Enabling A More Prosperous Space Era:
A Massive MIMO Perspective

IEEE Future Networks 2nd Massive MIMO Workshop
Date: Oct. 03-05, 2022

Presentation by: Yiming Huo

Department of Electrical and Computer Engineering
University of Victoria, BC, Canada

ymhuo@uvic.ca
yhuo@ieee.org

OUTLINE

- Space Broadband Access: The Race Has Just Begun

  a) Space Industry Getting More Prosperous! But Why (On Earth)?

  b) Major Players in SOTA Satellite Mega-Constellation Deployment and Services

  c) Future for Massive MIMO Communications in the Near-Earth Space

- Massive Sensing, Communication, and Defense in Space: A Matter of Life or Death

  a) The Real Threat Coming from the Space: Just a Matter of Time

  b) From Terrestrialization to Extra-Terrestrialization: Life’s ‘Have-To’ Evolution Path?

  c) Planetary Defense: Present and Future

  d) SCADN: A Framework Enabling Massive Sensing and Communications across the Entire Solar System

SPACE BROADBAND ACCESS:

THE RACE HAS JUST BEGUN

PHOTO LICENSED BY ISTOCK

SPACE BROADBAND ACCESS FOR NEAR-EARTH SPACE

A Critical Component for the 5G and Beyond, 6G Eco-System

- 2022 and beyond will be the time of '**Technological Singularity**' when significantly more **low Earth orbit (LEO) satellites** are to be launched, deployed, and planned [1].
- There was some temporary regression (~ 3 decades ago) due to the immature biz model, unaffordable cost, and other technical challenges, which have been alleviated nowadays.
- **Connecting the Unconnected**, the **Non-Terrestrial** wireless communication (including UAV, HAP) provides complementary and compatible solutions. LEO satellite mega-constellation can provide vast global coverage and constant broadband access services, in rural areas, mountainous areas, deep sea, etc.
- Space broadband access can robustly cope with terrestrial emergencies, e.g., Earthquake, Hurricane, Forrest fire, etc.

Fig. 1. The Apls mountainous area (licensed by iStock), and Mexico Beach after Hurricane Michael in 2018 (photo credit: Tampa Bay Times).

SPACE BROADBAND ACCESS FOR NEAR-EARTH SPACE

Why Does the Space Industry "Suddently" Boom Exponentially?

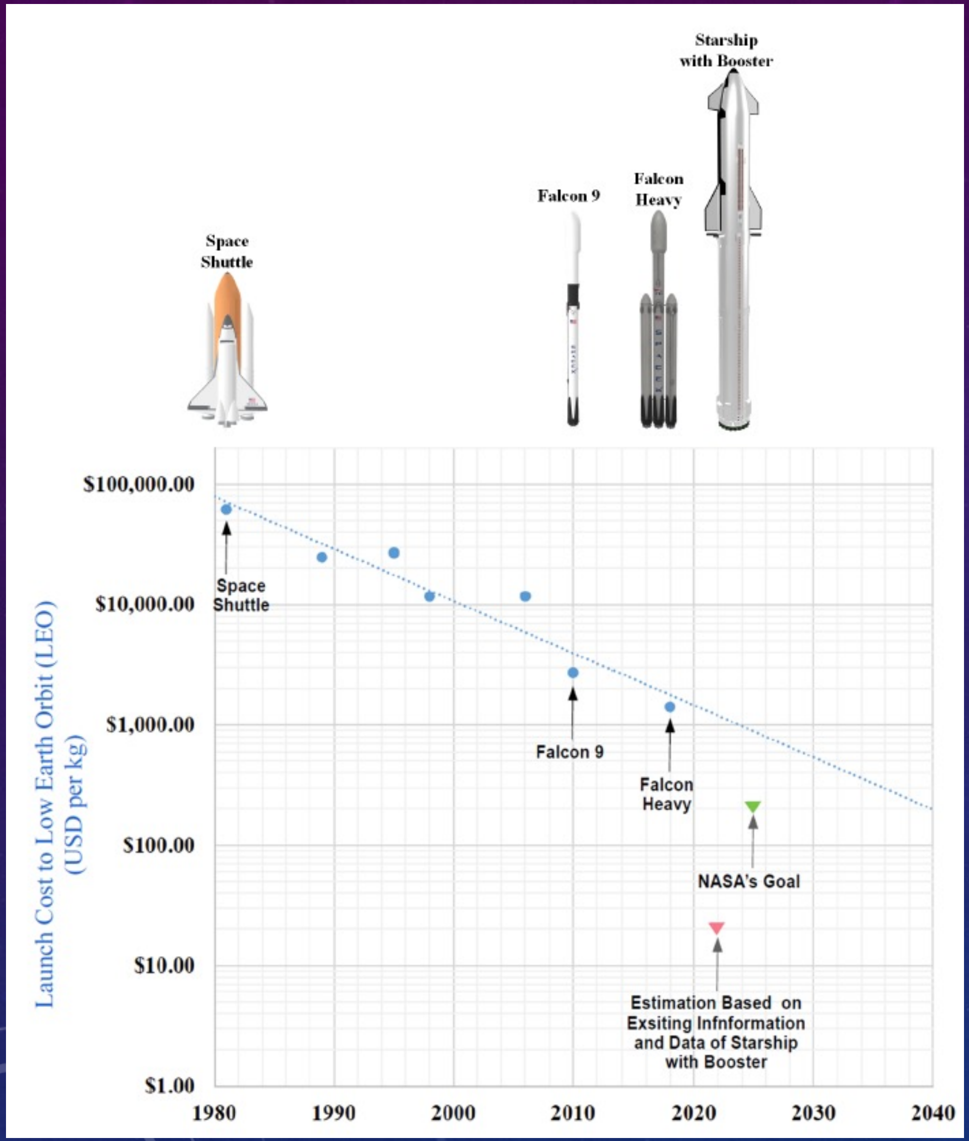


Fig. 2. Low earth orbit launch cost (with inflation rate weighted) change over time [1].

Wright's Law

a) Originated in an observation from Theodore P. Wright, an aerospace engineer and educator, with a formula as follows [2]

$$Y = aX^b$$

Y = cumulative average time (or cost) per unit
X = cumulative number of units produced
a = time (or cost) required to produce 1st unit
b = slope of the function
It forecasts cost as a function of units produced.

b). Compared to Moore's Law, Wright's Law offers better prediction for Lithium-Ion battery costs and auto industry for 109 years [2].

c). It also applies to satellite bandwidth. Since 2004 the cost has dropped 7,500-fold from $300M /Gbps to $40K/Gbps, and could fall another 40-fold during the next five years to $1K/Gbps [3].

SPACE BROADBAND ACCESS FOR NEAR-EARTH SPACE

Massive and Frequent Launch Missions

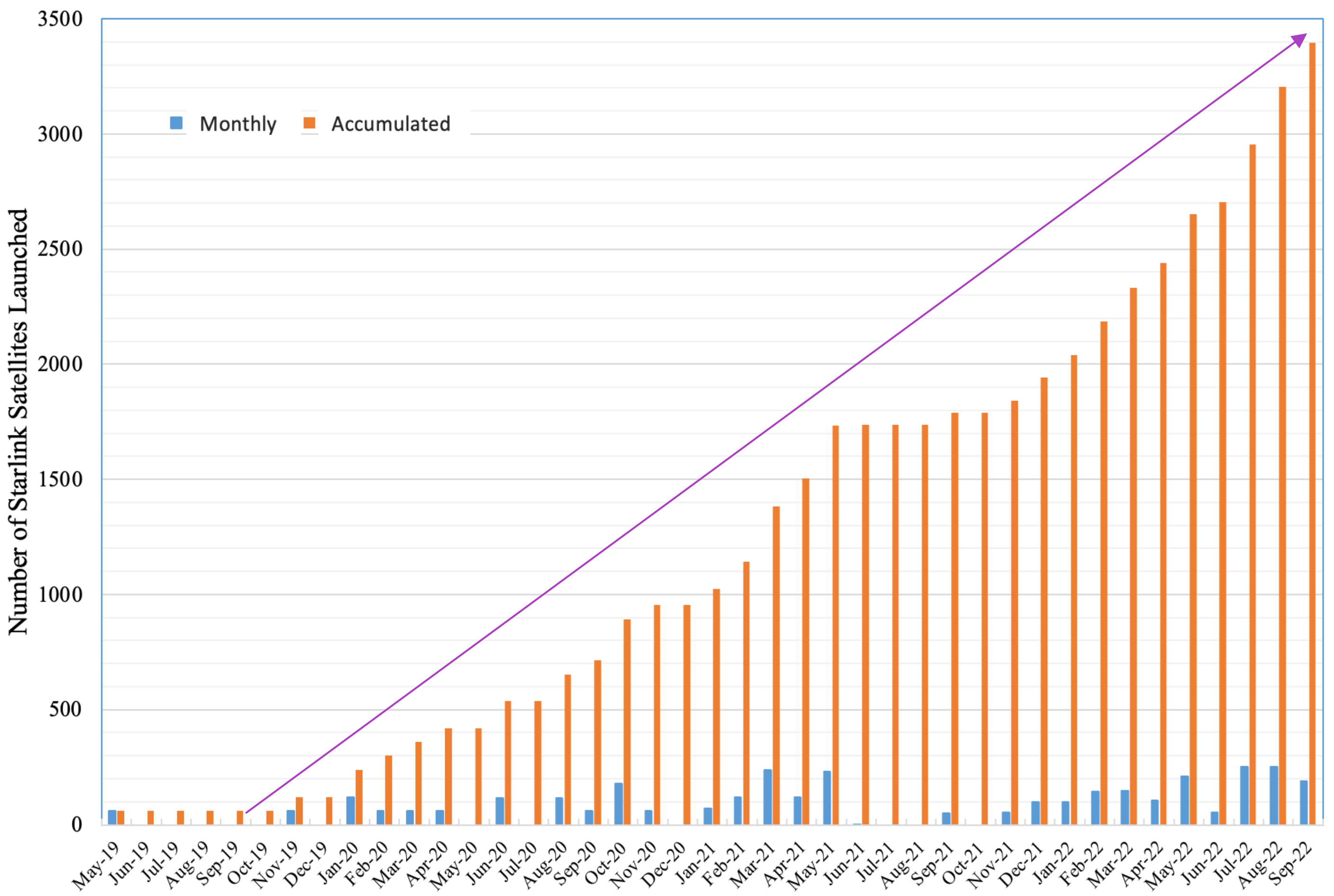


Fig. 3. Starlink satellites launch information on a monthly basis, as of Sep. 2022.

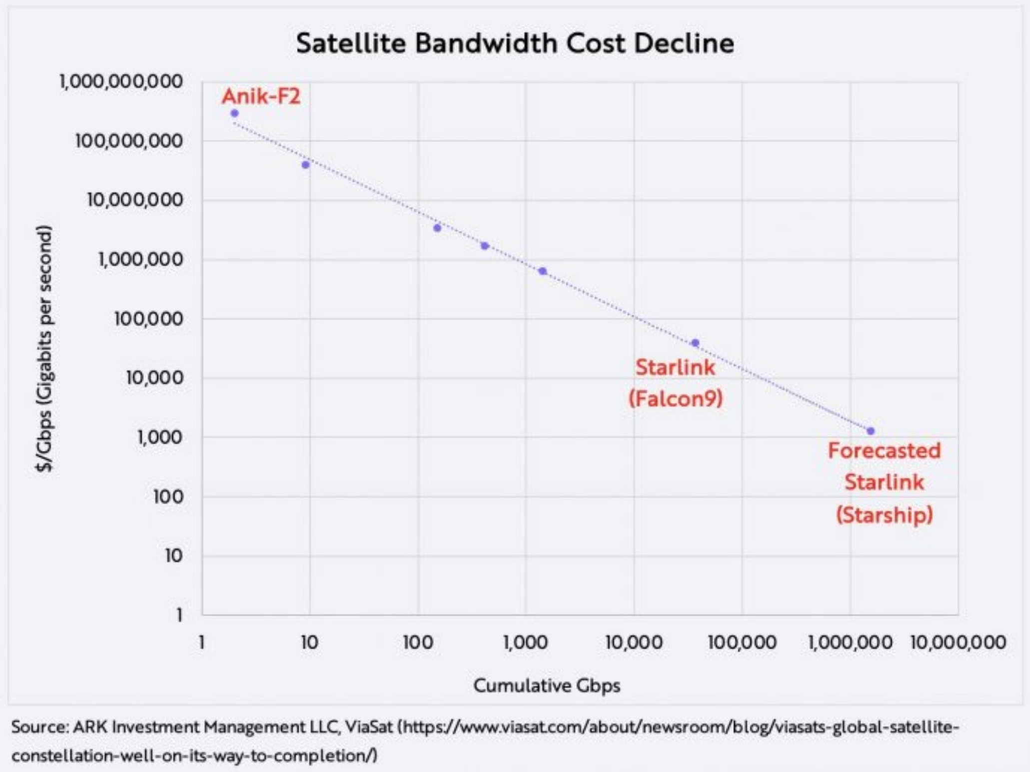


Fig. 4. Satellite Bandwidth Cost Decline (Photo Credit: ARK Invest) [3].

SPACE BROADBAND ACCESS FOR NEAR-EARTH SPACE

State-of-the-Art Satellite Constellations

Company and Constellation Name	Number of Satellites Deployed	Number of Satellites Proposed
SpaceX Starlink	3,085	41,939
OneWeb (NAA Ltd) OneWeb	428	6,372
Telestat Telestat Lightspeed	188	1,373
Amazon Project Kuiper	0	7,774
Boeing	0	5,789

Fig. 5. Comparison of LEO satellite constellations, as of Sep. 2022.

Type of Link and Transmission Direction	Gen1 Frequency Ranges (GHz)	Gen2 Frequency Ranges (GHz)
User Downlink Satellite-User Terminal	10.7–12.7	10.7–12.75[1] 17.8–18.6 18.8–19.3 19.7–20.2
Gateway Downlink Satellite to Gateway	17.8–18.6 18.8–19.3	17.8–18.6 18.8–19.3 71.0–76.0
User Uplink User Terminal to Satellite	14.0–14.5	12.75–13.25[2] 14.0–14.5 28.35–29.10 29.5–30.0
Gateway Uplink Gateway to Satellite	27.5–29.1 29.5–30.0	27.5–29.1 29.5–30.0 81.0–86.0
TT&C Downlink	12.15–12.25 18.55–18.60	12.15–12.25 18.55–18.60
TT&C Uplink	13.85–14.00	13.85–14.00

[1] SpaceX does seek authority to provide service in the United States using the 12.7–12.75 GHz band, but proposes to use that spectrum in other areas of the world where allowed

[2] At this time (when this application is filed), SpaceX seeks authority to use this band in the United States only with individually-licensed earth stations. No such limitations would apply outside the U.S.

Fig. 6. Frequency and channelization plan of Starlink system.

Critical Takeaways for Starlink

1) **Gen2** system will add more Ku and Ka bands frequencies to user downlink/uplink. Moreover, using the V-band frequencies with 5 GHz contiguous bandwidth at both downlink and uplink is also proposed [4].

2) **Gen2** system has offered to deploy 29,996 Starlink LEO and very low earth orbit (VLEO) satellites at altitudes from 328–614 km [5], which leads to a total throughput of > 1000 Tbps, or 10 times as Gen 1.

3) **Artificial Intelligence and Cloud/Edge computing**. Google cloud services and data centers; Microsoft Azure edge devices; Amazon Web Services (with Project Kuiper)

SPACE BROADBAND ACCESS FOR NEAR-EARTH SPACE

(a) (b)

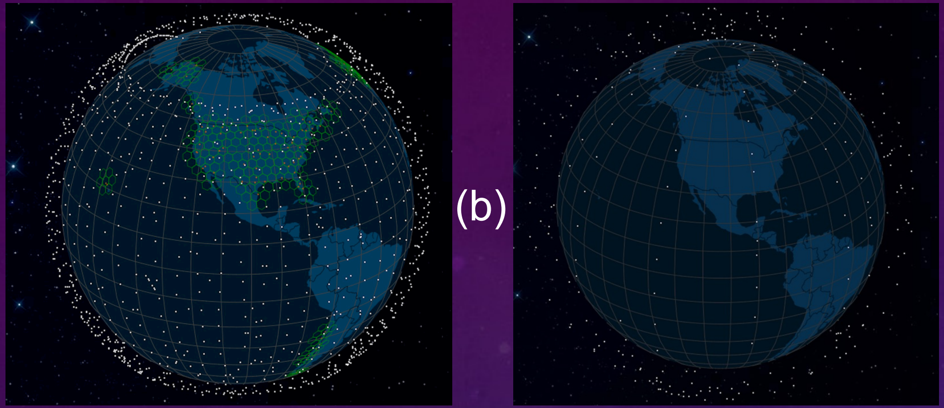


Fig. 7. Illustration of real-time orbital and location information of Satellites in (a) SpaceX Starlink constellation, and (b) OneWeb constellation, using online app.

Recent and Future **Trends of Near-Earth Space Communications**

❖ Near-Earth Space (NES) definition: Most often, it is the area from the layers of the neutral terrestrial atmosphere (160-200 km) up to the lunar orbit, which is about 384,400 km [6].

❖ SpaceX and T-Mobile announced (Aug. 25, 2022) collaborating on using **mid-band** 1.9 GHz PCS directly to mobile devices in 2023 (Yes, large LEO satellites https://www.youtube.com/watch?v=QzIi-Ww26Qs).

❖ iPhone 14 models (released Sep. 07, 2022) support Emergency SOS services via Globalstar's satellites.

Fig. 8. Illustration of satellite-enabled UE (photo licensed by iStock).

SPACE BROADBAND ACCESS FOR NEAR-EARTH SPACE

Recent and Future **Trends** of Near-Earth Space Communications (Cont'd)

- Deeper integration with terrestrial communications, UAV and HAP (High Attitude Platform) communications
- To the **Moon's** permanent base (first LTE network to be delivered by NOKIA Bell Labs for Artemis Program)

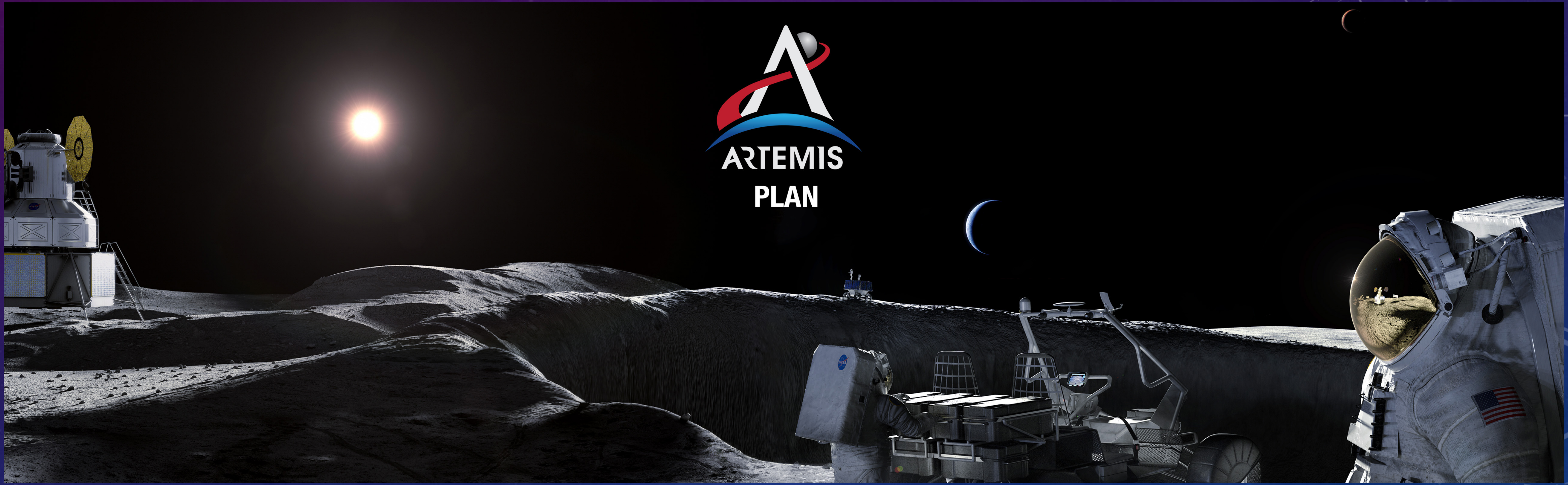


Fig. 9. Artemis program: the long-term goal is to establish a permanent base camp on the Moon and facilitate human missions to Mars (photo credit: NASA).

SPACE BROADBAND ACCESS FOR NEAR-EARTH SPACE

Challenges and Opportunities of Near-Earth Space Communications

- Coexistence and Integration. Mitigating Inter-Constellation (between Starlink and OneWeb) interference, Inter-Facilities (between LEOs and terrestrial) interference, and beam management are required.

- Space traffic and junk collision cases from NASA/ISS/ESA call for attention, regulations and techniques for collision-avoiding and safe deorbiting/disposal.

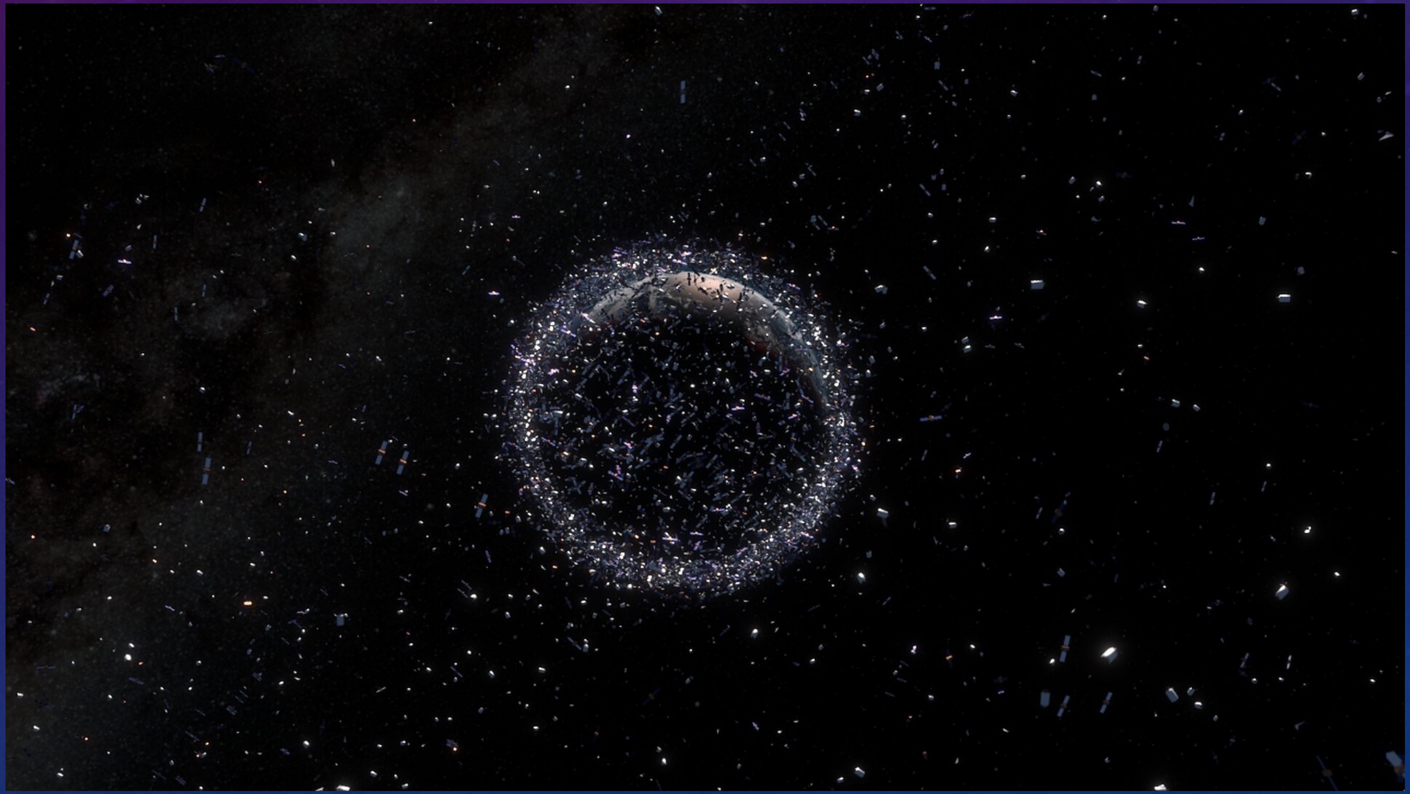


Fig. 10. Illustration of space junk such as broken spacecraft and inactive satellites (photo credit: European Space Agency (ESA))

SPACE BROADBAND ACCESS FOR NEAR-EARTH SPACE

Challenges and Opportunities of Near-Earth Space Communications (Cont'd)

- ❖ Fast satellites movement introduces a severe doppler effect (altitude dependent), frequent handover, and complicated beam alignment and management. More systematic optimization will be required for performance such as latency, throughput, etc.

- ❖ Handling extreme weather conditions needs better wireless hardware (e.g. phased arrays) and signaling algorithms; AI-assisted wireless communications; Cloud/edge-assisted data/computation offloading.

- ❖ "The space industry should reach **$1 Trillion** in annual revenue by 2040, with launch costs dropping 95%" - Citigroup analysts [7]

MASSIVE SENSING, COMMUNICATION, DEFENSE

IN SPACE

MASSIVE SENSING AND COMMUNICATIONS IN DEEP-SPACE

“*The cosmos is also within us, we’re made of star-stuff. We are a way for the cosmos, to know itself*”.
- Dr. Carl Sagan, in TV Series “*Cosmos*”

Fig. 11. First images from JWST (James Webb Space Telescope), and illustration of JWST (photo credit: NASA).

Curiosity and courage have constantly been motivating and inspiring humanity to explore the broad universe and unveil many of its mysteries. A historical milestone was marked on July 12, 2022, when the first full-color images and spectroscopic data of the James Webb Space Telescope (JWST) were released to unfold the infrared universe. This symbolized **the dawn of a new era** in astronomy.

MASSIVE SENSING AND COMMUNICATIONS IN DEEP-SPACE

Serious Threats from the Space: It Is Just a Matter of Time!

- Cretaceous–Paleogene (**K-Pg**) Extinction Event (Chicxulub crater in the Gulf of Mexico's Yucatán Peninsula), 66M BP (before present)
- Younger Dryas (**YD**) Event, 12,900 BP
- **Tunguska Event**, Jun. 30, 1908
- **Chelyabinsk Event**, Feb. 15, 2013. (**NO alarm was triggered** ahead because it was in a region of the sky giving no access to ground-based telescopes)

Fig. 12. Chicxulub impact, artist impression (photo credit: NASA)

Fig. 13. Comparisons of approximate sizes of three notable impactors with New York Manhattan as the background.

MASSIVE SENSING AND COMMUNICATIONS IN DEEP-SPACE

Historical Inspiration in the **Earth's Life Evolution**

- ~ 530 million years ago, sea creatures likely related to arthropods first began to make forays onto land [8], possibly to escape from hunters and competition in the water.
- To prepare for this terrestrial transformation, they developed a **massive increase** in the visual range [9]

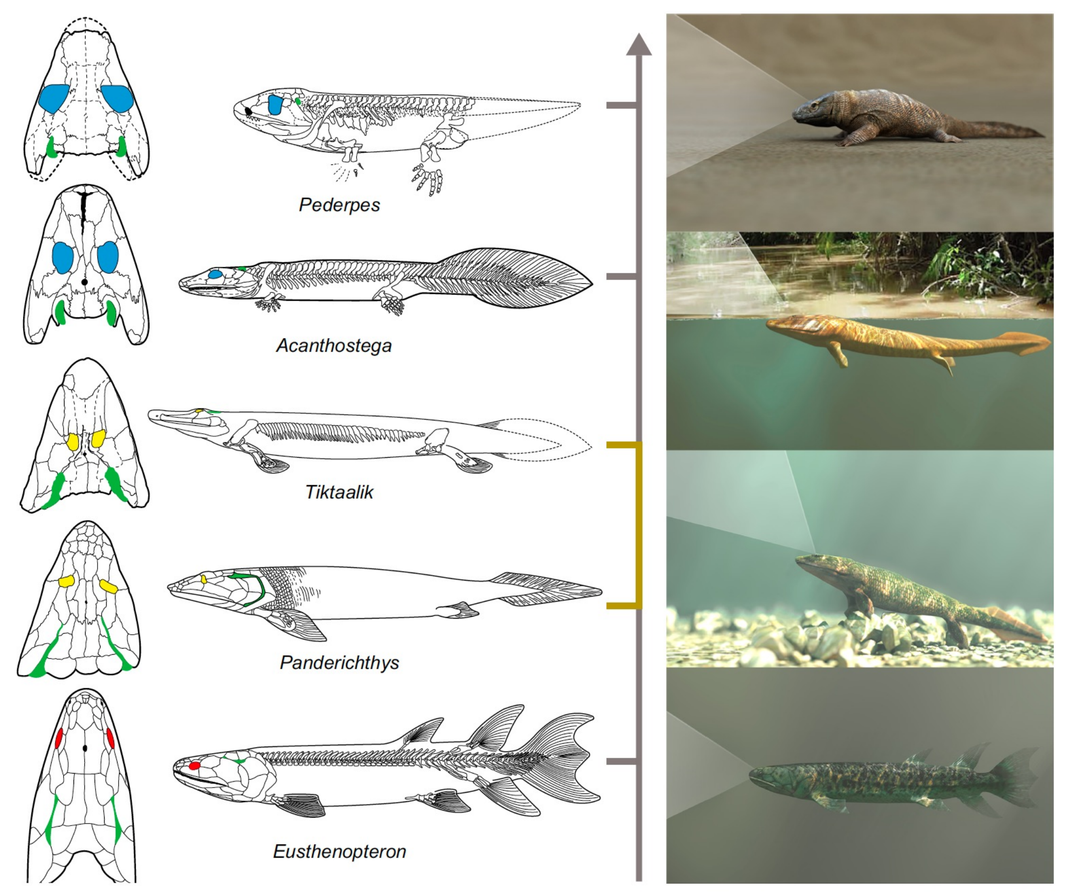


Fig. 14. A possible evolutionary scenario consistent with authors' results in [9] (Photo credit: [9])

For terrestrial vertebrates, Large Eyes Appeared Before Terrestriality!

HUGE QUESTIONS:

What about Mankind's **Sensing and Communication (SAC)** capabilities enhanced by various technologies today?

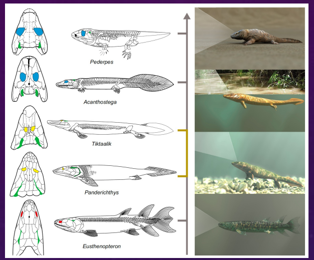
Where will our enhanced SAC capabilities lead us to?

How will we use these SAC capabilities to serve better the entire humanity and our planet(s)?

MASSIVE SENSING AND COMMUNICATIONS IN DEEP-SPACE

Making Humans a Multi-Planetary Species: **Extra-Terrestrialization** Feels a Must!

385 M-YRs BP



The evolution of Terrestrial vertebrates begun

245 M-YRs BP

First dinosaurs appeared on Earth

66 M-Yrs BP

K-Pg Extinction Event, wiping out dinosaurs

Present

Present day: Homo sapiens with SAC, aerospace, and various other technologies

Terrestrialization → **Extra-Terrestrialization?**

When the civilization levels reach some threshold, it is both spontaneous and mandatory for a species to leave its planet of origin, and becomes multi-planetary.

MASSIVE SENSING AND COMMUNICATIONS IN DEEP-SPACE

Unprecedented Transformation to Extra-Terrestrialization

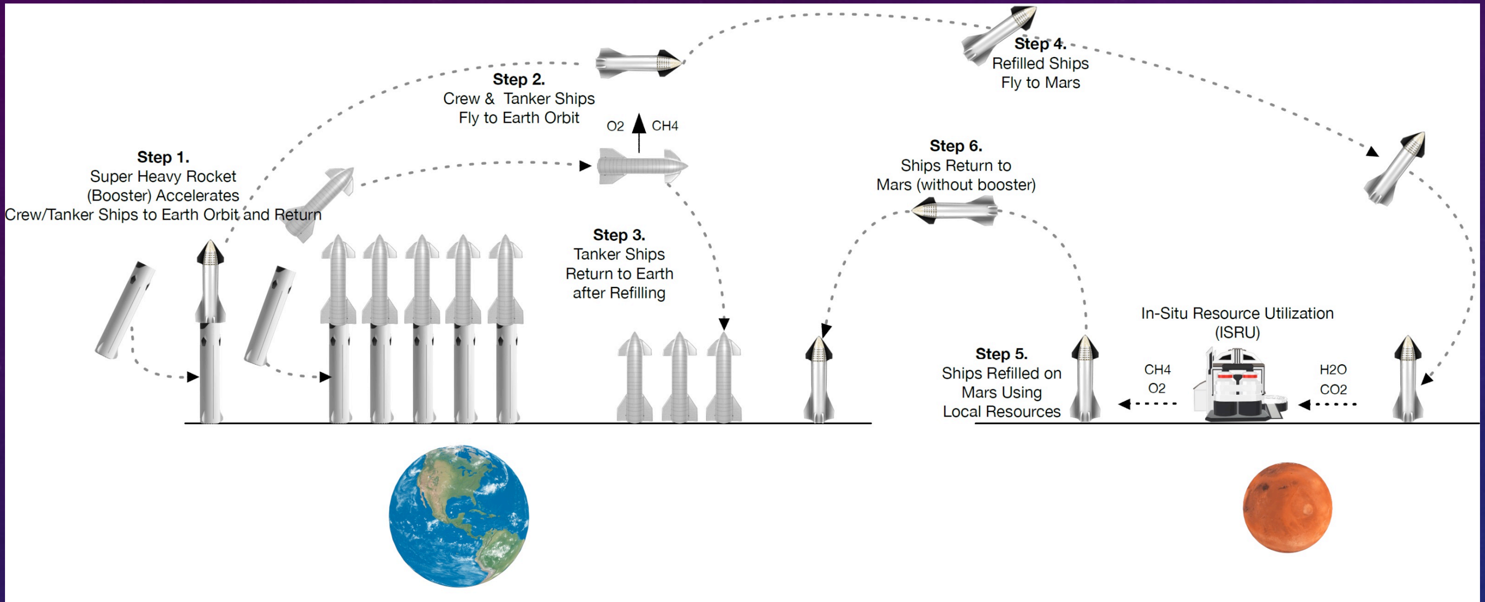


Fig. 15. Illustration of Mars transit system architecture and flowchart, redrawn based on the concept in [10].

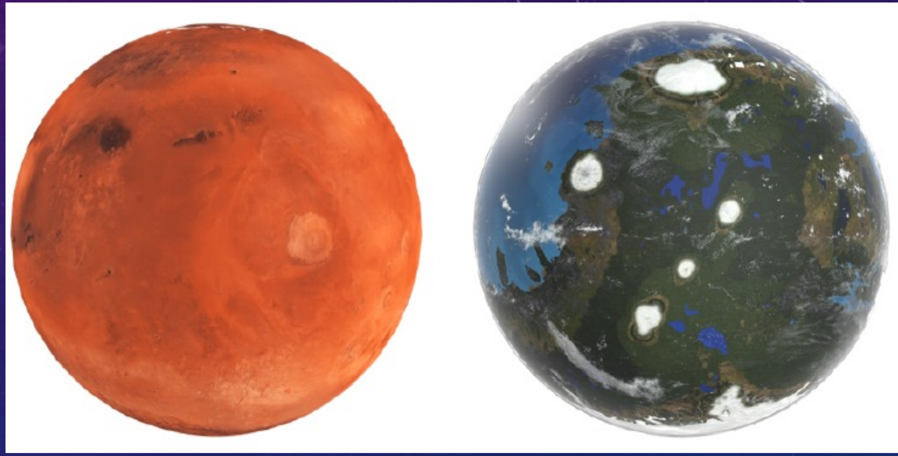


Fig. 16. Mars before and after terraforming.

MASSIVE SENSING AND COMMUNICATIONS IN DEEP-SPACE

Unprecedented Transformation to Extra-Terrestrialization in History

Fig. 17. Illustration of city as the permanent surface base [8].

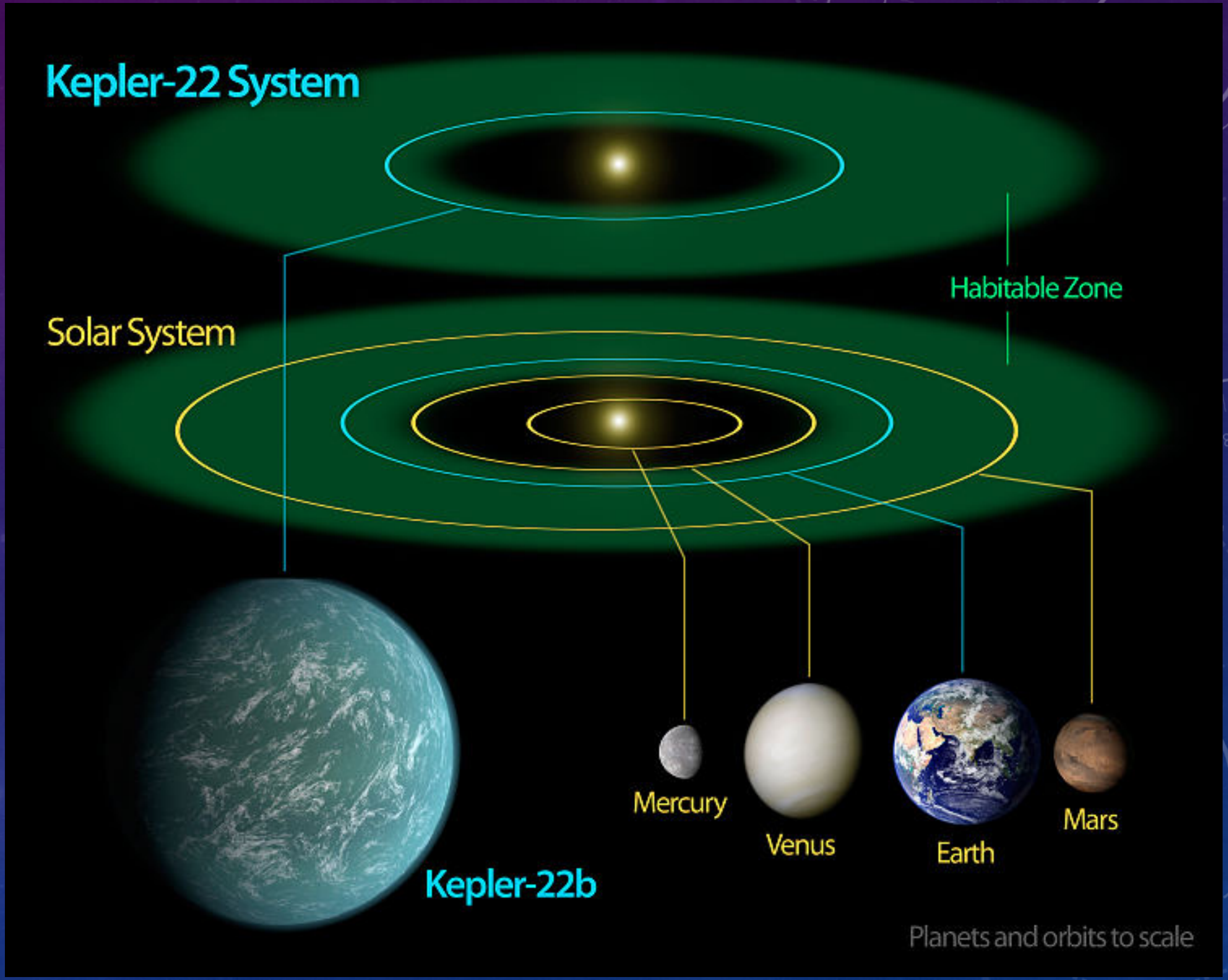


Fig. 18. EXO-Planet Example: Kepler-22b system, which is around 620 light years from Earth (Photo credit: NASA).

MASSIVE SENSING AND COMMUNICATIONS IN DEEP-SPACE

Planetary Defense: An Insurance for Evolution

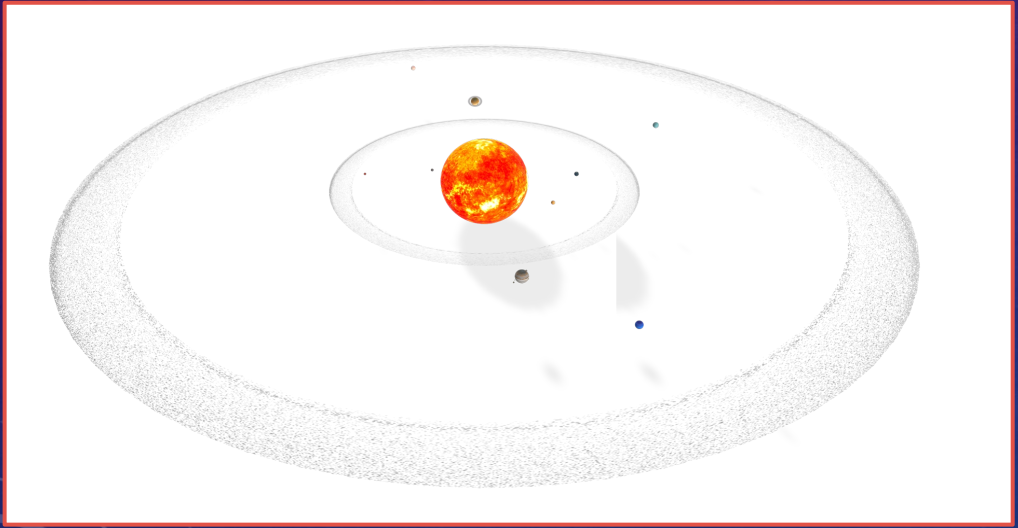
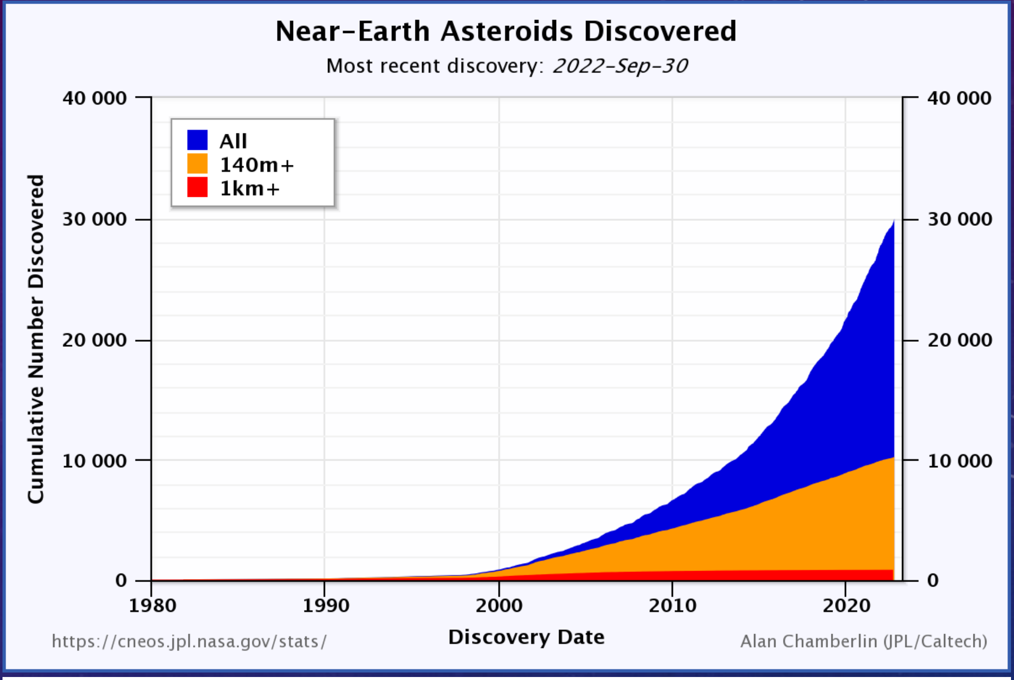
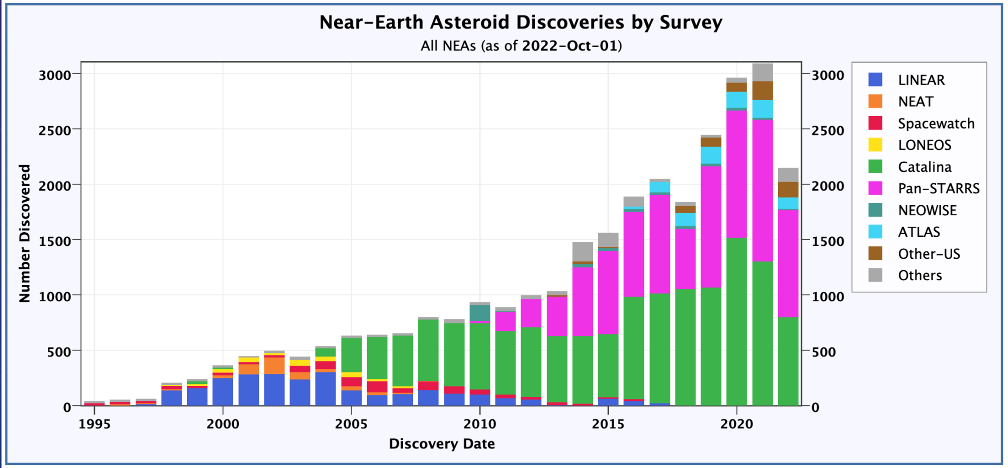


Fig. 19. (a) Planetary Defense Coordination Office (PDOC) (photo credit: NASA) and (b) the solar system with the Main Asteroid Belt and the Kuiper Belt.



(a)



(b)

Fig. 20. Near-Earth asteroids (NEAs) discovered as of Sep. 2022, by NASA PDOC, categorized by (a) NEAs dimension, and (b) survey stations.

MASSIVE SENSING AND COMMUNICATIONS IN DEEP-SPACE

Planetary Defense: Survey, Track and Categorize Near-Earth Objects/Asteroids

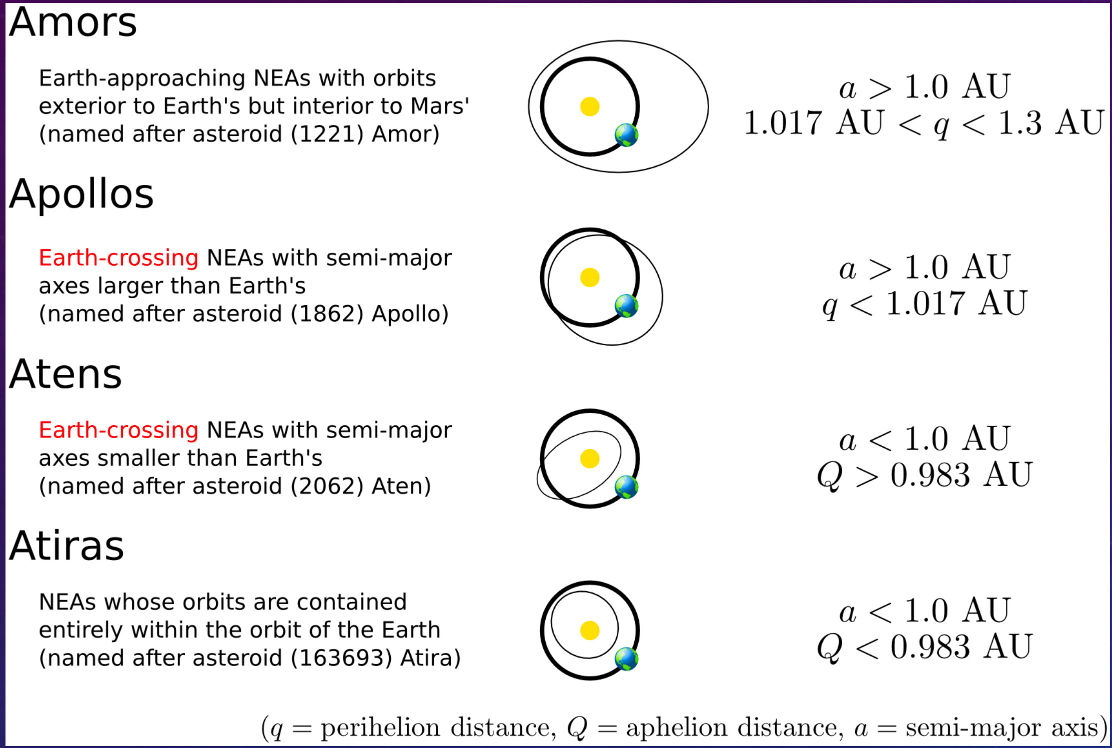


Fig. 21. Four types of near-Earth asteroids known as Atira, Aten, Apollo and Amor (photo credit: NASA)

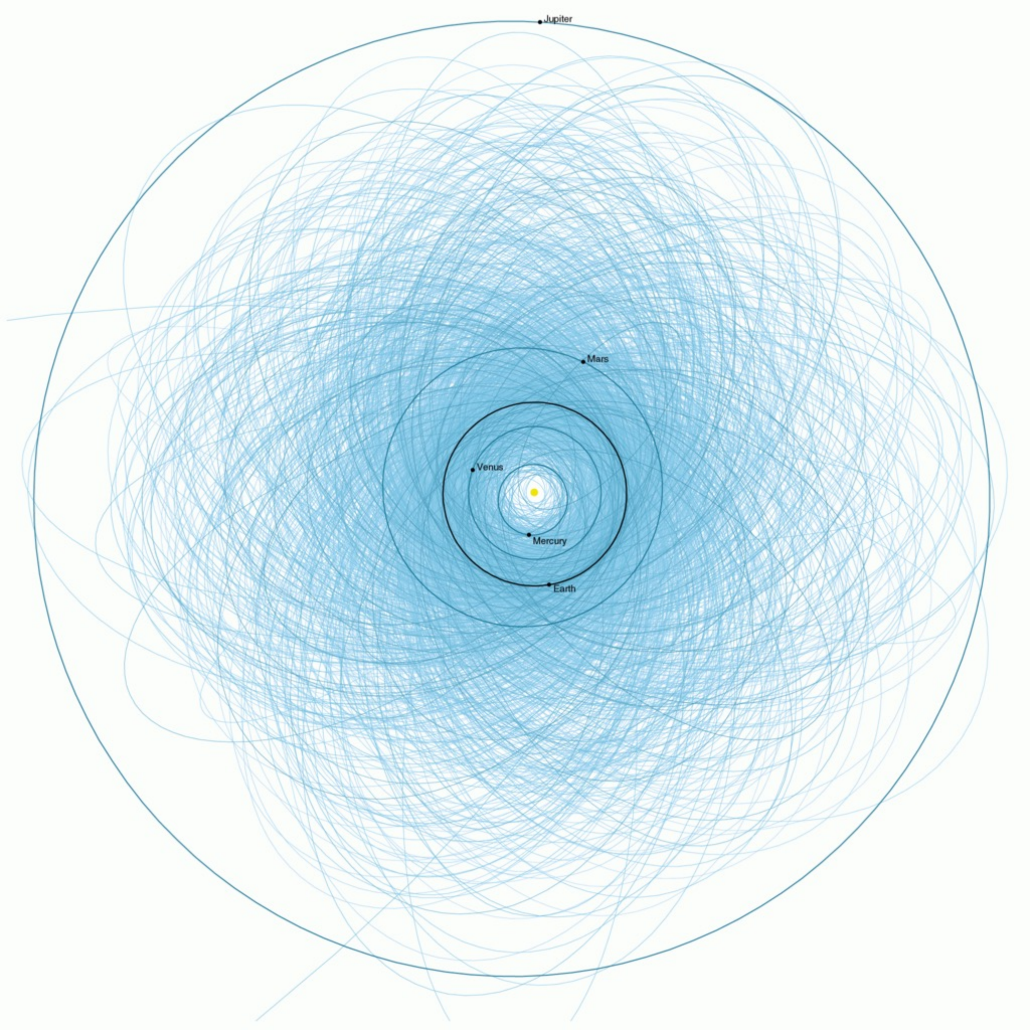


Fig. 22. Plot of orbits of known potentially hazardous asteroids with sizes over 140 metres as of early 2013 (photo credit: NASA)

MASSIVE SENSING AND COMMUNICATIONS IN DEEP-SPACE

Planetary Defense: Mitigation Technologies

❖ Kinetic Impact

1) Deep Impact (2005 Jan.12 – 2013 Aug. 8), the comet Tempel 1 probe, released an impactor to the comet on July 04, 2005.
2) DART (Double Asteroid Redirection Test), launched on Falcon 9, 2021 Nov. 24 – 2022 Sep. 26

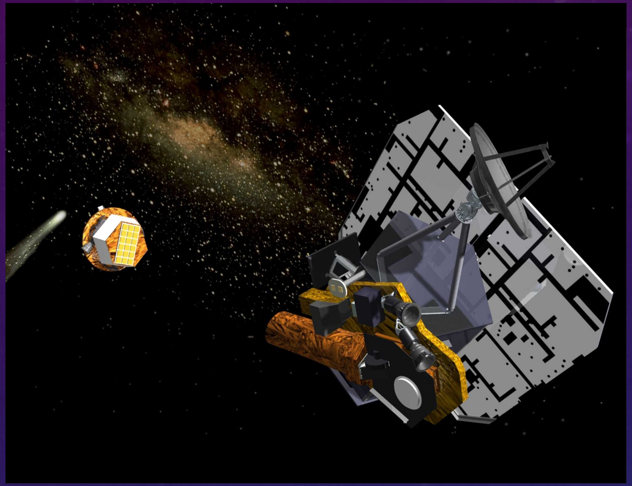


Fig. 23. Illustration of Deep Impact releasing the impactor to the commet (photo credit: NASA)

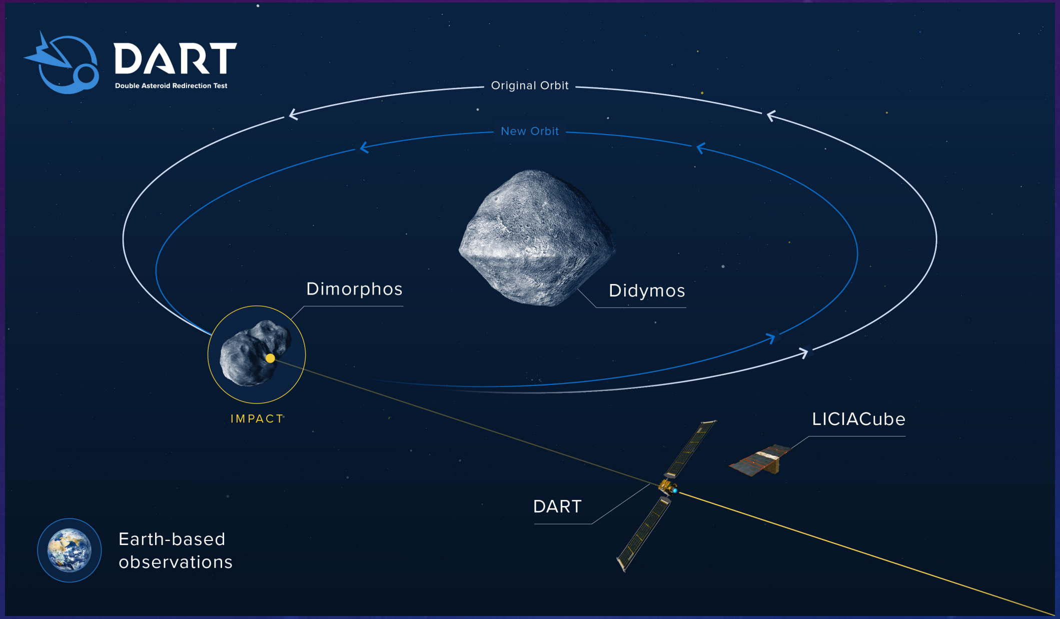
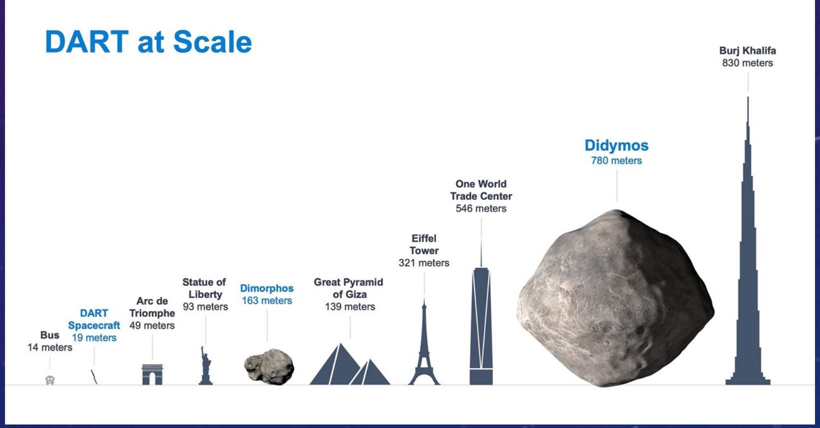


Fig. 24. Illustration of the deployment scheme of DART mission to impact Dimorphos (diameter of ~ 160-70 m) (photo credit: NASA/APL)



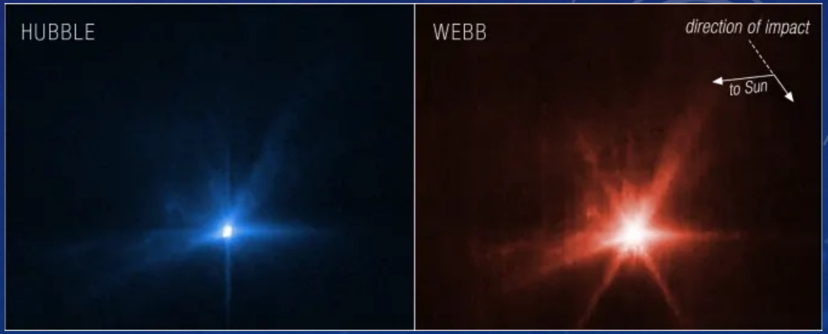


Fig. 25. Illustration of the DART mission at scale, and observations from Hubble/JWST several hours after impact (photo credit: NASA/APL)

MASSIVE SENSING AND COMMUNICATIONS IN DEEP-SPACE

Planetary Defense: Mitigation Technologies (Cont'd)

- Asteroid Gravity Tractor
- Focused Solar Energy
- Nuclear Explosive Device (NPT (Non-Proliferation Treaty) concerns)
- Asteroid Laser Ablation

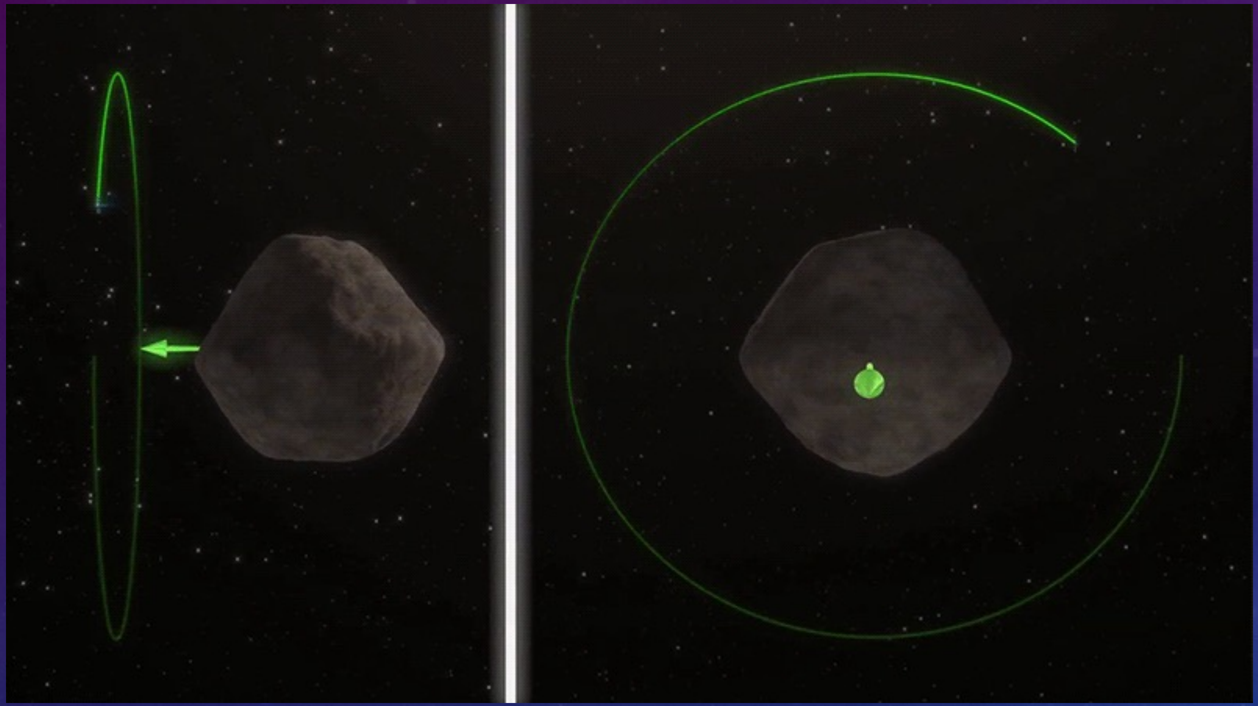


Fig. 26. Asteroid gravity tractor mitigation technology (photo credit: NASA)

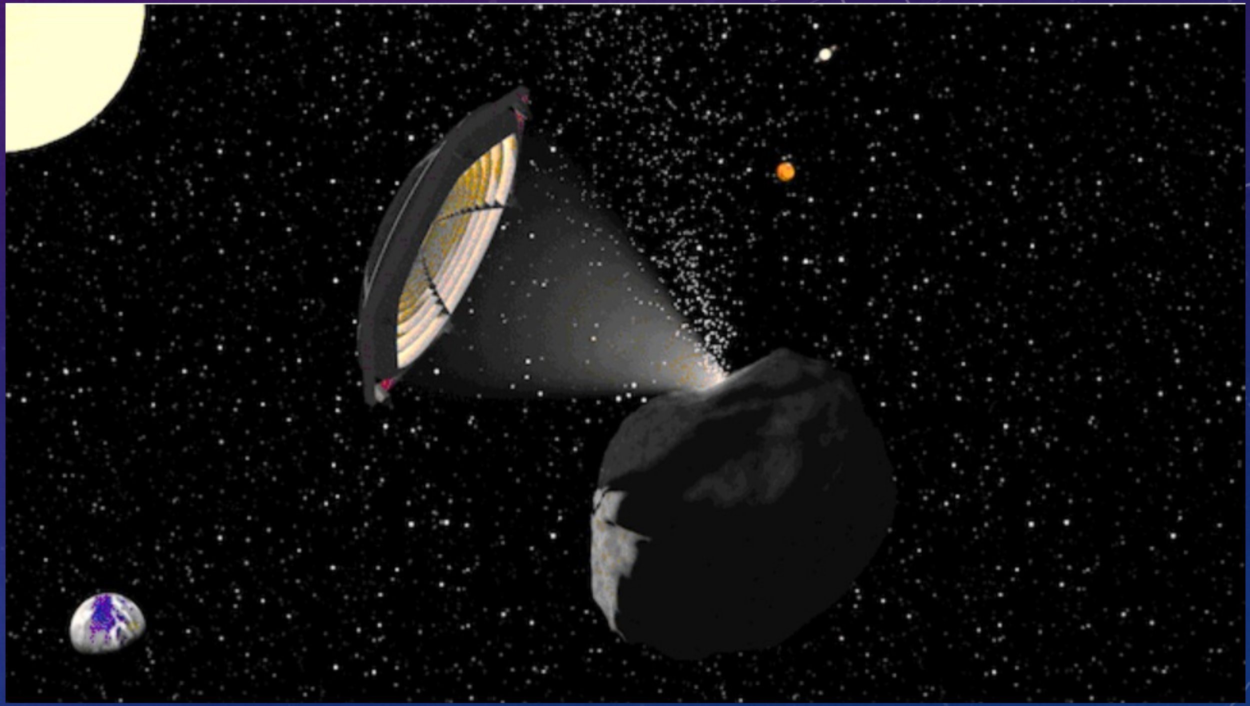
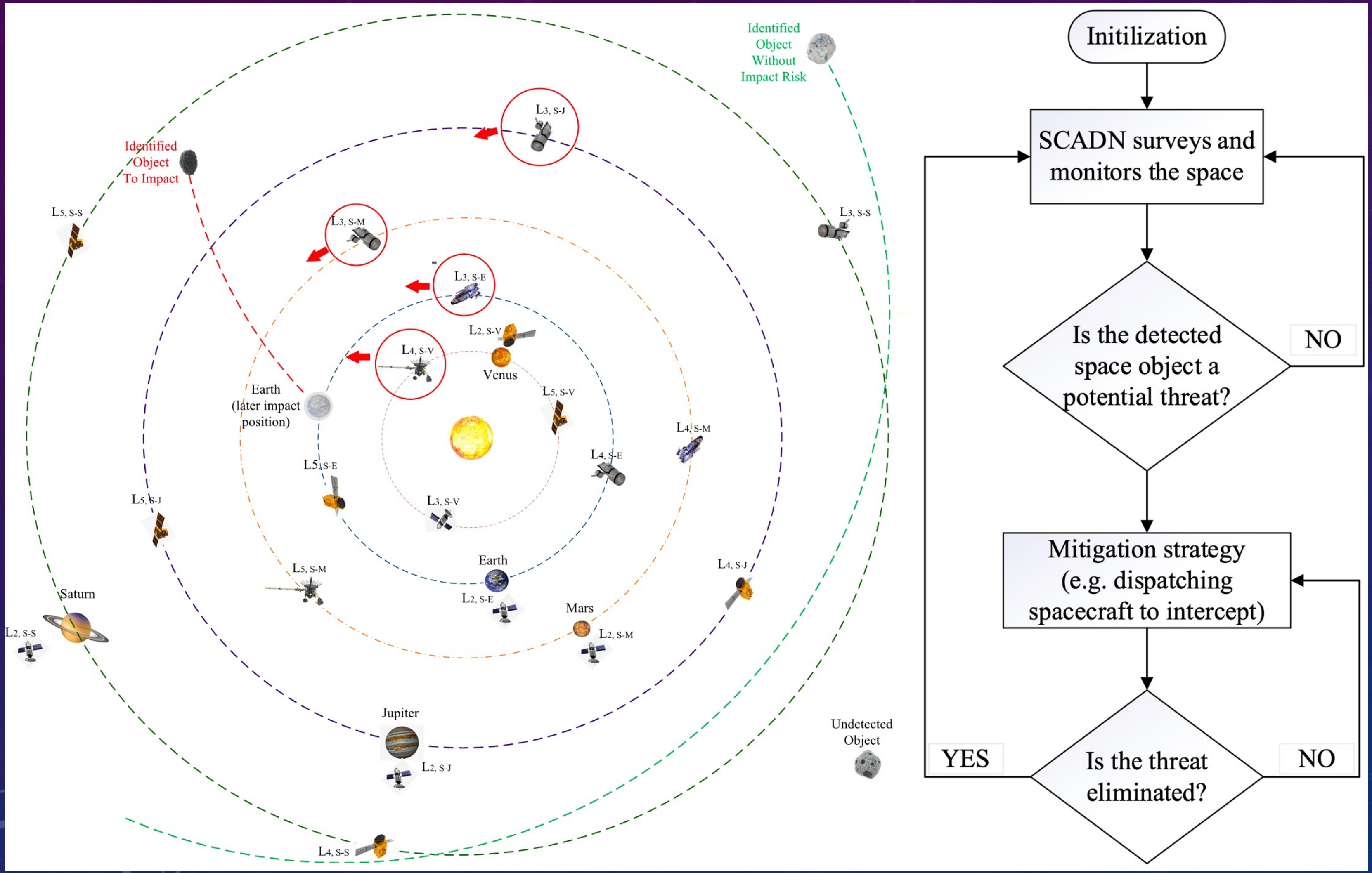


Fig. 27. Focused solar energy mitigation technology (https://commons.wikimedia.org/wiki/File:Ring_array_asteroid.gif License: CC BY-SA 4.0)

MASSIVE SENSING AND COMMUNICATIONS IN DEEP-SPACE

Solar Communication and Defense Networks (**SCADN**): Enabling **Massive Sensing & Communications** in Deep-Space!



- **Massive-MIMO-like Sensing and Communication** is enabled by a large number of spacecraft/survey stations (visible, mmWave, THz, Infrared, X-ray, etc.) in different orbits across the entire solar system.
- **Lagrange points** of each planet could be the most suitable candidate locations to deploy these spacecraft/ survey stations [8].
- Massive sensing with high spatial diversity enables **early detection and mitigation success rate**!
- SCADN also provides critical **communication infrastructure networks** for robust connectivity across different human bases in the solar system.
- **Artificial Intelligence**, space-based cloud/edge computing, machine learnings, will be very critical in enabling fully autonomous detection and mitigation and reduce manual errors and latency.

Fig. 28. Illustration of the SCADN framework consisting of spacecraft/survey stations, which monitors the space and detects and intercepts hazardous space objects (dimension of celestial bodies, space objects, and orbits are not scaled), with a brief flowchart of the SCADN framework.

MASSIVE SENSING AND COMMUNICATIONS IN DEEP-SPACE

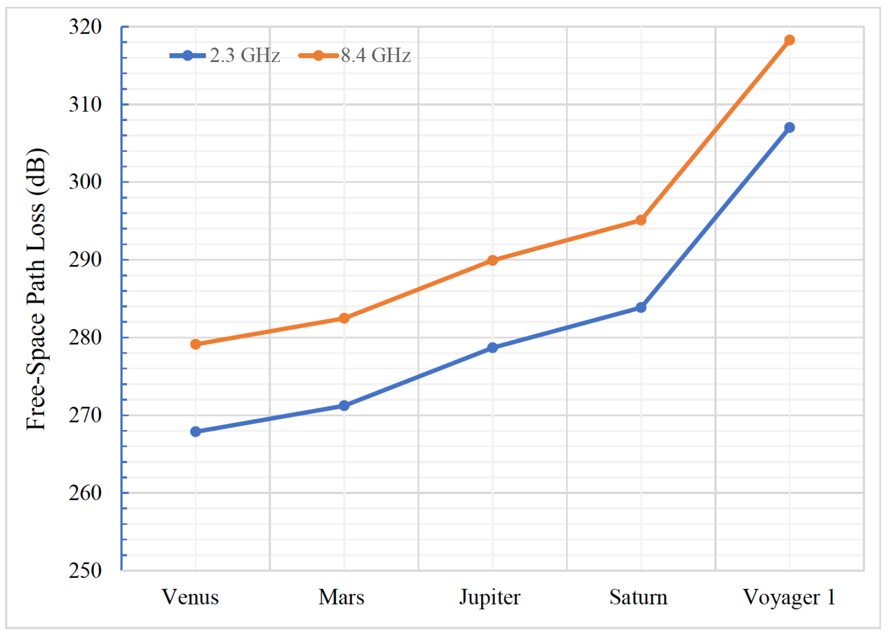
SCADN: Opportunities and Challenges

- Physical limitations: Propagation loss and speed of light (latency)
- Moore's Law and Wright's Law are co-enabling an enormous Internet of Spacecraft across the Solar System
- Long-term universal efforts and enormous investment by multiple organizations, governments, corporations, etc
- Rigorous legalization and supervision, considering the Non-Proliferation Treaty and Outer Space Treaty (OST)
- Other unexpected disruptive factors to the supply chain

Object/ Parameters	Distance to Earth (Large) (AU)	Free-Space Path Loss (Large) (dB)		Latency (Large) (s)	Distance to Earth (Small) (AU)	Free-Space Path Loss (Small) (dB)		Latency (Large) (s)
		2.3 GHz	8.4 GHz			2.3 GHz	8.4 GHz	
Venus	1.7170	267.8761	279.1272	856.8	0.2886	252.3874	263.6384	144.0
Mars	2.5233	271.2201	282.4711	1259.1	0.5444	257.8994	269.1505	271.7
Jupiter	5.9540	278.677	289.928	2971.1	3.9563	275.1265	286.3776	1974.2
Saturn	10.8109	283.8581	295.1091	5394.7	8.8564	282.1260	293.3770	4419.4
Voyager 1	155.6813*	307.0256	318.2766	77685.7	N.A.			

* As of May 25, 2022.

(a)



(b)

Fig. 29. (a) comparison of parameters of interest for Venus, Mars, Jupiter, Saturn and Voyager 1. (b) Comparison of free-space path loss (large distances for planets) at 2.3 GHz and 8.4 GHz, respectively [8].

SUMMARY

- ❖ A more prosperous and diverse space era Is unfolding in front of us
- ❖ Many catalysts in our civilization have accelerated its arrival at us
- ❖ Space technologies, and massive sensing and communication capabilities are reshaping fast
- ❖ It not only brings us the research and commercial opportunities, but also brings more fundamental but most critical concerns to us:

Where will humanity go, with these technologies?

Will becoming multi-planetary be sufficient?

How will humanity use them to better optimize its long-term evolution?

REFERENCE

[1] Y. Huo, “Space Broadband Access: The Race Has Just Begun,” *Computer*, vol. 55, no. 7, pp. 38-45, July 2022, doi: 10.1109/MC.2022.3160472.

[2] Ark Invest, “What is Wright’s Law?,” [Online]. Available: https://ark-invest.com/wrights-law/

[3] ARK Invest, “Wright’s law applies to satellite bandwidth, & more,” [Online]. Available: https://arkinvest. com/newsletters/issue-288/

[4] Space Exploration Holdings, LLC. Application for approval for orbital deployment and operating authority for the SpaceX Gen2 NGSO satellite System FCC Filing SAT-LOA-20200526-00055. Accessed on: Dec. 1, 2021. [Online]. Available: https://fcc.report/IBFS/SAT-LOA-20200526-00055/2378669.pdf

[5] Space Exploration Holdings, LLC. Amendment to pending application for the SpaceX Gen2 NGSO satellite system FCC Filing SATAMD-20210818-00105. Accessed on: Dec. 1, 2021. [Online]. Available: https://fcc.report/IBFS/SAT-AMD-20210818-00105/12943361.pdf

[6] E. H. Nikoghosyan, “Ecology of Near-Earth Space,” Accepted in CoBAO, 2017, [Online]. Available: https://arxiv.org/abs/1812.10478

[7] M. Sheetz, “The space industry is on its way to reach $1 trillion in revenue by 2040, Citi says,” CNBC, [Online]. Available: https://www.cnbc.com/2022/05/21/space-industry-is-on-its-way-to-1-trillion-in-revenue-by-2040-citi.html

[8] Y. Huo, “Internet of Spacecraft for Multi-Planetary Defense and Prosperity,” Signals, no. 3, pp. 428-467. https://doi.org/10.3390/signals3030026

[9] M. MacIver, L. Schmitz, U. Mugan, T. Murphey, and C. Mobley, “Massive increase in visual range preceded the origin of terrestrial vertebrates,” *Proceedings of the National Academy of Sciences* 114, 2017: E2375-E2384. DOI: 10.1073/pnas.1615563114

[10] E. Musk, “Making humans a multi-planetary species,” New Space 5, 2017: 46–61. http://doi.org/10.1089/space.2017.29009.emu

THANK YOU! Q & A

For more information, please contact me at:
yhuo@ieee.org or ymhuo@uvic.ca