PULSAR: Planetary pULSe-tAkeR

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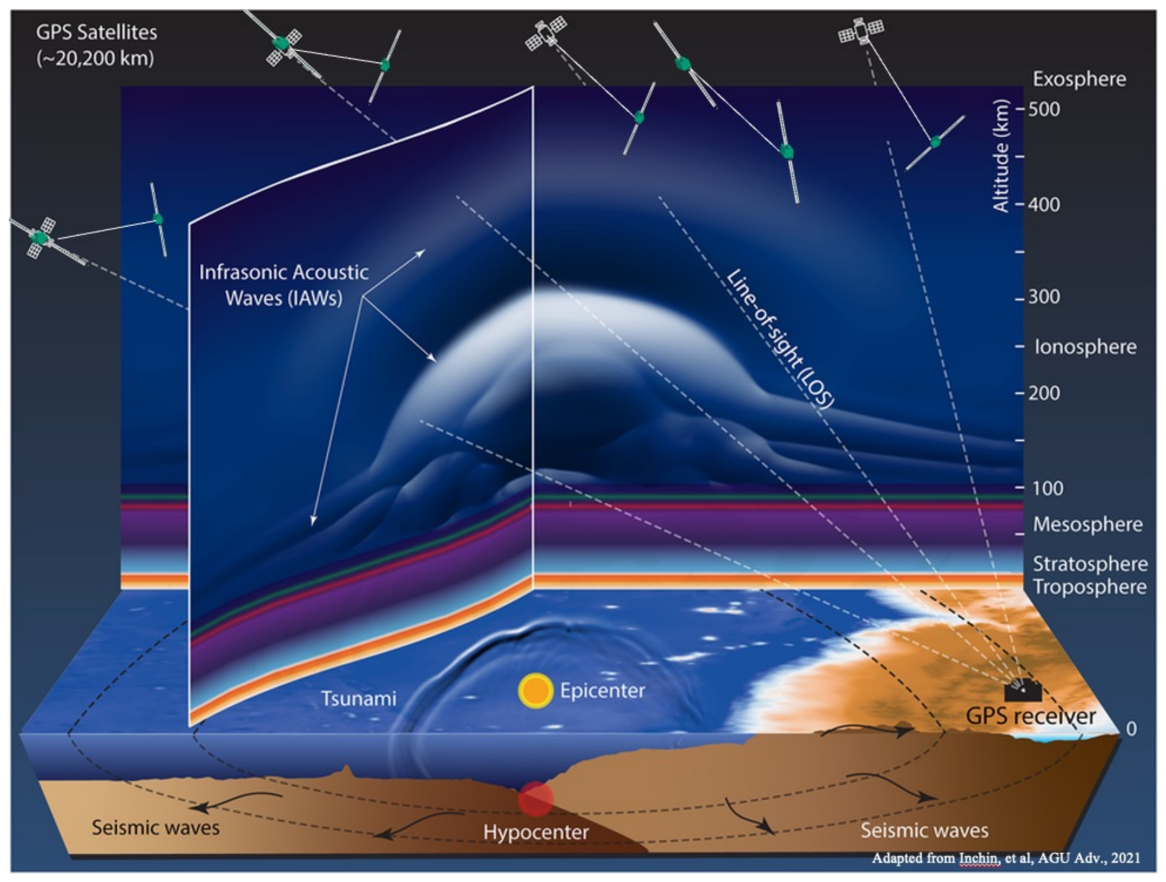
Innovation

- PULSAR leverages the coupling mechanism between the lithosphere, atmosphere, ionosphere, magnetosphere, and the plasmasphere of planets.
- PULSAR operates as a large baseline variable sensitivity detector network that can be reconfigured on demand.
- PULSAR enables new distributed measurements of coupled physical events occurring at different spatial and temporal scales operating as a planet-wide detector.
- ***Like a doctor taking vitals and monitoring the health state of a patient, PULSAR literally "takes the pulse of the planet".***
- Phase I applies PULSAR to the Earth geospace and Phase II and beyond extends PULSAR applicability to other planets with an ionosphere, such as Venus, Mars, Titan, and the Gas Giants.

Impact

- A global, holistic, system to detect planet-wide geophysical activity and sound an alarm with co-seismic detection for potentially catastrophic space weather events, at varying spatial and temporal resolution, does not yet exist.
- It also applies to other planets with an ionosphere, such as Venus, Mars, Titan, and the Gas Giants
- It will open new avenues for low-cost, persistent, and planet-wide detection of global geophysical events

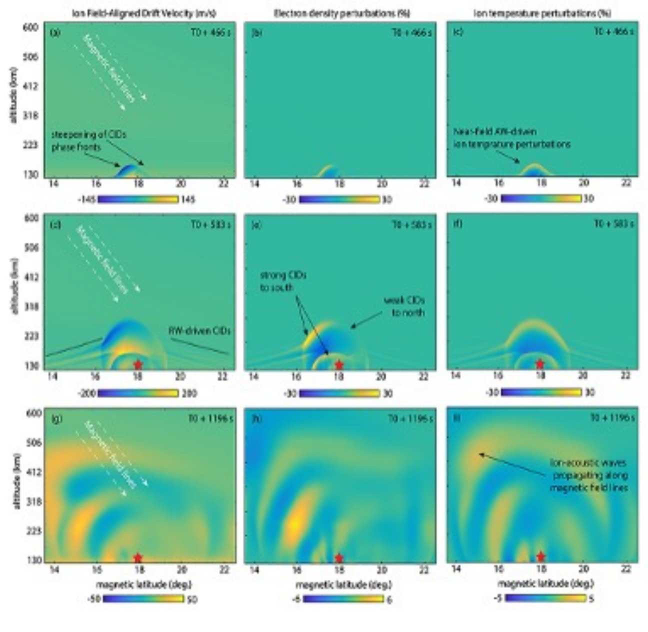


LIAIMC = Lithosphere Atmosphere Ionosphere Magnetosphere Coupling

Image adapted from Inchin, P. A., Snively, J. B., Kaneko, Y., Zettergren, M. D., & Komjathy, A. (2021): Inferring the evolution of a large earthquake from its acoustic impacts on the ionosphere. AGU Advances, 2, e2020AV000260. https://doi.org/10.1029/2020AV000260

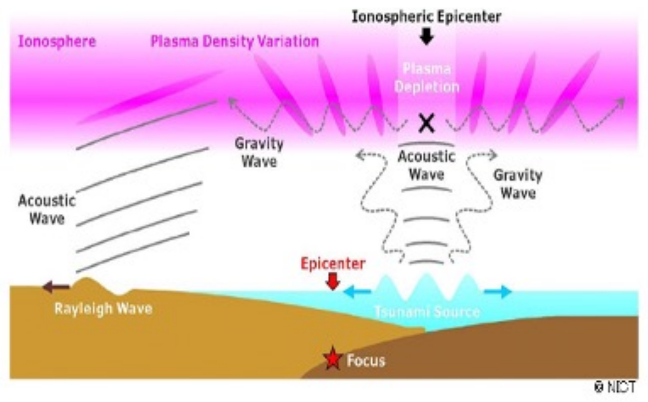
Vision: take vitals" of the Solar System in real-time

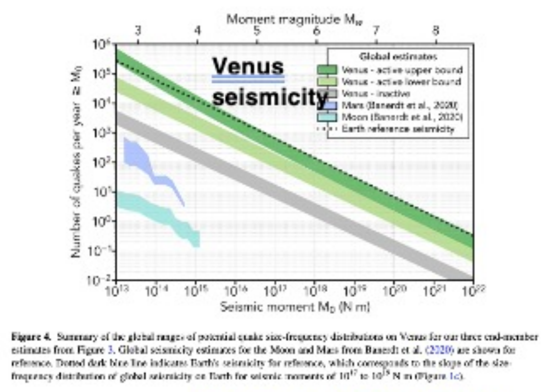
Almost all planets and many moons in the Solar System are geophysically active



Modeling of Ionospheric Responses to Atmospheric Acoustic and Gravity Waves Driven by the 2015 Nepal 7.8 Gorkha Earthquake

JGR Space Physics, Volume: 125, Issue: 4, First published: 03 February 2020, DOI: (10.1029/2019JA027200)





Van Zelst et al: https://doi.org/10.1029/2023JE00804

Occhipinti, G.: *The Seismology of the Planet Mongo: The 2015 Ionospheric Seismology Review*. Chapter 9 in Subduction Dynamics, From Mantle Flow to Mega Disasters, G. Morra et al editors, John Wiley, 2015.

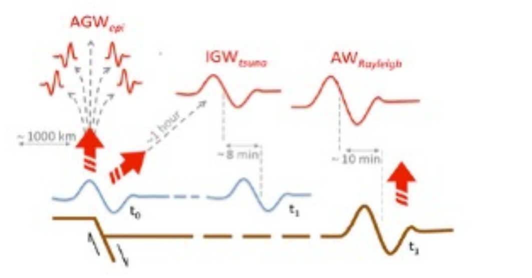
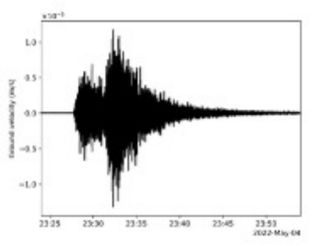


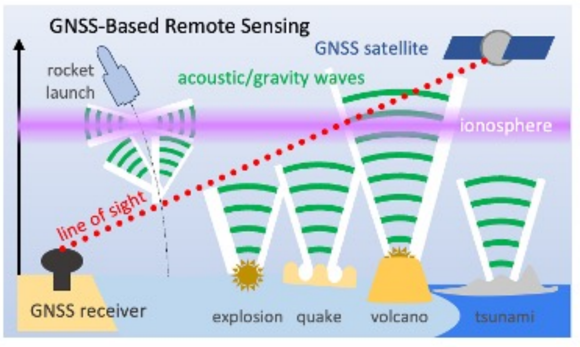
Illustration for coupling mechanisms for solid Earth, ocean, and ionosphere. Epicentral acoustic after 8 minutes (AGW_{epi}), gravity (IGW_{tsuna}) after 1 hour, and Rayleigh (surface or $AW_{Rayleigh}$) wave reaching ionosphere in about 10 minutes, detectable by available GPS receivers. Teleseismic distances can be > 1000 km.



Mars seismicity
This seismogram shows the largest quake ever detected on another planet. Estimated at magnitude 5, this quake was discovered by NASA's InSight lander on May 4, 2022.

https://www.nasa.gov/missions/insight/nasas-insight-records-monster-quake-on-mars/

Much work is being done in our geospace



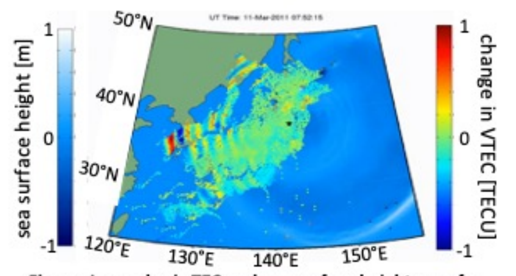
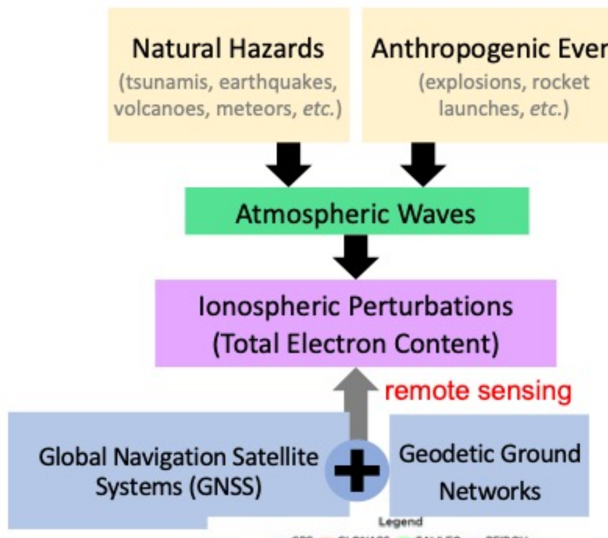
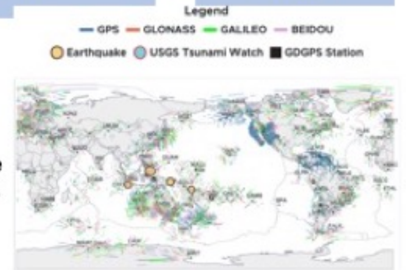


Figure: Ionospheric TEC and sea surface height map for the 2011 Tōhoku-Oki event (Galvan et al., 2012).



NASA + GDGPS + IGS Global Networks:
500+ Real-Time High-Rate Sites

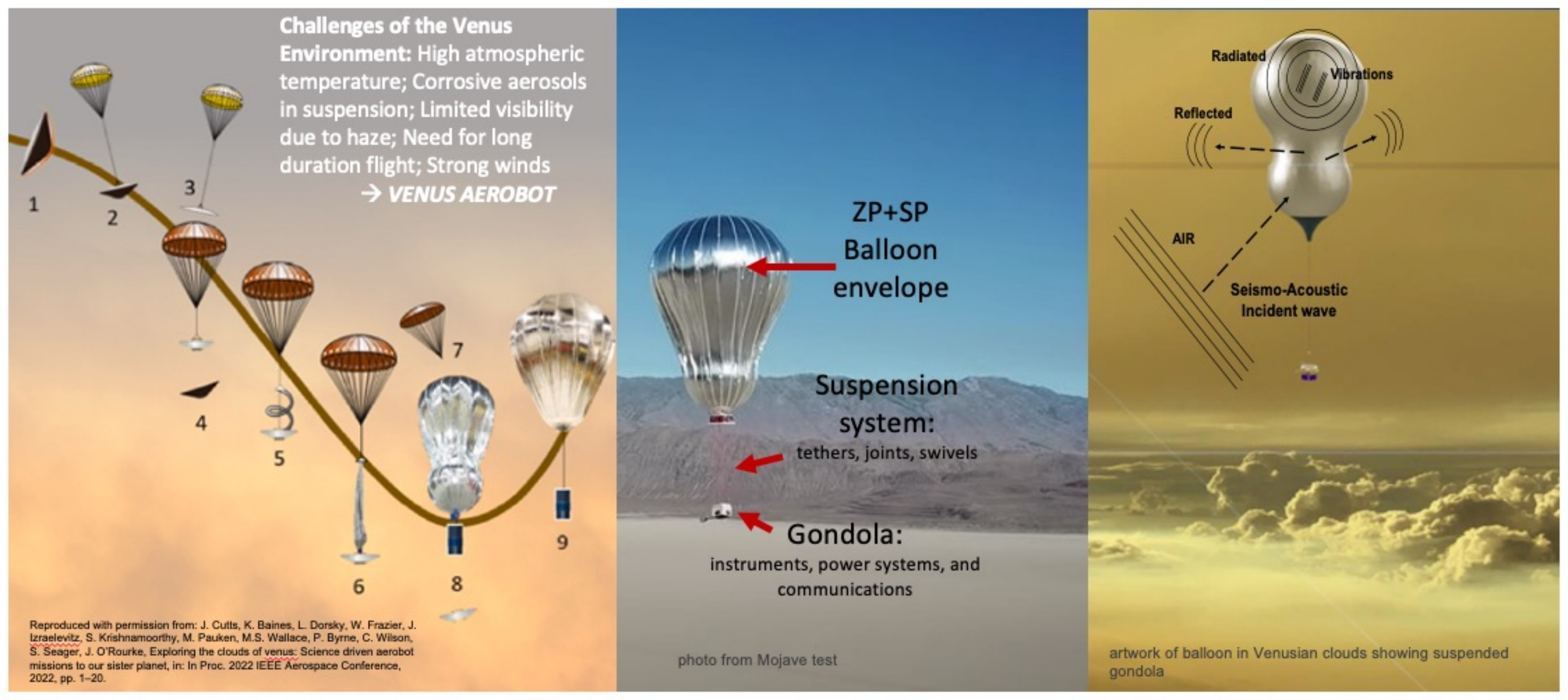


https://guardian.jpl.nasa.gov
(GNSS-based Upper Atmospheric Realtime Disaster Information and Alert Network)

- GUARDIAN is a near-real-time (NRT) ionospheric monitoring software for natural hazards warning.
- GUARDIAN uses total electronic content (TEC) time series to allow users to explore ionospheric TEC perturbations due to natural and anthropogenic events on Earth and characterize potential natural hazards.

Martire, L., Krishnamoorthy, S., Vergados, P., Romans, L. J., Szilágyi, B., Meng, X., Anderson, J. L., Komjáthy, A., Bar-Sever, Y. E. (2023) The GUARDIAN system - a GNSS upper atmospheric real-time disaster information and alert network, GPS Solutions 27(32).

...and for Venus LIAIMC exploration with Aerobots

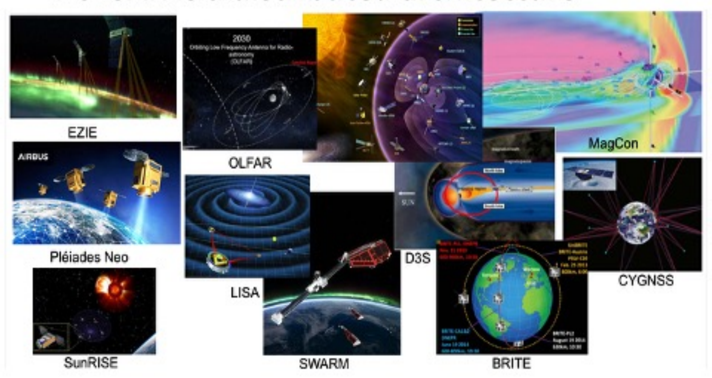


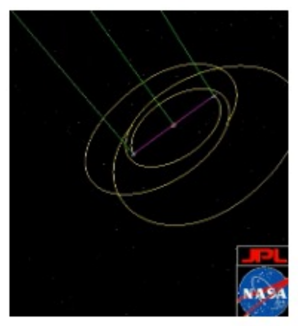
Graphic of deployment sequence at Venus (left), photo from Mojave test (center), and artwork of balloon in Venusian clouds showing suspended gondola (right)

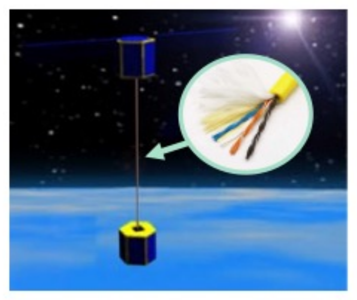
- Our work on modeling of planetary Aerobots, towed atmospheric probes, tethered systems: Quadrelli, et al, JCGD2004, IAC 2024, IPPW23, IPPW24, IPPW25
- Our work on Venus Aerobot testing: Izraelevitz, et al, Acta Astronautica 2024, 2025
- Our work on infrasound system design: Sherrit, et al: SPIE2025

How does PULSAR work

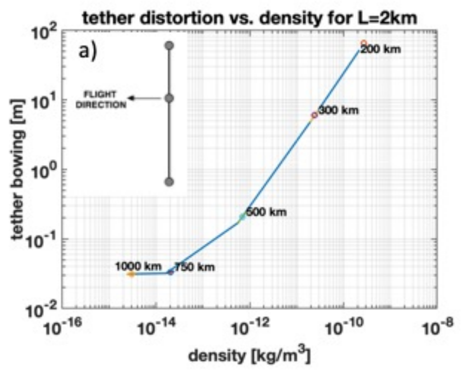
PULSAR is a distributed architecture







https://doi.org/10.1007/BF03546301



Example of 2 km long PULSAR tether bowing as a function of low-frequency induced density variations at different altitudes

- Instrument miniaturization and systems integration and multifunctionality are enablers
- If sufficient data can be returned and large baselines can be implemented, new scientific observations are possible
- Instrument resolution (strength, direction) is dictated by spatial sampling
- High sensitivity in the frequency band of interest is dictated by temporal sampling
- Many nodes leads to graceful degradation.
- Tethered constellations, lead to variable and very large detector sizes (even 1000's of km), at a fraction of the mass
  → the longer the tether, the more sensitive the detector, becoming a low frequency acoustic gradiometer

- The TEC changes are related to the pressure and density changes generated by the surface wave as they propagate upwards.
- For a surface displacement at the centimeter level, generated by events >Mag7, the pressure at H= 300 km altitude (F-layer of ionosphere) may be detected resulting in TEC changes at about 0.5 TEC units.
- This corresponds to about 8 cm range changes between the satellite and receivers, which is within the capability of existing radio-frequency metrology.
- Ionospheric signals from GNSS measurements can routinely discern the signal from the constant background noise level at approx. 0.05 TEC by using time of arrival, coherence, wave amplitude and period.

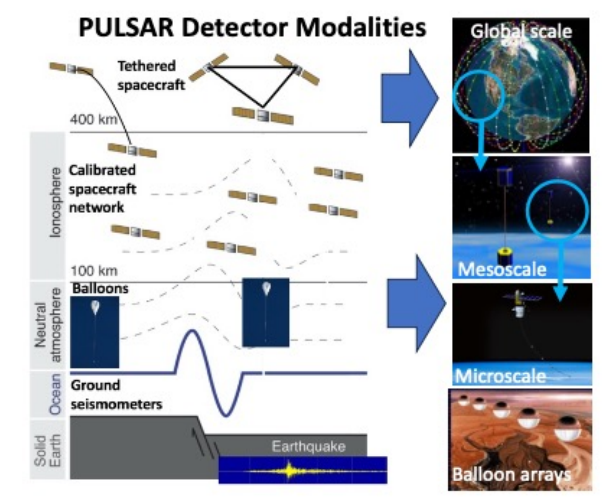
Phase I Study

***Phase I** studies the feasibility of PULSAR to Earth, limiting the study to a seismic lithospheric trigger event of the geospace as a pilot example.*

***Phase II**: Address challenges of non-terrestrial applications:*

- *No GNSS*
- *Planetary LIAMC phenomena still largely unexplored*
- *Missions are infrequent*
- *Long-duration, distant, limited communication/data*
- *System resources are very limited*
- *No opportunity for maintenance*

PULSAR Detector Modalities



Science Goal	Observables	Instrument	Data Product
Orbital constellation to study near-Earth EM, plasma, and particle environment	*Wave phenomena, ducting, and generation mechanisms of ULF, VLF, HF emissions.*	*Main ULF, ELF, VLF antenna options: three orthogonal dipoles, two V-shaped dipoles, two crossed dipoles. Mass-spectrometer, inlet direction along the satellite velocity vector. Magnetometer. Langmuir probe. Energetic particle detector.*	*Waveform data (time series) of electric and magnetic fields, ULF/VLF/HF emission characteristics*
A planetary seismology mission using one or more balloons	*Seismic event magnitude and location*	*An array of micro barometers can be deployed below a balloon with a tether to detect seismic infrasound in range 1-10 Hz at 0.01 – 1 Pa*	*Vector infrasound time series of pressure levels at multiple balloon receivers*

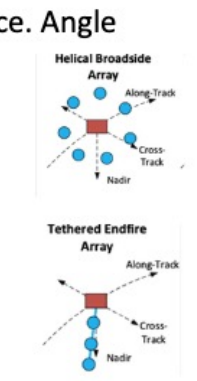
Science traceability matrix

Global: Reconfigurability as multi-objective optimization problem, Formation flight, GN&C, Cent./Decent. ops, Up-down link, HPC, Data storage

Mesoscale: Electrodynamic (bare) tethers: As it flies over the epicentral region, it senses peaks up to about $-10\ V$, $0.01A$.

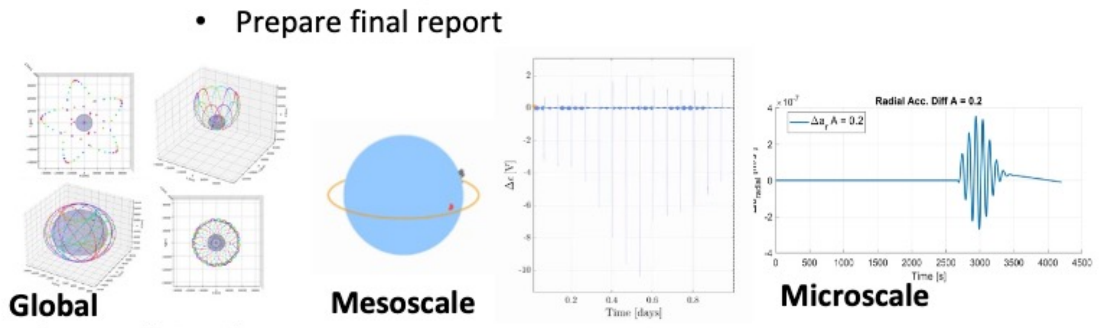
Microscale: Sensitivity analysis to detect impulsive density disturbance. Angle range: micro-degrees; Tether tension: nano-strain sensitivity; Radial acceleration: micro-g's → GRACE-level IMU

Distributed phased arrays: End-fire vs. formation flying arrays Efficiency and bandwidth of electrically small antennas at ELF/ULF/VLF frequency bands. Phased array coherence. Timing and signal synchronization. Polarization



Next steps:

- Update Science Traceability Matrix
- Continue analyses
- Prepare final report



Global
Flower constellation with N=77, H=1400 km, e=0.615

Mesoscale
10km long bare electrodynamic tether at 500 km sensing current/voltage at cathode

Microscale
10km long tether at 500 km resonating with density disturbance

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California
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