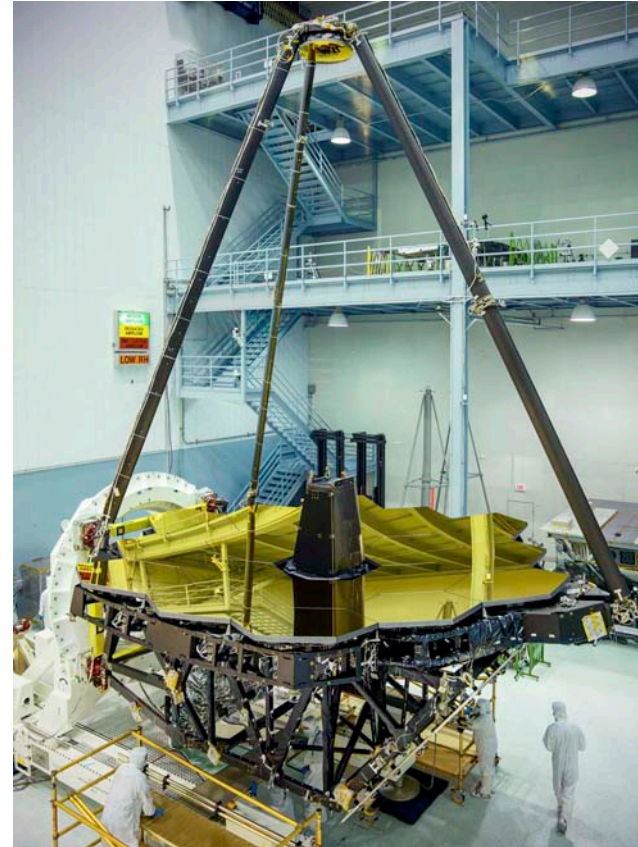




Space Telescopes & Optical Instruments

Dean Spieth

Seminar
2024





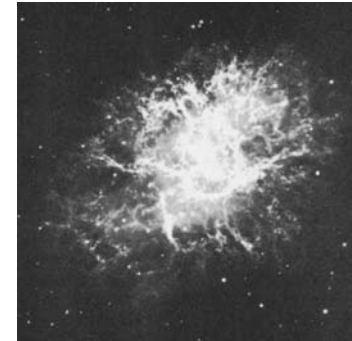
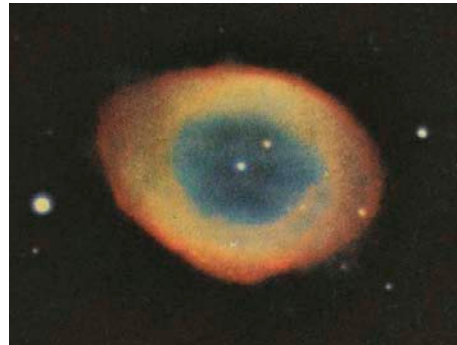
Topics

- 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

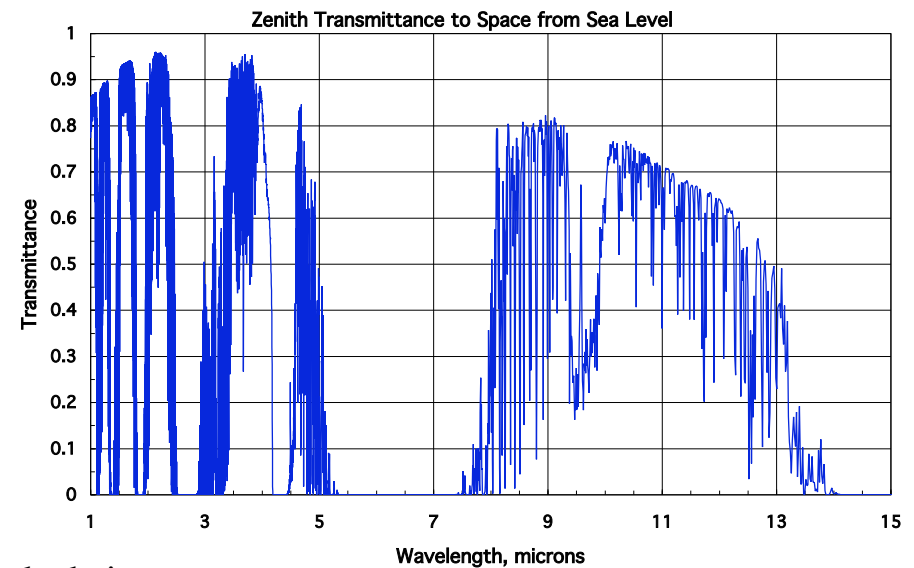
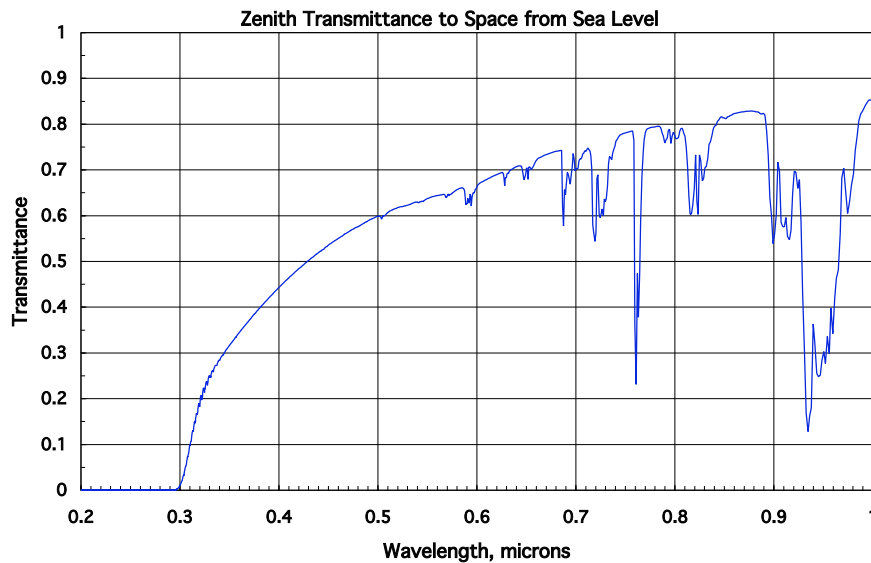
- Up Until the 1990s, the 200 inch (5 meter) Mt Palomar Telescope was the best
 - Limited by the atmosphere & film prior to the 1990s on clear nights
- The Hubble Space Telescope HST (2.4 meter) was Launched in 1990, vision corrected in 1993 with WFPC#2 & COSTAR during Shuttle Servicing Mission #1
- 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 14μ until RF
 - Elon Musk's Starlink satellites cause tracks in images & orbital debris



MODTRAN calculations



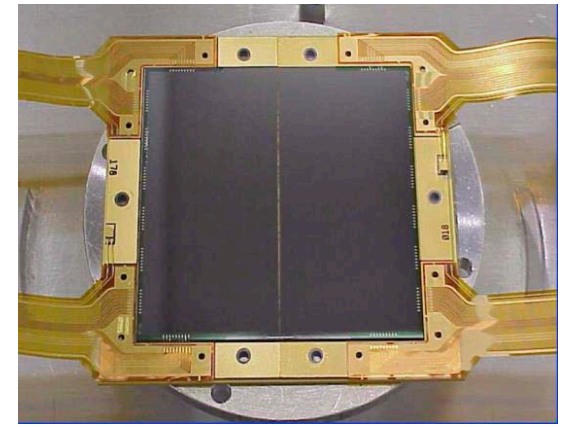
Typical Construction Practices

- 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

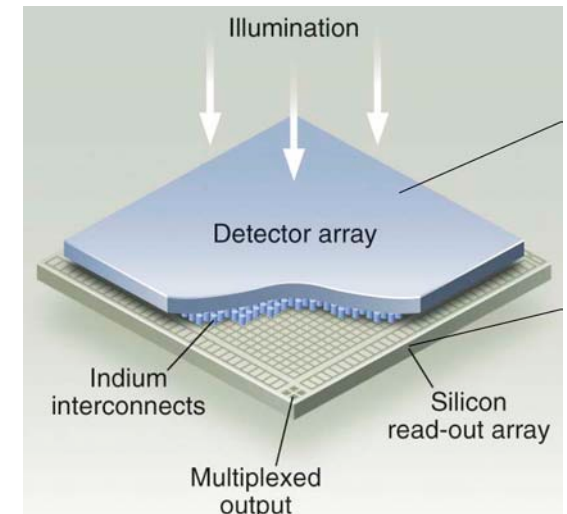


Breakthrough Detector Technologies

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

See Rogalski and Bielecki (2004), Detection of Optical Radiation, Bulletin Polish Academy Sci, V 52, #1. 7



Overview of Optical Telescope Designs

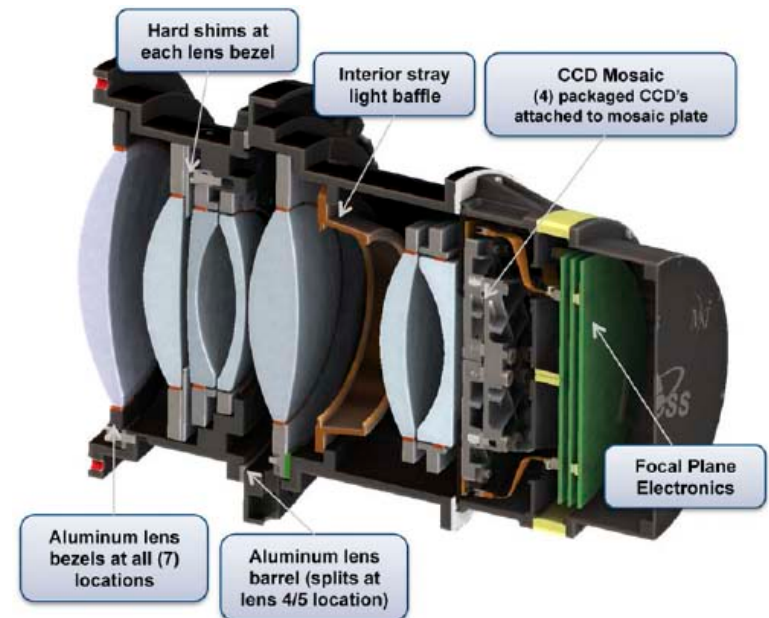
- A Refracting Telescope was first used to draw the Craters of the Moon and Moons of Jupiter in the 17th century by Thomas Harriot and Galileo Galilei
 - Has chromatic aberrations due to refractive index of lenses varying versus wavelength
 - Partially solved by using multiple elements with different 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 Crisp 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

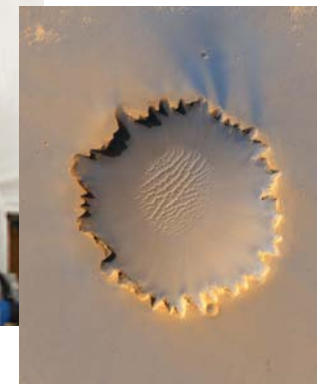


Some Cassegrain Space Telescopes

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



Comet Temple 1 Impact



Victoria Crater



Infrared Space Telescopes

- Ball 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.
- Ball 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 $\sim 1.4\text{K}$. (The heart of the Spitzer Space Telescope, aka SIRTF.) Launched 2002.

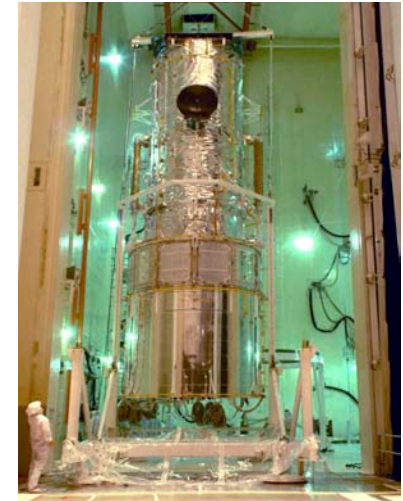


Note: Herschel 3.5 m was the largest space telescope, 55 to 672 μm

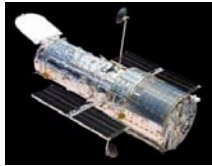


The Big Reflecting Space Telescopes

- The Hubble Space Telescope, 2.4m (94") 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)

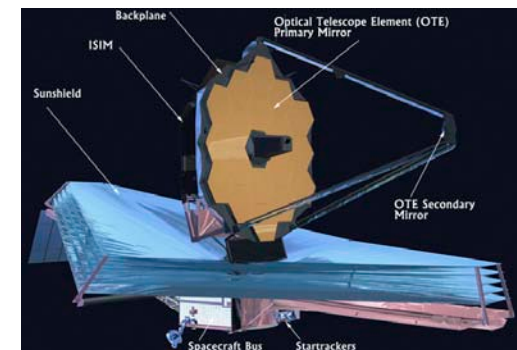
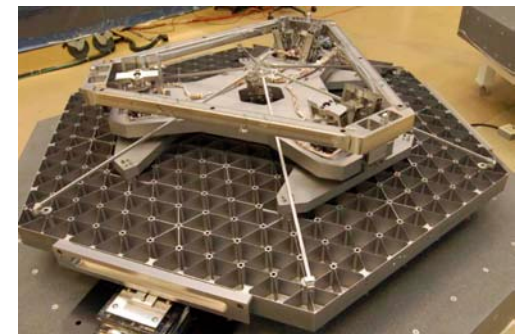


<http://www.nro.gov/history/csnr/gambhex/index.html>

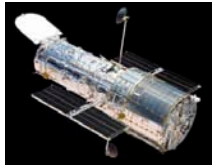


The Largest Space Telescope

- 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)

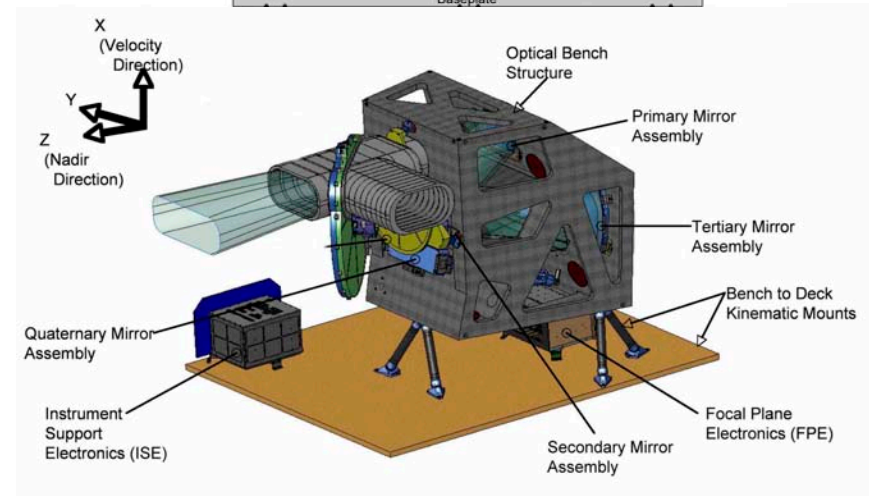
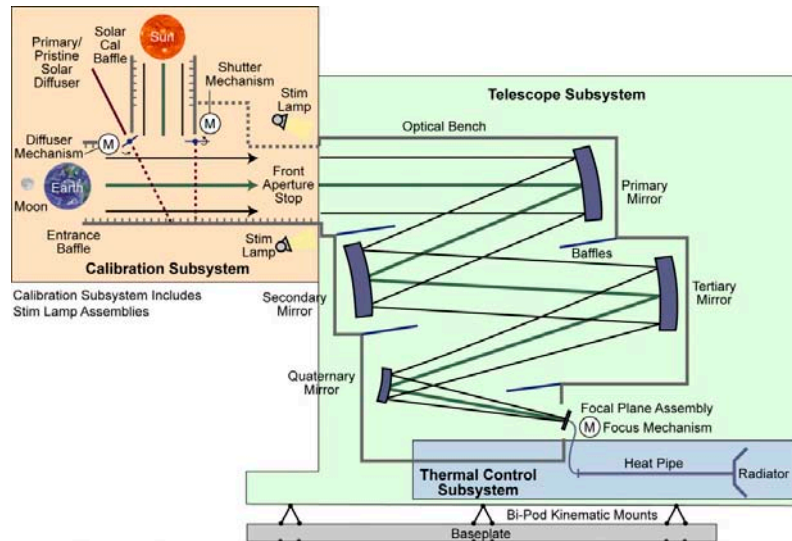
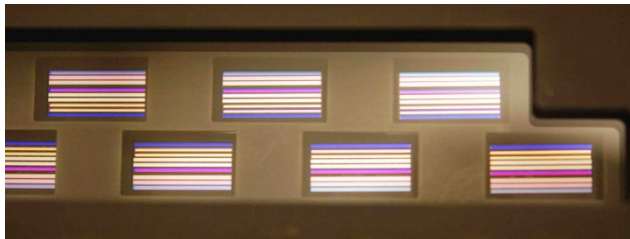


*Bob Warden (2006), Ball Aerospace, Cryogenic Actuators for JWST, Proc 38th Mechanisms Symposium



Off-Axis Reflecting Space Telescopes

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





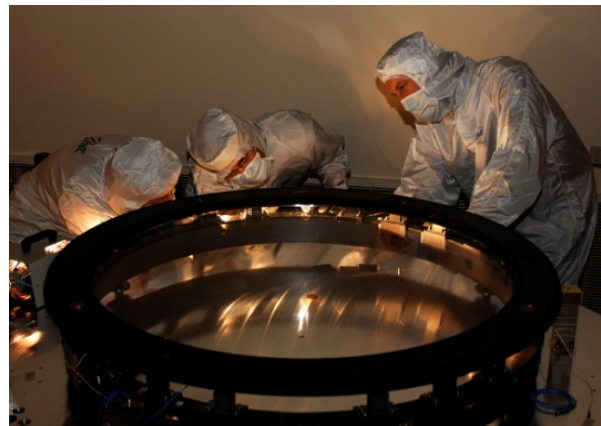
Catadioptric (Compound) Space Telescopes

- 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 $27\ \mu\text{m}$ 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.
- SBIRS, Schmidt telescopes, gimballed to scan the Earth, GEO & HEO spacecraft. MCT CMOS detector arrays. Lockheed-Martin Sunnyvale is prime contractor. GEO mission 2011 - present.

1970s Phase I
•Satellites 1-4



Last Phase
•Satellites 14-23



SBIRS GEO



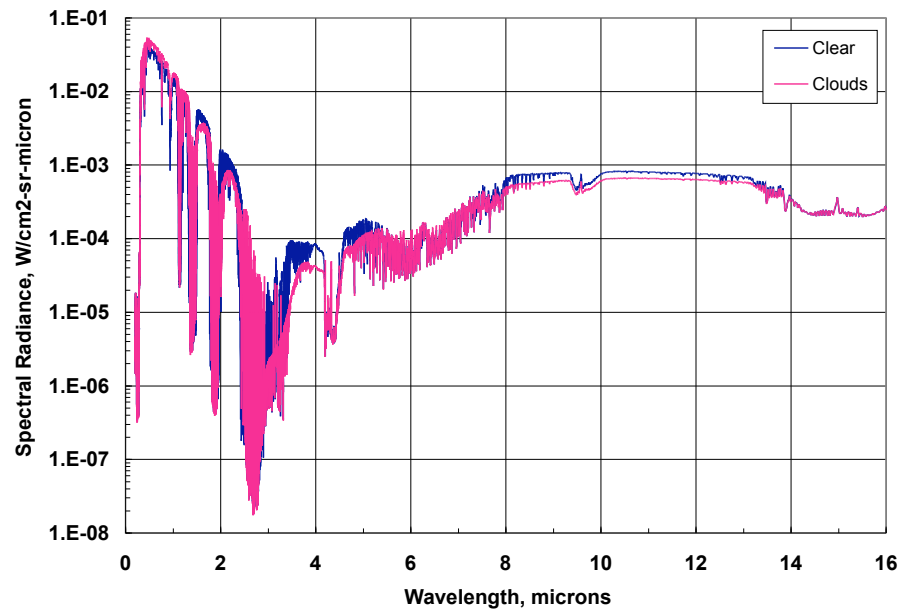
SBIRS HEO



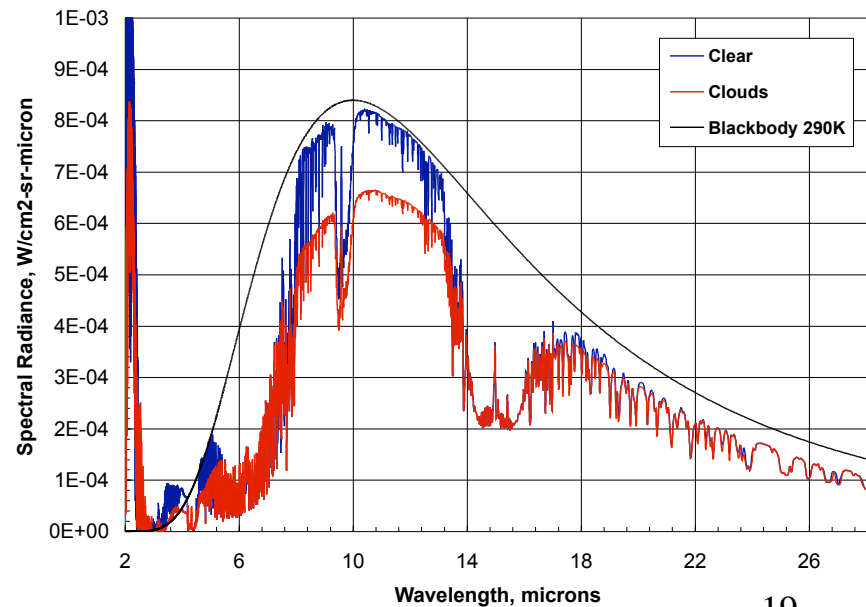
Daytime Earth Backgrounds from Space

- 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 CO₂ Bands, e.g., @ 4.3 & 15 μm
- Earth Radiance for Mid-Latitude Summer with 350 ppm CO₂, today ~420 ppm

Earth's Nadir Spectral Radiance 40 deg Lat to Space, Daytime



Nadir Spectral Radiance from 40 deg Latitude



MODTRAN calculations



The Earth Cools by Emitting to Space

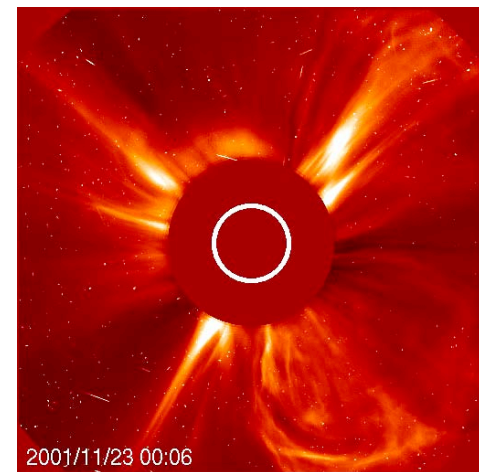
- The Earth's Temperature is Balanced by Incoming Absorbed Sunlight versus Outgoing Radiated Infrared Light, as Shown on the Prior Page
- The CO₂ 14 to 16 μm, or 15μm Bending Mode is the Primary Greenhouse Effect*
- The Water Vapor H₂O 5 to 8 μm, or 6.3μm Band is 2nd in Importance*
 - CO₂ warms the air, which in turn warms the oceans making more H₂O vapor*
 - However, if clouds form, the Earth stays warmer at night & cooler during day
- Methane (CH₄) Absorbs More than CO₂ on a Molecule to Molecule basis, but because its Concentration is only 1.9 ppm (1900 ppb) versus 420 ppm for CO₂, is Less Important than CO₂ for Global Air Warming at the Present Time
 - It's 7.2 to 8.3 μm, or 7.6μm absorption band is the band of interest, hidden in the 6.3μm H₂O band
- However, We Need Some CO₂ or an Ice Age Will Develop (a Snowball Earth), and Plants, Crops and Trees also need Some CO₂ for Photosynthesis
- There are Many Uncertainties, like underground Volcanoes Heating Oceans, aboveground Volcanoes Generating CO₂ but also Sulfuric Acid Aerosols that can Reflect Sunlight, and Solar Insolation Effects (Milankovic Solar Cycles)

*Dr. Scott Denning, CSU; also Pierrehumbert (2011), Physics Today, vol. 64, pp 33f.



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. $\sim 2e8$ 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

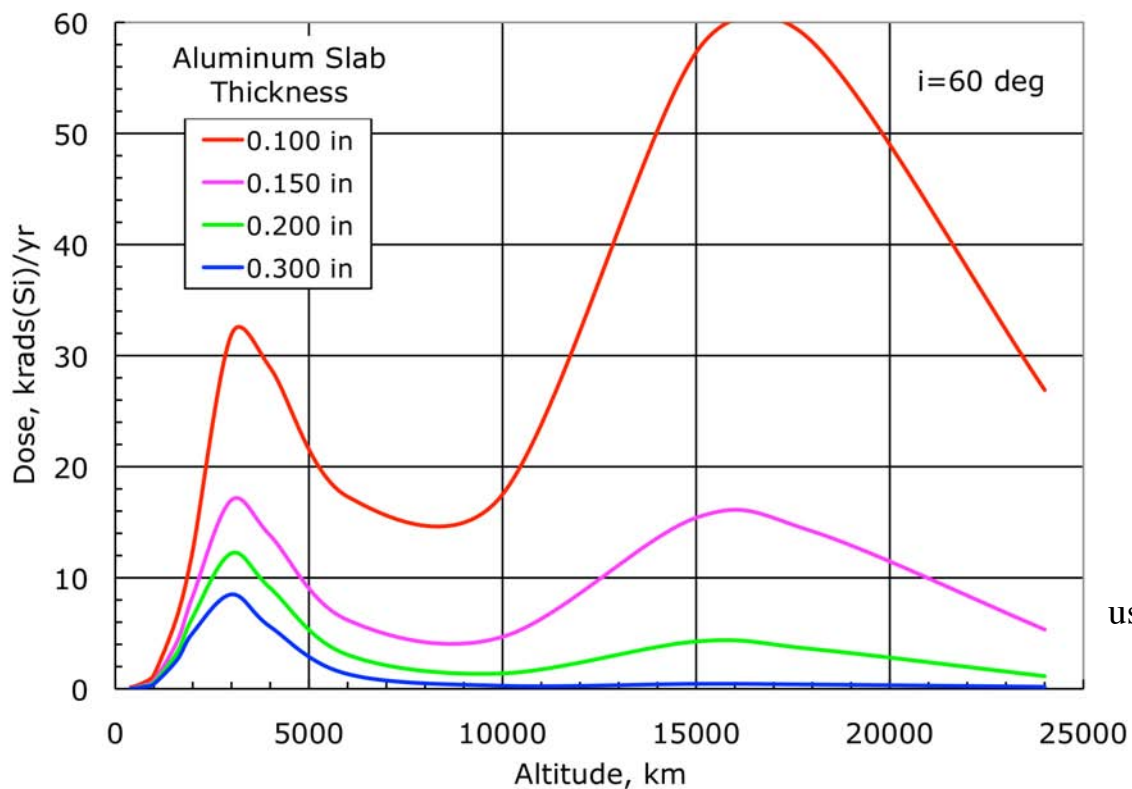


SOHO/LASCO video of CME radiation effects

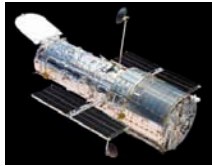


Radiation Dose vs Altitude in MEO

- 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

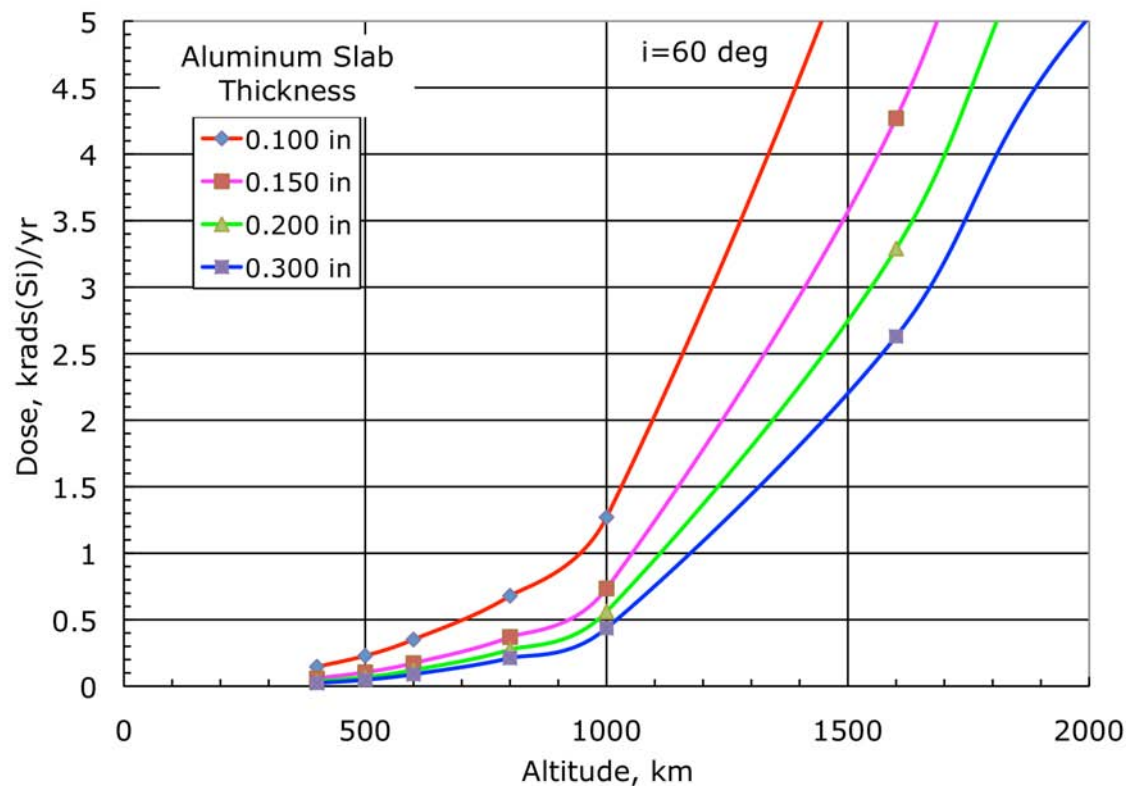


For info only –
use 3D models for design

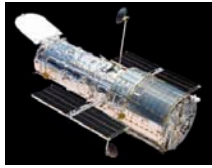


Radiation Dose vs Altitude in LEO

- 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 (not shown, ref 1962 Starfish nuclear tests)

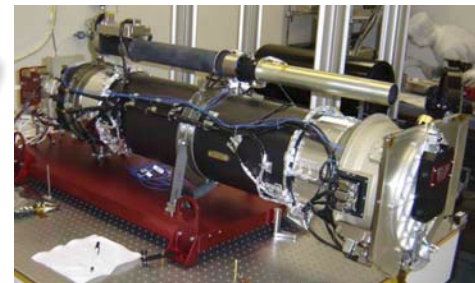
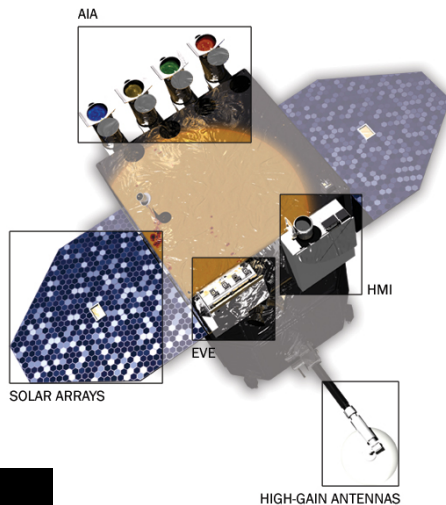


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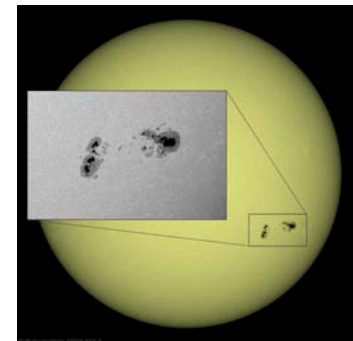


Solar Space Telescopes

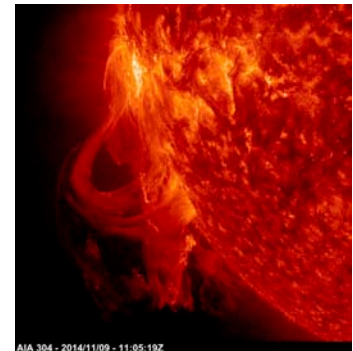
- Solar Dynamics Observatory (SDO) launched in 2010 in an inclined “GEO” orbit
 - Three major instruments: Helioseismic & Magnetic Imager (HMI), Extreme Ultraviolet Variability Experiment (EVE), Atmospheric Imaging Assembly (AIA)
 - AIA has four 20 cm f/20 Cassegrain telescopes, rejection filters at 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 $800 \times 800 \times 15 \mu\text{m}$ CCDs
 - 0.1" pixel @ f/12.9, 0.043" @ f/30 planets
 - WFPC#2 JPL, launched 1993 (SM1) $800 \times 800 \times 15 \mu\text{m}$ CCD, fixed Hubble images
 - WFC#3 Ball Aerospace, UV-VIS w/two $4\text{K} \times 2\text{K} \times 15 \mu\text{m}$ CCDs, NIR $1\text{K} \times 1\text{K} \times 18 \mu\text{m}$ 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 $4\text{K} \times 2\text{K} \times 15 \mu\text{m}$ CCDs
 - HRC no longer working, $1\text{K} \times 1\text{K} \times 21 \mu\text{m}$ CCD
 - SBC, $1\text{K} \times 1\text{K} \times 25 \mu\text{m}$ 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, $2.6' \times 2.6' = 80\text{kpc}$ 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

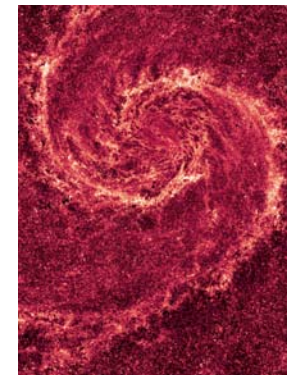
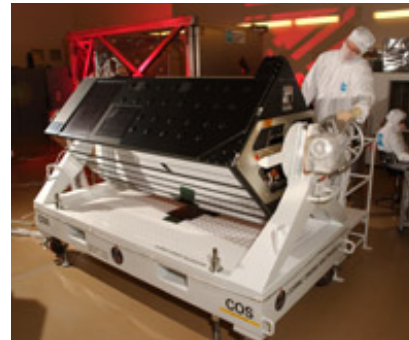


Ref: <http://hubblesite.org/gallery/album/>



Spectrometers on Hubble

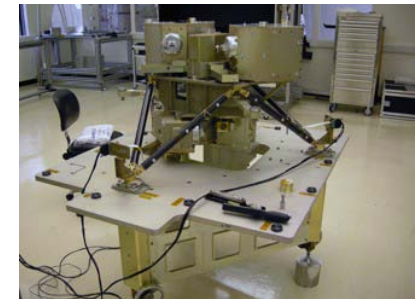
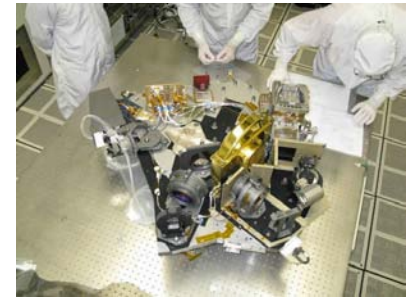
- Cosmic Origins Spectrograph (COS), Ball, launched 2009 (SM4)
 - 1Kx1Kx25 μ m MAMA
 - NUV, Cs₂Te, 165-320 nm
 - 16Kx1Kx24 μ m x 6 μ m MAMA
 - FUV, CsI, 90-215 nm
- Space Telescope Imaging Spectrograph (STIS), Ball, launched 1997 (SM2), repaired (SM4)
 - 16 gratings & 16 slits
 - 1Kx1Kx21 μ m CCD, 0.2-1 μ m
 - 1Kx1Kx25 μ m Cs₂Te MAMA
 - 1Kx1Kx25 μ m CsI MAMA
- Near Infrared Camera and Multi-Object Spectrometer (NICMOS), 0.8 - 2.5 μ m, Ball, launched 1997 (SM2)
 - 3 - 256x256x40 μ m 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 ($\sim f/20$ effective $f/\#$)
 - 2.4-5 μm , pixel 0.065 arcsec ($\sim f/10$ 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.