Queen Mary
University of London

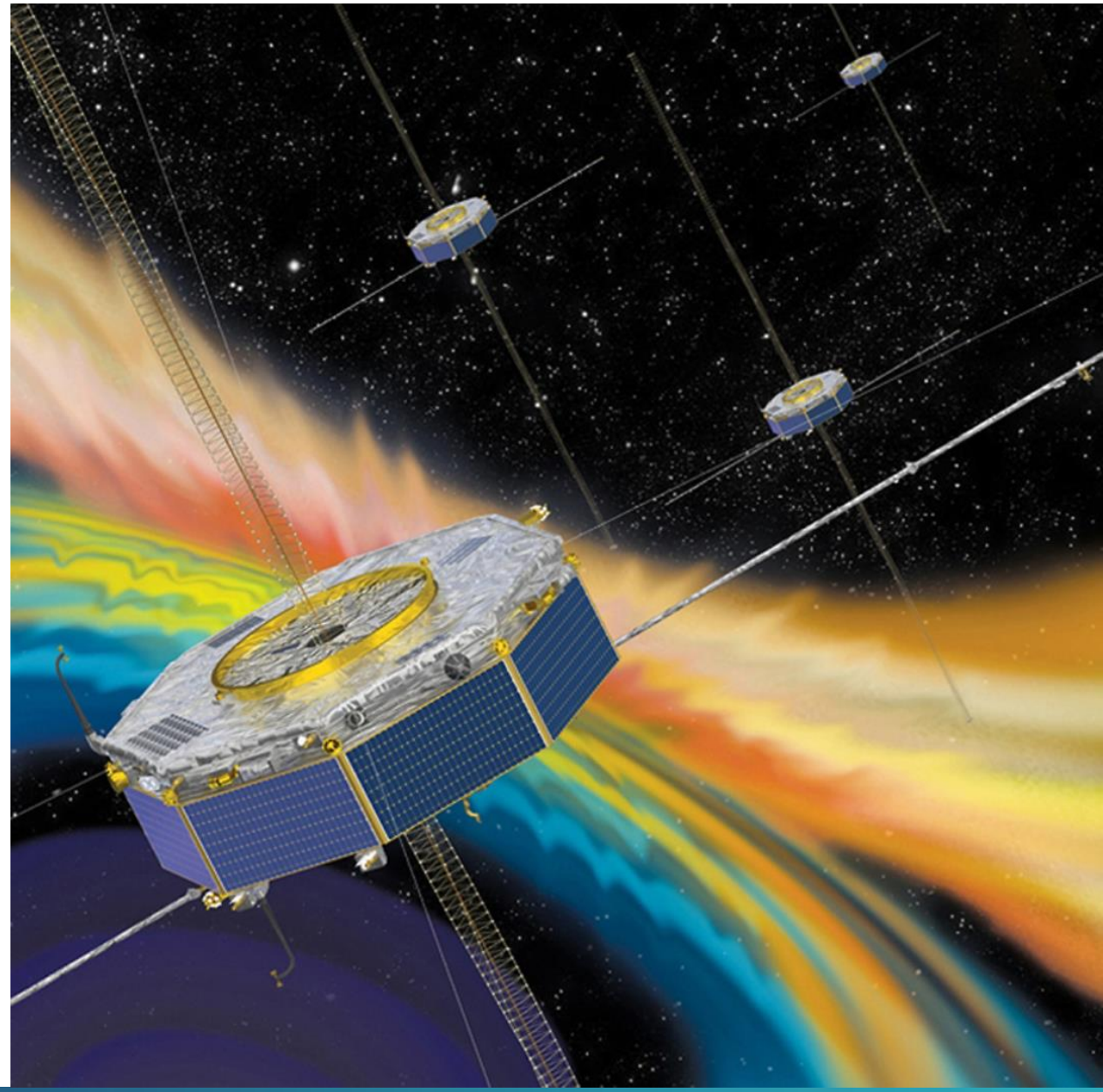
Communications and Materials for Space

Yang Hao, FREng

QinetiQ/Royal Academy of Engineering Research Chair

Introduction

- Space exploration and satellite technology rely on advanced communications and materials.
- In this presentation, we will explore the key aspects of both fields and their critical roles in space missions.

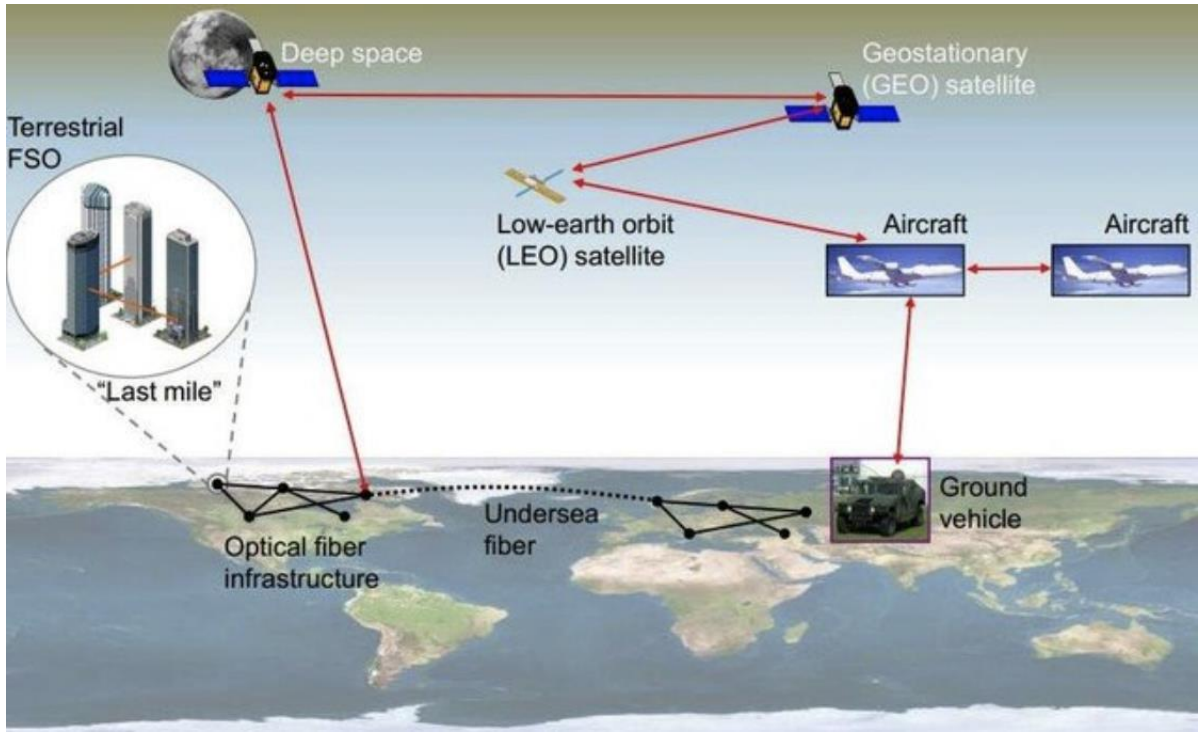


Importance of Space Communications

- Reliable and efficient communication systems are vital for space missions.
- They enable data transmission, remote control, and real-time monitoring.
- Challenges include long distances, signal strength, and signal latency.

Importance of Space Communications

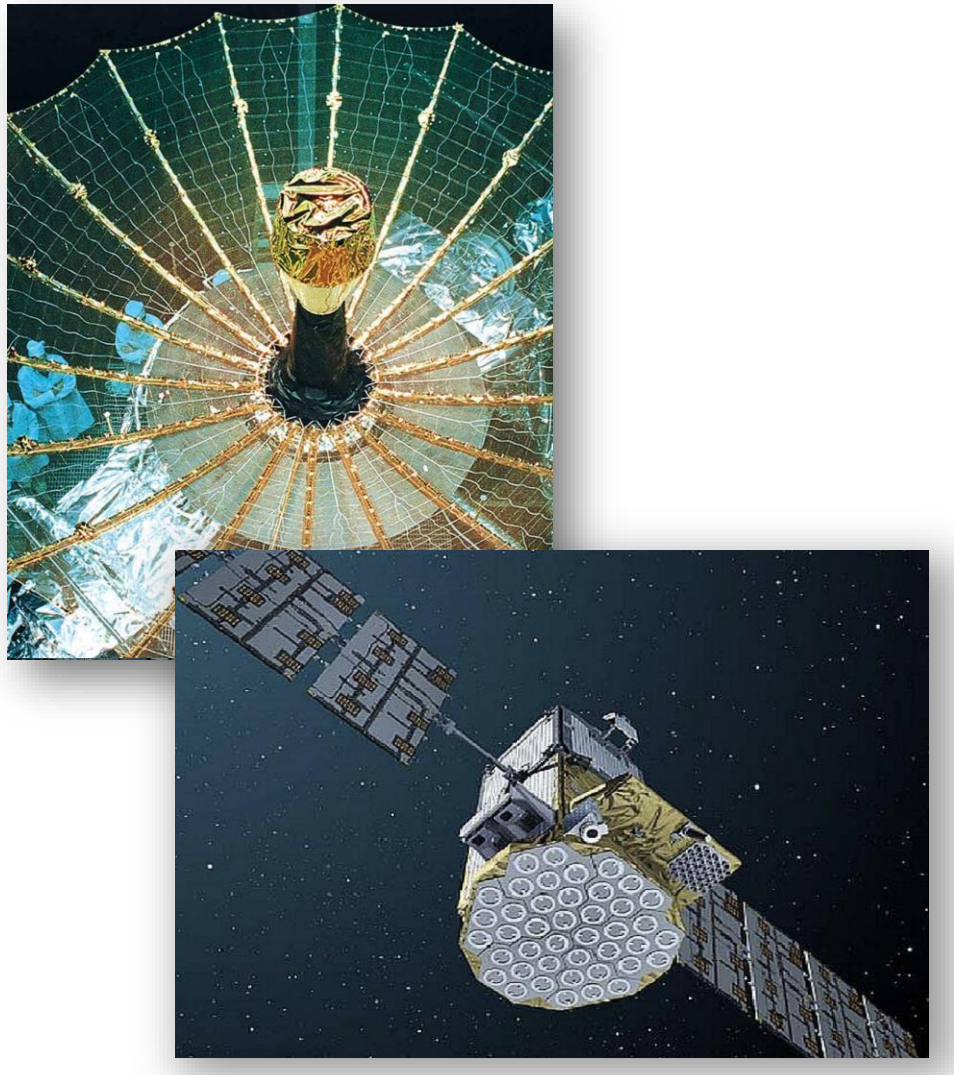
- Earth-to-Satellite: For enhanced data return from satellites.
- Satellite-to-Satellite: Inter-satellite links for constellations or relay missions.
- Deep Space: Improved data rates from distant spacecraft.



POTTOO, S.N., 2020. *DESIGN AND ANALYSIS OF M-ARY MODULATION DRIVEN FREE SPACE OPTICAL TRANSCEIVER USING COHERENT DETECTION AND DSP ALGORITHMS* (Doctoral dissertation, PUNJAB TECHNICAL UNIVERSITY).

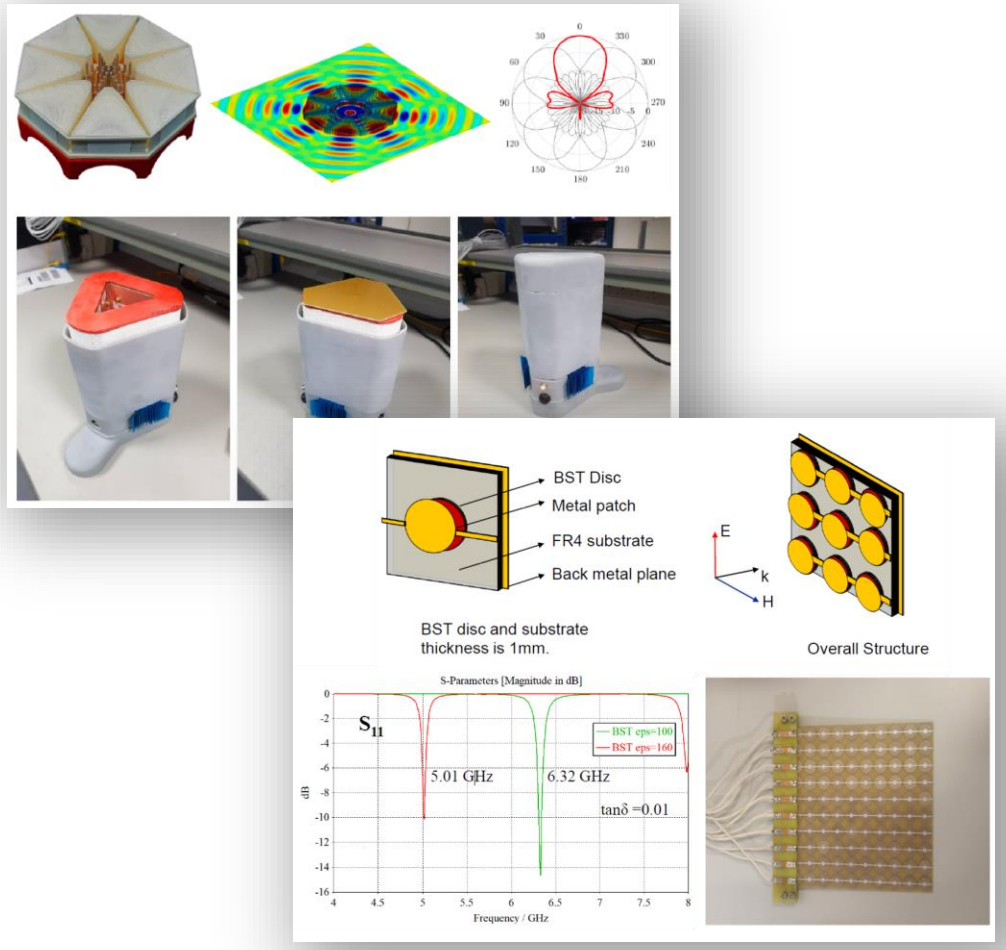
Current limitations: Antenna Technologies

- Traditional dish antennas mechanically steered
- Phased arrays are complicated, consume high power and expensive, especially for wideband operation
- Higher frequency bands like Ka and Q/V are susceptible to rain fade and other atmospheric disturbances.
- Atmospheric conditions, especially clouds, can severely degrade or block optical communications.
- On-board Processing increases the complexity. Heat generation needs to be managed.

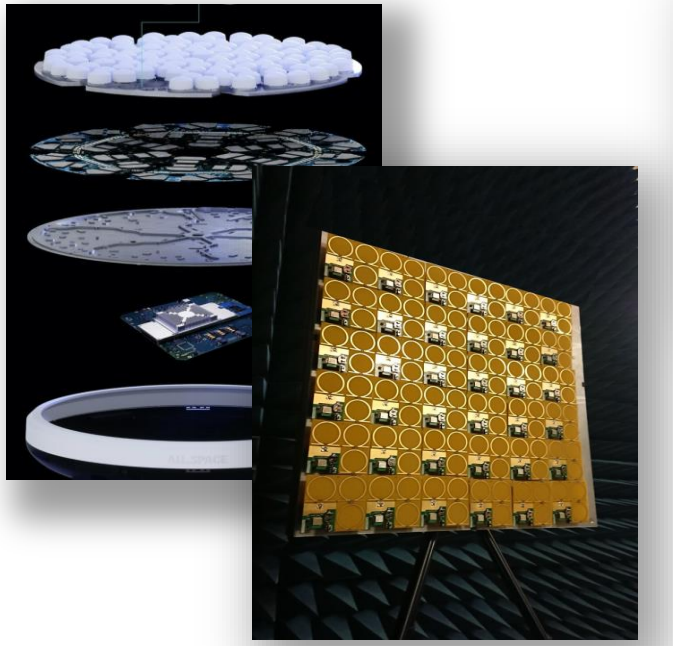


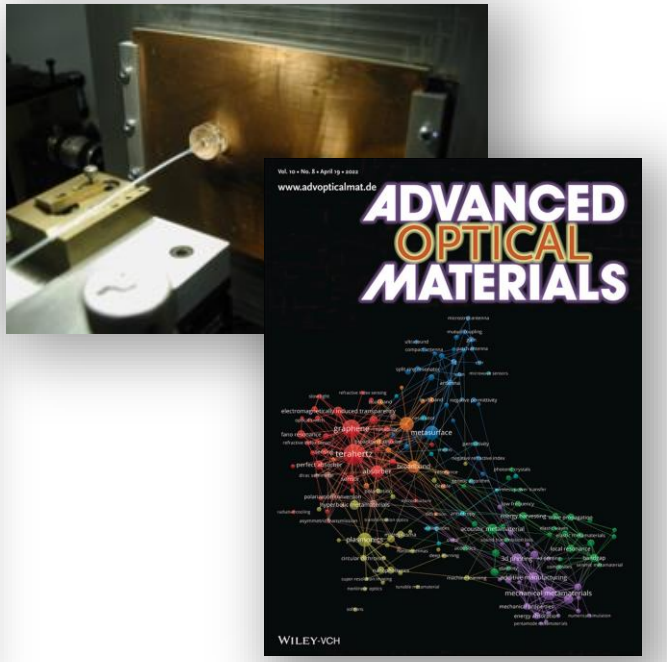
Emerging Technologies:

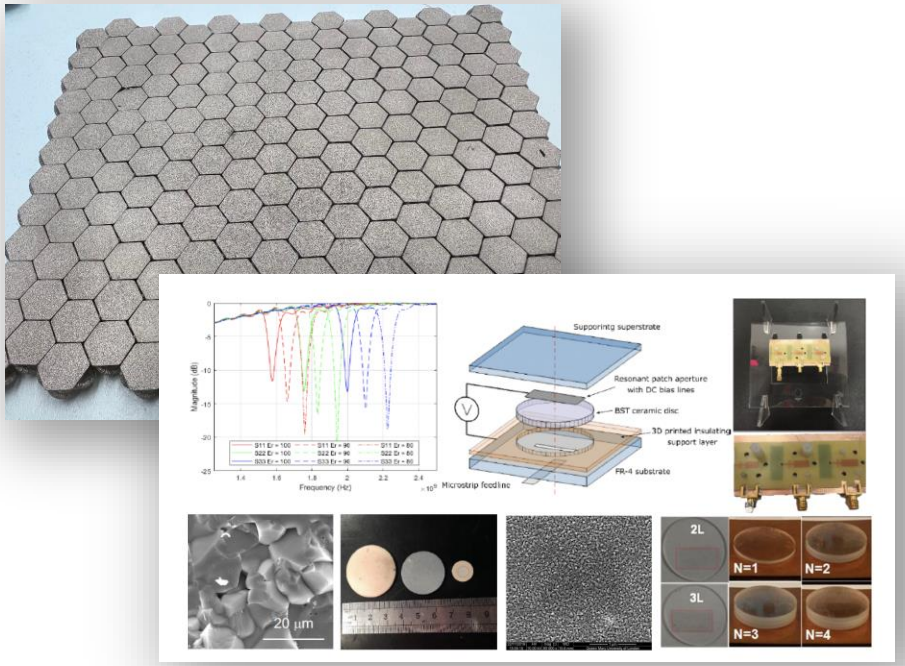
- MIMO (Multiple Input Multiple Output): Managing multiple data streams and antennas increases system complexity.
- Flexible and Reconfigurable Antennas: Some reconfigurable materials may degrade over time, especially in the harsh conditions of space.
- Network Management and Protocols for large constellations can be challenging.
- Technology Maturity: Quantum communication in space is still in its early stages due to environmental factors.
- Advanced AI can require substantial computational resources, lack of updatability.



Space Communications: Future Directions







Integrated Systems

- Combined analogue and digital beam-forming for Ka and Q/V bands for high data rate
- Integration of sensing, communications and on-board Processing through programmable systems

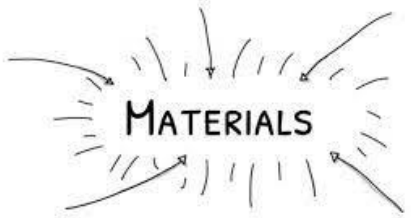
Hybridisation

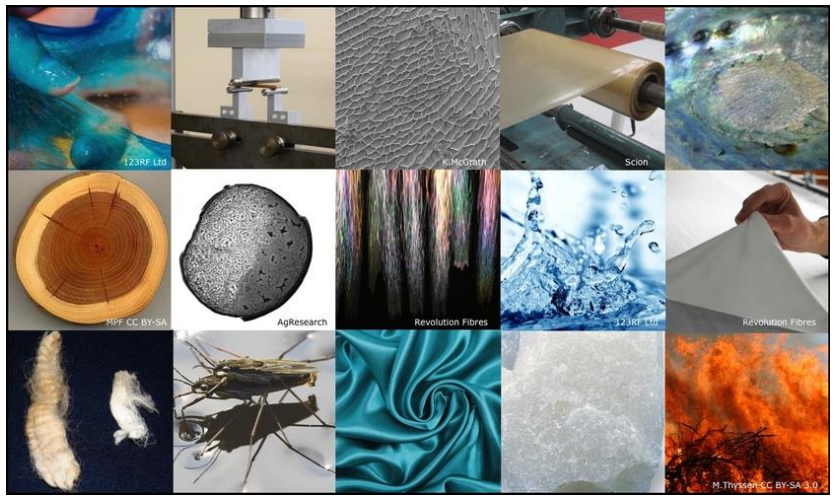
- Hybrid RF and optical systems, depending on conditions and requirements.
- Quantum communications for missions requiring ultra-secure communication links.
- AI-enhanced Systems in autonomous navigation and comms management.

Advanced Materials

- Metamaterials/Metasurfaces, could lead to the development of more compact, efficient, and versatile antennas with capabilities like better frequency tuning or increased sensitivity.

Materials and Geometry

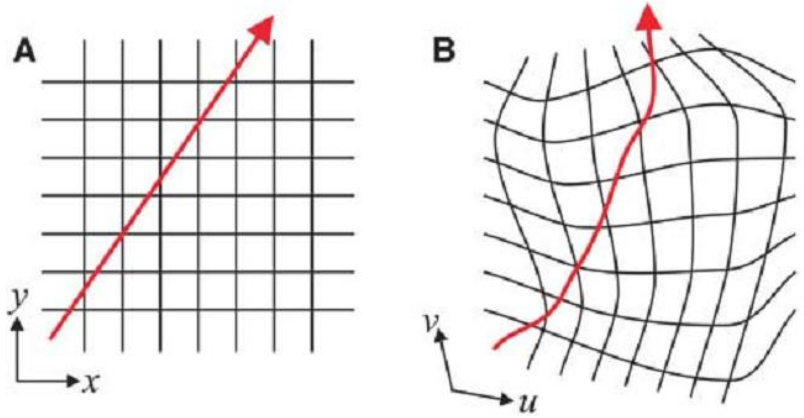


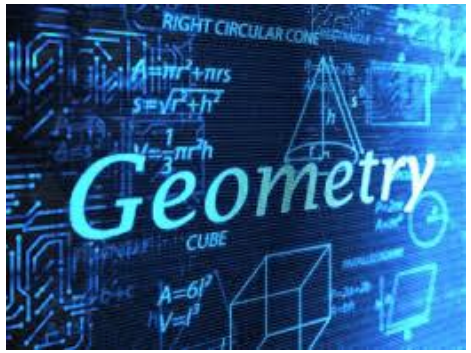


$$\varepsilon'_u = \varepsilon_u \frac{Q_u Q_v Q_w}{Q_u^2},$$

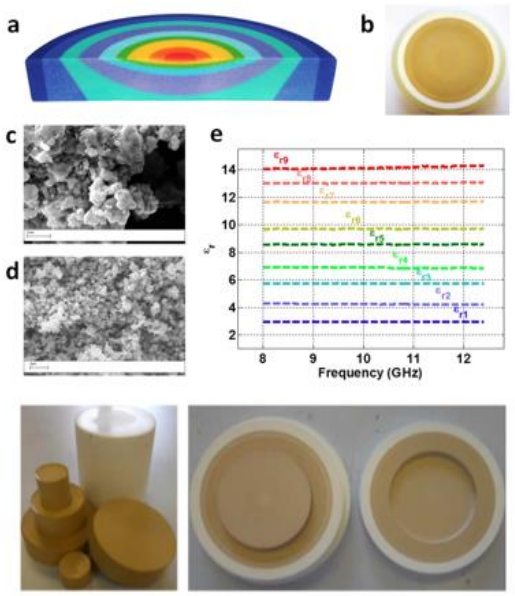
$$\mu'_u = \mu_u \frac{Q_u Q_v Q_w}{Q_u^2}, \text{ etc.}$$

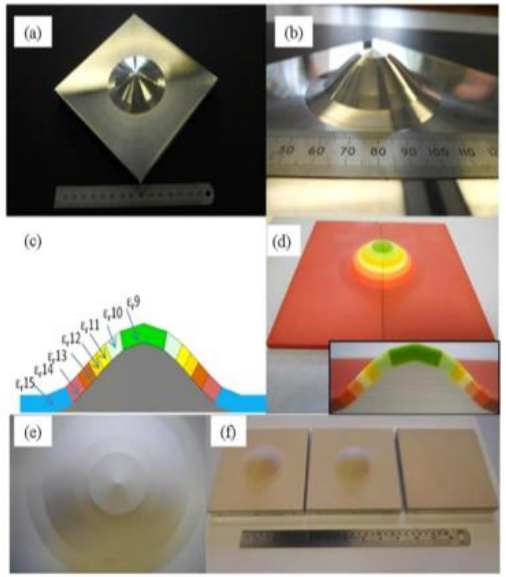
$$E'_u = Q_u E_u,\ H'_u = Q_u H_u, \text{ etc.}$$

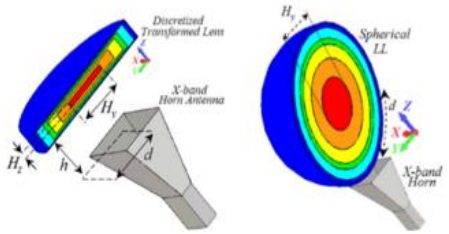


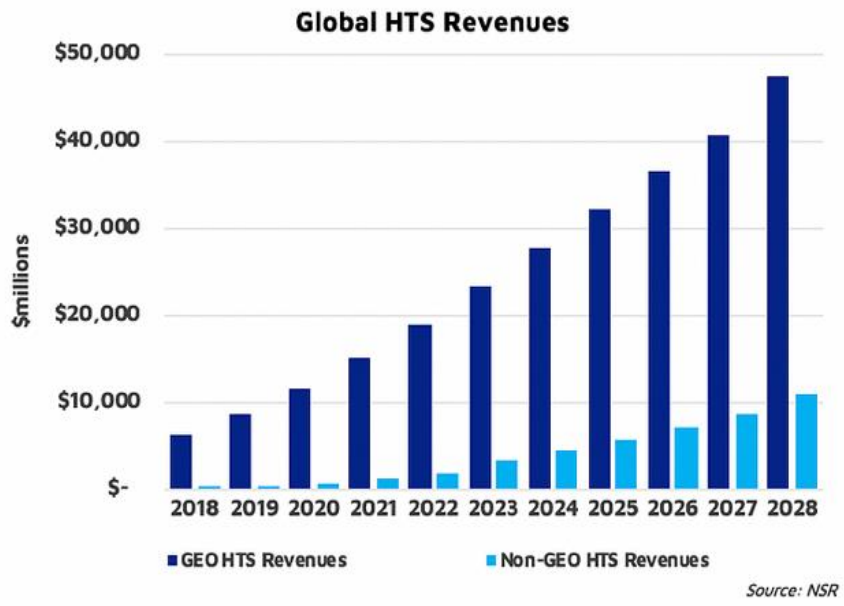


3D Printed Antennas from Metamaterials







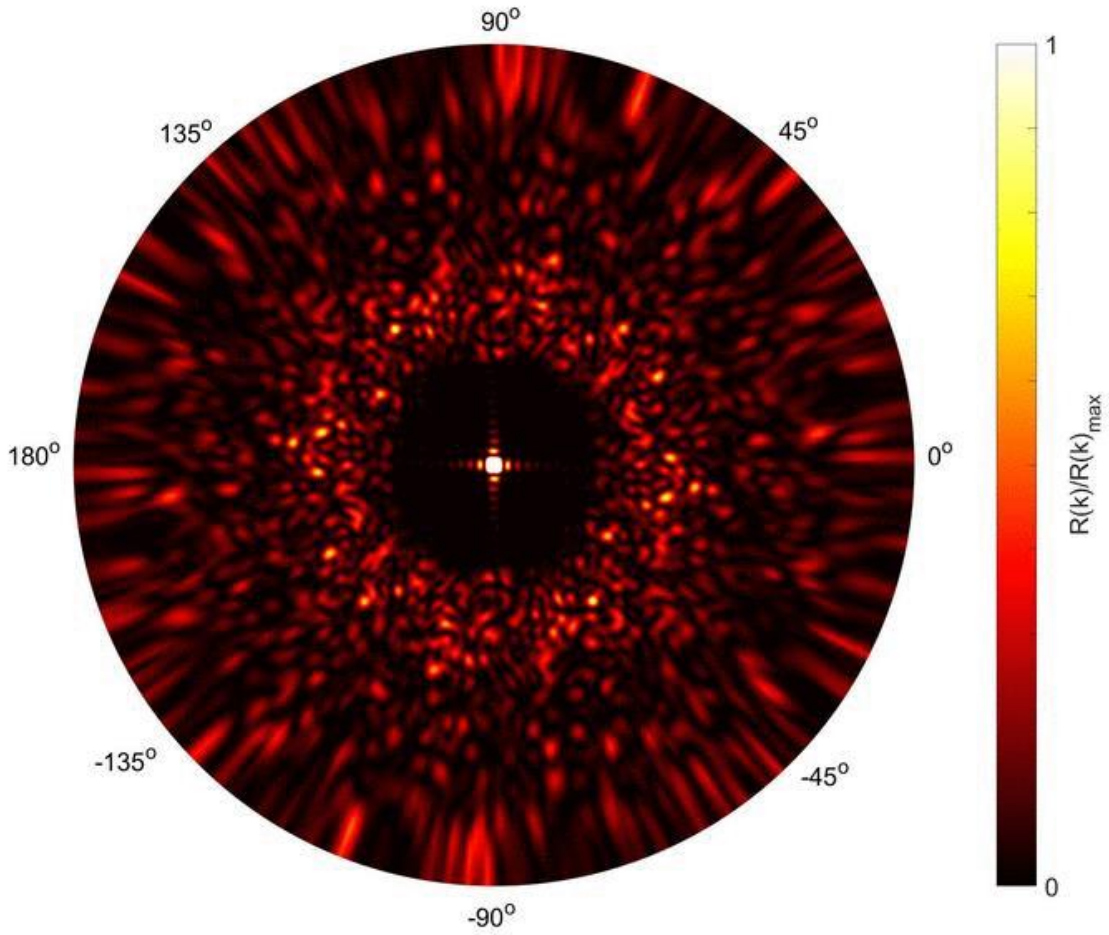


BAE SYSTEMS [dstl] QINETIQ THALES Plextek AGC isotropic systems

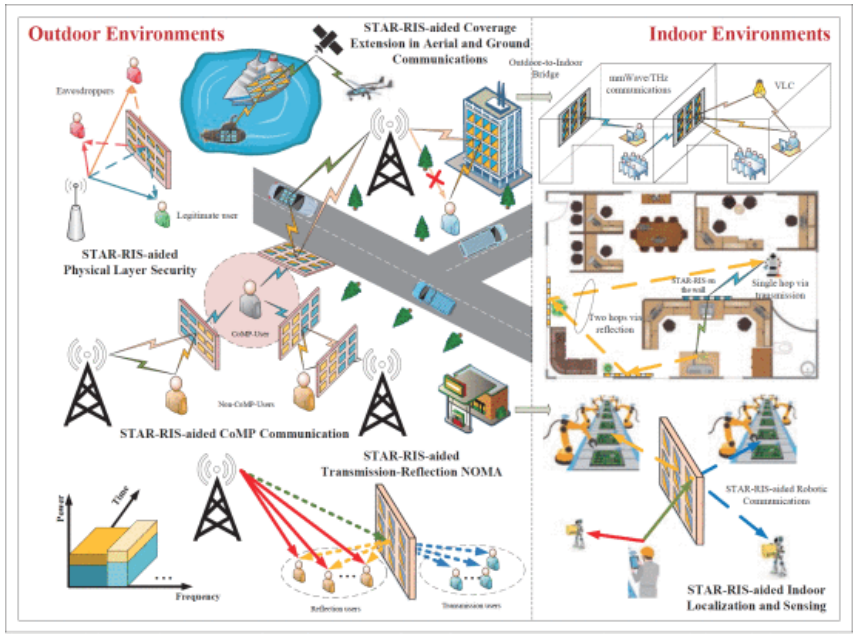
Broadband Phased Arrays for Space

Chickens possess not only the t
color cones that humans do (red
blue) but also an ultra-violet ligh
This allows them to differentiate
and see far more colors and sha
humans can.

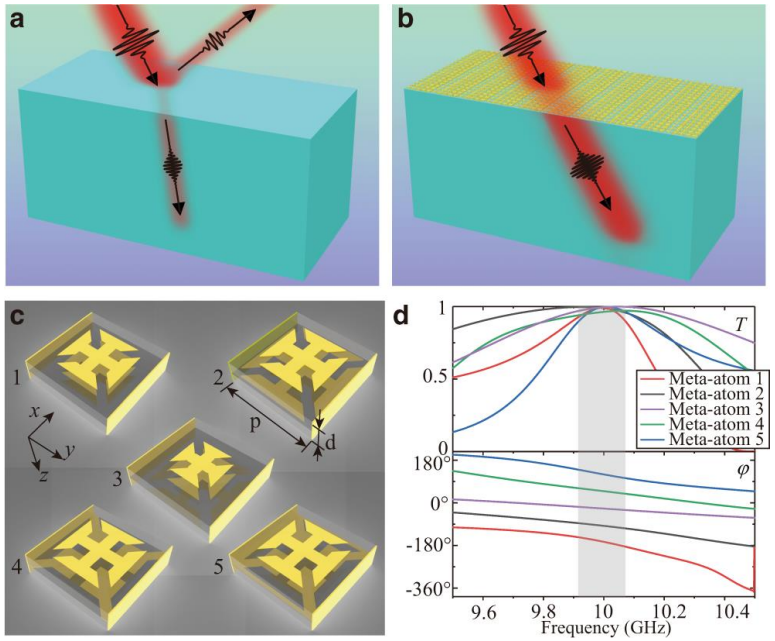
Torquato, Salvatore; Stillinger, Frank
2003). "Local density fluctuations, hyp
and order metrics". Physical Review l
Physical Society. 68: 041113.



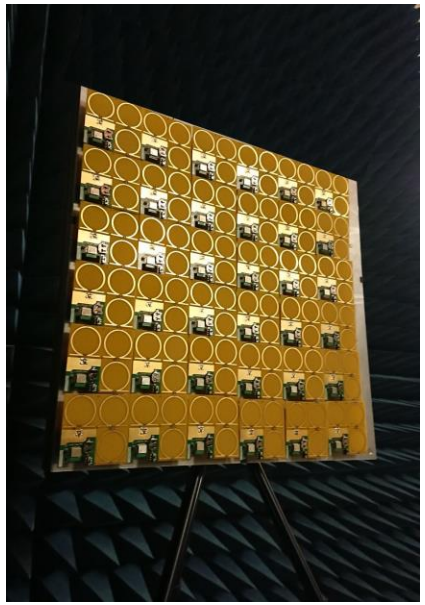
Integration of Sensing, Comms and On-board Processing



Y. Liu, Y. Hao et al., "STAR: Simultaneous Transmission, and Reflection for 360° Coverage by Intelligent Surfaces," in IEEE Wireless Communications vol. 28, no. 6, pp. 102-109, December 2021, doi: 10.1109/MWC.001.2100191.



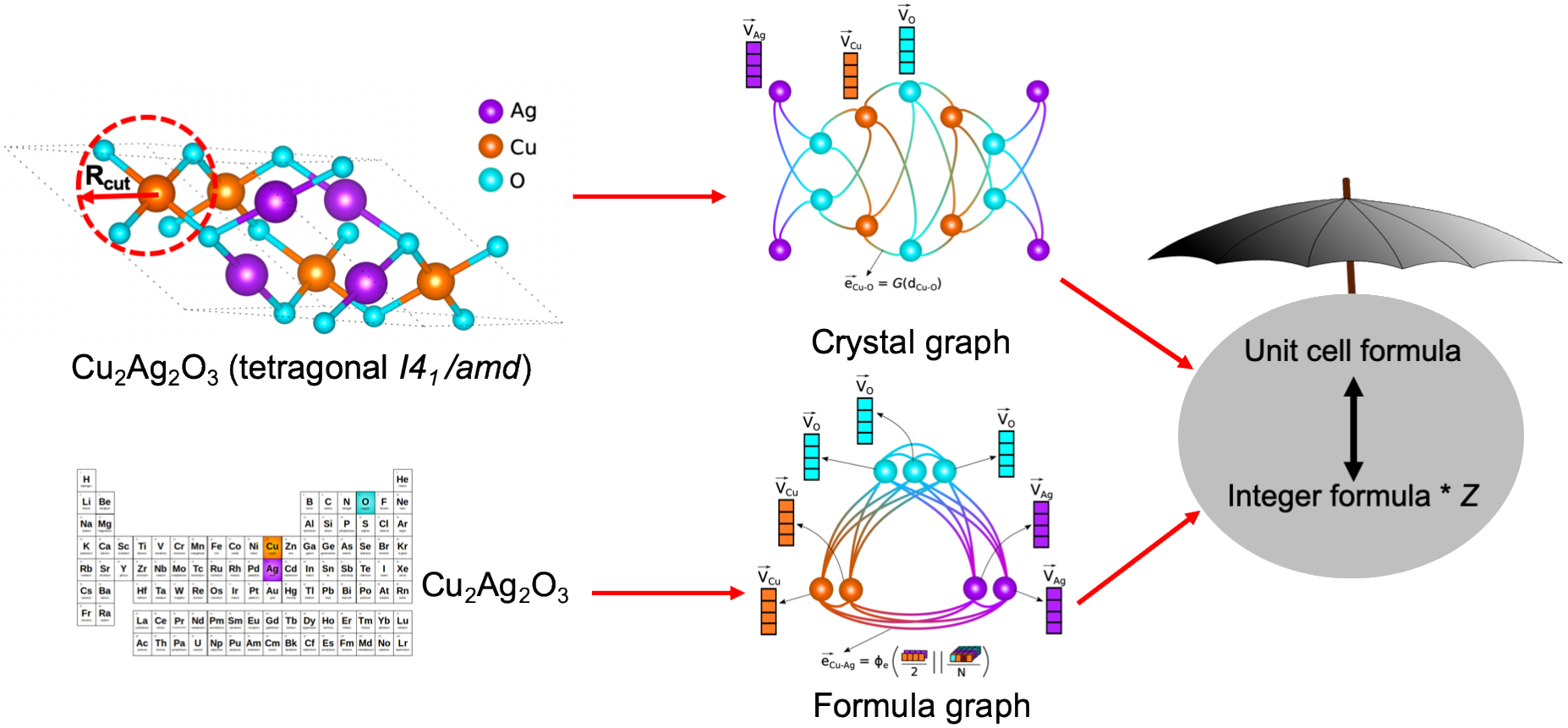
Chu, H., Zhang, H., Zhang, Y. Hao, Y. et al. Invisible surfaces enabled by the coalescence of anti-reflection and wavefront controllability in ultrathin metasurfaces. Nature Communications 12, 4523 (2021).



- Application Programming Interface (API) is able to dynamically reconfigure the meta-atoms
- Active and passive mode can be wirelessly controlled
- Software defined materials/surfaces can "sense", "learn", and "adjust" their behavior by changing themselves and environments.

Machine Learning in Materials Science

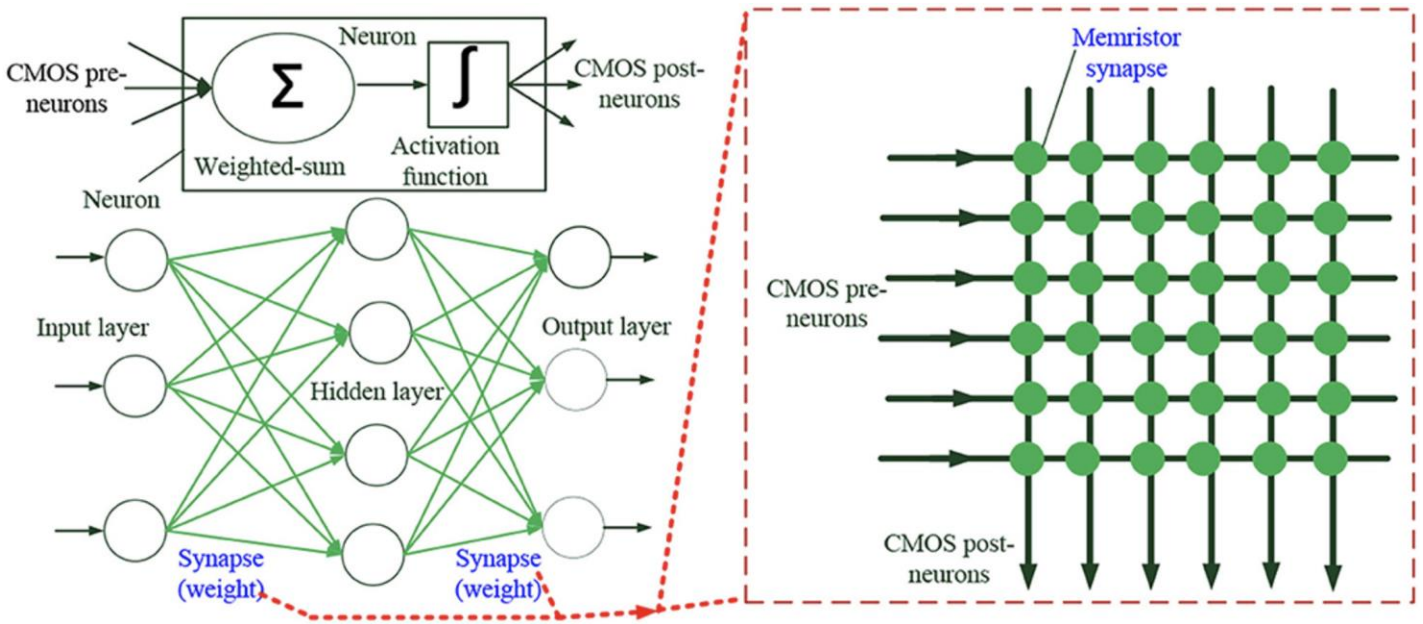
- A new concept of formula graph which unifies stoichiometry-only and structure-based material descriptors
- A self-attention integrated GNN that assimilates a formula graph is further developed to produce material embeddings transferable between the two domains

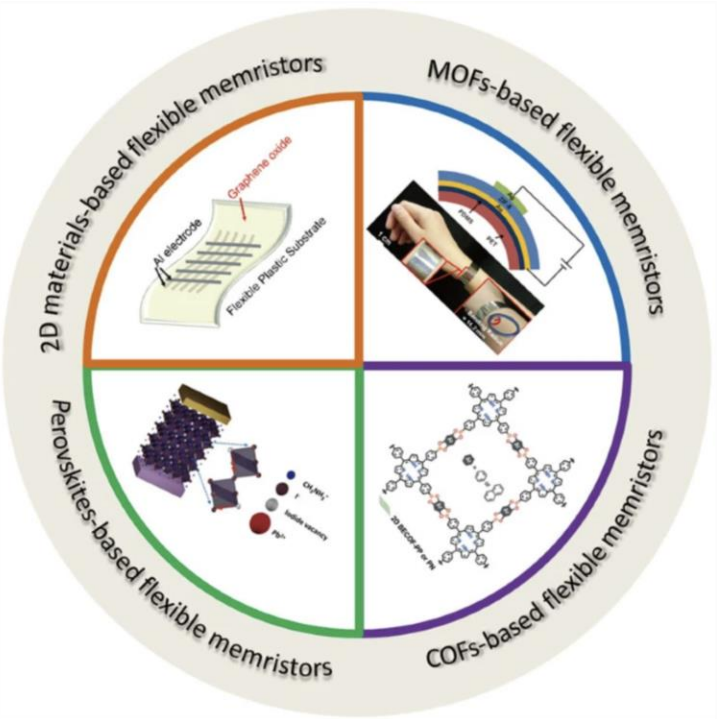


Ihalage, A., Hao, Y. Analogical discovery of disordered perovskite oxides by crystal structure information hidden in unsupervised material fingerprints. *npj Comput Mater* **7,** 75 (2021)

Ihalage, A., Hao, Y., Formula Graph Self-Attention Network for Representation-Domain Independent Materials Discovery. Adv. Sci. 2022, 9, 2200164.

Mimicking the Brain in Space



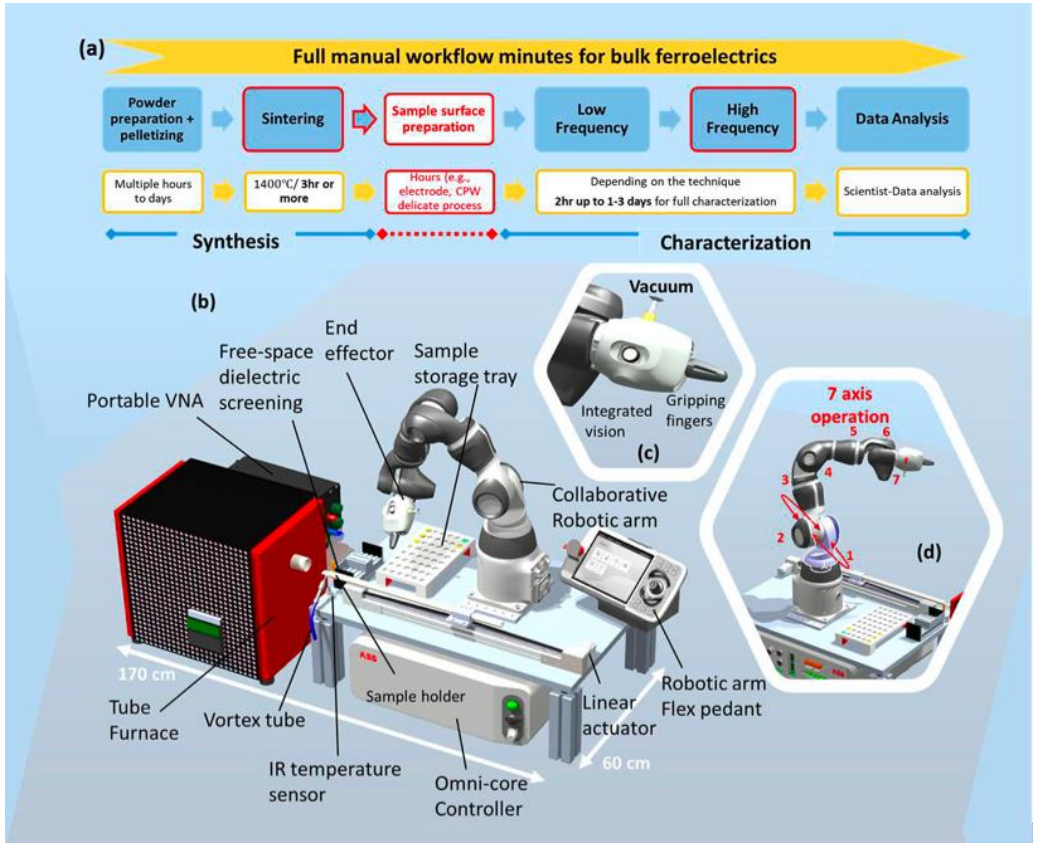


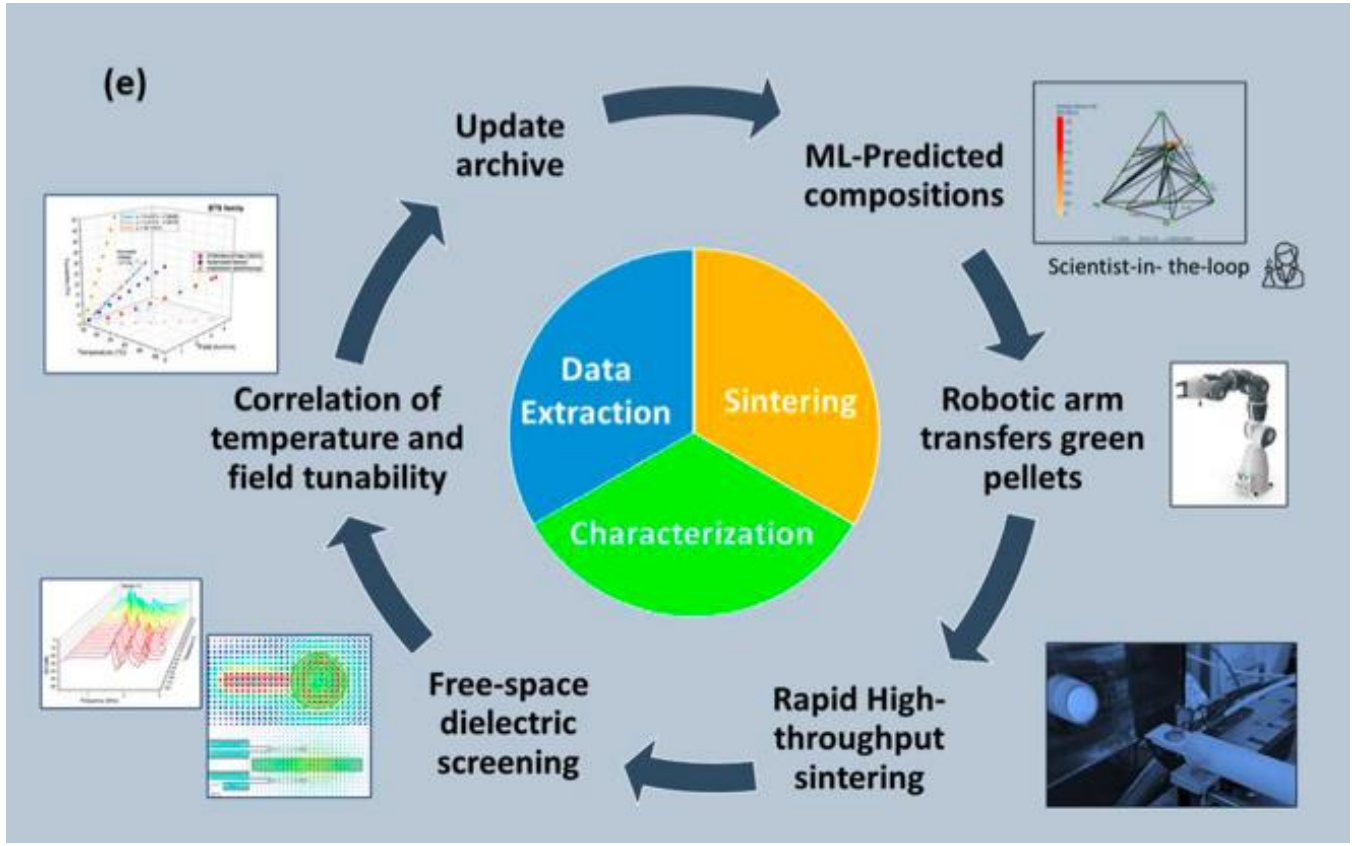
- Emulating neural networks for onboard AI tasks
- Adaptive, on-the-fly learning
- Low-power data processing

Li, Y., Zhang, C., Shi, Z., Ma, C., Wang, J. and Zhang, Q., 2022. Recent advances on crystalline materials-based flexible memristors for data storage and neuromorphic applications. *Science China Materials*, *65*(8), pp.2110-2127.

Xu, W., Wang, J. and Yan, X., 2021. Advances in memristor-based neural networks. Frontiers in Nanotechnology, 3, p.645995.

Towards Self-Driving Laboratory for Materials Discovery





M Omidvar, Y Hao, et al, Towards Self-Driving Laboratory for perovskite ceramics; An automated rapid-sintering and dielectric-analysis platform (ASAP), submitted, 2023

Queen Mary University of London

Summary

- Advancements in space communications and materials continue. They are the foundation of space exploration.
- Quantum communication promises secure, instantaneous data transmission.
- Nanomaterials and metamaterials are being explored for on-site construction in space.
- Memristive computing will enhance satellite and space intelligence.
- AI/ML will enable space material discovery and manufacturing automation.

Hao Lab @QMUL

EPSRC Engineering and Physical Sciences Research Council

[dstl]

Plextek

BAE SYSTEMS

ANIMATE

QINETIQ

THALES

ROYAL ACADEMY OF ENGINEERING

Queen Mary

University of London