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

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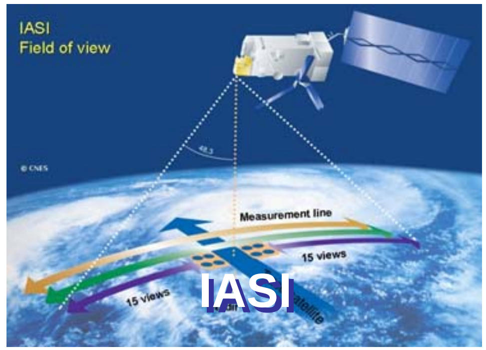
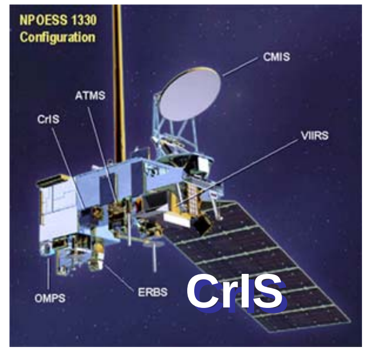
Introduction

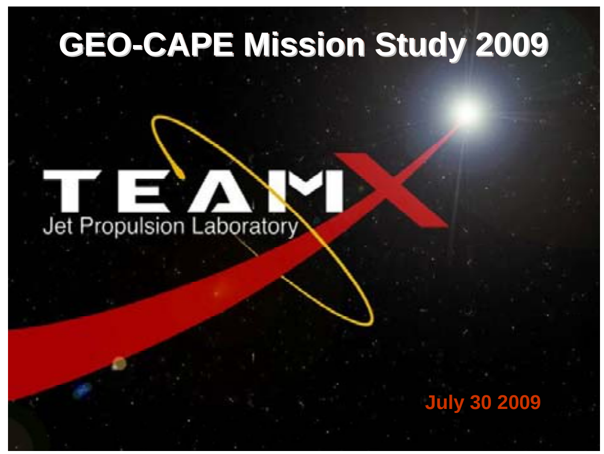
- JPL's experience with Earth science missions can contribute to the success of the GEO-CAPE mission

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



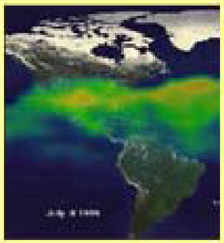


- A cursory mission concept study was done by JPL with internal funds to identify characteristics of a GEO-CAPE mission using a single FTS instrument, the Panchromatic Fourier Transform Spectrometer (PanFTS)

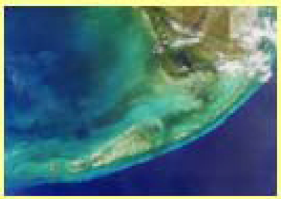


Background

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.



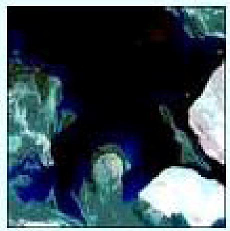
Identification of human vs. natural sources for aerosols and ozone precursors



Dynamics of coastal ecosystems, river plumes, tidal fronts

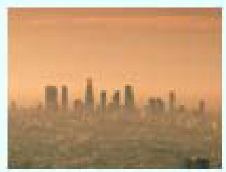
Observation of air pollution transport in North, Central, and South America

Predict track of oil spills, fires, and releases from environmental disasters



Detection and tracking water-borne hazardous materials

Coastal health



Air quality forecasts

Science Questions

Atmospheric Science	Ocean 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?	▪ 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

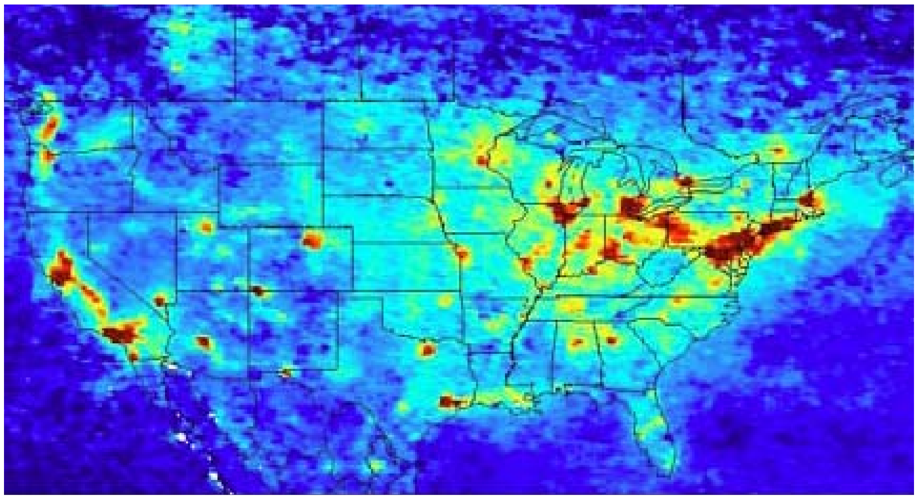
Science Goals

Atmospheric Science

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

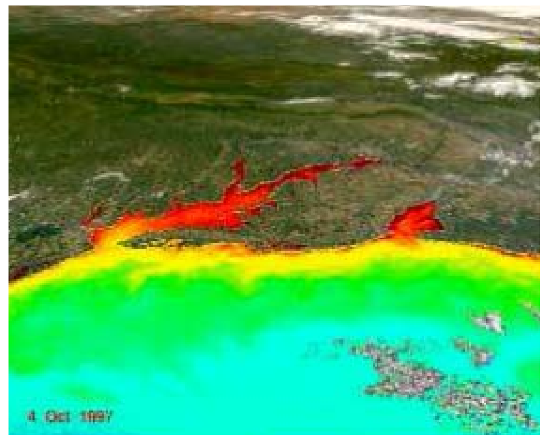
Ocean Science

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 O_3, CO, SO_2, HCHO, HNO_3, 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 O_3, NO_2, 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

Ocean Measurements Rationale

- 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

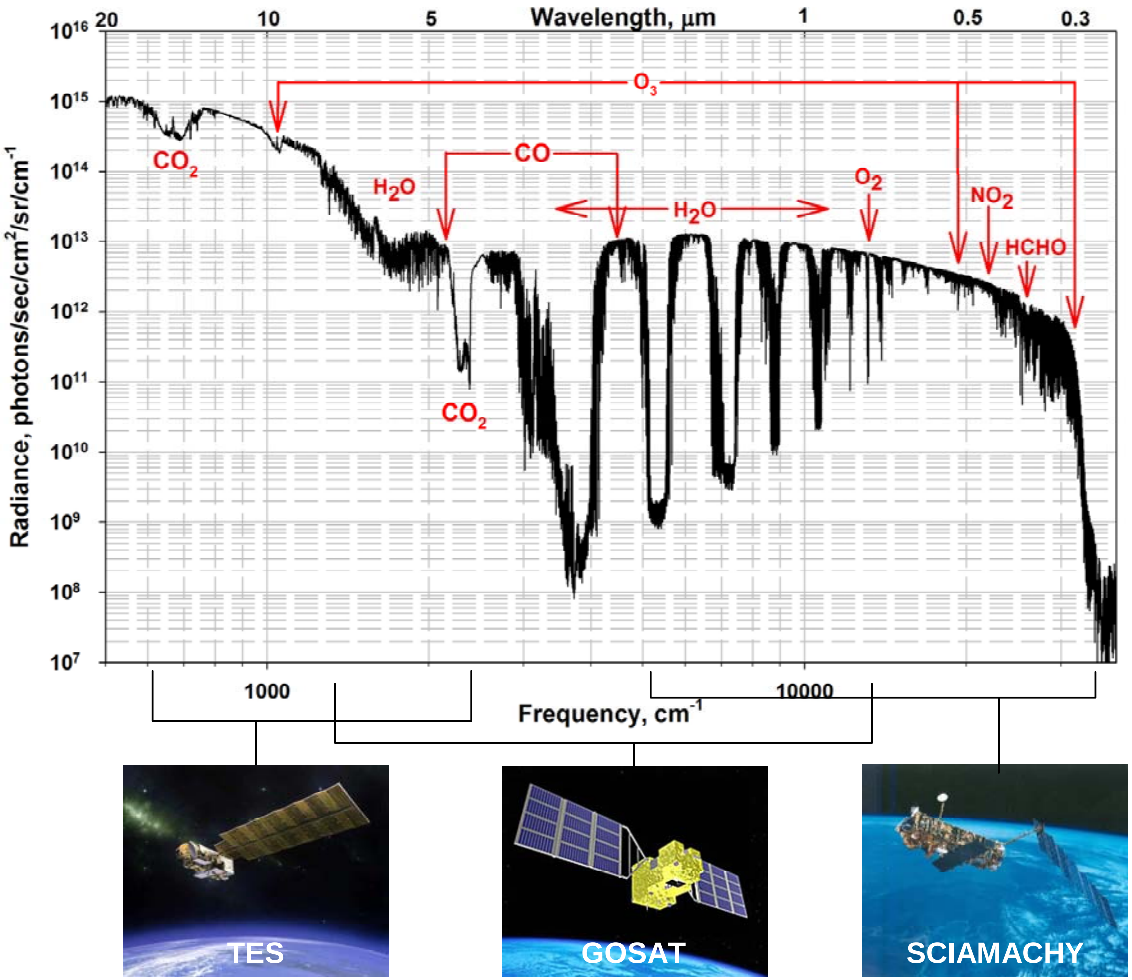
Atmospheric Science	
Mission	**Measurements**
Solar Backscatter Ultraviolet (SSBUV) Instrument	Column ozone
TOMS (many versions)	Column ozone, absorbing aerosol index
GOME, GOME-2	O_3, NO_2, BrO, OClO Column
SCHIAMACHY	O_3, NO_2 Column
OMI	O_3, NO_2 Column
TES	CO, O_3, H_2O, HDO Profiles CH_4, NH_3, CH_3OH Column
MOPPITT	CO Profiles CH_4 Column

Ocean Science	
Mission	**Measurements**
Coastal Zone Color Scanner (CZCS)	Ocean color: chlorophyll
Ocean Colour and Temperature Scanner (OCTS)	Ocean color: chlorophyll, particulate organic carbon, particulate inorganic carbon, atmospheric aerosols
SeaWiFS	
Ocean Color Imager (OCI)	
MODIS on Aqua and Terra	
Visible Infrared Imager Radiometer Suite (VIIRS)	

Previous missions provided infrequent observations from LEO; GEO-CAPE will enable frequent measurements of rapidly changing atmospheric chemistry and coastal ocean biogeochemistry

Atmospheric Composition Measurements

Earth Spectrum 20 to 0.26 μm
(Tropical noon, albedo 0.8)



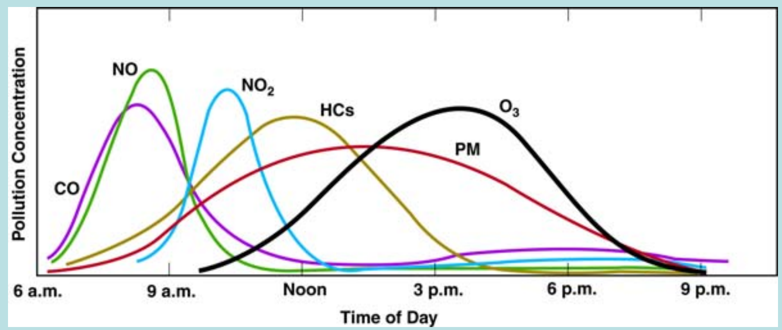
High spectral resolution (0.05 cm^{-1}) and wide spectral sensitivity (from 15 μm to 0.26 μm) allows simultaneous observations of reflected sunlight and thermal emission (day/night) enabling retrieval of several important species such as

<u>Pollutants:</u> O_3, NO_2, NH_3, SO_2, HCHO, CH_3OH, CO

<u>Greenhouse Gases:</u> CO_2, CH_4, N_2O, O_3, H_2O

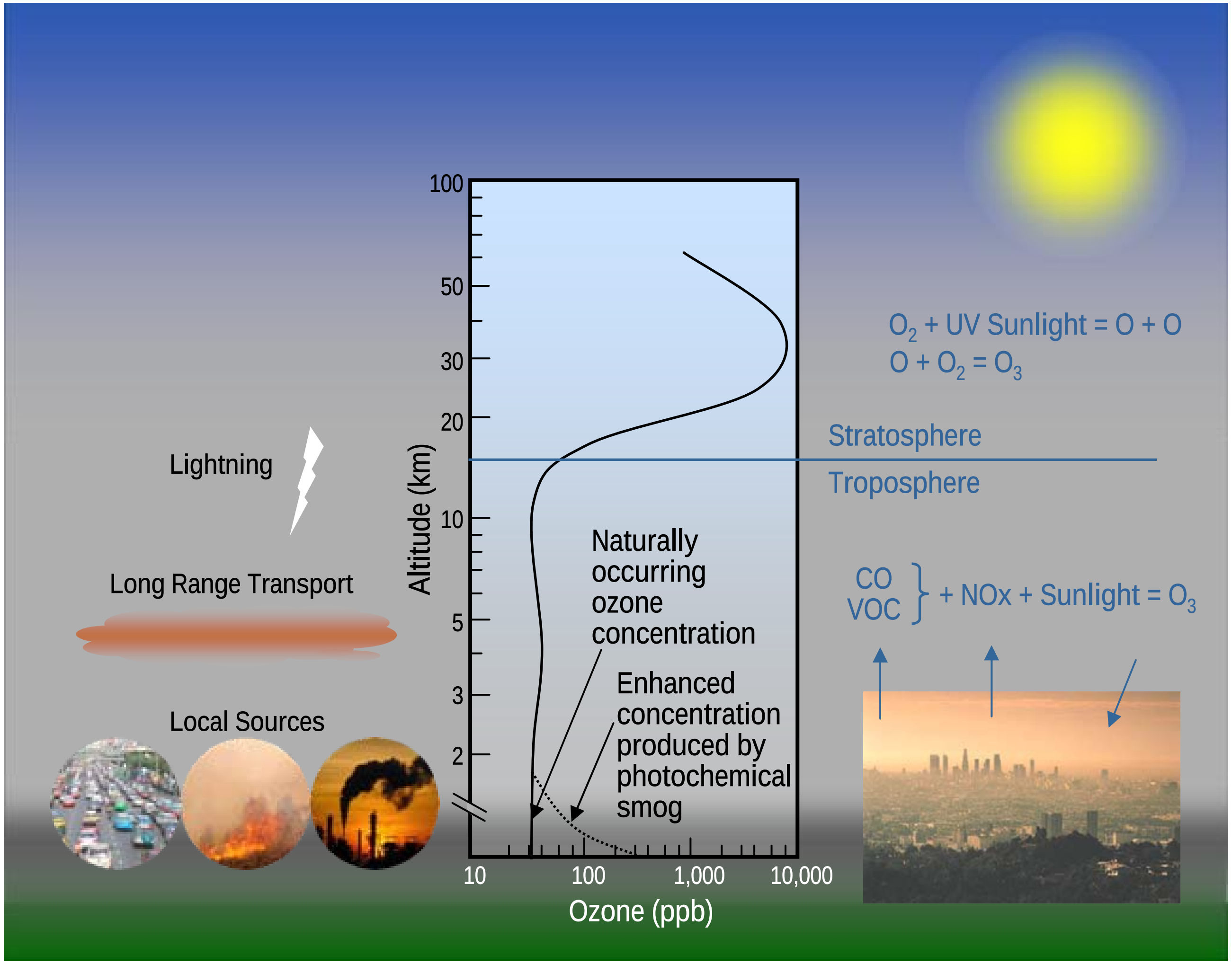
<u>Dynamical Tracers:</u> HDO, N_2O, O_2, O_4

Need to measure several species with high temporal and vertical resolution to capture rapidly evolving tropospheric chemistry



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"**

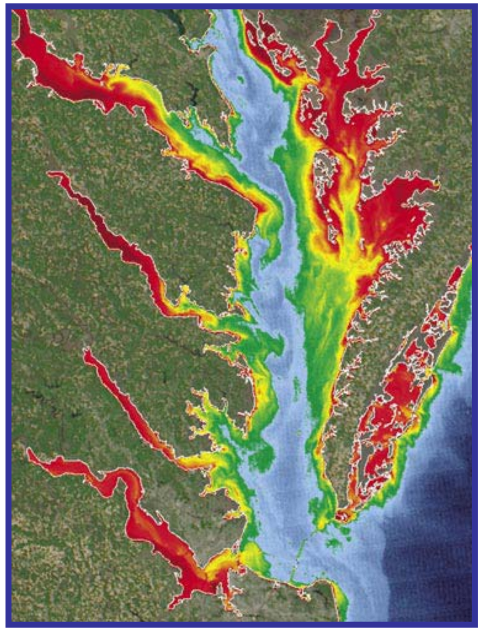
Ozone vertical profiles are crucial for understanding ozone processes that impact climate and air quality, and which threaten the public health and welfare of current and future generations

Ocean Color Measurements

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

** 50 cm^{-1} spectral sampling*

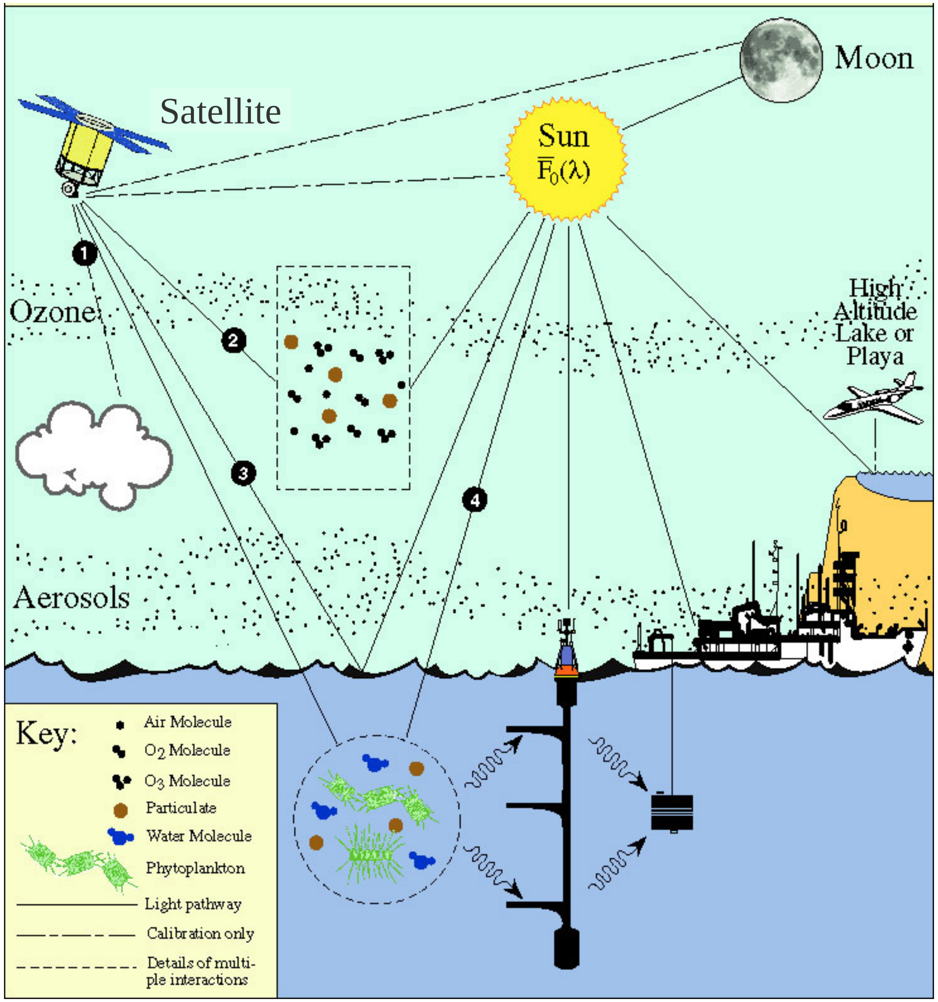
*** SNR requirements derived from MODIS and VIIR requirements*



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



$$L_t(\lambda) = L_r(\lambda) + L_a(\lambda) + L_{ra}(\lambda) + tL_{wc}(\lambda) + TL_g(\lambda) + tL_W(\lambda)$$

1 On Orbit — 2 Atmospheric — 3 Sea Surface — 4 In Situ

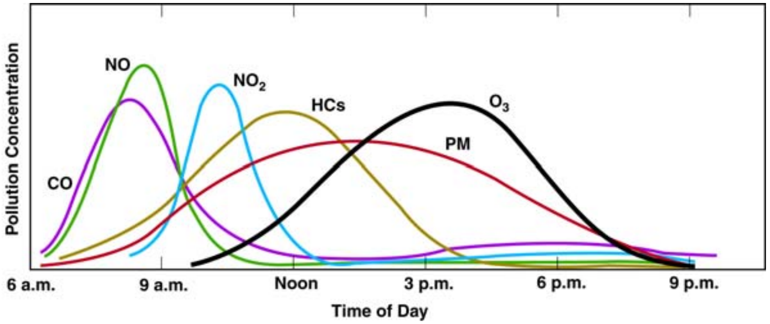
- **Total radiance observed by satellite is composed of 5-10% ocean signal and 90-95% atmosphere signal**
- **Atmospheric and ocean surface scattering effects must be accurately modeled and removed**
- **Atmospheric information derived from air quality measurements can be used to improve ocean water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

Atmospheric correction is critical for ocean color retrievals

GEO-CAPE Measurement Objectives

Atmospheric Science

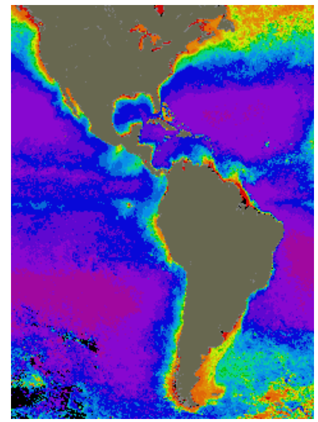
- Measure several species with high temporal and vertical resolution to determine tropospheric chemistry



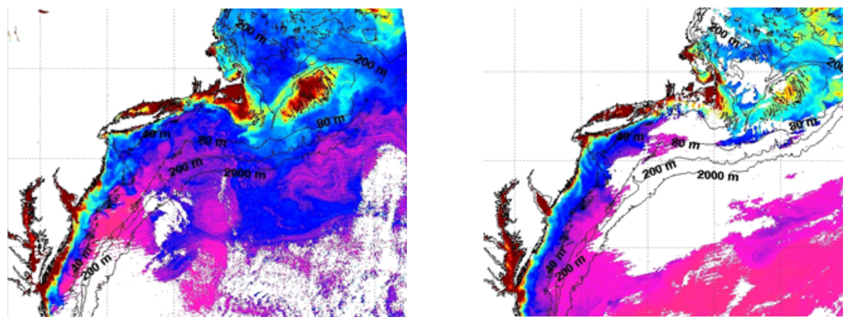
- Measurements for air quality applications are required every 1 to 3 hours over populated regions, with ground sampling distance of 7 km (nadir)
  - Ozone: observe 1-3 hrs, vertically resolved in troposphere (sensitivity to boundary layer needed)
  - NO_2: observe 1-3 hrs, column measurements
  - CO: observe 1-3 hrs, vertically resolved in troposphere
  - NH_3: observe 1-3 hrs, column measurements (precursor for atmospheric aerosol)
  - CO_2 and CH_4 (key green house gasses): observe 1-3 hrs, vertical profiles in lower troposphere
  - HCHO and CH_3OH (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)



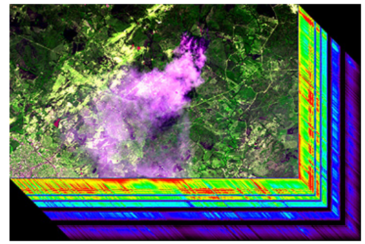
Sept. 2, 2007 12:00:00 *Sept. 4, 2007 12:00:00*

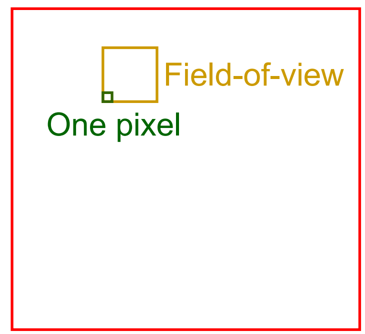
Current imagery like MODIS-AQUA are days apart

Observing Scenario Flexibility

- 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

hyperspectral data cube



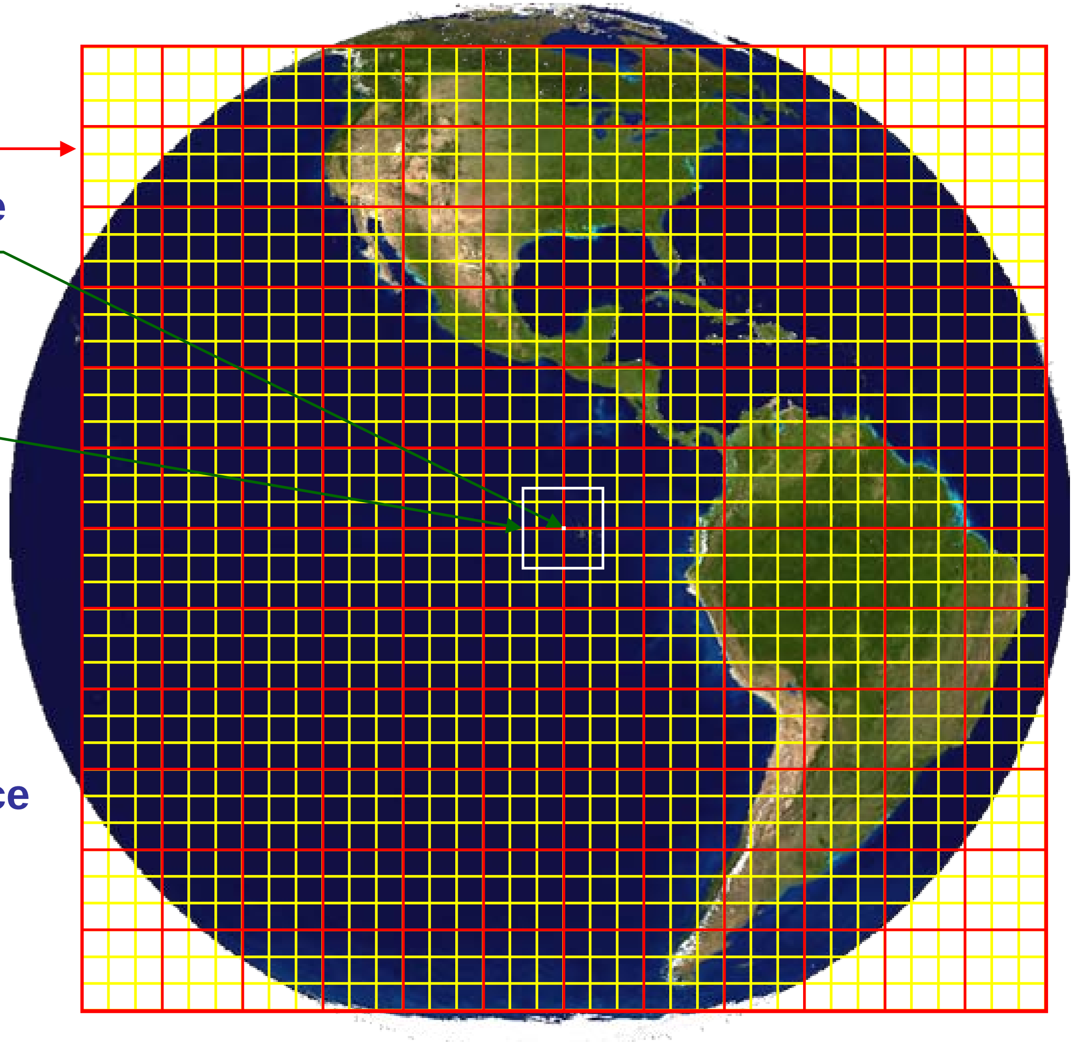


Field-of-regard

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

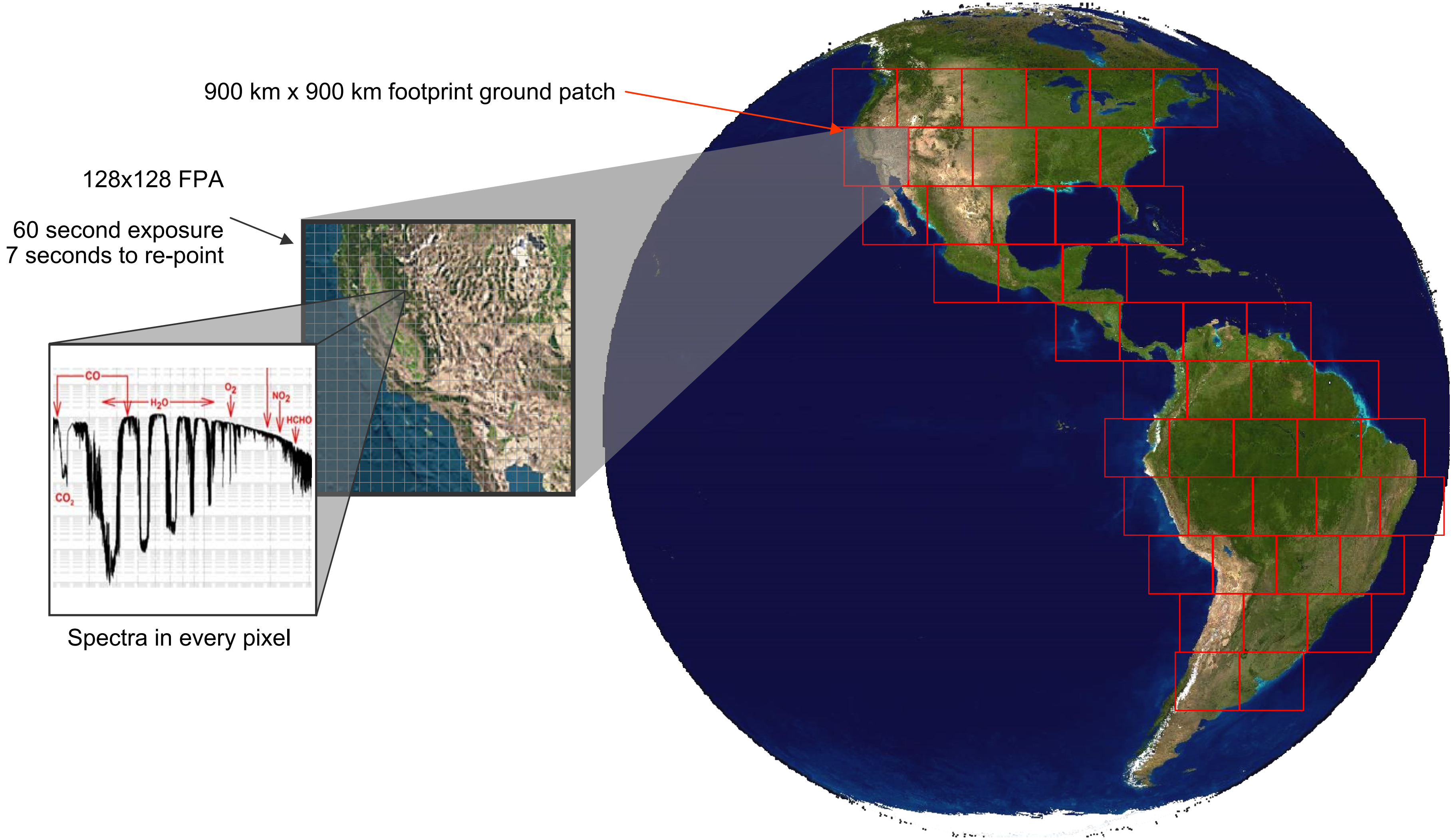
- ~11,000 km x 11,000 km field-of-regard
- 250 m ground sampling distance at nadir
- A 1200 x 1200 pixel array images a ~ 300 km x 300 km field-of-view at nadir
- 36 x 36 grid covers the entire field-of-regard

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

Day and Night Observing

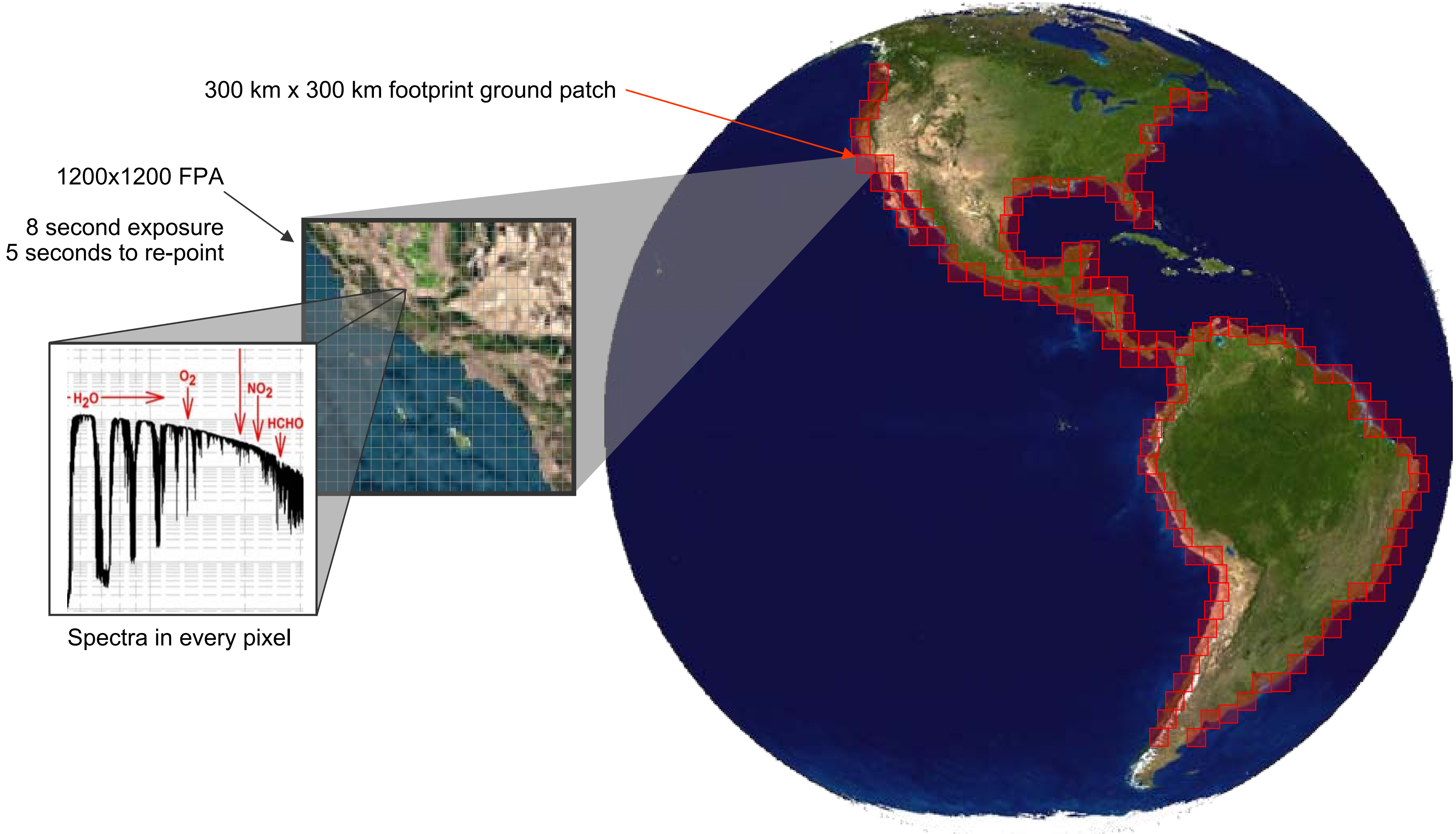
The observing scenario can be tailored to optimize day and night measurements

Wide-Field Observations Example



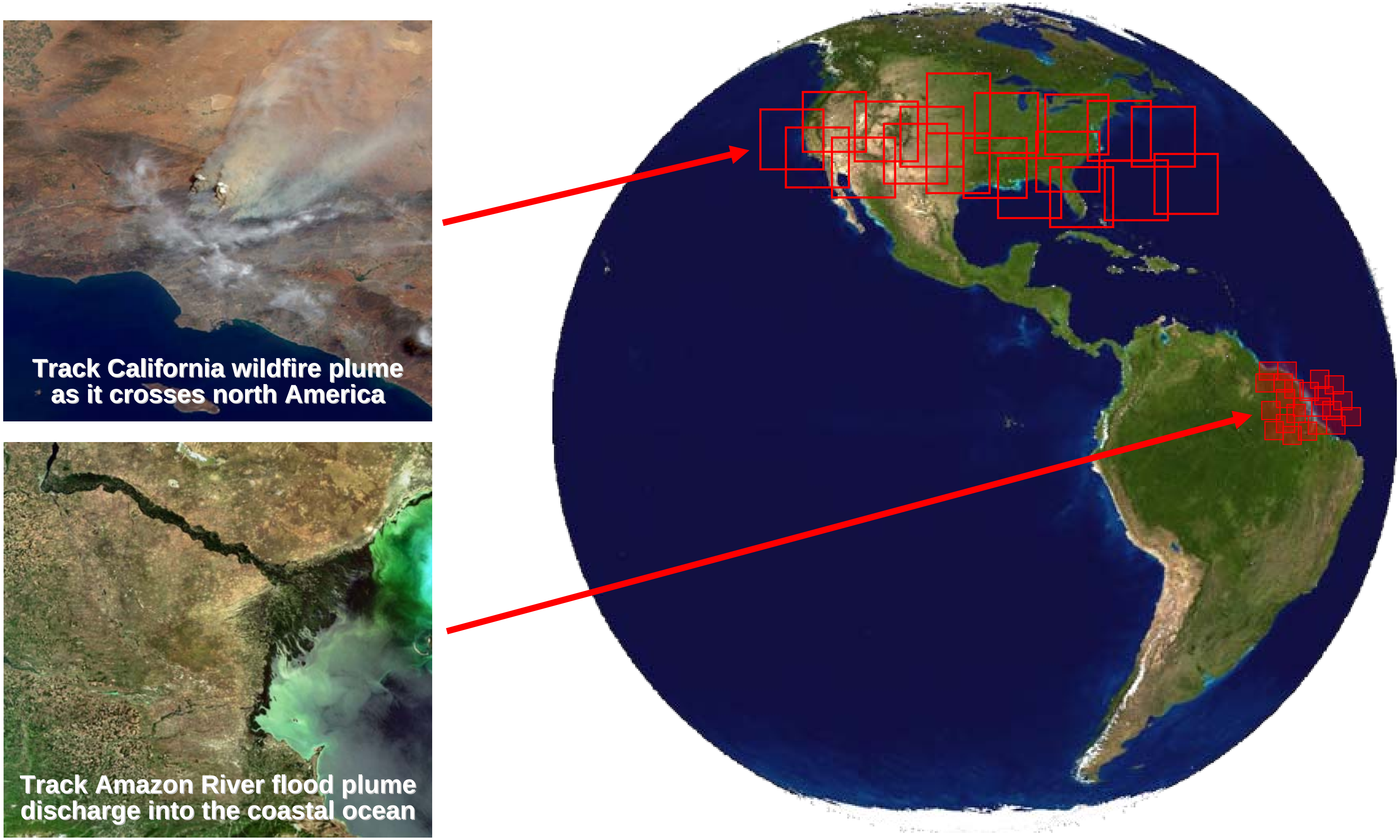
From geostationary orbit, PanFTS wide-field observations can sample ~50 patches per hour with a 900 x 900 km instantaneous field-of-view using a 128 x 128 pixel array which provides a ground footprint with 7 km ground sampling distance per pixel at nadir

Narrow-Field Observations Example



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

Pollution Event Observations Example



PanFTS has tremendous observing scenario flexibility because wide-field and narrow-field observations can be independent allowing simultaneous sampling of any pattern of patches

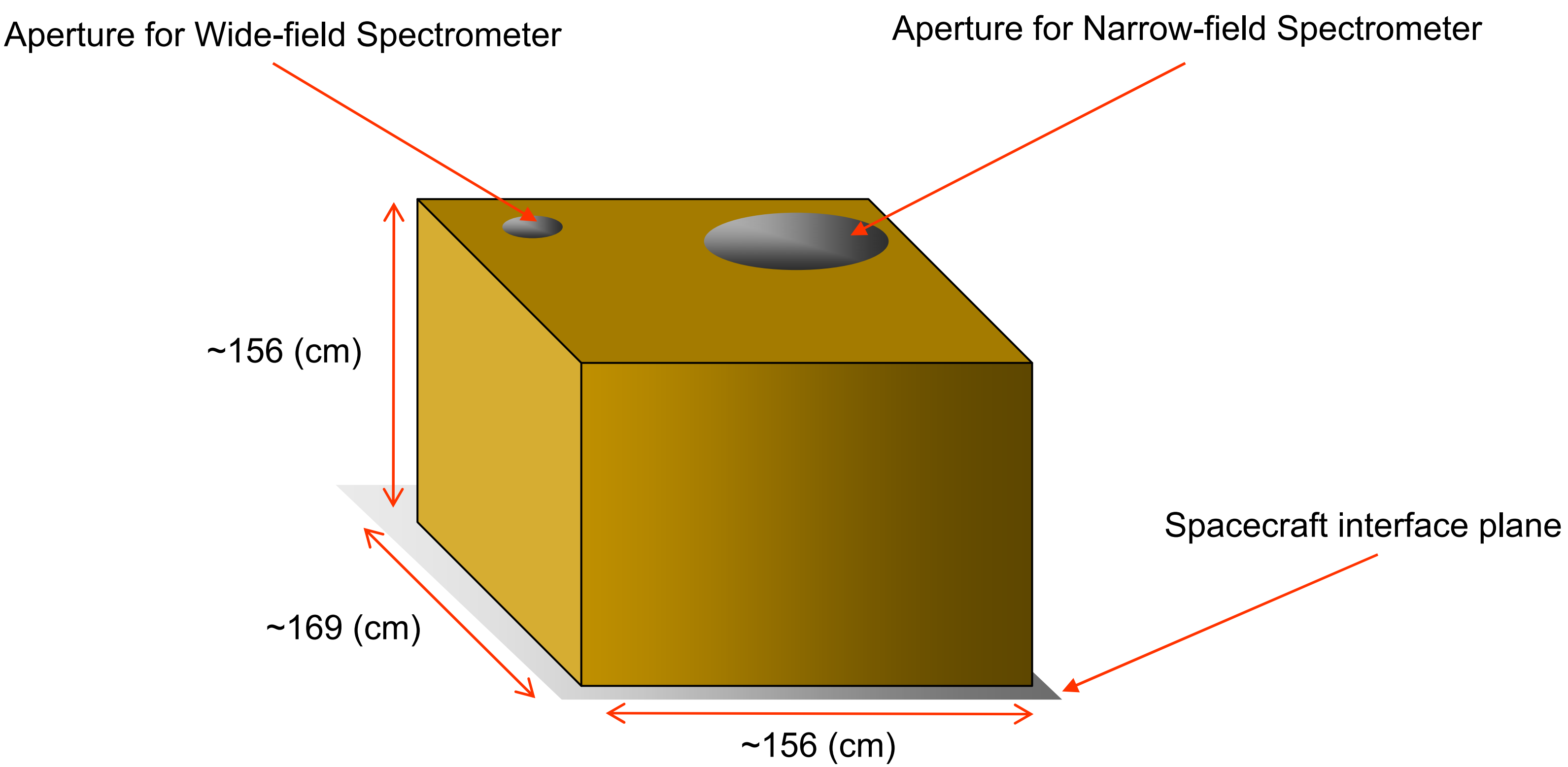
GEO-CAPE Instrument Design Drivers

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

Mission & Payload Summary

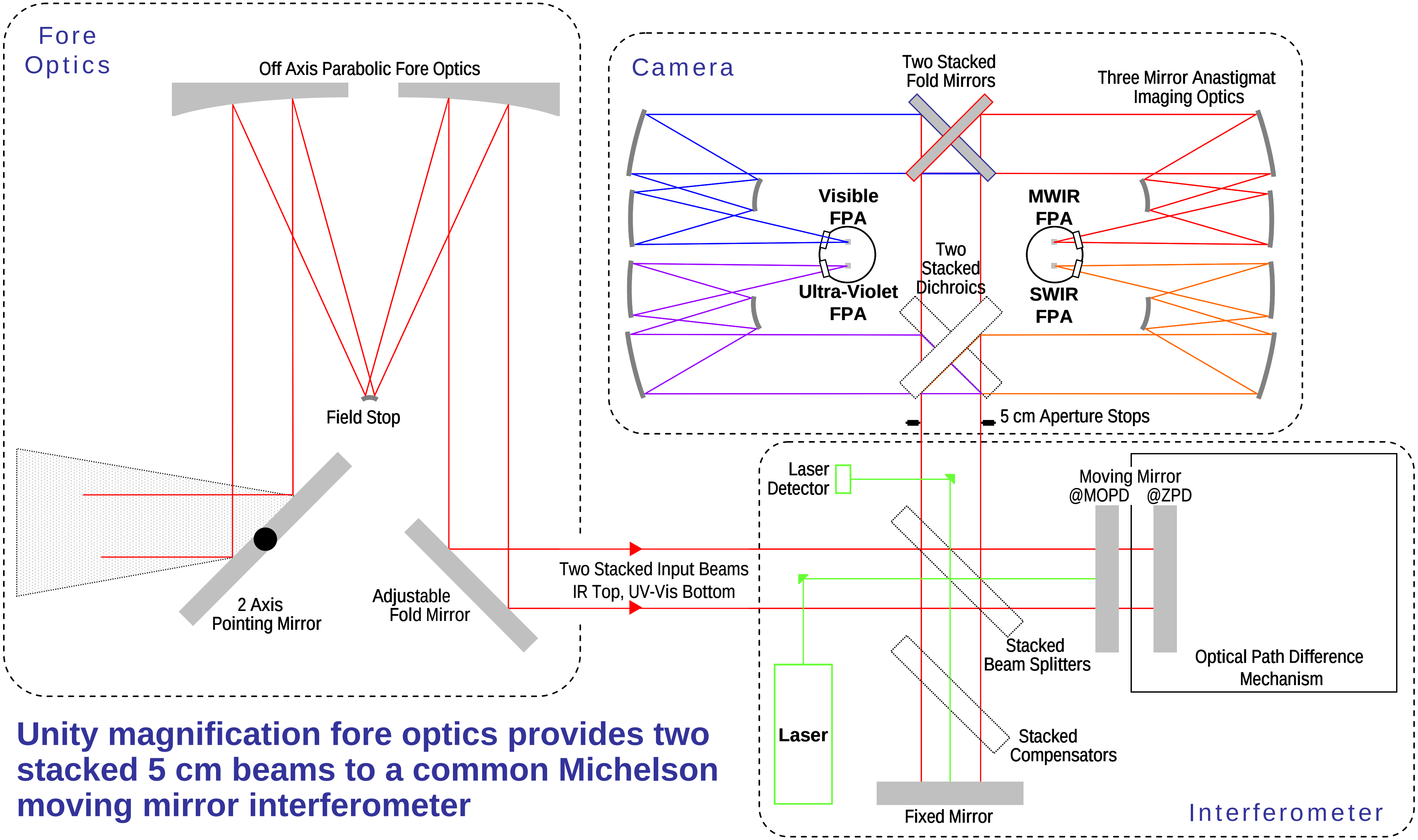
- **Science**
  - Satisfy GEO-CAPE science objectives for both coastal ocean biogeochemistry and atmospheric composition
- **Mission duration**
  - 2 years lifetime design (single string with selective redundancy)
  - 5 year lifetime goal and consumables
- **Geostationary orbit near 95 degrees west longitude**
  - 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**

PanFTS Flight Configuration



The PanFTS flight instrument architecture integrates wide-field and narrow field spectrometers

Flight PanFTS Wide-Field Architecture

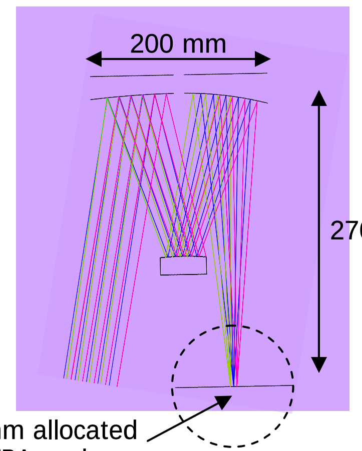


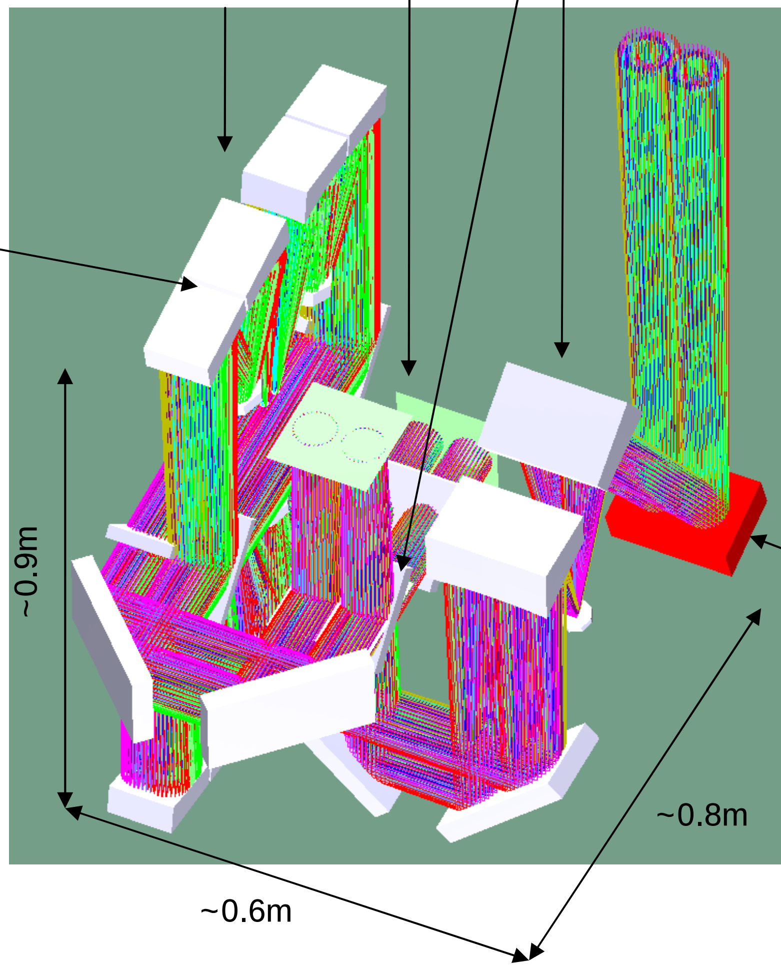
- **Unity magnification fore optics provides two stacked 5 cm beams to a common Michelson moving mirror interferometer**

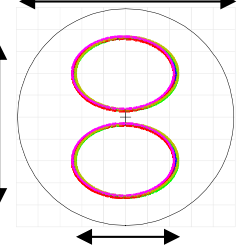
The PanFTS flight instrument design leverages successful experience with past instruments such as TES on AURA and FTUVS at the TMF

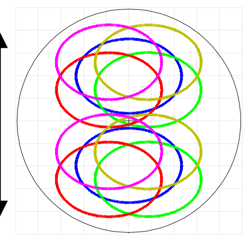
Flight PanFTS Wide-Field Spectrometer

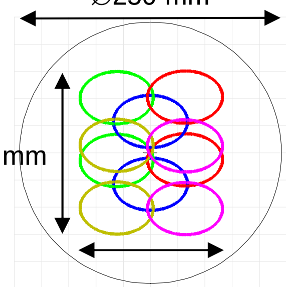
- For flight packaging, add 30% margin on optical layout to accommodate remaining instrument items such as structure, electronics, etc.
  - Height: 90 x 1.3 ~ 117 cm
  - Length: 80 x 1.3 = 104 cm
  - Width: 60 x 1.3 = 78 cm



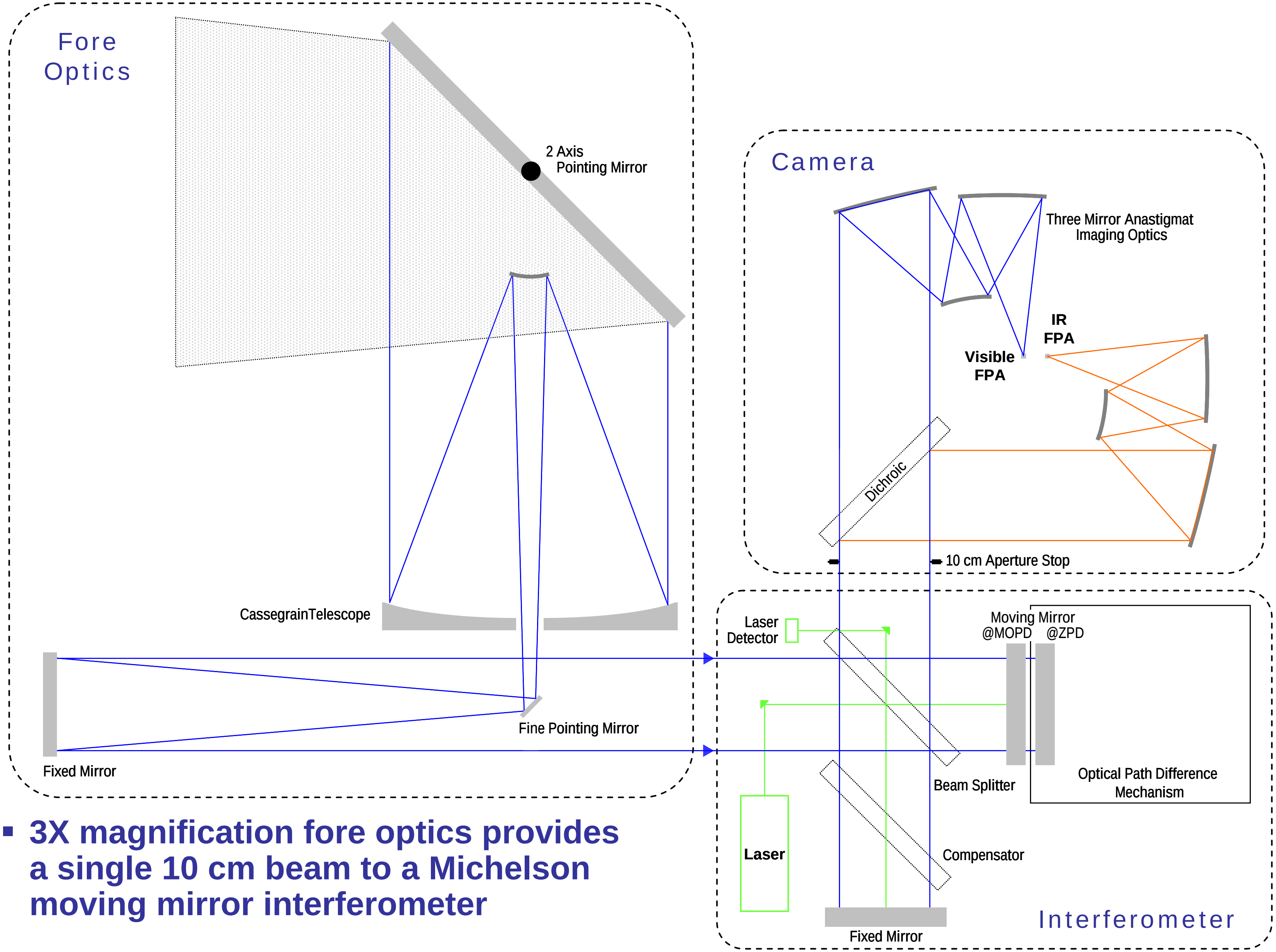








Flight PanFTS Narrow-Field Architecture



- **3X magnification fore optics provides a single 10 cm beam to a Michelson moving mirror interferometer**

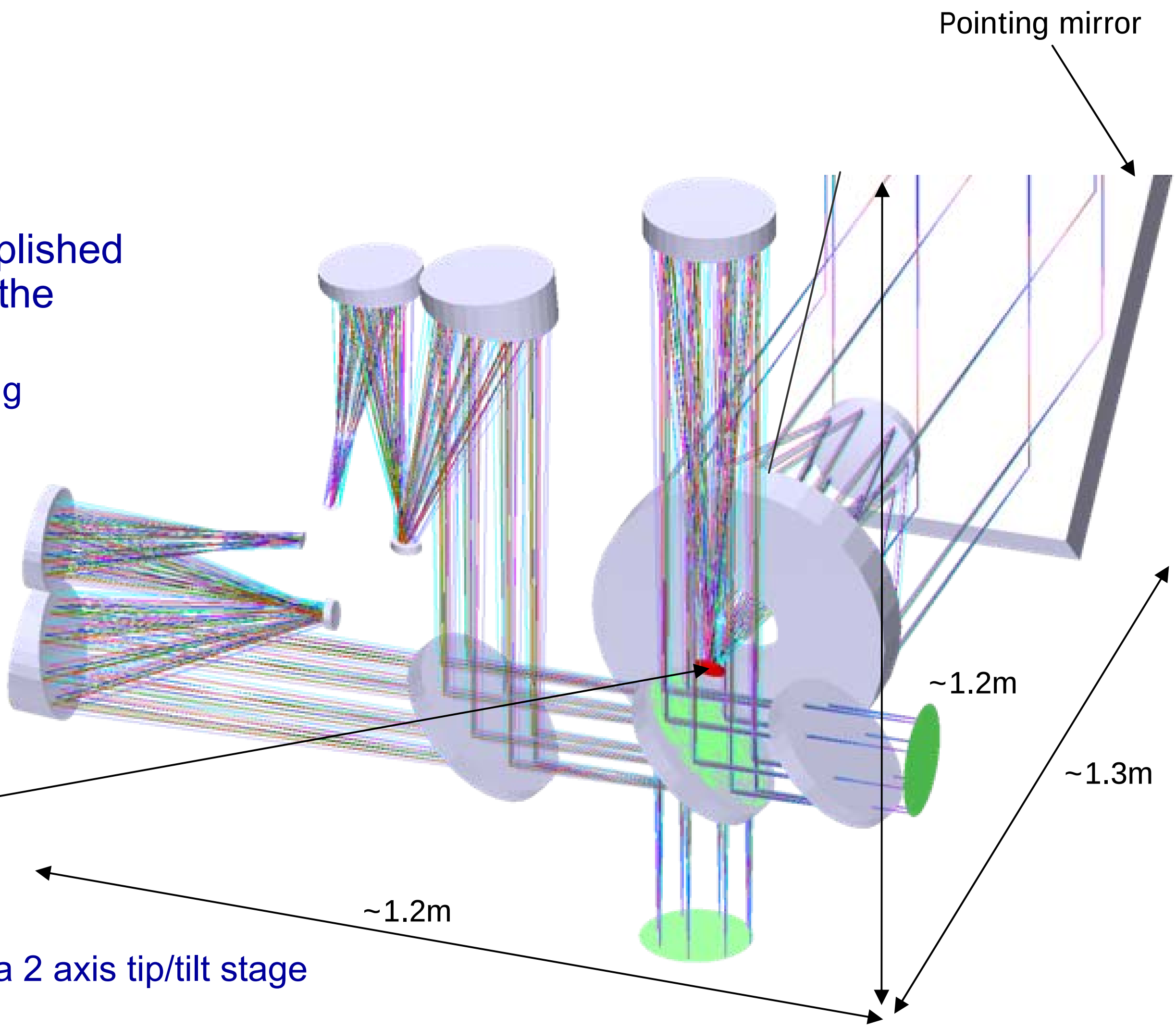
JF. Blavier
7/8/09

Flight PanFTS Narrow-Field Spectrometer

- 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

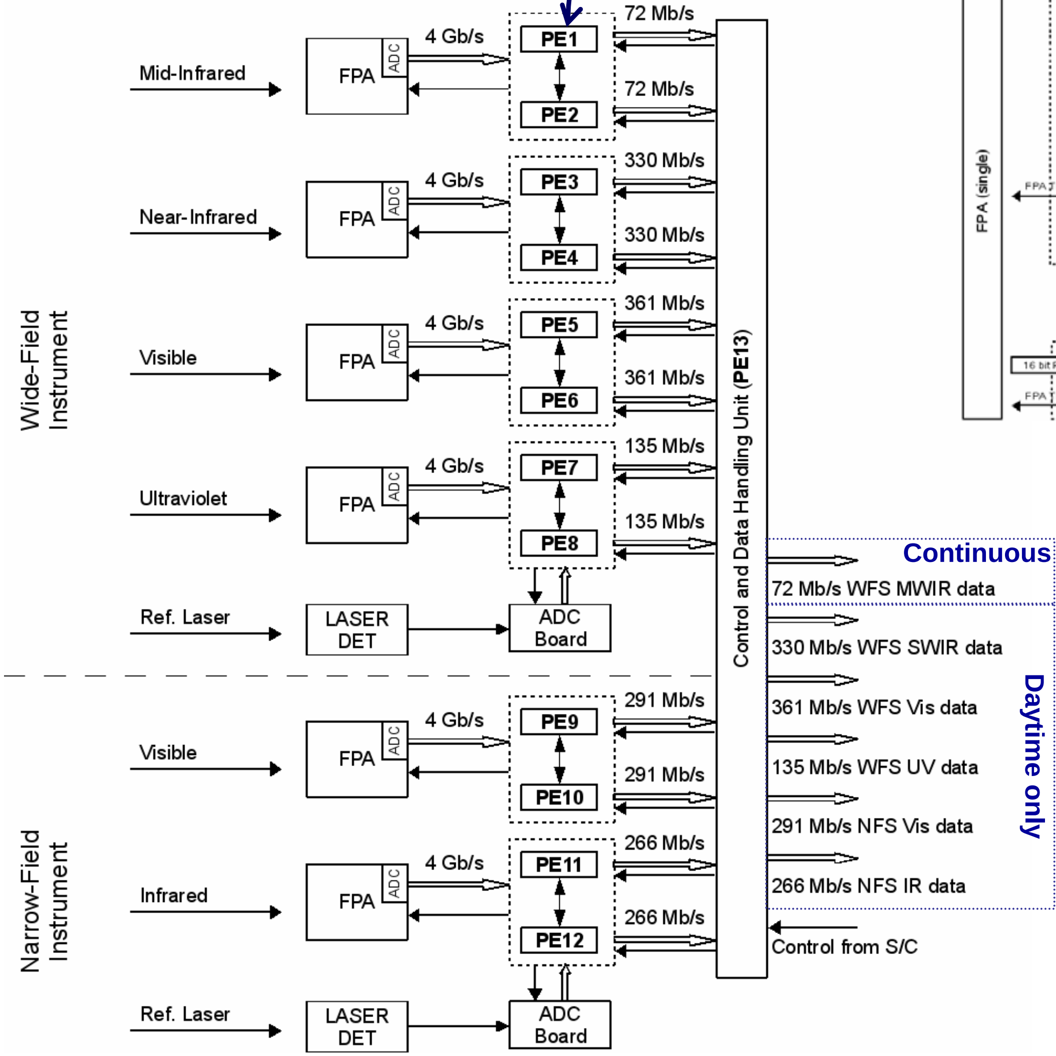
PI M-824 Compact 6-Axis-Positioning System

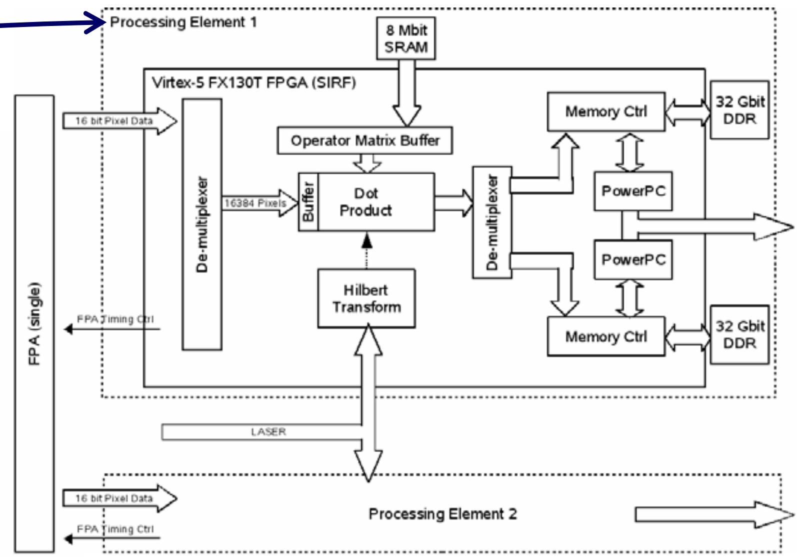
PI S-330 Piezo Tip/Tilt-Platform



- Fine pointing is accomplished with a 2 axis tip/tilt stage for the small fold mirror M3

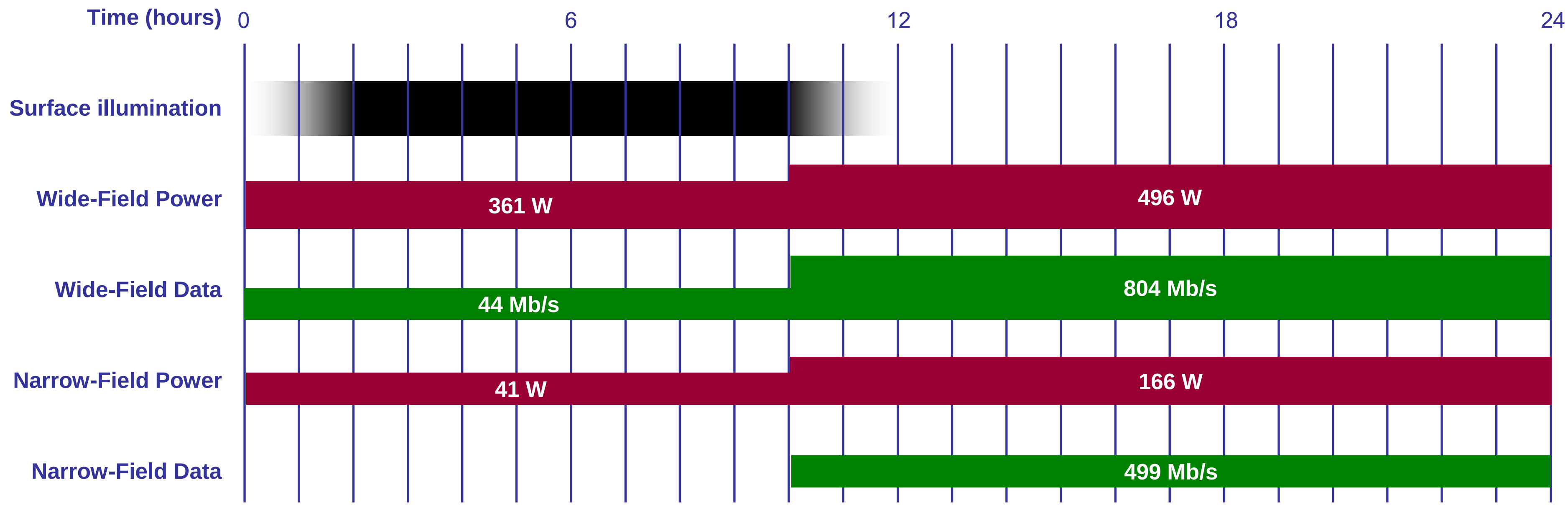
Flight PanFTS C&DH Architecture





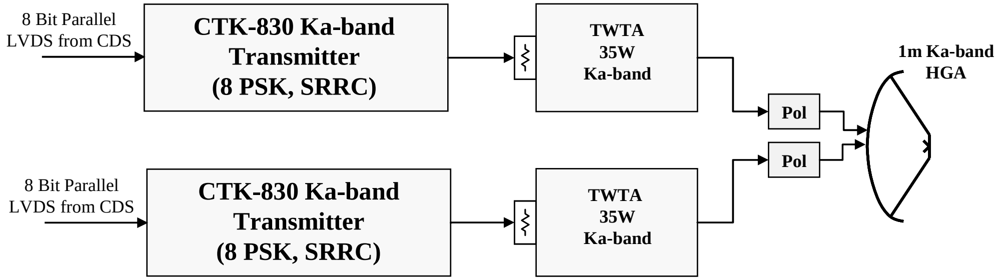
- **Processing Element Hardware**
  - **13 identical Virtex-5 SIRF 6U format boards**
  - **Radiation hardened > 300 krad total ionizing dose**
  - **Each board has 64 Gbit of DRAM to hold two successive scans**
  - **Error correcting code protects DRAM contents**
- **FPA Data Handling**
  - **FPA data 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 W
  - Daytime average (all systems collecting / transmitting data) is: 496+166 = 662 W
- Data comes from instrument continuously but at different rates during day and night
  - Nighttime average (no reflected solar radiation detectable) = 44 Mb/s (only MWIR data)
  - Daytime average (reflected solar radiation in the field of view) = 804+499 = 1,303 Mb/s

Telecommunications Architecture



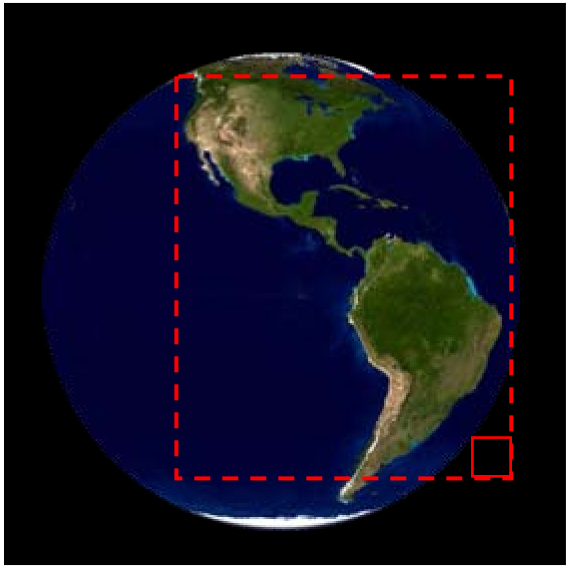
- The HGA is body fixed in an orientation that points it to the dedicated ground station while the S/C maintains its nominal nadir-pointed orientation
- The S/C will be able to keep the HGA pointed within 0.2 degrees of the ground station while taking science data
- 500 MHz of spectrum in the near-Earth 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/implementation losses
- Dedicated ground antenna assumptions:
  - 6 m dish with 62 dBic 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

D. Morabito
7/30/09

Calibration Architecture

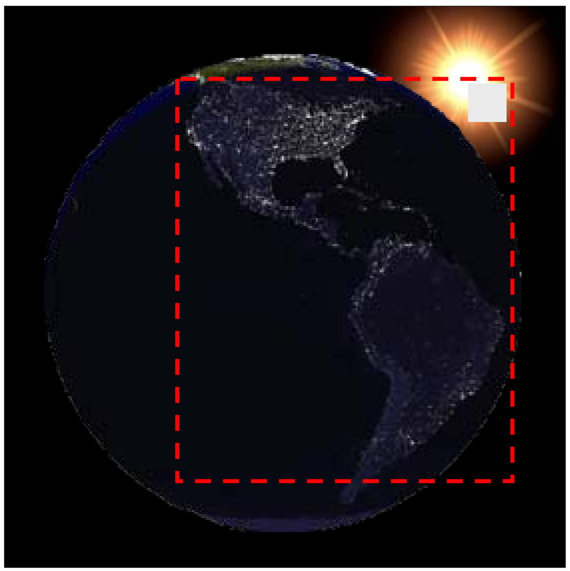
Periodic calibration views

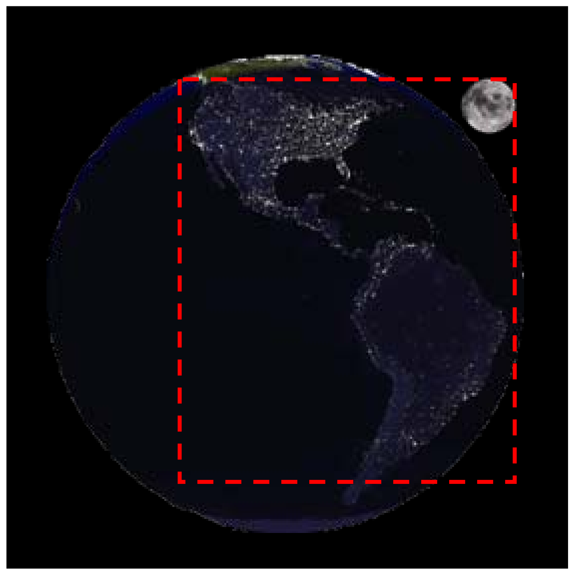
Cold / dark space hourly



Internal black body hourly

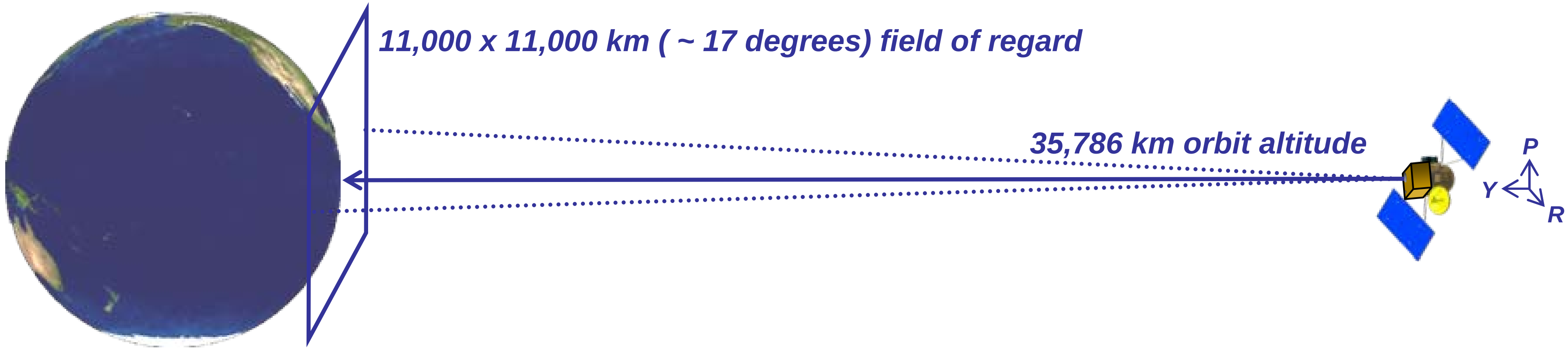
Solar via diffuser plate once a day





Direct lunar once a month

Pointing Architecture

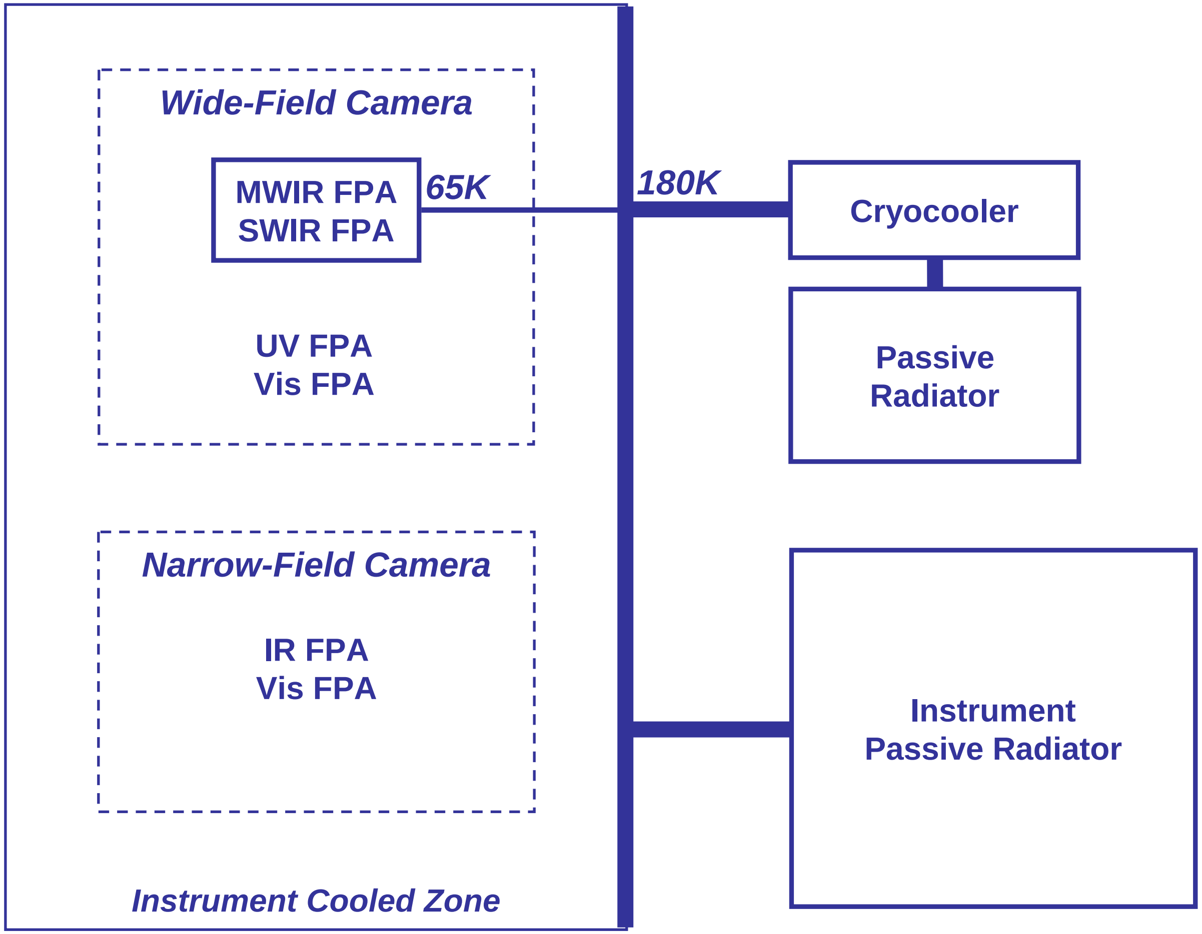


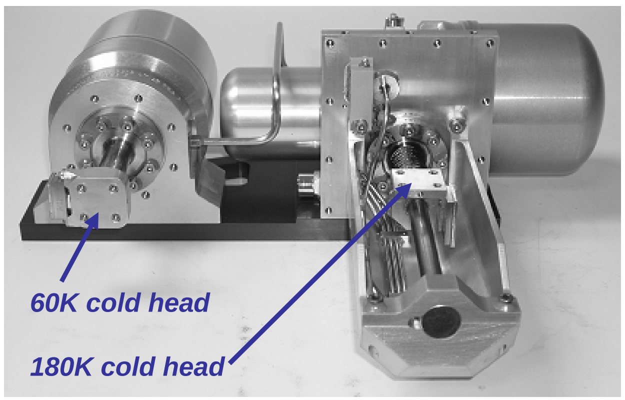
- Spacecraft always remains nadir pointed; wide and narrow-field systems have separate and independent line-of-sight pointing mirrors that use pointing knowledge provided by the spacecraft
  - Wide-field pointing needed for 60 second observation
    - Control: ±258 arcsec 3σ per axis R/P (0.072º, one-twentieth of 1.43º FOV)
    - Knowledge: ±206 arcsec 3σ per axis R/P (0.057º, which is 1 mrad)
    - Stability: ±4 arcsec over 60 sec 3σ per axis R/P (stay within one-tenth pixel)
  - Narrow-field pointing needed for 8 second observation
    - Control: ±172 arcsec 3σ per axis R/P (0.048º, one-tenth of 0.48º FOV)
    - Knowledge: ±120 arcsec 3σ per axis R/P (0.033º, which is 0.58 mrad)
    - Stability: ±0.14 arcsec over 8 sec 3σ 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 = 17.2º slew
      - Slew and settle in < 1 min, with no change to spacecraft orientation
    - Slew and settle during step/stare scan:
      - 1.43º in < 7 seconds for wide-field; 0.48º in < 5 seconds for narrow-field.
- Point the boresight of a 1-meter fixed Ka-band high gain antenna to within 0.2º (720 arcsec) 3σ
  - 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

R. Kinsey
7/30/09

Thermal Control Architecture

- 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





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.

Spacecraft Bus Options

Heritage Commercial Bus with Modifications

Boeing 601

GD SA-200HP

OSC STAR Bus

Recent missions
- GOES N-O-P

Recent missions
- GLAST
- Coriolis
- Swift

Recent missions
- MEASAT-3a
- AMC-21
- THOR 5

A spacecraft used for this study is for illustration purposes only, there are several buses that could satisfy the GEO-CAPE mission

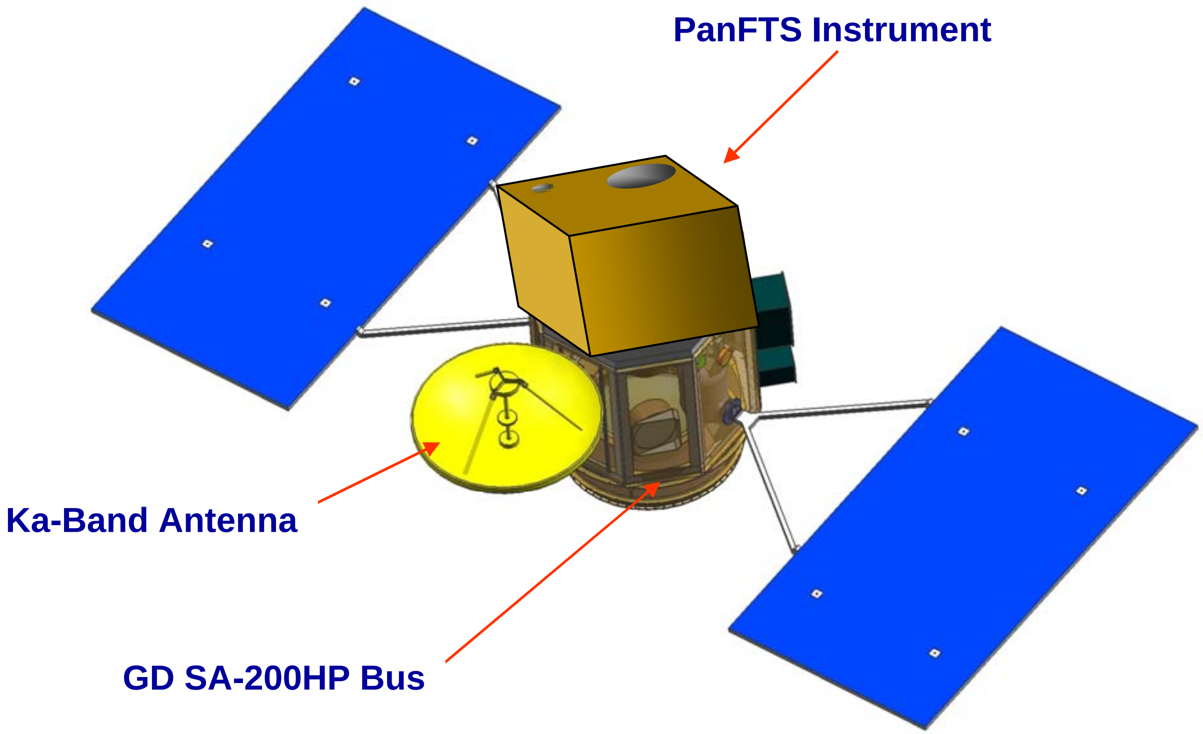
SA-200HP Spacecraft Bus Capabilities

SA-200 Series Standard Modular Spacecraft

Specifications/Performance Standards*

	SA-200B	SA-200S	SA-200HP
Bus Dry Mass: Std Config	90 kg	128 kg	354 kg
Payload Mass: Std Config	100 kg	50 kg	666 kg
Max Accommodated to Date	127 kg	59 kg	2888 kg
Redundancy	Single string with selected/functional redundancy		Partial to full redundancy
Design Lifetime	1 - 3 years		3 - 10 years
Solar Array Power @EOL: Std	330 W	280 W	2000 W
Max to Date	505 W	503 W	3852 W
Attitude Control to Date:	Spin or 3-axis stabilized w/wheels, RCS backup	3-axis stabilized w/wheels	3-axis stabilized w/wheels, RCS backup
Knowledge, Max 3σ Error	as low as144 arcsec	as low as 11.1 arcsec	as low as 0.14 arcsec
Control, Max 3σ Error	as low as 504 arcsec	as low as 200 arcsec	as low as 0.21 arcsec
Jitter, Max 3σ	as low as 15.7 arcsec/sec	as low as 6.2 arcsec	as low as 0.255 arcsec/sec (≥ 0.021, 50μs, 25-2000Hz)
Pointing Modes	Inertial, solar, nadir, offset, point tracking, maneuvering		
Onboard Propellant to Date	*none*	to 112.7 kg	to 358.5 kg
Structural Configuration	Six and eight-sided structures with honeycomb panels and aluminum frames		
Payload Interfaces	Externally accessible, bolt-on mounting; open architecture electrical interfaces		
PL Data Storage & DL to Date	≤ 1096 Gbits storage; ≤ 740 Mbps DL rate		
Launch Vehicles Used to Date	Pegasus XL, Minotaur	Pegasus, Scout, Minotaur	Delta II, Titan II, Minotaur
Missions Used On	MightySat II.1, RHESSI, C/NOFS	MSTI-1, MSTI-2, MSTI-3, NFIRE	DS1, Coriolis, Swift, Streak, GLAST, GeoEye-1, STSS
Procuring & Using Agencies	AFRL, SMC/SD (Det12), NASA/UCB	SMC, NASA/JPL, MDA	NASA/JPL, SMC/SD (Det12), NRL, NASA/GSFC, PSU, DARPA, GeoEye
Bus Delivery Times	25 to 42 months		

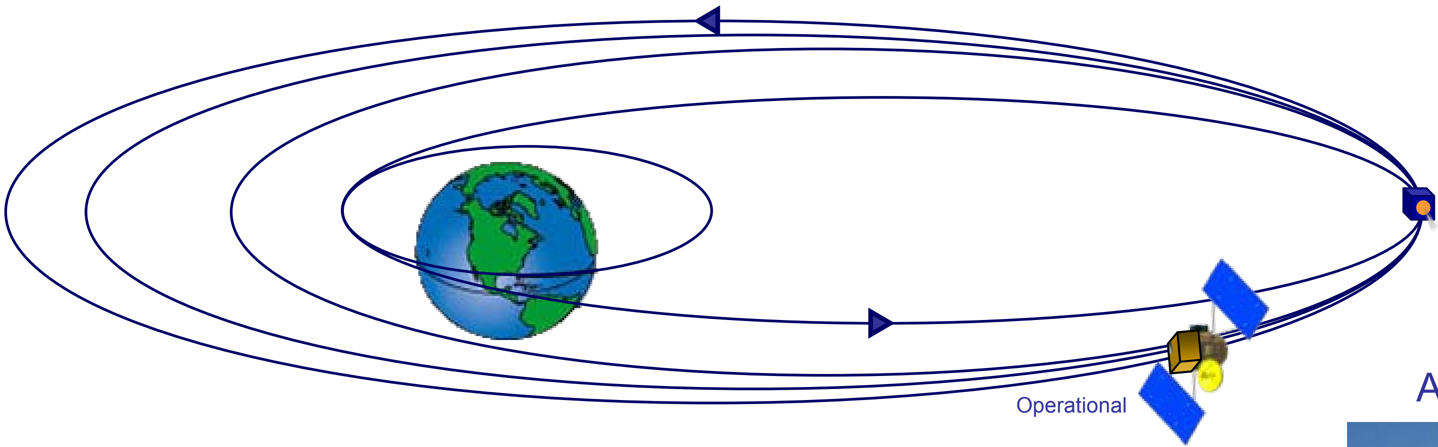
Spacecraft System Architecture



- 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

The science payload is one fixed instrument hard mounted to the spacecraft bus

Launch Concept



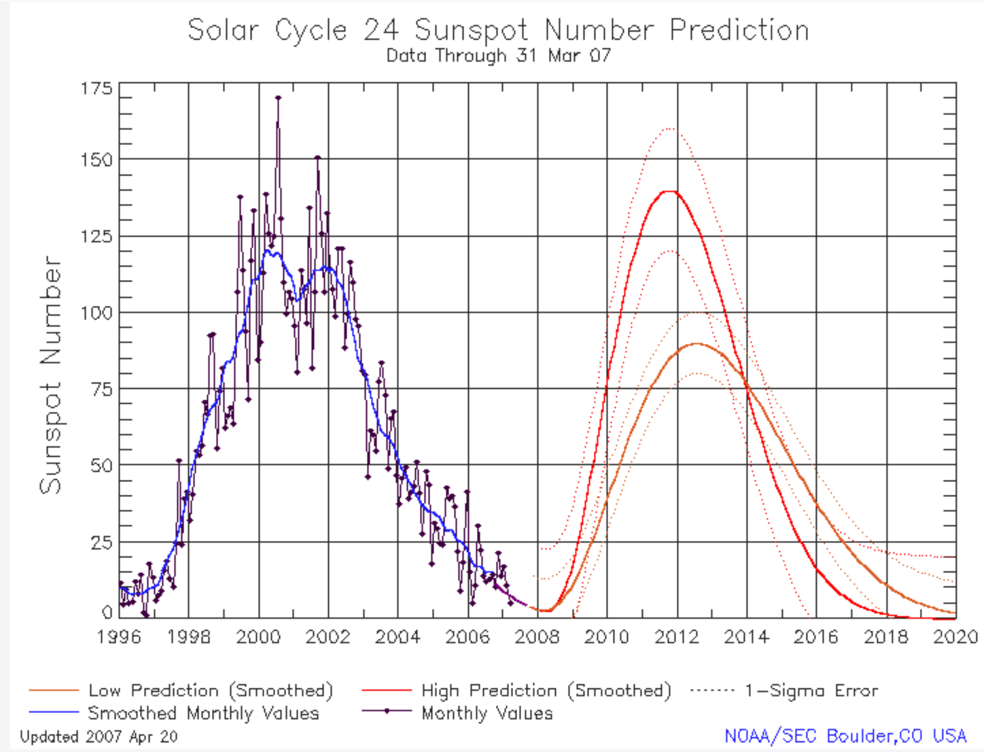
Atlas V (401)

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

LV Capability (kg)	Propellant mass (kg)	S/C dry mass CBE (kg)	S/C dry mass allocation (kg)	S/C dry mass margin (kg)	Margin (%)	LV Margin (kg)	LV Margin (%)
1513	358.5	776.7	1156	445	38%	239.4	16%

- GOES-like Super-Synchronous Transfer Orbit to geostationary orbit, 95º 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



Target Body: Earth		
Cruise Duration:		years
Cruise Radiation per year:		krad/year
Cruise Radiation Total:	0	krad
Orbiting Duration:	2	years
Orbiting Radiation per year:	19	krad/year
Orbiting Radiation Total:	38	krad
Surface Duration:		years
Surface Radiation per year:		krad/year
Surface Radiation Total:	0	krad
Total Radiation Dose:	38	krad
Radiation Dose Margin:	2	
Total Radiation Design Dose:	**76**	**krad**

- 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-m^2/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

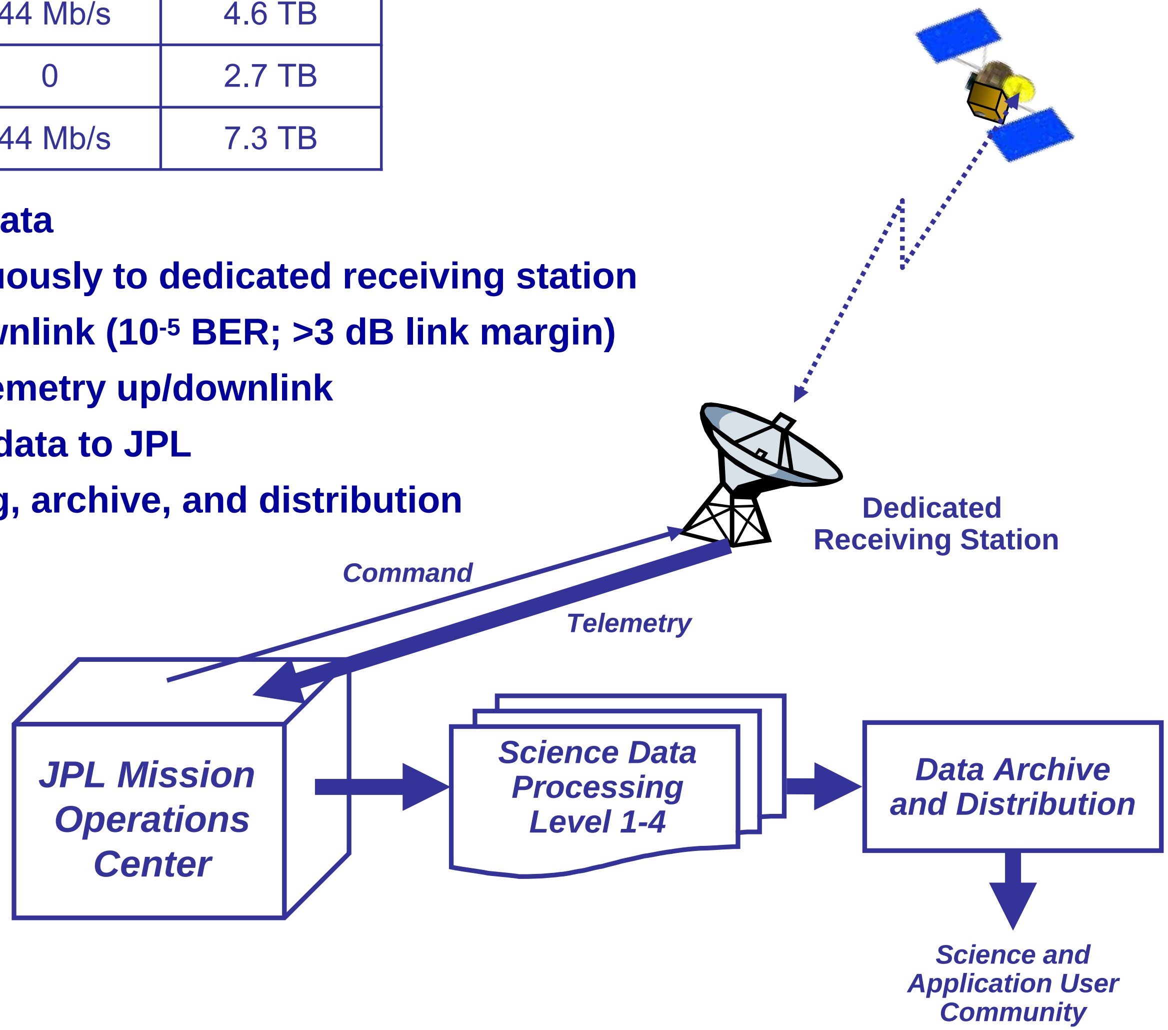
The geo radiation environment is well known and shielding methods are proven

Ground System Architecture

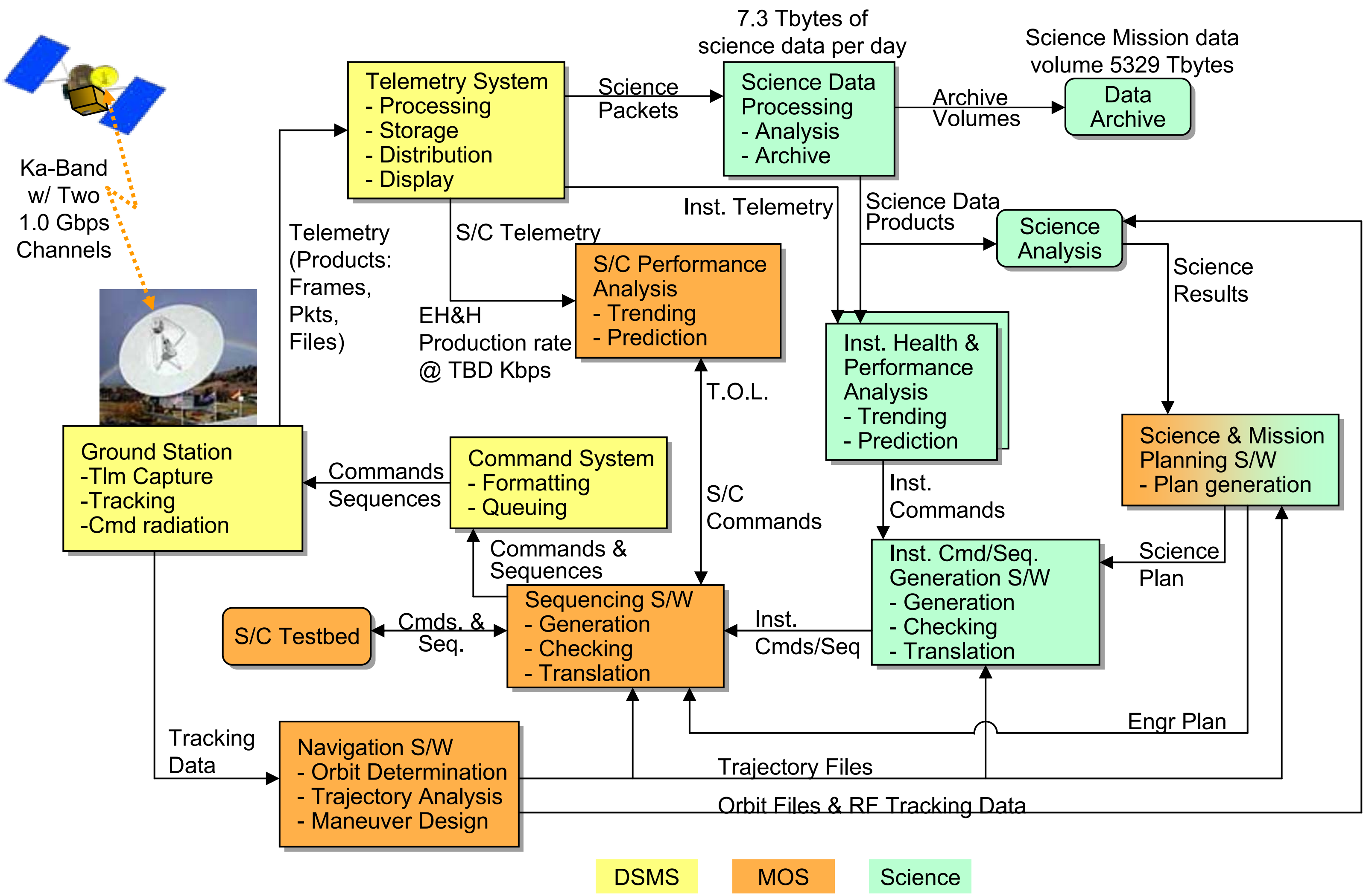
- **Instrument is always taking data and delivering it to the spacecraft telecom system**

System	Daytime	Nighttime	Daily Total
Wide-Field	804 Mb/s	44 Mb/s	4.6 TB
Narrow-Field	499 Mb/s	0	2.7 TB
Total	1303 Mb/s	44 Mb/s	7.3 TB

- **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



Science Data Products

Atmospheric Science Data Products

Level 1B

- Calibrated, geolocated radiances for each scene

Level 2

- Tropospheric columns of NO_2, HCHO, NH_3, CH_3OH, CH_4 hourly over North America and South America
- Tropospheric profiles of O_3 and CO over same region
- Total column SO_2 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 CO_2 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

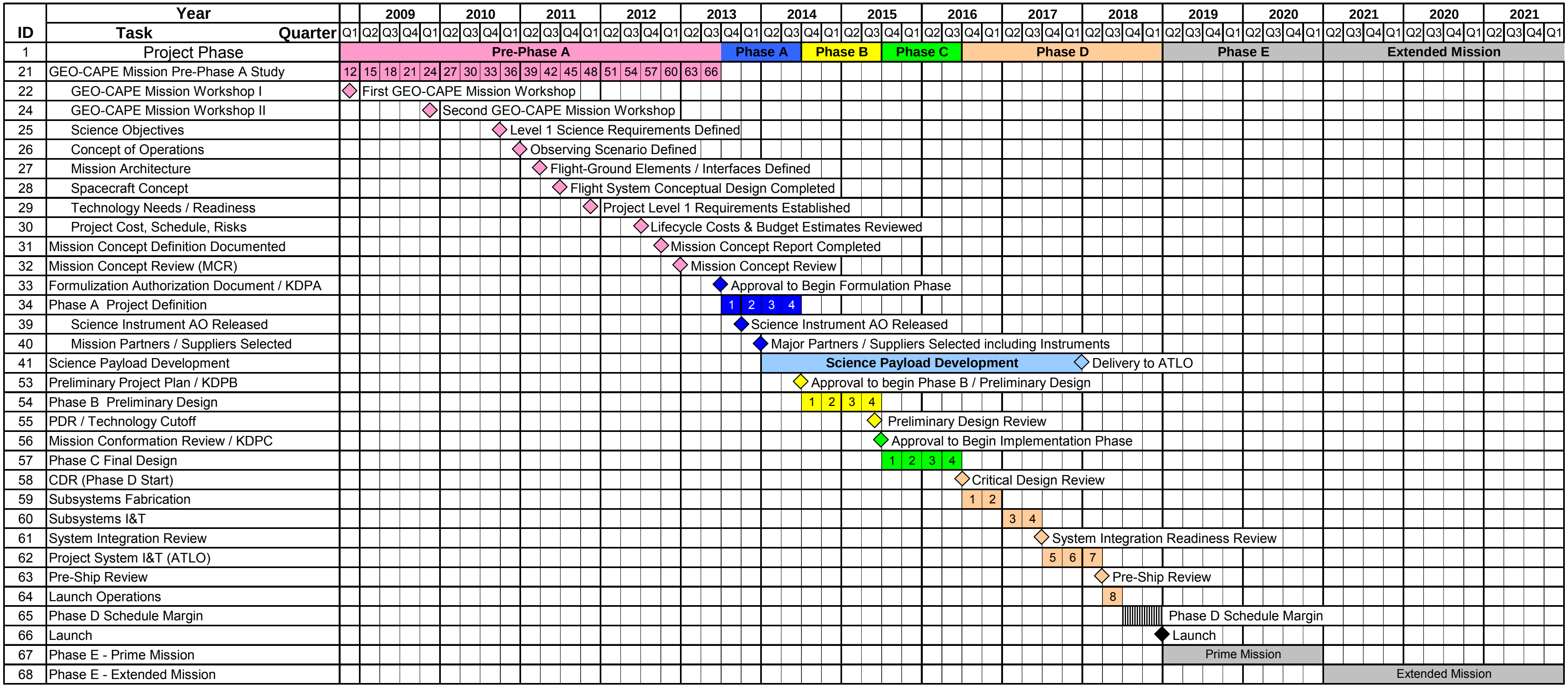
Costing Methods and Assumptions

- **Costing Methodology**
  - Project schedule (phase A-D) based on data from similar missions

Mission	Duration (months)					
	Pre-Phase A	Phase A	Phase B	Phase C	Phase D	A-D
GRACE	54	12	15	18	15	60
CloudSat	78	18	9	33	24	84
OSTM	71	21	27	15	18	81
OCO	26	15	30	21	24	90
Aquarius	59	15	33	36	21	105
SMAP	117 (54)	12	12	15	21	60

  - 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)

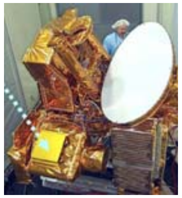
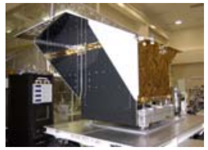
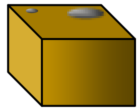
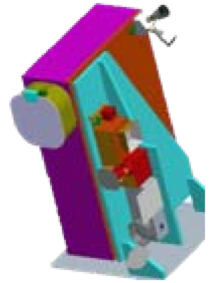
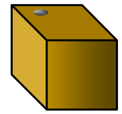
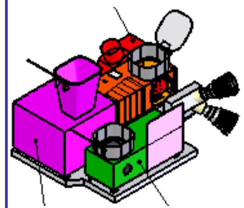
Notional GEO-CAPE Schedule



Project Phase	Pre A	A	B	C	D	A-D	E
Duration (mo)	66	12	12	12	24	60	24

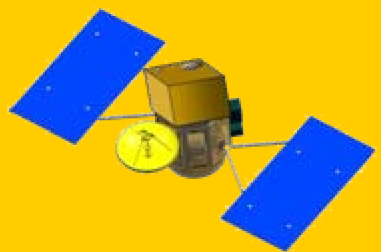
MCR gate products are defined in the SMD Management Handbook and NASA NPR 7120.5D (Program and Project Management) which invokes NASA NPR 7123 (Systems Engineering)

Instrument Characteristics Assessment

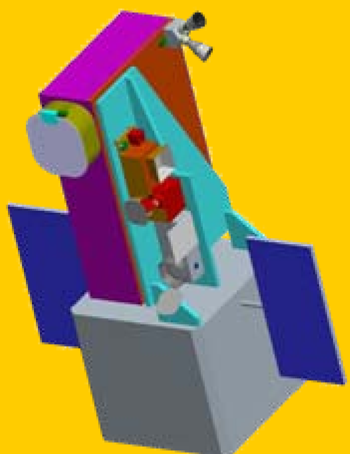
Instrument	 MISR	 MLS	 TES	 PanFTS (WF+NF)	 GMO	 PanFTS (WF)	 GeoMAC
Mass (kg) (actual or CBE+30%)	148	453	385	436 (335+30%)	1286 (989+30%)	245 (188+30%)	456 (351+30%)
Power (W) (actual or CBE+30%)	75	544	334	865	930	645	790
~Size (cm)	90 90 130	150 200 300	100 130 140	156 169 156	450 300 120	117 104 78	294 145 90
Phase A-D Schedule (months)	80	74	54	54		48	42
Cost ($M) (in FY07$)	115 (95x1.208)	152 (136x1.121)	179 (160x1.121)	321 (247+30%)		180 (138+30%)	349 (268+30%)

Mission Architecture Options (FY07 $M)

GEO-CAPE AC+OC

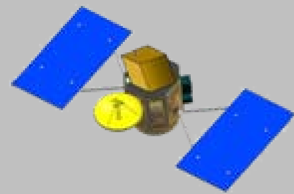


PanFTS (WF+NF)
$866M

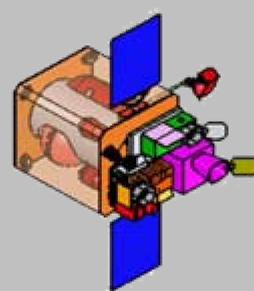


GMO
$1270M

Atmos. Composition Only

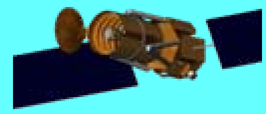


PanFTS (WF)
$629M



GeoMac
$842M

Ocean Color Only



COCOA
$227M

GOES / HES-CW
< $500M

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 indentify 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 green house 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