Jet Propulsion Laboratory
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HORUS – the High Orbit Ultraviolet-Visible Satellite

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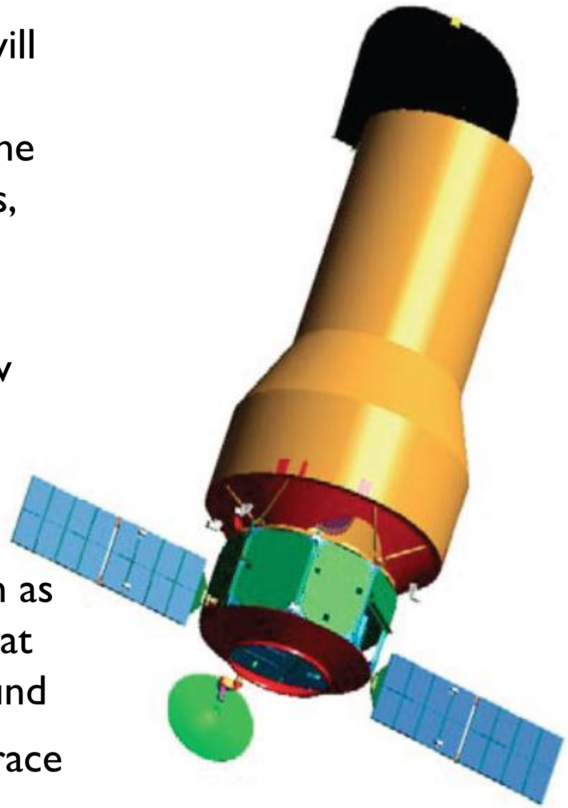
And the HORUS Mission SDT – affiliations at ASU, Planetary Resources, JPL, LMCO, U. Massachusetts, IPAC, U. Colorado, STScI, U. Wisconsin, SSI, Rice U., PSI, Caltech, U. Virginia, U. Michigan, GSFC, SSL, U. Arizona, ITT Exelis

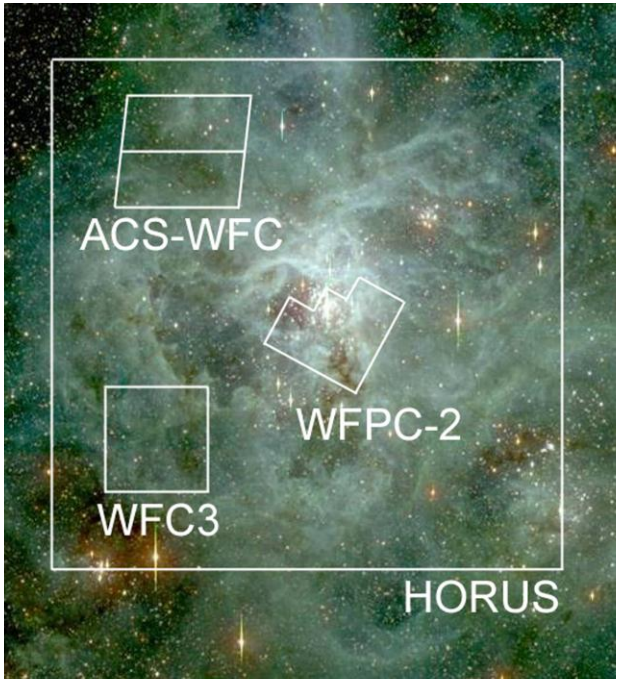
What is HORUS?

- *HORUS* is a 2.4-meter class UVO space telescope that will conduct a comprehensive and systematic study of the astrophysical processes and environments relevant for the births and life cycles of stars and their planetary systems, from our solar system to the farthest corners of the Universe
- The necessary design **combines** a ¼° wide field of view (FOV) **dual-channel imager** with diffraction limited resolution and a broad filter suite with a **FUV spectrograph**
- This will allow both the **discovery** of small objects such as protostellar and protoplanetary disks, or dwarf galaxies at high redshift, but also allow **characterization** once found
- We have an operational baseline optical design and raytrace using the NRO prescription that has **no** show stoppers
- The *HORUS* science goals are rooted in a Cosmic Origins science program that is well aligned with NASA science roadmaps, and has shaped the authoring of a **132-page DRM document**



What is HORUS?

- *HORUS* camera delivers near-ultraviolet (UV) / visible (200-1100nm) wide-field (14' square) **diffraction-limited imaging**
- *HORUS* spectrograph delivers high-sensitivity, high-resolution (R=40,000) **FUV (100-170nm) spectroscopy** (with an option to extend to 320nm)
- *HORUS* baseline is **L2 orbit** to provide a stable environment for thermal and pointing control, and long-duration target visibility
- *HORUS* Optical Telescope Assembly (OTA) makes optimal use of the SALSO capabilities using a **three-mirror anastigmatic** configuration to provide excellent imagery over a large FOV
- UV/optical Imaging Cameras use **two** 21k x 21k Focal Plane Arrays (FPAs) consisting of multiple tiled OTS Si CCD elements
- The FUV spectrometer uses cross strip anode based microchannel plates (MCPs) **improved** from *HST-COS* technology and is placed at the Cassegrain-like focus to minimize the number of reflections
- The FUV design is very challenging because the Cassegrain beam speed is f/8 – a full 3x faster than *HST*, but our holographic grating design maintains the necessary performance



Background

HISTORY

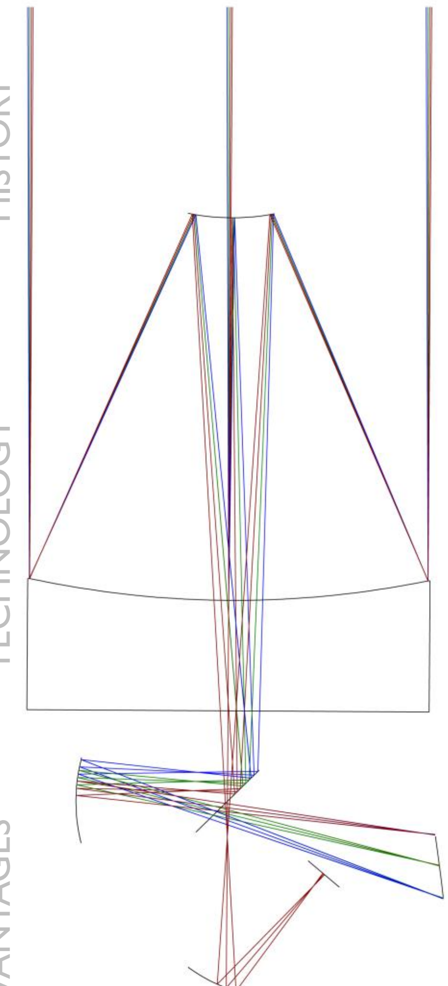
- *HORUS* was originally conceived as a NASA Origins Probe mission in 2004
- *HORUS* went through two JPL Team-X studies, and **independently costed** both times
- OTA is designed to use NRO-type optics with the **same properties** to deliver TMA-quality imaging and high-throughput FUV
- Mission re-costed, with technology updates and redesign, at the request of the Decadal Survey on Astronomy and Astrophysics, in 2009

TECHNOLOGY

- Takes advantage of new CCD **doping technology** and mass production
- Uses next generation **holographic gratings** and **cross-strip MCP** FUV technology
- *HORUS* baselines the use of **high-heritage Al / MgF_2** overcoats, but has an option to take advantage of new ALD coating technology to deliver higher throughput in the FUV (shortward of 115nm)
- *HORUS* requires the optics to be recoated for the UV, and optimized to drive the diffraction limit to shorter wavelengths. Ideally repolishing would be done, but a slightly reduced science set is possible

ADVANTAGES

- *HORUS* delivers **100x greater imaging efficiency** than *HST* with the combined **resolution** of *STIS* and the **throughput** of *COS*
- Provides general capabilities to the community to **enable more than 65% of UVO science** envisioned for the next decade
- Provides essential **complementarity** with *JWST* and *WFIRST* if launched by 2020



Enabling General Science

HORUS

- COPAG recently conducted an RFI call to determine the range of **next generation UVO science**: while not complete, the response was taken to be representative
- Results were tabulated into a matrix of science programs versus requirements – then inverted to give a matrix of **capability versus science** programs enabled
- *HORUS* capabilities were found to **enable more than 65%** of the next generation UVO science proposals envisioned by the community over the next 10 years

Imaging Science Programs:

Parameter	Enabled	Not Enabled
Waveband:		
≥ 92nm	18	0
≥ 115nm	11	5
≥ 250nm	4	13
Resolution:		
≥ 1 mas	13	3
≥ 10 mas	12	4
≥ 50 mas	8	8
Aperture:		
1-2m	7	10
2.4m	11	6
4m	12	5
8m+	16	1
FoV:		
1 arcmin	5	12
10 arcmin	11	6
30 arcmin	15	2

Spectroscopy Science Programs:

Parameter	Enabled	Not Enabled
Waveband:		
≥ 92nm	22	2
≥ 115nm	13	11
≥ 250nm	2	22
Spectral Resolution:		
R=1000	9	15
R=10,000	16	8
R=40,000	18	6
Aperture:		
1-2m	6	18
2.4m	12	12
4m	16	8
8m+	20	4
MOS:	8	N/A

Science Summary

- The **core *HORUS* science program** employs a step-wise approach in which **both** imaging and spectroscopy contribute essential information to our investigation of star and planet formation across cosmic time.
  - **Step 1** — Conduct a broad- and narrow-band imaging census of all high-mass star formation sites within 2.5 kpc of the Sun to determine how frequently solar systems form and survive, and develop observational criteria connecting properties of the ionized gas to the underlying stellar population and distribution and properties of protoplanetary disks.
  - **Step 2** — Survey all major star forming regions in the Magellanic Clouds, to resolve relevant physical scales and structures, access starburst analogs, and sample star formation in an initial regime of low metallicity applicable to galaxies at high redshift.
  - **Step 3** — Extend the star formation survey to galaxies in the nearby universe to increase the range of galaxy interaction and metallicity environments probed. *HORUS* will observe entire galaxies surveyed by *GALEX* and *Spitzer* with more than 100 times better spatial resolution.
  - **Step 4** — Measure star formation and metal production rates in the distant universe to determine how galaxies assemble and how the elements critical to life such as C and O are generated and distributed through cosmic time.
- A **General Observer program** is included in the mission lifetime.

Science Mission Flowdown

Science Investigations

Study the Formation of Planetary Systems, Stars, and Galaxies

Imaging Survey of Star and Planet Formation in the Milky Way; FUV Spectroscopy of YSOs, Protoplanetary Disks, and Extrasolar Giant Planets

Magellanic Clouds Imaging and Spectroscopic Survey: A Bridge to Nearby Galaxies

Hundred Nearby Galaxy Imaging and Spectroscopic Survey Program

Medium and Deep Imaging Survey of Cosmic Dawn, Galaxy Assembly and the Growth of AGN; Spectroscopic Study of the Origins of Modern Galaxies and the IGM/Galaxy Connection

Measurement Capabilities

Primary Mirror – 2.4 m

Wide-Field UV/Optical Imaging (200-1075 nm)

- **Angular Resolution**
  0.04" per pixel
- **Field of View**
  14' x14' square – blue and red channels using dichroic
- **Narrowband Diagnostics**
  Mg II, [O II], He II, Hβ, [O III], [O I], Hα, [N II], [S II], [S III]
- **Broadband Filters**
  F218M, F250W, F336W, F438W, F550M, F625W, F775W, F850W, F098M, F105M

High Throughput FUV Spectroscopy (100-170 nm)

Total Effective Area
1100 cm² @ 100 nm
2750 cm² @ 130 nm
2000 cm² @ 170 nm

Spectral Resolving Power
R = 40,000 mode

Gratings
G110H, G131H, G156H

Engineering Implications

Optics

- 2.4 m aperture
- Diffraction limited at 500nm
- Low UV scatter optics
- High throughput imager and spectrograph
- Dichroic beam splitter

Detectors

- Large format, high QE UV photon counters
- Large format, high QE arrays for NUV-Vis & Vis-NIR
- Radiation tolerant detectors

Miscellaneous

- Fine pointing/correction (~10 mas 3σ)
- Large data volumes and telemetry

Key Technology Developments

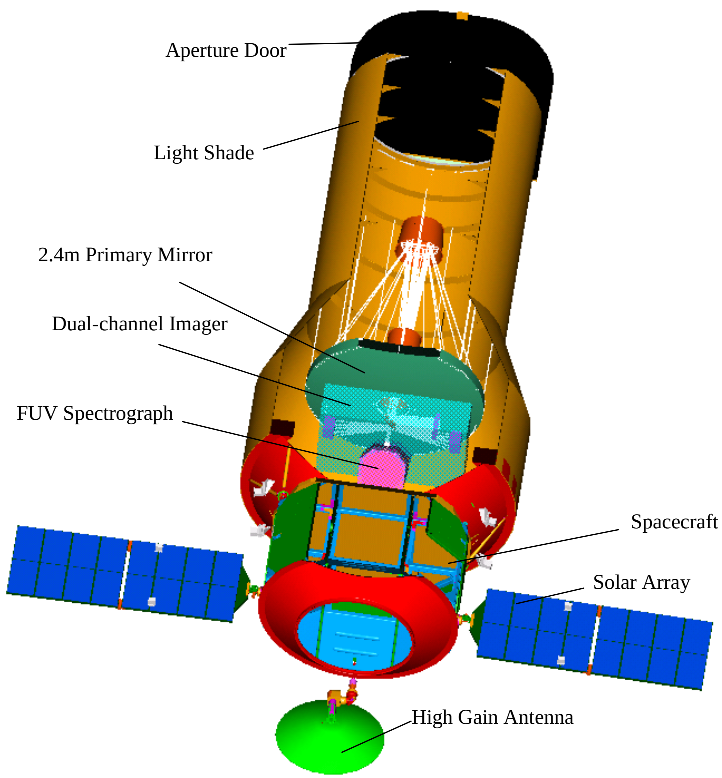
Optics

- Robust coating for 100 nm FUV performance
- Coating techniques for large optics
- Optimized dichroic and filters (λ range, out-of-band rejection)

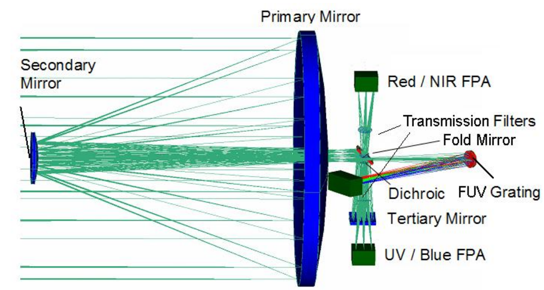
Detectors

- Si CCD devices optimized in response to each of the red and blue bands
- Optimized AR coatings
- High resolution anodes for microchannel plate (MCP) detectors
- ASIC for MCP detectors with large format

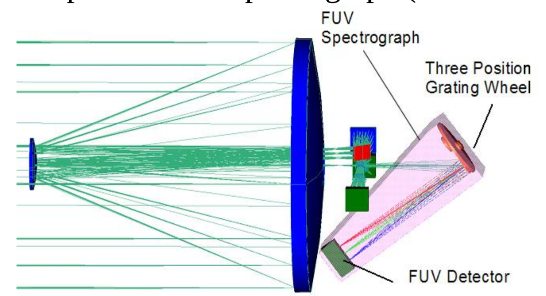
Concept of Operations

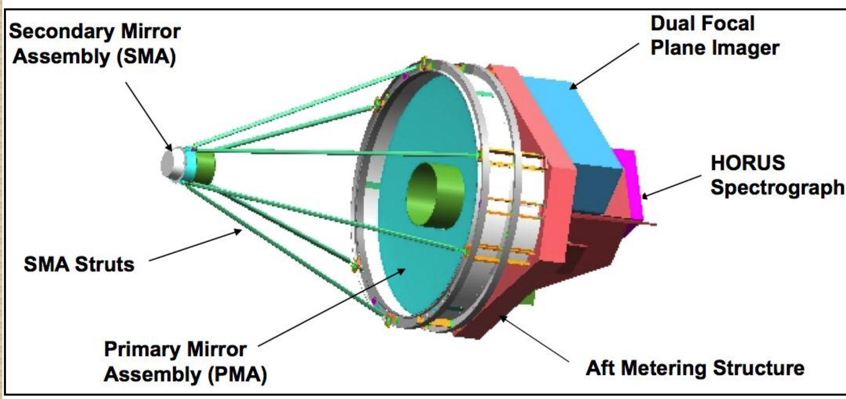


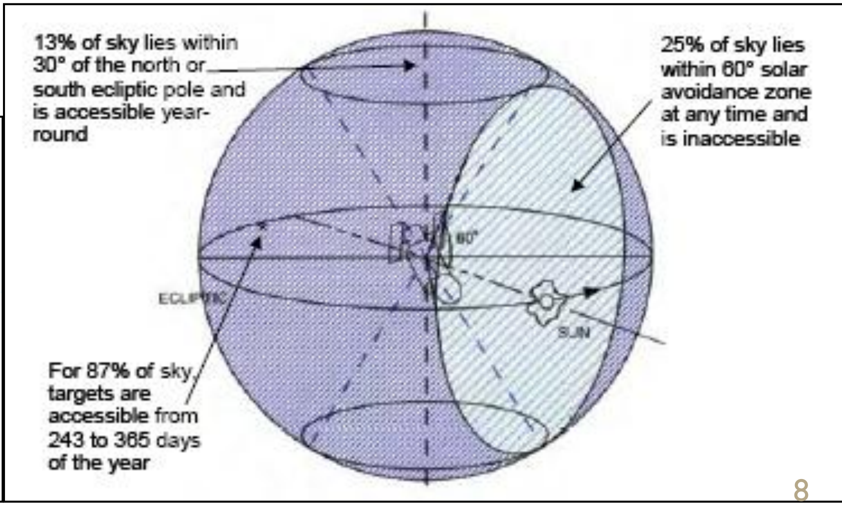
Dual-channel wide-field camera



FUV point source spectrograph (100-170nm)







Mission Requirements

- **Launch date** – Nominally 2020 (w/ monthly launch opportunities)
- **Mission lifetime** – 3 yr Primary mission (w/ onboard resources for significant mission extension), 5-10 yr with GO program
- **Target body** – Local and distant star formation regions (Core); general planetary/outer solar system, astrophysics, & cosmology targets (GO)
- **Trajectory/Orbital details** – Semi stable Sun-Earth L2 halo orbit, but will consider GEO to enable servicing
- **Cost target – $1.14B**
  - Original Decadal Mission was $1.48B ($FY09) – included OTA and LV. This becomes $1.01B ($FY09) without OTA, without LV, and adding $65M (explicit estimate from Exelis) for OTA Updates – all with 30% margin. Allowing for 3% annual cost escalation = $1.14B ($FY13) for *HORUS* payload (OTA + instruments + SC).

NRO-2 Considerations

- Design Possibilities:
  - Use of a 3rd powered mirror to realise the full capability of the TMA – provides a wide, well-corrected FoV
  - Addition of a wide field UVO camera to provide survey capability matched with diffraction limited resolution
  - Addition of a next-generation COS-like FUV spectrograph with 2 bounces to maximize throughput
  - Use of another 3rd mirror to enable the slow beam and prescription necessary for a coronagraph
- FUV Needs:
  - To enable FUV throughput, the mirrors would need to be recoated – they are currently covered in silver
  - To maximize throughput we would need to limit the number of bounces to 2
  - The FUV spectrograph would need to be an axial instrument and mounted with the entrance aperture at the Cass-like focus
  - While the 2.4m primary would need to be MgF2 over aluminum coated, the secondary (53 cm) could be LiF overcoated and kept under purge to preserve the coating and the FUV throughput (FUSE heritage)
  - Detectors could be cross-strip MCPs or new UV capable CCDs

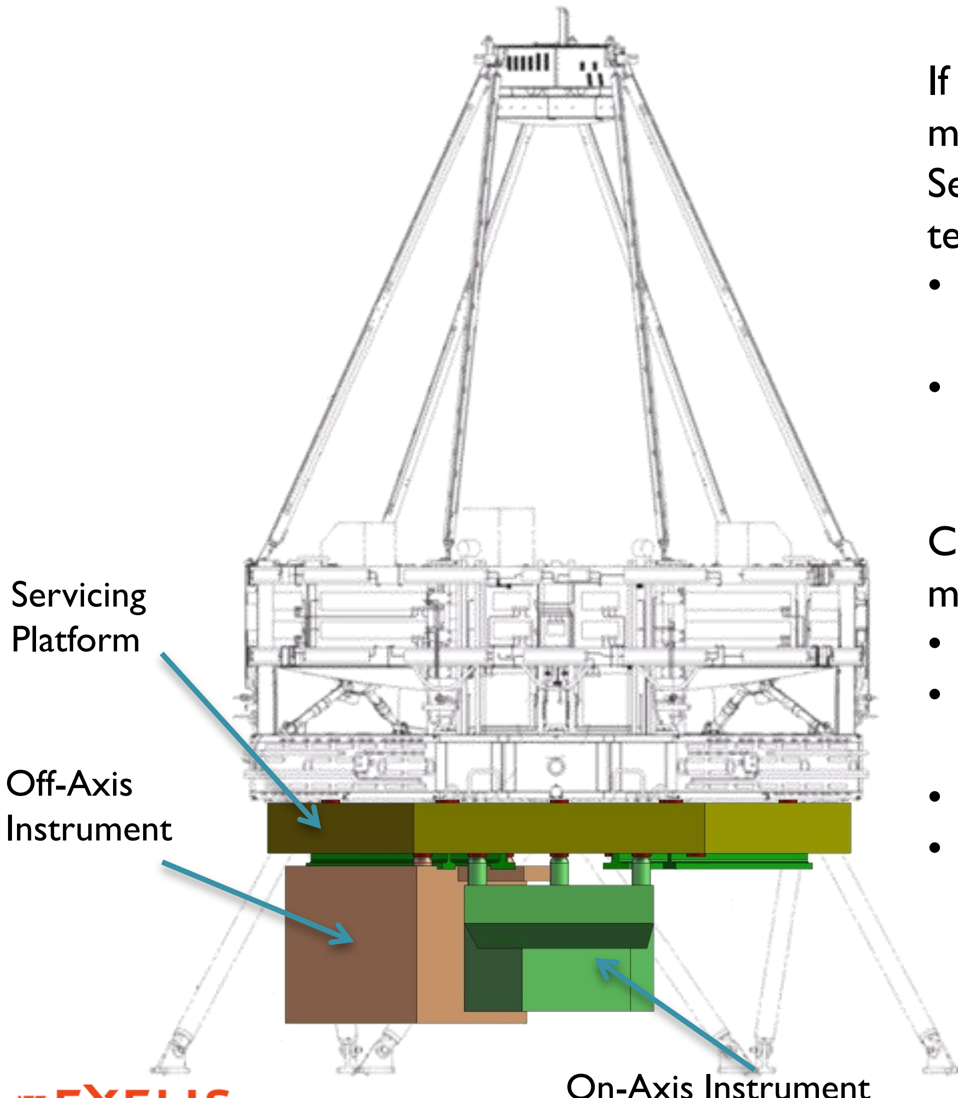
Summary

HORUS

- *HORUS* represents a compliant, straightforward, low-risk, mature implementation of the NRO telescopes to deliver a complementary UVO imaging and FUV spectroscopic capability to *JWST* and *WFIRST*
- *HORUS* provides a powerful high-sensitivity combination of a ¼° field of view diffraction-limited dual-channel imager with a FUV spectrograph
- *HORUS* has been built around a Cosmic Origins science program aligned with NASA science roadmaps
- *HORUS* will deliver a broad GO capability that meets > 65% of the community's UVO science needs
- *HORUS* is built around OTS technology and takes advantage of high TRL technologies in detector doping, detector mass production, FUV coatings, FUV detectors and data transmission bandwidth
- *HORUS* payload can be built for around $1B FY13 allowing for the OTA donation with minimal optic rework, and excluding the LV cost

Backup Slides

Concept of Operations - Servicing



If *HORUS* is flown to a GEO orbit, servicing might be possible using a Servicing Platform concept on the telescope shown with two notional ISP's:

- An On-Axis Instrument (FUV spectrograph)
- An Off-Axis Instrument (Dual-Channel Wide Field Camera)

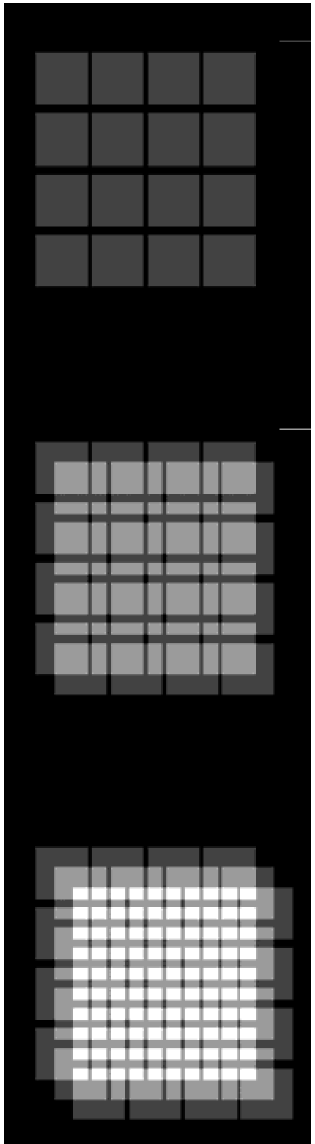
Current spacecraft interfaces can easily be modified to allow:

- Access to servicing area
- Attachment of the Outer Barrel Assembly
- Connection to the Spacecraft
- Additional axial space could also be allocated

Observatory Properties

Operating Wavelengths	Imaging: 200-1075nm (Si sensitivity passband) Spectroscopy: 100-170nm (FUV)
Imaging Observing Channels	Blue (200-517nm); Red (517-1075nm)
Imaging Broad-band Filters	F218M, F250W, F336W, F438W, F550M, F625W, F775W, F850W, F098M, F105M
Imaging Narrow-band Filters	Mg II, [O II], He II, Hβ, [O III], [O I], Hα, [N II], [S II], [S III]
Imaging Exposure Times	0.1 up to 2000 seconds
Imaging Detectors	LBL "SNAP" 3.5k square CCDs
Imaging Pixel Size	10.5 μm = 40 mas
Imaging Field Size	14' × 14' ≡ 6 × 6 CCDs = 21k × 21k pixels
Imaging Dark Noise	< 10 e-/pix/hr
Imaging Read Noise	< 3 e-
Imaging Gain	2 e-/ADU
Imaging Full Well Capacity	130,000 e-
Imaging Operational Temperature	175 K
Spectroscopy Detectors	Si MCP CsI w/ cross-strip readout
Spectroscopy Size	220 mm long, 15μm pores
Spectroscopy Resolution	R = 40,000
Spectroscopy Slit	0.5" × 5"
Pointing Accuracy (w/ FSM)	< ¼ pixel over 2000 seconds
Orbit	Earth-Sun L2
Cost (inc. 30% reserve)	$1.14B FY 2013
Observatory Lifetime	5-yr baseline, 10-yr design
Single Field Exposure Image Size	0.9 GB × 2 channels
On-board capacity	2.2 TB
Typical lossless compression	Factor of 2-3.5
Imaging Broadband Sensitivity	m_V ~ 29 in 2000 seconds
Imaging Narrowband Sensitivity	10^{-16} ergs/cm^2/s/arcsec^2 in 2000 seconds

Observing Approach and Campaign



n=3 FoV tiling coverage

Change in scatter of effective exposure times as a function of number of coverage steps

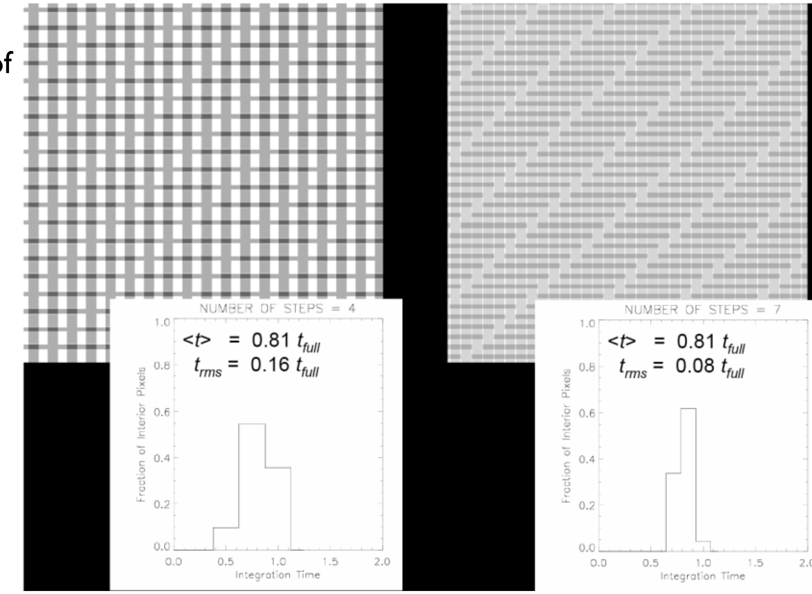


Table 1.1 - *HORUS* Design Reference Mission

DRM Program	Days
Star and Planet Formation in the Milky Way	400
From Protostars to Planetary Systems: FUV Spectroscopy of YSOs, Protoplanetary Disks, And Extrasolar Giant Planets	119
HORUS Magellanic Clouds Survey: A Bridge to Nearby Galaxies	170
HORUS Hundred Galaxy Survey (HHUGS)	32
Spectroscopic Survey of Gas in Metal-Poor Systems	100
Medium and Deep HORUS Survey of Cosmic Dawn, Galaxy Assembly, and the Growth of AGN	132
Origin of Modern Galaxies and the IGM/Galaxy Connection	150
TOTAL:	**1103 (3 yr)**

Mission Cost Funding Profile

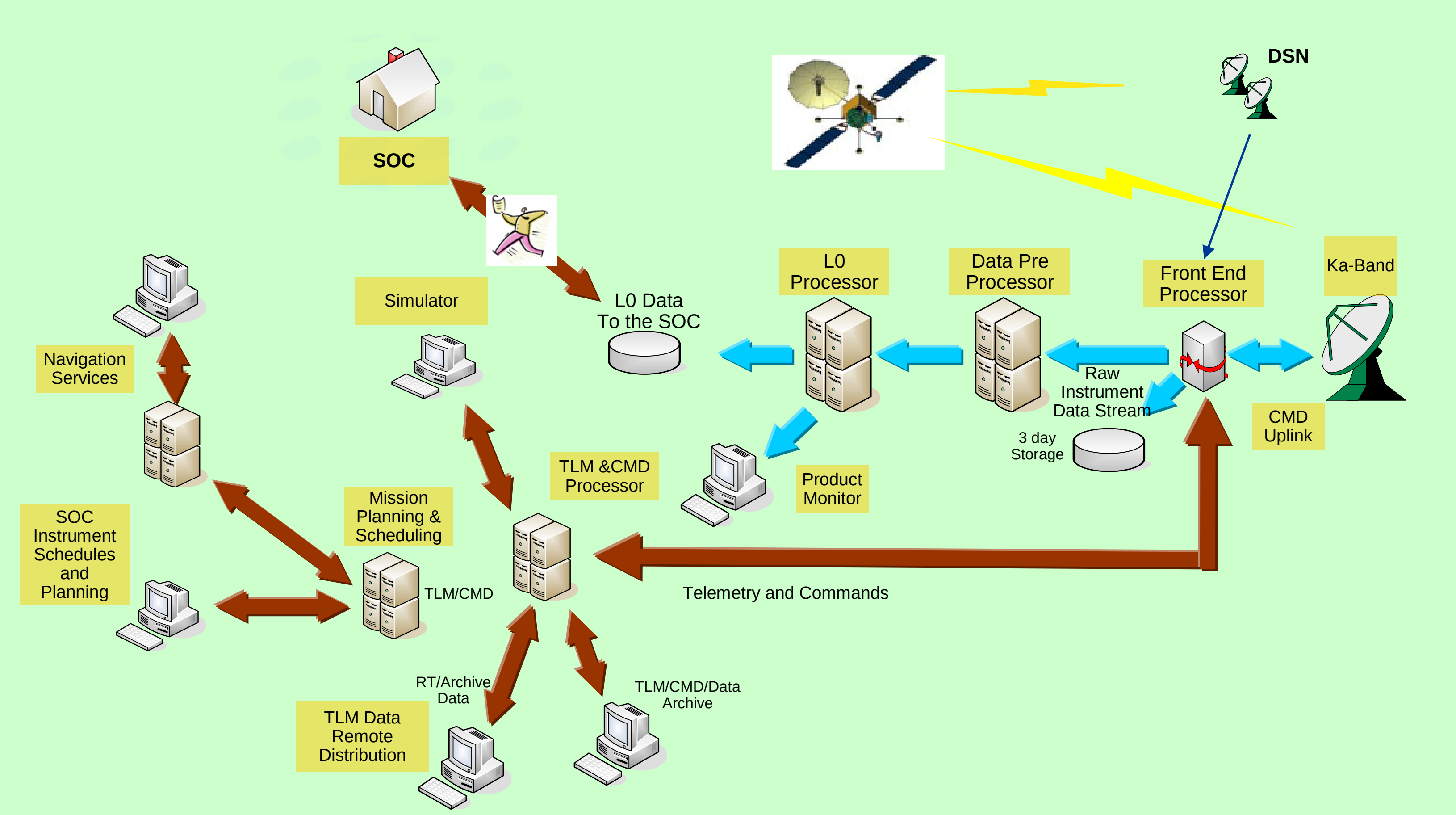
(excerpt from Astro 2010 submittal 3 August 2009)

	Formulation (Phase A Concept Study) ($M)	Formulation (Phase B) ($M)	Implementation (Phase C) ($M)	Implementation (Phase D) ($M)	Operations (Phase E) ($M)	Project Total (FY 2009 $M)
Phase Duration	6 months	12 months	42 months	18months	60 months	138 months
Phase A Concept Study	See total below					
PM/SE/MA	$4.3M	$8.6M	$52.4M	$22.5M	$10.7M	$98.6M
Instrument PM/SE	$0.6M	$0.4M	$1.3M	$0.6M	-	$2.9M
Instrument A - Telescope	$5.0M	$40.8M	$142.9M	$61.3M	-	$250.0M
Instrument B - Imaging Camera	$3.5M	$22.3M	$77.9M	$33.4M	-	$137.0M
Instrument C - FUV Spectrograph	$4.0M	$13.5M	$47.3M	$20.3M	-	$85.0M
Spacecraft including MSI&T	$7.0M	$43.3M	$151.7M	$65.0M	-	$267.0M
Pre-Launch Science	$0.8M	$1.6M	$16.8M	$6.0M	-	$25.2M
Ground Data System Dev	$3.0M	$9.5M	$33.3M	$14.3M	-	$60.0M
Total Dev w/o Reserves	$28.2M	$140.0M	$523.5M	$223.2M	$10.7M	$925.7M
Development Reserves	$8.5M	$42.0M	$157.1M	$67.0M		$274.5M
Total A-D Development Cost	$36.7M	$182.0M	$680.6M	$290.1M	$10.7M	$1200.2M
Launch Services (w/ 30% reserve)						$209.6M
MO&DA					$47.3M	$47.3M
MO&DA Reserves					$8.7M	$8.7M
Education / Outreach	$0.2M	$0.4M	$3.5M	$1.5M	$12.8M	$18.3M
Other (specify)	-	-	-	-	-	-
Total Cost	$36.9M	$182.4M	$684.1M	$291.6M	$79.5M	$1484.1M

HORUS SDT Members

- Paul A. Scowen (ASU, PI)
- Rolf Jansen (ASU, PS)
- Matt Beasley (Planetary Resources, IS)
- Brian Cooke (JPL, SE)
- Robert Woodruff (LMCO, OD)
- David Ardila (JPL)
- Daniela Calzetti (U. Mass.)
- Ranga-Ram Chary (IPAC)
- Steve Desch (ASU)
- Kevin France (U. Colorado)
- Alex Fullerton (STScI)
- John Gallagher (U. Wisconsin)
- Heidi Hammel (SSI)
- Patrick Hartigan (Rice U.)
- Amanda Hendrix (PSI)
- Sangeeta Malhotra (ASU)
- Jason Melbourne (Caltech)
- Shouleh Nikzad (JPL)
- Robert O'Connell (U. Virginia)
- Sally Oey (U. Michigan)
- Debbie Padgett (GSFC)
- James Rhoads (ASU)
- Aki Roberge (GSFC)
- Oswald Siegmund (SSL)
- Nathan Smith (U. Arizona)
- Jason Tumlinson (STScI)
- Rogier Windhorst (ASU)
- Jeff Wynn (ITT Exelis)
- Harold Yorke (JPL)

Mission Operations Architecture



Mission Operations and Ground Data System

Down link Information	Value, units
Number of Contacts per Day	1
Downlink Frequency Band, GHz	DSN Tlm: 8.5 GHz Ka Tlm: 32.3 GHz Ka Data: 32.3 GHz
Telemetry Data Rate(s), bps	DSN Tlm: 3,400 bps Ka Tlm: 3,400 bps Ka Data: 60,000,000 bps
S/C Transmitting Antenna Type(s) and Gain(s), DBi	DSN: Omni – 0 dBi Ka: Dish – 49 dBi
Spacecraft transmitter peak power, watts.	DSN – 10.6 watts at antenna input Ka: 76 watts at antenna input
Downlink Receiving Antenna Gain, DBi	DSN – 68 dBi (35 m dish) Ka – 70 dBi (12 m dish)
Transmitting Power Amplifier Output, watts	DSN – 15 watts Ka: 120 watts
Uplink Information	**Value, units**
Number of Uplinks per Day	1
Uplink Frequency Band, GHz	DSN Cmd: 7.2 GHz K-band Cmd: 16.85 GHz
Telecommand Data Rate, bps	DSN: 2,000 K-band: 2,000
S/C Receiving Antenna Type(s) and Gain(s), DBi	DSN: Omni – 0dBi K-band: 43.3 dBi