability development efforts of the GOES-R field campaign:
  - Geo-referenced hyperspectral and thermal IR measurements
  - 2D & 3D geo-referenced products over a targeted area
  - GOES-R feasibility demonstration study completes with an operational environmental test (rotary UAS) in Red Lake, AZ (April 3-7, 2017) during the GOES-R field campaign and will provide reference data in support of GOES-R ABI post-launch validation
- Rotary UAS – TRL 7 (current status)
- Fixed-Wing UAS – TRL 9
- Developing web-based data discovery and visualization tools to enhance data sharing and analysis
- Developing image quality and data product levels to optimize end products
- The GOES-R near surface UAS feasibility demonstration study supports advanced capability development for the GOES-R field campaign.
  - Final report to be completed summer 2017

BACK-UP

GOES-R Advanced Baseline Imager

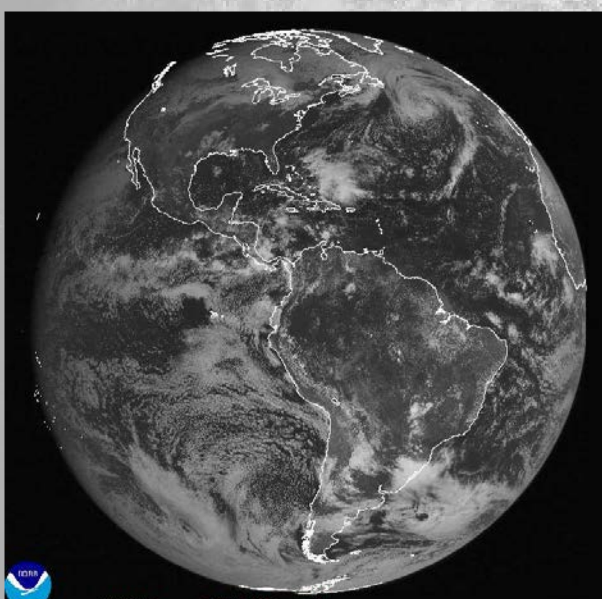
ABI MODES OF OPERATION

- **Full Disk:** Hemispheric Coverage of 83° local zenith angle, temporal resolution of 5-15 minutes, and spatial resolution of 0.5 to 2km
- **Mesoscale:** Provides coverage over a 1000x1000km box with a temporal resolution of 30 seconds, and spatial resolution of 0.5 to 2km.
- **Continental US:** The CONUS scan is performed every 5 minutes, providing coverage of the 5000km (E/W) and 3000km (N/S) rectangle over the United States. The spatial resolution is 0.5 to 2km.
- **Flex Mode:** The flex mode will provide a full disk scan every 15 minutes, a CONUS every 5 minutes, and two mesoscale every 60 seconds (or one sub-region every 30 seconds).

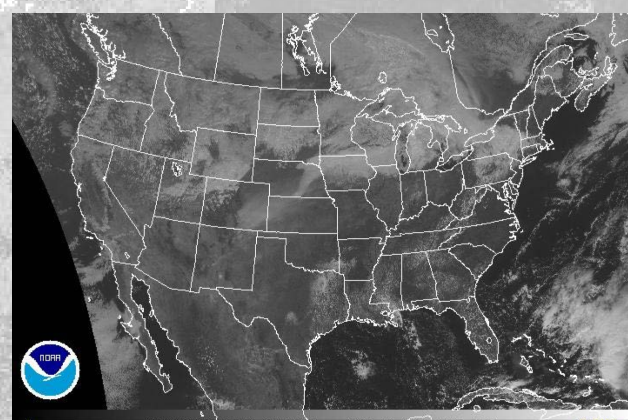
COMPARISON GOES-R SERIES ABI VS CURRENT GOES

ATTRIBUTE :	ABI	CURRENT GOES IMAGER
Spectral Coverage	16 bands	5 bands
Spatial Resolution		
0.64 μm Visible	0.5 km	~ 1 km
Other visible/near-IR	1.0 km	n/a
Bands (>2 μm)	2 km	~ 4 km
Spatial Coverage		
Full Disk	4 per hour	Scheduled (3 hrly)
CONUS	12 per hour	~4 per hour
Mesoscale	30 or 60 sec	n/a
Visible (reflective bands)		
On-orbit calibration	Yes	No

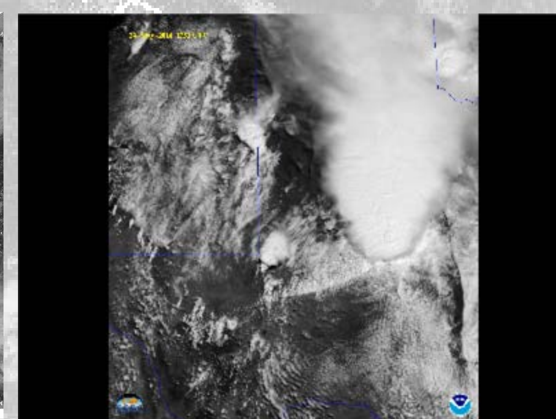
Full Disk



CONUS



Mesoscale



Information Courtesy: http://www.goes-r.gov/spacesegment/abi.html

ABI Field Campaign Approach:

Primary Objective: provide validation of ABI L1b spectral radiance observations to validate SI traceability

Secondary objective: provide surface and atmospheric geo-physical measurements to support L1b & L2+ product validation

Targets of Interest: