SCIENCE &
GLOBAL SECURITY

PRINCETON UNIVERSITY

Igor Moric (2022) Capabilities of Commercial Satellite Earth Observation Systems and Applications for Nuclear Verification and Monitoring, Science & Global Security

Igor Moric (2023) Nuclear stability in a world with overhead transparency, Comparative Strategy

Next generation satellite nuclear monitoring and nuclear stability

Igor Moric

How transparency helped shape the Cold War nuclear competition

1940s/1950s

knowledge of nuclear programs shrouded in **secrecy** since their beginning

no way to verify – only safe assumption about the adversary is the **worst-case scenario**

a quasi-balance established, "*reinforced by the further* ***deterrent of massive retaliatory power***" and the "*capacity to retaliate, instantly, by means and at places of choosing*" – John Dulles in 1954

1950s - US and Soviet Union continue to build nuclear weapons believing this would be advantageous in a potential nuclear war

1952 nuclear detonation, Yucca Lake in Nevada

How transparency helped shape the Cold War nuclear competition

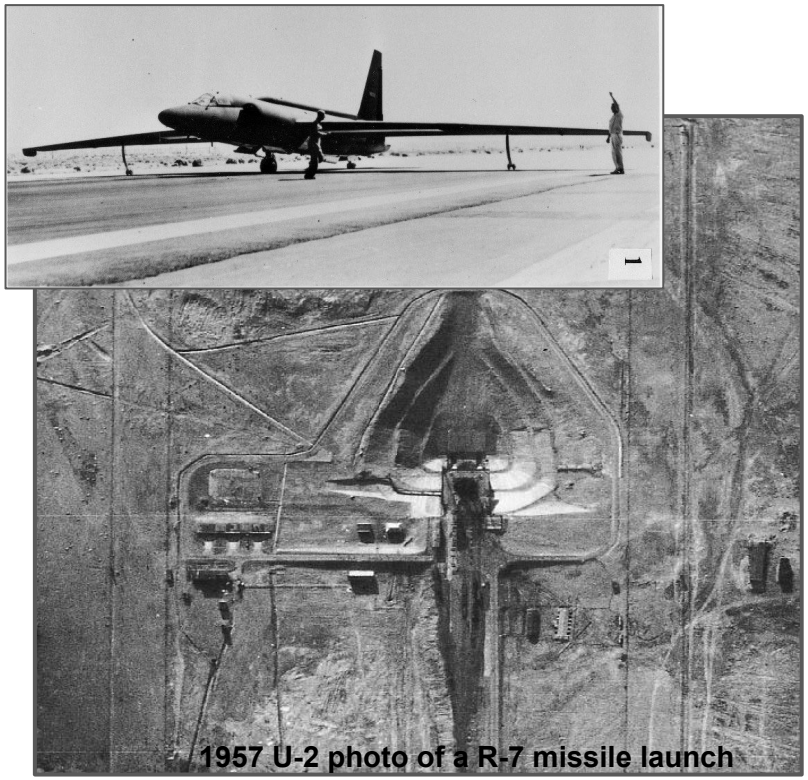
1950s/1960s

realization – **warning time needed** to allow for protection of nuclear retaliatory forces

US expanded **human** and **communication** intelligence capabilities, improved **sample collection** and introduced **U-2 spy planes**, proposed **“Open Skies”**

lack of intelligence and no methods to disprove the speculations made possible the **"bomber gap"** and the **“missile gap”**

fear of a surprise attack further stimulated increases of military spending and an accelerated buildup of weapons



1957 U-2 photo of a R-7 missile launch pad at the a missile test center

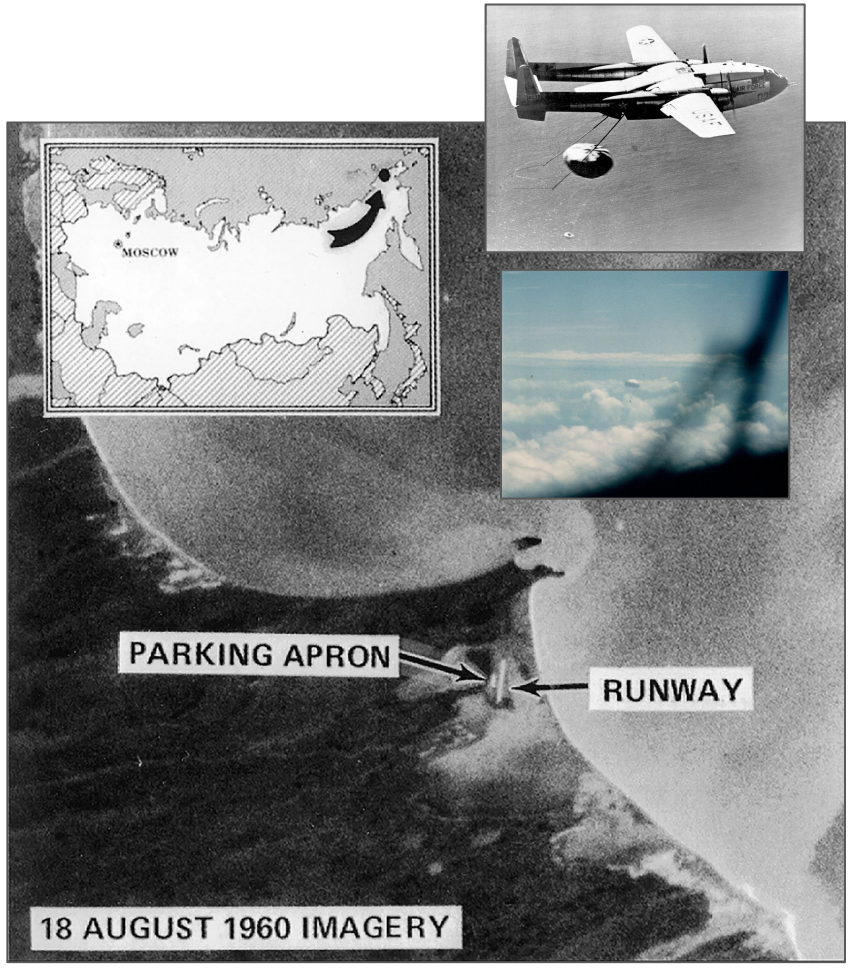
1950s/1960s

US started the **Corona space surveillance program**, first satellite providing 12.9-m resolution optical

→ **"missile gap" was real** – imagery demonstrated major deficiencies of Soviet nuclear forces

findings limited the development of hypotheticals by U.S. war planners and contributed to **a reduction in the number of nuclear warheads**

however, **imagery also revealed Soviet Union lacked a long-range delivery capability** – escalated with the Cuban Crisis



1960, **Discoverer 14** satellite with 13-m resolution sensor

Lop Nor, China

Lop Nor, China

*As recently as the mid-1950s, the Soviets had been able to fool the Americans concerning their air strength, and to touch off a major Washington flap over a supposed "bomber gap," merely by flying the same aircraft around twice at an air show. By contrast, a 1968 intelligence report contained the unequivocal statement: "**No new ICBM complexes have been established in the USSR during the past year.**" As early as June 1964, Corona had photographed all 25 of the complexes then in existence. If there had been any new ones, the CIA would have seen them.*

The Space Shuttle Decision: NASA's Search for a Reusable Space Vehicle, T. A. Heppenheimer

Start of Nuclear Arms Control

Cuban missile crisis and the growing visibility of arsenals made it clear – **a nuclear war cannot have winners**

If winning is not possible – a stalemate needs to be maintained

US and Soviet Union agreed on various arms control treaties aimed at managing their competition

development of EO satellites **did not drive political decisions** that led to arms control – but the **technology facilitated** verification required for it, once the political conditions and the security environment aligned

Start of Nuclear Arms Control

"... There can be no doubt that the photo reconnaissance satellite represents the primary means of verification for SALT..."

Director of Central Intelligence Richard Helms, from a speech in 1972

development of EO satellites **did not drive political decisions** that led to arms control – but the **technology facilitated** verification required for it, once the political conditions and the security environment aligned

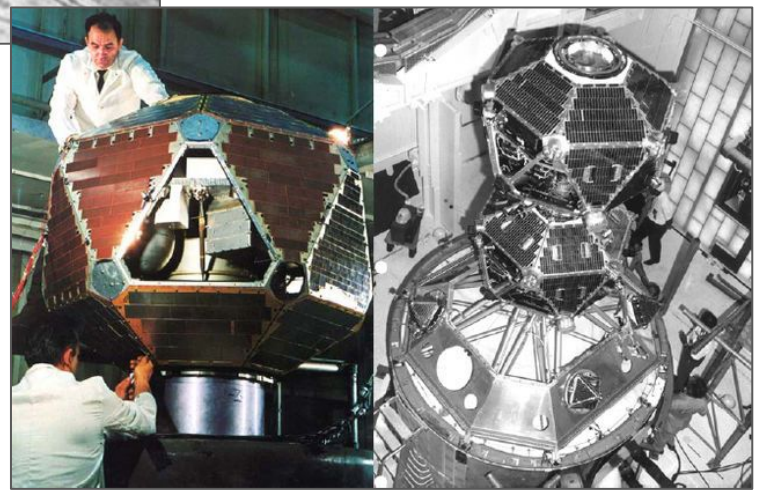
1970s/1980s

1983, Soviet aircraft carrier under construction

KH-11 optical systems with **better than 10-cm resolution** and digital downlink

space-radar satellites able to see through clouds, reconnaissance satellites that could detect **infrared ground emissions**, and satellites that could gather **signals and communication intelligence**

satellites equipped with sensors able to detect nuclear explosions by measuring **visible, ultraviolet and X-ray frequencies, fluorescence signals, gamma rays and neutrons**



Vela satellites to monitor nuclear detonations

1980s until today: rise of the commercial EO industry

1980's

Soviets offer commercial 5-m imagery and French SPOT-1 launched.

1990's

US Land Remote Sensing Policy Act. Maxar first licence. Ikonos-2 first commercial sub-1m.

2000's

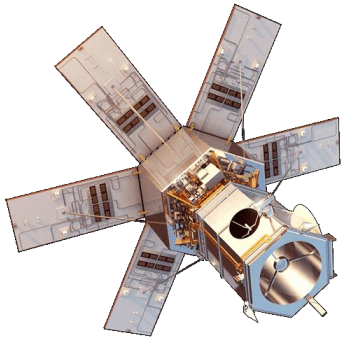
Commercial imagery to "fill military, intel and civilian needs". NOAA allows 50-cm imagery.

2010's

NOAA allows 25-cm imagery. NGA, NRO,.. sign contracts with US commercial companies.

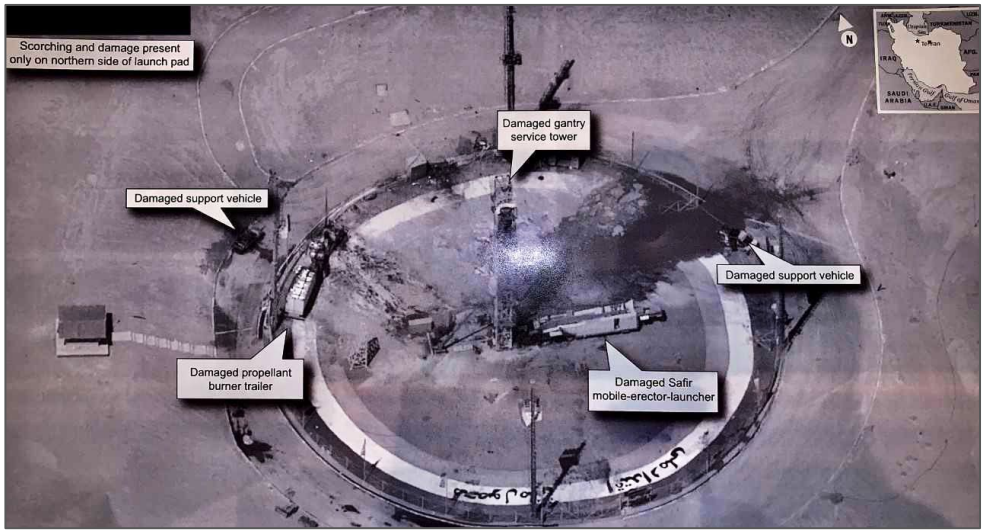
2020's

NOAA new tiered approach. 10-cm license approved.



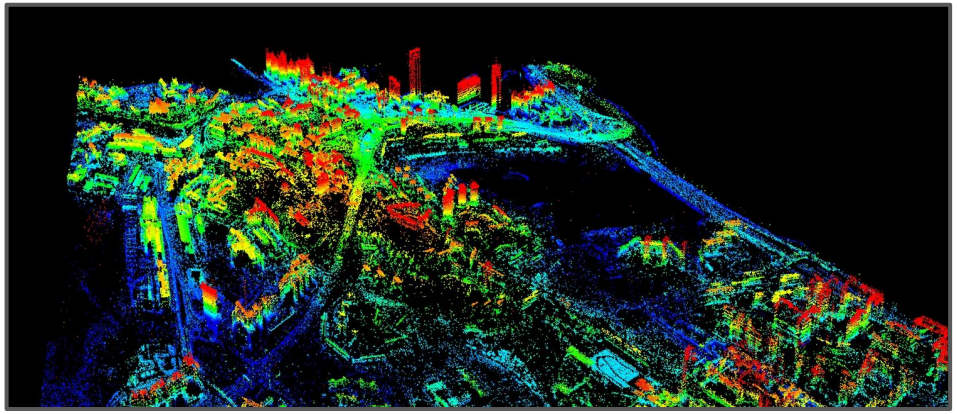
Maxar WorldView3 with
30-cm native resolution, 15-cm post

AIRBUS ~ 30 cm nadir



KH-11 with ~10-cm resolution

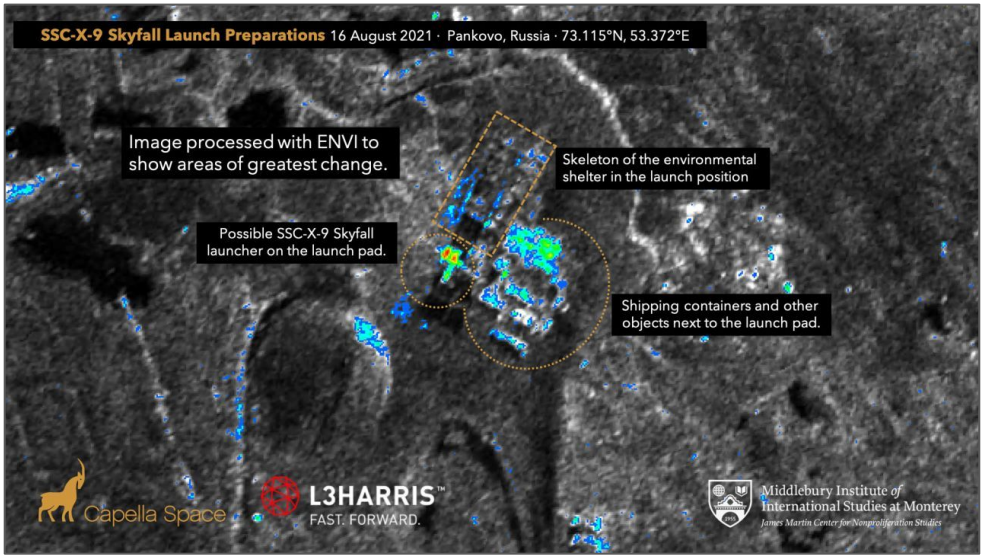
TODAY we can
SEE more detail



TODAY we can **SEE more bands**

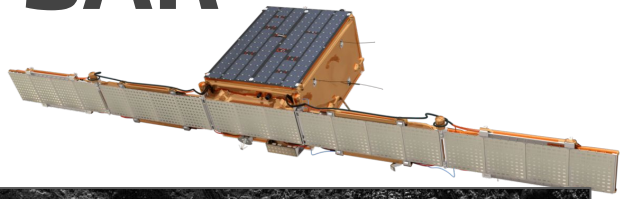
SAR (synthetic aperture radar)
Visibility during night and through clouds

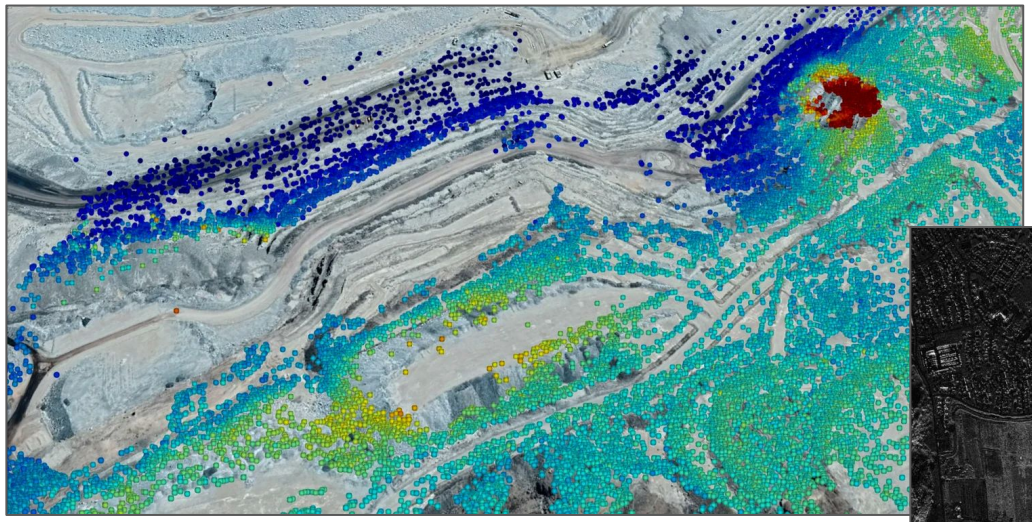
ICE-EYE
with 1-m resolution

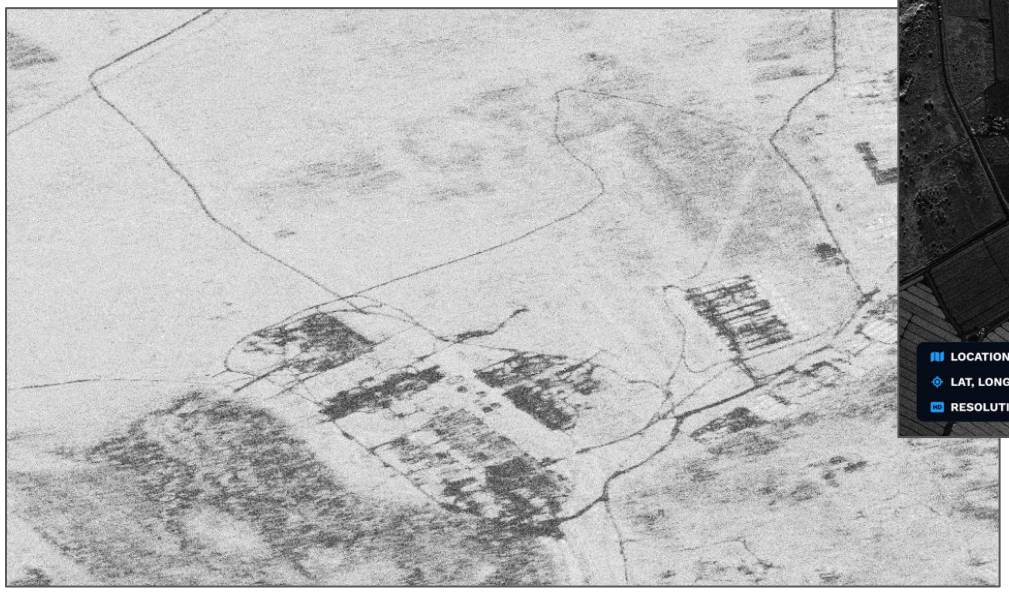


Capella Space
with 0.5-m resolution

SAR



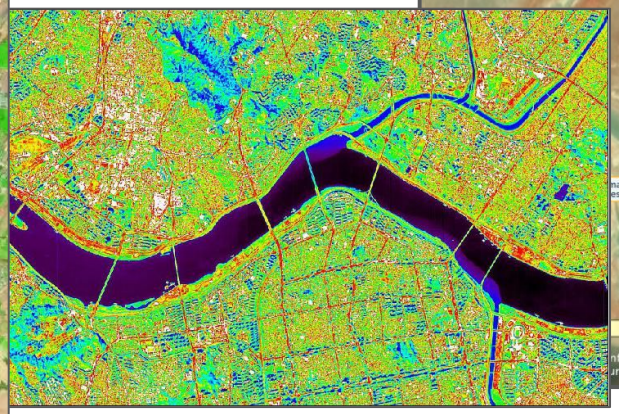


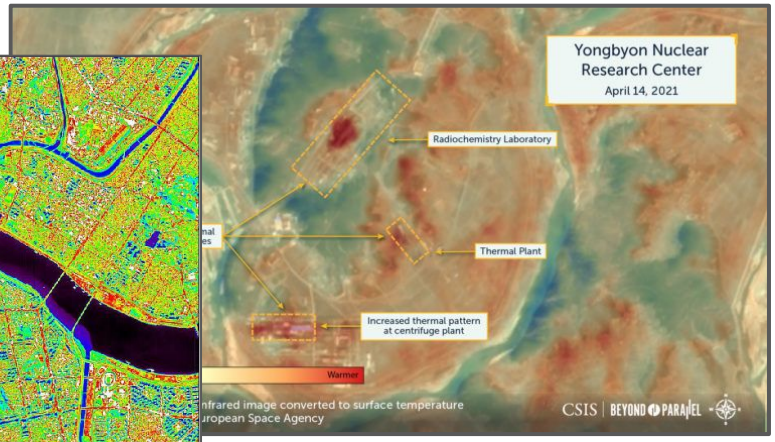


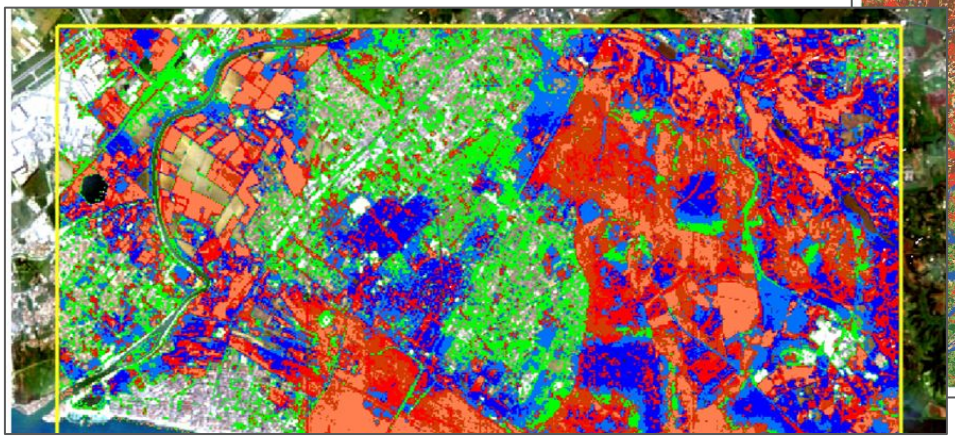
TOP LEFT: ground deformations from mining.
BOTTOM LEFT: vehicles tracks.
RIGHT: 16x16 cm resolution garden maze.

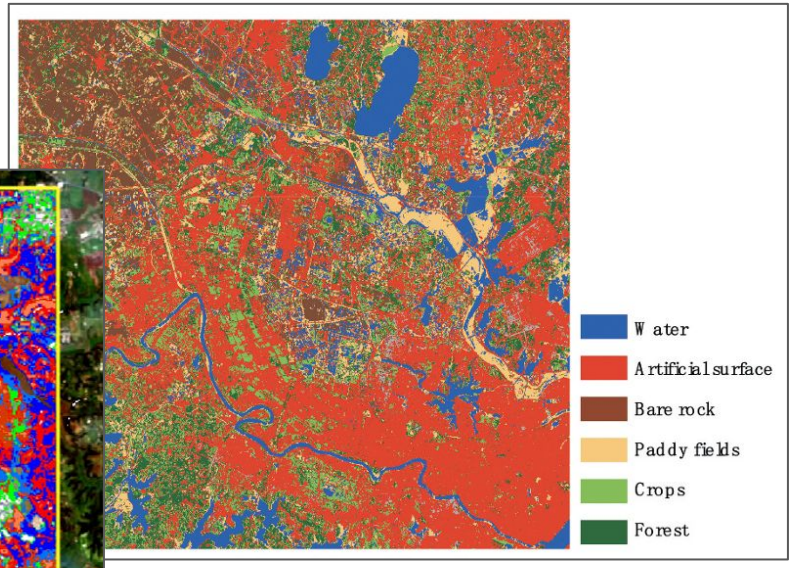
Source: ICEEYE, Umbra

Infra-red (THERMAL OUTPUT): Sentinel-2 SWIR 60-m, Kompsat 3A MWIR 5.5-m, Landsat LWIR 80-m







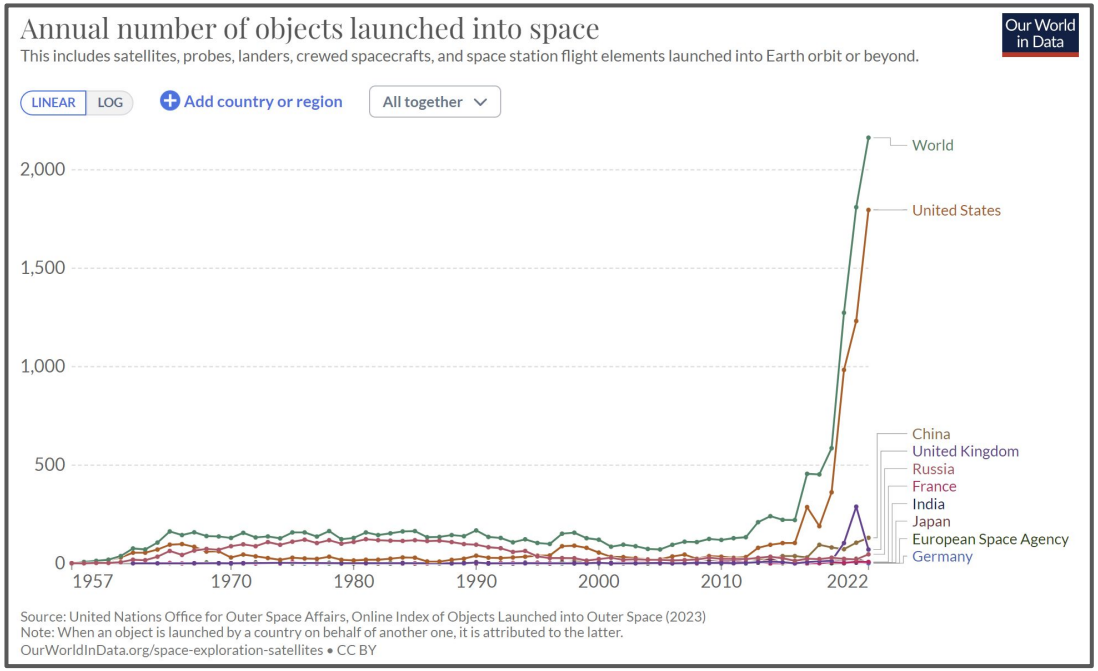


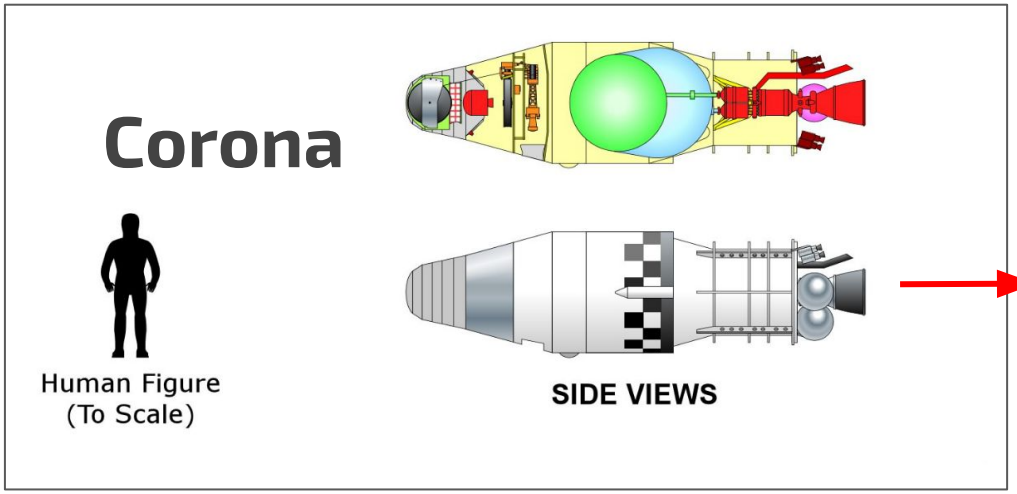
Hyperspectral (MATERIAL CLASSIFICATION): PRISMA and GF-5 with 30-m resolution

TODAY we can

SEE more often

(satellites are smaller, and there are more of them)





TODAY we can

SEE more often

(satellites are smaller, and there are more of them)

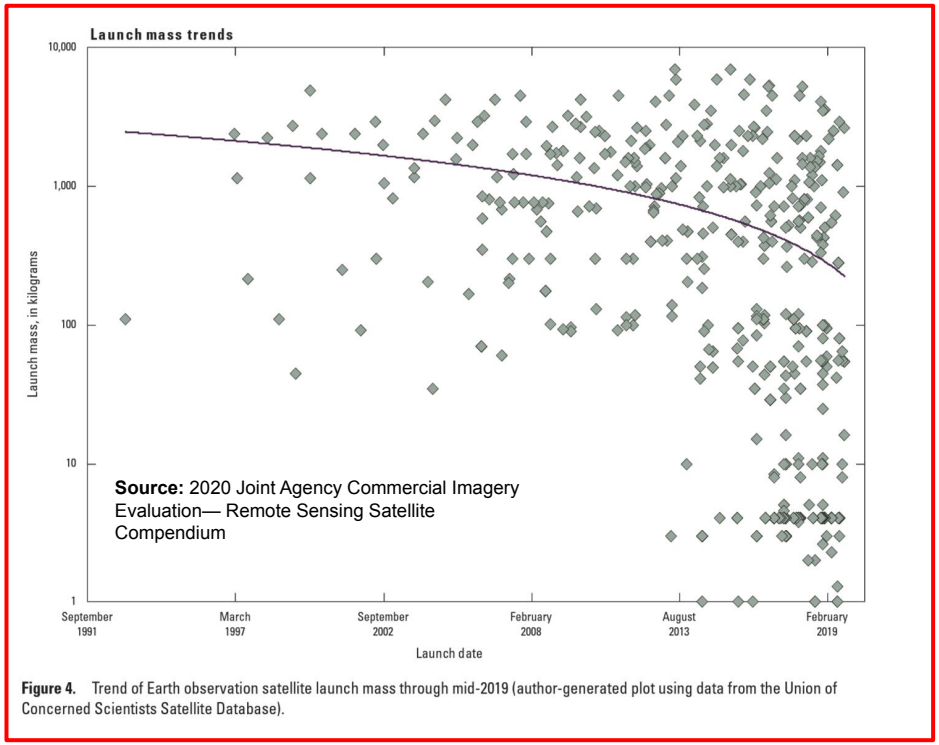
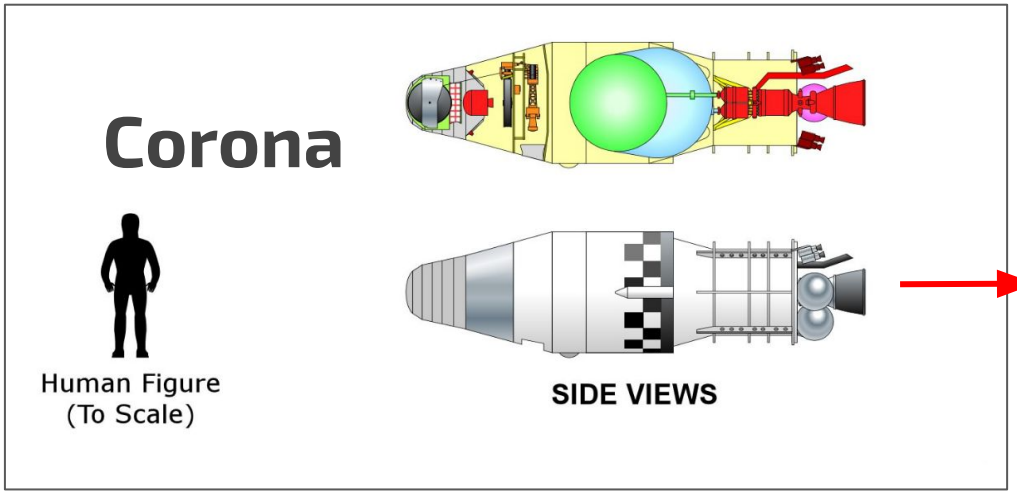
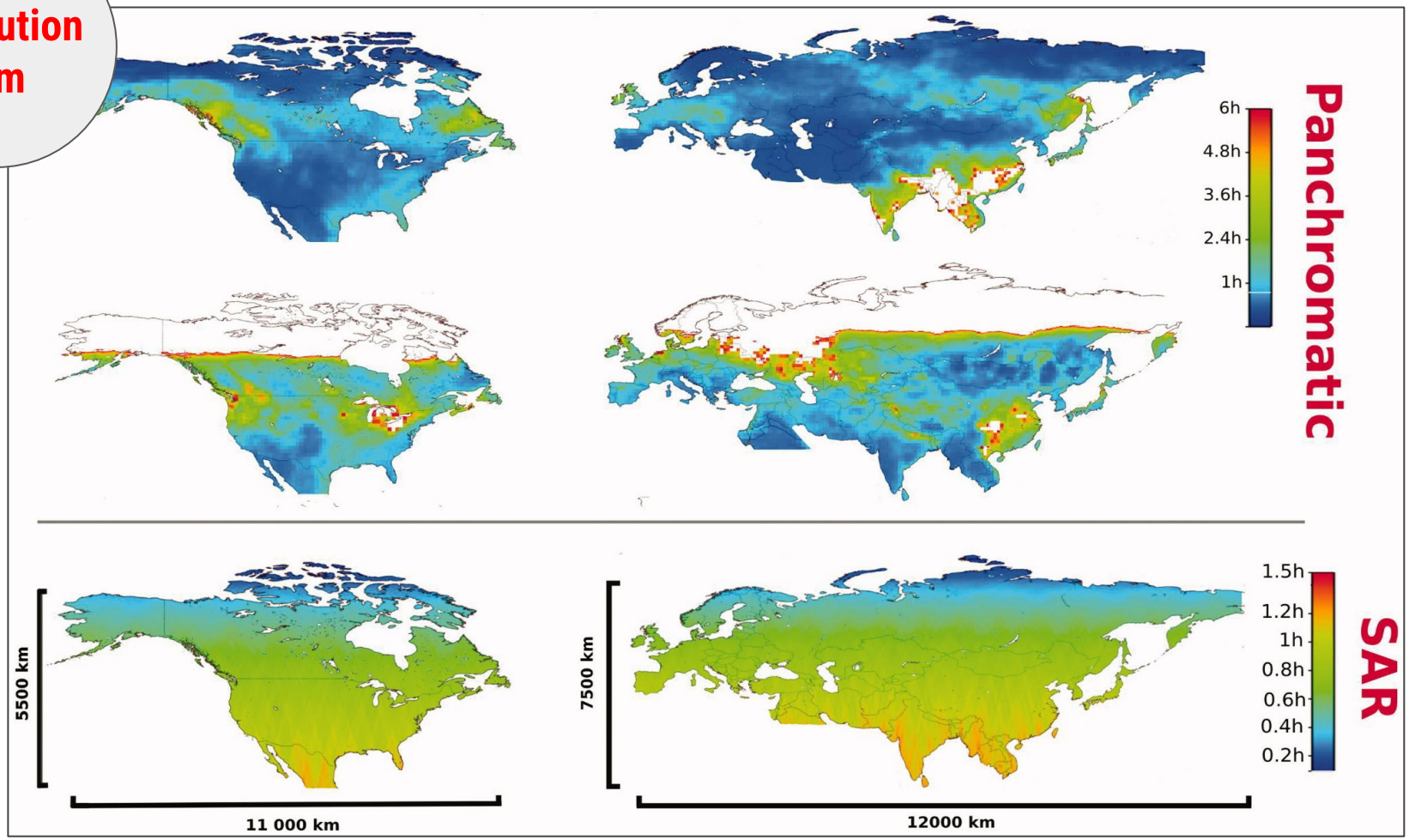


Figure 4. Trend of Earth observation satellite launch mass through mid-2019 (author-generated plot using data from the Union of Concerned Scientists Satellite Database).



Observation frequency with optical and SAR commercial systems

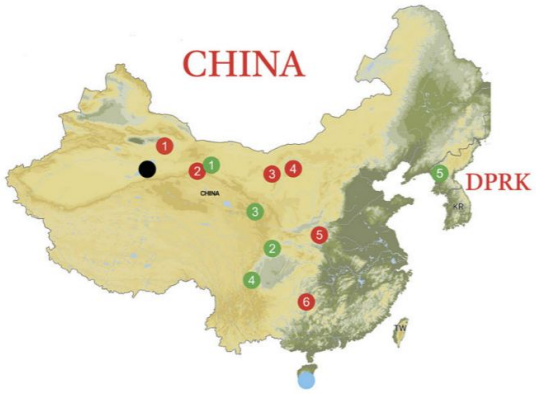
Resolution 5-m



Northern hemisphere average observation frequency
Under 6h with optical
Under 2h with SAR

SOURCE: Moric, "Capabilities of Commercial Satellite Earth Observation Systems and Applications for Nuclear Verification and Monitoring", Science & Global Security, 2022

Observation frequency with optical and SAR commercial systems – CHINA



NON-CHINESE EO SYSTEMS

OPTICAL	*SAR*
BlackSky (US)	Capella Space (US)
Deimos (EU)	Cosmo SkyMed (EU)
Maxar (US)	ICEYE (EU)
KOMPSAT (ROK)	RADARSAT+RCM (CAN)
Nusat (ARG)	Sentinel-1 (EU)
Planet (US)	TerraSAR-X + PAZ (EU)
Pleiades (EU)	ALOS-2 (JAP)
SPOT (EU)	ASNARO (JAP)
ASNARO (JAP)	STRIX-A (JAP)
EROS-B (ISR)	
PRISMA (EU)	

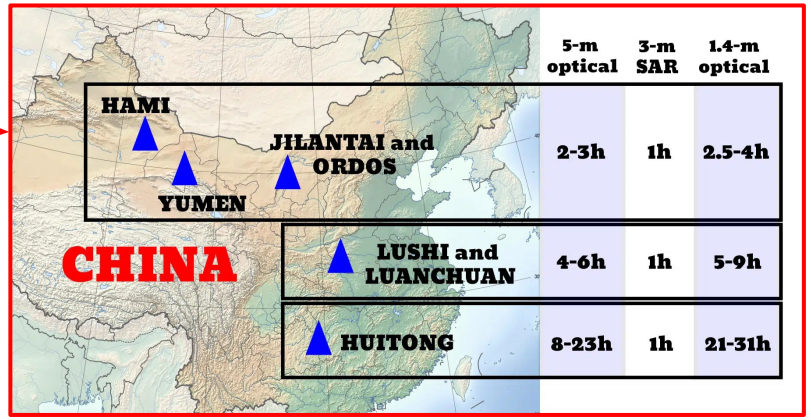
LOCATIONS & FREQUENCY

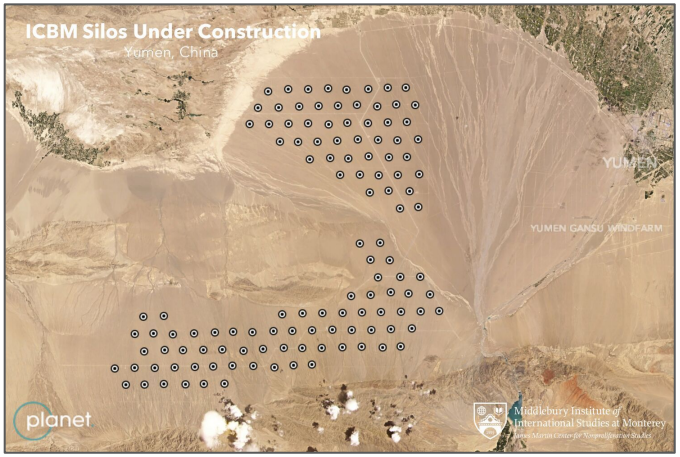
	SILOS	5-m optical*	5-m SAR	3-m SAR	1.4m optical*
1	Hami Missile Field	1h to 3h	1h		1.5h to 4h
2	Yumen Missile Field	2h to 3h	1h		2.5h to 4h
3	Jilantai Training Area	1.5h to 3h	1h		2h to 4h
4	Ordos Missile Field	1.5h to 3h	1h		2h to 4h
5	Lushi Base (DF-5B) and Luanchuan Base (DF-5A/B)	4h to 6h	1h		5h to 9h
6	Huitong Base (DF-5A)	8h to 23h	1h		21h to 31h

	NUCLEAR FACILITIES	5-m optical*	5-m SAR	3-m SAR	1.4m optical*
1	Jiuquan Plutonium Plant	2h to 3h	1h		2.5h to 4h
2	Guangyuan Plutonium Plant	7h	1h		4h to 10h
3	Langzhou Gaseous Diffusion Plant	2.5h to 5h	1h		3.5h to 7h
4	Heping Gaseous Diffusion Plant	6.5h to 8h	1h		9.5h to 11.5h
5	Yongbyon (DPRK)	2h to 3h	1h		3.5h to 4.5h

	OTHER	5-m optical*	3-m optical*	3-m SAR	0.9-m SAR
●	Lop Nor Nuclear Test Base	1.5h to 3h	1.5h to 4h	1h	2.5h
●	Yulin Naval Base	3h to 3.5h	4h	1h	3h

*Results are given for a period of 14 days during an average January/June month.





FUTURE

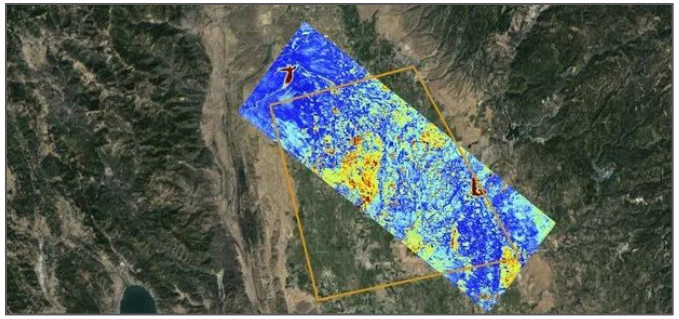
United States

Blackjack optical, space-based radar, Hypersonic and Ballistic Tracking Space Sensor (**HBTSS**), the Space Development Agency (**SDA**) architecture, **Next-Gen OPIR**.

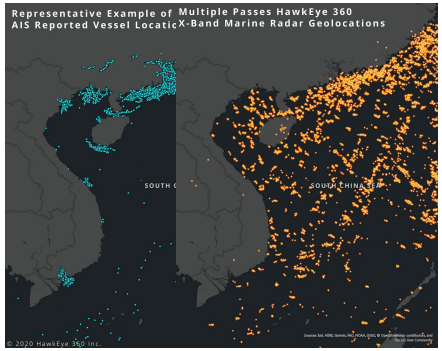
Commercial & Other

AIRBUS (30-cm), **MAXAR** Legion (30-cm), **Planet** Doves and Pelican (30-cm), **BlackSky** (1-m), **Satellogic** (1-m), **ICE-EYE** SAR, **Capella** SAR (36 with 50-cm), **Umbra** (25-cm), China (radar, optical, hyperspectral,...).

Optical: Albedo - 10cm

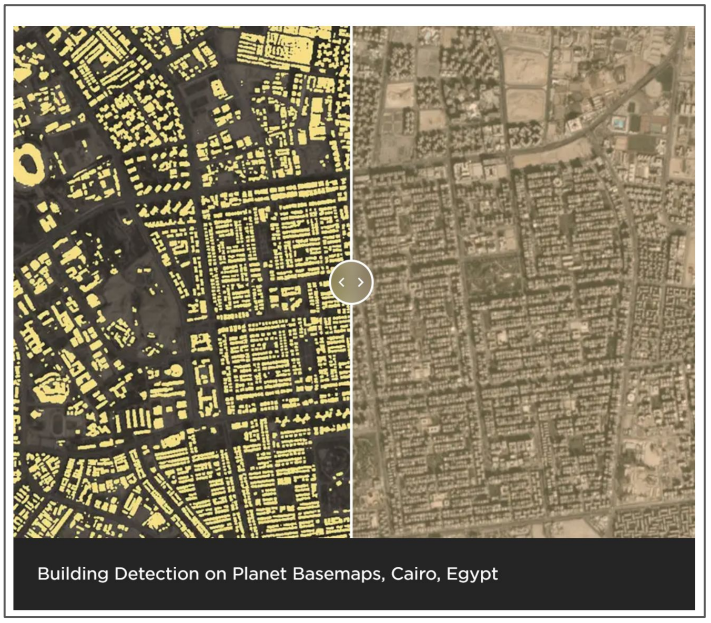


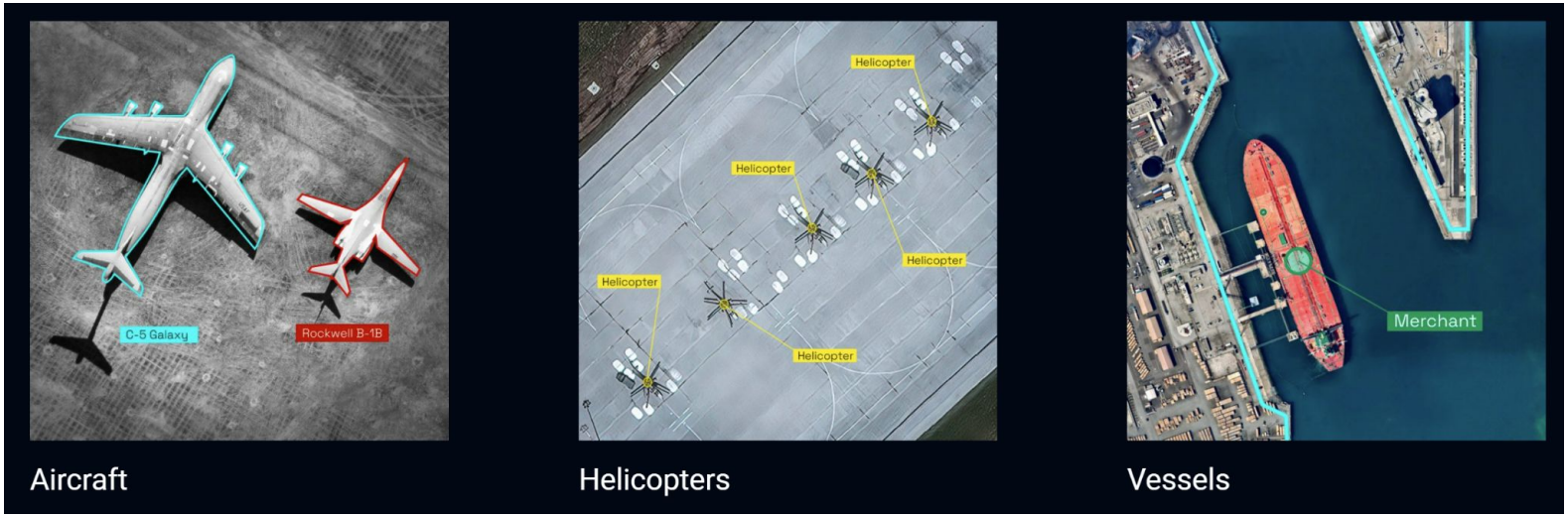
Hyperspectral: Orbital Sidekick - 8.3m



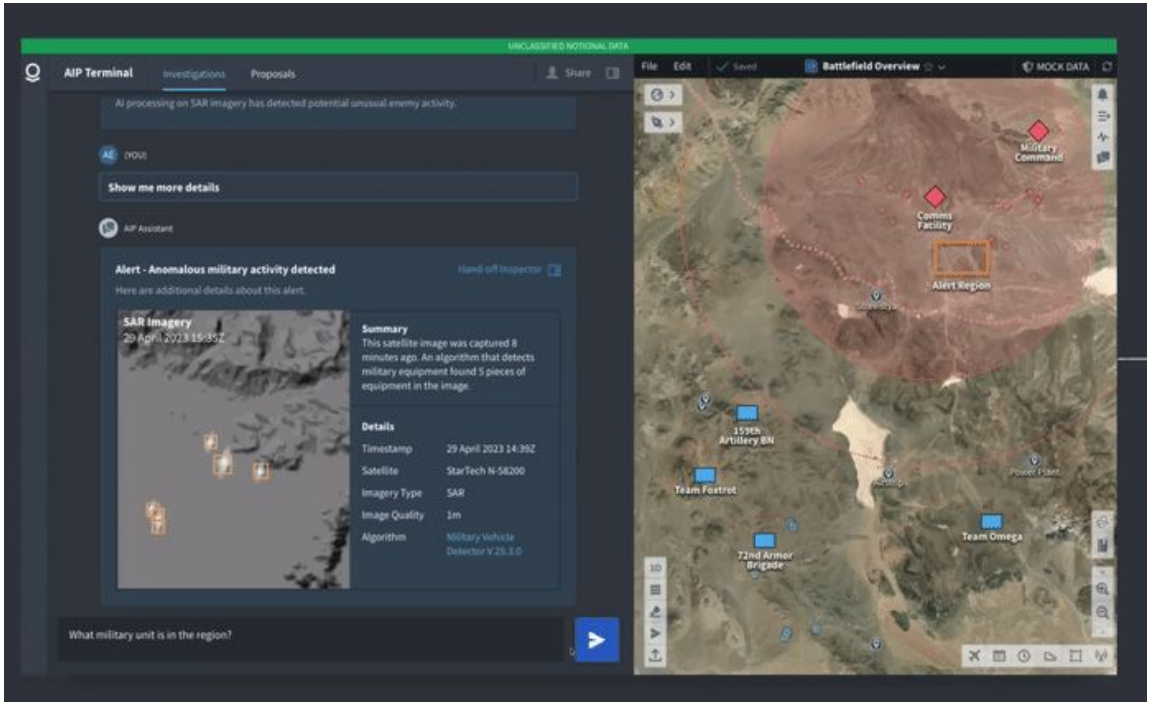
Radiofrequency: HawkEye360

DATA + AI: automated processing, detection, classification, tracking





Automated Detection, Classification, Kill – Palantir



AI intelligence gathering and battle-management software

Using “commercial” data and offering services to US agencies

BLACKSKY SECURES INVESTMENT FROM PALANTIR AND ENTERS INTO MULTI-YEAR STRATEGIC PARTNERSHIP FOLLOWING SUCCESSFUL PILOT PROJECT

Collaboration to Expand Delivery of High-Resolution Imagery and Deep Analytics

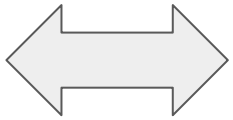
BlackSky and Palantir Collaboration Aids Government Agencies

Palantir to Provide Data-as-a-Service Platforms Under 3 Air Force Contracts

A Palantir Technologies (NYSE: PLTR) subsidiary has received from the U.S. Air Force three separate one-year contracts worth $110.5 million combined to provide data-as-a-service platforms to support command and control and decision-making operations.

“Nuclear Stability” and Transparency

Nuclear deterrence **belief** everyone is rational enough not to use nuclear weapons



“Stable” if leadership **rational**, and probability of success for a decapitating attack **low or uncertain**

➔ to augment the effectiveness of the nuclear deterrent, some states rely on **opacity and intentional ambiguity, and “playing crazy”**

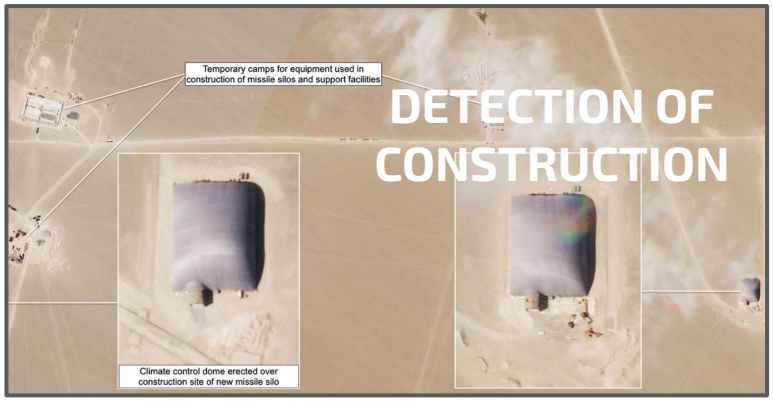
➔ lack of information and predictability → **worst-case scenarios**: safest to assume that the adversary is **actively developing new capabilities, deploying forces and preparing for a nuclear strike**

greatest danger for a nuclear war from an **accident or a misjudgment** – **humans are irrational** and guided by emotions, also even a sequence of seemingly rational decisions can result in increasingly risky behavior

with increased transparency (and more information available):

- ➔ **closes the gap** between the perceived intent of the adversary and their actual capabilities
- ➔ states **disincentivized** to attempt to obtain some threatening capability if this can be observed early enough to prepare and react
- ➔ clearer communication, makes it **easier to recognize peaceful intentions**

satellite imagery – a **tool** to monitor adversaries, better estimate their capabilities and verify compliance



Matt Korda and Hans Kristensen, “NATO Nuclear Weapons Exercise Over Southern Europe”, "China Is Building A Second Nuclear Missile Silo Field"

Arms Control Wonk, “New Construction at Yongbyon”, 2022

Nuclear verification and monitoring

geolocation of military targets and large troop movements

indirect observables of potential future military and nuclear activity

with real-time observation - immediate discovery of and automated classification and tracking of vehicles, artillery and units, aircrafts, ships and surfaced submarines

satellite imagery – a **tool** to monitor adversaries, better estimate their capabilities and verify compliance

Force buildup before Russia's invasion in 2022, Maxar

Increased activity at nuclear test sites in Russia, China and US, 2023, Planet, Monterey

Nuclear verification and monitoring

geolocation of military targets and large troop movements

indirect observables of potential future military and nuclear activity

with real-time observation - immediate discovery of and automated classification and tracking of vehicles, artillery and units, aircrafts, ships and surfaced submarines

Future of Arms Control

$$\mathcal{L}_{SM} = \underbrace{\frac{1}{4}W_{\mu\nu}\cdot W^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}G^{\alpha}_{\mu\nu}G^{\mu\nu}_{\alpha}}_{\text{kinetic energies and self-interactions of the gauge bosons}}$$

$$+ \underbrace{\bar{L}\gamma^{\mu}\left(i\partial_{\mu} - \frac{1}{2}g\tau\cdot W_{\mu} - \frac{1}{2}g'YB_{\mu}\right)L + \bar{R}\gamma^{\mu}\left(i\partial_{\mu} - \frac{1}{2}g'YB_{\mu}\right)R}_{\text{kinetic energies and electroweak interactions of fermions}}$$

$$+ \underbrace{\frac{1}{2}\left|\left(i\partial_{\mu} - \frac{1}{2}g\tau\cdot W_{\mu} - \frac{1}{2}g'YB_{\mu}\right)\phi\right|^2 - V(\phi)}_{W^{\pm},Z,\gamma \text{ and Higgs masses and couplings}}$$

$$+ \underbrace{g''\left(\bar{q}\gamma^{\mu}T_a q\right)G^{\alpha}_{\mu}}_{\text{interactions between quarks and gluons}} + \underbrace{\left(G_1\bar{L}\phi R + G_2\bar{L}\phi_c R + h.c.\right)}_{\text{fermion masses and couplings to Higgs}}$$

Future of Arms Control

satellite imagery - not intrusive and not able to observe everything → **a feature and not a bug:**

disclosure of sensitive information bounded by distance limiting what is possible to observe on ground – **easier early step to a more comprehensive regime**

leaves enough to chance to enhance deterrence, but limits worst-case speculations

initial probability of detection is low – with time uncertainty is reduced and trust between parties augmented

observers have on their side **time** and a **large amount of multi-domain data** – fusion of geo-tagged sources including satellite imagery, signals intelligence, open-source information, official statements, cyber espionage, human intelligence and even social media activity

More comprehensive verification:

- ➔ makes **deception more difficult**
- ➔ makes **initial assessment of forces and capabilities more accurate**
- ➔ allows **easier demonstration of compliance**

first step – improvement of New START-like verification procedures

Other scenarios:

- ➔ **demating** – monitor sites without gaps means inspectors ensured nuclear components not secretly transferred away
- ➔ **absence & counting** – verify absence of missiles in launchers or even count warheads in missile payloads

Nuclear-powered ballistic missile submarine OHIO (SSBN-726) and its missile tubes

Google Earth image from North Dakota

"Nuclear **In**stability" and Transparency

without fog of war – stronger military force more willing to engage in conflict?
→ **gap closed** by an arms race or by striking preemptively

remote sensor data remains partial information → **ability to see ≠ knowing why**

AI algorithms - **black boxes** with errors, inability to verify at decision-making speed

commercial imagery – more information, additional verification, but increased public pressure and **less opportunity for face-saving deals**

Source: https://digdipblog.com/2017/02/20/if-the-cuban-missile-crisis-were-tweeted

Survivability of Nuclear Retaliatory Forces

- nuclear deterrence relies on survivable retaliatory nuclear forces – it should not matter if you attack first or second

- TOOLS: **secrecy** in development and operations, building a **larger number of weapons than needed**, **hardening** by placing underground, **concealing**, making **mobile**, **diversification**

- most survivable methods to deploy are **mobile missile transporter-erector launchers (TELs)** and **ballistic missile submarines (SSBNs)**

Russian Topol-M, TASS.

Anchored Ohio-class U.S. USS Michigan, Reuters.

Survivability of Nuclear Retaliatory Forces

SEEKER → HIDER

TOOLS OF THE HIDER

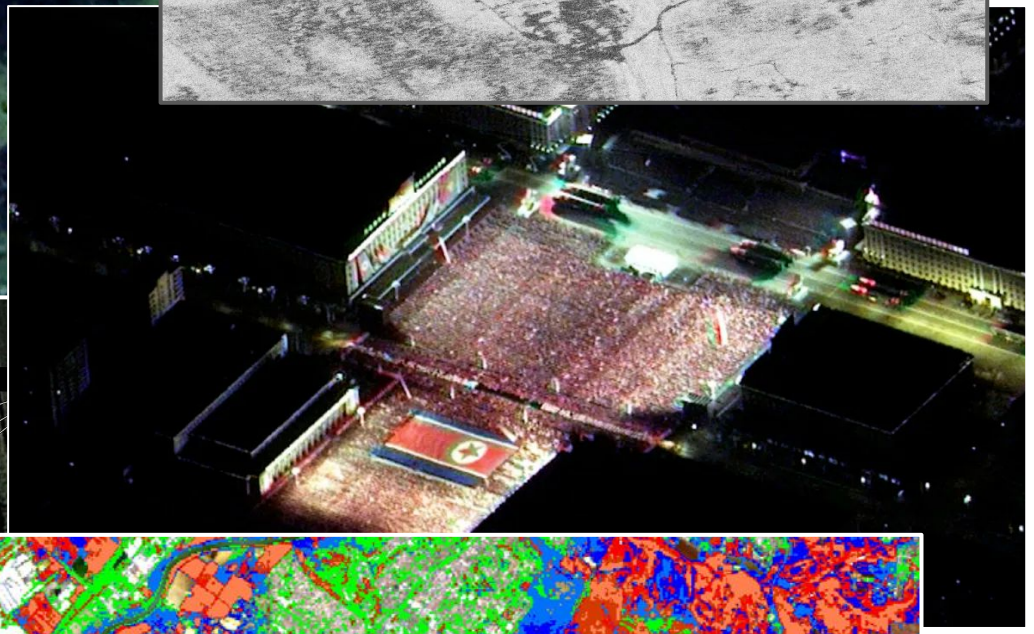
Passive countermeasures – terrain blocks sight, camouflage, hiding in urbanized areas and within traffic, use of tunnels and underpasses, deployment of decoys to overwhelm the imagers

Active countermeasures – jamming, spoofing, and dazzling that interfere with the satellite operation and deny visibility to the other side, ASAT

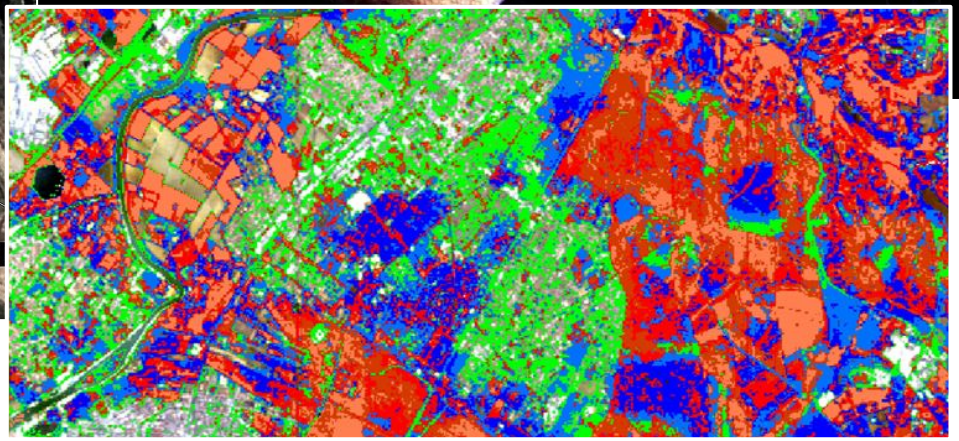
TOOLS OF THE SEEKER

- ➔ persistent multi-angle multi-band monitoring
- ➔ knowledge of terrain (digital maps), years of data & AI
- ➔ direct and indirect signatures of TELs
- ➔ humans leak information


RS-24 Yars ICBM




DF-31 Launch Drill at Haiyan Deployment Site
36°49'28.85"N, 101° 6'23.68"E
06/26/2011
DF-31 Launcher
Support Cargo Vans
Google Earth



Survivability of Nuclear Retaliatory Forces

SEEKER → HIDER

Active countermeasures – jamming, spoofing, and dazzling that interfere with the satellite operation and deny visibility to the other side, ASAT

Use of **ballistic missiles**, releasing a **pellet cloud** in orbit, employing **maneuverable satellites**, **detonating nuclear weapons** in space, **cyber attacking** the constellation,...

- ➔ Perceived as **preparatory to a first-strike**
- ➔ Other: launch on warning, integration of AI into nuclear decision-making

CASES AND CONDITIONS

LOCALIZING TELs ≠ DEFEATING TELs

a bolt out of the blue attack – attack bases, disrupt command and control	**prolonged crisis** – forces alerted and with increased authority, targets multiply

attacker needs to destroy **at the same time ALL** mobile missile launchers, TELs are mobile and would **require > 1 barrage of warhead**

attacker **ALSO** needs to destroy silos, bombers, submarines, ports and bases, command and control → **US does not have have enough to destroy retaliatory forces**

LACK OF PARITY DOES NOT DEFAULT TO AN ALL-OUT NUCLEAR WAR, nonzero chance of retaliation is sufficient to maintain deterrence

with **persistent multi-angle multi-band monitoring and years of observation**, the seeker can locate TELs

to defeat a fleet of TELs the attacker **needs to destroy them at the same time**, with >1 warhead/vehicle

attacker **ALSO** needs to destroy silos, bombers, submarines, ports and bases, command and control → **US cannot destroy all the nuclear forces**

LACK OF PARITY DOES NOT DEFAULT TO AN ALL-OUT NUCLEAR WAR, nonzero chance of retaliation is sufficient to maintain deterrence

Findings

Overhead transparency – more **predictability** to relationships of NWS could reduce the nuclear danger and facilitate a **new generation of arms control**

Increased transparency can also invite conflict, and introduces new dangers → **it can enhance deterrence or be abused and weaken it**

It may soon become possible to localize TELs. **Survivability not binary but a spectrum**: more visibility → survivability of TELs eroded and perceived effectiveness as a deterrent reduced

US cannot destroy retaliatory forces → it remains **irrational** to attempt to **DESTROY** TELs and start a nuclear war

Greatest danger of a nuclear war from miscommunication and miscalculation

Conclusion: Accepting Transparency

PAST

arms reduction made possible by a change in political relationships, arms control facilitated by technology

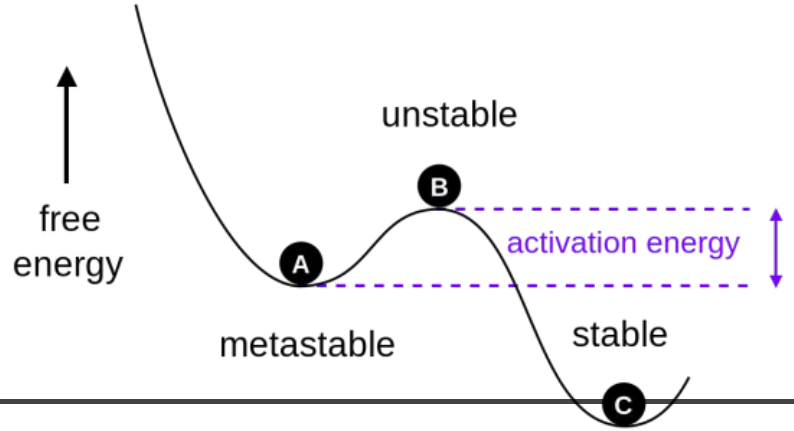
FUTURE

driven by technological change but possibly without effective arms control treaties

OPTION 1: more secrecy, further fueling worst-case projections, and by pursuing enlargement and diversification of delivery vehicles and weapons

→ **nuclear arms race**

Conclusion: Accepting Transparency



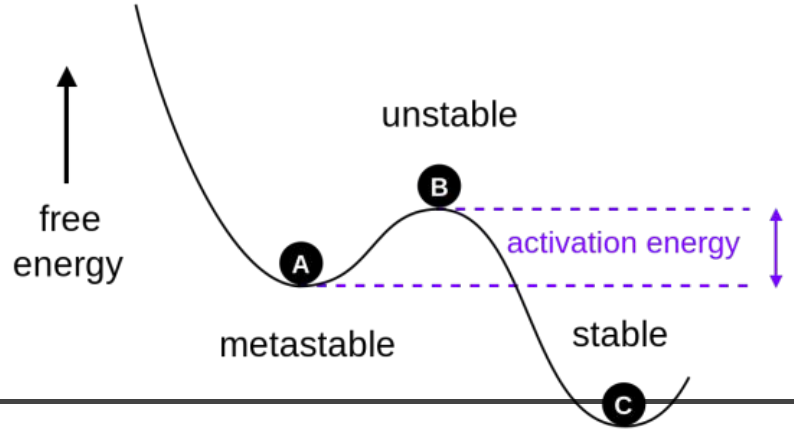
OPTION 2:

a) accept that rational leaders do not start nuclear wars, and that the greatest danger of a nuclear war is due to miscalculation or miscommunication

b) establish norms of behavior where evolving transparency does not fuel instability and instigate a nuclear buildup, but mitigates dangers, limits arms racing and reduces the probability of escalation

a nuclear arms race was started in secrecy – the nuclear danger can end only with full transparency and in plain sight, and overhead transparency provided by satellites is one of the tools

Conclusion: Accepting Transparency



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