Rockets & Missiles - the Big Ones

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Seminar
2024

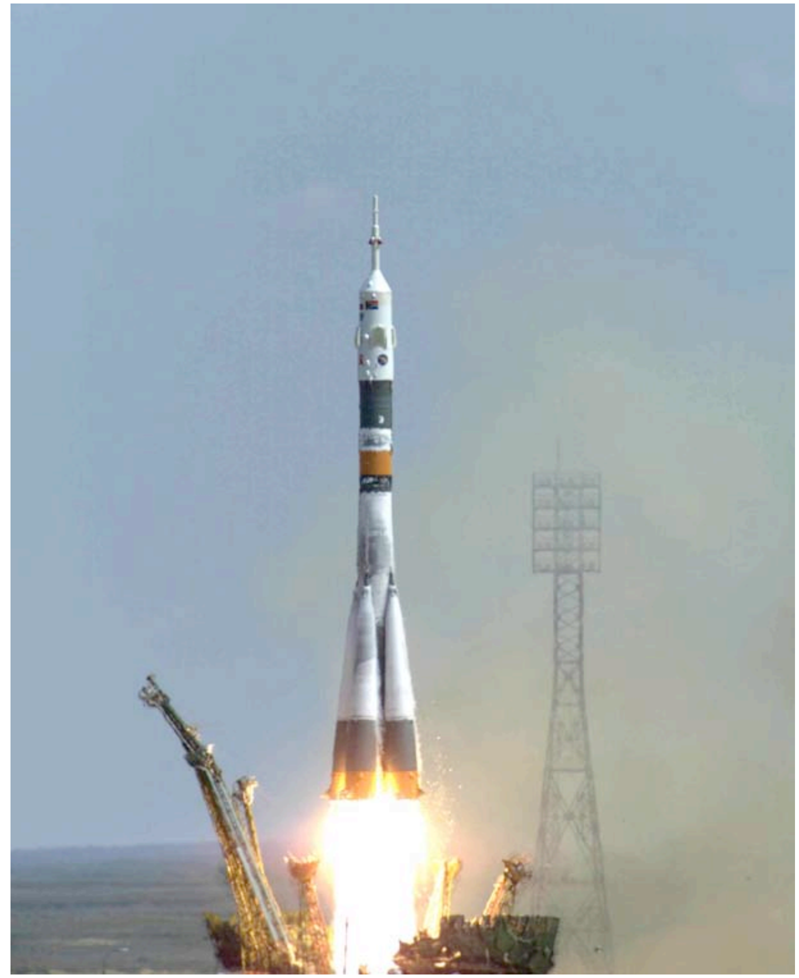
Brief History of the Big Rockets

- Big Rockets Started Flying in the Late 1950s
  - Russian R7 ICBM using Liquid Oxygen (LOX)/Kerosene
    - Sputnik and the first men in orbit
- Cryogenic Propellants are Used Today for Satellite and NASA Launches
  - LOX/RP1 (Kerosene), LOX is cryogenic (-183C)
    - 1st stages of Atlas, Delta I,II,III; Titan I; Saturn V 1st stage; Space X Falcon
  - LOX/Methalox (Liquid Methane) for re-useable rockets
    - Liquid Methane is cryogenic (-162C), less dense and cleaner burning vs RP-1
  - LOX/LH_2 (-253C or 20K) gives the best performance (more expensive)
    - Saturn V moon rocket upper stages, Shuttle main engines, Delta IV, Artemis
- Storable Propellants (not cryogenic) are Needed for Ballistic Missiles
  - Liquids: Titan II (retired), Russian SS-18,-19,-N18,-N23, RS-28 Sarmat
  - Solids are lowest cost and lower performance: MMIII, Trident, SS-25,-27
- Chemical Rockets are Currently the Only Solution for Booster Stages
  - High flowrate and high specific impulse ISP (thrust per flowrate)
  - Thrust (lbf) = Flowrate (lbm/second) x ISP

Russian R7 - the 1st Big Rocket

- LOX/Kerosene Propellants
- Launched Sputnik and 1st men to space

R7 Rocket Engine Cluster



Soyuz 1

RP-1 Bipropellant Rocket Engines

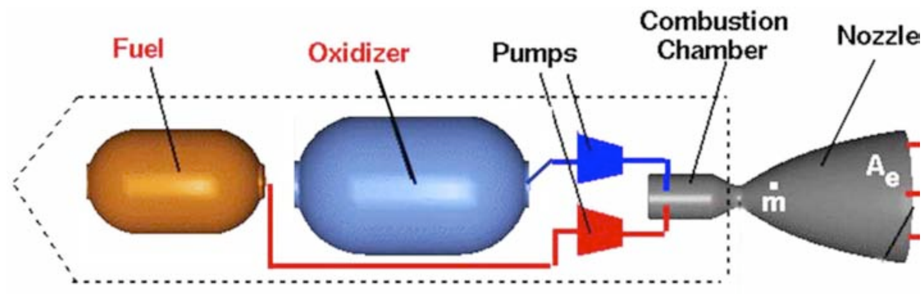
- “Dirty” Propellants, Like hydrocarbon RP-1 (“Kerosene”), Produce Bright Visible Plumes and More Intense Infrared Signals. LOX is the oxidizer.
- Brightness is Due to Hot Sub-micron Carbon Particulates (carbon soot)

Atlas V 401 First Stage (LOX/RP-1)

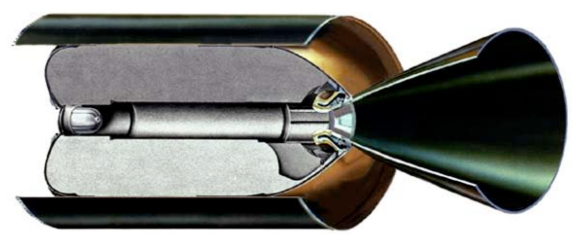
Apollo 17 First Stage (LOX/RP-1)

Booster Rocket Types

- Liquid Bipropellant Engines (typically with fuel rich nozzle film cooling)
  - Cryogenic, e.g. LOX (Atlas, Delta, Saturn, etc.)
  - Storable, e.g. NTO/AZ-50 (Titan II)

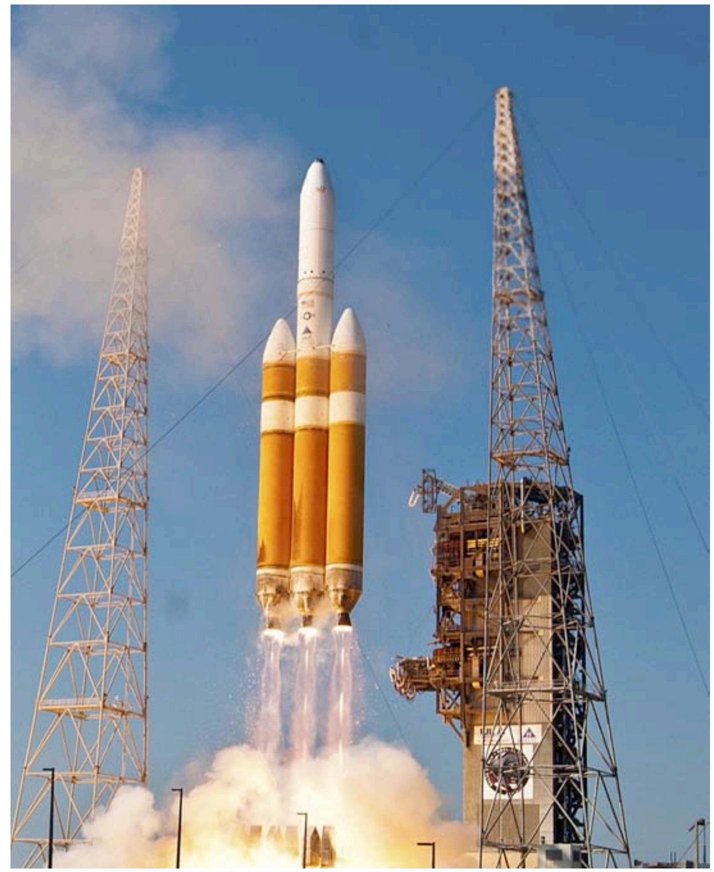


- Solid Rocket Motors
  - Aluminized (Many large missiles use ammonium perchlorate, aluminum, and binders, considered a Composite Propellant)
  - Other Composite Propellants (e.g., HMX or RDX)
  - Double Base (Nitrocellulose, nitroglycerin, and additives)



Cryogenic Bipropellant Rocket Engines

- Delta IV Launches
- Cleanest Burning Propellant is LOX/LH_2
- Primary Byproduct is H_2O – Steam!



High Altitude Rocket Plumes

- Plumes Expand Dramatically at Higher Altitudes due to Low Ambient Pressures
- Apollo 11 Staging, Stage I (LOX/RP-1), Stage II (LOX/LH_2)
  - 1st men to land on the moon, July 1969

Storable Bipropellant Rocket Engines

- Storable Propellants are Needed for Ballistic Missiles
- Titan II Missiles Deployed in 1960s-1980s had the largest US warhead 9 MT
- Clean Burning Propellants like NTO/AZ-50 Produce Little Visible Signal
- However, Short-Wave & Mid-Wave Infrared Signals are Intense

Storable Bipropellant Rocket Plumes in Vacuum

- In the Vacuum of Space, Clean Burning Propellants Produce Minimal Visible Signal
- Apollo 17 Lunar Module, N_2O_4/AZ-50
- AZ-50 is a 50-50 blend (see MIL-PRF-27402):
  - Hydrazine [N_2H_4]
  - UDMH [$(CH_3)_2N_2H_2$]

Minuteman Launch from Vandenberg AFB

- Storable Solid Propellants Offer Reduced Cost but with Decreased Performance and Warhead Size, partially offset using 3 stages
- Minuteman, an Aluminized Solid Propellant, fires out of the Hole
- MMIII originally used a post-boost vehicle (PBV) with 3 warheads

Aluminized Solid Rocket Motors (SRM)

- Peacekeeper (MX missile) used Gas Ejection from a Silo, then Ignited
- Visible Signal Dominated by Aluminum Oxide Particulates
- 50 Deployed around Warren AFB, Wyoming, then Negotiated Away
- 10 RVs, Unclassified Sources Estimated Yield from 300 to 475 kT each RV

Liquid + Solid Rocket Boosters

- The Space Shuttle
  - Last launch 2011
- Titan IV; IIIC, D, E
  - Last launch 2005
- ESA’s Ariane V

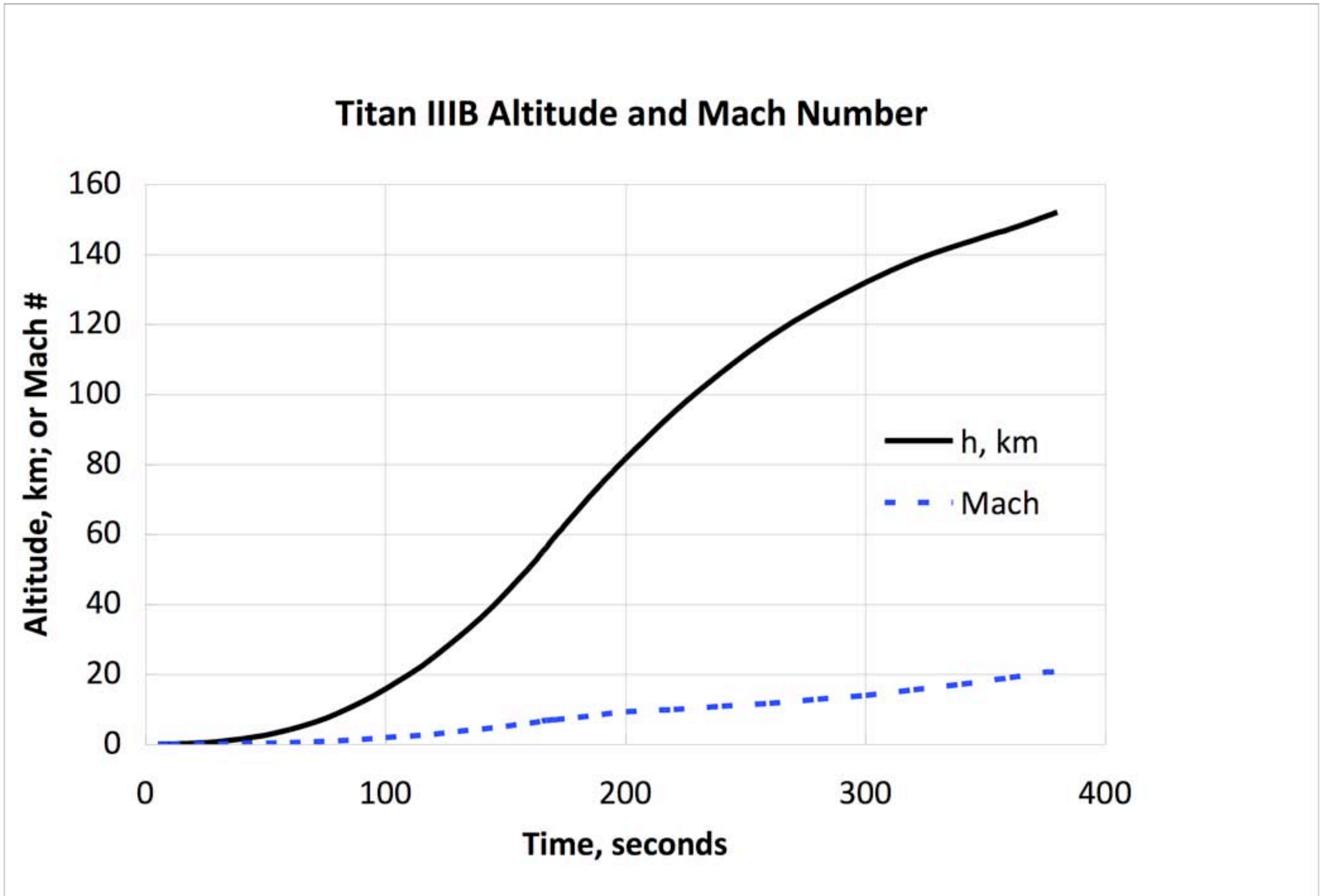
Rocket Performance

- Velocity gain of each stage, $\Delta v = g_c$ ISP ln (m_i/m_{bo}) - gravity - drag
- ISP = Thrust/Flowrate = $lb_f/(lb_m/s)$ = “seconds” = $kg_f/(kg/s)$
- Cryogenic propellants give highest ISP, but T = -297F (LOX), -423F (LH_2)
- Solid propellants give much lower ISP

Propellant	ISP (SL or Altitude Avg)	ISP (Vac)
LOX/LH_2	365 s (SL), Delta IV Stg I,	460 s, Delta IV Stg II
LOX/RP-1	311 s (SL), Atlas V Stg I	330 s, Soyuz Stg II 340 s, Falcon 9 Merlin
NTO/AZ-50	300 s (Alt), Titan IIIC28 Stg I	317 s, Titan IIIC28 Stg II
Aluminized Solid (Composite)	265 s (Alt), Titan III Stg 0	294 s, IUS motor for Chandra X-ray Observatory

Titan IIIB Altitude & Speed

- After Stage I/II Burns, Speed was Mach 20 at ~160 km (100 miles) Altitude
- Stage II Ignition at 167 seconds after Launch



Rocket Exhaust Products

- Note that Water and Carbon Dioxide are Common Products

Propellant	Exhaust Species	Notes
LOX/LH_2 Liquid (HO)	H_2O, H_2, OH, O_2 + minor species	Cleanest Burning, and no Carbon Dioxide
NTO/Amine Liquid (CHNO)	H_2O, CO_2, H_2, CO, NO, N_2, OH, O_2 + minor species	Clean Burning
LOX/RP-1 Liquid (CHO)	Carbon Soot, H_2O, CO_2, H_2, CO, OH, O_2 + minor species	Visibly Bright, Dirty Exhaust
Aluminized Solid Composite	Al_2O_3, H_2O, CO_2, H_2, CO, HCL…	Dirty, Visibly Bright, Aluminum oxide
Double Base Solid (NC/NG)	H_2O, CO_2, H_2, CO, NO, N_2, OH, O_2 + minor species	No Primary Smoke, i.e., no Al_2O_3

Chemical Composition of Exhaust Products

- Liquid vs Solid Propellant Predicted Species at Nozzle Exit, Finite Rate Chemistry

	Titan II Stage I Storable Biprop	Titan 34D Stage 0 Aluminized Solid	
Propellant	NTO/AZ-50	AP/Al/PBAN/misc	AP=NH_4ClO_4
$(O/F)_w$	2.0	67.5/16.1/10.3/6.1%	PBAN=$CH_{1.43}N_{0.032}O_{0.036}$
Nozzle Expansion Ratio	8.0	8.0	
Exit Temperature, K	1944	2019	
Species	Mole Fractions	Mole Fractions	
H_2O	0.467	0.106	May form vapor trail
CO_2	0.0901	0.0177	
CO	0.0356	0.257	Afterburns to CO_2
H_2	0.0377	0.320	Afterburns to H_2O
N_2	0.356	0.0772	
NO	0.0087	0.00025	
OH	0.0033	0.001	
Al_2O_3 (s)	0	0.0734	~120 tons per launch
HCL	0	0.136	~80 tons per launch
Other			

START Treaties Reductions

- Russia ICBMs (Land Based) per NASIC 2017 & 2020 unclassified reports
  - About 50 SS-18, up to 10 warheads each missile (Bull Atomic Sci est 40)
  - About 50 SS-19, up to 6 warheads each (est 6 with Avangard)
  - About 100 SS-25 Solids, 1 warhead (2022 Bull Atomic Sci est 9)
  - About 130 SS-27 Solids, up to 3 warheads (est 233 silo & mobile)
- Russian SLBMs (Submarines) per NASIC 2017 & 2020 unclassified reports
  - About 100 reduced to 16 SS-N-18, up to 3 warheads each (est 0)
  - About 100 reduced to 96 SS-N-23, up to 4 warheads each (est 80)
  - About 70 reduced to 48 SS-N-32 Solids, up to 6 warheads each (est 80)
- US ICBMs
  - About 400 Minuteman III Solids, reduced from 3 to 1 warheads each
- United States SLBMs
  - About 240+ Trident II Solids, 4 to 8 warheads each

New START treaty (2011) limited Ballistic Missile + nuclear bomber numbers to 700 each side (540 Russian vs 659 US*), additional 100 not deployed, and 1550 deployed nuclear warheads (1549 vs 1420*). *9/1/2022 Dept of State

ICBM/SLBMs of the 1970s and Earlier

- DSP and MiDAS Satellites detected Many of these Missile Launches
- Note the Large Size of the SS-6, SS-7, Titans, SS-9, and SS-18 ICBMs
- Solid Motor ICBMs Generally have Three Stages to Compensate for their Lower Performance as Compared to Liquid Engine ICBMs
- Note the Smaller Size of the SLBMs (short to medium range)

SS-6 Atlas II, F SS-7 Titan I,II SS-9 MMIII N6 SS-16,17 N8 SS-18,19

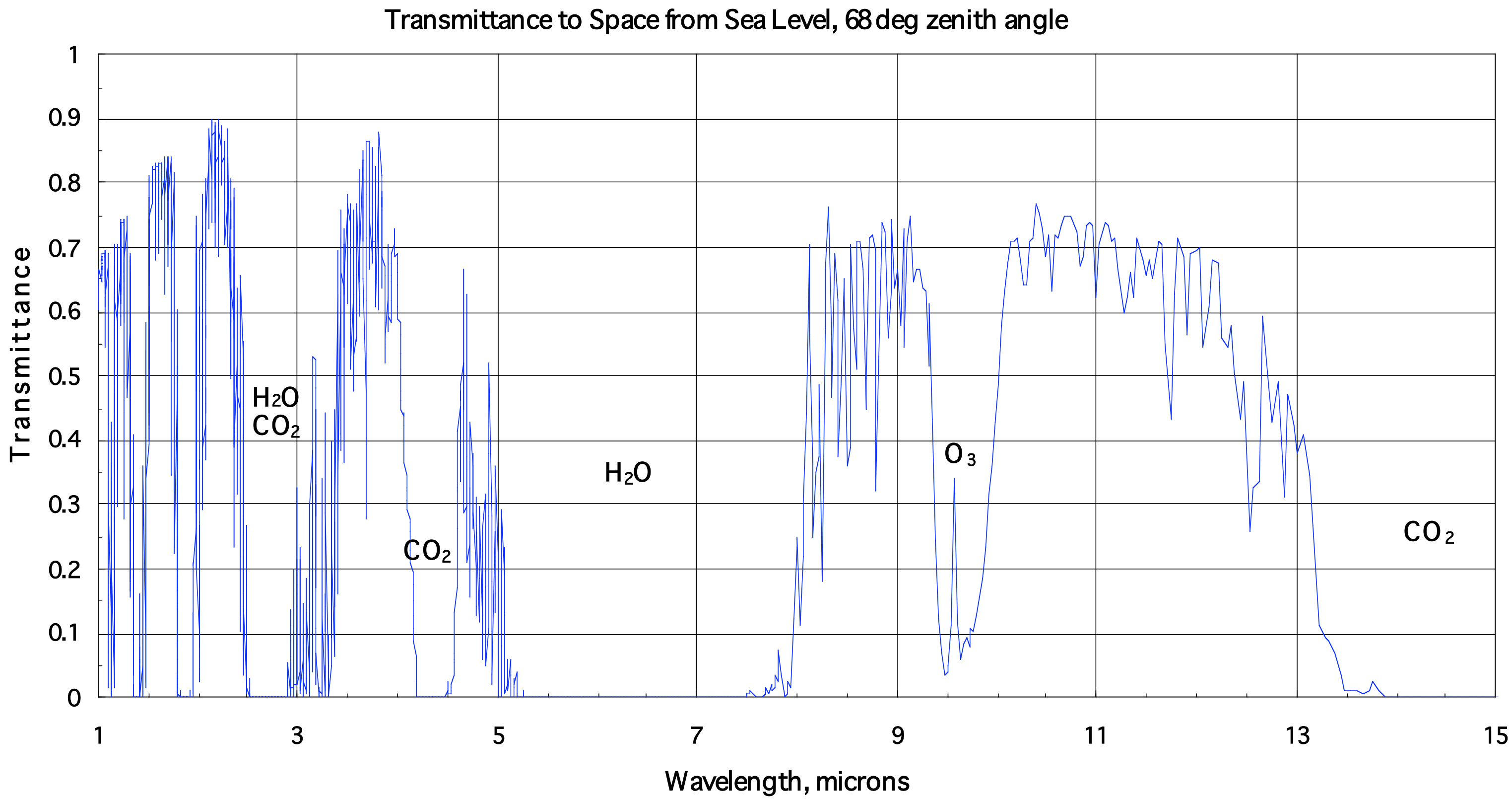
Ref: Gunston (1979), The Illustrated Encyclopedia of the World's Rockets & Missiles, Crescent Books.

A Few References

- G. Sutton (2000), Rocket Propulsion Elements, 7th edition, Wiley & Sons.
- Podvig (2001), Russian Strategic Nuclear Forces, MIT Press.
- NASIC (2017), Ballistic and Cruise Missile Threat, NASIC-1031-0985-17, June 2017, NASIC public affairs office.
- Photos courtesy of the Air Force and NASA.
- F.S. Simmons (2000), The Aerospace Corporation, Rocket Exhaust Plume Technology, AIAA.

Atmospheric Transmission from Sea Level to Space

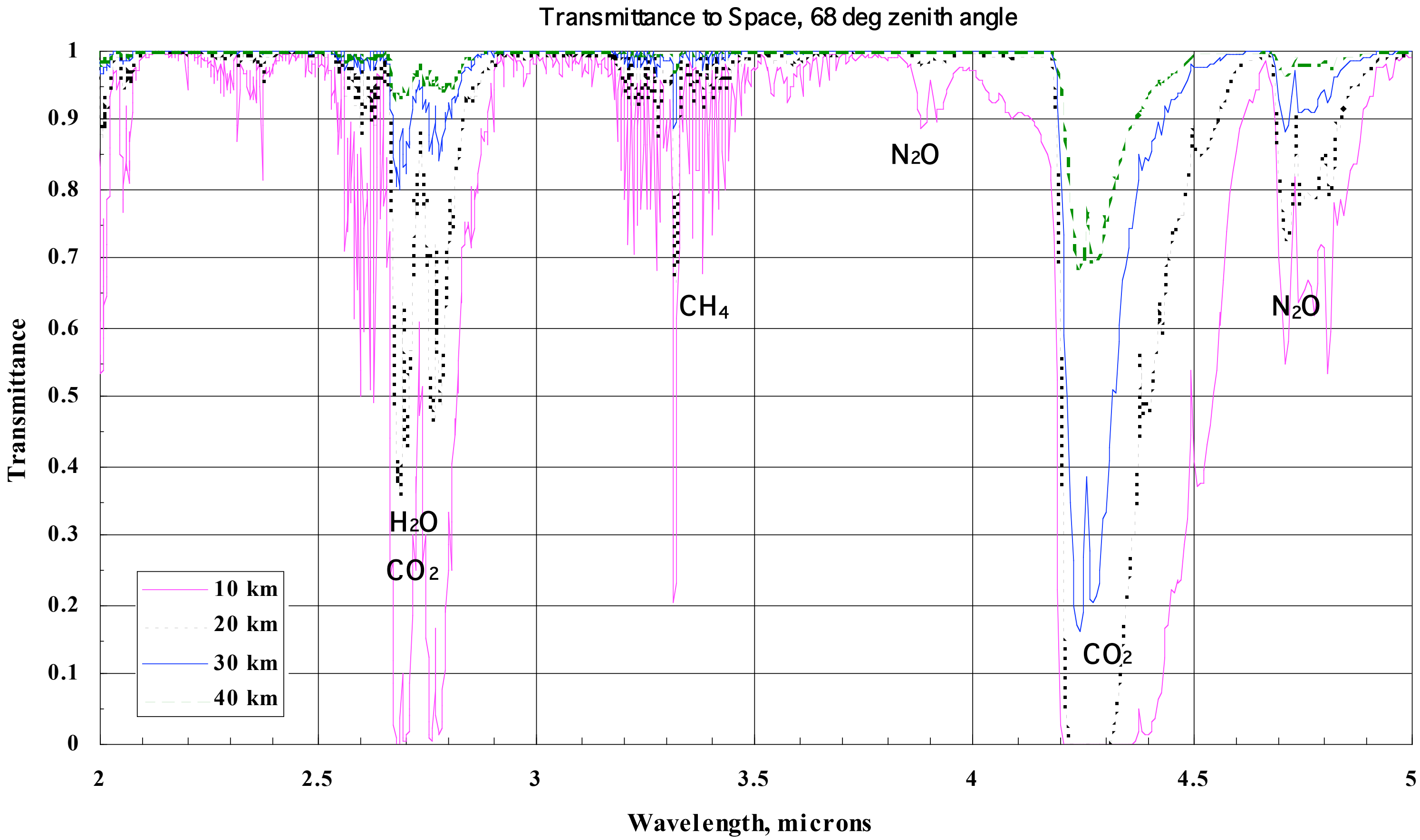
- Atmospheric Absorption is Strong from Sea Level in Major Plume Emission Bands
- However, There are Many Atmospheric Windows, as well as the 8-12 micron Window



MODTRAN calculation

Atmospheric Transmission from Altitude to Space

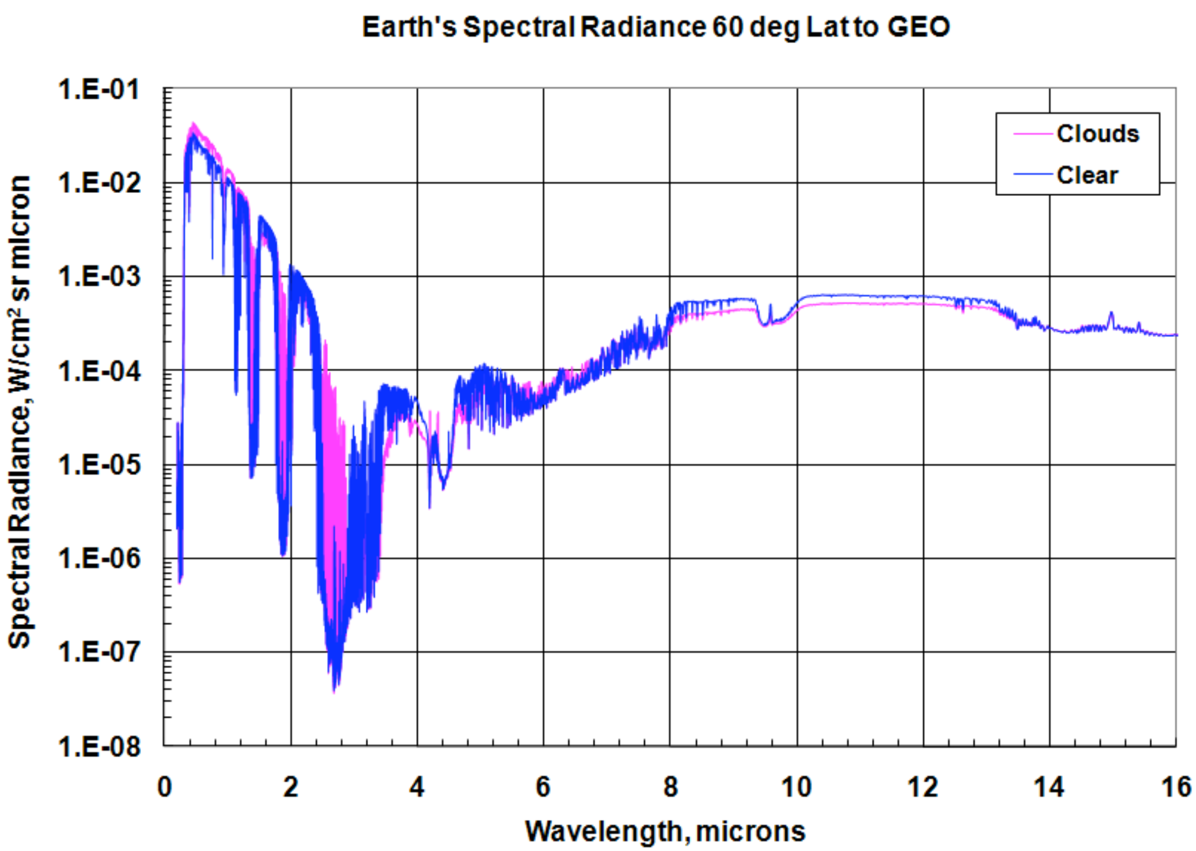
- Major Plume Emission Regions Still Correspond to Atmospheric Absorption Bands
- However, Atmospheric Absorption Decreases with Altitude



MODTRAN calculation

Daytime Earth Backgrounds from Space

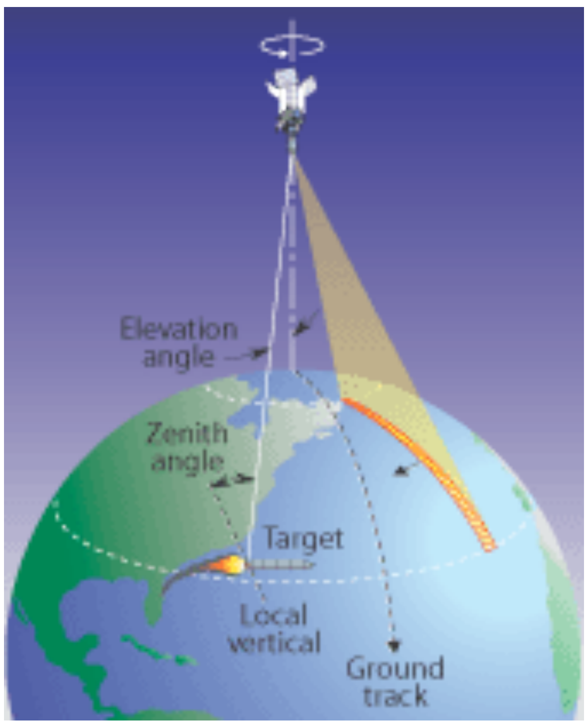
- Clouds Increase Backgrounds and Clutter at Shorter Wavelengths
- Minimum Background Radiance in the 2.7 Micron Water/Carbon Dioxide Band
- Low Clutter Backgrounds for Uniformly Mixed Gases, e.g., in 2.7, 4.3 and 15 μ CO_2 Bands



MODTRAN calculation

Titan II SWIR MiDAS Signatures

- Program 461 Rocket Signatures (Declassified in 1999 from the 1960s)
- Apparent Target Radiant Intensity vs Time after Launch
- Polar Orbit, 2000 nmi Altitude
- Bandpass 2.65 – 2.80 microns



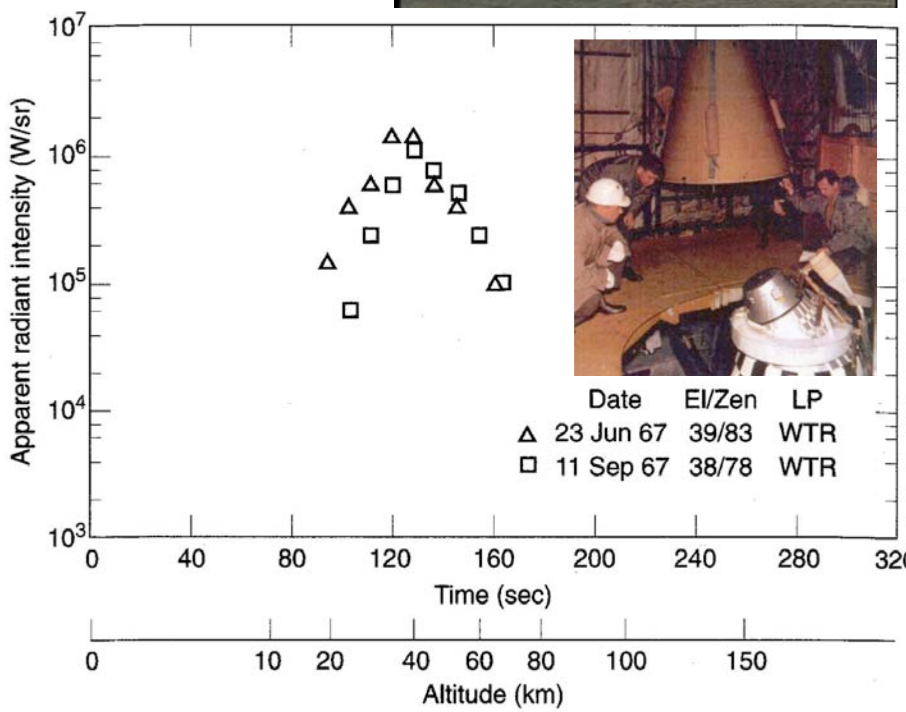
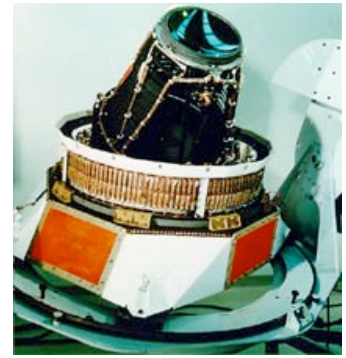


Fig. 14.3. Observations of Titan II ICBM test launches.

Courtesy The Aerospace Corp., Simmons (2000)

Titan III SWIR MiDAS Signatures



- Program 461 Data (1967)
- Titan IIIB Similar to Titan II – NTO/AZ-50 Two Stages
- Titan IIIC Added Stage 0 Strap On SRBs
  - Enhancement Radiation >90 km
  - Staging Events

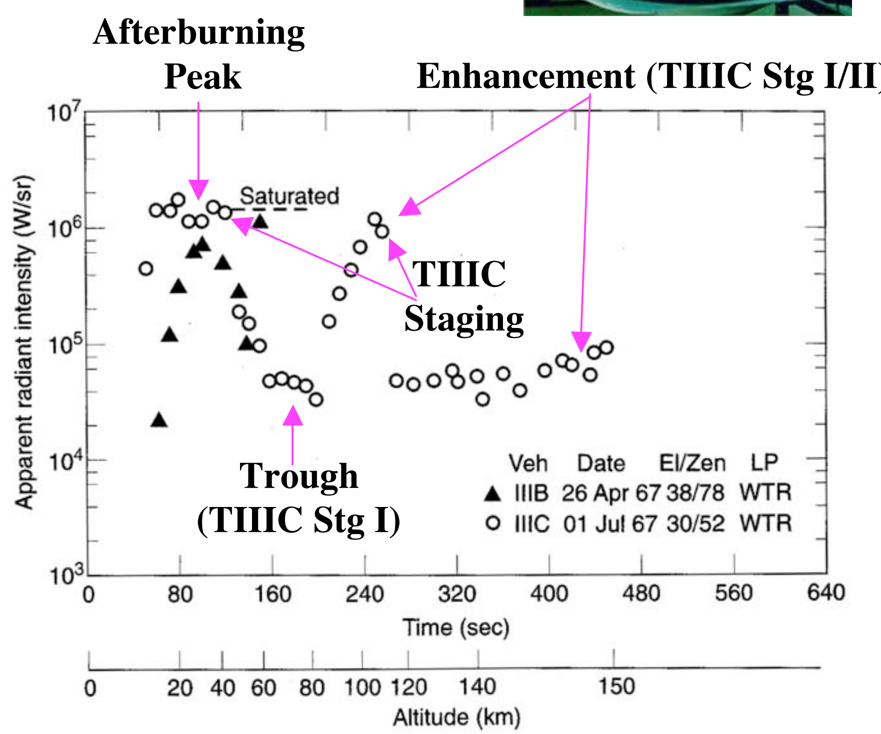


Fig. 14.4. Observations of Titan III space launch vehicles.

Courtesy The Aerospace Corp., Simmons (2000)

Defense Support Program

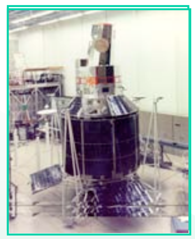
37 Years of Success -- A Solid Foundation

- A legacy of successful support to the National Command Authority
- Provides integrated tactical warning attack assessment

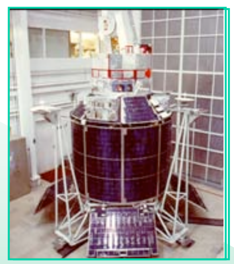
1970

Phase I
•Satellites 1-4

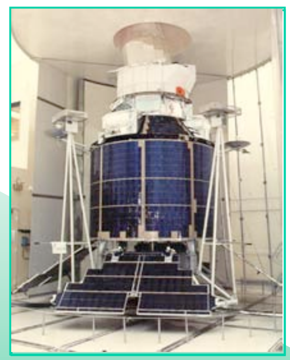
Phase II
• Satellites 7-9



MOS/PIM
• Satellites 10-13



Phase II Upgrade
• Satellites 5R,6R

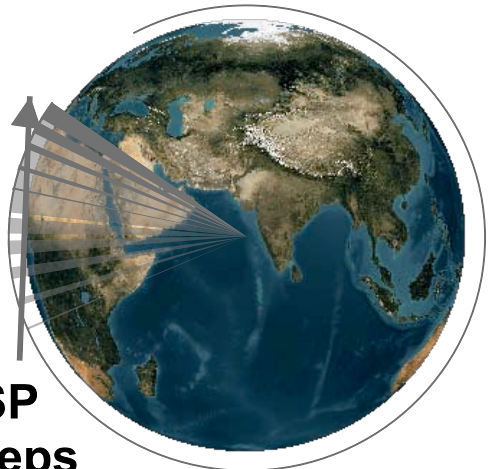


2007

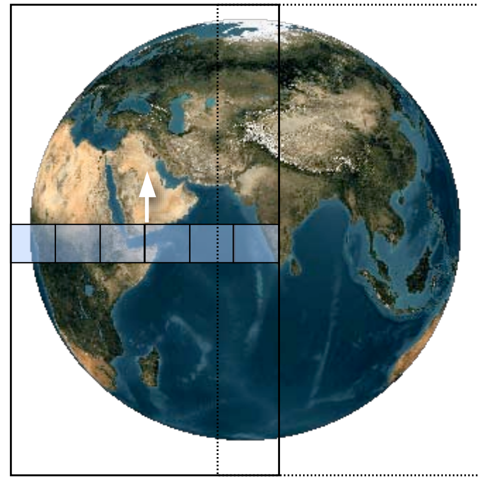
DSP-1
• Satellites 14-23

Courtesy USAF, SBIRS Briefing, 2001, Cleared for Public Release, updated thru 2007

DSP/SBIRS Sensor Coverage Comparison

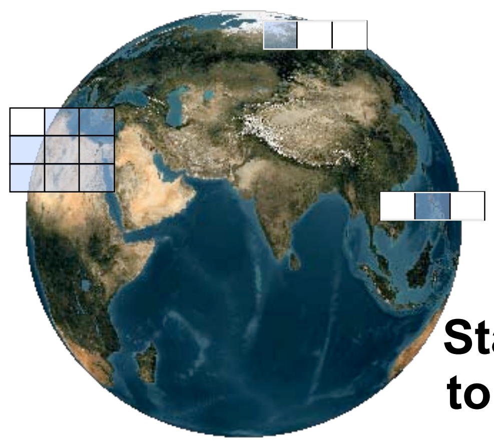


DSP
Sweeps
Earth Disk
(Scanner)



SBIRS
Scanning
sensor rapidly
revisits Earth
disk

SBIRS High (Scanner & Starer)



Staring sensor tasked
to theater and special
area coverage

Courtesy USAF, SBIRS Briefing, 2001, Cleared for Public Release, added globe to show GEO view

Overview of Missile Plume Missions

- Early Warning & Missile Typing
  - MiDAS (461), DSP (647), SBIRS, NextGen
  - Initially one bandpass (SWIR), expanded to two (SWIR & MWIR)
  - Generally low spatial and temporal resolution
  - Covers most of the Earth every <10 seconds above cloud deck
- Impact Point Determination
  - Difficult - low signal levels in post boost phase (verniers, bus engines)
  - Need high spatial & temporal resolution
- Missile Defense
  - Hit-to-kill interceptors (non-nuclear), plume sensor self-interference
  - Handover from plume to hardbody for directed energy systems (SDI)
  - Requirements for high spatial & temporal resolution
- Technical Intelligence
  - High temporal resolution, multiple wavelengths desirable
- Missile ID at Launch
  - High temporal resolution needed, possibly multiple wavelengths that see to ground
  - Optical sensors not useful with cloud cover
  - Heading and Number of Stages Unknown at Liftoff
- Battlespace Characterization
  - Wider Bandpasses to “See to Ground”
  - Higher spatial & temporal resolution

Summary

- Infrared Signals are Intense
  - SWIR/MWIR for Early Warning
- May have Large Visible Signals
- Scanners are Still the Choice for Wide Area Surveillance; however, when 10k x 10k IR arrays become Available, Starers will Enable Giant Leaps in Surveillance Sensitivity
- Follow the Water (& Carbon Dioxide)!