An Imaging Fourier Transform Spectrometer for the Geostationary Coastal and Air Pollution Events (GEO-CAPE) Mission

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JPL’s experience with Earth science missions can contribute to the success of the GEO-CAPE mission.

The science capability of FTS instruments has been successfully demonstrated by other earth science missions and needs to be considered for GEO-CAPE.

A cursory mission concept study was done by JPL with internal funds to identify characteristics of a GEO-CAPE mission using a single FTS instrument, the Panchromatic Fourier Transform Spectrometer (PanFTS).

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TES | GOSAT | IASI | CrIS
GEO-CAPE is a Decadal Survey Tier 2 mission that will advance science in two important areas, coastal ecosystems, and air quality. By having both measurements on the same platform, aerosol information derived from the air quality measurements can be used to improve ocean ecosystem measurements.
Science Questions

Atmospheric Science
- What are the emissions of gases and aerosols important for air quality and what are the processes controlling these emissions?
- How do atmospheric transport, chemical evolution, and deposition determine tropospheric composition over scales ranging from urban to continental?
- How do we improve air quality forecast and assessment models?
- How do changes in air quality drive climate forcing on a continental scale?
- How does intercontinental transport affect air quality?

Ocean Science
- How do short-term coastal and open ocean processes interact with and influence larger scale physical, biogeochemical and ecosystem dynamics?
- How are variations in exchanges across the land-ocean interface related to changes within the watershed, and how do such exchanges influence coastal and open ocean biogeochemistry and ecosystem dynamics?
- How do natural and anthropogenic changes including climate-related forcing impact coastal ecosystem biodiversity and productivity?
- How do airborne-derived fluxes from precipitation, fog and episodic events such as fires, dust storms & volcanoes significantly affect the ecology and biogeochemistry of coastal and open ocean ecosystems?
- How do episodic hazards, contaminant loadings, and alterations of habitats impact the biology and ecology of the coastal zone?

Geostationary orbit enables sub-diurnal day and night regional to continental observations
Science Goals

Atmospheric Science
Understand and improve capability for predicting changes in the ozone layer, climate forcing, and air quality associated with changes in atmospheric composition.

Ocean Science
Understand and improve predictive capability for changes in coastal ocean ecosystems, and how ocean ecosystems and biogeochemical cycles will respond to and affect global environmental change.

Tropospheric NO$_2$ (August 2004) from SCIAMACHY
(Courtesy K. Chance, Harvard-Smithsonian Center for Astrophysics)

Terra/MODIS April 2000

SeaWiFS October 1997

Chesapeake Bay Estuary
Atmospheric Measurements Rationale

- GEO-CAPE builds on air quality science developed over the past two decades using satellite data from instruments like TOMS, GOME, TES, and OMI – GEO-CAPE data will improve the fidelity of chemical models for forecasting air quality

- Broad spectral sensitivity enables simultaneous measurements of key air quality species and crucial vertical sensitivity for O₃, CO, SO₂, HCHO, HNO₃, and aerosols

- High spectral resolution enables vertical sounding of tropospheric ozone as is currently done by the AURA/ Tropospheric Emission Spectrometer (TES)

- Frequent temporal sampling allows sub-diurnal resolution which is important for measuring rapidly time varying photochemical species such as O₃, NO₂, HCHO – Many important air quality species go from minimum to maximum concentration levels in about four hours

- Modest ground sampling distance, especially coupled with frequent temporal sampling, is needed to differentiate concentration levels in urban, suburban, and in the background, and is also compatible with regional scale models used by EPA, NOAA, and researchers

- Vertical information on ozone into the boundary layer is crucial for understanding ozone processes that impact air quality and climate
GEO-CAPE builds on long heritage of ocean color observations from space.

Improved spectral resolution will enable improved determination of carbon species (biogeochemistry) and of phytoplankton functional groups (biogeochemistry and ecosystem structure).

Frequent temporal sampling allows dramatically improved viewing opportunities (given intermittent and moving cloud cover) as well as an opportunity to follow rapid dynamics, such as tidal mixing, storms, river plumes:
- A given population of phytoplankton can double its numbers about once per day; frequent observations are needed to measure the rapid response of phytoplankton to changes in their environment.

High spatial resolution, especially coupled with frequent temporal sampling, enables unprecedented quantification of local and regional dynamics.

Information from atmospheric composition measurements will lead to:
- Improved atmospheric correction, a key constraint to current ocean color measurement
- Novel understanding of the rates and impact of atmospheric deposition
- Coupled to spatial and temporal resolution, unprecedented coverage of the time course of dust storms, industrial plumes, etc. and their impact on ecosystem structure and function.
## Science Objectives

### Atmospheric Science
- Air quality assessments several times daily and forecasting to support air program management and public health
- Measure emission of ozone and aerosol precursors including human versus natural sources
- Monitor pollutant transport into, across, and out of North, Central, and South America
- Detect, track, and predict the location of extreme pollution events such as large puff releases from environmental disasters, and plumes from wildfires

### Ocean Science
- Quantify response of marine ecosystems to short-term physical events, such as passage of storms and tidal mixing
- Assess importance of variability in coupled biological-physical coastal ecosystem models
- Monitor biotic and abiotic material in transient surface features, such as river plumes and tidal fronts
- Detect, track, and predict the location of hazardous materials, such as oil spills, ocean waste disposal, and harmful algal blooms
- Detect floods from various sources including river overflows
### Antecedent Missions

#### and Measurements of Complementary Value

<table>
<thead>
<tr>
<th>Atmospheric Science</th>
<th>Ocean Science</th>
</tr>
</thead>
<tbody>
<tr>
<td>** Mission **</td>
<td>** Measurements **</td>
</tr>
<tr>
<td>Solar Backscatter Ultraviolet (SSBUV) Instrument</td>
<td>Column ozone</td>
</tr>
<tr>
<td>TOMS (many versions)</td>
<td>Column ozone, absorbing aerosol index</td>
</tr>
<tr>
<td>GOME, GOME-2</td>
<td>O$_3$, NO$_2$, BrO, OCIO Column</td>
</tr>
<tr>
<td>SCHIAMACHY</td>
<td>O$_3$, NO$_2$ Column</td>
</tr>
<tr>
<td>OMI</td>
<td>O$_3$, NO$_2$ Column</td>
</tr>
<tr>
<td>TES</td>
<td>CO, O$_3$, H$_2$O, HDO Profiles CH$_4$, NH$_3$, CH$_3$OH Column</td>
</tr>
<tr>
<td>MOPPITT</td>
<td>CO Profiles CH$_4$ Column</td>
</tr>
</tbody>
</table>

Previous missions provided infrequent observations from LEO; GEO-CAPE will enable frequent measurements of rapidly changing atmospheric chemistry and coastal ocean biogeochemistry.
Retrieval of important atmospheric composition species and chemistry requires hourly sampling with broad spectral sensitivity and high spectral resolution.
Ozone Vertical Profiles Are Crucial

Although ~ 90% of atmospheric ozone is in the stratosphere and only 10% in the troposphere, the tropospheric ozone is important for many reasons including it:

(a) acts as a greenhouse gas and influences the radiative forcing of the climate system
(b) serves indirectly as a 'detergent' that removes gases such as carbon monoxide and methane
(c) is a pollutant at the surface

Tropospheric ozone profiles are crucial for understanding ozone processes such as production, loss, photochemical, etc.) in:
- vertical transport from the stratosphere
- atmospheric radiative forcing
- long range transport and subsidence
- urban and regional “smog”

Ozone vertical profiles are crucial for understanding ozone processes that impact climate and air quality, and which threaten the public health and welfare of current and future generations.
Ocean Color Measurements

<table>
<thead>
<tr>
<th>Wavelength (&quot;color&quot;)</th>
<th>Wavelength (nm)*</th>
<th>Required SNR**</th>
<th>Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>393</td>
<td>250</td>
<td></td>
<td>Surface/Cloud Temperature</td>
</tr>
<tr>
<td>412</td>
<td>880</td>
<td></td>
<td>Dissolved organic matter (organic carbon)</td>
</tr>
<tr>
<td>443</td>
<td>840</td>
<td></td>
<td>Chlorophyll absorption maximum</td>
</tr>
<tr>
<td>490</td>
<td>800</td>
<td></td>
<td>Pigment absorption (Case 2), K (490)</td>
</tr>
<tr>
<td>510</td>
<td>790</td>
<td></td>
<td>Phytoplankton, suspended sediment</td>
</tr>
<tr>
<td>555</td>
<td>750</td>
<td></td>
<td>Pigments, optical properties, sediments</td>
</tr>
<tr>
<td>620</td>
<td>840</td>
<td></td>
<td>Turbidity, suspended sediment</td>
</tr>
<tr>
<td>670</td>
<td>1010</td>
<td></td>
<td>Atmospheric correction and sediments</td>
</tr>
<tr>
<td>681</td>
<td>1090</td>
<td></td>
<td>Chlorophyll fluorescence</td>
</tr>
<tr>
<td>705</td>
<td>700</td>
<td></td>
<td>Atmospheric correction, red edge</td>
</tr>
<tr>
<td>754</td>
<td>590</td>
<td></td>
<td>Oxygen absorption reference</td>
</tr>
<tr>
<td>760</td>
<td>570</td>
<td></td>
<td>Oxygen absorption reference, ocean aerosols</td>
</tr>
<tr>
<td>775</td>
<td>540</td>
<td></td>
<td>Aerosols, vegetation</td>
</tr>
<tr>
<td>865</td>
<td>520</td>
<td></td>
<td>Aerosols correction over ocean</td>
</tr>
<tr>
<td>890</td>
<td>170</td>
<td></td>
<td>Water vapor absorption reference</td>
</tr>
<tr>
<td>936</td>
<td>250</td>
<td></td>
<td>Water vapor absorption, vegetation</td>
</tr>
<tr>
<td>1240</td>
<td>600</td>
<td></td>
<td>Land/Cloud/Aerosols properties</td>
</tr>
<tr>
<td>1640</td>
<td>300</td>
<td></td>
<td>Land/Cloud/Aerosols properties</td>
</tr>
<tr>
<td>2130</td>
<td>110</td>
<td></td>
<td>Land/Cloud/Aerosols properties</td>
</tr>
</tbody>
</table>

* 50 cm⁻¹ spectral sampling  
** SNR requirements derived from MODIS and VIIR requirements

Water clarity is a performance indicator for Chesapeake Bay restoration efforts. This MODIS 250-meter ground sampling distance image shows significant details (turbid waters are red; clear waters are blue) in the rivers and main body of the bay. High resolution hourly imagery like this can resolve tides (which reverse every six hours), diel winds (such as the land/sea breeze), river runoff, upwelling and storm winds that drive coastal currents.

Characterization of the dynamic coastal ocean environment requires hourly observations yielding MODIS quality measurements (or better)
Measurement Synergy

- Total radiance observed by satellite is composed of 5-10% ocean signal and 90-95% atmosphere signal.
- Atmospheric and ocean surface scattering effects must be accurately modeled and removed.
- Atmospheric information derived from air quality measurements can be used to improve ocean water leaving radiance measurements.

Atmospheric correction is critical for ocean color retrievals.
Atmospheric Science

- Measure several species with high temporal and vertical resolution to determine tropospheric chemistry

- Measurements for air quality applications are required every 1 to 3 hours over populated regions, with ground sampling distance of 7 km (nadir)
  - Ozone: observe 1-3 hrs, vertically resolved in troposphere (sensitivity to boundary layer needed)
  - NO₂: observe 1-3 hrs, column measurements
  - CO: observe 1-3 hrs, vertically resolved in troposphere
  - NH₃: observe 1-3 hrs, column measurements (precursor for atmospheric aerosol)
  - CO₂ and CH₄ (key green house gasses): observe 1-3 hrs, vertical profiles in lower troposphere
  - HCHO and CH₃OH (proxies for VOCs): observe 1-3 hrs, column measurements

- Long range transport studies can use relaxed temporal and spatial measurements, but chemical weather forecasts require vertical profile information

Ocean Science

- Sea Surface Reflectance measurements for
  - Concentration of chlorophyll, suspended and dissolved matter
  - Concentration of particulate inorganic carbon (PIC) and particulate organic carbon (POC)
  - Concentration of dissolved inorganic carbon (DIC) and dissolved organic carbon (DOC) will be estimated from regionally-specific algorithms
  - 250 m ground sampling distance (nadir)

- Temporal sampling sufficient to resolve processes in coastal dynamics which are dominated by tides and winds (sub-diurnal)

Current imagery like MODIS-AQUA are days apart
An imaging spectrometer acquires a spectrally-resolved image of a scene by holding the line-of-sight fixed on the scene for the period of time needed to record interferograms of the scene.

From geosynchronous orbit the field-of-regard (roughly the full earth disk) can be divided into a grid of scenes defined by the size of the field-of-view.

Be able to point the instrument field-of-view anywhere within the field-of-regard in any sequence/pattern desired.

Need independent wide-field and narrow-field observations to simultaneously measure atmospheric composition and ocean color.

A square pixel array maps the scene with spatial sampling defined by the optical system design.
Spatial Sampling Approach

**Wide-Field Observations**
- ~11,000 km x 11,000 km field-of-regard
- 7 km ground sampling distance at nadir
- A 128 x 128 pixel array images a ~ 900 km x 900 km field-of-view at nadir
- 12 x 12 grid covers the entire field-of-regard

**Narrow-Field Observations**
- ~11,000 km x 11,000 km field-of-regard
- 250 m ground sampling distance at nadir
- A 1200 x 1200 pixel array images a ~ 300 km x 300 km field-of-view at nadir
- 36 x 36 grid covers the entire field-of-regard

The GEO-CAPE mission concept of operations requires simultaneous wide-field and narrow-field observations
Day and Night Observing

The observing scenario can be tailored to optimize day and night measurements.
From geostationary orbit, PanFTS wide-field observations can sample ~50 patches per hour with a 900 x 900 km instantaneous field-of-view using a 128 x 128 pixel array which provides a ground footprint with 7 km ground sampling distance per pixel at nadir.
From geostationary orbit, PanFTS narrow-field observations can sample ~277 patches per hour with a 300 x 300 km instantaneous field-of-view using a 1200 x 1200 pixel array which provides a ground footprint with 250 m ground sampling distance per pixel at nadir.
PanFTS has tremendous observing scenario flexibility because wide-field and narrow-field observations can be independent allowing simultaneous sampling of any pattern of patches.
# GEO-CAPE Instrument Design Drivers

<table>
<thead>
<tr>
<th>Capability</th>
<th>Wide-Field</th>
<th>Narrow-Field</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field of regard</td>
<td>50° N to 45° S latitude -35° to -125° longitude</td>
<td>50° N to 45° S latitude -35° to -125° longitude</td>
<td>Approximately 11,000 km by 11,000 km</td>
</tr>
<tr>
<td>Spatial sampling</td>
<td>7 km ground sampling distance at nadir</td>
<td>250 m ground sampling distance at nadir</td>
<td>Drives fore optics (telescope) design, and focal plane pixel count</td>
</tr>
<tr>
<td>Spectral range</td>
<td>0.26 µm to 15 µm</td>
<td>0.35 µm to 2.1 µm</td>
<td>Drives camera design, and interferometer materials and coatings</td>
</tr>
<tr>
<td>Spectral resolution</td>
<td>0.05 cm⁻¹</td>
<td>50 cm⁻¹</td>
<td>Drives interferometer design</td>
</tr>
<tr>
<td>Spectral SNR</td>
<td>1000</td>
<td>1000</td>
<td>Drives instrument design &amp; observing scenario</td>
</tr>
<tr>
<td>Interferogram dynamic range</td>
<td>$2^{16}$</td>
<td>$2^{15}$</td>
<td>Drives ADC design</td>
</tr>
<tr>
<td>Sampling interval</td>
<td>Approximately hourly</td>
<td>Approximately hourly</td>
<td>Drives data management design</td>
</tr>
<tr>
<td>Lifetime</td>
<td>5 years</td>
<td>5 years</td>
<td>Drives reliability</td>
</tr>
</tbody>
</table>
### Mission & Payload Summary

- **Science**
  - Satisfy GEO-CAPE science objectives for both coastal ocean biogeochemistry and atmospheric composition

- **Mission duration**
  - 2 years lifetime design (single string with selective redundancy)
  - 5 year lifetime goal and consumables

- **Geostationary orbit near 95 degrees west longitude**
  - Simple, repeating, hourly mapping observing scenario

- **One instrument (Panchromatic Fourier Transform Spectrometer)**
  - Wide-field UV-Vis-SWIR-MWIR high spectral resolution imaging spectrometer mapping North and South America approximately hourly
  - Narrow-field Vis-SWIR high spatial resolution coastal ocean and special event imaging spectrometer

- **Continuous downlink to dedicated ground station**
  - No science data stored onboard spacecraft
    - Direct data interface from instrument to telecom subsystem (bent pipe downlink)
    - Dedicated receiving station (e.g. Goldstone with backup at White Sands)
  - Minimal data latency to support applications like chemical weather forecasting

- **Science data processing, archive and distribution at JPL**
The PanFTS flight instrument architecture integrates wide-field and narrow field spectrometers.
The PanFTS flight instrument design leverages successful experience with past instruments such as TES on AURA and FTUVS at the TMF.

- Unity magnification fore optics provides two stacked 5 cm beams to a common Michelson moving mirror interferometer.
For flight packaging, add 30% margin on optical layout to accommodate remaining instrument items such as structure, electronics, etc.
- Height: 90 x 1.3 ~ 117 cm
- Length: 80 x 1.3 = 104 cm
- Width: 60 x 1.3 = 78 cm
Flight PanFTS Narrow-Field Architecture

- 3X magnification fore optics provides a single 10 cm beam to a Michelson moving mirror interferometer
For flight packaging, add 30% margin on optical layout to accommodate remaining instrument items such as structure, electronics, etc.
- Height: 120 x 1.3 ~ 156 cm
- Length: 130 x 1.3 = 169 cm
- Width: 120 x 1.3 = 156 cm

Line-of-sight pointing is accomplished with a 2 axis pointing mirror at the entrance to the optical train
- Hexapod for line-of-sight pointing

Fine pointing is accomplished with a 2 axis tip/tilt stage for the small fold mirror M3
**Flight PanFTS C&DH Architecture**

- **Processing Element Hardware**
  - 13 identical Virtex-5 SIRF 6U format boards
  - Radiation hardened > 300 krad total ionizing dose
  - Each board has 64 Gbit of DRAM to hold two successive scans
  - Error correcting code protects DRAM contents

- **FPA Data Handling**
  - FPA data are interferograms which are converted from time domain to path difference domain
  - Phase correction and Fourier transform are then performed to produce spectra
  - Wavelengths regions where detectors are not sensitive are discarded
  - 2:1 lossless data compression sets max data rate coming from each instrument output channel
Repeated Daily Operational Cycle

- Instrument operates continuously drawing different power levels during day and night
  - Nighttime average (Wide-Field Spectrometer MWIR only) is: \( 361 + 41 = 402 \text{ W} \)
  - Daytime average (all systems collecting / transmitting data) is: \( 496 + 166 = 662 \text{ W} \)

- Data comes from instrument continuously but at different rates during day and night
  - Nighttime average (no reflected solar radiation detectable) = 44 Mbit/s (only MWIR data)
  - Daytime average (reflected solar radiation in the field of view) = 804+499 = 1,303 Mbit/s
The HGA is body fixed in an orientation that points it to the dedicated ground station while the S/C maintains its nominal nadir-pointed orientation.

The S/C will be able to keep the HGA pointed within 0.2 degrees of the ground station while taking science data.

500 MHz of spectrum in the near-Earth Ka-band (25.5-27 GHz) will be available for the high rate downlink.

Downlink will use 8 PSK modulation with Square Root Raised Cosine (SRRC) pulse shaping (roll-off factor of 0.35) and use two cross-polarized channels:

- Allows 1 Gsps per polarization to fit in 450 MHz [Reference D. Lee et al. "A Gb/sec Ka-band Demo using a Reconfigurable FPGA Module"]
- For uncoded 8PSK with a BER of 1E-5, a threshold Eb/No of 13.5 dB is assumed
- Additional 3 dB is assumed for system/implemention losses

Dedicated ground antenna assumptions:

- 6 m dish with 62 dBi gain at ~26 GHz
- System noise temp of ~300 K, which would not require much cooling of the LNA equipment
- Station can receive both LCP and RCP simultaneously and support up to 1 Gbps on each polarization
- Station supports the modulation and pulse shaping scheme described above

S/C elevation angle at the ground station is > 45 degrees, keeping atmospheric attenuation below 1 dB (based on 99.8% worst case attenuation at Goldstone)

S-band system with LGAs will provide near 2pi steradian coverage and meet all tracking, uplink, and engineering telemetry downlink requirements.
Calibration Architecture

Periodic calibration views

Cold / dark space hourly

Internal black body hourly

Solar via diffuser plate once a day

Direct lunar once a month
Spacecraft always remains nadir pointed; wide and narrow-field systems have separate and independent line-of-sight pointing mirrors that use pointing knowledge provided by the spacecraft

- Wide-field pointing needed for 60 second observation
  - Control: $\pm 258 \ \text{arcsec} \ 3\sigma$ per axis R/P ($0.072^\circ$, one-twentieth of $1.43^\circ$ FOV)
  - Knowledge: $\pm 206 \ \text{arcsec} \ 3\sigma$ per axis R/P ($0.057^\circ$, which is 1 mrad)
  - Stability: $\pm 4 \ \text{arcsec}$ over 60 sec $3\sigma$ per axis R/P (stay within one-tenth pixel)

- Narrow-field pointing needed for 8 second observation
  - Control: $\pm 172 \ \text{arcsec} \ 3\sigma$ per axis R/P ($0.048^\circ$, one-tenth of $0.48^\circ$ FOV)
  - Knowledge: $\pm 120 \ \text{arcsec} \ 3\sigma$ per axis R/P ($0.033^\circ$, which is 0.58 mrad)
  - Stability: $\pm 0.14 \ \text{arcsec}$ over 8 sec $3\sigma$ per axis R/P (stay within one-tenth pixel)

- Slew requirements to support calibration and step/stare scan strategy
  - Worst case re-point from one edge of the field of regard to the other = $17.2^\circ$ slew
    - Slew and settle in < 1 min, with no change to spacecraft orientation
  - Slew and settle during step/stare scan:
    - $1.43^\circ$ in < 7 seconds for wide-field; $0.48^\circ$ in < 5 seconds for narrow-field.

- Point the boresight of a 1-meter fixed Ka-band high gain antenna to within $0.2^\circ$ (720 arcsec) $3\sigma$
  - Small variations in spacecraft orientation relative to nadir are allowed to point HGA

- Solar arrays track the sun with an independent pointing system within the bus
The next generation of the NOAA GOES (Geosynchronous) weather satellite will use an active cryocooler. The Advance Baseline Imager (ABI) uses a pulse tube cooler manufactured by NGST with two separate cold heads. One cold head cools the Mid-Wave/Long-Wave IR focal plane to 60K, and the remote second coldhead cools the optics and the Visible/Near IR focal plane to 200K.

Two stage cryocooler provides 180K cooling for ambient instrument temperature control and 65K cooling to the IR FPAs.

Instrument radiator provides continuous supplemental cooling to maintain 180K instrument cooled zone temperature.
A spacecraft used for this study is for illustration purposes only, there are several buses that could satisfy the GEO-CAPE mission.
### SA-200HP Spacecraft Bus Capabilities

**SA-200 Series Standard Modular Spacecraft**

#### Specifications/Performance Standards

<table>
<thead>
<tr>
<th></th>
<th>SA-200B</th>
<th>SA-200S</th>
<th><strong>SA-200HP</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bus Dry Mass:</strong></td>
<td>Std Conf</td>
<td>90 kg</td>
<td>128 kg</td>
</tr>
<tr>
<td><strong>Payload Mass:</strong></td>
<td>Std Conf</td>
<td>100 kg</td>
<td>50 kg</td>
</tr>
<tr>
<td><strong>Max Accommodated to Date</strong></td>
<td>127 kg</td>
<td>59 kg</td>
<td>2888 kg</td>
</tr>
<tr>
<td><strong>Redundancy</strong></td>
<td>Single string with selected/functional redundancy</td>
<td>Partial to full redundancy</td>
<td></td>
</tr>
<tr>
<td><strong>Design Lifetime</strong></td>
<td>1 - 3 years</td>
<td>3 - 10 years</td>
<td></td>
</tr>
<tr>
<td><strong>Solar Array Power @EOL:</strong> Std</td>
<td>330 W</td>
<td>280 W</td>
<td>2000 W</td>
</tr>
<tr>
<td><strong>Max to Date</strong></td>
<td>505 W</td>
<td>503 W</td>
<td>3852 W</td>
</tr>
<tr>
<td><strong>Attitude Control to Date:</strong> Spin or 3-axis stabilized w/wheels, RCS backup</td>
<td>3-axis stabilized w/wheels</td>
<td>3-axis stabilized w/wheels, RCS backup</td>
<td></td>
</tr>
<tr>
<td><strong>Knowledge, Max 3σ Error</strong>: as low as 144 arcsec</td>
<td>as low as 11.1 arcsec</td>
<td>as low as 0.14 arcsec</td>
<td></td>
</tr>
<tr>
<td><strong>Control, Max 3σ Error</strong>: as low as 504 arcsec</td>
<td>as low as 200 arcsec</td>
<td>as low as 0.21 arcsec</td>
<td></td>
</tr>
<tr>
<td><strong>Jitter, Max 3σ</strong>: as low as 15.7 arcsec/sec</td>
<td>as low as 6.2 arcsec</td>
<td>as low as 0.255 arcsec/sec (≥ 0.021, 50μs, 25-2000Hz)</td>
<td></td>
</tr>
<tr>
<td><strong>Pointing Modes</strong></td>
<td>Inertial, solar, nadir, offset, point tracking, maneuvering</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Onboard Propellant to Date</strong></td>
<td>none</td>
<td>to 112.7 kg</td>
<td>to 368.5 kg</td>
</tr>
<tr>
<td><strong>Structural Configuration</strong></td>
<td>Six and eight-sided structures with honeycomb panels and aluminum frames</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Payload Interfaces</strong></td>
<td>Externally accessible, bolt-on mounting; open architecture electrical interfaces</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>PL Data Storage &amp; DL to Date</strong></td>
<td>≤ 1096 Gbits storage; ≤ 740 Mbps DL rate</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Launch Vehicles Used to Date</strong></td>
<td>Pegasus XL, Minotaur</td>
<td>Pegasus, Scout, Minotaur</td>
<td>Delta II, Titan II, Minotaur</td>
</tr>
<tr>
<td><strong>Missions Used On</strong></td>
<td>MightySat II.1, RHESSI, C/NOFS</td>
<td>MSTI-1, MSTI-2, MSTI-3, NFIRE</td>
<td>DS1, Coriolis, Swift, Streak, GLAST, GeoEye-1, STSS</td>
</tr>
<tr>
<td><strong>Procuring &amp; Using Agencies</strong></td>
<td>AFRL, SMC/SD (Det12), NASA/UCB</td>
<td>SMC, NASA/JPL, MDA</td>
<td>NASA/JPL, SMC/SD (Det12), NRL, NASA/GSFC, PSU, DARPA, GeoEye</td>
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<tr>
<td><strong>Bus Delivery Times</strong></td>
<td>25 to 42 months</td>
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</table>
The science payload is one fixed instrument hard mounted to the spacecraft bus.

- **SA-200HP modifications**
  - C&DH instrument interface
  - Telecom Ka-band system
  - Larger propulsion tank
  - Structure for tank
  - Star tracker & gyro

- **Deployables**
  - Solar Arrays
  - K-Band Antenna

- **Launch vehicle compatibility**
  - Taurus XL
  - Athena
  - Titan II
  - Atlas series
Launch Concept

- Atlas V (401) launch from Kennedy Space Center; GTO 4,725kg

<table>
<thead>
<tr>
<th>LV Capability (kg)</th>
<th>Propellant mass (kg)</th>
<th>S/C dry mass CBE (kg)</th>
<th>S/C dry mass allocation (kg)</th>
<th>S/C dry mass margin (kg)</th>
<th>Margin (%)</th>
<th>LV Margin (kg)</th>
<th>LV Margin (%)</th>
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<td>1513</td>
<td>358.5</td>
<td>776.7</td>
<td>1156</td>
<td>445</td>
<td>38%</td>
<td>239.4</td>
<td>16%</td>
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</tbody>
</table>

- GOES-like Super-Synchronous Transfer Orbit to geostationary orbit, 95° W longitude

- Delta-V requirements
  - ~1840 m/s for GSO insertion (this is conservative given GOES-M was ~1784 m/s)
  - ~15 m/s for statistical cleanup of the injection
  - ~53 m/s per year for stationkeeping (maintaining period and inclination)
  - ~10 m/s to put spacecraft in disposal orbit at the end of the mission

- 30 day commissioning period to deploy and outgas all components, power-up (but not open up) the instrument; day 25 open instrument cover and begin instrument calibrations / commissioning
Space Environment Protection

- All parts will be screened for radiation sensitivity: goal is > 100 krad hard behind 100 mils of Al
  - Spot shielding will be used for additional protection of any critical / sensitive components

- Parts will be screened for SEU latch-up sensitivity: goal is latch up immune LET > 100 MeV-m²/mg;
  upset error rate < 1×10⁻¹⁰ errors/bit-day

- A comprehensive flight system grounding architecture will minimize charging effects

- Debris / micro-meteoroid hazard should be low

The geo radiation environment is well known and shielding methods are proven
- Instrument is always taking data and delivering it to the spacecraft telecom system

<table>
<thead>
<tr>
<th>System</th>
<th>Daytime</th>
<th>Nighttime</th>
<th>Daily Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wide-Field</td>
<td>804 Mb/s</td>
<td>44 Mb/s</td>
<td>4.6 TB</td>
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<tr>
<td>Narrow-Field</td>
<td>499 Mb/s</td>
<td>0</td>
<td>2.7 TB</td>
</tr>
<tr>
<td>Total</td>
<td>1303 Mb/s</td>
<td>44 Mb/s</td>
<td>7.3 TB</td>
</tr>
</tbody>
</table>

- No onboard storage of science data
- Science data transmitted continuously to dedicated receiving station
  - Ka-band for science data downlink (10^{-5} BER; >3 dB link margin)
  - S-band for command and telemetry up/downlink
- Receiving station transmits raw data to JPL
- JPL provides science processing, archive, and distribution
Ground System Functional View

- Telemetry System:
  - Processing
  - Storage
  - Distribution
  - Display
- S/C Telemetry
- Inst. Telemetry
  - EH&H Production rate @ TBD Kbps
- Command System:
  - Formatting
  - Queuing
- Commands & Sequences
- Sequencing S/W:
  - Generation
  - Checking
  - Translation
- S/C Testbed
- Navigation S/W:
  - Orbit Determination
  - Trajectory Analysis
  - Maneuver Design
- Tracking Data
- Commands & Sequences

- Science Packets
- Science Data Processing:
  - Analysis
  - Archive
- Archive Volumes

- Science Data Products
- Science Analysis
- Inst. Health & Performance Analysis:
  - Trending
  - Prediction

- Inst. Commands
- Science Data Products

- S/C Commands
- Inst. Cmd/Seq. Generation S/W:
  - Generation
  - Checking
  - Translation
- Inst. Commands

- Sequencing S/W

- Science Mission Planning S/W:
  - Plan generation
- Science Plan

- Science & Mission Planning S/W:
  - Plan generation

- Science & Mission Planning S/W

- DSMS
- MOS
- Science

7.3 Tbytes of science data per day
Science Mission data volume 5329 Tbytes
7.3 Tbytes of science data per day
Science Mission data volume 5329 Tbytes

Science Results

Science Plan

Engr Plan

Tracking Data

Orbit Files & RF Tracking Data
Science Data Products

Atmospheric Science Data Products

Level 1B
- Calibrated, geolocated radiances for each scene

Level 2
- Tropospheric columns of NO₂, HCHO, NH₃, CH₃OH, CH₄ hourly over North America and South America
- Tropospheric profiles of O₃ and CO over same region
- Total column SO₂ for events
- Aerosol optical depth
- All gas L2 data includes averaging kernel and error covariance matrix

Level 3
- Maps of all columns measured within 1 hour time intervals for AQ forecasting – gridded column and profile data at 2 levels

Ocean Science Data Products

Level 1B
- Calibrated, geolocated radiances for each scene

Level 2 – Ocean color
- Normalized Water Leaving Radiances (full spectra)
- Chlorophyll-a concentrations
- Suspended sediments
- Chlorophyll fluorescence line height
- Colored dissolved organic material (CDOM)
- Detritus
- Particulate organic carbon (POC)
- Dissolved organic carbon (DOC)

Level 3 – Daily, weekly and monthly binned and mapped products

Level 4 – Carbon-flux products
- Primary productivity
- Rate of photochemical breakdown of DOC
- Air-Sea CO₂ exchange
- Export production
Project Assumptions for Costing

- JPL in-house project
  - Class B mission

- RSDO commercial spacecraft bus with upgrades
  - Bus vendor also provides spacecraft I&T and flight operations support

- Launch services provided by KSC via NLS launch vehicle contract
  - Launch timeframe: 2018
  - 2015:Q3 PDR / technology cutoff (5 years available to validate any needed technologies)

- Service agreement for DSN ground station support

- Science processing, archive and distribution provided by JPL
Costing Methods and Assumptions

- **Costing Methodology**
  - Project schedule (phase A-D) based on data from similar missions
  - Standard NASA Project WBS per NPR 7120.5D
  - Team X provided project life-cycle cost estimates for options studied
    - NASA Instrument Cost Model (NICM) to estimate instrument cost and compared to similarly complex earth science instruments
      - PanFTS instrument mass based on the AURA / Tropospheric Emission Spectrometer (TES) “as-built” master equipment list with deltas incorporated where PanFTS is different
  - Project cost reserve levels (30% Phase A-D, 15% Phase E)
  - Launch vehicle options and costs from KSC Launch Services office
  - No outside contributions (total mission cost borne by NASA)

<table>
<thead>
<tr>
<th>Mission</th>
<th>Pre-Phase A</th>
<th>Phase A</th>
<th>Phase B</th>
<th>Phase C</th>
<th>Phase D</th>
<th>A-D</th>
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### Notional GEO-CAPE Schedule

#### Project Phase

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<th>Year</th>
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<td>Spacecraft Concept</td>
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<td>Technology Needs / Readiness</td>
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<td>Mission Concept Definition Document</td>
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#### Duration (mo)

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<th>Duration (mo)</th>
<th>Pre A</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>A-D</th>
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MCR gate products are defined in the SMD Management Handbook and NASA NPR 7120.5D (Program and Project Management) which invokes NASA NPR 7123 (Systems Engineering)
<table>
<thead>
<tr>
<th>Instrument</th>
<th>MISR</th>
<th>MLS</th>
<th>TES</th>
<th>PanFTS (WF+NF)</th>
<th>GMO</th>
<th>PanFTS (WF)</th>
<th>GeoMAC</th>
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<tbody>
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<td>Mass (kg)</td>
<td>148</td>
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<td>385</td>
<td>436 (335+30%)</td>
<td>1286 (989+30%)</td>
<td>245 (188+30%)</td>
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<td>(actual or CBE+30%)</td>
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<td>~Size (cm)</td>
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<td>156 (351+30%)</td>
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<td>Cost ($M)</td>
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<td>321 (247+30%)</td>
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<td>180 (138+30%)</td>
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<td>(in FY07$)</td>
<td>(95x1.208)</td>
<td>(136x1.121)</td>
<td>(160x1.121)</td>
<td></td>
<td>(138+30%)</td>
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</table>

Note: The table presents the characteristics and specifications of different instruments, including mass, power, size, phase schedule, and cost. The values are provided in both actual and CBE+30% scenarios.
It may be more cost effective to do separate science missions for atmosphere and ocean.
Future Work / Trade Studies

- GEO-CAPE mission architecture study to assess alternative mission designs such as a phased implementation and hosted payloads that offer potential cost savings and risk reduction while maintaining full science capability / return.

- Observing scenario studies to identify the most scientifically valuable ones which can guide development of a baseline concept of operations.

- GEO-CAPE / PanFTS mission study to investigate engineering designs that offer potential cost savings, risk reduction, and keep full science capability.

- Investigate alternative lower cost, lower risk PanFTS instrument designs that could launch on shared or hosted opportunities which also supports a phased implementation of GEO-CAPE.

- PanFTS flight instrument packaging and design study to refine engineering designs that lead to improved science capabilities while reducing cost and risk.

- Investigate the use of commercially available FPAs to assess potential cost savings, lower technical risk, and higher instrument maturity level.
Summary

- The PanFTS instrument could accomplish all GEO-CAPE science objectives (atmospheric composition and coastal ocean biogeochemistry)

- No changes are needed for the PanFTS instrument as designed for GEO-CAPE to measure several greenhouse gases and dynamical tracers

- PanFTS IIP and In-Pixel Digitization ACT will demonstrate technical maturity needed for flight instrument design

- Mission and instrument trade studies could identify design alternatives with lower cost and lower technical risk