CASTOR Status and Update

The Cosmological Advanced Survey Telescope for Optical and uv Research

John Hutchings and Patrick Côté (NRC-HAA)

Summary:

- CASTOR is the top space astronomy priority in Canada's decadal plan (LRP2020).

- After several years of concept and technical studies, the mission is preparing for flight with final technical (STDP) and mission definition (phase 0) contracts. These will be complete by mid-2023.

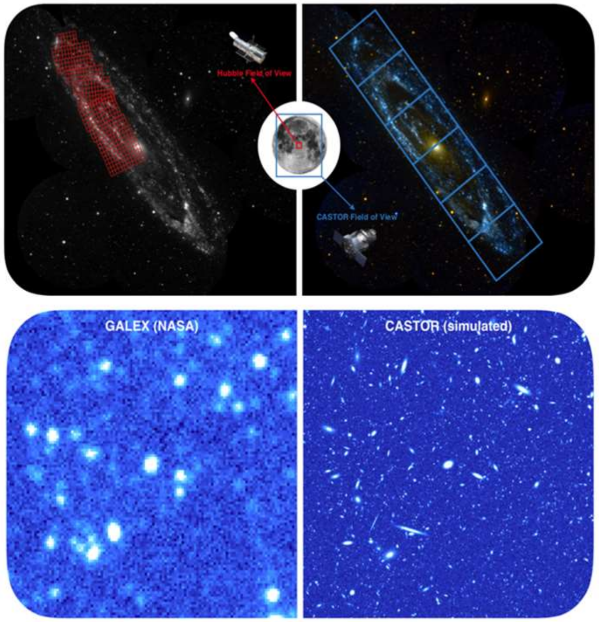
- Significant partnerships are in development on the same timescale, with ISRO, NASA/JPL, and UKSA.

- Further participations are still welcome.

CASTOR Capabilities

The Cosmological Advanced Survey Telescope for Optical and uv Research

- **CASTOR is Canada's #1 priority in space astronomy for the 2020s**.
  - Wide field (0.25 deg^2) 1m-aperture telescope with Hubble-like resolution (0.15″).
  - Simultaneous UV (150-300nm), u (300-400nm), and g (400-550nm) imaging, to AB~27 mag in ~600s.
  - R~300-420 grism spectroscopy over the full field in the UV and u bands (150-400 nm).
  - R~2000 UV MOS in parallel field (150-300nm).
  - 3-channel photometry fields (~10 ppm precision).
  - Filter option in UV and u bands



A transformative engine for astronomical discoveries

Primary Cosmology survey matched with Euclid, LSST, Roman

Targets of Opportunity photometric & spectroscopic within 1 hour

High-precision proper motions, below Gaia (~20 mag)

3-band exoplanet transit photometry.

SSPO orbit gives >70% observing efficiency.

Parallel UV Multi-object spectrometer

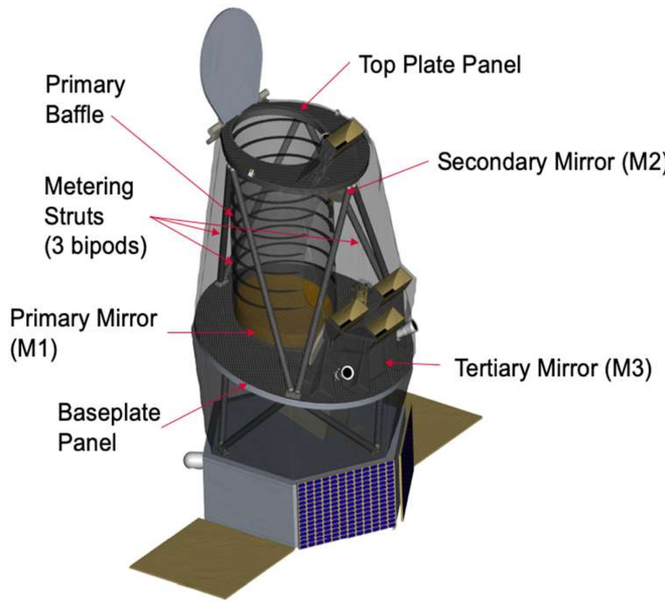
Minimum 5 year mission (Goal: >10 years).

Time domain and proposal science

Telescope Design

The Cosmological Advanced Survey Telescope for Optical and uv Research

- Light-weighted Zerodur primary
- TMA design with ~0.25 deg^2 field of view.
- UV, u, and g bands observed, simultaneously.
- M2 WFE compensation. 0.15″ resolution
- Deployable cover/earth-baffle.
- Fast Steering Mirror for image stabilization.
- g-band sub-window guide stars down to 14th mag.
- Unobscured aperture eliminates diffraction spikes.

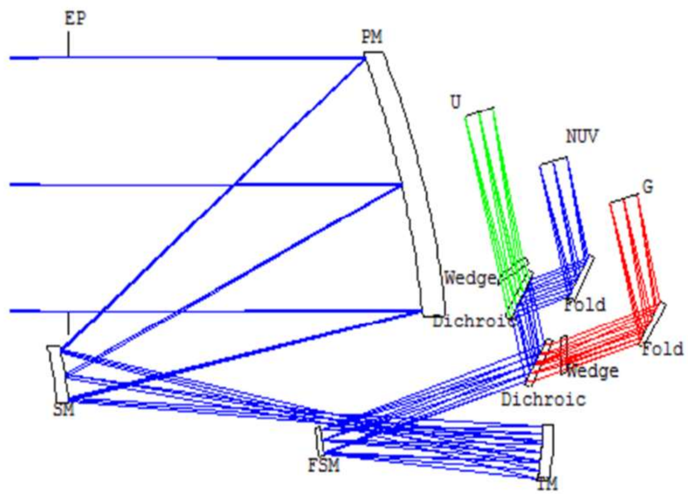


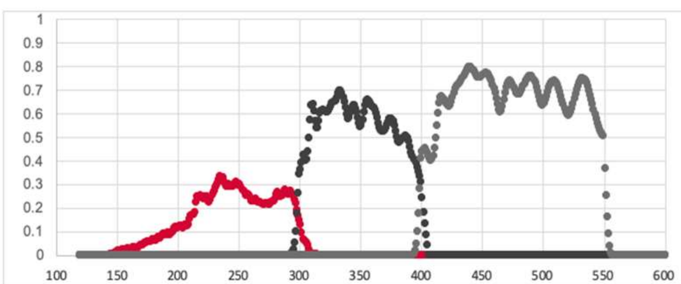
Telescope specifications

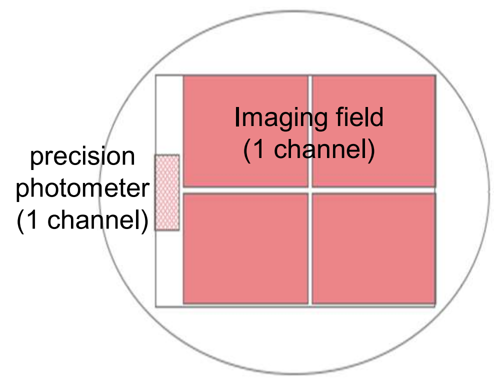
Entrance Pupil Diameter	1000 mm
Field	0.6646 x 0.36 degree
Focal Length	20 m
Image Size	225 x 125 mm
Image Wavebands	G (400 – 550 nm) U (300 – 400 nm) UV (150 – 300 nm)

Focal Plane Arrays

- 3 x 300 Megapixel arrays sampled at 0.1”/pixel.
- Back-illuminated large format CMOS detectors with MBE-defined bandpass filtering.
- Good radiation tolerance.
- Sub-window capability for 100 Hz guide star tracking.
- Low noise: < 2 electrons readout.
- Low dark current: $\lesssim$ 0.01 e/p/s.







T-e2v CIS301 and Active Cooling

10 micron pitch radiation tolerant BICMOS detector comparison:

- T-e2v CIS301 has on board 8-14 bit ADC simplifies ROE, but adds thermal load.
- SRI option is likely compatible with passive radiators cooling design.
- STDP FPA work package has baselined the T-e2v CIS301 BICMOS detector.

Detector Type	Proton Radiation Tolerance	ROE Difficulty	In-Band QE	Space Heritage	Sub-Windowing	Read-Noise	Dark Current	Power
BICCD	Poor	Medium	Good	Yes	No	Very Low	Low	High
BICMOS	Good	Low	Good	Yes	Yes	Low	Low	Low
Si PIN/CMOS	Good	JWST re-use	Good	Yes	Yes	Low	Medium	Low

Detector Type	Pixel Size (µm)	FPA dissipation (1 of 3)	No. of Detectors (Total)	TRL UV	TRL detector	TRP pkg	Cost	IPC	Read-Noise	EOL Operating Temp (est)
T-e2v CIS113 1.9K x 5.8K	12	~540 mW	54	5	4 (12 µm px)	4		<2%	5 e^-	180 K
T-e2v CIS301 9K x 8.6K	10	~6 W	12	5	4 (similar to CIS120)	4		<2%	~2 e^- (TBC)	180 K
SRI 10K x 6K	10	~640 mW	12	5	4 (similar to MK NK)	4		TBD	5 e^-	180 K

Finding Optics Requirements and Exposure-times for CASTOR (FORECASTOR)

Mission planning tools

- Exposure Time Calculator for imaging and photometry.
- Image Simulations for deep fields and resolved stellar populations.
    - Galsim and ArtPop modules customized for CASTOR.
- UVMOS Exposure Time Calculator.
- Grism Exposure Time Calculator.
- Astrometric tools.

- Thanks to Isaac Cheng, Laurie Amen, Jennifer Glover, Laura Ferrarese, Gaël Noirot, Joe Postma, Tyrone Woods, Madeline Marshall.

GUI-Based ETC for Imaging

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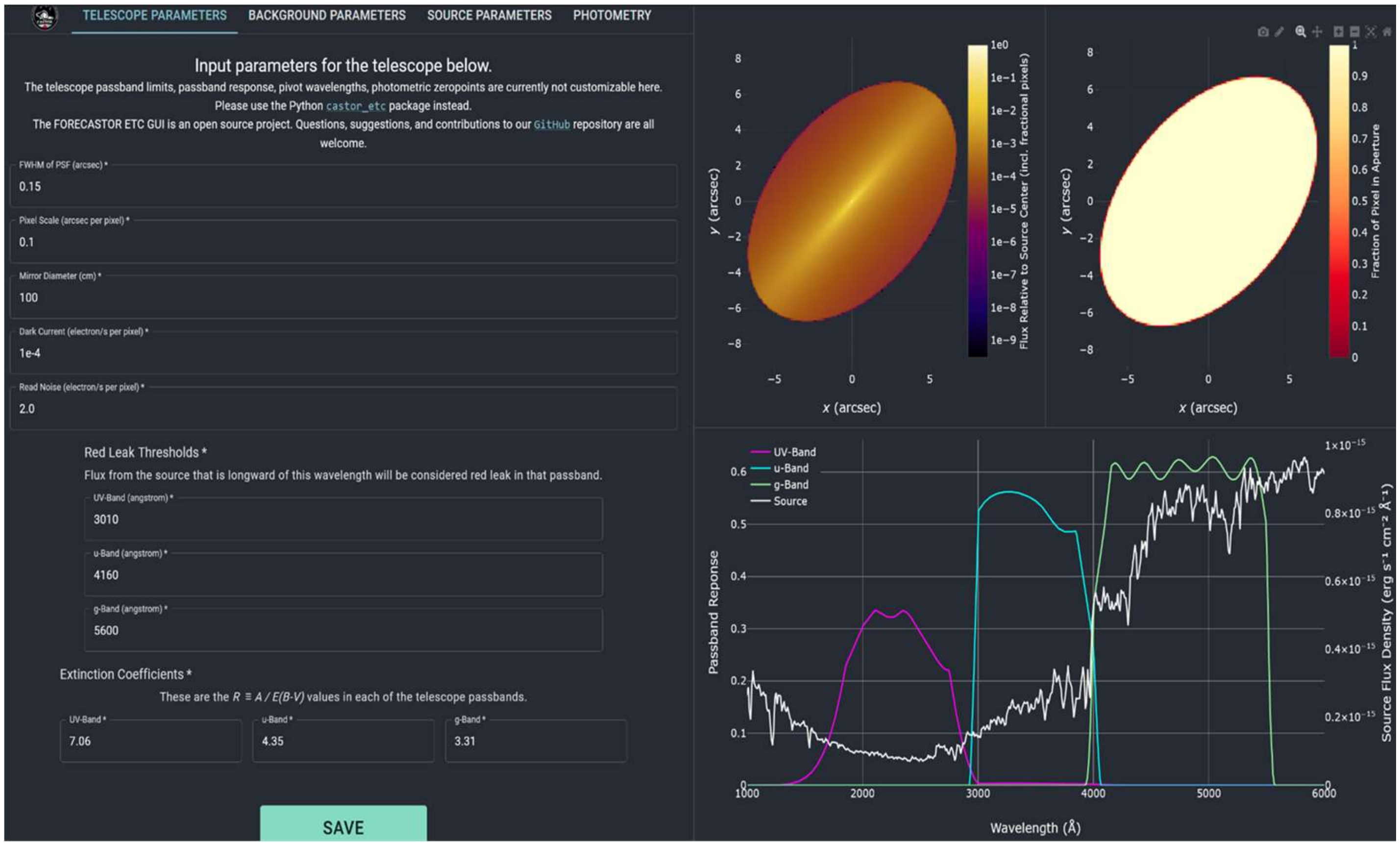


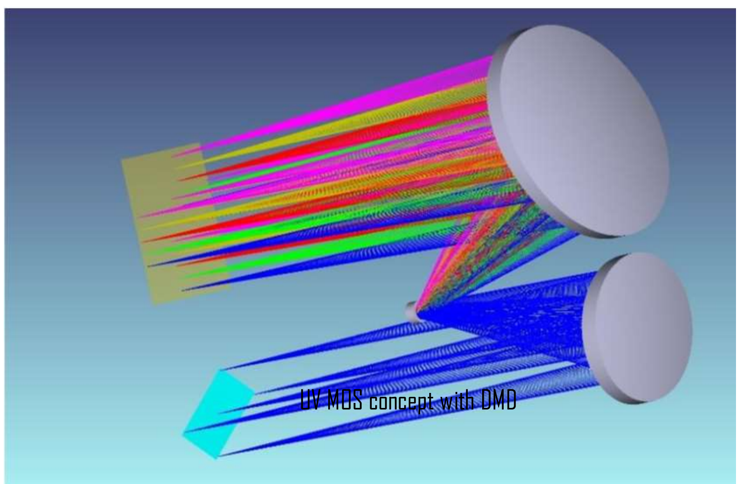
Additional Payload Concepts

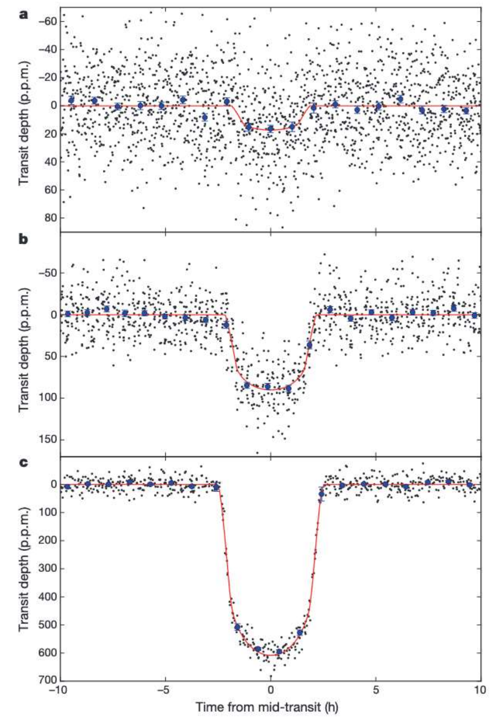
Two Spectroscopic Modes:

1. NUV multi-object spectrometer R ~ 2000, 207” x 117” using DMD selector.
2. Deployable slitless grism spectrometer: R ~ 300 in UV, R ~ 420 in u.

Precision Photometers:

1. Separate field in all three bands (10 ppm precision).





Barclay, Rowe et al. (2013), Nature, 494, 452

Mission Components Breakdown for Partnerships

New hardware items:

- *Cryocooler*
- *Optical ground-links*
- *Filter/grism2 choice*
- *Steerable solar panels*

Technical risk-reduction contract:

- *Optics and baffling*
- *Fast Steering Mirror*
- *Detector and FPA testing*
- *High Precision photometry*
- *UVMOS spectrograph*

Total Baseline Mission	Mission Support		Contingency
			Science Support
			Operation support
			Launch
			Testing (shake and bake)
	Payload	Optical Telescope Assembly	Telescope
			FSM
			Dichroics
			Shutter
		Instruments	Detectors
			FPA
			FPA radiators and straps
			Fine Guidance System
			Spectrographs/GRISM
			Spectrograph/UVMOS
		Payload support structure	
	BUS and power systems		Bus
			Optical links
			Solar Array
	Satellite Engineering Management		System Engineering
			Program Management

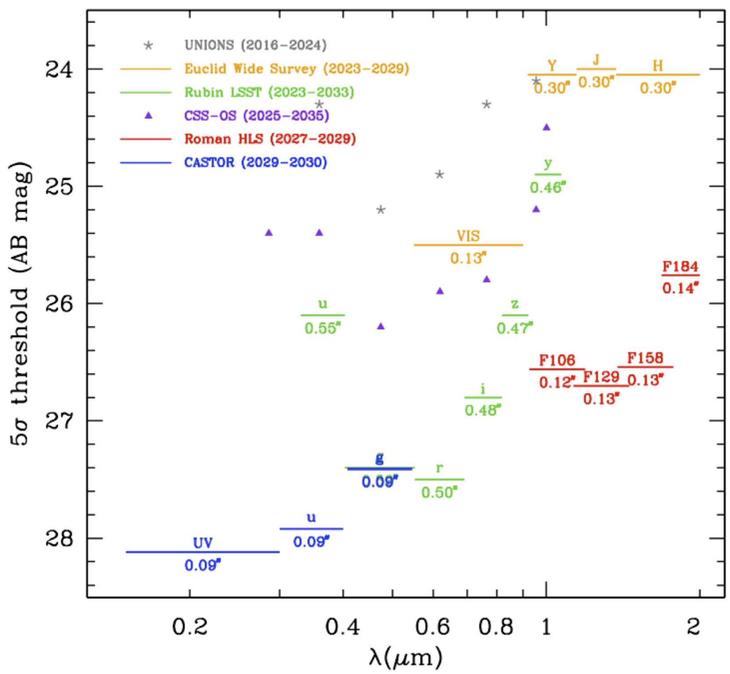
Observing Modes

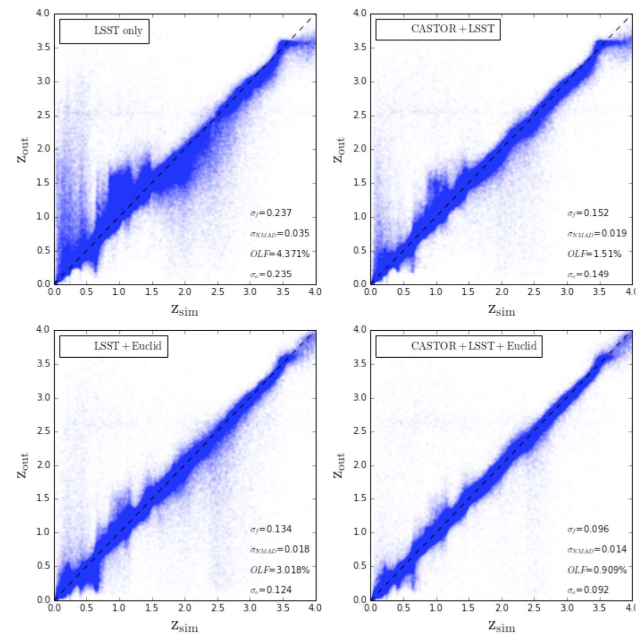
Wide-Field Imaging	
Field of View	0.44° x 0.56° = 0.25 deg^2
Image Quality	FWHM = 0.15" in all channels
Photometric Channels	UV (150-300 nm), u (300-400 nm), g (400-550 nm)
Spacecraft Orientation	Telescope is always pointed > 90° away from the sun. Long duration, continuous observing fields pointed in the anti-sun direction.
Data Volumes	~200 GB/day with 10-min exposures in survey mode. High-speed optical downlink (~10 Gbps)

Spectroscopy and Precision Photometry	
Multi-slit spectroscopy	DMD UV spectroscopy in parallel field (150-300 nm). FoV = 207”x117”, R ≈ 1500.
Slit-less spectroscopy	Full spatial coverage (0.25 deg^2) in UV and u, simultaneously. R ≈ 300 (UV) and 420 (u)
Precision photometry	High-speed photometric monitoring (10 ppm) in the UV-, u- and g-bands using dedicated CMOS detectors.

Strategic Niches

- Current science plan philosophy: legacy surveys (~70%) and GO programs (~30%).
- **Proposed surveys**:
  - Primary Survey: deep UV/u/g imaging of the overlap region (7700 deg^2) between Rubin-WFD and Euclid-Wide, including the Roman HSL.
  - Secondary Surveys: 10 candidates identified by 8 science working groups.





Science Requirements and Traceability

The Cosmological Advanced Survey Telescope for Optical and uv Research

Candidate Legacy Survey	Lead SWG	Traceability				
		Sensitivity	UV/Blue	Image Quality	Field of View	Scheduling
CASTOR Primary Survey	Cosmology	2	1	1	1	5
CASTOR Deep Field	Galaxies	1	1	2	1	5
CASTOR MMA	Time Domain	2	1	2	4	1
CASTOR Cadence	Time Domain	2	1	2	1	1
AGN Reverberation Mapping	AGN	2	1	3	1	2
Galactic Substructures Survey	NFC/Stars	1	3	1	1	2
Galactic Plane Survey	Stars	1	1	1	1	5
Nearby Galaxies Survey	Galaxies/NFC	2	1	1	1	5
Transits and Occultations	Exoplanets	2	1	5	5	1
Bond Albedo	Exoplanets	1	1	5	5	1
Return to Kepler	Exoplanets	1	1	5	5	1
TNO Wide Survey	Solar System	1	4	1	1	3
TNO Deep Survey	Solar System	1	4	2	1	3

Highest Priority — Lowest Priority

1 2 3 4 5

Science Readiness Level 4

- Validation of an end-to-end science investigation concept of high scientific merit.
- Demonstration of high value science objectives, including literature review.
- Validation of science requirements using models or simulations, including sources of error.

TABLE 2-1: SCIENCE READINESS LEVELS

SRL	Description	Mission Phase
1	Basic scientific principles observed and reported	Fundamental research
2	Science investigation defined	SE R&D programs (preparatory phases including: Science Definition, Concept Studies, Science Maturation)
3	Science investigation proof of concept	
4	Science investigation validated using simulated and/or instrument breadboard data	
5	Science investigation validated using analogue and instrument prototype data	CSA Capability Demonstration Programs; Phase 0/A
6	Science investigation validated using (ground) calibrated instrument Engineering Model data products	Phase BCD
7	Science investigation validated using (ground) calibrated instrument Flight Model data products, and analogue science operations, where relevant	
8	Science investigation data production validated through successful mission operations	Phase E operations
9	Science investigation outcomes generated through publication of results	Phase E data analysis or post operations analysis

Science Objectives and Science Plan

Science Readiness Level 4

- Define science investigation traceability matrix.
- Measurement requirements in time and space, including accuracy and precision.
- Instrument performance and functional requirements.
- Flight and ground software requirements, including data acquisition, processing and archiving.

TABLE 3-1 – SCIENCE INVESTIGATION AND REQUIREMENTS

Requirement	Instrument (FPA, Photometer, Spec)	Bands or wavelengths	Sensitivity	Areal coverage	FoV	Depth (SNR)	Sampling	Image quality (arcsec)	PSF stability	Exposure time (sec)	Observing cadence	Scheduling priority	Photometric precision	Astrometric precision	Spectroscopic resolution (R)	SRL
Science Investigation																
Cosmology (DE, Primary)																
Time Domain Astrophysics																
Galaxies and Cosmic Star Formation																
Active Galaxies and SBH																
Near Field Cosmology																
Stellar Astrophysics																
Extra-Solar Planets																
Solar System																

Science Team Structure

The Cosmological Advanced Survey Telescope for Optical and uv Research

- The science team consists of eight Science Working Groups (SWGs), each with a Canadian lead and a representative from each prospective partner. In all, the team numbers some 80 persons.
- Each SWG is developing detailed plans for Legacy Surveys and PI programs. These will be combined to serve shared science goals.
- The mission plan will have time for surveys, PI proposals, TOOs, and parallel programs when precision photometry or UVMOS is prime.

Science Working Group	Lead	India	JPL/IPAC	UK
Cosmology	Katie Mack (Perimeter Institute)	Hum Chand (CUHP)	Jason Rhodes (JPL)	Catherine Heymans (Edinburgh)
Time Domain Astronomy	Maria Drout (Toronto)	Kuntal Misra (ARIES)	Daniel Stern (JPL)	Matt Nichol (Birmingham)
AGN	Sarah Gallagher (Western Ontario)	Vivek. M (IIA)	Andreas Faisst (IPAC)	Poshak Gandhi (Southampton)
Galaxies	Michael Balogh (Waterloo)	Kanak Saha (IUCAA)	Anahita Alavi / Harry Teplitz (IPAC)	Sean McGee (Birmingham)
Near Field Cosmology	Vincent Henault-Brunet (St. Mary's)	Smitha Subramanian (IIA)	Pat Morris (IPAC)	Vicky Scowcroft (Bath) [Ruben Sanchez-Janssen
Stellar Astrophysics	Simon Blouin (Victoria)	Annapurni Subramaniam (IIA)	Pat Morris (IPAC)	Boris Gaensicke (Warwick)
Exoplanets	Jason Rowe (Bishop's)	Thirupathi Sivarani (IIA)	Jessie Christiansen (IPAC)	Suzanne Aigrain (Oxford)
Solar System	JJ Kavelaars (NRC-HAA)	Shashkiran Ganesh (PRL)		Cyrielle Opito (Edinburgh)

CSA Mission Phases

TABLE 1-1 – MISSION DEVELOPMENT CONTEXT FOR PHASE 0

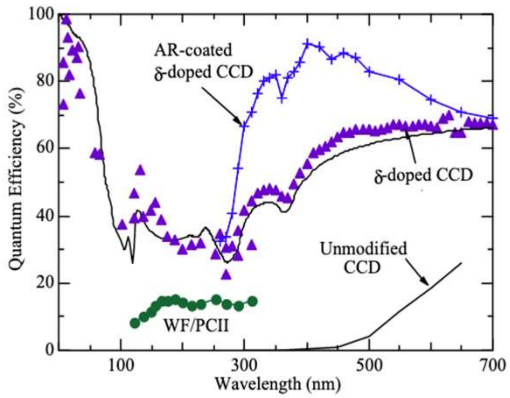
Project Phases	Description	Milestones	Mechanism
-	Science / Technology / Application Development Programs	Produce Science / Technology / Applications required for future missions	Various RFPs
0	Concept (Opportunity assessment and feasibility studies)	Identification and characterization of the intended mission/payload Mission Concept Review (MCR) Mission Requirements Review (MRR)	**Technical RFP (industry)**
A	Concept Development and Option Selection (Trade studies to select baseline mission / payload and science / mission floor) / System Definition	System Requirements Review (SRR)	Phase A RFP
B	Preliminary Design	Preliminary Design Review (PDR)	Usually Mission RFP by Phase (B/C+D)
C	Detailed Design	Critical Design Review (CDR)	
D	Manufacturing and Assembly, Integration and Testing (AIT)	Acceptance Review (AR) / Operations Readiness Review (ORR) Others	
E	Operations	Decommissioning Review (DR)	Various RFPs (if required)
F	Disposal	-	Various RFPs

Partner Contributions: Ongoing and Planned

The Cosmological Advanced Survey Telescope for Optical and uv Research

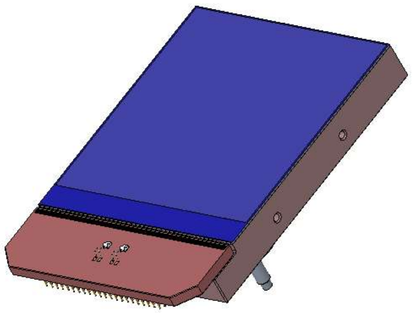
Focal Plane Arrays (UV/u/g) — [JPL]

- Advanced processing of large-format BICMOS detectors.
- QE enhancement (i.e., delta-doping) of detectors and passband definition via antireflection coatings.
- Readout electronics, packaging and software.
- Assembly and testing of three focal plane arrays.
- Survey development and scientific exploitation.
- Data centre, contributions to data processing (IPAC).



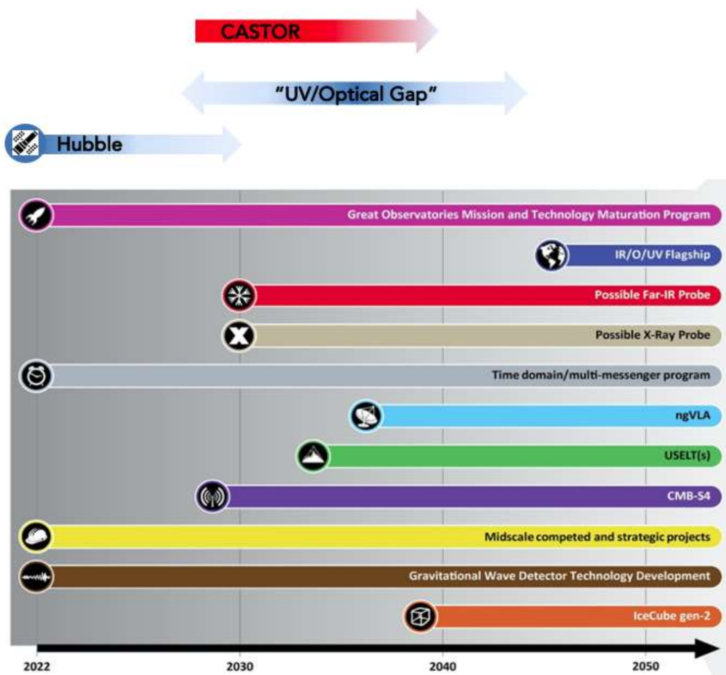
UV-Optimized Optical Elements & Detectors — [UK]

- Next-generation T-e2v CIS301 detectors.
- Detector characterization and space qualification.
- Optimized UV/optical elements and hardware components.
- Survey development and scientific exploitation.
- The UK team is currently responding to a new UKSA program for bilateral space science and exploration missions with NASA, CSA or JAXA.



CASTOR and MIDEX Complementarity

The Cosmological Advanced Survey Telescope for Optical and uv Research



Astro2020

Mission Comparison

	CASTOR	STAR-X UVT	UVEX
Aperture (cm)	**100**	30	75
Field of view (deg^2)	0.25	**1.0**	**12.25**
Wavelength Coverage	150 — 550	160 — 300	139 — 270
Bands (nm)	**150-300 (UV) 300-400 (u) 400-550 (g) 218-292 (UV') 295-355 (u')**	180 (FUV) 275 (NUV)	139 — 270 (FUV) 203 — 270 (NUV)
Image Quality (")	**0.15**	< 4.0	2.25
Sensitivity: 5σ (1000s)	**27.5, 27.4, 27.0**	≥ 22.7, ≥ 22.3	24.6, 24.6
Average TO time (hrs)	< 3	< 2	< 3
Launch readiness date	2027	2028	2028
Mission duration (yrs)	**≥5**	?	2

CASTOR and MIDEX Imaging Comparison

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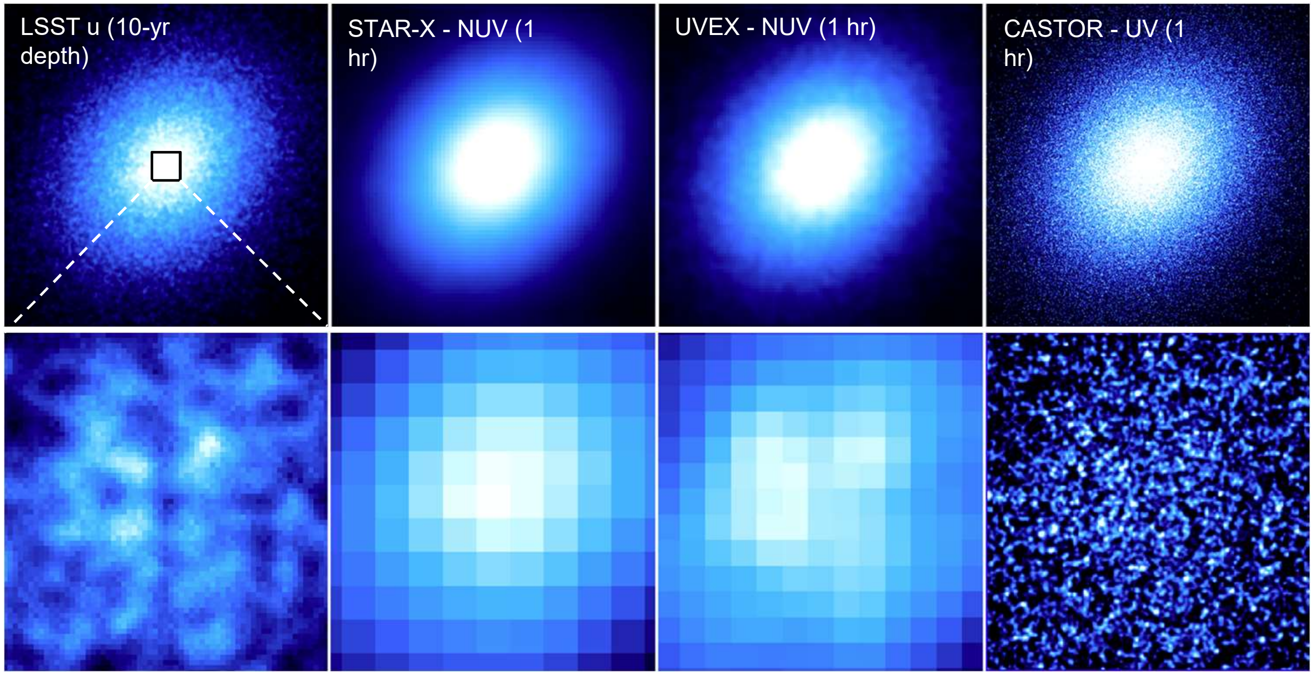
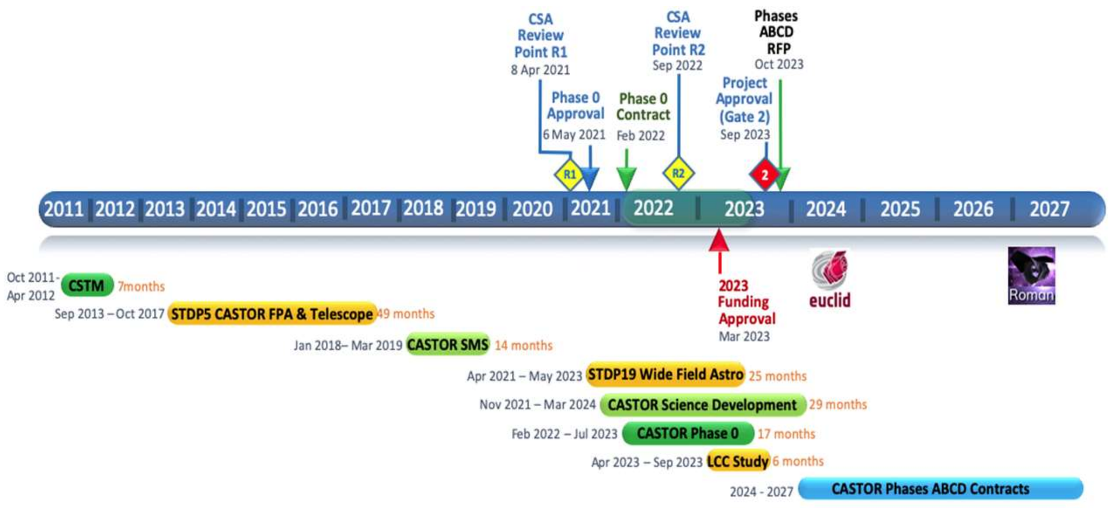


Schedule and Collaborations

The Cosmological Advanced Survey Telescope for Optical and uv Research

- Coordinated CSA science (Phase 0) and technology (risk-reduction) studies are underway (both concluding in spring 2023) with the participation of JPL/USA, India and the UK.
- CSA is aiming for government approval in late 2023, ideally with significant contributions by NASA/USA, UKSA/UK and India/ISRO. The door is still open to additional partners.
- Canada seeks initial partner commitments by early 2023, but it would be feasible to proceed with a later infusion of funds, subject to further discussion.



CASTOR Summary and Capabilities

The Cosmological Advanced Survey Telescope for Optical and uv Research

- **An engine for astronomical discoveries**

  - A "Primary Survey", matched to LSST, Roman and Euclid, with vast legacy value.
  - Multi-Messenger and Time Domain Astronomy: UV ToO photometric and spectroscopic follow-up of kilonovae and other transients within ~3 hours. MIDEX/Ultrasat synergy.
  - High-speed UV/optical photometer for exoplanet transits to characterize Earth-like planets and stellar hosts (Kepler heritage, TESS synergy).
  - Astrometric capabilities well matched to build on the heritage of HST and Gaia.
  - A technology development pathway to a 6m IROUV in the 2040s, while bridging the post-Hubble "UV/optical gap".