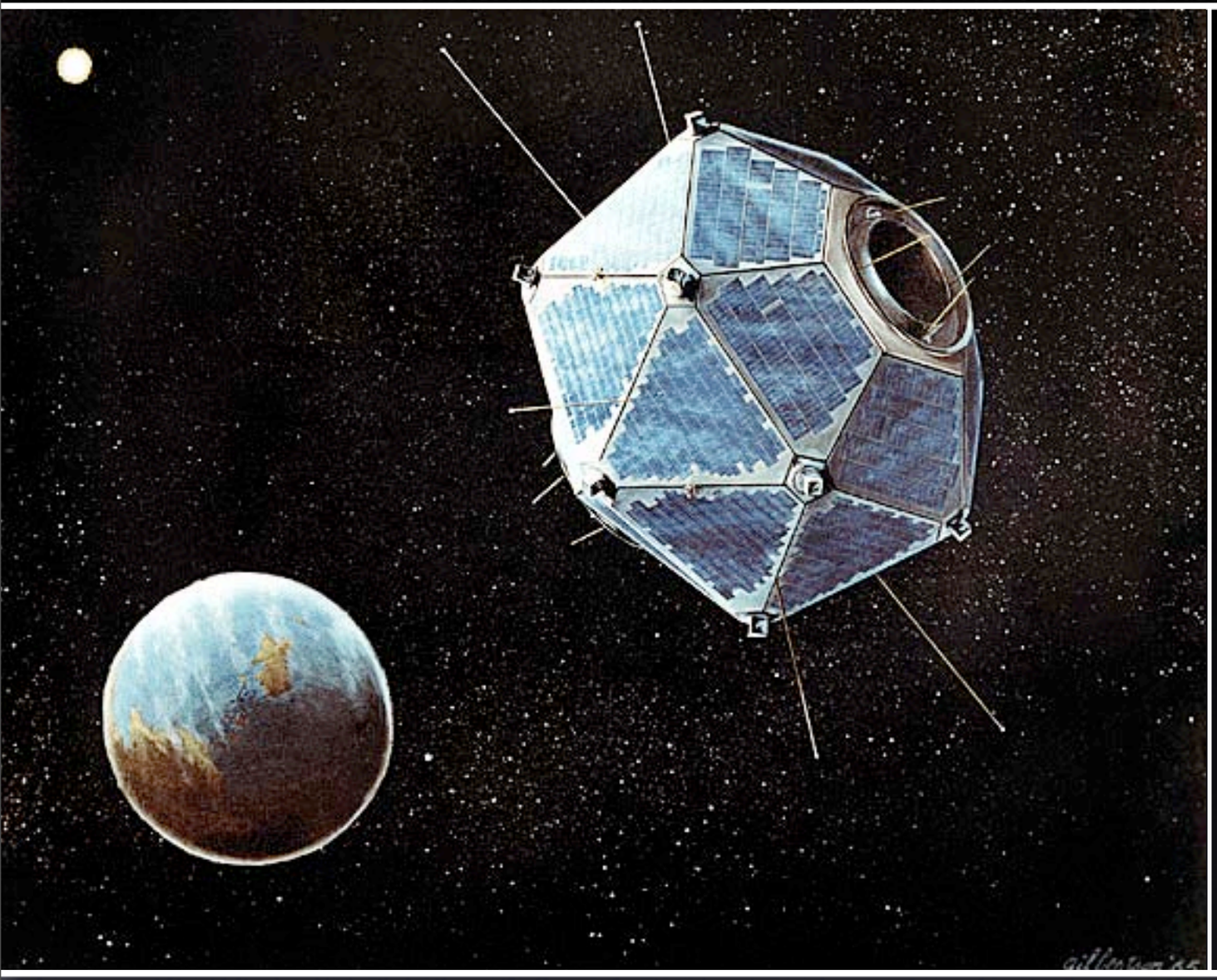


Satellite Imagery

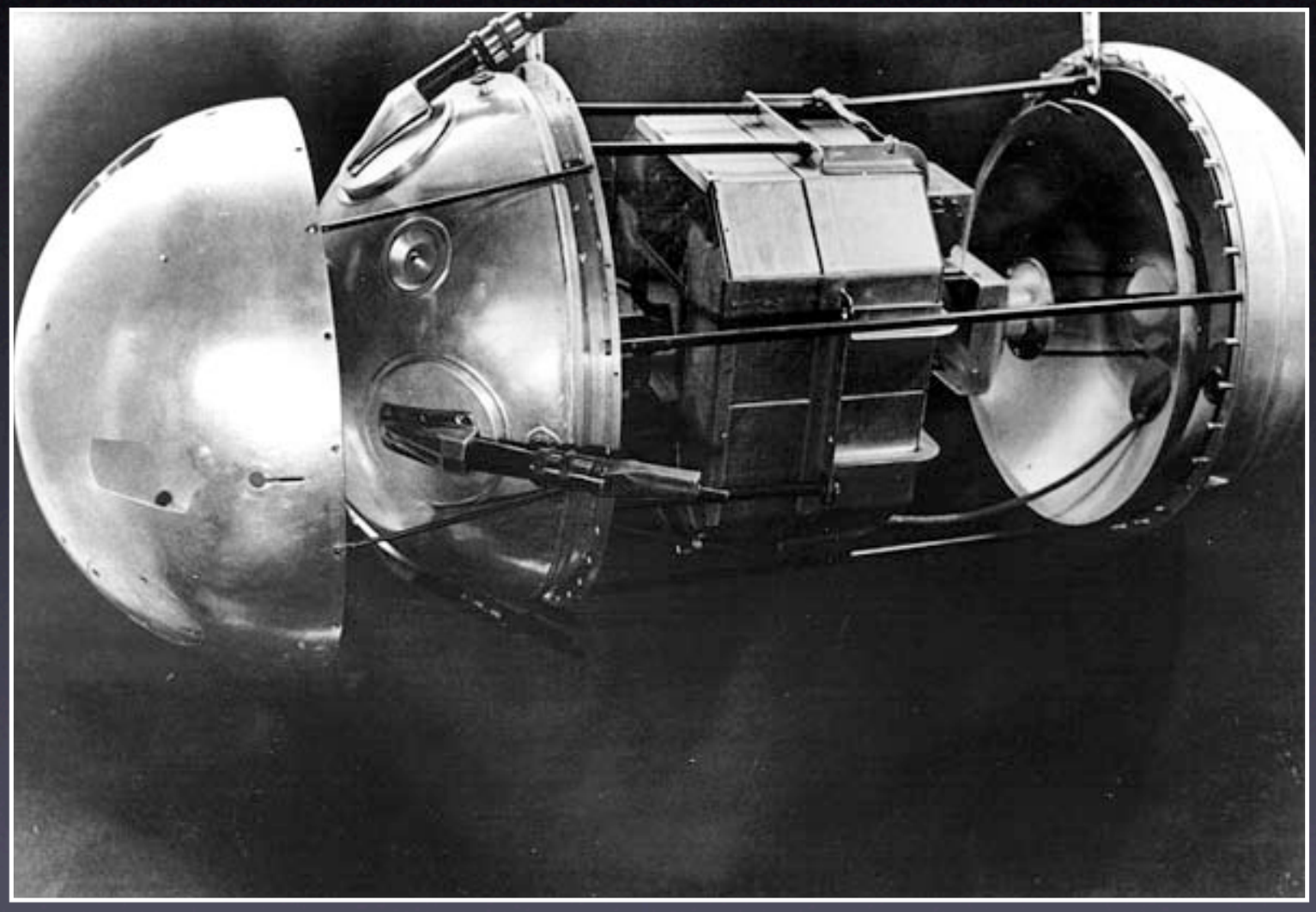
Alexander Glaser

WWS556d
Princeton University
February 19, 2007

Overview

Sputnik 1

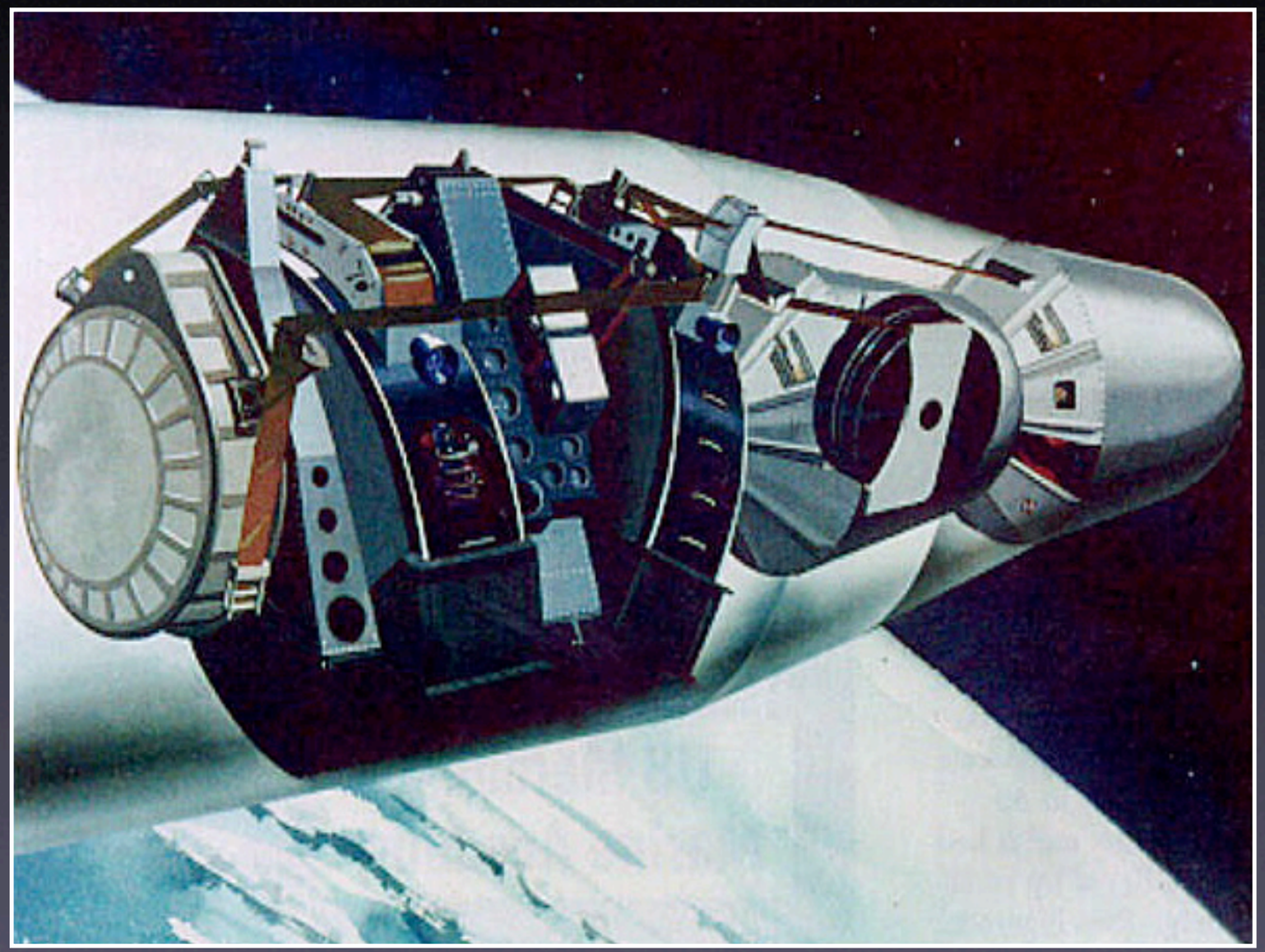
4 October 1957



83.6 kg (in orbit), 58 cm diameter, aluminum sphere
operational for 3 weeks, decay of orbit after 3 months, about 1400 orbits of earth

The First Reconnaissance Satellites

CORONA series, first mission in early 1959 (initially called Discoverer)



Soviet Airbase in August 1960

Hubble Space Telescope
launched 1990

reportedly similar to early KH-11 satellites (1976-1988/2005)
first successful electronic imaging satellites

Source: NASA

Satellite Missions

Communication

Navigation

Earth observation and remote sensing
(weather, environment, map making, etc.)

Science
(especially astronomy)

IMINT (Imagery Intelligence) and other special reconnaissance

Total today: about 2,500 satellites in orbit (operative and inoperative)

About 8,500 man-made objects are being tracked by USSTRATCOM
(600,000 objects larger than 1 cm are in orbit)

NASA J-Track 3D

http://science.nasa.gov/Realtime/jtrack/3d/JTrack3D.html

EarthNow! Landsat Image Viewer

http://earthnow.usgs.gov

Satellite Orbits and Capabilities

(Why Satellites are Where They Are)

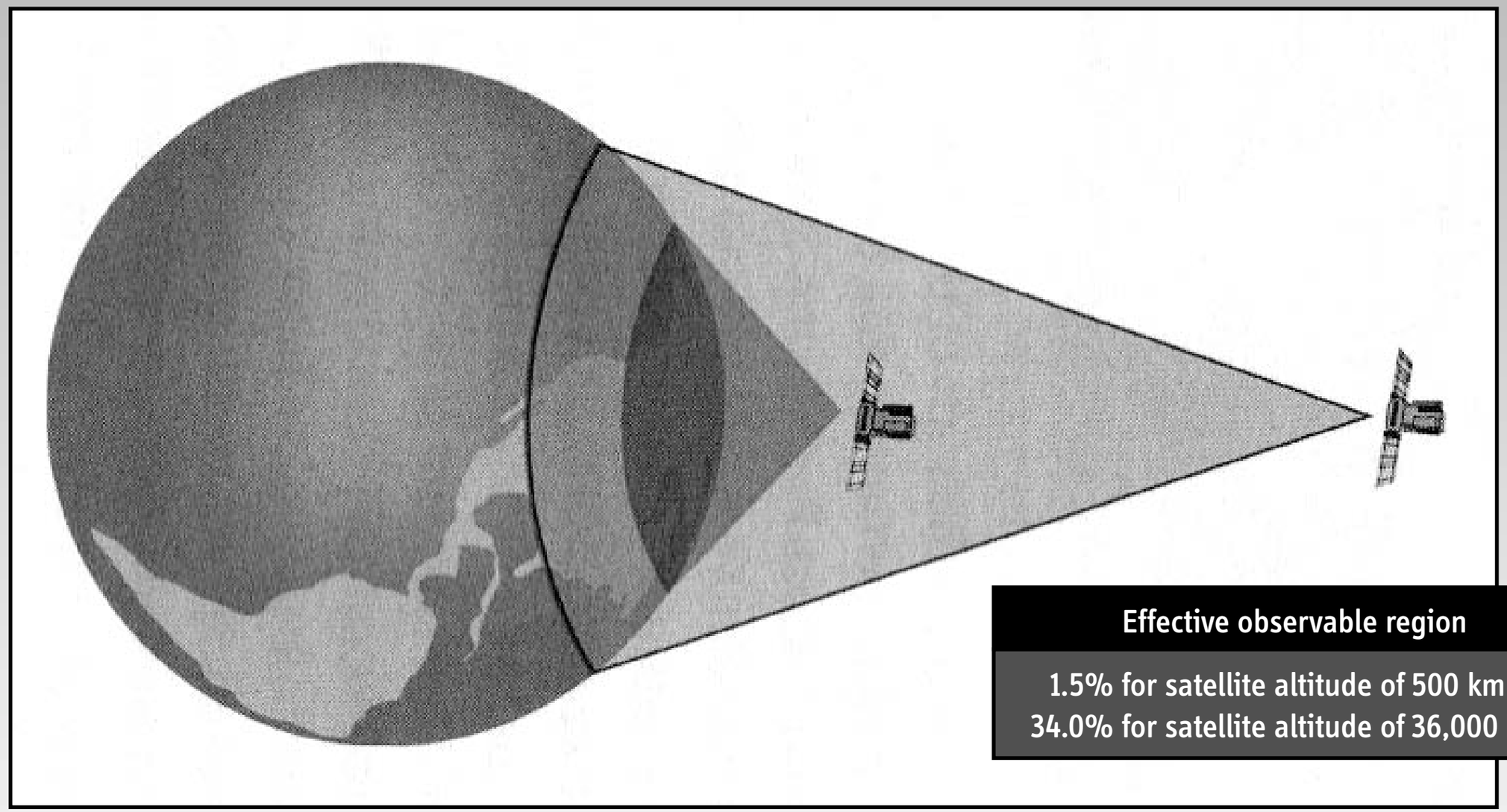
Orbital Period

$$T_s = 2\pi\sqrt{\frac{(R_e + h_s)^3}{G\,M_e}}$$

Orbital period for a small satellite orbiting a central body

	Altitude	Orbital Period
Low Earth Orbits	200 km	1 hour and 28 min
	500 km	1 hour and 35 min
	1000 km	1 hour and 45 min
	5000 km	3 hours and 21 min
	10000 km	5 hours and 48 min
	20200 km	12 hours
	36000 km	24 hours

Maximum Observable Ground Area



Effective observable region

1.5% for satellite altitude of 500 km
34.0% for satellite altitude of 36,000 km

Source: D. Wright, L. Grego, and L. Gronlund, *The Physics of Space Security. A Reference Manual*, American Academy of Arts & Sciences, 2005

What Are We Looking For/With?

Visible Light

Wavelength: 450-700 nm

Thermal Infrarad

Wavelength: 8000-14000 nm

Radar

Wavelength: 1-100 mm

Advanced imaging techniques include: Synthetic Aperture Radar (SAR)

Sample SAR imagery from www.sandia.gov/RADAR/sar.html
Primarily relevant for military satellites ("Space Based Radar") and real-time targeting (not discussed here)

Ground Resolution of Imagery

$$\frac{x}{h} \approx \sin\theta = 1.22\,\frac{\lambda}{d}$$

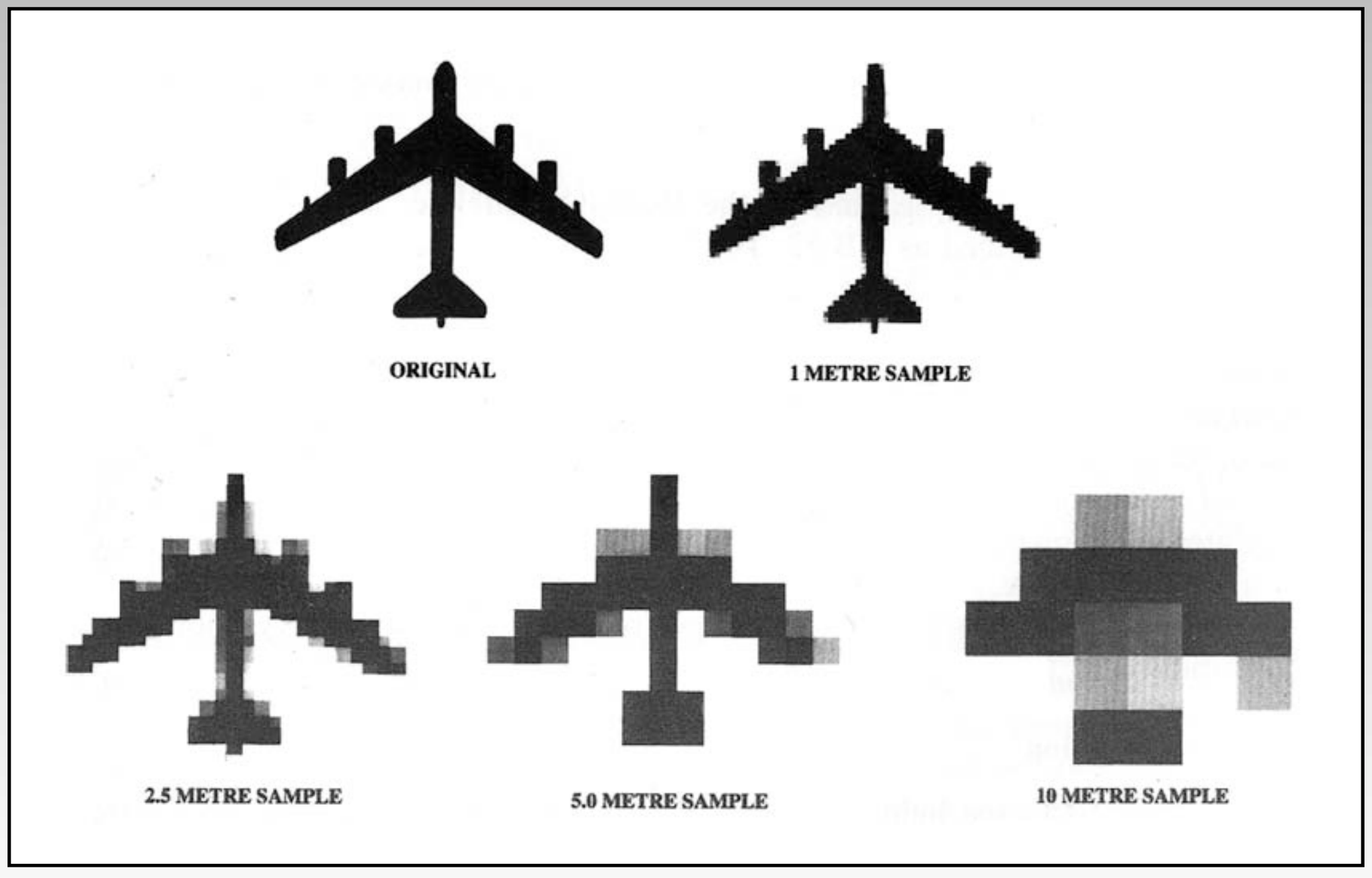
Rayleigh criterion for the resolution of an optical system
(d: diameter of the lens or mirror, h: altitude of satellite, x: ground resolution)

Altitude of Satellite	Diameter of lens or mirror: 0.5 m	2.4 m	5 m
300 km	40 cm	8 cm	4 cm
450 km	60 cm	13 cm	6 cm
1000 km	130 cm	28 cm	13 cm
36000 km	48 m	10 m	5 m

Values for a wavelength of 550 nm

Resolution for thermal infrared (TIR) imagery at 10,000 nm is about 20x poorer

Satellite Image of a B-52 Bomber



Source: B. Jasani and G. Stein, *Commercial Satellite Imagery. A Tactic in Nuclear Weapon Deterrence*, Springer, 2002


Image © 2007 DigitalGlobe
©2007 Google™
Pointer 48°25'01.98" N 101°20'57.17" W
Streaming 100%
Eye alt 747 m

Ground Resolution Requirements

(for various interpretation tasks)

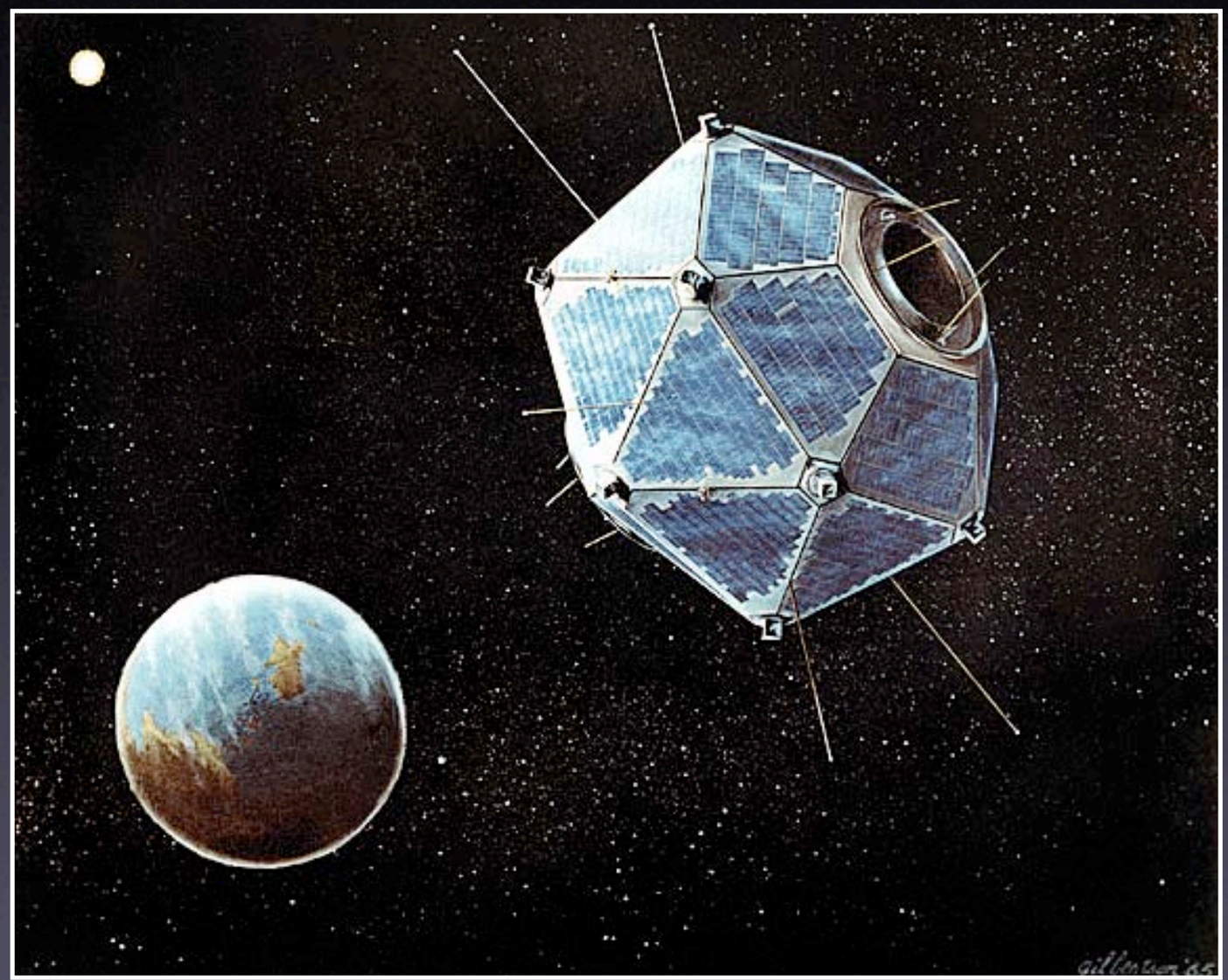
Object / Target	Detection	General ID	Precise ID	Description
Urban area	60 m	30 m	3.0 m	3.0 m
Ports and harbors	30 m	15 m	6.0 m	3.0 m
Surfaced submarine	30 m	6 m	1.5 m	0.9 m
Roads	9.0 m	6.0 m	1.8 m	0.6 m
Surface ships	7.5 m	4.5 m	0.6 m	0.3 m
Bridge	6.0 m	4.5 m	1.5 m	0.9 m
Aircraft	4.5 m	1.5 m	0.9 m	0.15 m
Missile sites (SSM, SAM)	3.0 m	1.5 m	0.6 m	0.30 m
Nuclear-Weapon Components	2.4 m	1.5 m	0.3 m	0.03 m
Vehicles	1.5 m	0.6 m	0.3 m	0.05 m

Source: D. Schroeer, *Science, Technology, and the Arms Race*, John Wiley & Sons, 1984
Selected data from a NASA Authorization Hearing before the U.S. Senate Committee on Commerce, Science, and Transportation

Satellites as a Tool for Arms-Control-Treaty Verification

The Vela Satellite Program

(1963-1984)

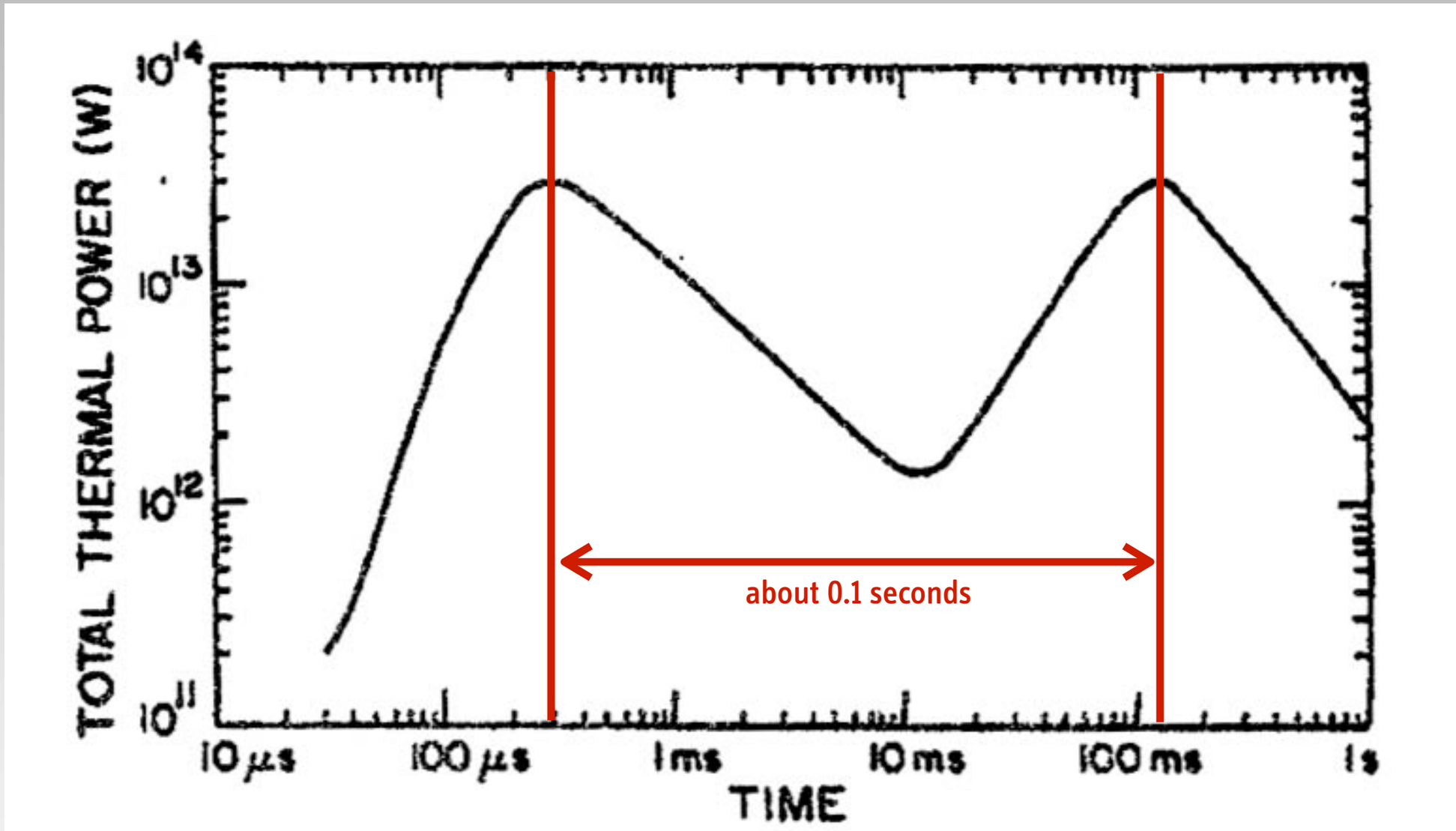


Part of the system of “national technical means” to monitor compliance with the 1963 Limited Test Ban Treaty

(Treaty Banning Nuclear Weapon Tests in the Atmosphere, in Outer Space and Under Water)

Satellites used non-imaging photodiodes to monitor light levels

Signature of a Nuclear Explosion



Light flash produced by a 19-kiloton atmospheric nuclear test conducted in Nevada, 1 May 1952

G. E. Barasch, *Light Flash Produced by an Atmospheric Nuclear Explosion*
Los Alamos Scientific Laboratory, LASL-79-84, November 1979

The VELA Incident

(Vela Satellite 6911, Event Alert 747, 22 September 1979)

"I doubt that any responsible person now believes that a nuclear explosion occurred because no one has broken security, among South Africans or elsewhere. U.S. experience teaches that secrets of such import can't be kept long."

Luis Alvarez, 1987

"The explosion was clean and was not supposed to be detected. But they were not as smart as they thought, and the weather changed—so the Americans were able to pick it up."

Commodore Dieter Gerhardt, 1994
Former Commander of the Simonstown naval base near Cape Town

(Resources at: www.gwu.edu/~nsarchiv/NSAEBB/NSAEBB190)

Monitoring of the 1972 SALT I Treaty

Main provisions to be monitored

Deployment of additional missiles and bombers
Test of new strategic weapons
Modification of existing weapon-systems into more advanced modifications

ARTICLE V

1. For the purpose of providing assurance of compliance with the provisions of this Interim Agreement, each Party shall use national technical means of verification at its disposal in a manner consistent with generally recognized principles of international law.

2. Each Party undertakes not to interfere with the national technical means of verification of the other Party operating in accordance with paragraph 1 of this Article.

3. Each Party undertakes not to use deliberate concealment measures which impede verification by national technical means of compliance with the provisions of this Interim Agreement. [...]

"Orbital satellite reconnaissance has become one of the most stabilizing technologies for the arms race as it gives detailed information about the enemy's actual weapons inventory—not just uncertain information about possible capabilities."

D. Schroeer, *Science, Technology, and the Arms Race*, 1984

The Era of Google Earth

(and of Commercial Imagery)

Google Earth

Search

Fly To | Find Businesses | Directions

e.g., New York, NY

Places

My Places

Temporary Places

Layers

View: Core

Primary Database

Image © 2007 TerraMetrics
Image © 2007 NASA
© 2007 Europa Technologies

©2007 Google™

Pointer 37°40'54.95" N 95°27'06.31" W Streaming 100% Eye alt 6371.00 km

One-meter resolution satellite
image of Manhattan
collected at 11:43 a.m. EDT
on September 12, 2001
by GeoEye's IKONOS satellite

Commercial Vendors

of Satellite Imagery

DigitalGlobe

founded in 1992 as WorldView (then EarthWatch)
Primary satellite: QuickBird, launched in October 2001
Next satellites: WorldView I and II (2007 and 2008)

(Customer: Google Earth)

GeoEye

founded in 2006 (following acquisition of Space Imaging by OrbImage)
Primary satellites: IKONOS (1999), OrbView-3 (2003), and OrbView-2 (low-res, 1997)
Next satellite: GeoEye-1 (2007)

Main Commercial Imagery Satellites

IKONOS (or: IKONOS-2)

www.geoeye.com/products/imagery/ikonos/

1-meter panchromatic, 4-meter multispectral
Altitude: 680 km, sun-synchronous orbit: given longitude at 10.30 AM local time
Orbital period: 1 hour and 38 minutes, revisit rate: 3-5 days off-nadir and 144 days true-nadir

QuickBird (or: QuickBird-2)

www.digitalglobe.com/about/quickbird.html

0.6-meter panchromatic, 2.4-meter multispectral
Altitude: 450 km, sun-synchronous orbit
Orbital period: 1 hour and 33.5 minutes, revisit rate: 3-7 days depending on latitude

OrbView-3

www.geoeye.com/products/imagery/orbview3/

1-meter panchromatic, 4-meter multispectral
Altitude: 470 km, sun-synchronous orbit: given longitude at 10.30 AM local time
Orbital period: 1 hour and 34 minutes, revisit rate: less than 3 days

Examples

Plutonium Production

at Seversk (Tomsk-7) in Russia, IKONOS imagery taken on 10 July 2000

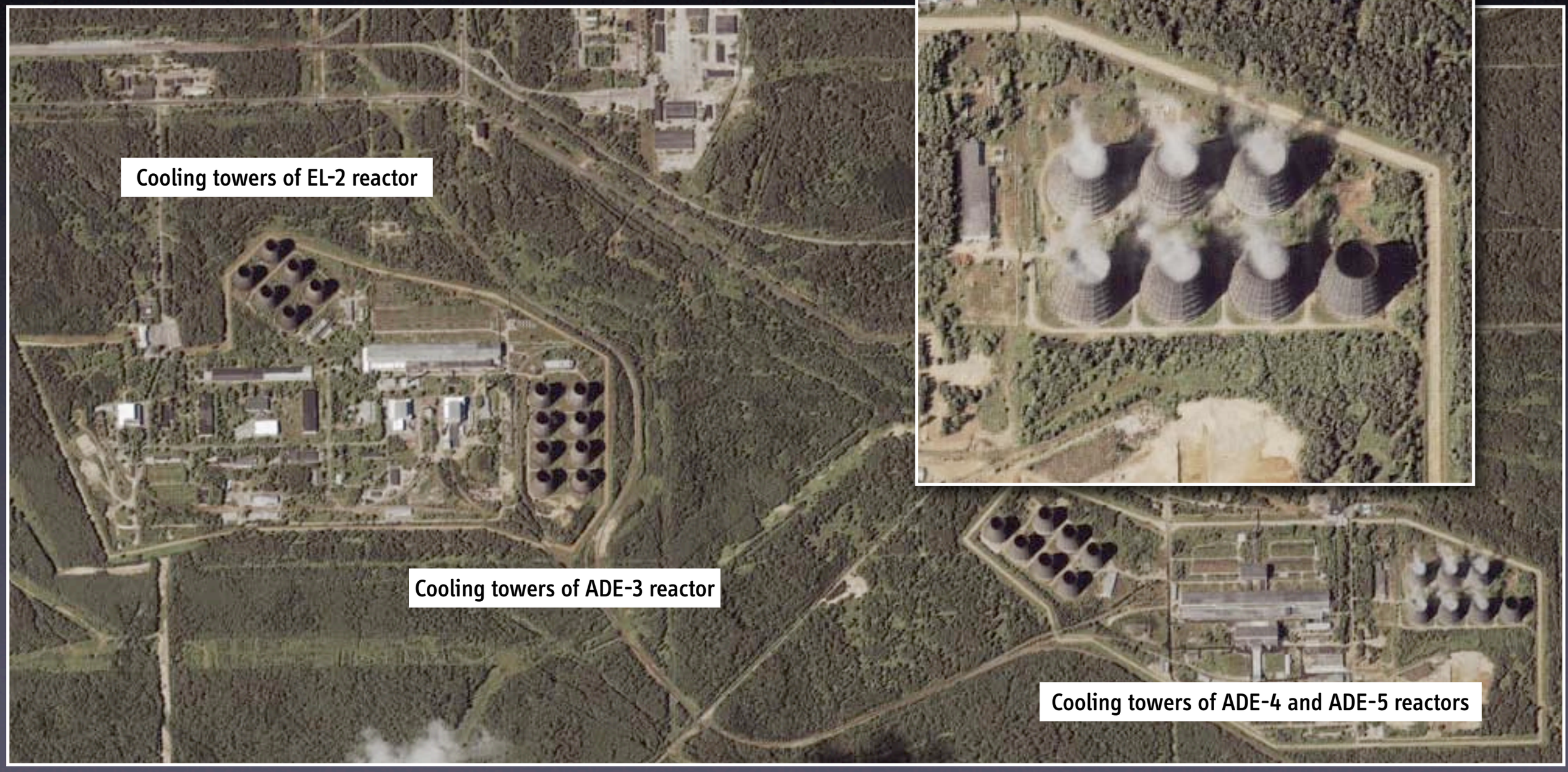
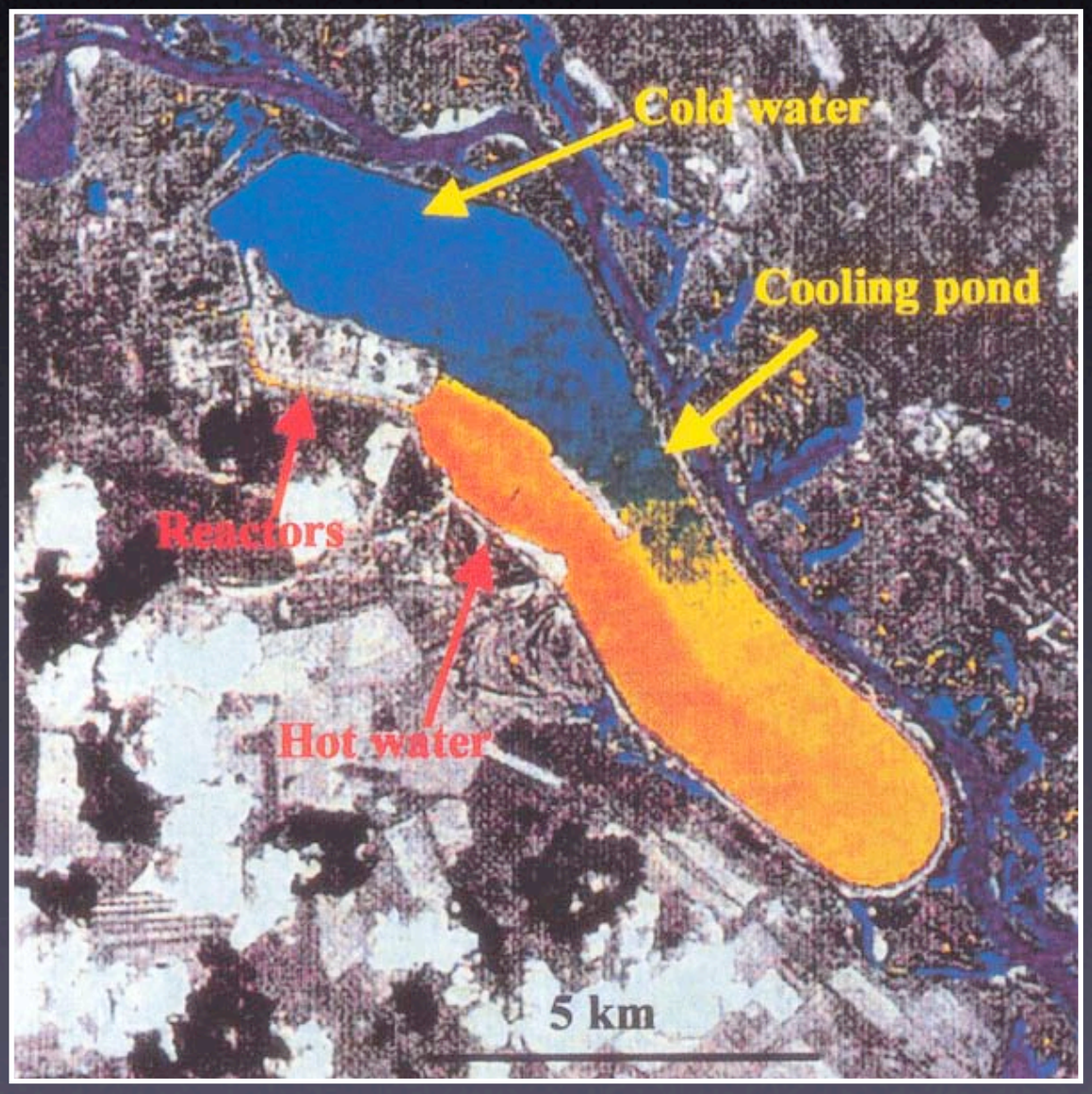



Image © 2007 DigitalGlobe
©2007 Google™
Pointer 56°38'47.12" N 84°54'49.17" E
Streaming 100%
Eye alt 1.43 km

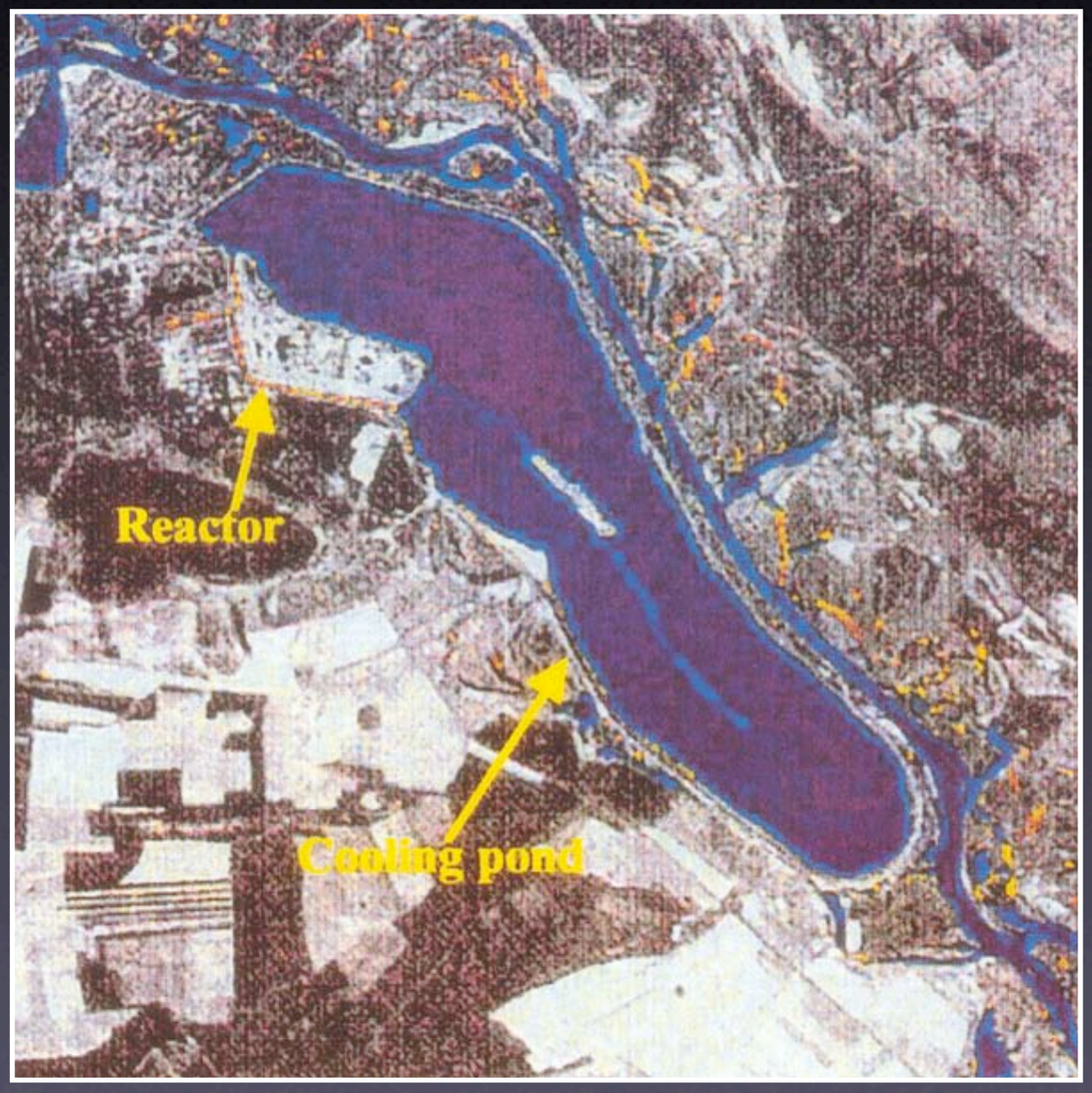
Chernobyl Reactor Site

LANDSAT-5 Thermal Infrared imagery taken before and after 26 April 1986

Ground resolution of LANDSAT-5: 120 m (new LANDSAT-7: 60 m)



22 April 1986



8 May 1986

Source: Hui Zhang and F. von Hippel, *Science & Global Security*, 8(3), 2000

Satellite Imagery for Nuclear Safeguards?

(for use by the International Atomic Energy Agency)

How satellite imagery can support the mission of the IAEA

Verification of declarations to the IAEA + up-to-date inspection aids

Operational status of nuclear facilities
(especially of nuclear reactors and large enrichment plants of certain types)

New construction activities and change-detection in facilities

Indirect detection of (clandestine) facilities
via detection of passive and active security features typically associated with “strategic assets”
(multiple perimeter fences, active defensive systems, etc.)

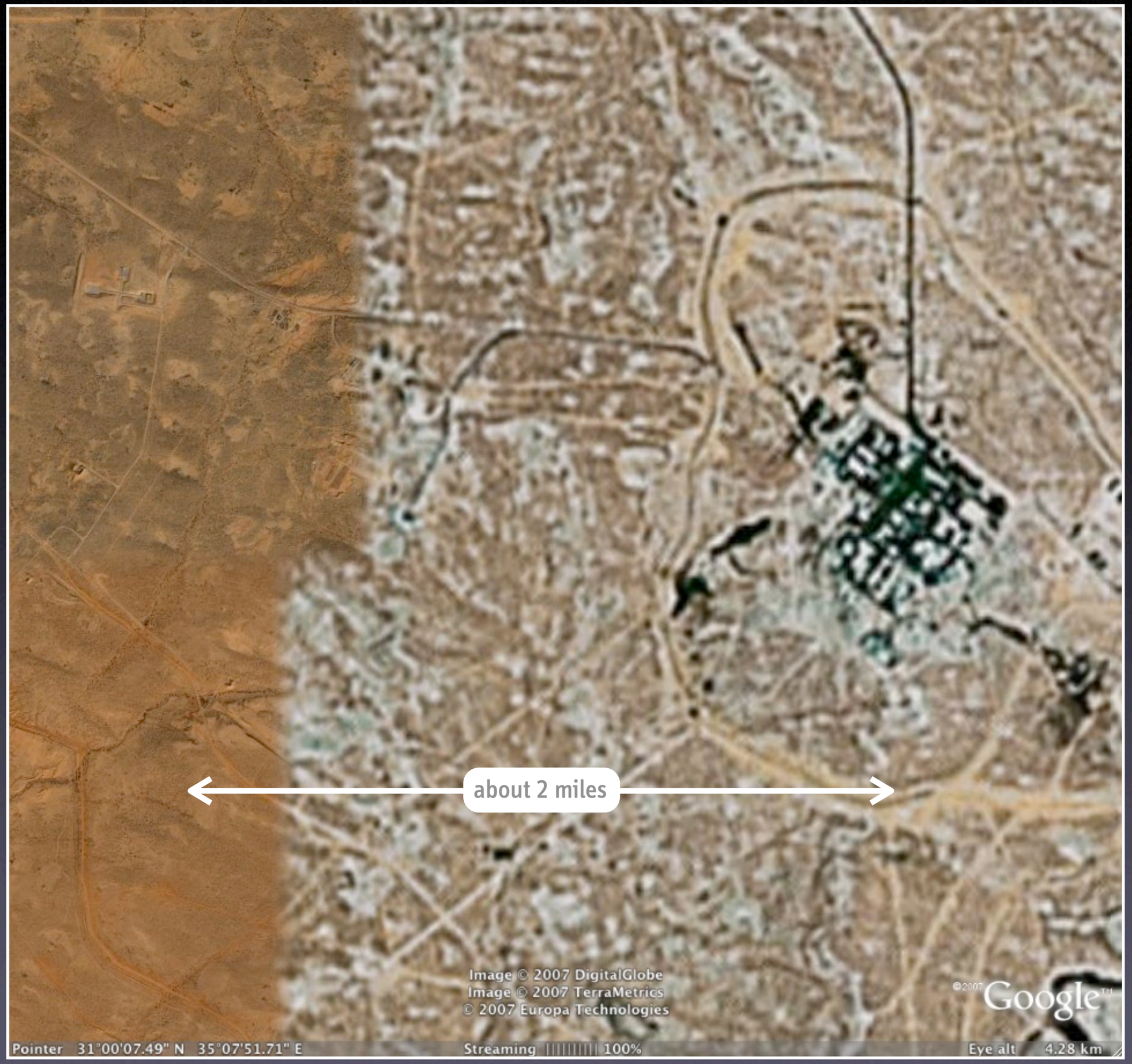
Bilateral versus multilateral/international monitoring

Many unresolved issues regarding the “appropriate use” of satellite imagery by the IAEA

What is considered “sensitive” and what “non-sensitive” data?

B. Jasani and G. Stein, *Commercial Satellite Imagery. A Tactic in Nuclear Weapon Deterrence*, Springer, 2002

Caveats


about 2 miles
Image © 2007 DigitalGlobe
Image © 2007 TerraMetrics
© 2007 Europa Technologies
©2007 Google
Pointer 31°00'07.49" N 35°07'51.71" E
Streaming 100%
Eye alt 4.28 km

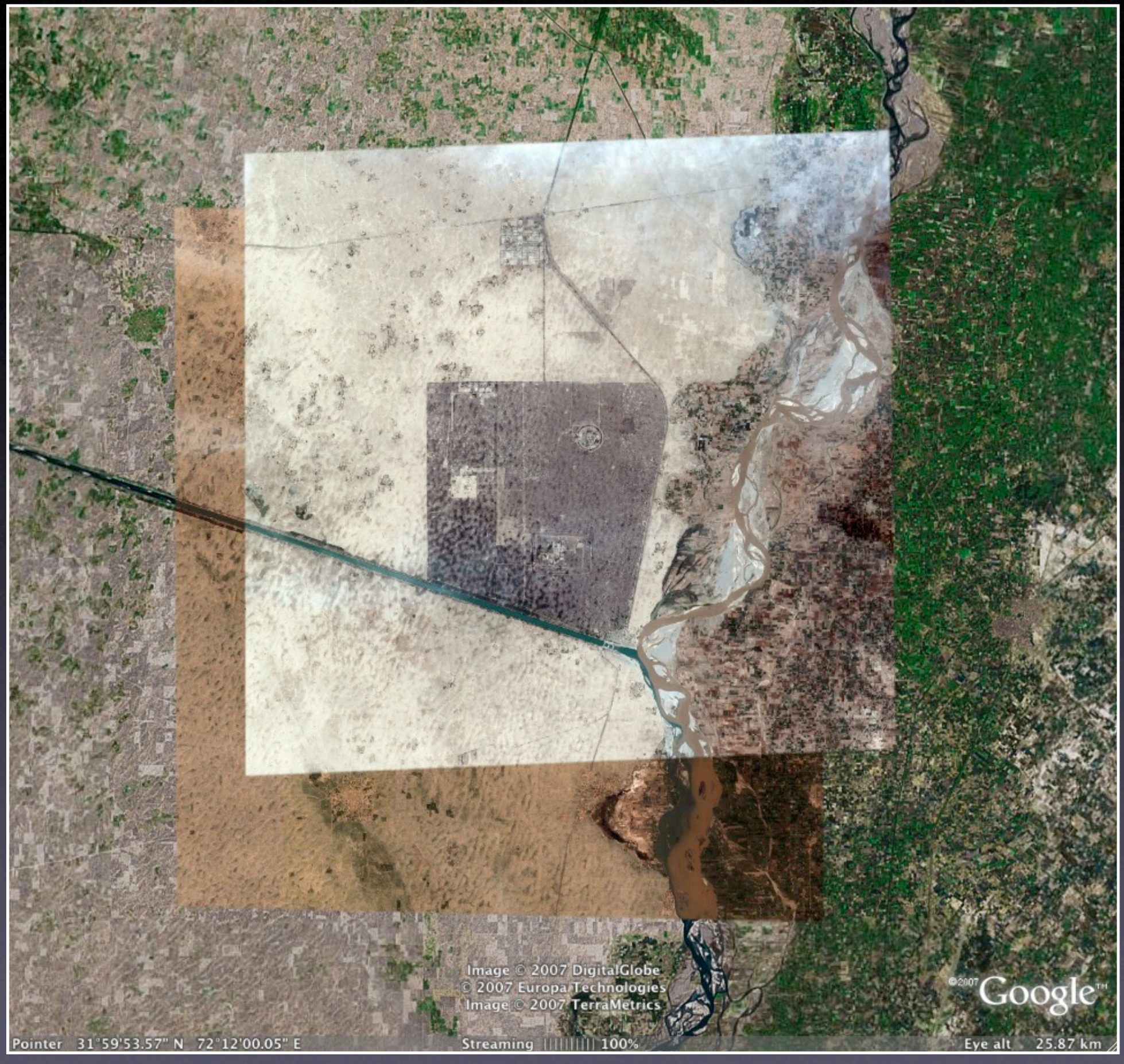


Image © 2007 DigitalGlobe
© 2007 Europa Technologies
Image © 2007 TerraMetrics
©2007 Google™
Pointer 31°59'53.57" N 72°12'00.05" E
Streaming 100%
Eye alt 25.87 km


Image © 2007 DigitalGlobe
© 2007 Europa Technologies
©2007 Google™
Pointer 32°00'33.94" N 72°10'20.10" E
Streaming 100%
Eye alt 1.01 km