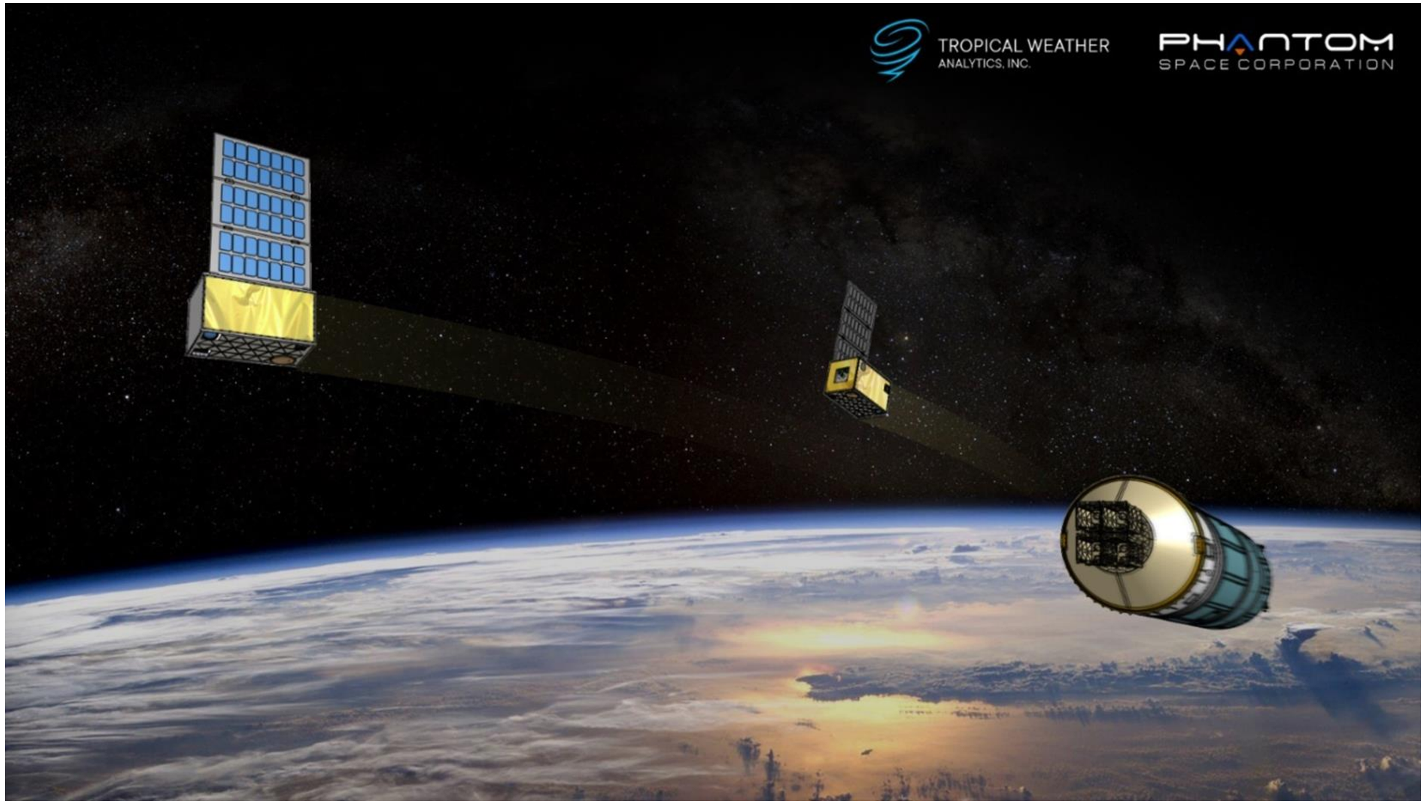
The Hurricane Hunter Satellites: A Weather Nanosatellite Constellation



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NATIONAL TROPICAL WEATHER CONFERENCE

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The Importance of Winds

- Wind is one of the fundamental variables in weather and its characterization is among the more important pieces of information contributing to the accuracy of global numerical weather prediction (NWP) models
- While twice-daily deployments of radiosondes as well as near-continuous data from ground stations, buoys, as well as appropriately instrumented ships at sea and aircraft, deliver vital in situ measurements of wind at various altitudes needed to provide initial conditions for NWPs, their data are geographically scattered and sparse
- Wind data acquired by satellites provides an important global data set to supplement the in situ data but there are limitations with today's data sets

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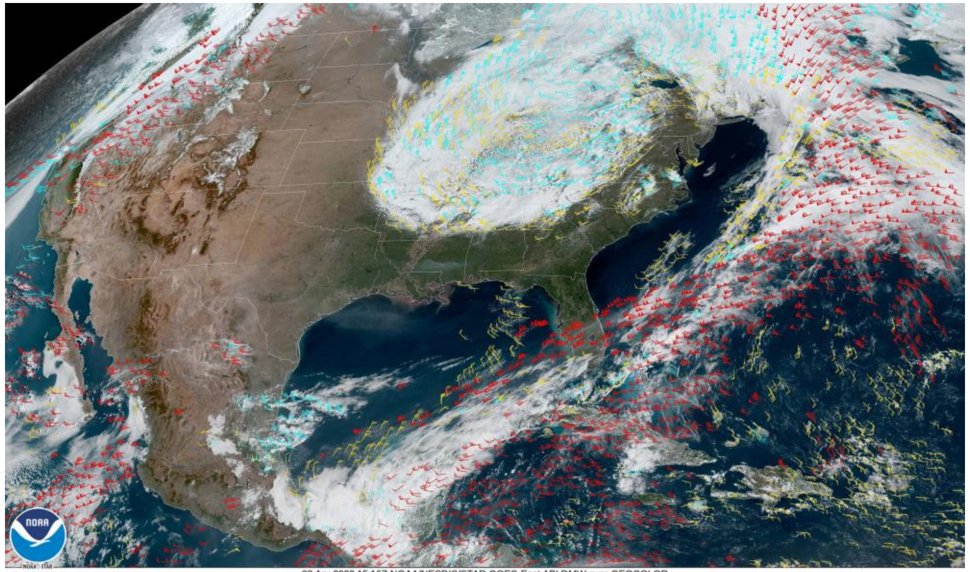
Existing Satellite Wind Data



08 Apr 2022 15:16Z NOAA/NESDIS/STAR GOES-East ABI DMW over GEOCOLOR

- One of the more commonly employed satellite wind data products uses atmospheric motion vectors (AMVs) to infer the winds, such as the GOES Derived Motion Winds (DMW) data product but, there are limitations
  - The altitudes are determined using sounding methods which divide the troposphere into just a few broad altitude bands
  - The spatial footprint of these data are tens of km and only horizontal wind vector components are measured

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A New Approach

- For over half of a century, the existing paradigm has been to incrementally upgrade the instruments and techniques of sounding methods to improve the altitude determination of features used in AMV analysis resulting in ever larger and more expensive weather satellites
  - Cloud top height measurements (another important input for NWPs) using sounding methods are still limited to accuracies of hundreds of meters in the lower troposphere and much worse at higher altitudes
- For the past three decades, the science team at Tropical Weather Analytics, Inc. (TWA), and its corporate antecedent Visidyne, have been developing a totally new approach of using true stereo observations of clouds from a pair of co-orbital satellites to measure cloud top altitudes to an accuracy of ~100 m throughout the troposphere – far superior to the long-used sounding techniques

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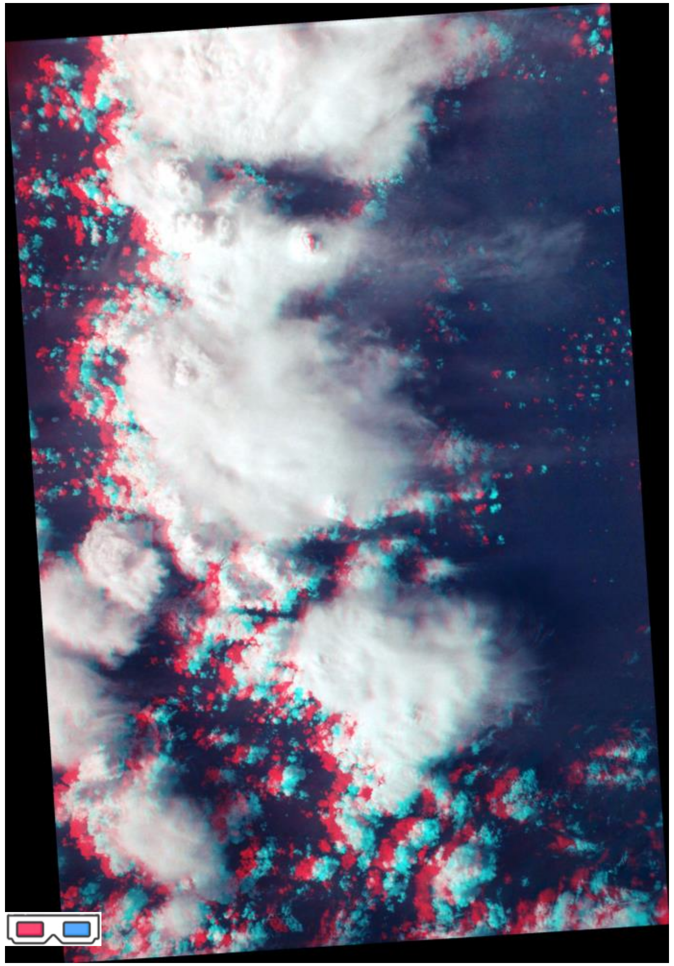
Stereo Measurements of Clouds from Space



3D view of a thunderstorm over Africa taken by Apollo 6 in April 1968

- The first analyses of stereo observations of clouds from orbit appeared in the open literature in the late 1960s using pseudo-stereo observations from single satellites
  - The accuracy of these early attempts was affected, in part, by cloud motions during the time between the two observations from a single satellite
- The first experiments of true-stereo measurements of clouds used GOES satellites back in the early 1980s
  - The accuracy of these results was limited by comparatively low resolution of the imagers and lack of precision pointing information

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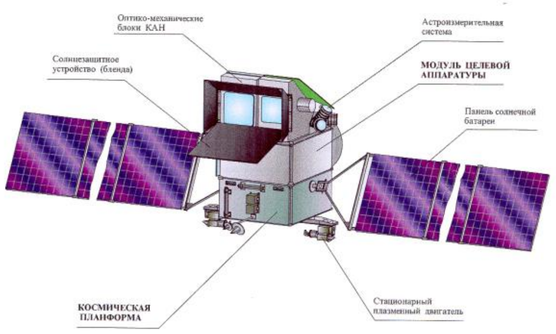
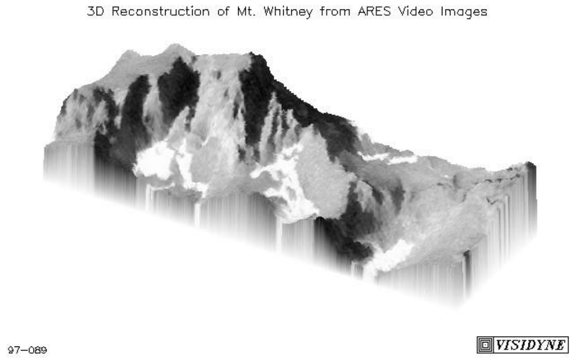
TWA's Work in Stereo Satellite Measurements



The RAMOS satellite



3D reconstruction of Mt. Whitney from October 1996

- The joint US-RF RAMOS (Russian-American Observation Satellites) was started in 1993 to make multispectral, true-stereo measurements of the atmosphere using a pair of Russian-built satellites carrying US & RF instruments
- Funded by the US DoD, RAMOS program primary objectives were to support development new early warning satellites
- RAMOS also included environmental experiments
  - Fast Changing Events (FCE) included characterizing the strength of hurricanes using the Carnot Engine model
  - Wind Velocity Distribution (WVD) would have measured winds in 3D – both horizontal and unique vertical
- Joint experiments with aircraft and satellites were flown 1995 to 1999 to aid in instrument and stereo imaging technology development
- DoD cancelled RAMOS in 2004 with no replacement proposed

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TWA's Work in Stereo Satellite Measurements

- In 2012, Visidyne started work to revive the characterization of the intensity of hurricanes using stereographic cloud altitude measurements as input into a physics-based Carnot Engine model
  - This technique offered a significant improvement in accuracy over existing satellite remote sensing methods
- In order to address outstanding issues with stereo observations of clouds from space, Visidyne's CyMISS (tropical Cyclone intensity Measurements from the ISS) was run from 2014 to 2019 with support from CASIS which manages the US National Laboratory on the ISS
  - This project was funded as NASA's Tropical Cyclone Experiment as part of the ISS CEO (Crew Earth Observations) program and used existing cameras on the ISS employing a specially designed photography procedure to create pseudo-stereo image swaths to answer specific questions about stereo imaging of clouds and to develop new data processing techniques

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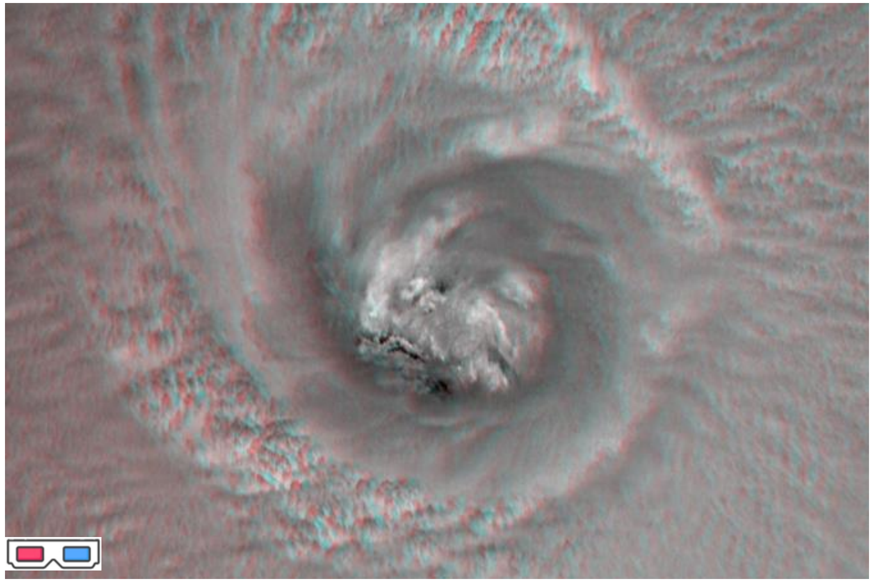
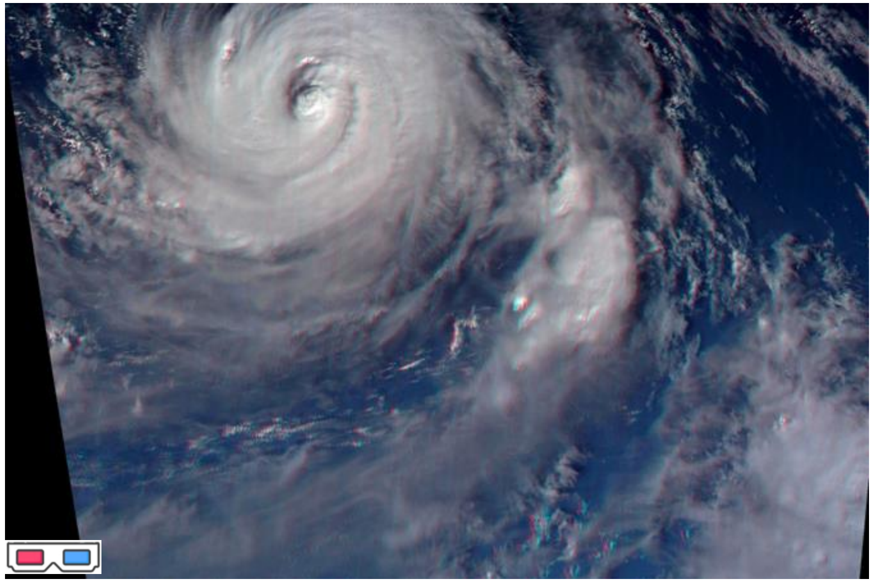
TWA's Work in Stereo Satellite Measurements



3D View of Super Typhoon Atsani - August 19, 2015



3D View of Typhoon Noru - August 1, 2017

- Because of the lack of precision pointing information to make accurate cloud altitude measurements, CyMISS objectives were limited
  - Characterize cloud scene structure on spatial scales of 100 meters or better its persistence over intervals of up to ~100 seconds
  - Provide realistic image sequences to support the development of stereo reconstruction software
- With the vital information and experience from RAMOS and CyMISS, TWA was spun off in 2016 to create the Hurricane Hunter Satellites (HHSats) as a privately funded commercial effort

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The Hurricane Hunter Satellite (HHSat)

- The Hurricane Hunter Satellites (HHSats) will consist of a constellation of low-cost satellite pairs to provide sequences of stereo image pairs to accurately measure cloud heights and motions in 3D
- The HHSats will be built, launched, and operated by our strategic partner, Phantom Space
  - Partnering with Phantom will provide much needed flexibility to build and launch the HHSat constellation
- The first generation HHSats will be 12U CubeSats that will include an onboard propulsion system to maintain their orbits over a planned 5-year lifetime as well as a satellite pair separation of ~300 km ideal for stereo cloud imagery
- The HHSats will be deployed into 500 km Sun synchronous orbits to provide global coverage

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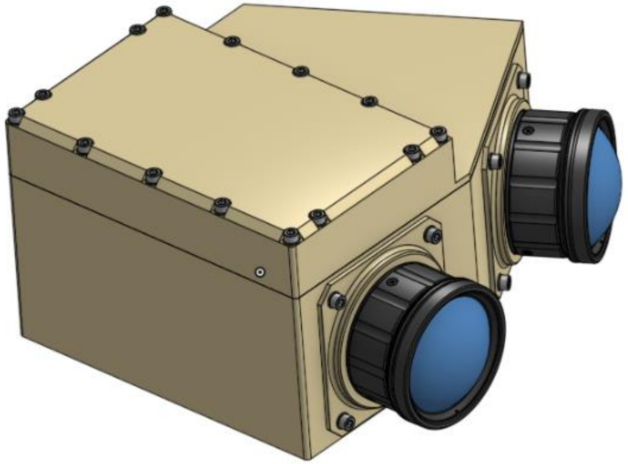
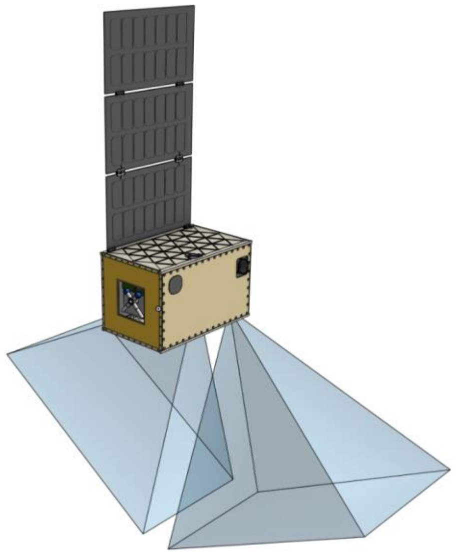
Hurricane Hunter Cam





- Each HHSat will carry a Hurricane Hunter Cam being customed designed and built by Phantom Space to meet HHSat's unique mission requirements
- Each Hurricane Hunter Cam will consist of a pair of monochromatic 5,320x3,032-pixel FPAs to provide a wide ~120°x~38° FOV with the long axis oriented perpendicular to the ground track
  - The FOV will provide a ~2,000 km wide swath with a nominal 100 m pixel footprint
- The first generation HHSat will be limited to daytime observations to minimize the initial costs
- About 1U of payload space is available for piggyback payloads

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The HHSat Constellation

Typical daily coverage of a single HHSat pair

- TWA and Phantom Space have agreed to build and launch a total of ten satellite pairs for the initial HHSat constellation
    - Launch of the first pair of HHSats is planned for early 2027 on Phantom’s new Daytona launch vehicle
- The orbital planes of the HHSat constellation will be evenly spaced between 5:00 LST and 17:00 LST to provide repeated coverage throughout daylight hours
    - Revisit times as short as 1¼ hours are possible with the full 10 satellite pair constellation – far more frequently than JPSS or other polar orbiting weather satellite constellations
    - Revisit times and area coverage can be improved by expanding the constellation beyond the initial 10 satellite pairs

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HHSat Data Products

- The initial HHSat data products offered by TWA will include:
  - 2D & 3D image mosaics
  - Cloud top height measurements
  - 3D Wind measurements
  - Characterization of hurricane strength using a Carnot Engine model
- A massively parallel cloud computing architecture will be used to perform the image data processing with a goal to release data products less than an hour after an observation session
  - 2D & 3D image mosaics could be available within minutes of receipt of data from ground stations
- HHSat data products will use file formats (e.g. CDF, HDF, GeoTIFF) and emulate data structures used by current weather satellite systems to facilitate their use with existing tools and models

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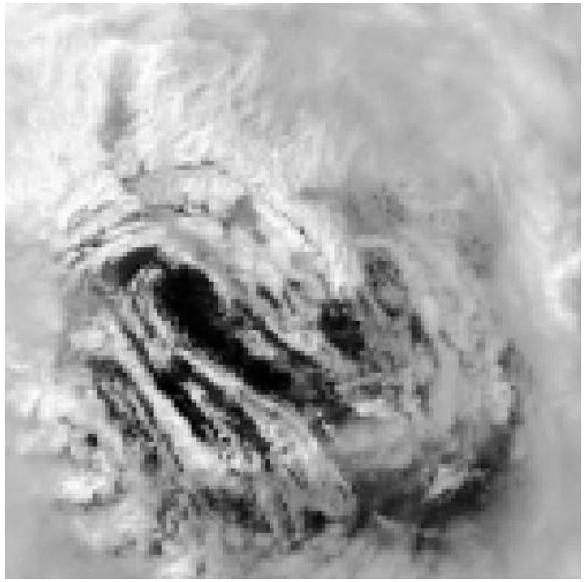
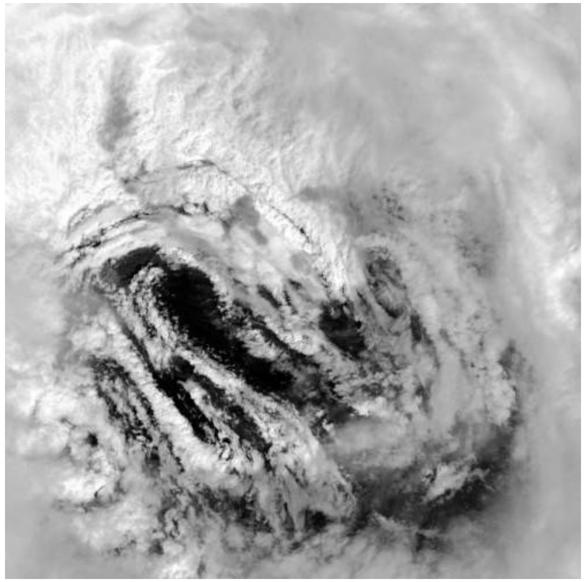
2D & 3D Imagery

Simulated GOES Image



Simulated JPSS Image



Simulated HHSat Image

- Image sequences from the HHSats will be remapped and assembled into 2D and unique 3D image mosaics
  - Mosaics will be ~2,000 km wide and up to ~4,000+ km long with a 100 m pixel scale
- Up to 10X better resolution than GOES Vis/NIR imagery & 4X better than JPSS Vis imagery

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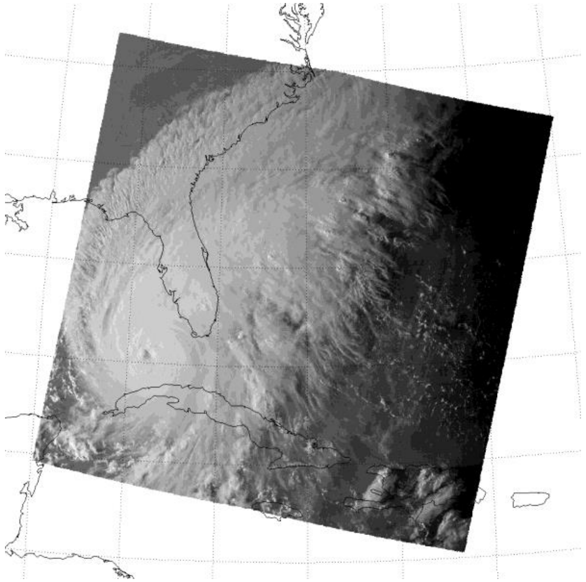
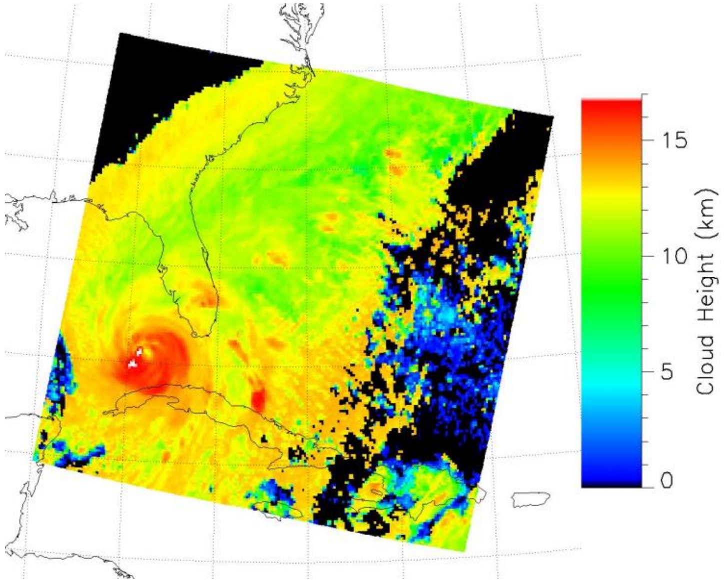
Cloud Top Height



Simulated HHSat Image



Simulated HHSat Cloud Top Height Map

- TWA's proprietary stereo data processing techniques will be used to determine cloud top heights to an accuracy as good as 100 m
  - Area covered will be ~2,000 km wide and up to 4,000+ km long with a sub-km footprint
- Cloud top height measurement accuracy over 5X better than existing satellite sounding methods with over 10X finer spatial footprint

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3D Winds

- Tracking the 3D motions of cloud features visible for a minute or more during an overpass will allow for AMVs with sub-km spatial footprints to be measured over the typical ~2,000x4,000+ km swaths
- These AMVs can be used to infer the wind velocity vectors to as good as ~1 m/s in each vector component including unique satellite measurements of the vertical wind components
  - The measurements of the vertical wind components will allow the characterization of regions with strong convection associated with especially severe weather (e.g. strong rains and tornadoes)
- Wind velocity measurements with up to ~7X better accuracy than GOES Derived Wind Motion data product with up to 40X better spatial footprint and altitude accuracy

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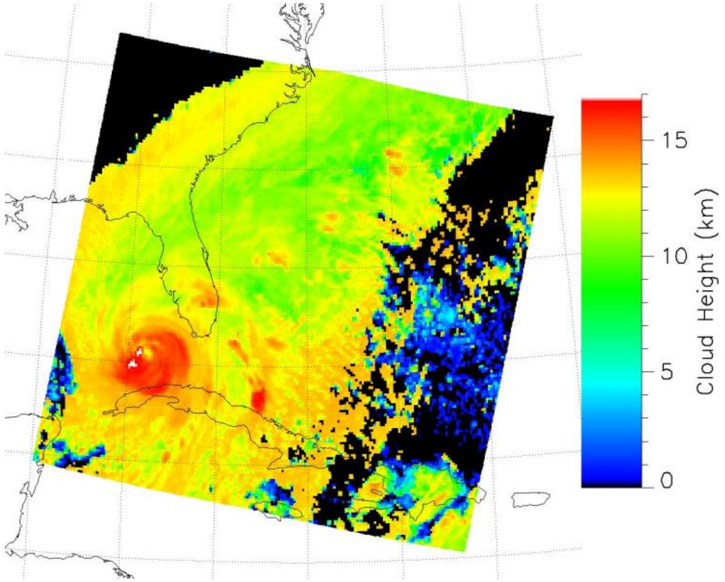
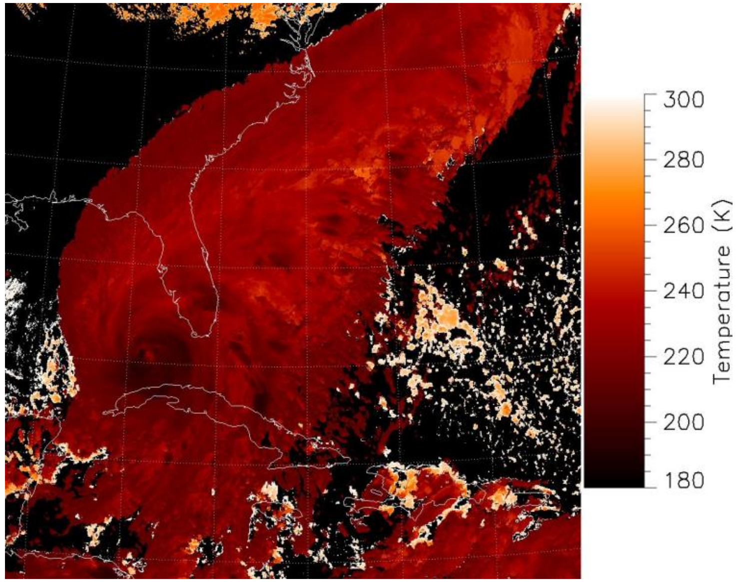
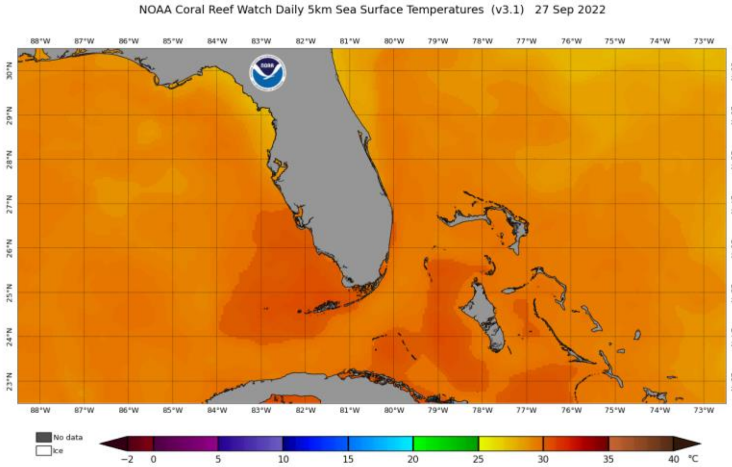
Characterization of Hurricane Strength



HHSat Cloud Height



GOES Cloud Top Temperature



NOAA Sea Surface Temperature

- Measurements of cloud top heights near the hurricane eye (HHSat), cloud top temperatures (GOES), and sea surface temperature (NOAA) can be incorporated into a Carnot Engine model to characterize the strength of a hurricane
  - For Cat 3+ hurricanes, the strength can be inferred to ~3.5 hPa - more accurately than existing overhead remote sensing techniques like the Advanced Dvorak Technique or SATCON

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Putting the Pieces Together

- **2D & unique 3D imagery**
  - Will provide analysts with higher resolution views of hurricanes and their surroundings to provide important context of other observations on as short as an hourly basis
- **Cloud top height measurements**
  - Will provide a vital input for NWPs
  - Can be used to supply high precision boundary conditions for various sounding techniques to improve their accuracy
- **3D wind measurements**
  - Will provide a vital input for NWPs on low-altitude winds, winds along the hurricanes' cloud tops and the high-altitude outflow from the eye
  - These data will supply needed information about steering winds and high-altitude wind sheer that affect predictions of hurricane intensity and track
  - HHSat's unique vertical wind measurements can be used to identify areas with strong convection associated with severe rains and tornadoes in hurricanes
- **Carnot Engine model characterization**
  - Will provide more accurate information on the strength of a hurricane

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Business Road Map

- **Mission**:
  - TWA aims to create a global 3D weather observation system from space to address climate change and improve weather forecasting, and hurricane prediction by creating commercial products to several industries like transportation, aviation, insurance, and others
- **Business Strategy**:
  - Provide fast, higher resolution, custom weather analytics and forecasting to predict and prepare for extreme weather phenomena.
  - Sell advanced products as subscription to customers from large weather aggregators, forecasters, and modelers to end users.
  - Put forecasting apps on smart phones for various users and industries who rely on timely weather for safety, scheduling and decision making
- **Revenue and ROI**:
  - $15M yearly for advanced hurricane forecasts to 20 countries vulnerable to hurricanes
  - Tiered monthly subscriptions for data ranging from $3k - $8k per month
  - Low-cost weather and custom apps for millions of general users
  - Total revenue of $500M over 5 years

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The Next Steps

- Phantom Space is currently developing and building the first pair of HHSats and the Hurricane Hunter Cam payload for launch in early 2027
  - If the needed funding can be secured, an option to build an additional pair of less capable 6U satellites (HHSat-Lite) for a quick launch in 2026 is being considered by TWA and Phantom Space to start the flow of commercial data sooner
- TWA is currently raising the funds needed to build and launch the following 9 pairs of HHSats as well as build the ground segment needed to processes HHSat data and distribute it to customers
  - The option to carry 1U piggyback payloads (weather-related or not) is being pursued
- A next-generation HHSat will be a much larger satellite with an IR capability being planned for the late 2020s
  - The IR camera will provide HHSat with nighttime and enhanced daytime capability
  - Carrying additional instruments, including from new partners, is an option

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More Information

For more information on HHSat and TWA, check out our website https://weathersats.com/

A gallery of dozens of 3D images from the CyMISS Project from 2015 to 2019 with links to detailed articles for each can be found here: https://www.drewexmachina.com/gallery-for-cymiss-tropical-cyclone-intensity-measurements-from-the-iss-2015-2019/

Thank you!

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