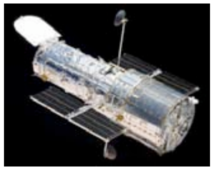
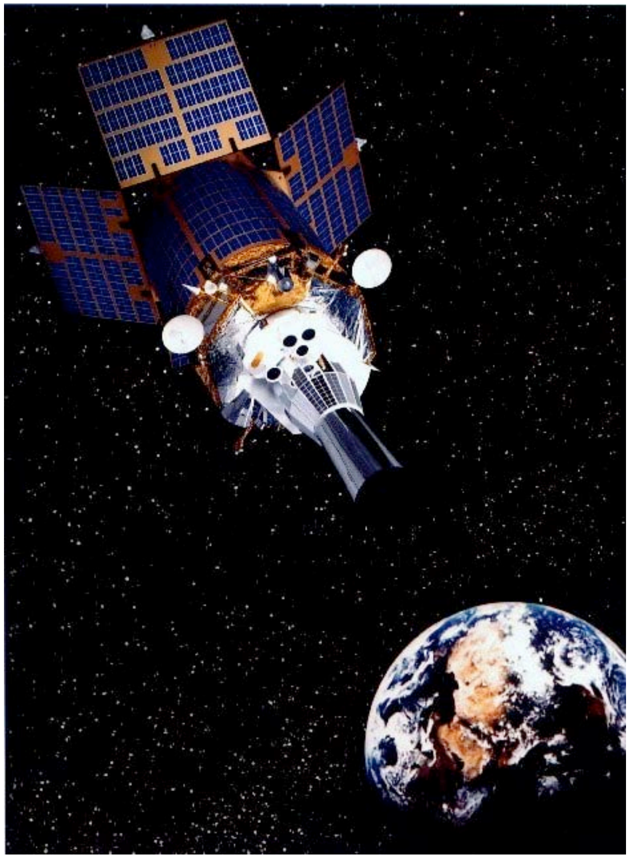
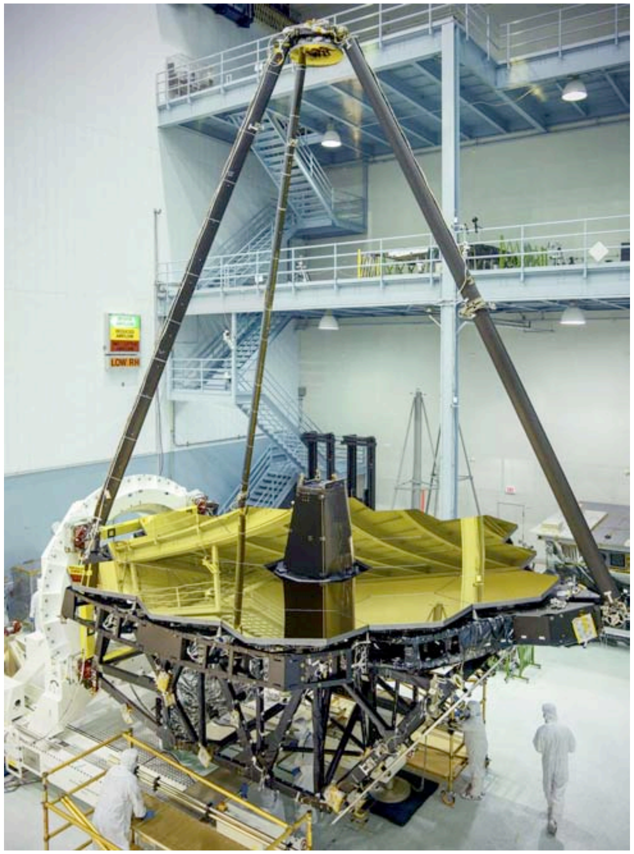


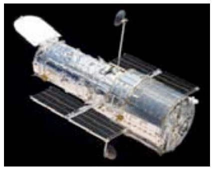
Space Telescopes & Optical Instruments

Dean Spieth



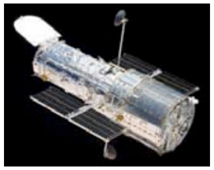
Seminar
2024





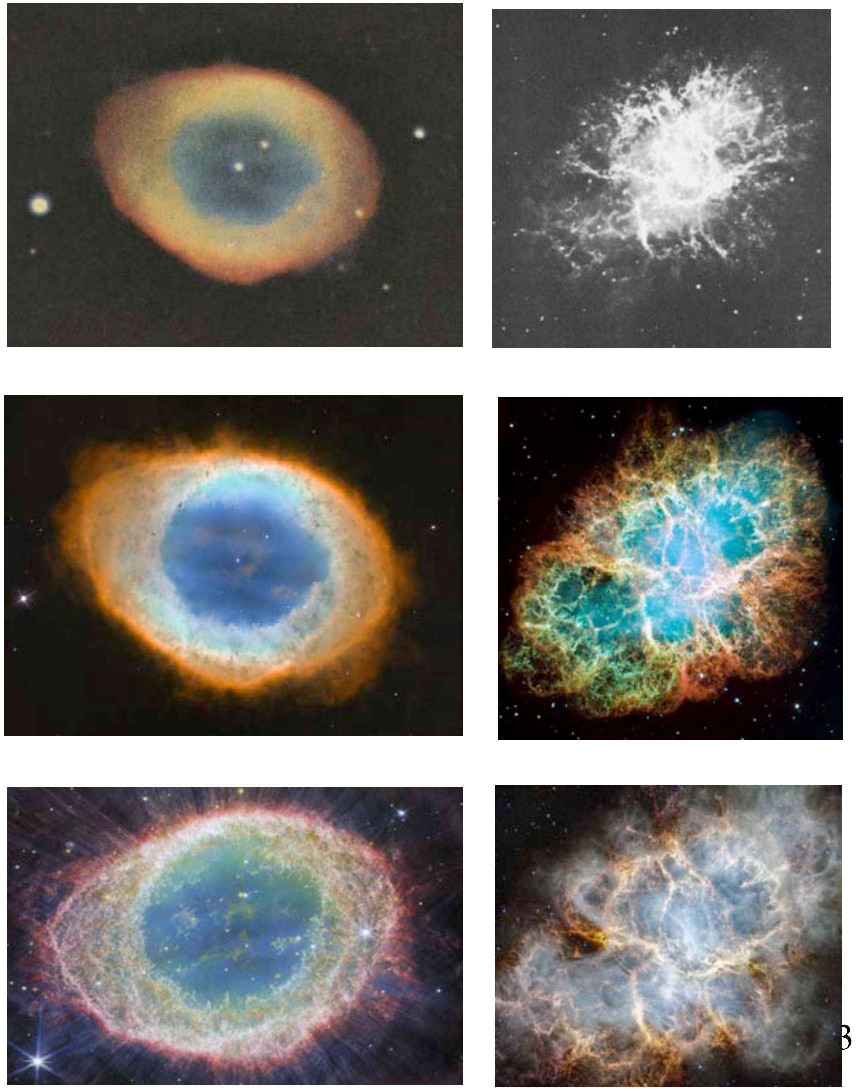
Topics

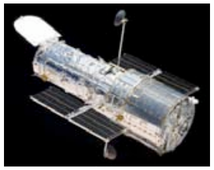
- Brief History, Background & Rationale
- Optical Detectors
- Basic Telescope Designs
- Small Refracting Telescopes - Star Trackers, TESS
- Reflecting Space Telescopes - DI, HiRISE, IRAS, Spitzer, Hubble, JWST
- Schmidt Telescopes - Kepler, DSP, SBIRS
- Radiation Effects
- Solar Telescopes - SOHO, SDO
- Space Optical Instruments - Cameras (Images) & Spectrometers
- Summary



Ground vs Space Based Telescopes

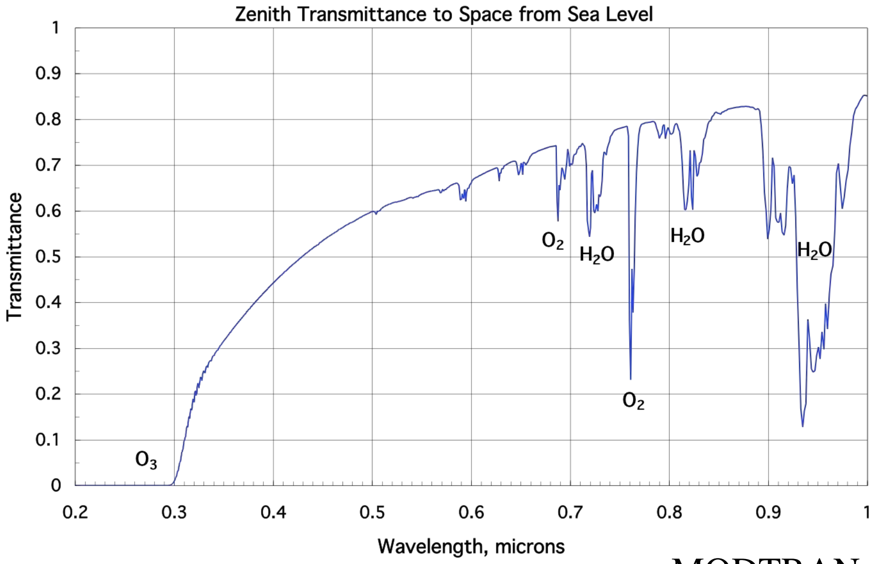
- Up Until the 1990s, the 200 inch (5 meter) Mt Palomar Telescope was the best
    - Limited by the atmosphere & film prior to the 1990s on clear nights
- The Hubble Space Telescope HST (2.5 meter) was Launched in 1990, vision corrected in 1993 with the WFPC#2 & COSTAR during Shuttle Servicing Mission #1
- The James Webb Space Telescope JWST (~6 meter) was Launched in 2021 using infrared images shown in false visible colors

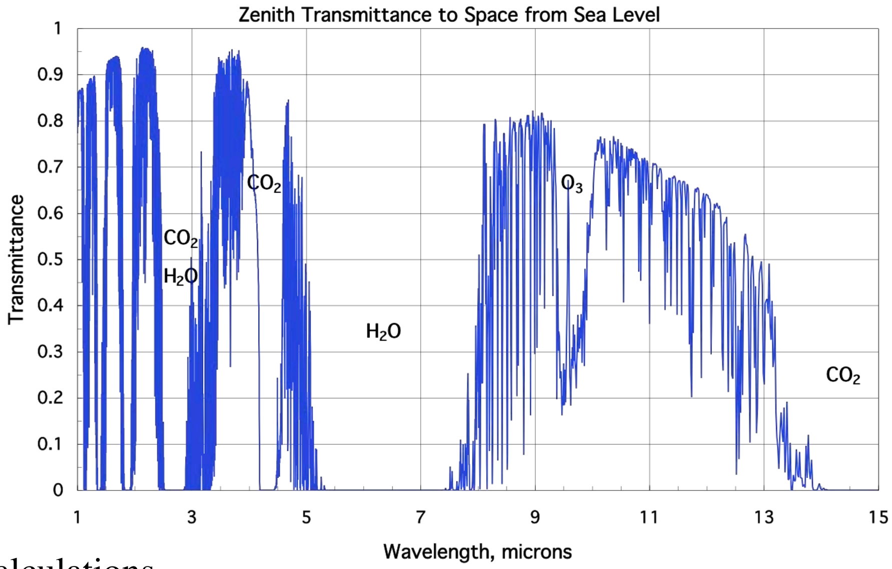




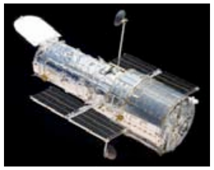
Why Space Telescopes for Astronomy?

- High Stray Light Scattering from the Sky for Earth-based Telescopes
  - Daytime solar scattering (stars not visible)
  - Nighttime city lights & lunar stray light (Milky Way not visible)
- Looking Up from the Ground has More Problems
  - Cannot see through clouds with optical instruments - not UV, not VIS, not IR!
  - Atmospheric turbulence limits resolution to ~1 arcsecond, which adaptive optics (AO) can sometimes improve
  - The atmosphere absorbs much of the Ultraviolet (UV) Light & much of the Infrared (IR) Light - virtually total absorption above 14 μ until RF
  - Elon Musk’s Starlink satellites cause tracks in images & orbital debris



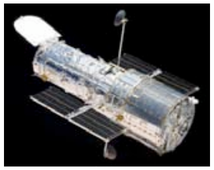


MODTRAN calculations



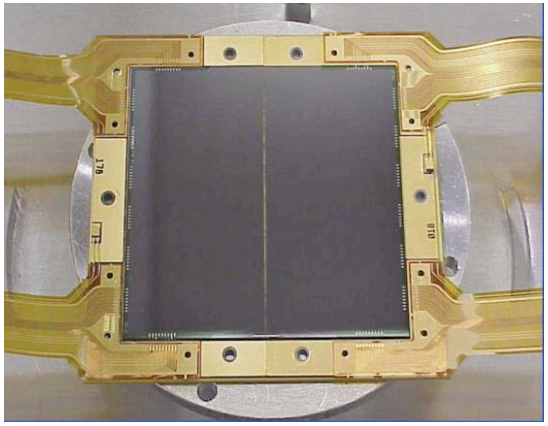
Typical Construction Practices

- Least Expensive Design uses All Aluminum Structure and Mirrors
  - Example is the Pluto imager (called Ralph built by Ball Aerospace)
  - Aluminum has the highest Coefficient of Thermal Expansion (CTE) among metals, but use of similar CTE materials enables an athermal design (focus doesn't change much with temperature)
- All Beryllium (Be) Structure and Mirrors are Very Lightweight & Stiff (good for pointing), and Work Well at Cold Cryogenic Temperatures
  - Expensive and safety issues, so only a few companies can safely machine, grind and polish Be materials
  - JWST "cryogenic" mirror assemblies and some defense sensors
- Carbon Composite Structure ("graphite" cyanate ester) and Low Expansion Glass (Zerodur and fused silica) give Great Performance
  - Also expensive but very lightweight
  - Kepler space telescope
  - Hubble space telescope

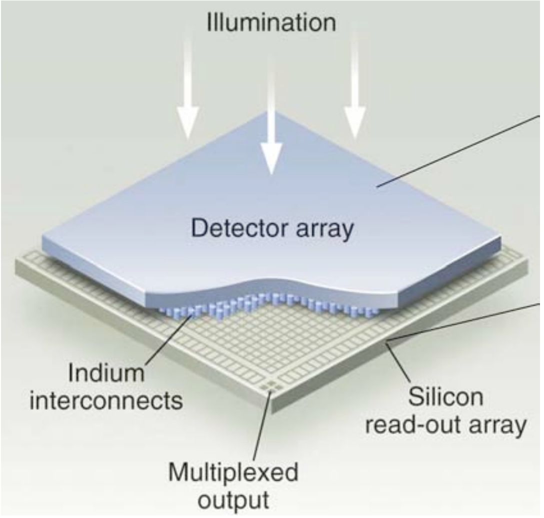


Breakthrough Detector Technologies

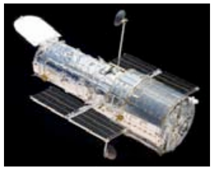
- CCD Array Detectors (UV-VIS-Near IR) started flying on photorecon satellites ~1977 per Pres Carter
  - TV video was previously used in the 1960s-70s on weather satellites with poor resolution, then scaned single element detectors
  - Replaced film on photoreconnaissance satellites in the mid-1980s
  - Still used in UV-VIS imaging sensors for space
  - Most commercial cameras use CMOS, not CCDs
- CMOS Array Detectors for Space Telescopes are Primarily used in the Infrared
  - Detector arrays indium bump bonded to silicon readout chips
    - Examples: InSb, MCT, doped silicon like Si:As
  - Custom CMOS with analog outputs generally rad-hard to ~100 to 200 krads
  - Amplifiers behind each pixel (DI, SF, CTIA)



Hubble WFC3 Si CCD



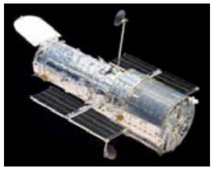
Detector/ CMOS ROIC



Some Optical Detectors of Interest

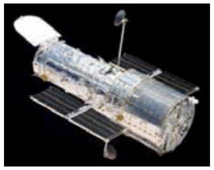
Region	QE (with AR)	Detector Temp	Comments
Ultraviolet (0.1-0.4 μ)			VUV <0.2 μm = 200 nm
PMT		Ambient	High Voltage, Single Detector
Microchannel Plate	~20-34%	Ambient	High Voltage, Array, e.g. MAMA CsI
Si CCD (0.25-0.4μ)	~20-80%	>230K	"Noisy" compared to PMT
Visible & NIR (0.4-1 μ)			Visible is ~0.4-0.7μm = 400-700 nm
Si CCD	80-90%	>180K &	Low noise; many satellite sensors
Si CMOS	70-90%	Ambient	Lower cost; LANDSAT 8&9 OLI
SWIR (1-3 μ)			Short Wave Infrared
PbS	20-30%	>193K	Passive Radiator for Space; DSP
MCT (short cutoff)	80-90%	<170K	Passive Radiator; SBIRS, JWST, OLI
MWIR (3-5 μ)			Mid wave DOD; "short" wave astronomy
InSb	80-90%	<80K	Cryocooler or LN2, Low Cost, Tactical
MCT (mid cutoff)	70-80%	~100K	Passive Radiator; SBIRS, JWST
LWIR (8-14 μ)			Long wave; mid wave for astronomy
MCT	60-80%	<80K	Cryocooler; GOES ABI, JPSS VIIRS
VLWIR (to 28 μ)			Astronomers consider this mid wave
Si:As Extrinsic IBC	40-70%	~5-7K	JWST; LHe, Cryogens, e.g. OAMP
Astronomical LWIR			<200 μm
Ge:Ga	~5%	<2K	Cryogens, e.g. IRAS, Spitzer (SIRTF)

See Rogalski and Bielecki (2004), Detection of Optical Radiation, Bulletin Polish Academy Sci, V 52, #1.



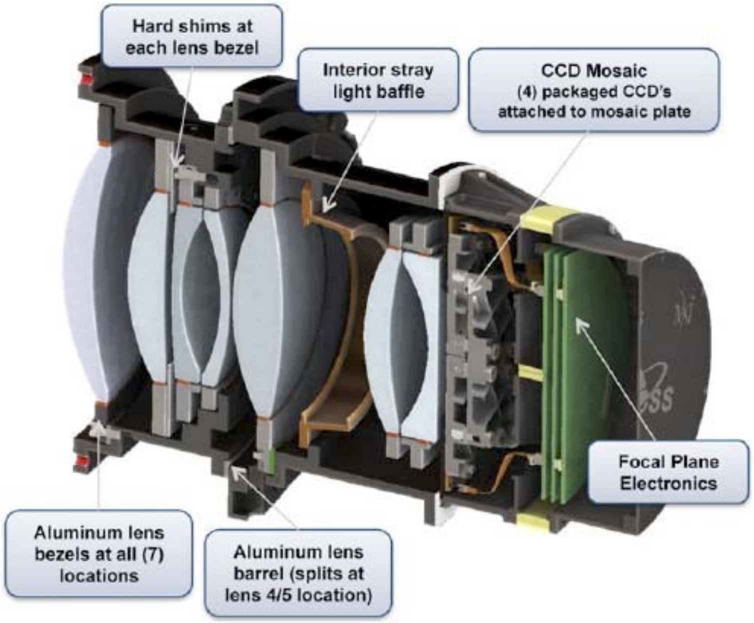
Overview of Optical Telescope Designs

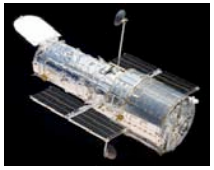
- A Refracting Telescope was first used to draw the Craters of the Moon and Moons of Jupiter in the 17th century by Thomas Harriot and Galileo Galilei
  - Has chromatic aberrations due to refractive index of lenses varying versus wavelength
    - Partially solved by using multiple elements with different glass materials in the 18th century
  - Transmissive lenses can have a wide field-of-view (WFOV)
  - Weight is an issue for large lenses, so refractors are typically smaller telescopes
  - Transiting Exoplanet Survey Satellite (TESS) uses four WFOV small telescopes
- Reflecting Mirror Telescopes were invented later in the 17th century
  - Sir Isaac Newton is credited with inventing the Newtonian telescope
  - On-axis Cassegrain telescopes have a narrow field-of-view (NFOV)
  - Off-axis telescopes have no central obscuration
    - Earth science instruments (GOES Imager, Operational Landsat Imager, VIIRS)
- Catadioptric (Compound) Telescopes combine Transmissive and Reflective optics
  - Schmidt telescopes invented in the 1930s can obtain ~12 degree total FOV
    - Kepler - planet finder via slight occultation of stars - launched in 2009
    - Ballistic missile warning like DSP and SBIRS telescopes
  - Baker Nunn, Maksutov, etc.



Refracting Space Telescopes – TESS

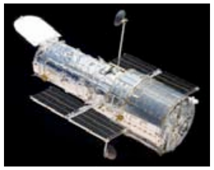
- TESS has four small refracting telescopes, similar to a telephoto lens
- Launched in 2018 to search for planets around bright, nearest stars
- Each telescope, 4.1 inch aperture, f/1.4, 24x24 deg FOV, red and Near IR
- Four silicon detector CCDs per telescope
  - Better quantum efficiency (QE) and lower detector noise at relatively fast readout rates than CMOS, although CMOS is catching up
  - 2048x2048x15 micron active pixels per CCD (2Kx4K frame transfer)
- MIT Lincoln Lab optical design, ref Chrisp et.al. (2015), Optical Design for the Transiting Exoplanet Survey Satellite, SPIE conference, June 2015. https://tess.mit.edu





Reflecting Space Telescopes

- Reflectors maintain focus at all UV, visible and IR wavelengths
- Reflectors weigh less than refractors for large systems
- On axis is common for large telescopes - but is like looking thru a soda straw (i.e., a NFOV)
  - Classic Cassegrain uses a parabolic primary mirror
    - Deep Impact imager has a 2nd hyperbolic mirror
    - HiRISE Mars imaging camera is actually a 3 mirror anastigmat
  - Ritchey-Chretien design used for most large telescopes (hyperbolic primary & secondary)
    - Hubble, 2.4 m f/24 at prime focus
    - Spitzer Space Telescope, aka previously SIRTF
- Off-axis is popular for smaller Earth imaging space telescopes
  - No central obscuration but off-axis aberrations acceptable
  - Weather imagers like VIIRS on NPP/JPSS and GOES imagers

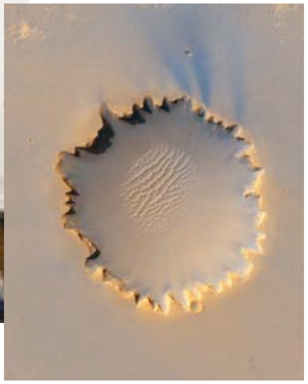


Some Cassegrain Space Telescopes

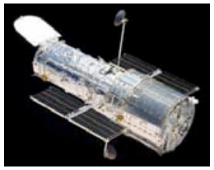
- Deep Impact High Resolution Imager (HRI), 30 cm Cassegrain telescope, f/35 at detector, beamsplitter for MWIR Hawaii 1Kx1K CMOS and VIS 1Kx1K CCD with filter wheel. Composite structure. Spacecraft pointing. ~60 kg, <60 W. Launched 2004.

Comet Temple 1 Impact

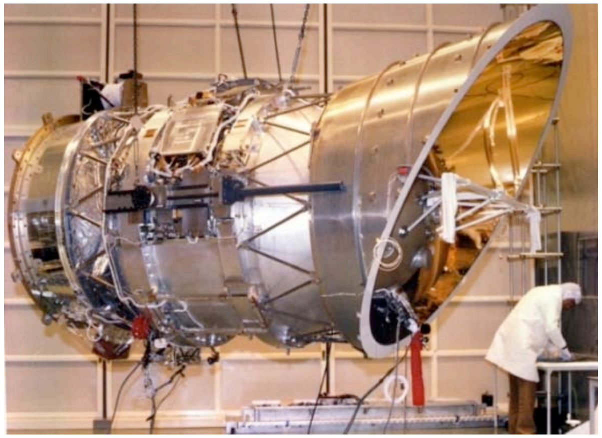
- HiRISE Mars Imager, 50 cm, f/8.4 at Cassegrain focus, f/24 after tertiary, 3 mirror anastigmat + fold mirrors, 14 CCDs with 12 μm pixels & various filters, 1 μrad IFOV, Mars GSD <1/3 m/pixel, color. Focus mechanism, composite optical bench. ~65 kg, 60 W. Launched 2005 on MRO.



Victoria Crater



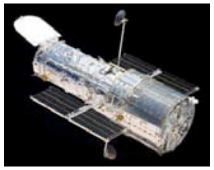
Infrared Space Telescopes



- The Infrared Astronomy Satellite (IRAS), a 60 cm Ritchey-Chretien telescope, f/9.6, LWIR (8 to 120 μm), focal plane cryogenically cooled to 2.7K (-455F). 62 discrete detectors. Launched 1983.

- The Cryo-Telescope Assembly (CTA), an 85 cm Ritchey-Chretien beryllium telescope within a super-fluid helium enclosure, f/12, LWIR (3 to 180 μm). Beamsplitters send signals to three science instruments cooled to ~1.4K. (The heart of the Spitzer Space Telescope, aka SIRTF.) Launched 2002.

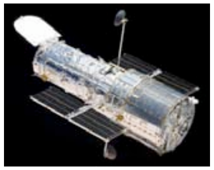
Note: Herschel 3.5 m was the largest space telescope, 55 to 672 μm



The Big Reflecting Space Telescopes

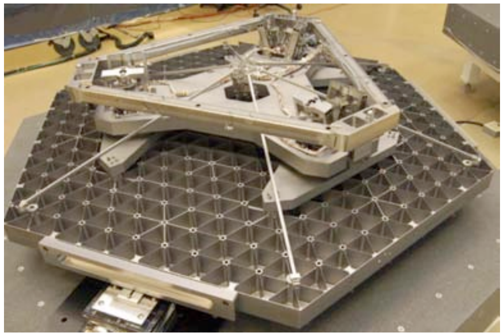
- The Hubble Space Telescope, 2.4m (100”) f/24 Ritchey-Chretien telescope, UV-VIS-NIR split to multiple instruments, launched 1990, altitude ~570 km LEO
  - Lockheed, prime contractor
  - COSTAR & WFPC2 fixed spherical aberration problem in 1993 (SM1)
- Digital Photoreconnaissance Satellites are Classified. Note that 2.4m f/8 mirror systems were donated to NASA in 2012.
- Older Film Photoreconnaissance Satellites are on display including a Hexagon KH-9 (20” f/3) that held 60 miles of film & a higher resolution GAMBIT (43” f/4)

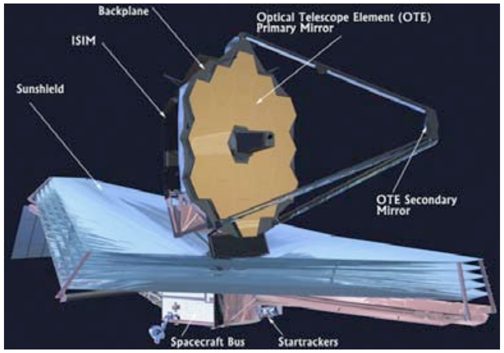
http://www.nro.gov/history/csnr/gambhex/index.html



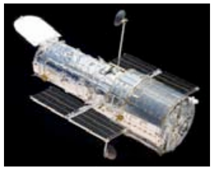
The Largest Space Telescope

- The James Webb Space Telescope (JWST), aka Next Generation Space Telescope
  - Peering further out into the universe at red-shifted objects in the infrared, launched Dec 25, 2021
  - 0.6-28 µm, <40K, 6½ m wide but 5.68 m equivalent aperture, EFL=131.4 m, 18 segments ea 1.3 m elliptical
  - 7 actuators focus each primary mirror & adjust position to within 10 nm (~0.0004 mil)*
  - Lagrange L2 “orbit”, 1.5 million km
  - Tennis court sized spacecraft (mock-up behind folks at NASA/GSFC)



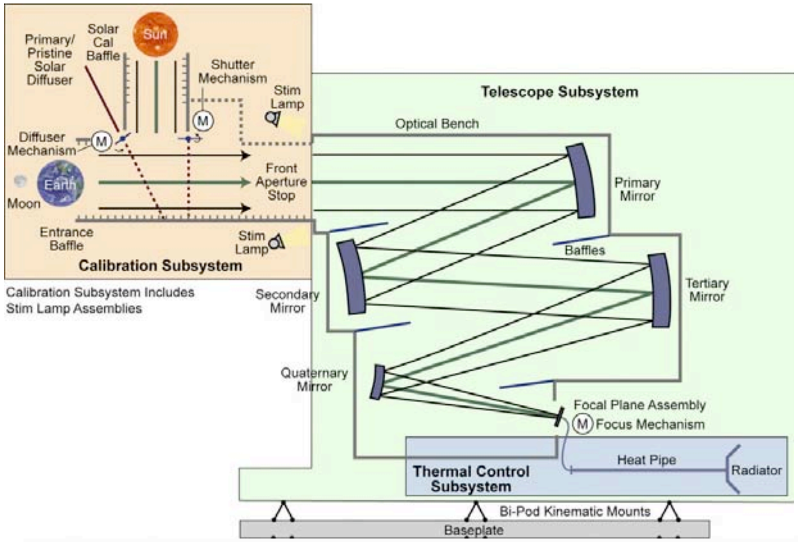


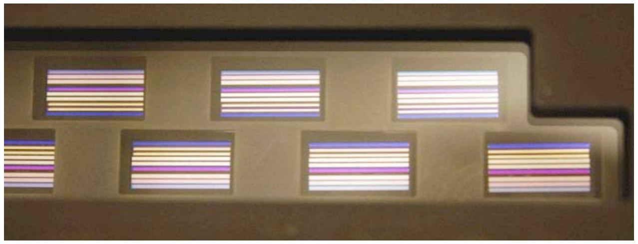
*Bob Warden (2006), Ball Aerospace, Cryogenic Actuators for JWST, Proc 38th Mechanisms Symposium

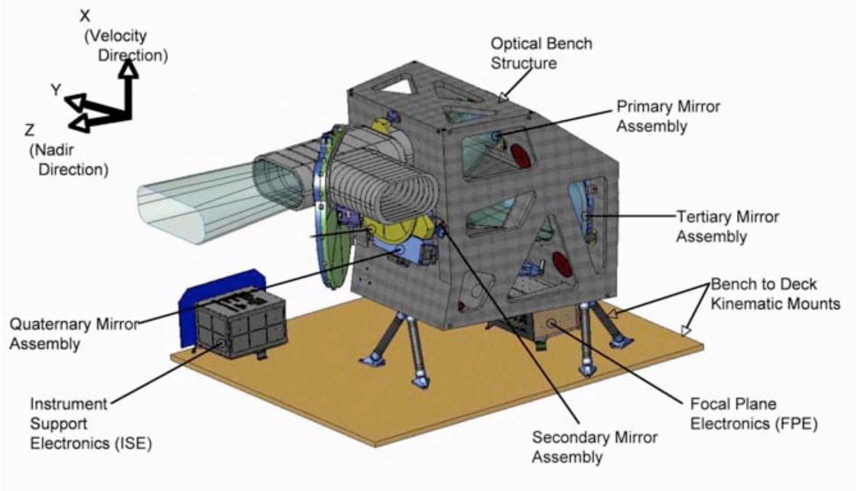


Off-Axis Reflecting Space Telescopes

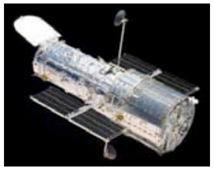
- OLI on Landsat 8 & 9
  - 4 mirrors, solar diffusers
  - Focal Plane Arrays are Staggered Using TDI & Many Filters, Si-PIN & MCT on CMOS





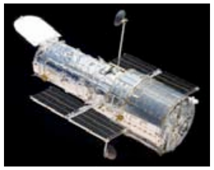


Ed Knight & Geir Kvaran, Ball Aerospace, Landsat-8 Operational Land Imager Design, Remote Sensing, 2014, #6



Catadioptric (Compound) Space Telescopes

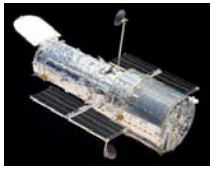
- Schmidt Prime Focus Design for “Wide” Fields-of-View (WFOV)
  - Spherical primary mirror with a front corrector plate, ~12 to 14 degree FOV on a curved image plane, some Schmidt space telescopes include:
  - Kepler “Photometer”
    - 0.95 m aperture, f/1.5 (primary mirror is 1.4 m diameter)
    - Corrector transmissive optic intentionally miss-figured to blur image over ~2x2 pixels
  - Defense Support Program (DSP) Spinning Satellites in GEO since 1970s
    - Discrete single element PbS detectors for primary infrared channel
    - MCT CMOS detectors added in later block designs for a secondary MWIR infrared channel
    - Spinning scanner
  - SBIRS 3-axis Stabilized Satellites in GEO and MEO
    - MCT infrared array CMOS detectors, SWIR & MWIR
    - Gimbaled scanner



Catadioptric Space Telescope

- Kepler, 1 meter aperture class Schmidt “telescope” photometer, 1.4 m primary, f/1.5, 42 CCDs, ~95 million 27 µm pixels at minus 90C, passive radiator, composite structure, focus mechanisms, reaction control wheels, photometer mass 478 kg. Spacecraft pointing. Earth trailing orbit. Discovery class mission built by Ball for NASA. Mission 2009-2018.



Catadioptric Space Telescopes

- DSP, Schmidt telescope, ~3000 PbS individual detectors at prime focus 1st launched in the 1970s. Later increased to ~6000 detectors and a MWIR channel. The spacecraft spins to produce a scan like a radar screen. TRW was prime contractor, Aerojet Electrosystems built the sensor.

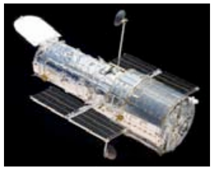
1970s Phase I
•Satellites 1-4

Last Phase
•Satellites 14-23

- SBIRS, Schmidt telescopes, gimbaled to scan the Earth, GEO & HEO spacecraft. MCT CMOS detector arrays. Lockheed-Martin Sunnyvale is prime contractor. GEO mission 2011 - present.

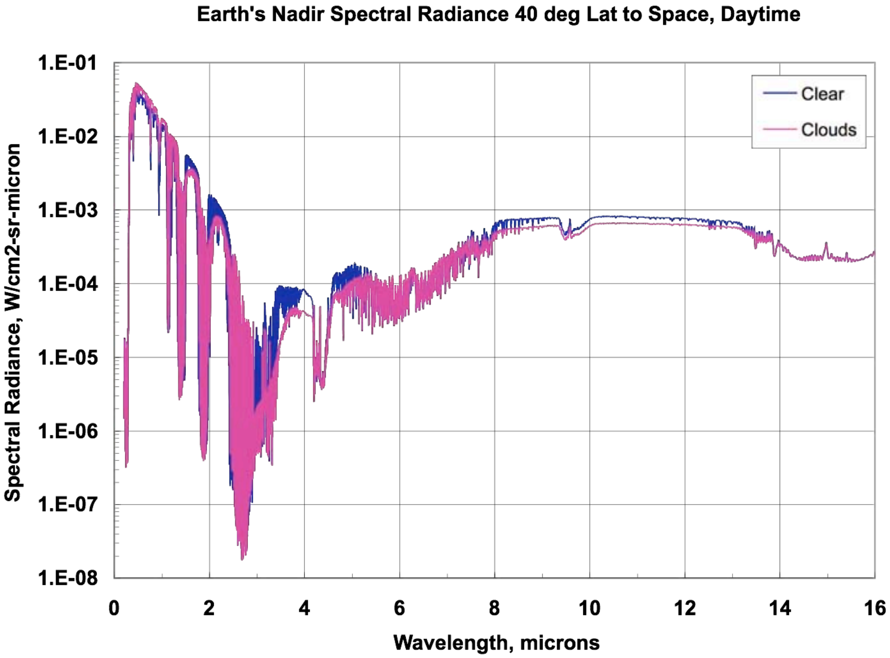
SBIRS GEO

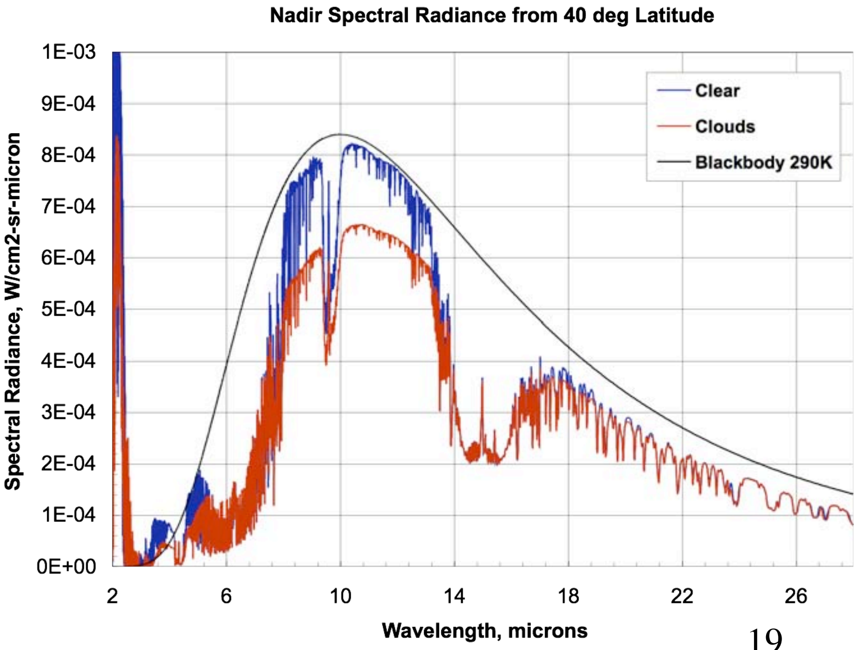
SBIRS HEO



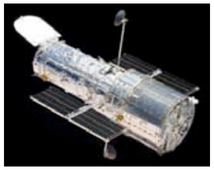
Daytime Earth Backgrounds from Space

- Sensors can Monitor the Entire Earth from Space
- Clouds Increase Backgrounds and Clutter at Shorter Wavelengths, but Decrease Backgrounds at Longer Infrared Wavelengths
- Minimum Daytime Background Radiance is in the 2.7 Micron Water/Carbon Dioxide Band
- Low Clutter Backgrounds for Uniformly Mixed CO_2 Bands, e.g., @ 4.3 & 15 μm
- Earth Radiance for Mid-Latitude Summer with 350 ppm CO_2, today ~420 ppm



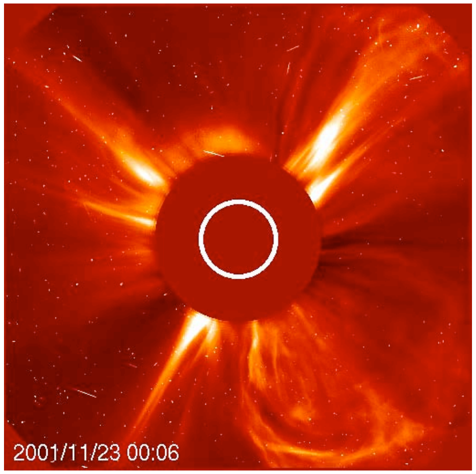


MODTRAN calculations

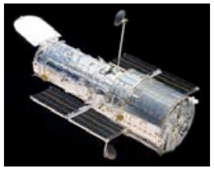


Radiation in Space

- Charged Particle Radiations in the Van Allen Belts, and from the Sun, Limit Lifetime of Satellite Electronics in Earth Orbit
  - Energetic protons in the inner belt >700 km (5-10 yr lifetimes)
  - Energetic electrons in the outer belt and GEO (>15 yr lifetimes)
- Single Event Effects can Lead to Upsets, Bad Data, or Worse - Latchup or Burnout of Electronics Parts - Heavy Ions of Concern
- Detectors are Affected
  - Primarily displacement damage (NIEL), but also ionization damage (dose) limit lifetimes. ~2e8 MeV/g & ~10 krads affect CCDs. Annealing at hot temperatures can help.
  - Temporary blinding from solar events
    - Coronal Mass Ejections (CMEs)
    - Solar flares
  - Solar & Heliospheric Observatory (SOHO)
    - Orbit L1 point
    - LASCO videos

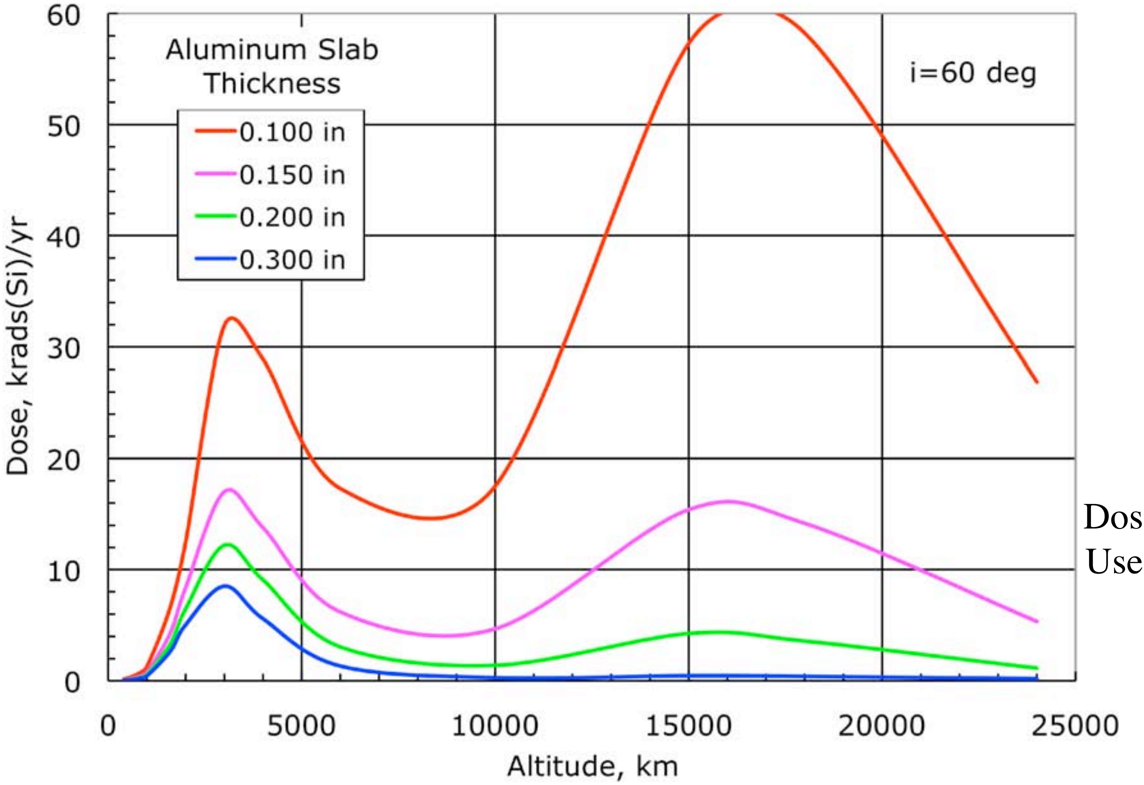


SOHO/LASCO video of CME radiation effects

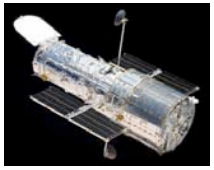


Radiation Dose vs Altitude in MEO

- High Dose Rates exist in the Inner Van Allen Belt above 1600 km
  - Satellite lifetime is very limited due to high energy protons
- Higher Dose Rates in the Outer Belt above ~8000 km can be Shielded
  - Satellite lifetimes of ~15 yrs for the Outer Belt and GEO

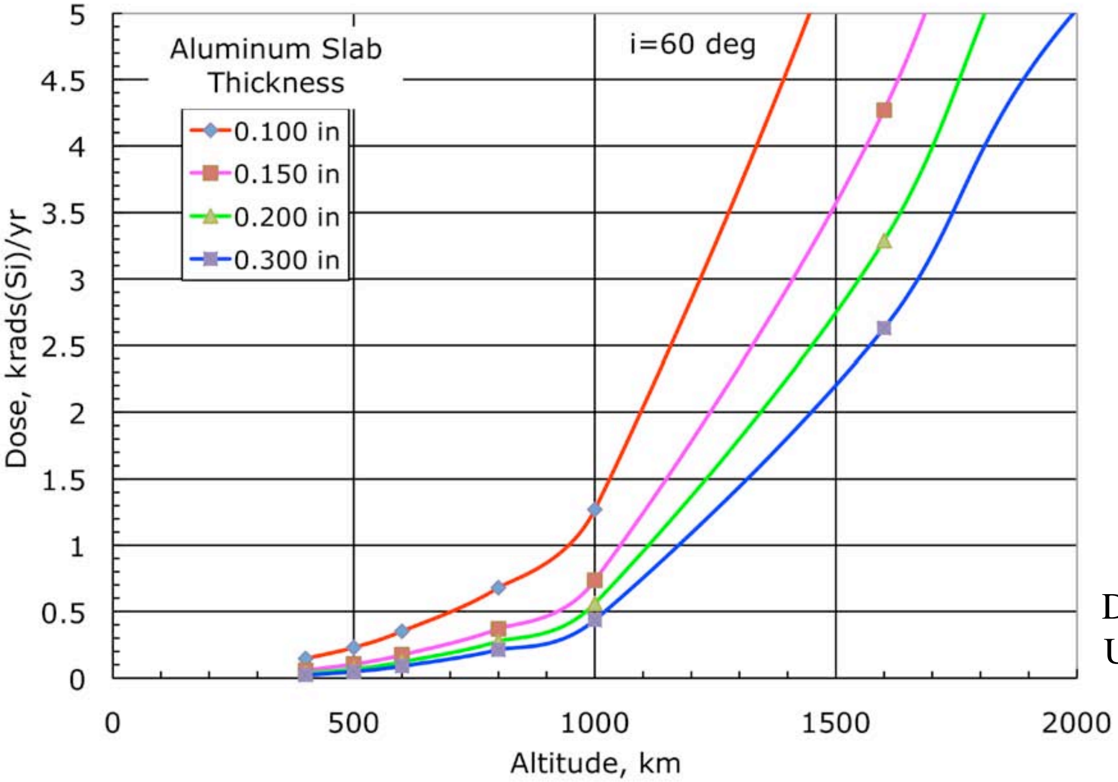


For info only –
Dose from one hemisphere
Use 3D models for design

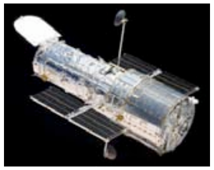


Radiation Dose vs Altitude in LEO

- Long Duration Manned Flight Needs to Stay Below ~400 km (1 Sv=100 rem)
- Satellite Design Life of ~7 yrs Limited by High Energy Belt Protons
- Nuclear Explosions in LEO will destroy satellite electronics in LEO in weeks to months due to an enhanced electron belt (ref 1962 Starfish nuclear tests)

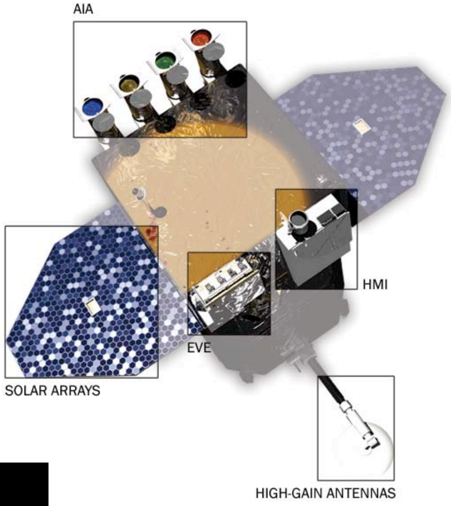


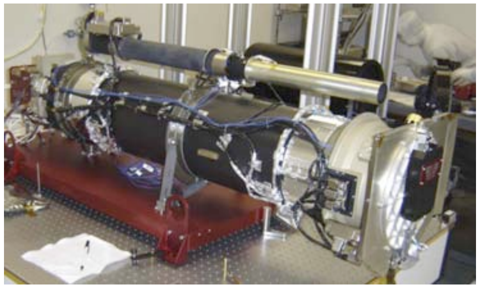
For info only –
Dose from one hemisphere
Use 3D models for design



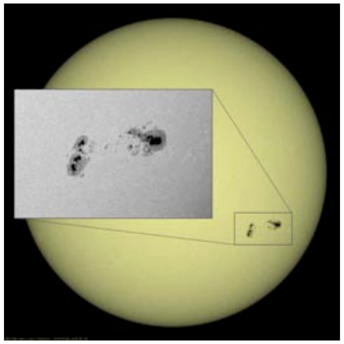
Solar Space Telescopes

- Solar Dynamics Observatory (SDO) launched in 2010 in an inclined "GEO" orbit
  - Three major instruments: Helioseismic & Magnetic Imager (HMI), Extreme Ultraviolet Variability Experiment (EVE), Atmospheric Imaging Assembly (AIA)
  - AIA has four 20 cm f/20 Cassegrain telescopes, rejection filters at the entrance aperture, and narrow bandpass filters over 4Kx4K 12 micron pixel CCDs

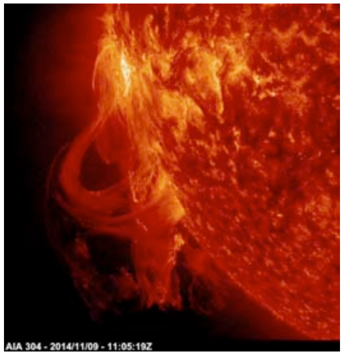


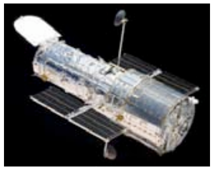


Courtesy NASA/SDO



2017 Solar Eclipse using
a 6" Earth telescope

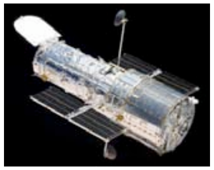




Space Optical Instruments

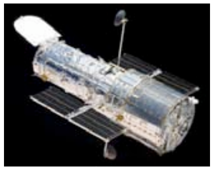
- Imaging Cameras
  - UV-VIS cameras typically use Si CCDs (Si CMOS is getting better)
  - IR cameras use smaller CMOS arrays, typically MCT, InSb, or doped Si
  - Can be scanners or “starers”

- Spectrometers
  - Blazed reflecting gratings are most commonly used
    - Generally limited to a factor of two wavelength range per grating due to overlapping grating orders
    - Vacuum coated with aluminum for UV-VIS spectrometers
    - Vacuum coated with gold for IR spectrometers
    - 2D detector arrays enable hyperspectral sensors
  - Prisms are used for high optical throughput and large wavelength range
    - But spectral dispersion varies strongly with wavelength
  - A few space spectrometers use Fourier Transform Infrared Spectroscopy known as FTIR spectroscopy (e.g. the CrIS instrument flying on NPP/JPSS)



Space Cameras on Hubble

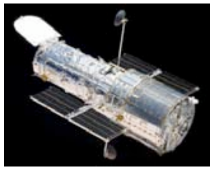
- Wide Field Cameras (WFC)
  - WFPC#1 JPL, launched with Hubble in 1990 with four 800x800x15μm CCDs
    - 0.1” pixel @ f/12.9, 0.043”@f/30 planets
  - WFPC#2 JPL, launched 1993 (SM1) 800x800x15μm CCD, fixed Hubble images
  - WFC#3 Ball Aerospace, UV-VIS w/two 4Kx2Kx15μm CCDs, NIR 1Kx1Kx18μm MCT array, Launched 2009 (SM4)
    - 0.04” pixel IFOV, ef/#32, 160” array FOV
- Advanced Camera for Surveys (ACS), Ball, launched 2002 (SM3b) to replace the Faint Object Camera, repaired 2009 (SM4)
  - WFC w/two 4Kx2Kx15μm CCDs
  - HRC no longer working, 1Kx1Kx21μm CCD
  - SBC, 1Kx1Kx25μm CsI MAMA
    - 0.03” pixel IFOV, ef/#43



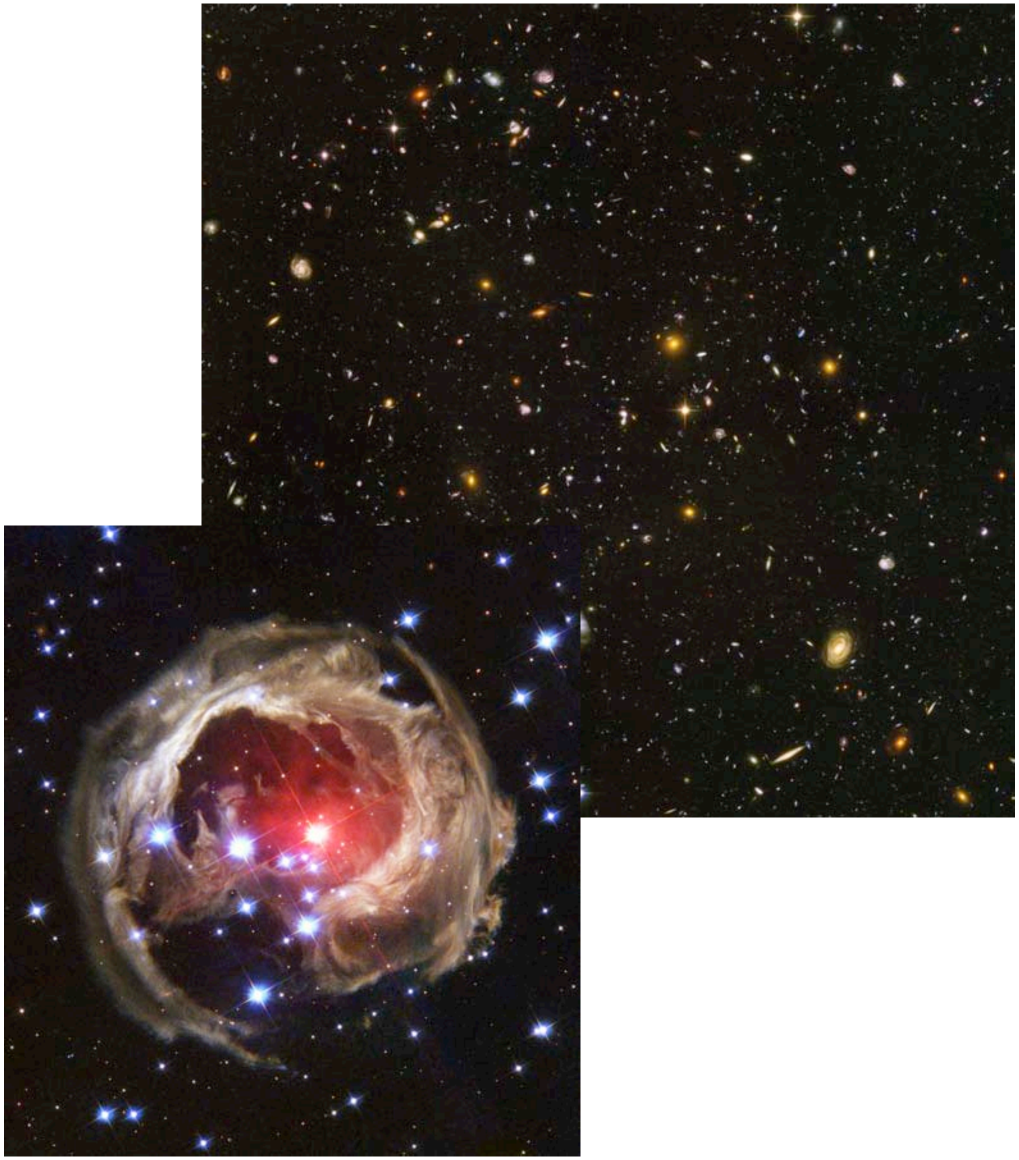
Some HST/WFC3 Images

- Veil Nebula, 5 filters, 4/14-17/2015, 640 parsecs
- Bubble Nebula in Cassiopeia, 4/21/2016, 3.5 hr exposure, 3 filters, 2100 parsecs
- Pillars of Creation Revisited, Sep 2014, M16 Eagle Nebula in Serpens, 2000 parsecs
- Arp273, Interacting galaxies in Andromeda, 12/17/2010, 5.9 hrs, 105 million parsecs, 2.6’x2.6’ = 80kpc wide

Ref: http://hubblesite.org/gallery/album/



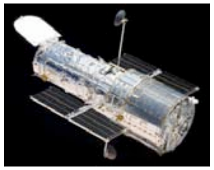
A Couple HST/ACS Images



- The Hubble Ultra Deep Field
  - ~10,000 galaxies within 3’x 3’ in Fornax
  - 9/24/2003-1/16/2004
  - 400 orbits, ~800 images added together

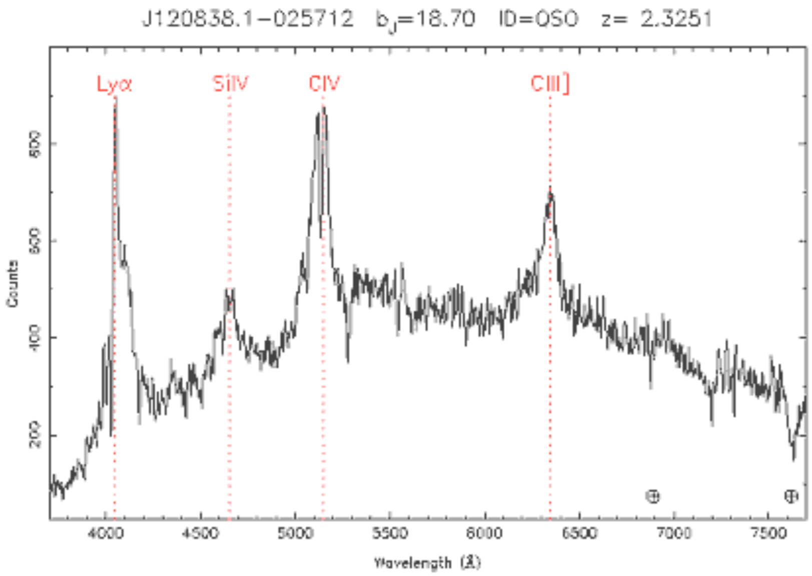
- V838 Monocerotis Nova
  - 6000 parsecs away
  - 2.4’ x 2.4’= 4.2 pc
  - 2/8/2004

Ref: http://hubblesite.org/gallery/album/

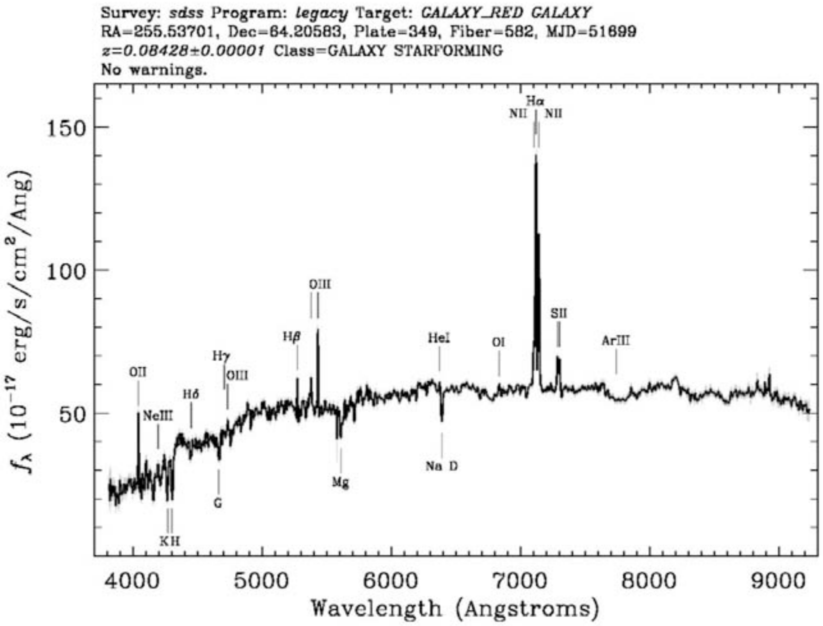


Spectrometers Split Light into “Colors”

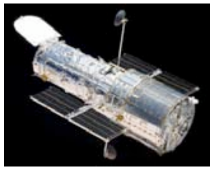
- Identify Gases & Molecules Based on Wavelengths, but these Wavelengths Shift to Longer Wavelengths (“Redshift”) when Galaxies are Moving Away from Us
- Below Left is an Example of a Quasar with a Redshift z = 2.3
  - With no redshift, the Lyman alpha line should be in the VUV @ 1216 Angstroms = 0.1216 microns
- Below Right is an Example of a Galaxy with Absorption & Emission Lines
- Both Spectra are from Ground Based Telescopes



Ref: www.2dfQuasar.org

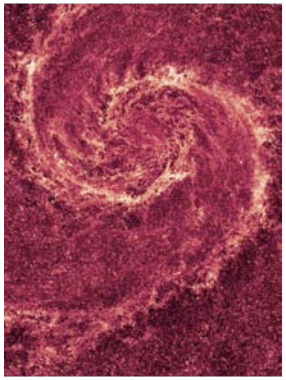


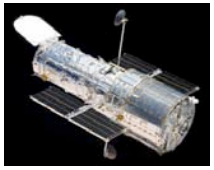
Ref: Sloan Digital Sky Survey



Spectrometers on Hubble

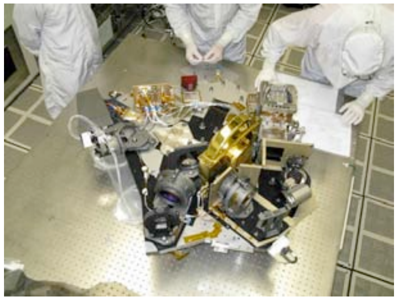
- Cosmic Origins Spectrograph (COS), Ball, launched 2009 (SM4)
  - 1Kx1Kx25μm MAMA
    - NUV, Cs_2Te, 165-320 nm
  - 16Kx1Kx24μmx6μm MAMA
    - FUV, CsI, 90-215 nm
- Space Telescope Imaging Spectrograph (STIS), Ball, launched 1997 (SM2), repaired (SM4)
  - 16 gratings & 16 slits
  - 1Kx1Kx21μm CCD, 0.2-1μm
  - 1Kx1Kx25μm Cs_2Te MAMA
  - 1Kx1Kx25μm CsI MAMA
- Near Infrared Camera and Multi-Object Spectrometer (NICMOS), 0.8 - 2.5 μm, Ball, launched 1997 (SM2)
  - 3 - 256x256x40μm MCT array

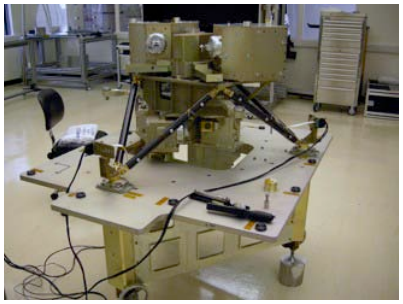


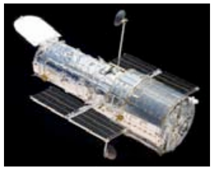


Instruments on JWST

- NIRCam (U of Arizona, Lockheed-Martin ATC)
  - 10 MCT detectors, 18 micron pixels, 2Kx2K
    - 0.6-2.3 μm, pixel 0.032 arcsec (~f/20 effective f/#)
    - 2.4-5 μm, pixel 0.065 arcsec (~f/10 ef/# for fast imaging)
  - Mirrors/Lenses TFOV 2.2x4.4 arcmin
  - Low spectral resolution 4, 10, 100
- MIRI 5-28 μm (Europe Consortium, JPL)
  - 3 Si:As detectors, 25 micron, 1Kx1K, cooled to 7K
  - Mirrors, pixel 0.068 arcsec, TFOV 1.9x1.4 arcmin
  - Much better spectral resolution 5, 100, 2000
- NIRSpec 1-5 μm (European Space Agency ESA)
  - Higher spectral resolution, 100, 1000, 3000
  - 2 MCT detectors, 18 micron pixels
- Fine Guidance Sensor/Tunable Filter (FGS/TF) Canada
  - 3 MCT detectors, 2Kx2K







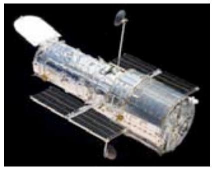
Summary

- Detector Arrays have Enabled Enormous Advances in Space Telescopes
  - CCDs will still be used for quite some time at UV-VIS wavelengths (larger formats, lower noise, higher QE), but CMOS is catching up (CMOS is already dominate in commercial markets)
  - CMOS is the technology for >1 microns (infrared) in space
  - Most have analog outputs, which are digitized using A/D converters on electronic cards
  - Digital outputs are becoming available on CMOS devices, but be wary of radiation hardness or anything less than 14 bits

- Cryocoolers for MWIR and LWIR Wavelength Detectors

- Multiple Mirror Space Telescopes & Lightweighting Enable Larger Telescopes, but with Much Greater Complexity in Deployment & Focusing (wavefront control)

- Automation of Optics Fabrication has reduced the Role of the Old Optics Technique of Hand Grinding and Polishing, but it is still an Art. Vacuum Coating Technology has Greatly Advanced, but is also an Art.



Notes & Key References

- This Presentation is UNCLASSIFIED.
- Photos courtesy of the Air Force and NASA.
- Some DSP Satellite Characteristics have been Declassified:
  - Air University Space Primer, Chapter 15, Missile Warning Systems, Maxwell AFB, Alabama, August 2003
  - F.S. Simmons and Jim Creswell, The Defense Support Program, The Aerospace Program Crosslink, Summer 2000, Vol 1, No 2.
  - Northrop-Grumman fact sheets
- Other Sources:
  - Handbook of Optics, Optical Society of America, McGraw-Hill.
  - National Reconnaissance Organization website, www.NRO.gov
  - Ball Aerospace public releases
  - The Hubble website
  - Numerous papers in the Society for Photo-optical Instrumentation Engineers (SPIE) & Applied Optics journals, etc.