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Tropical cyclone track forecasts have improved in accuracy by ~50% since 1990, largely as a result of improved mesoscale and synoptic modeling and data assimilation. In that same period, there has been essentially no improvement in the accuracy of intensity forecasts.

Irene forecasts on track; not up to speed on wind

(A.P. wire service, August 29, 2011)

by Seth Borenstein & Christine Amaro:

Hurricane Irene was no mystery to forecasters. They knew where it was going. But what it would do when it got there was another matter. Predicting a storm's strength still baffles meteorologists. Every giant step in figuring out the path highlights how little progress they've made on another crucial question: How strong?

…the forecast after Irene hit the Bahamas had it staying as a Category 3 and possibly increasing to a Category 4. But it weakened and hit as a Category 1…“We're not completely sure how the interplay of various factors is causing the strength of a storm to change,” [National Hurricane Center Director Bill] Read said. One theory is that a storm's strength is dependent on the storm's inner core. Irene never had a classic, fully formed eye wall, even going through the Bahamas as a Category 3. “Why it did that, we don't know,” Read said. “That's a gap in the science.”
CYGNSS Science Goals & Objectives

• CYGNSS Science Goal
  – Understand the coupling between ocean surface properties, moist atmospheric thermodynamics, radiation, and convective dynamics in the inner core of a tropical cyclone (TC)

• CYGNSS Objectives
  – Measure ocean surface wind speed in TC precipitating conditions
  – Measure ocean surface wind speed in the TC inner core with sufficient frequency to resolve genesis and rapid intensification

• Questions Answered by CYGNSS
  – How do the dynamics within TCs determine their intensity at landfall?
    • CYGNSS measures surface winds in the TC inner core with a 4 hr average revisit time, enabling the dynamics of the TC to be investigated
  – How do moist atmospheric thermodynamics, radiation and convection interact to control the development of TCs?
    • CYGNSS measures wind speed through intense rain fall, enabling better understand of the complex feedback between mass and energy interchange processes
    • Combine with 3 hr revisit precipitation fields by GPM
CYGNSS Core Team

- **University of Michigan**
  - Chris Ruf (PI), Aaron Ridley (Project Scientist)
  - Damen Provost (UM Project Mgr), Linda Chadwick (Business Mgr), Bruce Block (Technical Mgr)

- **Southwest Research Institute**
  - John Scherrer (CYGNSS Project Manager), Randy Rose (System Engineer), John Eterno (Spacecraft), Debbie Rose (Mission Ops)

- **Surrey Satellite Technology US**
  - Brian Johnson (DDMI)

- **NASA Ames Research Center**
  - Elwood Agasid (Deployment Module)

- **Science Team**
### GNSS Scientific Measurements

<table>
<thead>
<tr>
<th>Science Objective</th>
<th>Scientific Measurement Estimated Performance</th>
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<tbody>
<tr>
<td><strong>Observable</strong></td>
<td><strong>Physical Parameter</strong></td>
</tr>
<tr>
<td>Measure ocean surface winds under TC conditions</td>
<td>Precip &lt; 100 mm/hr (25 km footprint)</td>
</tr>
<tr>
<td>Windspeed uncertainty</td>
<td>Greater of 2 m/s or 10% of windspeed</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>Variable 5-50 km (ground processing)</td>
</tr>
<tr>
<td>Windspeed dynamic range</td>
<td>&lt; 70 m/s (Cat 5)</td>
</tr>
<tr>
<td>Measure ocean surface winds in TC inner core with high temporal frequency</td>
<td>Mean revisit time 4 hr</td>
</tr>
<tr>
<td>Earth coverage</td>
<td>&gt; 70% coverage of all historical TC storm tracks</td>
</tr>
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</table>
Bi-Static Quasi-Specular Ocean Surface Scatterometry

- Bi-static scattering geometry with GPS direct signal proving reference and quasi-specular forward scattered signal containing ocean surface roughness information.
- Scattering cross-section image measured by UK-DMC-1 demonstration spaceborne mission with variable lag correlation and Doppler shift enabling resolution.
CYGNSS End-to-End Simulator

- Software model of all critical steps in the wind speed retrieval process:
  - Dynamic orbit propagators for GPS and CYGNSS constellations
  - Signal generation by GPS transmitter satellites
  - Free space propagation to the specular reflection point on the Earth surface
  - Bi-static forward scattering from the wind driven, roughened ocean surface
  - Receive antenna gain pattern projected onto the Earth surface
  - Link budget for received signal strength
  - Fading and thermal noise statistics of received signal
  - Accuracy, precision and resolution of Delay Doppler Map data product
  - Wind speed retrieval algorithm
Deriving Coverage Mask

- (left) One of 2 nadir antenna patterns projected onto Earth (altitude 500 km, 60° rotation, 28° tilt)
- (center) SNR of received signal (10 m/s WS, 45° inc. angle)
- (right) +8 dB SNR contour with both antennas (meets WS retrieval uncertainty requirement)
Hurricane Overpass Case Study

- Time lapse simulation comparing CYGNSS and ASCAT coverage of Hurricane Frances just before landfall
- Snapshots of all samples taken in 3 hour intervals
- Hurricane inner core shown as large blue dot
CYGNSS Earth Coverage

• 90 min (one orbit) coverage showing all specular reflection contacts by each of 8 s/c
• 24 hr coverage provides nearly gap free spatial sampling within +/- 35 deg orbit inclination
CYGNSS Revisit Time Requirement is 12 hr mean revisit

- Probability distribution of revisit time for all Earth samples within +/-35° (solid) and for samples of historical storm tracks (dashed).
- Revisit stats derived from PDF demonstrate 4 hr mean storm revisit and ~9 hr to revisit 90% of all storms

<table>
<thead>
<tr>
<th>Revisit Statistics</th>
<th>Median</th>
<th>Mean</th>
<th>90% Cumulative</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Samples</td>
<td>1.6 hr</td>
<td>4.8 hr</td>
<td>14.4 hr</td>
</tr>
<tr>
<td>Storms Only</td>
<td>1.5 hr</td>
<td>4.0 hr</td>
<td>9.3 hr</td>
</tr>
</tbody>
</table>
CYGNSS Historical Storm Track Overlay

CYGNSS coverage map overlaid on historical record of all named (wind speed >30 kt) storm tracks during 2000-2009. Red indicates Cat 1 or higher TC.
CYGNSS Spatial Coverage
Baseline Requirement is 70%

- Spacecraft dispersion after initial deployment spreads apart s/c and improves coverage

- Constellation-level redundancy allows for s/c failures while still meeting coverage requirement
Tropical Cyclone Inner Core Sampling Capability

- Figure shows the percentage of 3 hr intervals during the 2005 Atlantic hurricane season in which each of three ocean wind scatterometers (QuikScat on NASA SeaWinds, OSCAT on ISRO OceanSat-2, and ASCAT on EUMETSAT Metop) would have sampled the inner core region of every TC that occurred that year.
- Also shown is the percentage sampled by the combined OSCAT+ASCAT constellation and the percentage that would have been sampled by CYGNSS.
WS Uncertainty v. Spatial Resolution

- CYGNSS software simulator using truncated Delay Doppler Map

![Graph showing wind speed error vs. spatial resolution with categories 1 to 5 labeled:]

- Category 1: 33 m/s
- Category 2: 43 m/s
- Category 3: 50 m/s
- Category 4: 59 m/s
- Category 5: 70 m/s
Wind Speed Retrieval Uncertainty
Requirement is the greater of 2 m/s or 10% of wind speed

- CYGNSS software simulator developed to model WS retrieval performance on any platform and in all wind conditions
  - Airborne (P-3) flights demonstrations for WS<40 m/s
  - Spaceborne (UK-DMC-1) flight demo for WS<10 m/s

<table>
<thead>
<tr>
<th>Platform</th>
<th>Altitude (km)</th>
<th>Wind speed (m/s)</th>
<th>Science antenna gain (dBi)</th>
<th>Incidence angle of specular point (°)</th>
<th>Empirical wind speed uncertainty (m/s)</th>
<th>Model wind speed uncertainty (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-3</td>
<td>3</td>
<td>10</td>
<td>3</td>
<td>45</td>
<td>±1.2</td>
<td>±0.9</td>
</tr>
<tr>
<td>P-3</td>
<td>3</td>
<td>40</td>
<td>3</td>
<td>45</td>
<td>±4.8</td>
<td>±3.7</td>
</tr>
<tr>
<td>UK-DMC-1</td>
<td>680</td>
<td>10</td>
<td>11</td>
<td>45</td>
<td>±2.3</td>
<td>±2.0</td>
</tr>
<tr>
<td>CYGNSS</td>
<td>500</td>
<td>10</td>
<td>11</td>
<td>45</td>
<td>To be completed after CYGNSS on-orbit cal/val</td>
<td>±0.7*</td>
</tr>
<tr>
<td>CYGNSS</td>
<td>500</td>
<td>33 (Cat 1)</td>
<td>11</td>
<td>45</td>
<td></td>
<td>±4.23*</td>
</tr>
<tr>
<td>CYGNSS</td>
<td>500</td>
<td>50 (Cat 3)</td>
<td>11</td>
<td>45</td>
<td></td>
<td>±5.73*</td>
</tr>
<tr>
<td>CYGNSS</td>
<td>500</td>
<td>70 (Cat 5)</td>
<td>11</td>
<td>45</td>
<td></td>
<td>±6.8*</td>
</tr>
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(* Assumes 25x25 km CYGNSS spatial resolution)
• Data Flow Plan and Science Data Products
CYGNSS Science Payload

- Next generation version of the UK Surrey Delay Mapping Receiver flown on the UK-DMC-1 mission
- Simultaneously tracks and generates Delay Doppler Maps from up to 4 GPS s/c transmitters
  - 60 ns Delay res
  - 250 Hz Doppler res
CYGNSS Observatory (exploded view)
### CYGNSS Observatory (fully integrated)

#### Key Flight Segment Characteristics

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<tr>
<th><strong>Observatory</strong></th>
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<tbody>
<tr>
<td>- <strong>Configuration:</strong> Accommodate DDMI antennas and 100% DDMI duty cycle</td>
</tr>
<tr>
<td>- <strong>Power:</strong> 48.8 W (Available: 70.1 W EOL, Margin: 30.3%)</td>
</tr>
<tr>
<td>- <strong>Attitude:</strong> 3-axis stabilized, pitch momentum-biased nadir-pointed, 2.1° (3σ) knowledge and 2.8° (3σ) control (horizon sensors, magnetometer, pitch momentum wheel, torque rods)</td>
</tr>
<tr>
<td>- <strong>Communication:</strong> 1.25 Mbps S-band with 6.7 dB margin provides 31% Science data downlink margin</td>
</tr>
<tr>
<td>- <strong>Mass (ea):</strong> 17.6 kg (Margin: 59%)</td>
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<tr>
<th><strong>Launch Vehicle (LV), NASA (GFE)</strong></th>
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<tr>
<td>- <strong>Attitude:</strong> 500 km</td>
</tr>
<tr>
<td>- <strong>Inclination:</strong> 35°</td>
</tr>
<tr>
<td>- <strong>Injection mass:</strong> 174.6 kg</td>
</tr>
<tr>
<td>- <strong>LV Margin (Pegasus):</strong> 106%</td>
</tr>
<tr>
<td>- <strong>Launch:</strong> 10-Feb-2016</td>
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<th><strong>Deployment Module (DM)</strong></th>
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<tr>
<td>- 8 observatory deployment</td>
</tr>
<tr>
<td>- Provides pre-launch S/C Command &amp; Telemetry, and battery trickle charge interface</td>
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<tr>
<td>- 2 tier design to facilitate I&amp;T</td>
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CYGNSS Constellation

- Blue dots are GPS satellites
- Yellow dots are CYGNSS Observatories
Complete Flight Segment with Deployment Module

Deployment Module

Dynamic Envelope

Ø 50.8 cm

Ø 106.3 cm

Integrated CYGNSS Flight Segment fits within all EV-2 NLS-II LV dynamic envelopes
## CYGNSS Schedule

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<th>Mission Timeline</th>
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<td>Phase A</td>
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- **Phase D**: Launch