The HORUS Origins Science Probe Mission

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Activity White Paper for the Astro2010 Decadal Survey
Subcommittee on Programs

Abstract

The High-ORbit Ultraviolet-visible Satellite (*HORUS*) is a 2.4-meter class 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, and to investigate and understand the range of environments, feedback mechanisms, and other factors that most affect the outcome of the star and planet formation process. To do so, *HORUS* will provide 100 times greater imaging efficiency and more than 10 times greater UV spectroscopic sensitivity than has existed on the *Hubble Space Telescope* (*HST*). The *HORUS* mission will contribute vital information on how solar systems form and whether habitable planets should be common or rare. It also will investigate the structure, evolution, and destiny of galaxies and universe. This program relies on focused capabilities unique to space and that no other planned NASA mission will provide: near-UV/visible (200-1100nm) wide-field, diffraction-limited imaging; and high-sensitivity, low- and high-resolution UV (100-320nm) spectroscopy. Our implementation offers ample opportunity for international participation. *HORUS* is designed to be launched into a semi-stable orbit at Earth-Sun L2. From this vantage *HORUS* will enjoy a stable environment for thermal and pointing control, and long-duration target visibility. The core *HORUS* design will provide wide field of view (WFOV) imagery and high efficiency point source FUV spectroscopy using a novel combination of spectral selection and field sharing. The *HORUS* OTA design is based on modern light weight mirror technology with a faster primary mirror to shorten the overall package and thereby reduce mass in a three-mirror anastigmat configuration to provide excellent imagery over a large FoV. The UV/optical cameras use an 8k x 8k Focal Plane Array (FPA) that is a mosaic of Si 2k x 2k CMOS subarrays. The FUV spectrometer uses cross strip anode based MCPs based on the *HST-COS* technology. Fine guidance sensing is accomplished via Si arrays mounted at the Cassegrain focus. We have baselined the cost for the mission to be $976M FY04 including 30% contingency, but not including the cost of the Atlas V launch vehicle.

Key Science Goals

Introduction

Science investigation. We employ a step-wise approach to our observing program in which both imaging and spectroscopy contribute essential information to our investigation.

- **Step 1 —** Conduct a 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 of protoplanetary disks.
- **Step 2 —** Survey all major star forming regions in the Magellanic Clouds, where we can still resolve relevant physical scales and structures, access starburst analogs, and sample star formation in an initial regime of low metallicity applicable to high-redshift galaxies.
- **Step 3 —** Extend the star formation survey to galaxies in the nearby universe in order to increase the range of galaxy interaction and metallicity environments probed. *HORUS* can 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.

Step 1 – From Protoplanetary Disks to Extrasolar Planets

Star and Planet Formation in the Milky Way [1]

This phase involves the assembly of a comprehensive imaging survey of Galactic star formation regions to probe all aspects of the star formation process. Our primary goal is to understand the evolution of circumstellar protoplanetary disks and other detailed aspects of star formation in a wide variety of different environments. This requires a comprehensive emission-line survey of nearby star-forming regions in the Milky Way, where the high spatial resolution of *HORUS* will be capable of resolving circumstellar material and shock structures. Our survey will provide the basic data required to understand star formation as a fundamental astrophysical process which controls the evolution of the baryonic contents of the Universe.

Young stellar objects (YSOs): (*Masses, mass-spectra, rotation rates, variability, ages, multiplicity, clustering statistics, motions, brown dwarfs, free-floating proto-planets*)

Disks: (*Sizes, masses, structure, mass-loss rates, photo-evaporation, density distributions, survival times*)

Outflows: (*Microjets, jets, wide-angle flows, winds, motions, momenta, mass-loss rates, turbulence, shocks*)

Nebulae: (*Excitation, motion, ionization fronts, triggered star formation*)

Massive stars: (*Motions, variations, winds, interactions with siblings, HII regions*)

Recycling: (*Supernova remnants and planetary nebulae, bulk motions, excitation, shocks*)

Superbubbles: (*Destruction of clouds, OB associations, T associations. Global structure and evolution of star forming regions*)

The Galactic Ecology: (*Impact of spiral arms. Formation of clouds, Galactic gradients in YSO and cluster properties. The Galactic Center*)

Unique science that can only be conducted by *HORUS*:

Precision Photometry: *HORUS* provides a wide FOV with 0.05 to 0.1 arcsecond angular resolution. The use of visual and UV wavelengths enables the realization of the best angular resolution for a given aperture (20 milli-arcseconds at $\lambda = 0.2$ μm, and 100 milli-arcseconds at $\lambda = 1.0$ μm). Stable PSFs combined with a stable focal-plane geometry will permit unprecedented precision in astrometry and photometry.

Outflow and Nebular Motions: The exquisite proper motion sensitivity of *HORUS* will enable unique measurements of the motions of supersonic protostellar outflows and stellar wind bubbles to a distance of several kpc; the mildly supersonic motions of expanding HII regions to about 1 kpc; as well as the motions in planetary nebulae and supernova remnants.

From Protostars to Planetary Systems : FUV Spectroscopy of YSOs, Protoplanetary Disks, and Extrasolar Giant Planets [2]

Understanding the abundance and diversity of worlds in the Galaxy involves tracing the path of interstellar material from dense cloud cores, to young stellar objects, protoplanetary disks, and finally extrasolar planets. Here we discuss the critical information provided on these objects by point-source far-ultraviolet spectroscopy with *HORUS*.

Mapping the Shock Waves and Accretion Columns in Classic T-Tauri Stars:

- Clearly establish the connection between classical T Tauri stars and higher mass young stars by measuring accretion rates in Herbig Ae/Be stars of various ages and the frequency and typical lifetime of Herbig Ae/Be accretion disks.
- Determine the extent to which magnetic fields cushion material infalling from the disk onto the star.
- Uncover the basic geometry of accretion in classical T Tauri stars by combining Doppler mapping of FUV emission lines using *HORUS* with similar maps of Balmer lines using ground-based facilities.

The Evolution of Gas in Protoplanetary Disks:

- Determine the typical lifetime of primordial H_2 gas in protoplanetary disks around low-mass stars in various environments.
- Determine what factors, like central object mass, affect primordial gas dissipation.
- Measure secondary gas abundance and composition in debris disks.

The Composition and Structure of Extrasolar Giant Planets:

- Determine the structure and composition of the outer atmospheres of hot Jupiters.
- Measure the evaporation rates of hot Jupiters.

Unique science that can only be conducted by *HORUS*:

The science goals require sensitive FUV spectroscopy for several reasons. Accurate measurement of accretion rates in Herbig Ae/Be stars requires observation of hot emission lines at short wavelengths where the stellar photospheres are faint, in particular OVI λ1032. To locate the areas on the surface of CTTS where accretion flows impact, Doppler imaging must be done using optically thin emission lines formed in the accretion shock, i.e. hot FUV emission lines like CIV. Measurement of protoplanetary disk gas masses requires observations of H_2. The FUV transitions of this molecule are very strong, in contrast to the IR transitions, and small amounts of gas with a wide range of temperatures may be observed. The secondary gas in debris disks is cold and possibly mostly atomic. The transitions out of the ground states of the most cosmically abundant atomic species lie in the FUV (i.e. H, C, N, O). This is also the reason why FUV spectroscopy is needed to characterize the outer atmospheres of transiting extrasolar giant planets.

Step 2 - The *HORUS* Magellanic Clouds Survey: A Bridge to Nearby Galaxies [3]

The *HORUS* Magellanic Clouds Survey consists of three components: I) A complete-area, broadband survey in 8 UV-optical filters; II) A narrowband survey in 7 nebular filters to cover 21 HII regions and a large-area, contiguous survey of the diffuse, warm ISM; and III) a comprehensive FUV spectroscopic survey of 1300 early-type stars. The science areas to be investigated are as follows: A) Massive star feedback in both HII regions and the diffuse, warm ISM; B) A comprehensive study of the 30 Doradus giant extragalactic HII region; C) Quantitative parameterization of stellar clustering properties; D) FUV studies of early-type stellar atmospheres and energy distributions; E) FUV absorption-line studies of molecular cloud structure and ISM extinction properties. Many additional studies relating to the stellar populations will also be enabled. In less than 1 year *HORUS* will be able to map both Magellanic Clouds in their entirety at < 0.1" spatial resolution in eight NUV/visible broad-band filters (NUV to Z band) to $m_{AB} > 26$ and in four narrow-band filters to depths of 10^{-16} erg cm^{-2} s^{-1} arcsec^{-2}.

Unique science that can only be conducted by *HORUS*:

The *HORUS* survey of the Magellanic Clouds will be unique in its powerful combination of angular resolution, depth, and spatial coverage. The separate capability of FUV spectroscopy will itself be a unique and vital component, whose coordination with the imaging capability will provide a truly comprehensive advance in the available data for these stepping-stone galaxies. The FUV capability offered by *HORUS* is superior to *FUSE* in both spectral coverage and sensitivity. Each of the Magellanic Clouds survey components is designed to obtain significant coverage in its domain. The broadband survey will be essentially complete in area coverage; the narrowband survey will cover 5% and 14% of the LMC and SMC, respectively, plus a sample of HII regions representative of the range of star-forming conditions in these galaxies; the FUV spectroscopic survey of 1300 stars will allow for both representative and unique massive star spectra.

Step 3 – Star Formation in Nearby Galaxy Environments [4]

HORUS Hundred Galaxy Survey (HHUGS) Program

We intend to learn how galaxies work through studies of their stars. To this end HHUGS will use a full set of analysis options extending from color-magnitude diagram fitting for resolved stars to modeling of multi-band colors through population synthesis to derive physical properties of target galaxies. This program relies on *HORUS's* powerful combination of a substantial field of view, wavelength agility, sensitivity, and angular resolution that will allow the first full survey of galaxies to be undertaken with a 2.4m telescope at diffraction-limited resolution. The resulting 21st century digital 'Hubble Atlas' of ~100 representative nearby galaxies will provide a standard for testing our understanding of how galaxies came to have their present forms and how their stellar components are likely to evolve into the future.

Unique science that can only be conducted by *HORUS*:

- The 14 arcmin FOV (14 arcmin ~ (40D/10 Mpc) kpc) covers the main bodies of all but the nearest few galaxies to be observed in one pointing. It is therefore is efficient to survey nearby galaxies.
- The high angular resolution of *HORUS* is essential for measuring properties of star forming regions, star clusters and subcomponents within galaxies.
- Experiments with model SEDs from simple stellar populations show that MUV colors allow age and extinction to be separated and enhance sensitivity of the models to metallicities.
- The sky background beyond near-Earth orbit in space is substantially darker than from the ground which further multiplies the advantages of *HORUS* imaging, especially for $\lambda < 0.4$ microns and $\lambda > 0.7$ microns.

A Spectroscopic Survey of Stars and Gas in Metal-Poor Environments

This *survey* aims to obtain high-resolution FUV spectra for ~40 early-type stars in 3-4 Local Group galaxies beyond the Magellanic Clouds. These spectra will be used to measure the properties of the interstellar medium and constrain the evolution of massive stars in galaxies characterized by drastically different metallicities. In each galaxy, the targets will be selected to cover both stellar parameter space and a wide variety of interstellar environments, with the overall aim of clarifying the feedback between these two components that drives galactic evolution.

Unique science that can only be conducted by *HORUS*:

HORUS is a uniquely capable observatory: three critical factors enable our survey. These are (1) access to $1000 \le \lambda \le 1100$ Å, (2) effective area sufficient to reach S/N = 10 in $t_{exp} \sim 100$ ksec for a target with $F_\lambda = 10^{-15}$ erg cm^{-2} s^{-1} Å^{-1} at 1050 Å, and (3) spectral resolution of R = 40,000 to separate blended components in the interstellar absorbers of interest. When compared with *FUSE*, which also covers $1030 \le \lambda \le 1150$ Å, *HORUS* will have up to 40× the effective area at twice the spectral resolution. *HORUS* will be the only instrument with combined high efficiency and access to $\lambda < 1100$ Å needed to extend stellar and interstellar studies to extragalactic environments. *FUSE* (R=20,000) and *STIS* (R = 44,000) achieve S/N=10 per resel for $F_\lambda \sim 10^{-14}$ erg cm^{-2} s^{-1} Å^{-1}, and both are needed to cover the full range 1000 - 1700 Å. *HORUS* will cover this entire range down to $F_\lambda \sim 10^{-15}$ erg cm^{-2} s^{-1} Å^{-1} in three exposures for a total of 100 ksec.

Step 4 – Galaxy Formation and the IGM/Galaxy Connection [5]

The Medium and Deep HORUS survey of Cosmic Dawn, Galaxy Assembly and the Growth of AGN.

We propose to use *HORUS* to make a combined MEdium and DEep Areal (“MEDEA”) survey using ≥ 8 filters at $\lambda \approx 0.2$ - 1.1 μm that will cover ~ 1 deg^2 to AB ≤ 28 and ~ 3 deg^2 to AB ≤ 27 mag. Doing this with the best ground-based facilities would take 30-1500× longer. This *HORUS* survey is an essential complement to *JWST* (which will cover ≤ 0.1 deg^2 to AB ≤ 31 mag at $\lambda \ge 1.1$ μm). With *HORUS*, we will cover deep fields surrounding the *HST* HDF-N and CDF-S fields, but vastly expand on their area, and cover most fields in each color over at least two epochs. Part of the proposed survey may be implemented as *HORUS* Parallel observations. MEDEA will allow us to address the following science goals:

- Measure the luminosity function (LF) of dwarf galaxies from $z \approx 9$ to $z \approx 5$. Stars at the high-mass end of the Pop II IMF in these objects likely completed the reionization of the universe by $z \approx 6$.
- Measure galaxy assembly in the redshift range $5 \geq z \geq 1$. With ≥ 8 UV-optical filters, exquisite photometric redshifts z_{phot} will be available for 6×10^5 objects to AB ≤ 27 mag. For each, structural parameters and types (i.e. "morphology") will be measured using Artificial Neural Networks (ANNs) that are anchored in the rest-frame UV.
- Using specific galaxy classes that are rare locally but abundant at high redshifts (e.g. "tadpole" galaxies), MEDEA will directly measure the strongly epoch-dependent merger rate, and hence constrain how the Cosmological Constant, Λ, has affected galaxy assembly.

Unique science that can only be conducted by *HORUS*:

(1) How HORUS Surpasses Previous *HST* Surveys in Areal Coverage and Numbers of Objects: *HORUS* will make a combined MEdium and DEep Areal ("MEDEA") survey using ≥ 8 filters $\lambda \approx 0.2$-1.1 μm. The *HORUS* BLUE+RED/CAM have a FOV of 14'×14' that covers 0.2-1.1 μm with a quantum efficiency of ≥ 60-80%. The MEDEA survey will therefore cover ~ 1 deg^2 to AB ≤ 28 and ~ 3 deg^2 to AB ≤ 27 mag.

(2) How HORUS Surpasses Previous HST Surveys in Wavelength and Photo-z Accuracy: From its concept, *HORUS* has been equipped with the filters needed to search for large numbers of faint galaxies at $z \approx 1$-9. *HORUS* will add a much wider wavelength coverage (0.2-1.1 μm) using its BLUE+RED/CAM, and therefore it will result more robust photometric redshifts at all redshifts $z \approx 1$-6 compared to previous optical *HST* deep fields.

The Origins of Modern Galaxies and the IGM/Galaxy Connection

The origins of modern galaxies lie in their accretion of gas from the intergalactic medium (IGM), their return of matter, metals, and energy to the IGM, and in galaxy/galaxy mergers and interactions. *HORUS* will address three important issues in conclusive fashion: (1) the bimodal accretion of baryons into galaxies, via "hot", "cold", or "multiphase" accretion, (2) the return of the products of star formation to the IGM, and subsequent feedback effects, by supernova-driven winds, and (3) the "missing baryons" in the IGM, both directly seen and as indicated by their interactions with cooler gas in IGM/galaxy interface regions.

Unique science that can only be conducted by *HORUS*:

The major survey we advocate here has not been done owing to two technical barriers to large samples. First, obtaining high-resolution QSO spectra that cover all interesting IGM absorption lines usually requires $t_{exp} > 50$ ksec on a high-resolution UV spectrograph. Second, these studies often must observe only the UV-brightest targets, which are usually selected without regard to the foreground galaxy populations. *HORUS* will "invert" this problem by allowing us to select galaxies paired with *SDSS* QSOs, and will thus far surpass in statistical power any undirected survey, with followup, that has gone before.

Technical Overview

HORUS is a 2.4m UV-visible telescope to be launched into a semi-stable orbit at Earth-Sun L2. From this vantage *HORUS* will enjoy a stable environment for thermal and pointing control, and long-duration target visibility. The core *HORUS* design will provide wide field of view (WFOV) imagery and high efficiency point source FUV spectroscopy using a novel combination of spectral selection and field sharing. The *HORUS* OTA design is based on modern light weight mirror technology with a faster primary mirror to shorten the overall package and thereby reduce mass in a three-mirror anastigmat configuration to provide excellent imagery over a large FoV. The UV/optical cameras use an 8k x 8k Focal Plane Array (FPA) that is a mosaic of Si 2k x 2k CMOS subarrays. The FUV spectrometer uses cross strip anode based MCPs based on the *HST-COS* technology. Fine guidance sensing is accomplished via Si arrays mounted at the Cassegrain focus.

The spacecraft bus is derived from the *SIRTF* bus with orbit maintenance propellant added because of the L2 orbit. The payload will be launched by a Delta IV M+ or Atlas 511 or 521 Medium launch vehicle.

Concept Design: Telescope and Instrument Design

Our baseline optical design derives from on-axis three-mirror anastigmats (TMA) developed by Korsch (1980). In this TMA, three conic sections combined with the geometry of the mirrors allow the correction of third-order spherical aberration, coma, astigmatism, and field curvature. Component alignment tolerances are small, but reasonable. LOS jitter must be controlled at a fractional pixel level (21 mas - 3σ) to maintain specified spatial resolution. Based on our error budgeting diffraction-limited imagery can be achieved at 900 nm with HST-like mirror tolerances. Such performance at 600 nm requires mirror figures similar to that demonstrated on the Technology Demonstration Mirror for TPF-C. The spectral characteristics of the dichroic filters for wavelengths greater than 400 nm is within today's technology. The response from 200 to 400 nm will have spectral structure, and therefore the design needs to be optimized to

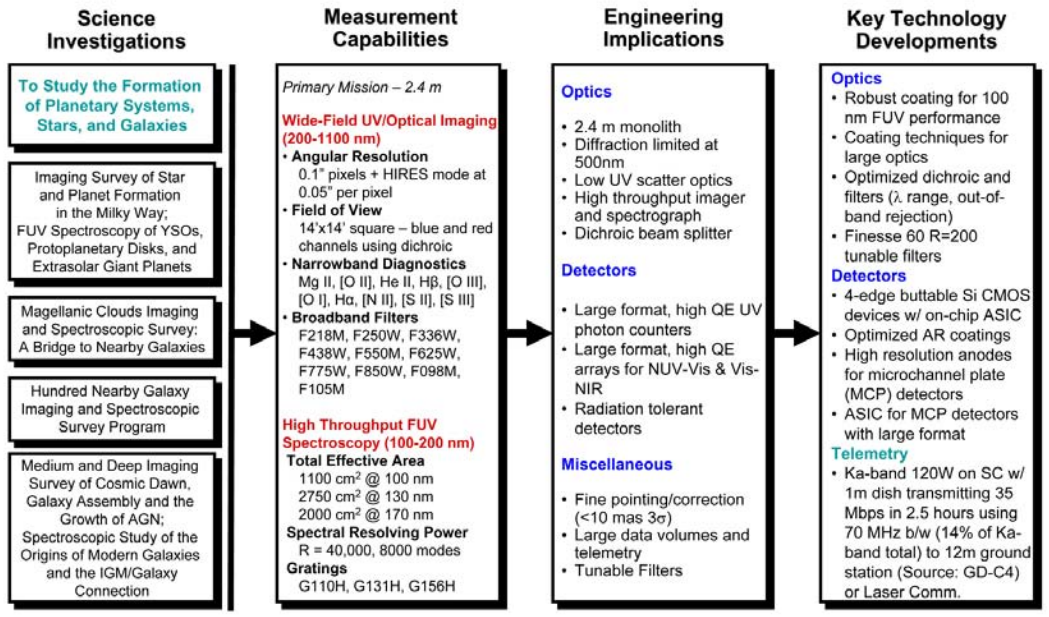
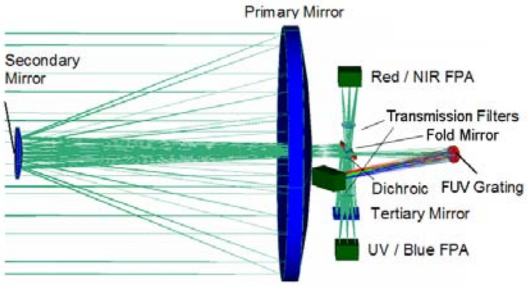


Figure 1 – *HORUS* Core Mission Science Requirements Flowdown to Technology Development

conform to the spectral bands of the UV bandpass filters. **Figure 1** summarizes *HORUS* and its flowdown between the core mission science requirements and the technology development needed.

- Dual-channel wide-field camera



- FUV point source spectrograph (100-170nm)

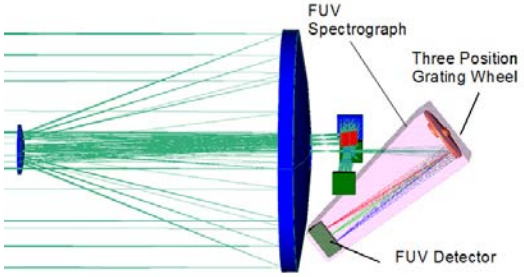


Figure 2 – *HORUS* Baseline Instruments

We use a novel approach to package both imaging instrumentation and the FUV & NUV spectrograph channels. The entrance slits of the UV channels are positioned at the Cassegrain focus. We place the imaging instruments at the TMA focal plane. The imagery on-axis is adequate for the small FOV spectrometers. We thereby ensure maximum throughput for these channels with only two mirror reflections and one grating. The nominal performance of all instrument modes is adequate for *HORUS*.

As shown in **Figure 2**, *HORUS* uses a dichroic beam splitter to image UV-blue, red wavelengths onto separate 8k×8k mosaics. The FOV is simultaneously imaged by the blue and red channels, increasing the observing efficiency by a factor of two. The detector and optics performance (e.g., DQE, red leak control) are optimized for the wavelength regime of each channel.

The camera FOV is 13.7'×13,7', or ~190 square arc minutes, yielding at least a factor of 25 better angular coverage than *WFPC2*, and a factor of 17 better than *ACS/WFC* (keeping in mind *ACS/WFC* does not image in the UV). Currently, our baseline detector system is to use mosaics of Rockwell HyViSI Si CMOS devices mounted on the Hawaii-2RG readout. The individual 2k×2k detectors may be abutted to produce 8k×8k arrays, delivering 0.1” (survey) and 0.05” (hi-res) pixels. The H-2RG readouts are currently in development for *JWST*. Using CMOS active pixel devices instead of conventional CCDs will mitigate the deleterious effects from degraded charge transfer efficiency that have plagued other space-based imaging instruments.

The core instrument will also provide a spectroscopic capability to cover the FUV (100-170nm) pass band at resolving power R=40,000. The spectrograph will have a small 30 mas entrance slit intended to study point-sources. Each channel will use a Rowland circle spectrograph with the entrance slit at the Cassegrain-like focus of the OTA. With a beam speed of ~f/9.4, the Rowland circle with aberration-correcting holographic gratings is quite capable of producing 40,000 resolving power over a modest bandpass (~20 nm).

Optical Coatings. We would prefer to maintain high efficiency down to 100nm, which, using today’s technology implies LiF coatings over aluminum. However LiF is fragile (hygroscopic) and this may curtail its use. We will also consider MgF_2 over aluminum, this will retain some reflectivity to 100nm, but recognize that coating technology needs more development.

Mission Implementation

Introduction & Overview

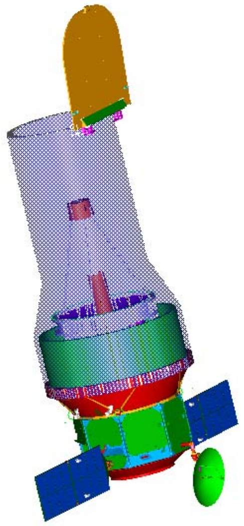


Figure 3 – the *HORUS* Mission Concept

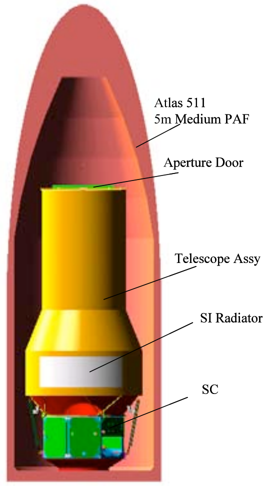


Figure 4 – *HORUS* Launch Configuration

The *HORUS* mission concept is shown in **Figure 3**, and the *HORUS* Mission requirements and Bus capability are listed below. The flight system uses a spacecraft design already used for *Spitzer*; proven telescope and lightweight mirror technology; and line-of-sight stabilization technologies yielding a low risk program. The ground system uses heritage equipment, processes, and procedures.

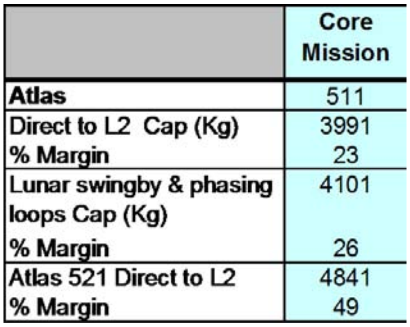
Mission Description

The *HORUS* Observatory would be launched into a Lissajous orbit about the sun-earth/moon L2 libration point, approximately 1.5 million km from the earth. Station keeping burns are used to maintain the spacecraft in this orbit. Except for infrequent short lunar eclipses the spacecraft is continuously in sunlight.

HORUS **Mission Requirements**		***SIRTF*** **Bus Capability**
Lifetime	5 yrs, 10 yrs goal	5 yrs
Launch date	2014	August 2003
Orbit altitude	L2 Halo	Supports
P/L Mass	2374 kg (core) 2779 kg (ext'd)	Supports
Optics Temp	290 K	Supports
Focal Plane	290/<150K(core) <140K (ext'd)	Supports
P/L Power (EOL)	1500 W	Supports
Science data rate	35 Mbps, Ka	Supports
Uplink	2 kbps, X	Supports
Data Storage	44 Gbits	Supports
Grd Contact	150 min /day	Supports
Pointing Control	100 mas	5 arcsec
Pointing Knowledge	3 arcsec (1σ)	2 arcsec (1σ)
Jitter(3s) /Stability	21 arcsec/sec 10.5 mas goal	0.021 arcsec jitter
Slew Rate	1.5 arc min/sec	
Fine Guidance Cntl	Focus at Cass focus	Supports
Sun Avoidance	60 deg	Supports
Radiation	20Krad	~30 Krad
Launch vehicle	Atlas V	Supports
PAF	5m	Supports

Launch Vehicle

The baseline Launch Vehicle is the Atlas V series with a 5m fairing. The *HORUS* launch configuration inside the fairing is shown in **Figure 4** and the launch capability with over 23% margin is shown in **Figure 5**.



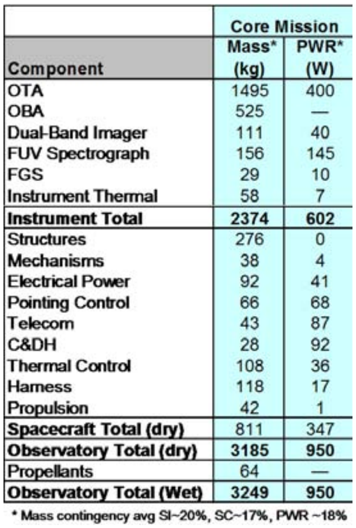
	Core Mission
Atlas	511
Direct to L2 Cap (Kg)	3991
% Margin	23
Lunar swingby & phasing loops Cap (Kg)	4101
% Margin	26
Atlas 521 Direct to L2	4841
% Margin	49

Figure 5 – Launch Capability (Atlas V)

SC Bus

SC Mission Element Requirements

Lockheed-Martin (LM) has completed an initial systems engineering assessment of concepts for implementing the *HORUS* mission. Mission requirements and SC features are summarized above. The LM developed *Spitzer* spacecraft, which has been in flight since August 2003, forms the basis for the *HORUS* SC design. The *HORUS* mission launch capability margin and mass property and power summary are shown in **Figure 5** & **Figure 6**. The *SIRTF* Spacecraft Bus adopted for *HORUS* is at TRL-9. Each component & technology is flying successfully today on either *Spitzer*, *Ikonos*, or *Mars Odyssey*, or will soon fly on *MRO*.



	Core Mission	
Component	Mass* (kg)	PWR* (W)
OTA	1495	400
OBA	525	—
Dual-Band Imager	111	40
FUV Spectrograph	156	145
FGS	29	10
Instrument Thermal	58	7
Instrument Total	**2374**	**602**
Structures	276	0
Mechanisms	38	4
Electrical Power	92	41
Pointing Control	66	68
Telecom	43	87
C&DH	28	92
Thermal Control	108	36
Harness	118	17
Propulsion	42	1
Spacecraft Total (dry)	811	347
Observatory Total (dry)	**3185**	**950**
Propellants	64	—
Observatory Total (Wet)	**3249**	**950**

* Mass contingency avg SI~20%, SC~17%, PWR ~18%

Figure 6 - *HORUS* mass property and power summary

Spacecraft Bus Design

Structure

The *SIRTF* composite-structure design provides a highly stable platform for pointing critical components and provides affordable low-risk performance. The structures subsystem includes all primary and secondary structure, solar array and HGA support structure. The structure is tailored to *HORUS* mission requirements using heritage materials and processes, and is derived from the heritage spacecraft of low weight, high stiffness and pointing stability drive the structure subsystem design. Kinematic mounts are provided between the optical bench and the SC and eliminates thermal strain of the SC propagating and affecting alignment of the optics.

Mechanisms

The *HORUS* spacecraft includes gimbal mechanisms for deployment and pointing the HGA (high gain antenna) and both solar array wings, and separation from the Ascent Stage. The HGA gimbal is an internally redundant two axis unit, identical to those used on *Ikonos*. The gimbal was developed for the *Ikonos* commercial remote sensing satellite to generate extremely low disturbance. The HGA provides greater than hemispherical coverage, allowing uninterrupted high data rate communications throughout the entire mission and most of the transfer orbit.

Guidance Navigation and Control Subsystem

Coarse attitude knowledge is provided by redundant wide angle Sun sensors, star trackers, and high performance inertial reference units. These are used to control the attitude in transitional and contingency modes of operation and to initially orient the observatory within the acquisition range of the instrument's fine guidance function.

Three-axis attitude control is provided by a 3 for 4 redundant set of reaction wheel assemblies (RWAs). The RWAs are nominally operated with zero net momentum with the speeds of the RWAs biased to avoid vibrational harmonics and wheel stops. RWA momentum is periodically unloaded using thrusters. Unloading can be autonomous or timed to avoid disturbing sensitive observations.

Fine guidance at the 21 mas (3σ) level will be provided by the FGS at the Cassegrain-like focal plane. Observing maneuvers can also be performed relative to a programmed path, allowing observation of solar system objects. The software also provides for a sophisticated toolkit of maneuvers which support numerous observing modes beyond the *HORUS* primary and secondary missions, as well as orbit injection and maintenance, and contingency operations.

Pointing Stability: The pointing stability for *HORUS* is 21 mas (10.5 mas goal). Error sources include the Spacecraft (solar arrays, reaction wheels, gyros/photon noise, and antenna gimbals), Telescope and Focal Plane. The pointing stability allocations for the telescope and FPA are due to thermal deformations. Using as a bench mark *HST* we should experience something less than 0.003 arcsec for the telescope and 0.002 arcsec for the FPA.

Electrical Power

The *HORUS* Power design is based on flight heritage from *Spitzer*. The selected EPS design consists of flight-proven designs for the Solar Array (SA), NiH2 Battery, Charge Control Unit (CCU) and Power Distribution and Drive Unit (PDDU).

Solar Array: Electrical power is generated by articulated Solar Panel wings mounted on both sides of the S/C bus. The panel area will be populated by state-of-the-art Multi-Junction solar cells. The selected solar panel area has been analyzed under End-of-Life mission conditions as being capable of supporting the total mission power loads, after a failure of any single solar array circuit. The panels are heritage Iridium panels with the exception that their length is reduced to match the *HORUS* power requirements.

C&DH

The *HORUS* C&DH design utilizes a dual string RAD750 processor. Each processor provides 128 Mbytes of dynamic random access memory (DRAM) storage. Redundant hardware command decoder (HCD) and Reed-Solomon downlink (RSDL) encoding functions are performed in the C&DH. A 88 Gigabit (w/ compression) Solid-State Recorder (SSR) is added to provide data storage between daily downlinks. The SSR interfaces directly between the high rate science data output of the instrument, and the Communications subsystem high rate input.

Communication Subsystem (Comm)

Comm provides reception and transmission of commands and telemetry data respectively through two low gain antennas (LGA's), operating in X and Ka-Bands respectively. Science data is transmitted back to the ground network through a 120W Ka-Band link transmitting 35Mbps in 2.5 hours using 70MHz bandwidth to 12m ground station.

Thermal

Passive cooling of the *HORUS* science payload is achieved by removing the heat from the SI through flexible heat straps to the SI radiator. The *SIRTF* bus thermal design provides for the required payload and bus power dissipation. Mission-unique bus modifications will include relocation of internally mounted equipment to accommodate the payload electronics. The heat pipes are at TRL 9.

Propulsion

The *HORUS* SC baselines a single blow-down hydrazine system similar to the *Ikonos* design. The eight 0.2 lbf thrusters provide delta-V and moments for orbit east-west station keeping, and momentum wheel desaturation during the science mission management after spacecraft separation.

Technology Drivers [6]

As part of a parallel study, we have studied the problem of tiling large focal planes. The strong scientific case for the use of large focal plane arrays that combine areal coverage with high resolution has been made in a series of 4 white papers to the Decadal Survey (2 by Scowen et al; 2 by Jansen et al). The study has yielded invaluable insight into cost and yield, as well as the likely problems associated with the production and testing of a large number of flight-rated detectors.

As input to the Decadal Survey we are authoring a technology development white paper on the technical issues we have encountered and the expectation for finding a cost effective solution within the next decade. To achieve the capabilities we believe are necessary to make our science goals attainable, we have to surmount serious technological challenges, requiring corresponding investment over the next decade. The issues that we have identified that need particular attention are: how to mass produce large numbers of chips with low read noise, low dark current and high yield from modern lot run manufacture; how to test large numbers of detectors while preserving the fidelity of the product and mitigating the risk associated with fabricating the final array; investment in facilities and opportunities to provide a path to raise the TRL of these emerging technologies; investment in alliances between government labs and academia; development of new packaging designs to minimize interchip gaps when mosaicing large numbers of detectors; critical assessment of what changes in acceptable specifications for flight-rated detectors should look like in the era of mass production; and the expansion of high-capacity data storage, compression and transmission technology.

As part of this study, we have developed an outline to what we believe is necessary to move from the current state of the art to a production line environment capable of tiling a large FPA like the one envisioned for *HORUS*. First, complete the infrastructure for processes and facilities (detectors, readout, packaging), 1 year; second, fabrication and validation of prototype detector modules (SCA) - procure ASIC readout chips, procure detector fabrication run at foundry, process wafers at JPL, packaging: development and fabrication of 10 units, testing and qualification of the module, two years; third, fabrication and validation and demonstration at a ground observatory of prototype 3×3 raft modules (SCA) - procure ASIC readout chips second iterative lot, procure detector fab run, process wafers at JPL, packaging: development and fabrication of 2 units, cold flatness test, shake and bake, radiation, observation including dewar, thermal, miscellaneous additional instrumentation, two years; fourth, fabrication and validation of prototype FPA by assembling two rafts (SCA), 1 year; and fifth, detector balloon demonstration (parallel with above steps 2-4). Overall schedule is four years for first flight with a second flight in the fifth year. Overall ROM cost is $40M FY08.

In light of all this work we believe the low-risk, low-cost, high-fidelity assembly and integration of large focal plane arrays is a vital area of technological development that needs to be invested in over the next decade to enable not only this mission concept but a host of other missions and instrumentation that would also benefit from such a capability.

Activity Organization, Partnerships and Current Status

This project evolved out of an earlier MIDEX concept study, and led to the *HORUS* proposal under the Origins Probe Concept Study opportunity in 2004. The team was selected to study the feasibility of combining a wide field UV/optical camera with a FUV next-generation spectrograph on a single platform for a mandated cost of $650M FY05. The observatory team consists of scientists and engineers at ASU and many other partner universities, NASA centers (JPL, GSFC), and industry partners (Lockheed Martin and ITT). The program produced a very competitive package that was 1 of 9 selected for study, and the project stands ready to be developed under pre-Phase A should both the Decadal Survey and NASA deem it attractive enough to pursue.

Activity Schedule

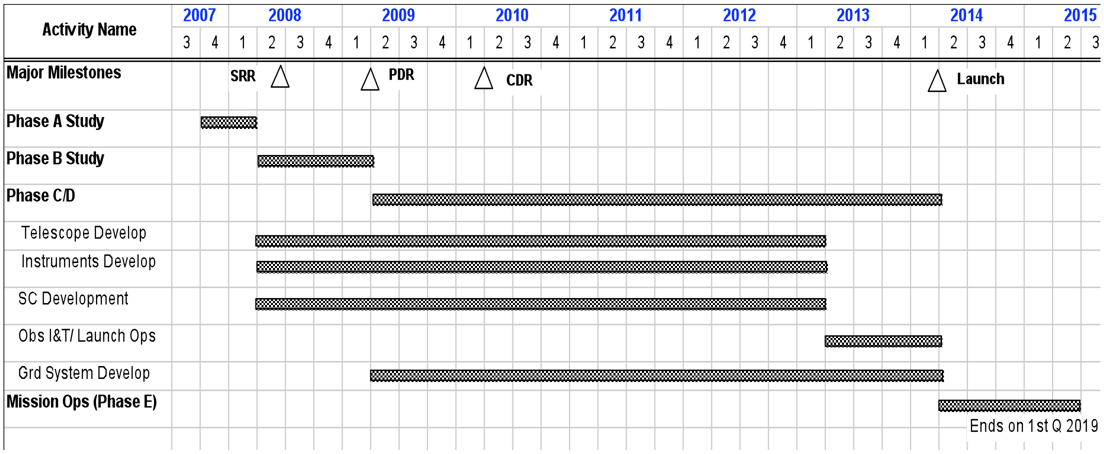


Figure 7 - Original *HORUS* Program Summary Schedule

The *HORUS* program summary schedule (**Figure 7**) outlines the top level milestones and the program phasing, as was crafted assuming a start of 2007 for Phase A study. If approved in 2010, the whole schedule would slide 3 years to the right. The 5-year C/D phase is built-in with over 30 days of schedule reserve. Mission operation starts 30 days after launch (Jan 2014; or 2017 if started in 2010) and continuous for 5 years.

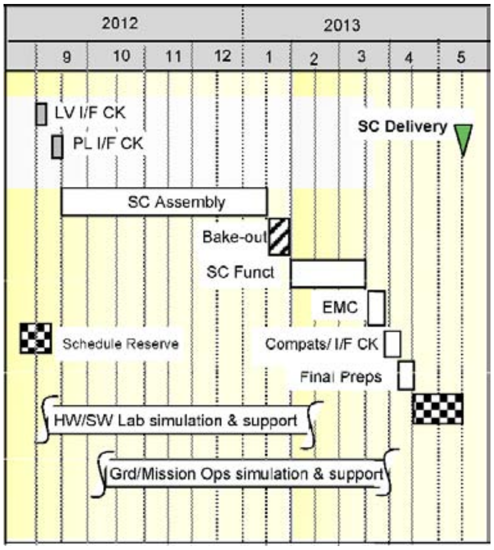


Figure 8 – Original SC I&T Timeline

SC I & T flow

Our planned SC protoqual test program is shown in **Figure 8**. In additional to the functional test, a EMI/EMC test involves verification of all external I/Fs that it is free of electromagnetic interference.

Environmental tests are deferred to Observatory level since this is a proven *SIRTF* bus. We will further assess the environmental test requirements to ensure the SC bus met all test requirements prior to the delivery.

Observatory Integration & Test

The *HORUS* SC/Telescope integration and test flow is shown in **Figure 9**. Upon receipt of the telescope/FPA, it is mated to the SC bus and aligned. SC and FPA functional and I/F tests are performed to verify compatibility using the same SC/SI level procedures, all I/Fs are previously verified by the simulators. In additional to the ambient and I/F functional verification, the Observatory also undergoes environmental test which includes EMC, modal/jetter, acoustic, pyroshock, and thermal vacuum/balance test to demonstrate the Observatory's ability to withstand the launch and space environments as well as uncover workmanship defects.

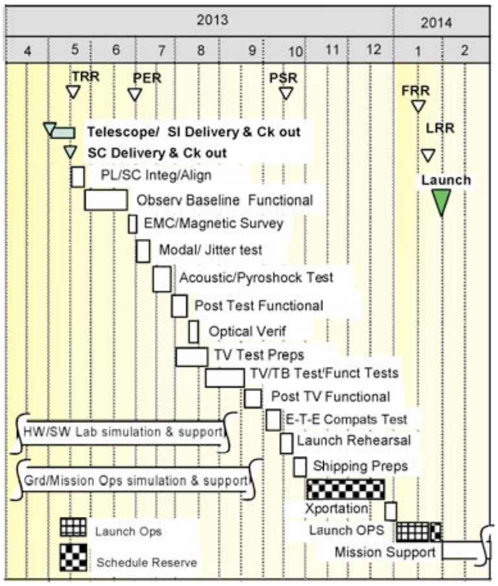


Figure 9 - Original Observatory I&T Timeline

Launch Support. LM will support final mission operational testing prior to launch. The Observatory will be prepared and transported to the pad. The launch vehicle contractor will move the spacecraft and stack it on top of the Atlas rocket.

On-Orbit Support. The SC health and status will be check-out and verified during the first 30 days of orbit where commands, telemetry and measurements will be calibrated. During all critical phases of the mission, the spacecraft will be controlled by fully trained and qualified flight control team on a 3 shift, 24 hour basis.

Cost Estimates

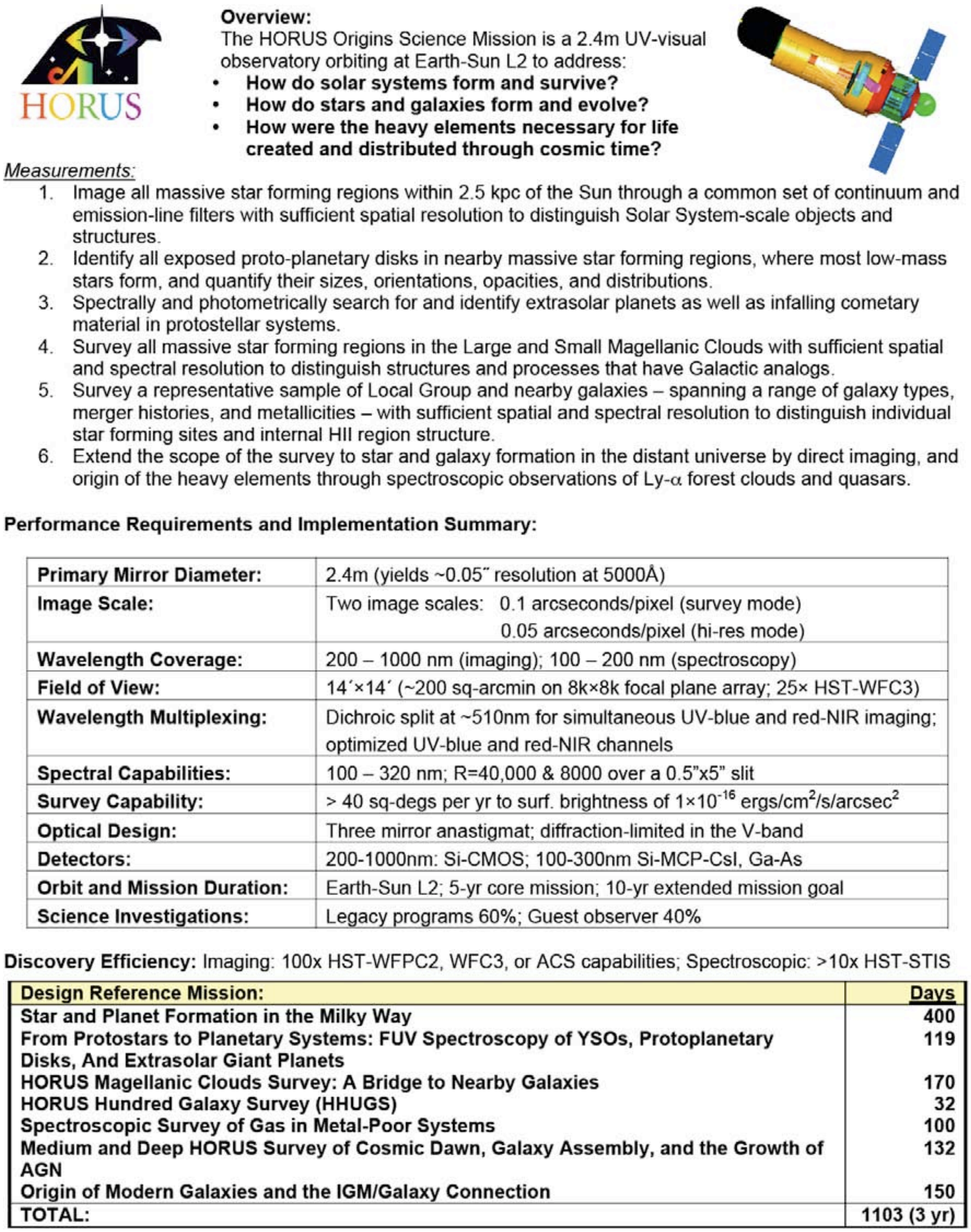
The *HORUS* mission cost estimate (**Figure 10**) was derived through a bottom-up process utilizing actual comparisons on similar mission hardware and experience. Telescope and focal plane array/electronics costs are based on inputs from ITT and RSC. Spacecraft cost is based on heritage data of the "as-built" *Spitzer* spacecraft. The Ground System cost data were estimated based on comparable costs from *Spitzer* and *Ikonos*.

Item		FY04 $M
1	Spacecraft Bus	100
2	Payload: Optics	230
3	Payload: Instruments	207
4	SE(SC SE,System SE, PA, Mission Design)	61
5	PM(SC PM, systen PM, Insight/Oversight, Travel	41
6	IAT(SC and system level Testing, Integration of PL, STL, EGSE/MGSE, LV IAT)	32
7	Mission Ops Plan/ Ground	6
8	O&S (Phase E)	8
9	Phase A / B	10
10	Science Team / Science Ops	55
	Subtotal	**751**
	W/30% Contingency	**976**
11	Atlas V Launch Vehicle	110
	Total	**1086**

Figure 10 - Original *HORUS* Mission Cost Summary
(Partnership on SI's, FGS, S/C, and Ops could keep cost to NASA <$650M)

A cost reserve of about 30% (excluding the launch vehicle) is included in this estimate. This reserve was derived by a risk analysis together with prudent margin within the program constraints. Reserve funds will be allocated to mitigate risks actually encountered. Reserve allocations are 40% through CDR, 30% through fabrication and system assembly and 30% through test and launch.

Summary



HORUS

Overview:
The HORUS Origins Science Mission is a 2.4m UV-visual observatory orbiting at Earth-Sun L2 to address:

- **How do solar systems form and survive?**
- **How do stars and galaxies form and evolve?**
- **How were the heavy elements necessary for life created and distributed through cosmic time?**

Measurements:

1. Image all massive star forming regions within 2.5 kpc of the Sun through a common set of continuum and emission-line filters with sufficient spatial resolution to distinguish Solar System-scale objects and structures.
2. Identify all exposed proto-planetary disks in nearby massive star forming regions, where most low-mass stars form, and quantify their sizes, orientations, opacities, and distributions.
3. Spectrally and photometrically search for and identify extrasolar planets as well as infalling cometary material in protostellar systems.
4. Survey all massive star forming regions in the Large and Small Magellanic Clouds with sufficient spatial and spectral resolution to distinguish structures and processes that have Galactic analogs.
5. Survey a representative sample of Local Group and nearby galaxies – spanning a range of galaxy types, merger histories, and metallicities – with sufficient spatial and spectral resolution to distinguish individual star forming sites and internal HII region structure.
6. Extend the scope of the survey to star and galaxy formation in the distant universe by direct imaging, and origin of the heavy elements through spectroscopic observations of Ly-α forest clouds and quasars.

Performance Requirements and Implementation Summary:

Primary Mirror Diameter:	2.4m (yields ~0.05″ resolution at 5000Å)
Image Scale:	Two image scales: 0.1 arcseconds/pixel (survey mode) 0.05 arcseconds/pixel (hi-res mode)
Wavelength Coverage:	200 – 1000 nm (imaging); 100 – 200 nm (spectroscopy)
Field of View:	14′×14′ (~200 sq-arcmin on 8k×8k focal plane array; 25× HST-WFC3)
Wavelength Multiplexing:	Dichroic split at ~510nm for simultaneous UV-blue and red-NIR imaging; optimized UV-blue and red-NIR channels
Spectral Capabilities:	100 – 320 nm; R=40,000 & 8000 over a 0.5"x5" slit
Survey Capability:	> 40 sq-degs per yr to surf. brightness of 1×10^{-16} ergs/cm^2/s/arcsec^2
Optical Design:	Three mirror anastigmat; diffraction-limited in the V-band
Detectors:	200-1000nm: Si-CMOS; 100-300nm Si-MCP-CsI, Ga-As
Orbit and Mission Duration:	Earth-Sun L2; 5-yr core mission; 10-yr extended mission goal
Science Investigations:	Legacy programs 60%; Guest observer 40%

Discovery Efficiency: Imaging: 100x HST-WFPC2, WFC3, or ACS capabilities; Spectroscopic: >10x HST-STIS

Design Reference Mission:	**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)**

References

[1] Scowen et al., SWP, "*Understanding Global Galactic Star Formation*"

[2] Scowen et al., SWP, "*From Protostars to Planetary Systems: FUV Spectroscopy*"

[3] Scowen et al., SWP, "*The Magellanic Clouds Survey – a Bridge to Nearby Galaxies*"

[4] Jansen et al., SWP, "*A Systematic Study of the Stellar Populations and ISM in Galaxies out to the Virgo Cluster*"

[5] Jansen et al., SWP, "*Galaxy Assembly and SMBH/AGN Growth from Cosmic Dawn to the End of Reionization*"

[6] Scowen et al., TWP, "*Large Focal Plane Arrays for Future Missions*"