# LEO PNT with Nano Satellites

## What is the New Space for GNSS?

Joshua Critchley-Marrows

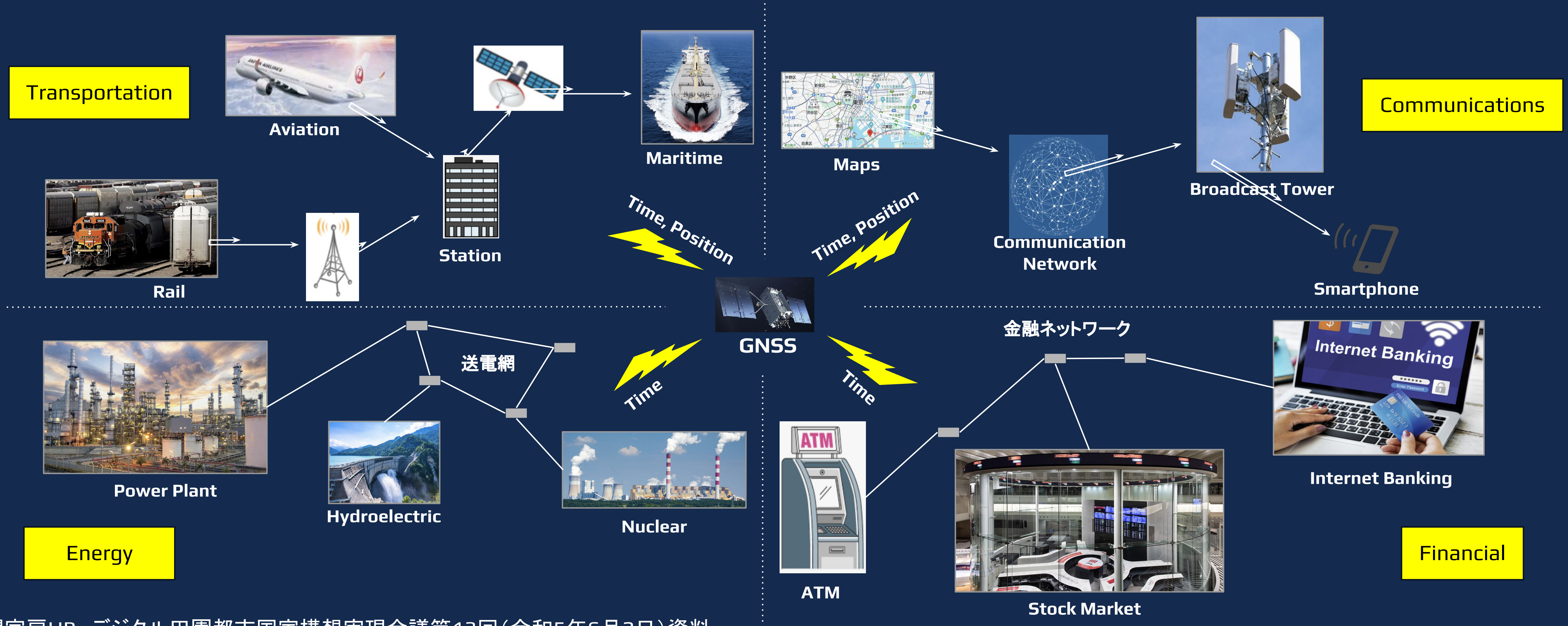
*7th Cis-lunar PNT Conference*

28th May 2024

# PNT Today

PNT is firmly embedded into modern society today, including transportation, communications, finance and energy.

In fact, so firmly embedded is its value, in the US, **a loss to GNSS** will cost the economy **$1 billion (¥130 billion) per day** (NIST study).

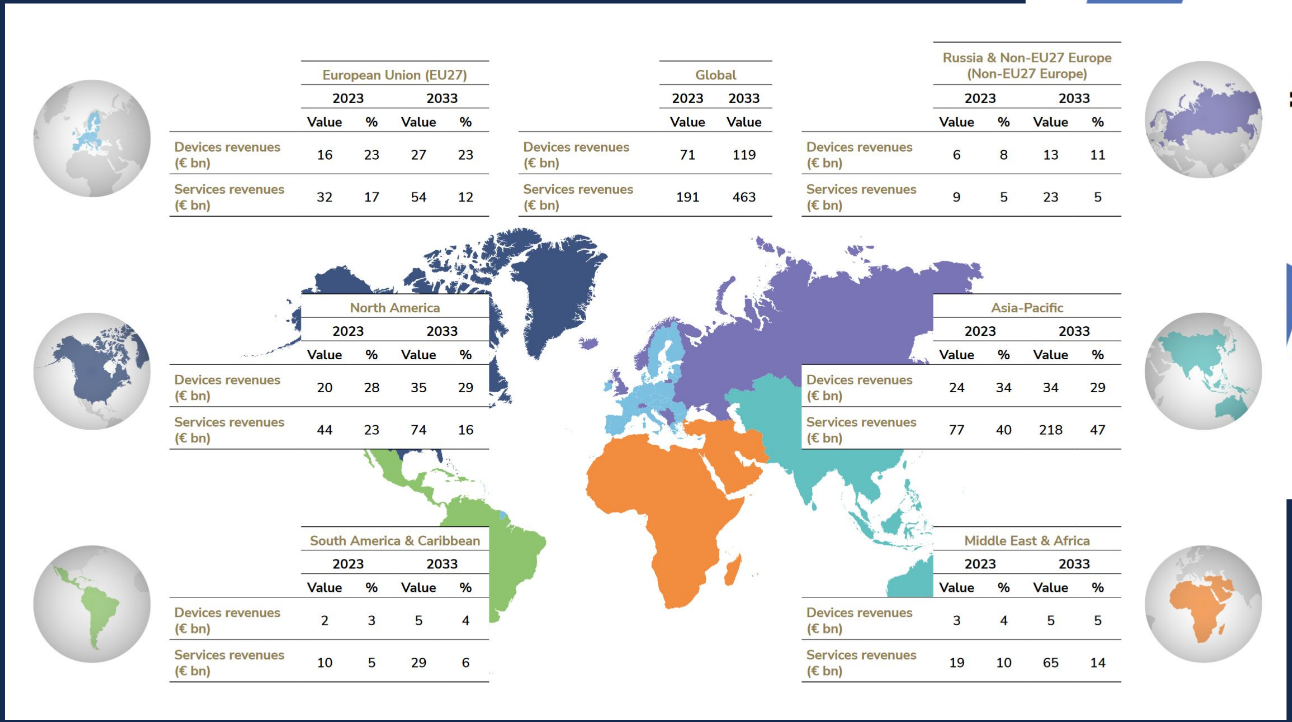



参考：内閣官房HP、デジタル田園都市国家構想実現会議第13回（令和5年6月2日）資料
https://www.cas.go.jp/jp/seisaku/digital_denen/dai13/04_muraiinn.pdf

# PNT Today

The economic value of the GNSS industry is expected to increase greatly over the next decade.

This is especially the case for the **Asia-Pacific** (to share **47% of the GNSS market**).



| European Union (EU27) | 2023 Value | 2023 % | 2033 Value | 2033 % |
|---|---|---|---|---|
| Devices revenues (€ bn) | 16 | 23 | 27 | 23 |
| Services revenues (€ bn) | 32 | 17 | 54 | 12 |

| Global | 2023 Value | 2033 Value |
|---|---|---|
| Devices revenues (€ bn) | 71 | 119 |
| Services revenues (€ bn) | 191 | 463 |

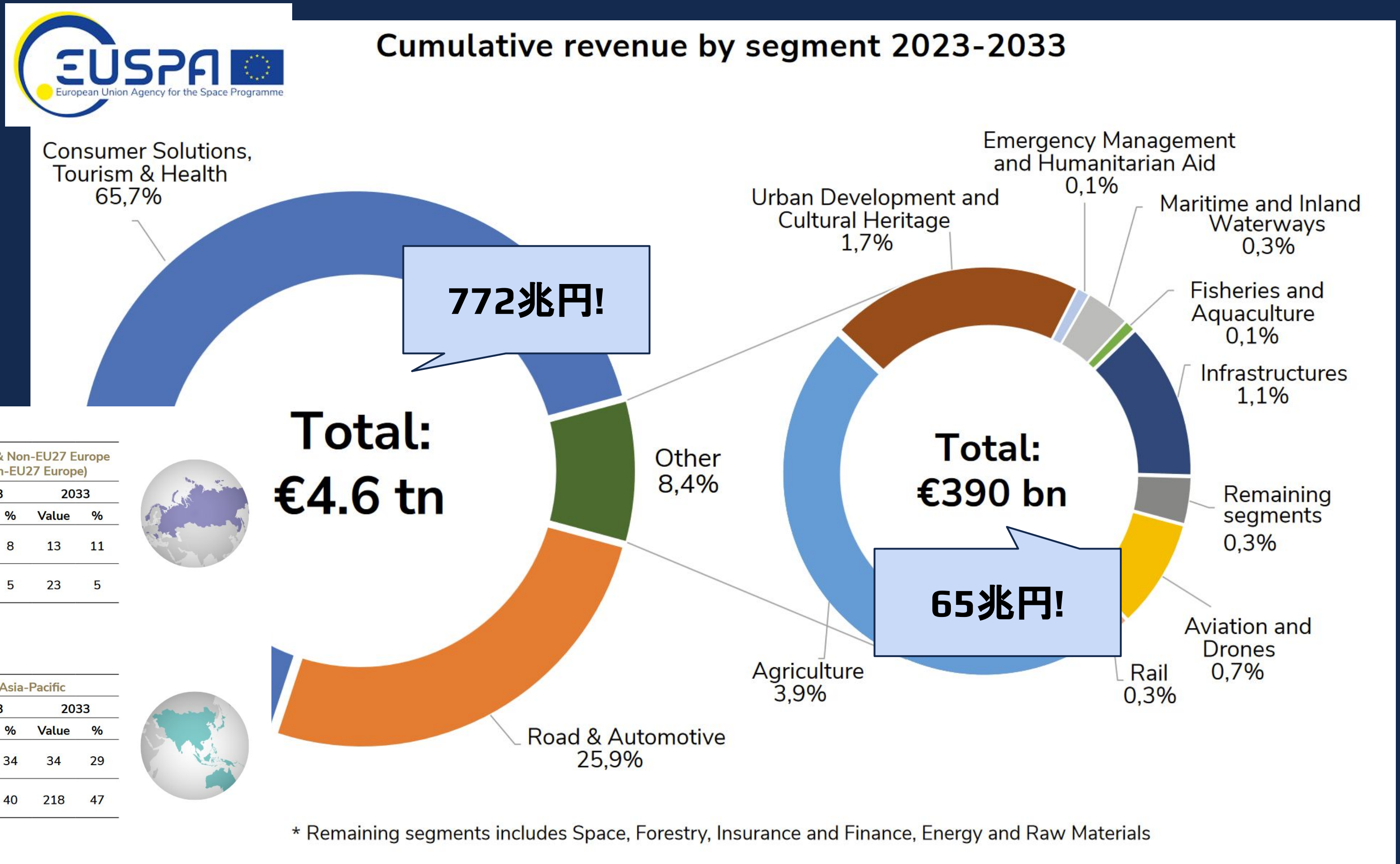
| Russia & Non-EU27 Europe (Non-EU27 Europe) | 2023 Value | 2023 % | 2033 Value | 2033 % |
|---|---|---|---|---|
| Devices revenues (€ bn) | 6 | 8 | 13 | 11 |
| Services revenues (€ bn) | 9 | 5 | 23 | 5 |

| North America | 2023 Value | 2023 % | 2033 Value | 2033 % |
|---|---|---|---|---|
| Devices revenues (€ bn) | 20 | 28 | 35 | 29 |
| Services revenues (€ bn) | 44 | 23 | 74 | 16 |

| Asia-Pacific | 2023 Value | 2023 % | 2033 Value | 2033 % |
|---|---|---|---|---|
| Devices revenues (€ bn) | 24 | 34 | 34 | 29 |
| Services revenues (€ bn) | 77 | 40 | 218 | 47 |

| South America & Caribbean | 2023 Value | 2023 % | 2033 Value | 2033 % |
|---|---|---|---|---|
| Devices revenues (€ bn) | 2 | 3 | 5 | 4 |
| Services revenues (€ bn) | 10 | 5 | 29 | 6 |

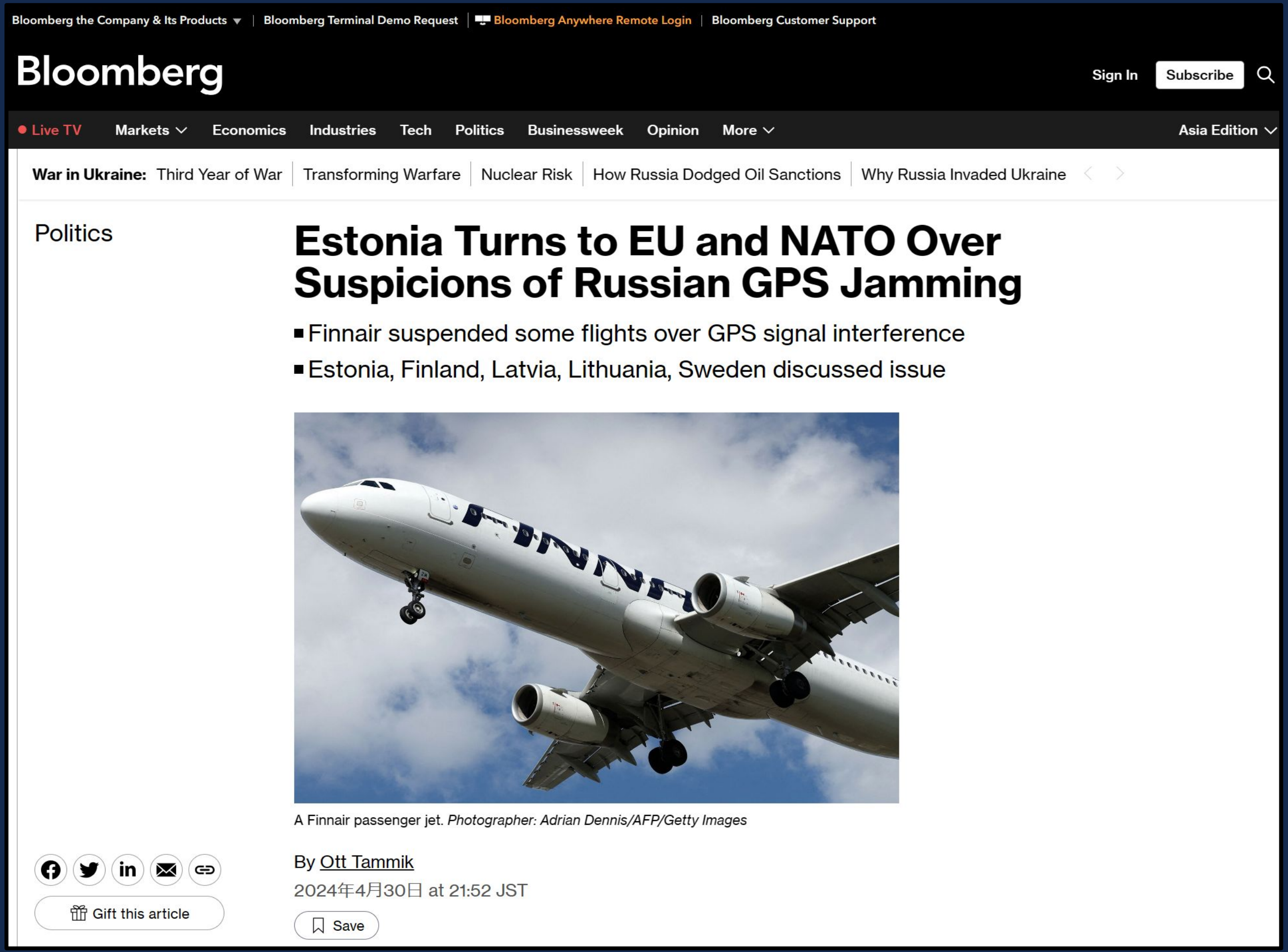
| Middle East & Africa | 2023 Value | 2023 % | 2033 Value | 2033 % |
|---|---|---|---|---|
| Devices revenues (€ bn) | 3 | 4 | 5 | 5 |
| Services revenues (€ bn) | 19 | 10 | 65 | 14 |




'EUSPA GNSS Market Report 2024', *EUSPA*

# PNT Under Threat

ArkEdge Space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Politics

## Estonia Turns to EU and NATO Over Suspicions of Russian GPS Jamming

- Finnair suspended some flights over GPS signal interference
- Estonia, Finland, Latvia, Lithuania, Sweden discussed issue

A Finnair passenger jet. *Photographer: Adrian Dennis/AFP/Getty Images*

By Ott Tammik

2024年4月30日 at 21:52 JST

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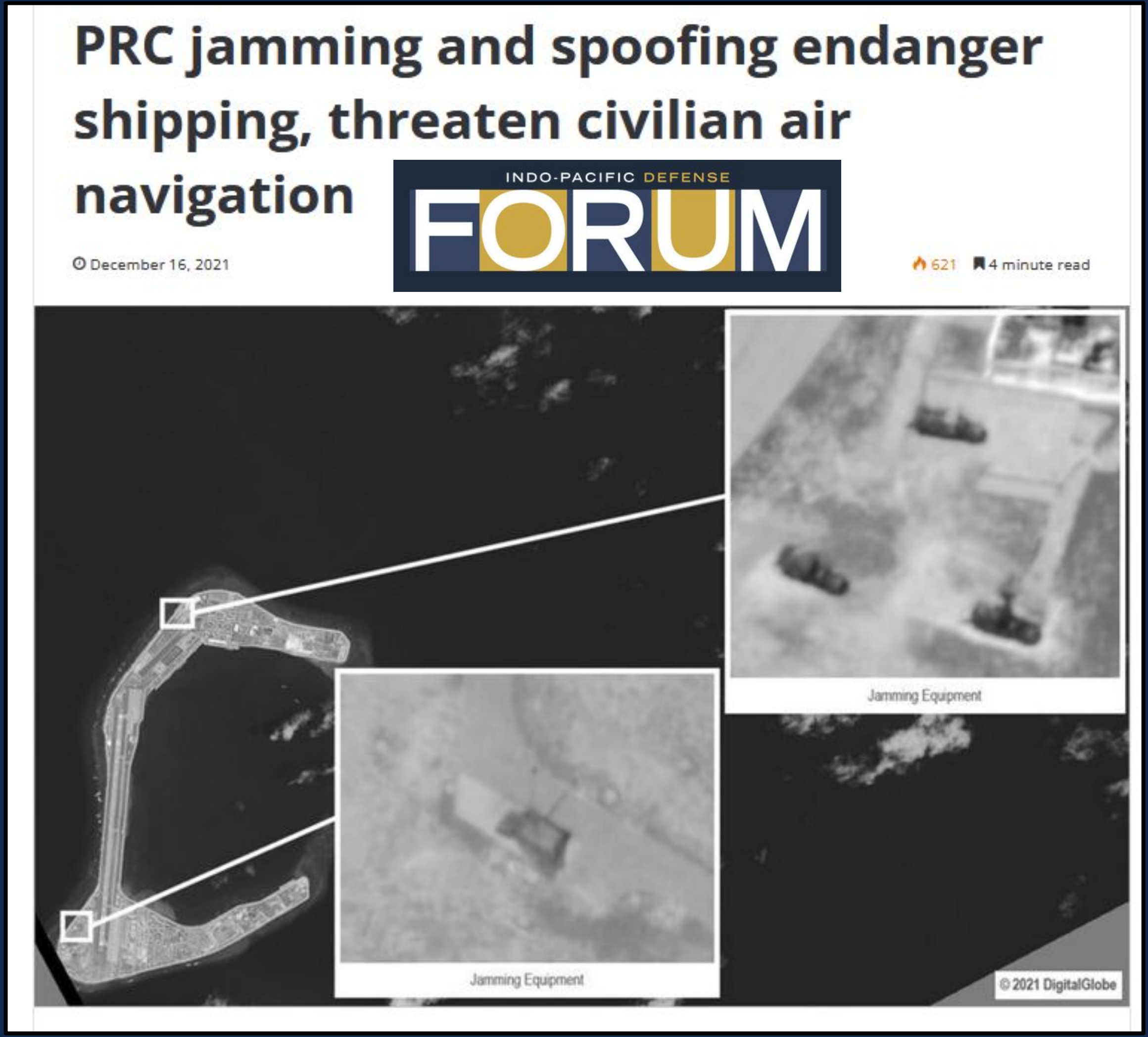

## PRC jamming and spoofing endanger shipping, threaten civilian air navigation

INDO-PACIFIC DEFENSE FORUM

December 16, 2021 | 621 | 4 minute read

# PNT Under Threat

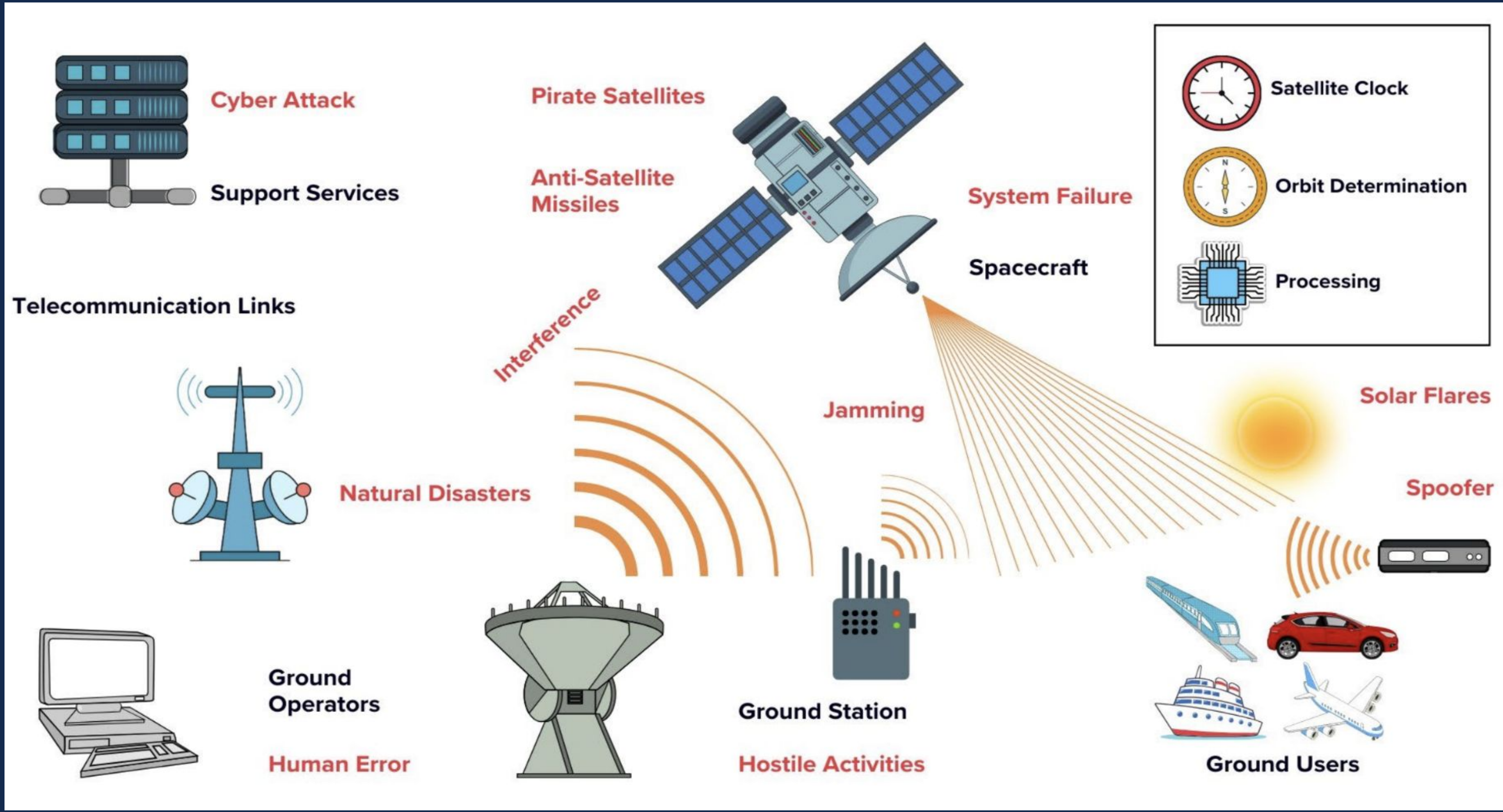
| Target | Impact | Region | Source |
|---|---|---|---|
| Jamming and spoofing across the Middle East and Ukraine confound civilian pilots, including Qantas | Disruption and safety risks to air traffic | Russia, Ukraine, Middle East | *New York Times* (2023) |
| Russia performs anti-satellite missile test capable of impacting GPS | Heightened risk of GNSS failure, disrupting global economy | Russia | *Inside GNSS* (2021) |
| Iran jams GPS on ships in Strait of Hormuz | Disruption and safety risks to shipping and maritime | Persian Gulf | *GPS World* (2019) |
| GPS jamming and spoofing attacks creating circular patterns in the Port of Shanghai | Disruption and safety risks to shipping and maritime | China Sea | *The Maritime Executive* (2019) |
| Australian Qantas pilots subject to GPS jamming from supposed Chinese warships | Disruption and safety risks to air traffic | China Sea | *Australian Aviation* (2023) |
| GPS jamming disrupts Australian motocross | Disruption to events and surrounding area, including motorists and critical infrastructure | Melbourne | *CNET* (2013) |
| SBAS outage significantly affected trust and operations in agriculture and shipping | Disruption and safety risks to shipping and maritime<br>Disruption to farmers and mining | Australia | *ABC* (2023) |
| Nine Galileo satellite clocks have stopped working | Heightened risk of GNSS failure, disrupting global economy | Europe | *BBC* (2017) |
| Multiple timing issues have been experienced with GLONASS satellites | Heightened risk of GNSS failure, disrupting global economy | Russia | *ICONCOX* (2013) |
| Three atomic clocks fail on Indian regional GNSS NAVIC | Heightened risk of GNSS failure, disrupting global economy | India | *GPS World* (2017) |
| GPS ground infrastructure is hacked every day | Heightened risk of GNSS failure, disrupting global economy | USA | *New York Times* (2023) |

'A Time and a Place for Resilience', *FrontierSI*

# PNT Under Threat

Vulnerabilities of GNSS

From down-stream to up-stream




A Time and a Place for Resilience, *FrontierSI*

# Definitions of Resilient PNT

ArkEdge Space

Where it concerns issues to PNT, and to ensure its resilience, it is best to consider the literature.

**_Resilient PNT_**
Ensures the ability the PNT service will recover and/or continue operation, with some acceptable degradation to satisfy critical needs, in the face of adversity.

Commonly adopted in military fields →

**_Assured PNT_**
Remove doubt that PNT services will be continuous and available by verbal and/or written confirmation.

**_Robust PNT_**
The use of a suite of technology that ensures PNT services will recover and/or continue, with some acceptable degradation to satisfy critical needs, in the face of adversity.

← To ensure the continuity and availability

The largest market →

**_Augmented PNT_**
The use of technology that is dependent on GNSS to improve performance metrics such as accuracy, precision, availability, continuity and integrity.

**_Alternative PNT_**
The use of a technology that is independent of GNSS to calculate PNT information that meets the same critical application needs.

← When GNSS is unavailable

'Ensuring PNT resilience: A global review of navigation policies and roadmaps', *University of Tokyo*

# Maritime Sector is in trouble, especially…

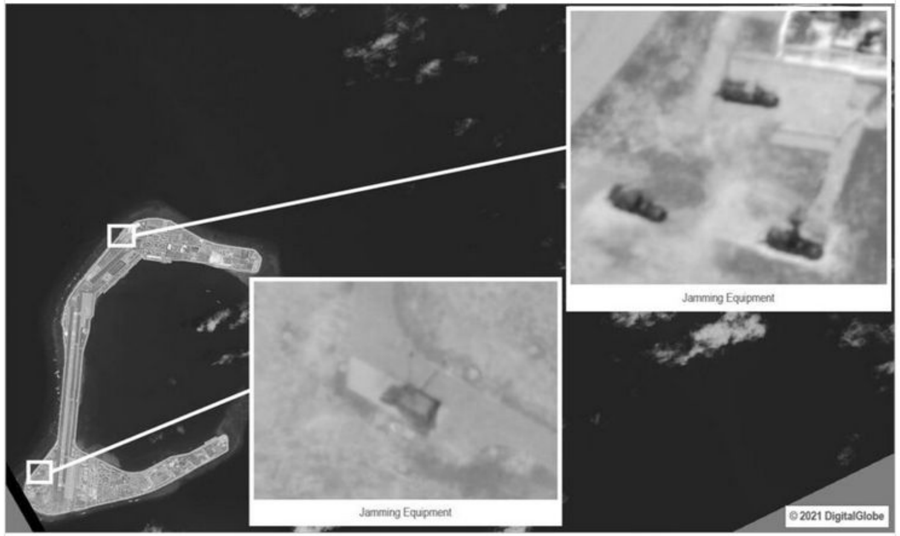
Suspected Russian GPS Jamming Risks Fresh Dangers In Black Sea Region

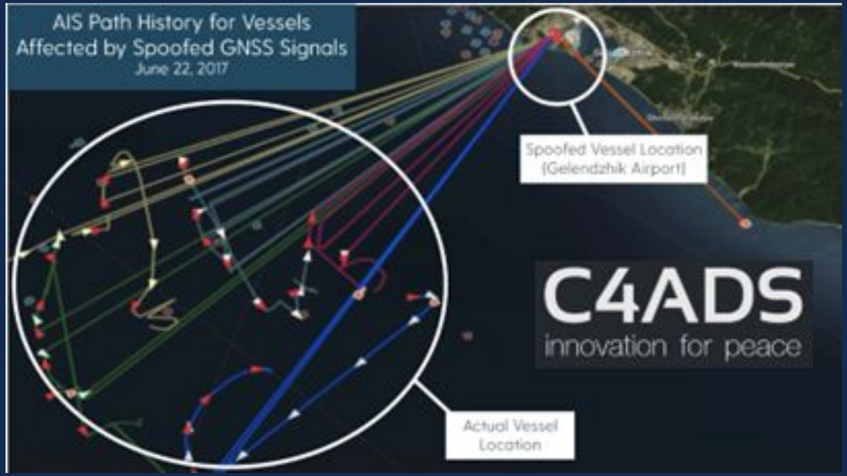
RadioFreeEurope RadioLiberty

## PRC jamming and spoofing endanger shipping, threaten civilian air navigation

INDO-PACIFIC DEFENSE FORUM

December 16, 2021 621 4 minute read



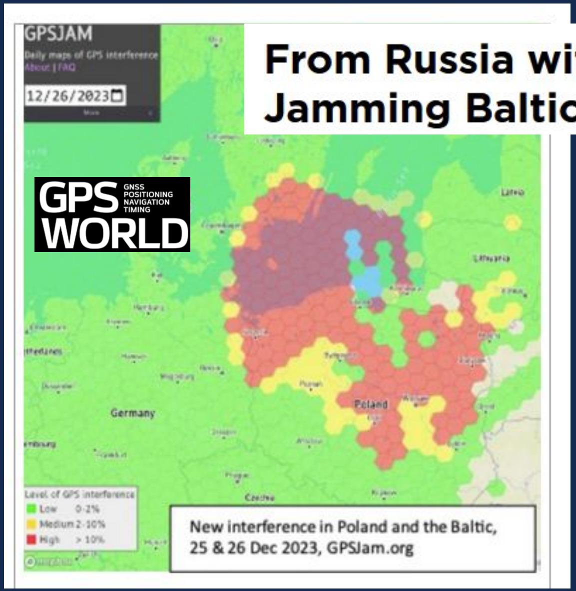




## Ghost ships, crop circles, and soft gold: A GPS mystery in Shanghai

A sophisticated new electronic warfare system is being used at the world's busiest port. But is it sand thieves or the Chinese state behind it?

MIT Technology Review

## From Russia with love for Christmas: Jamming Baltic GPS




**Perhaps we should start here?**

# What are the performance requirements?

Published in 'IALA R-129 GNSS Vulnerabilities and Mitigation Measures'

## APPENDIX 1 SUGGESTED MINIMUM MARITIME USER REQUIREMENTS FOR GENERAL NAVIGATION – BACKUP SYSTEM

*Table 2 Suggested minimum maritime user requirements for general navigation – backup system*

| | System level parameters | | | | Service level parameters | | | |
|---|---|---|---|---|---|---|---|---|
| | Absolute Accuracy | Integrity | | | Availability % per 30 days | Continuity % over 15 minutes[3] | Coverage | Fix interval (seconds) |
| | Horizontal (metres) | Alert limit (metres) | Time to Alarm[2] (seconds) | Integrity Risk (per 3 hours) | | | | |
| Ocean | 1000 | 2500 | 60 | $10^{-4}$ | 99 | N/A[2] | Global | 60 |
| Coastal | 100 | 250 | 30 | $10^{-4}$ | 99 | N/A[2] | Regional | 15 |
| Port approach and restricted waters | 10 | 25 | 10 | $10^{-4}$ | 99 | 99.97 | Regional | 2 |
| Port | 1 | 2.5 | 10 | $10^{-4}$ | 99 | 99.97 | Local | 1 |
| Inland Waterways | 10 | 25 | 10 | $10^{-4}$ | 99 | 99.97 | Regional | 2 |

Target Domains

*Notes:*

1. This table is derived from IMO Resolution A.915(22).
2. Continuity is not relevant to ocean and coastal navigation
3. IMO Resolution A.1046(27) amended the Continuity Time Interval to 15 minutes, rather than 3 hours as originally required in IMO Resolution A.915(22).
4. This table should be read in conjunction with paragraph 2.1 and 2.2. Although these are suggested minimum requirements, a Risk Assessment will include many variables that may alter the minimum requirements. Refer to IALA Guideline on the Provision of Aids to Navigation for Different Classes of Vessels, including High Speed Craft, Dec. 2003 for details of the variables of different waterways, ships and environments

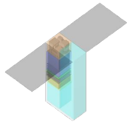
# Our Solutions

ArkEdge Space

Our micro satellites to meet various demonstration and business needs

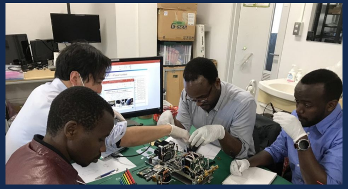
- **Flexible and efficient production** system
- **Multiple manufacturing** technologies

## Education and Research



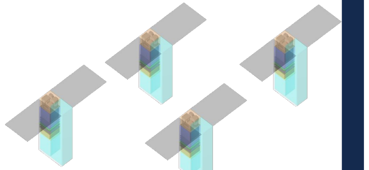
Hosted payload for easy access to space

Education, advertising and demonstration opportunities



Scientific Education

## IoT communications for SDGs

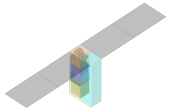


IoT Communications for SDGs

Advertising and demonstration opportunities

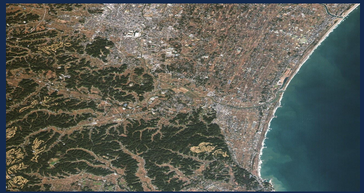
Smart Agriculture

## Optical / IR for SDGs



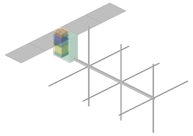
High-resolution optical, infrared, spectroscopic missions

Adapted to high-spec hosted payloads



Disaster Prevention

## VHF antenna for maritime DX

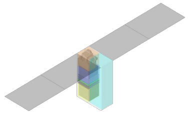


VDES communication, ship monitoring

Next AIS system
(AIS+ASM+VDE)

Ship monitoring

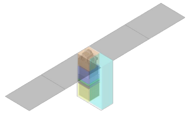
## Lunar infrastructure



High-precision pointing attitude control for optical communication for lunar infrastructure

Lunar Infrastructure

## Resilient and High-Precision PNT



Ranging for mass market applications

Timing synchronization for critical infrastructure

Critical Infrastructure

# Our Solutions

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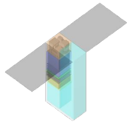
But first I want to discuss VDES...

### Education and Research



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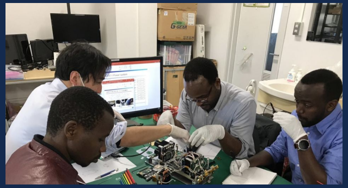

Scientific Education

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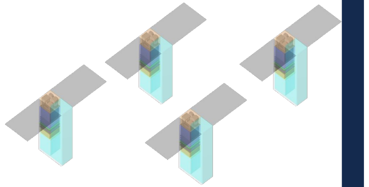
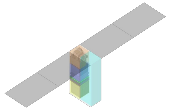


IoT Communications for SDGs

Advertising and demonstration opportunities

Smart Agriculture

### Optical / IR for SDGs



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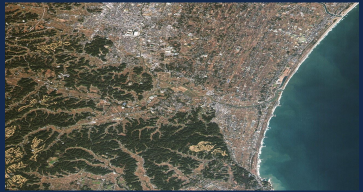

Disaster Prevention

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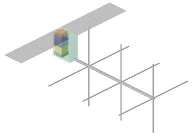
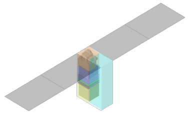


VDES communication, ship monitoring

Next AIS system (AIS+ASM+VDE)

Ship monitoring

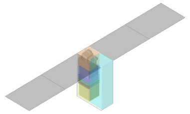
### Lunar infrastructure



High-precision pointing attitude control for optical communication for lunar infrastructure

Lunar Infrastructure

### Resilient and High-Precision PNT



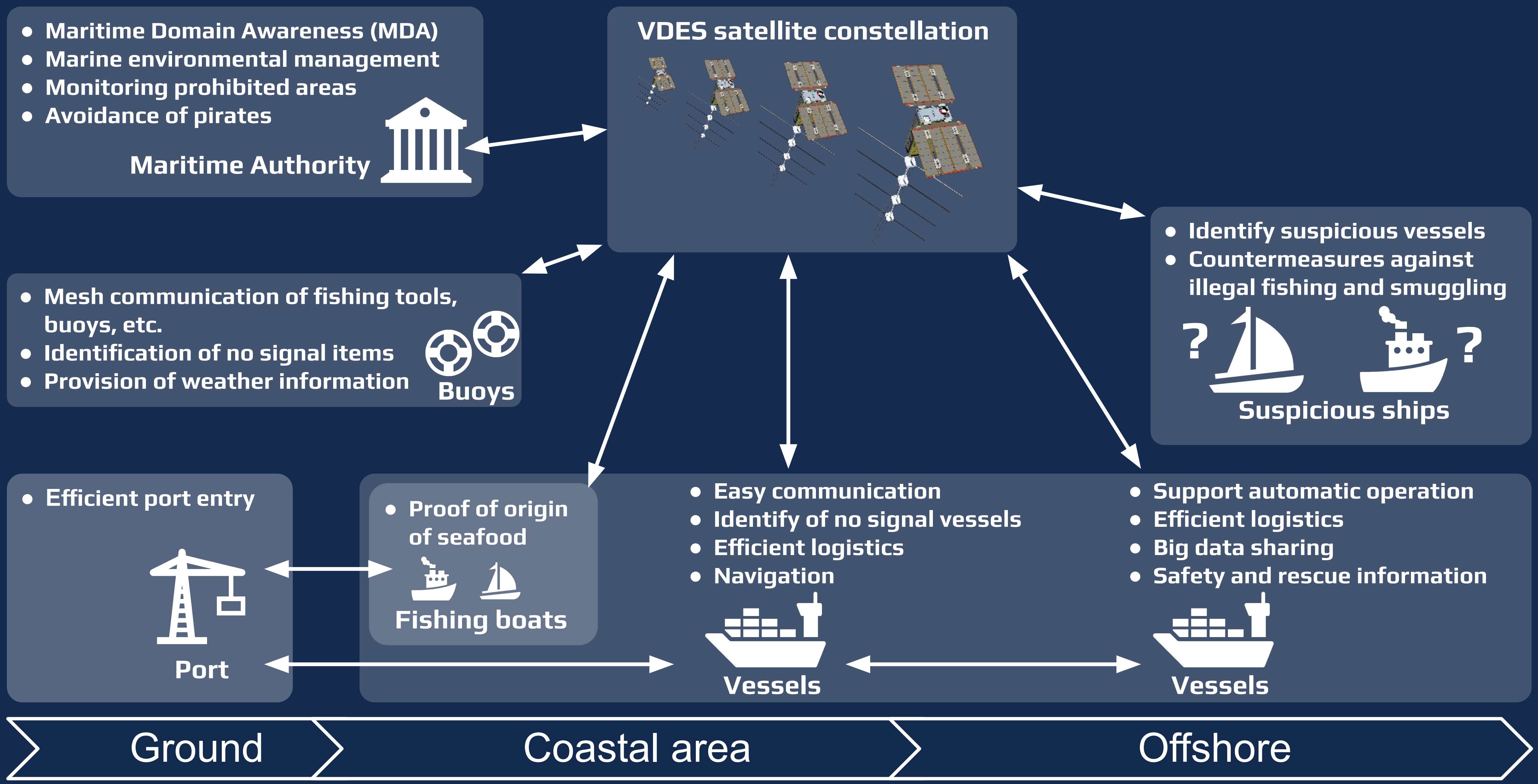
Ranging for mass market applications

Timing synchronization for critical infrastructure

Critical Infrastructure

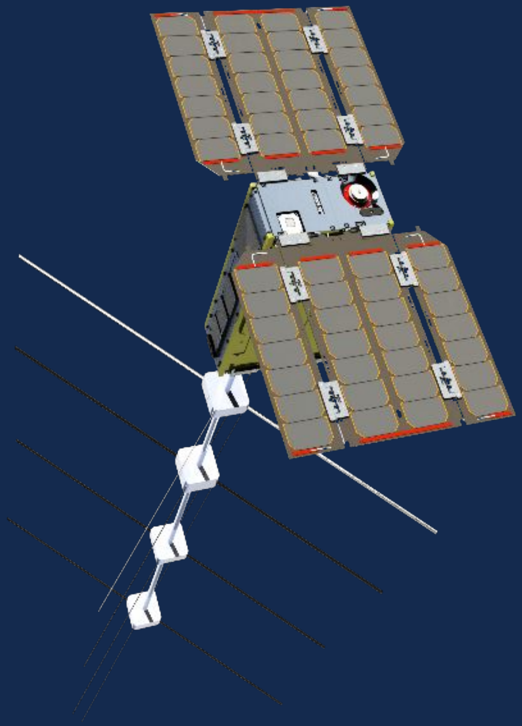
# VDES(VHF Data Exchange System)

ArkEdge Space



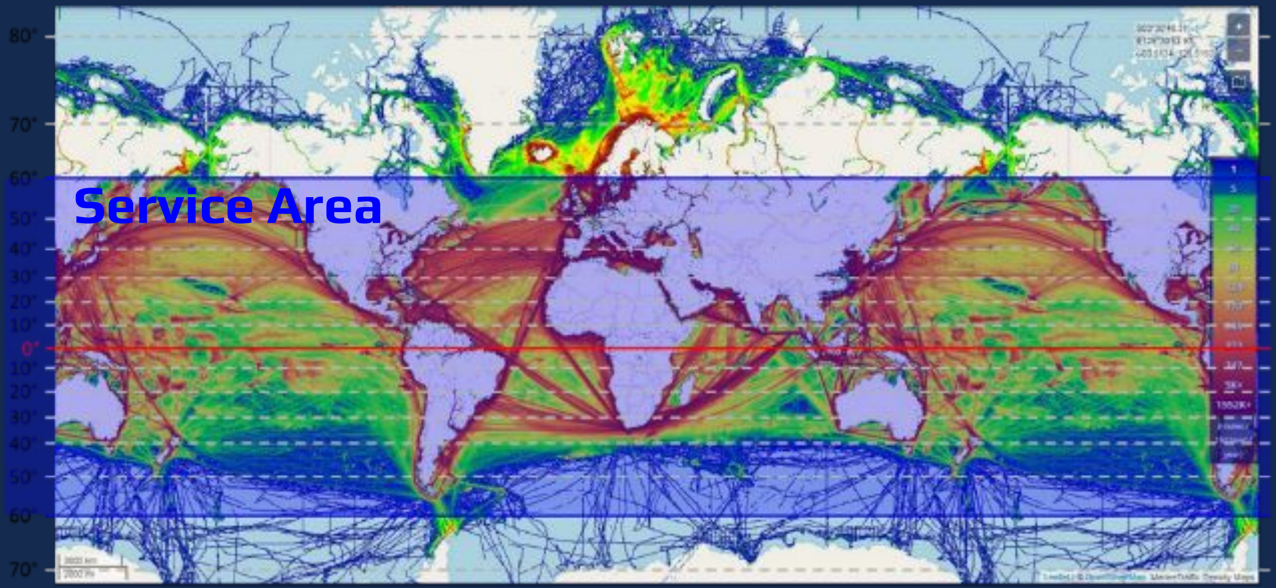
# VDES(VHF Data Exchange System)

ArkEdge Space



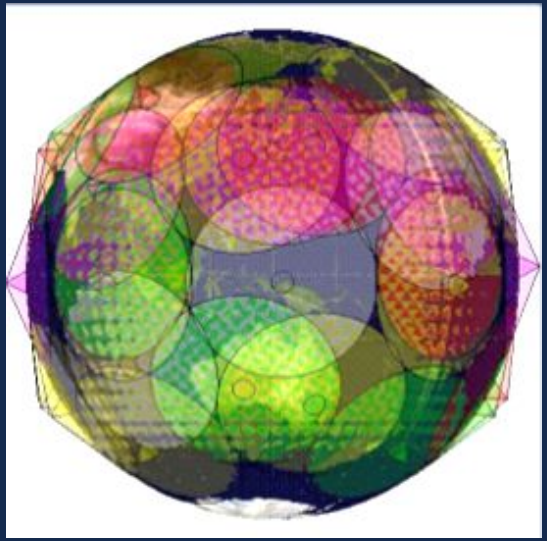
## AE VDES Satellites 1st Gen.

- Size: W6U (100 x 226.3 x 366 mm)
- Power: 50W
- TT&C: S-band
- Mission data downlink: X-band

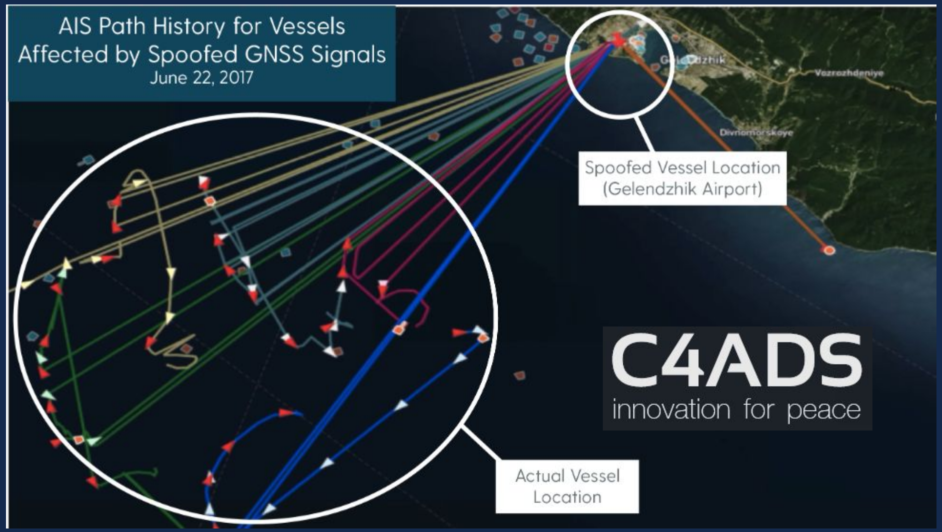



## Satellite Constellation

- 50~100 Satellites
- Coverage from 60ºN to 60ºS at all times



# Next Generation Marine AIS – VHF Data Exchange System




Reported attacks across the world on GNSS – including jamming, spoofing, cyber and kinetic weapons.

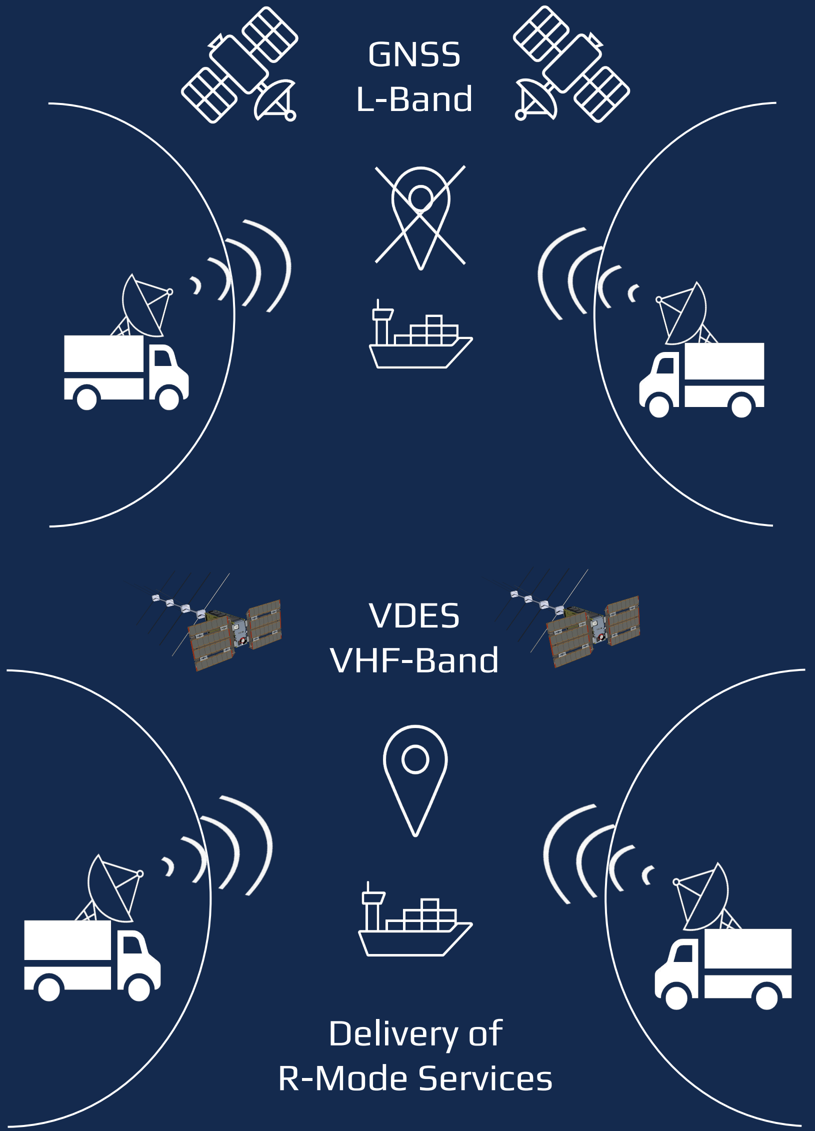
GNSS is at risk for maritime vessels, and ensuring resilient services are essential.

One of the most significant challenges to LEO PNT is the allocation of spectrum for supporting services.

VDES offers the opportunity to provide a supplementary, dedicated pseudocode on an already ITU supported frequency allocation, with a ready market.

**Known as R-Mode**, these LEO PNT signals may operate from 157-162 MHz.

VHF would require much larger jamming and spoofing equipment.



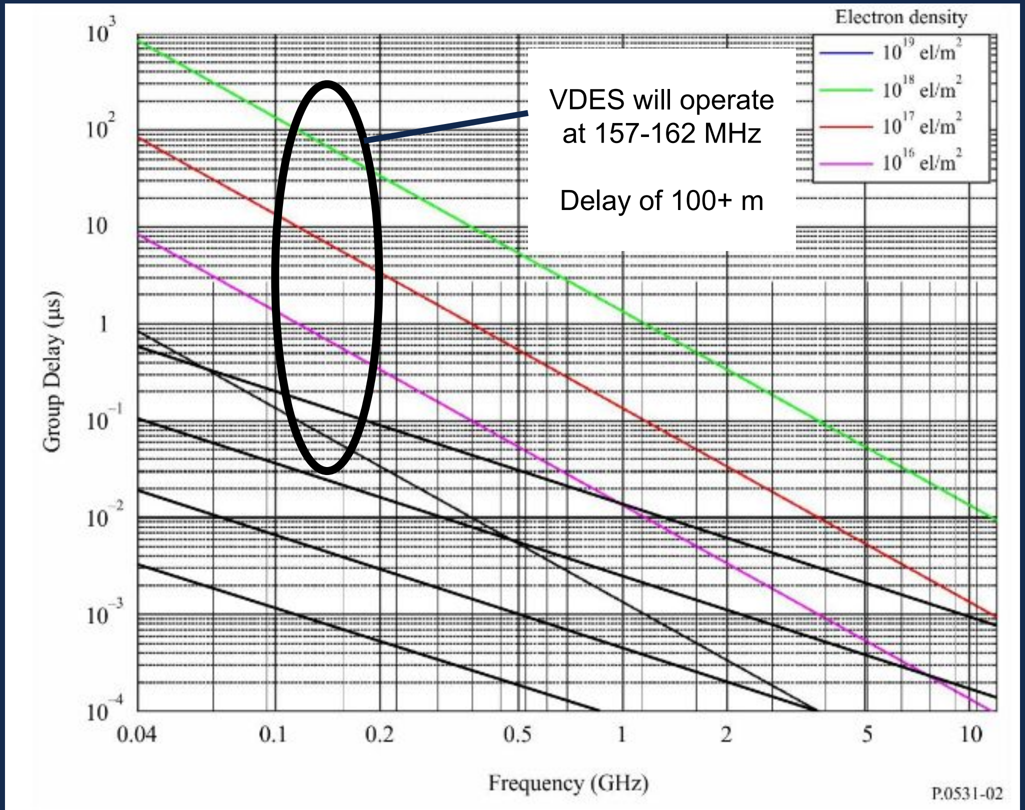

**Could this be a first generation LEO PNT?**

Challenges

# Ionospheric Factor

The **ionosphere** is a major challenge at the VHF.

The ionospheric delay according to the atmospheric model of ‘P.531-15’ will cause a delay of over 100+ m – highly variable according to current atmospheric activity.

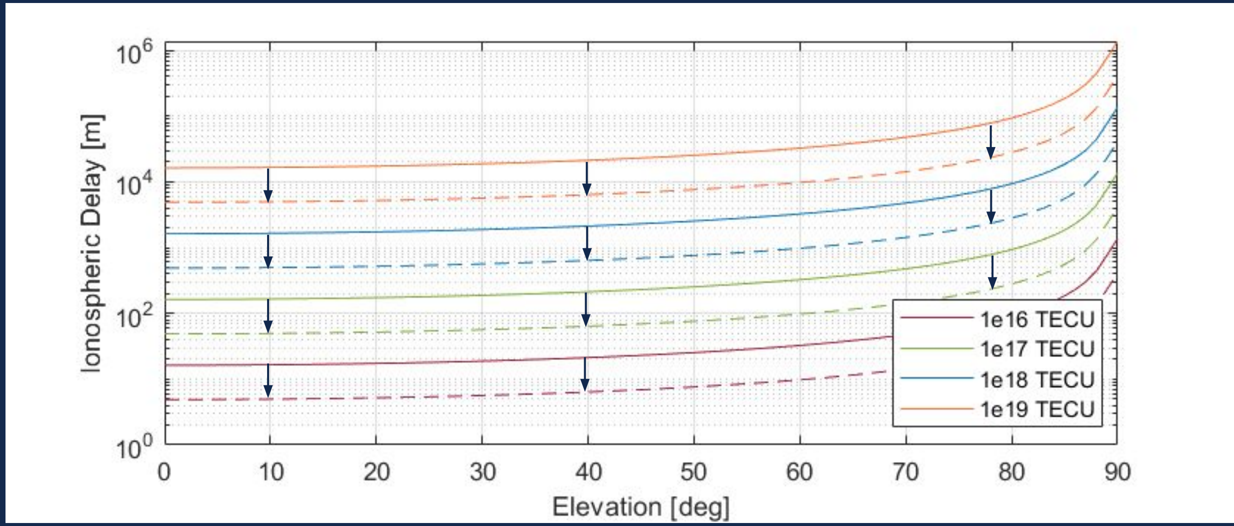



ITU-R P.531-15

**How to remove it?**

By introducing ionospheric modelling, the delay can be reduced to approximately 30-50% for VDES.

Still, it is very poor at high ionospheric activity - above 1 km in some cases. Other methods are needed…




TECU : Total Electron Content Unit

Challenges

# Channel Performance

Another consideration is the **channel model** offered by a VDE-SAT R-Mode.

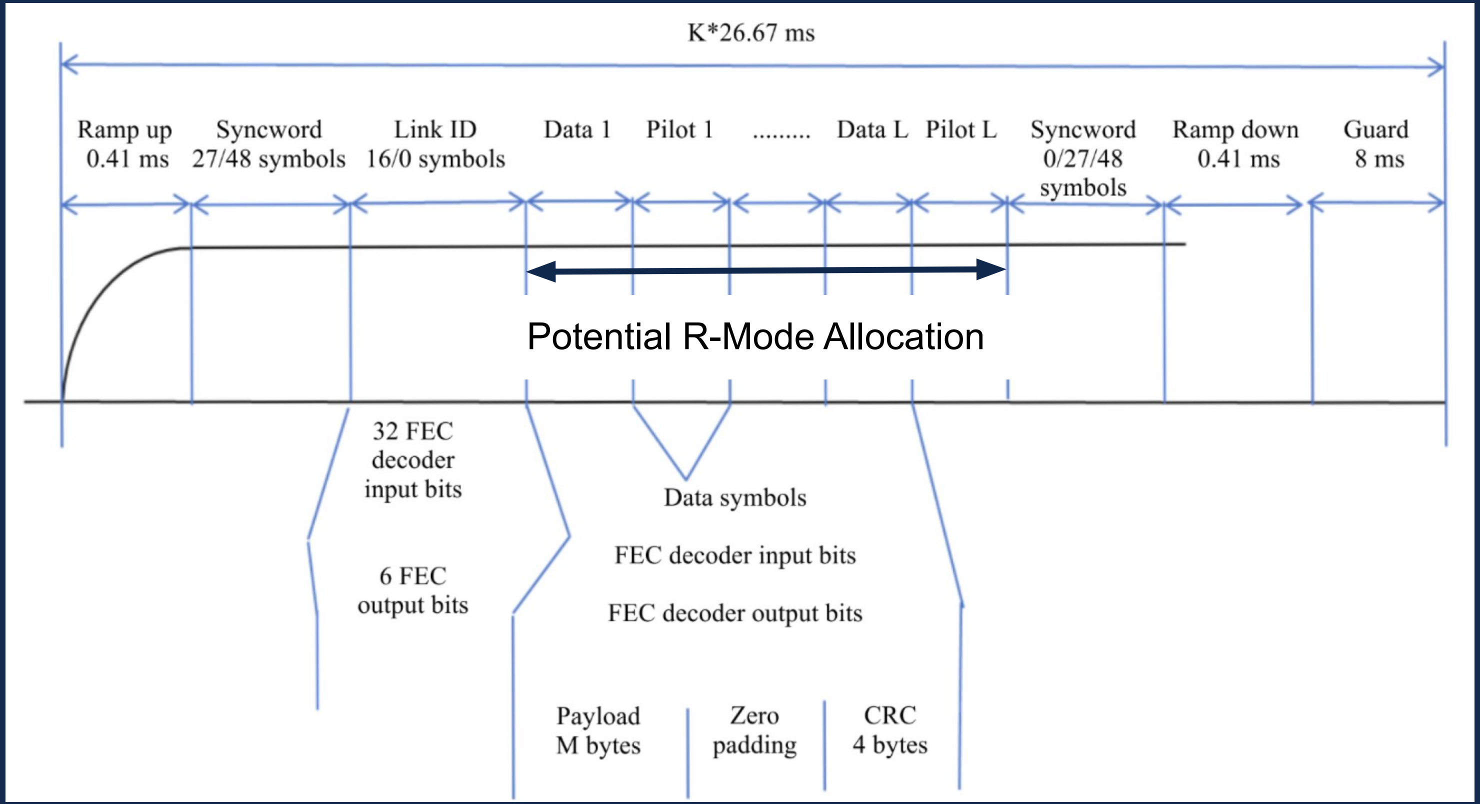
Each message could use an existing or implement a dedicated pseudocode for transmission.

We are confined by the standard…

How much could be allocated?

How to design?

What is the rate of transmission?




ITU-R M.2092-1

Only **8% of the signal bandwidth** can be dedicated to delivering an R-Mode.

## Challenges

# Channel Performance

Various VDES parameters have been established for each signal waveform.

**VHF data exchange-satellite downlink identification parameters**

| PL format | SAT-MCS-0.50-1 | SAT-MCS-1.50-1 | SAT-MCS-3.50-1 | SAT-MCS-0.100 | SAT-MCS-0.150 |
|---|---|---|---|---|---|
| Link ID | 25 | 26 | 27 | 28 | 29 |
| Channel BW (kHz) | 50 | | | 100 | 150 |
| Roll off filtering(1) | 0.25 | | | | |
| Signal BW (kHz) | 42.0 | | | 90.0 | 141.0 |
| CDMA chip rate (kcps) | 33.6 | N/A | | 72.0 | 112.8 |
| Spreading factor (chips) | 8 | | | 2 | |
| Symbol rate (ksps) | 4.2 | 33.6 | | 36.0 | 56.4 |
| Burst size (slots) | 90 | | | | |
| Guard time (ms) | 8 | | | | |
| Burst duration (ms) | 2392.0 | | | | |
| Symbols/burst (symbols) | 10046 | 80371 | | 86112 | 134908 |
| Ramp-up/down (symbols / chips) | 14/14 | | | 30/30 | 47/47 |
| Ramp-up/down (ms) | 0.41/0.41 | | | | |
| Syncword size (symbols) | 48 | 27 | | 48 | |
| Number of syncwords | 10 | 35 | | 32 | |
| Total syncword symbols (symbols) | 480 | 945 | | 1536 | |
| Syncword distance (symbols) | 1004 | 2268 | | 2690 | 4214 |
| Syncword modulation | BPSK/ CDMA | π/4-QPSK (00 /11) | | BPSK/CDMA | |
| Link ID size (symbols) | 0 (N/A) | | | | |
| Link ID modulation | N/A | N/A | | N/A | |
| Pilot distance (symbols) | N/A | 27 | | N/A | |

ITU-R M.2092-1

Critical parameters include:

- Channel bandwidth
- Symbol number
- Roll-off filtering / cut-off
- Symbol / chip rate
- Modulation
- Burst length

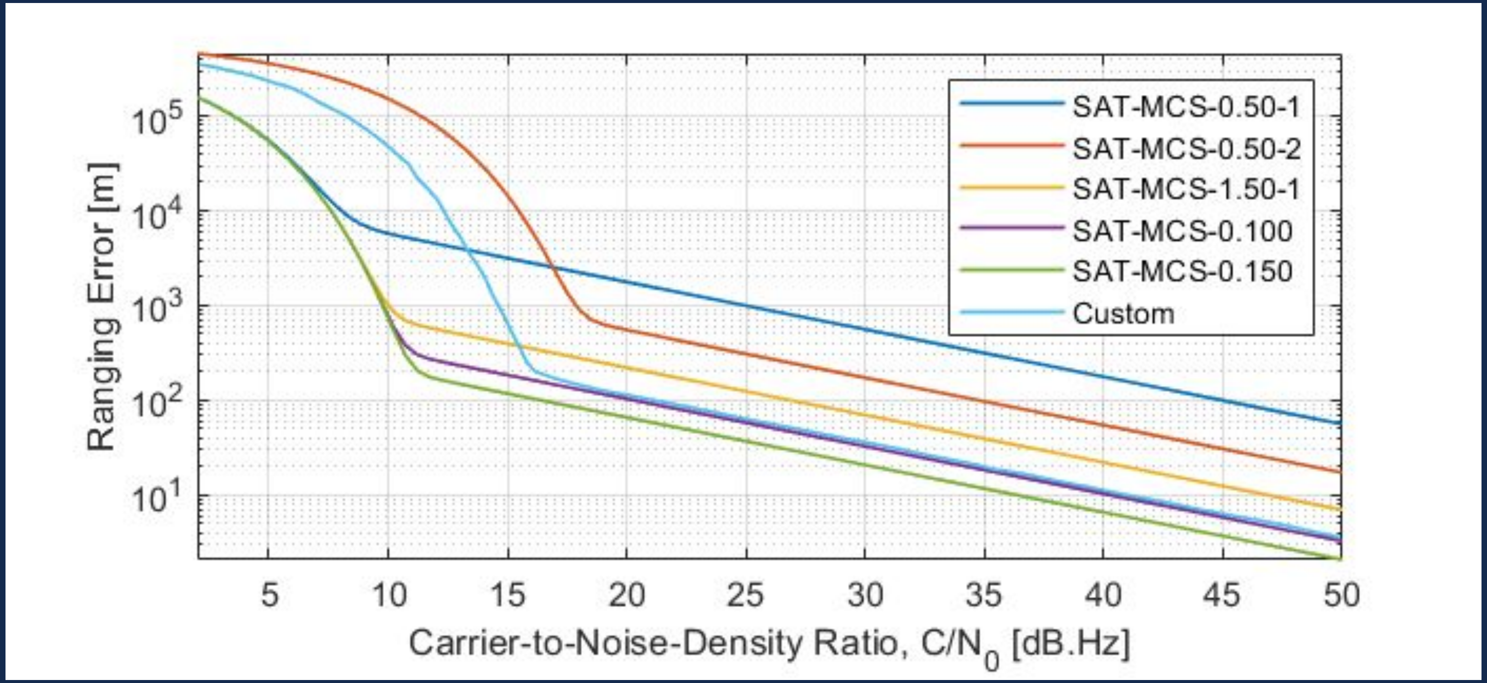
| Parameter | SAT-MCS-0.50-1 | SAT-MCS-0.50-2 | SAT-MCS-1.50-1 | SAT-MCS-0.100 | SAT-MCS-0.150 |
|---|---|---|---|---|---|
| Symbol Number | 13,128 | 80,336 | 80,343 | 172,164 | 269,720 |
| Roll-Off Cutoff | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 |
| Bandwidth | 50 kHz | 50 kHz | 50 kHz | 100 kHz | 150 kHz |
| Symbol Rate | 33,600 -/s | 33,600 -/s | 33,600 -/s | 72,000 -/s | 112,800 -/s |
| Ramp-up/-down | 14/14 | 14/14 | 14/14 | 30/30 | 47/47 |
| Burst Length | 90 slots | 15 slots | 90 slots | 90 slots | 90 slots |

J. Šafář, A. Grant, and M. Bransby, 'Performance bounds for VDE-SAT R-Mode', *International Journal of Satellite Communications and Networking*, vol. 41, no. 2, pp. 134–157, 2023, doi: 10.1002/sat.1429.

Challenges

# Channel Performance

Under separate channel considerations, initially introduced by research from the **UK General Lighthouse Authority**, modelling of Ziv-Zakai (modification to the Cramer-Rao Bound) can indicate potential performance.




*Custom employs a **dedicated Gold Code** with a 150 kHz bandwidth signal.

**SAT-MCS-0.100, SAT_MCS-0.150 and Custom performs best** - each using the highest bandwidth.


J. Šafář, A. Grant, and M. Bransby, ‘Performance bounds for VDE-SAT R-Mode’, *International Journal of Satellite Communications and Networking*, vol. 41, no. 2, pp. 134–157, 2023, doi: 10.1002/sat.1429.

Challenges

# A New Ephemeris

What about the **navigation message**?

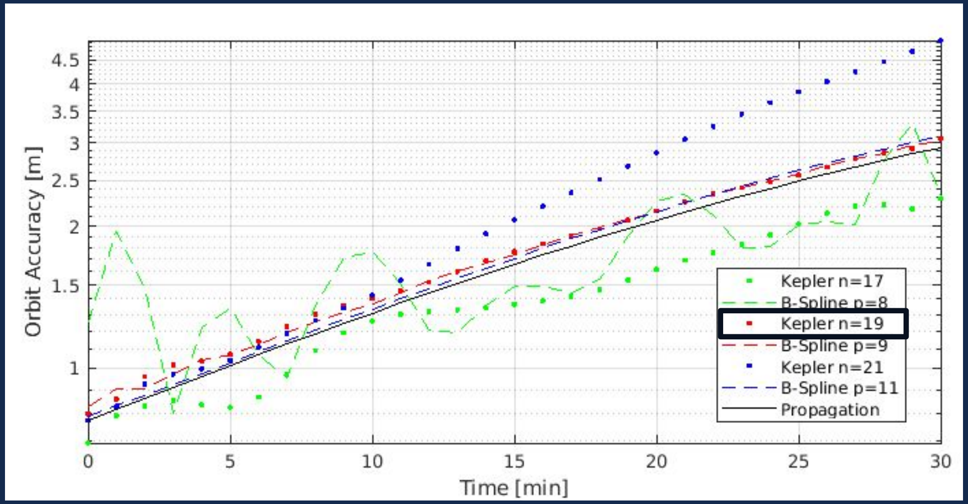
We have proposed an extension to the traditional Kepler parameters to account for additional orbital dynamics in LEO.

The validity interval is reduced sharply – satellite visibility time is approximately 10 min…

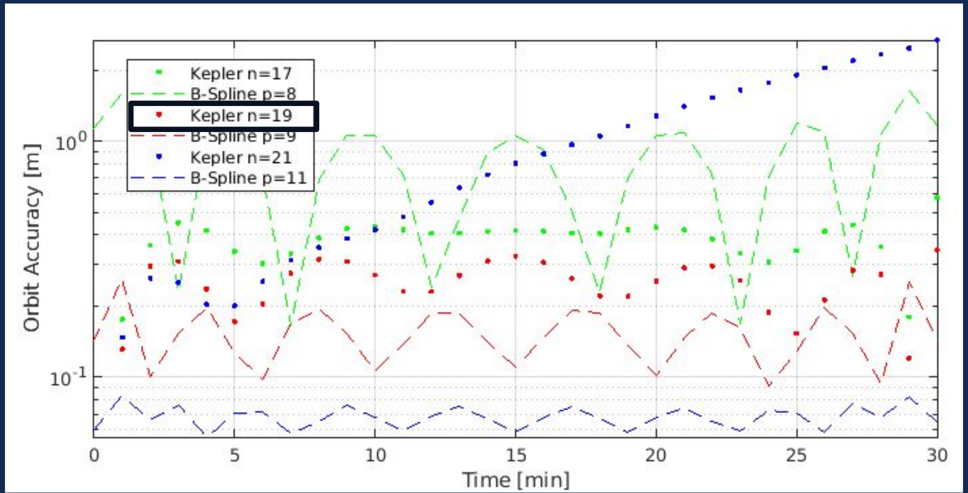
| | |
|---|---|
| $t_{op}$ | CEI Data sequence propagation time of week |
| $\Delta A$ **** | Semi-major axis difference at reference time |
| $\dot{A}$ | Change rate in semi-major axis |
| $\Delta n_0$ | Mean Motion difference from computed value at reference time |
| $\Delta\dot{n}_0$ | Rate of mean motion difference from computed value |
| $M_{0-n}$ | Mean anomaly at reference time |
| $e_n$ | Eccentricity |
| $\omega_n$ | Argument of perigee |

| | |
|---|---|
| $t_{oe}$ | Ephemeris data reference time of week |
| $\Omega_{0-n}$ | Longitude of Ascending Node of Orbit Plane at Weekly Epoch |
| $\Delta\dot{\Omega}$**** | Rate of right ascension difference |
| $i_{0-n}$ | Inclination angle at reference time |
| IDOT | Rate of inclination angle |
| $C_{is-n}$ | Amplitude of the sine harmonic correction term to the angle of inclination |
| $C_{ic-n}$ | Amplitude of the cosine harmonic correction term to the angle of inclination |
| $C_{rs-n}$ | Amplitude of the sine correction term to the orbit radius |
| $C_{rc-n}$ | Amplitude of the cosine correction term to the orbit radius |
| $C_{us-n}$ | Amplitude of the sine harmonic correction term to the argument of latitude |
| $C_{uc-n}$ | Amplitude of the cosine harmonic correction term to the argument of latitude |

GPS ICD: 'IS-GPS-200N' (2022), *US Department of Defense*




*GNSS derived orbit propagated to 30 min validity interval*




*Precise orbit propagated to 30 min validity interval*

# VDES R-Mode Potential Performance

**Scenario** : Stationary ship on the ocean for 10 min.

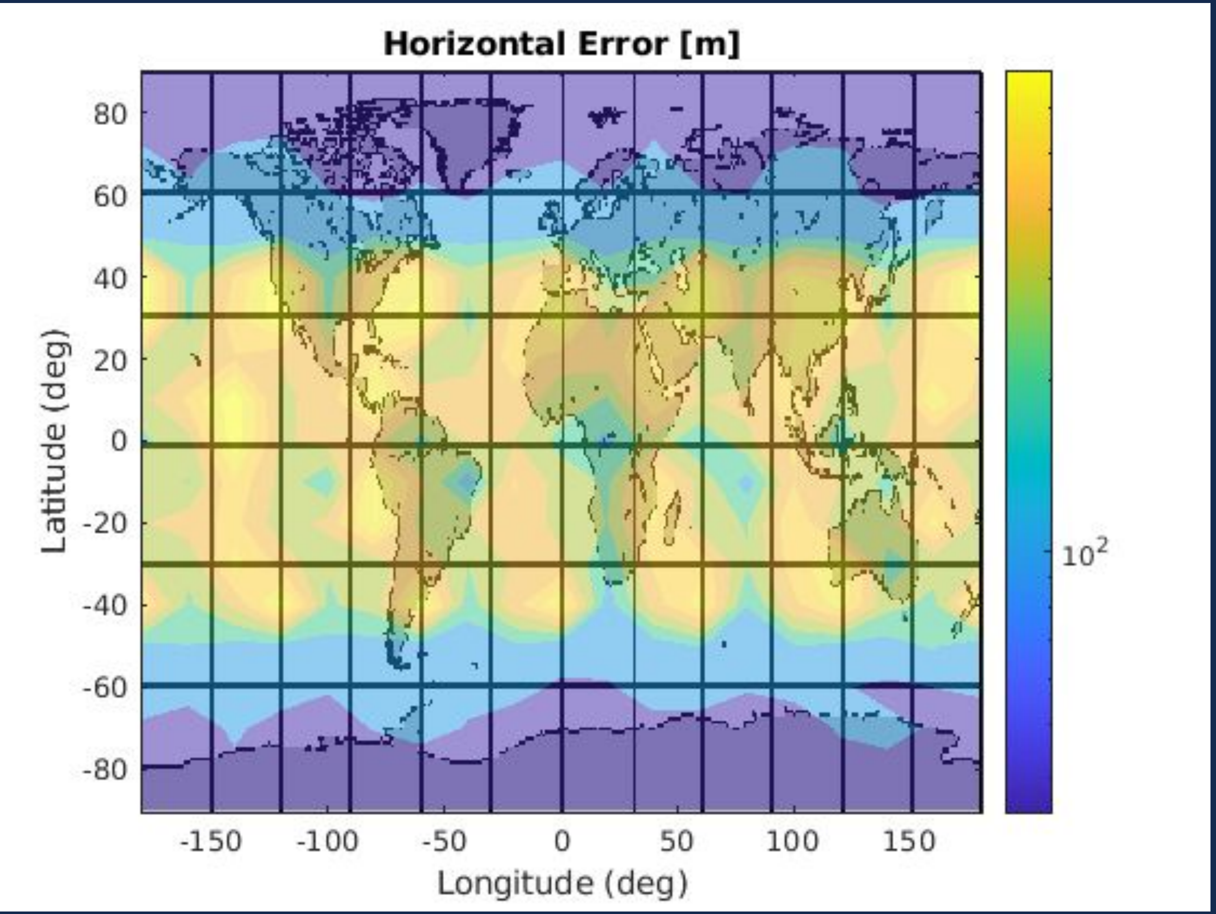
**Constellation Size** : ~50 satellites

**Orbit** : Sun-Synchronous Orbit

**Update Interval** : 15 s

**Frequency** : 161.275 MHz

Monte-Carlo is performed over many orbital scenarios.




Performs best at polar regions because of orbit design.

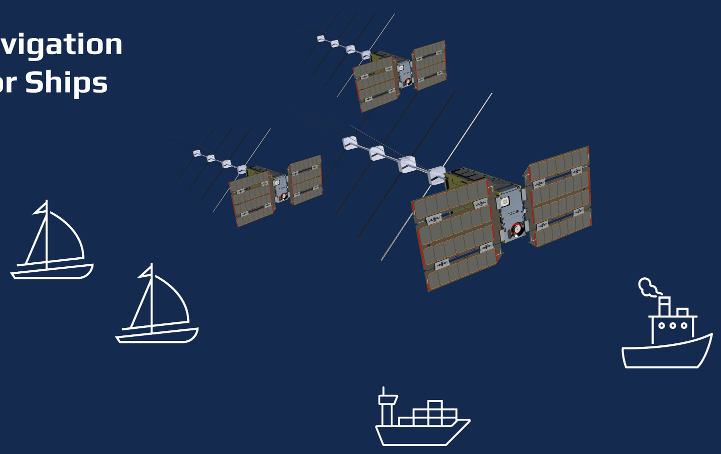
Is this performance sufficient however – need to overcome the ionosphere!

Solutions for PNT

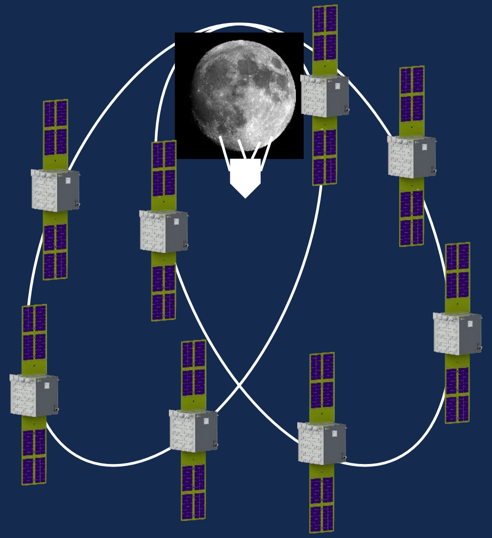
# High-Precision and Critical Applications

## ArkEdge Heritage

**Navigation for Ships**



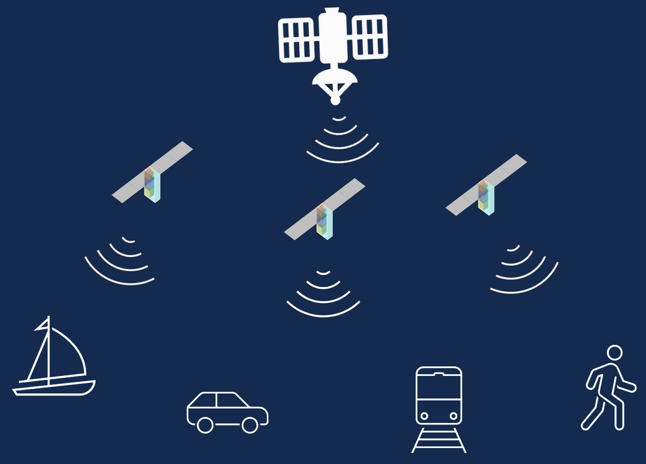
**Navigation for the Moon**



Translating our Systems to Deliver

Service Depends on the…
**Customer**

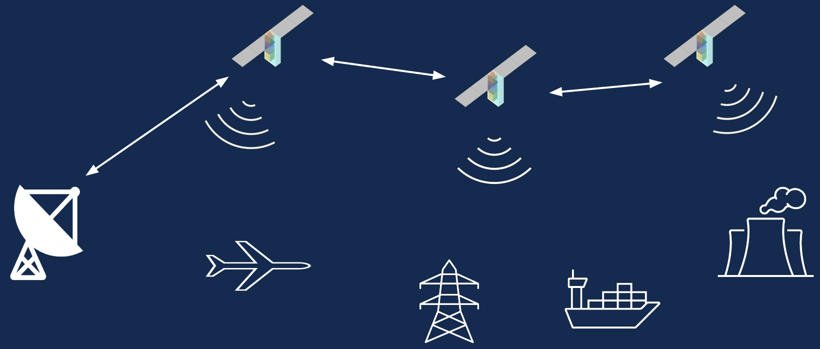
## ArkEdge Future



*Mass Market Applications*

### High-Precision, Augmented PNT

- Higher SNR
- More orbital diversity
- Greater precision



*Critical Applications*

### Alternative PNT

- Greater resilience
- Timing and navigation support

Thank you for listening