Astronomy and Astrophysics Advisory Committee
September 28, 2021

Electromagnetic Spectrum Management Update

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Jonathan Williams, Program Officer
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NSF's Core ESM Office

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AAAS Science and Technology Policy Fellow

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Senior Advisor for Facilities

Mission

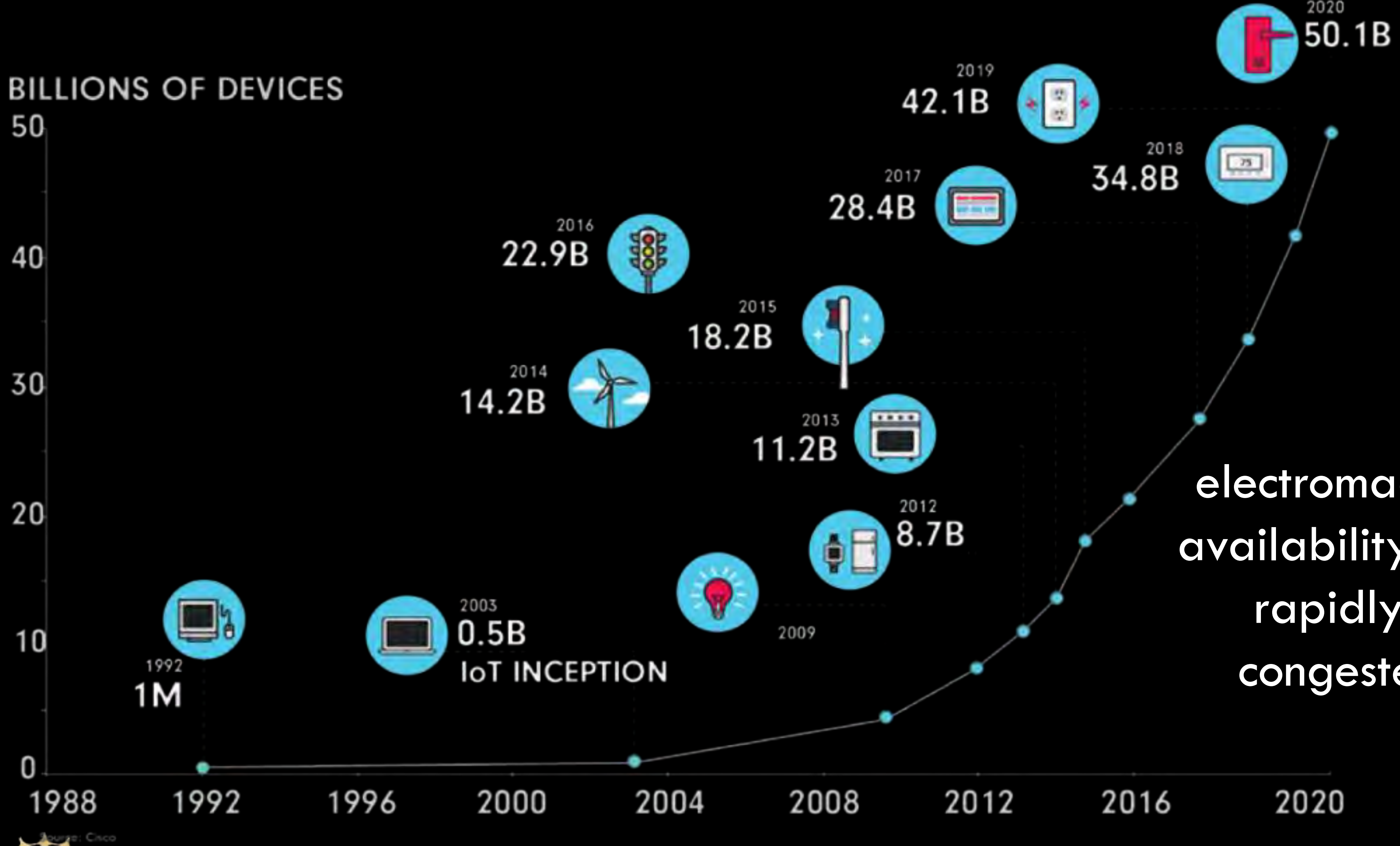
- The Astronomical Sciences Division supports:
  - Forefront research in ground-based astronomy; to help ensure the scientific excellence of the U.S. astronomical community;
  - Provides access to world-class Research Facilities through merit review;
  - Supports development of New Instrumentation and next-generation facilities; and
  - Encourages broad understanding of the astronomical sciences by a Diverse Population of scientists, policy makers, educators, and the public at large.

What do all of these have in common?

Access to the Electromagnetic Spectrum

- Broadband internet and reliable mobile access is ***critical for equity***
  - GSMA reports ~66% of the world's population has a mobile
  - Internet/social media – a great avenue for collaboration, sharing science broadly, participation in discovery
- Increase in usage of wireless devices presents a challenge to sensitive astronomical research which requires ***dark and quiet skies***
  - radio observations
  - optical/infrared

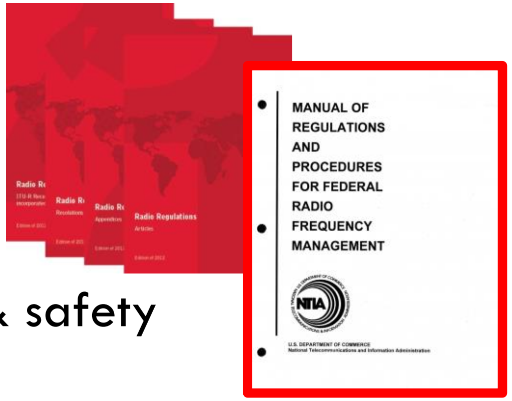
Credit: Christina S. Murrey, College of Education, University of Texas at Austin

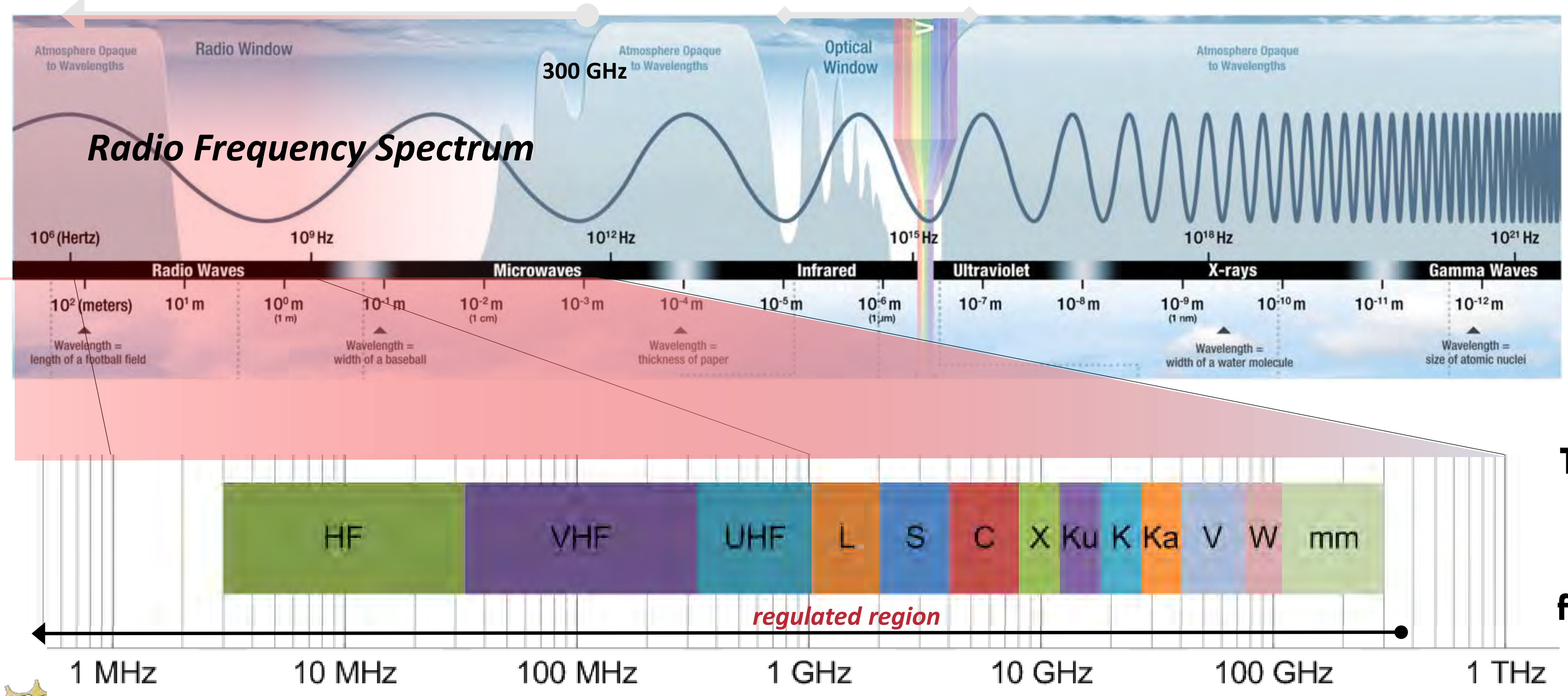


Demands for electromagnetic spectrum availability are increasing rapidly in an already-congested environment

Scientists and Engineers use the entire spectrum of which only 8.3 kHz to 275 GHz is regulated:

- ***Radio Frequency Spectrum*:** frequency region of the EM Spectrum that is managed via international and national laws and regulations
- **Limited regulations in the near-infrared and optical region** (e.g., laser coordination & safety standards)





Terminology used with portions of the radio frequency domain

Slide Credit: NASA

Image Credit: www.ntia.doc.gov

Science applications share the spectrum with many other users

GPS

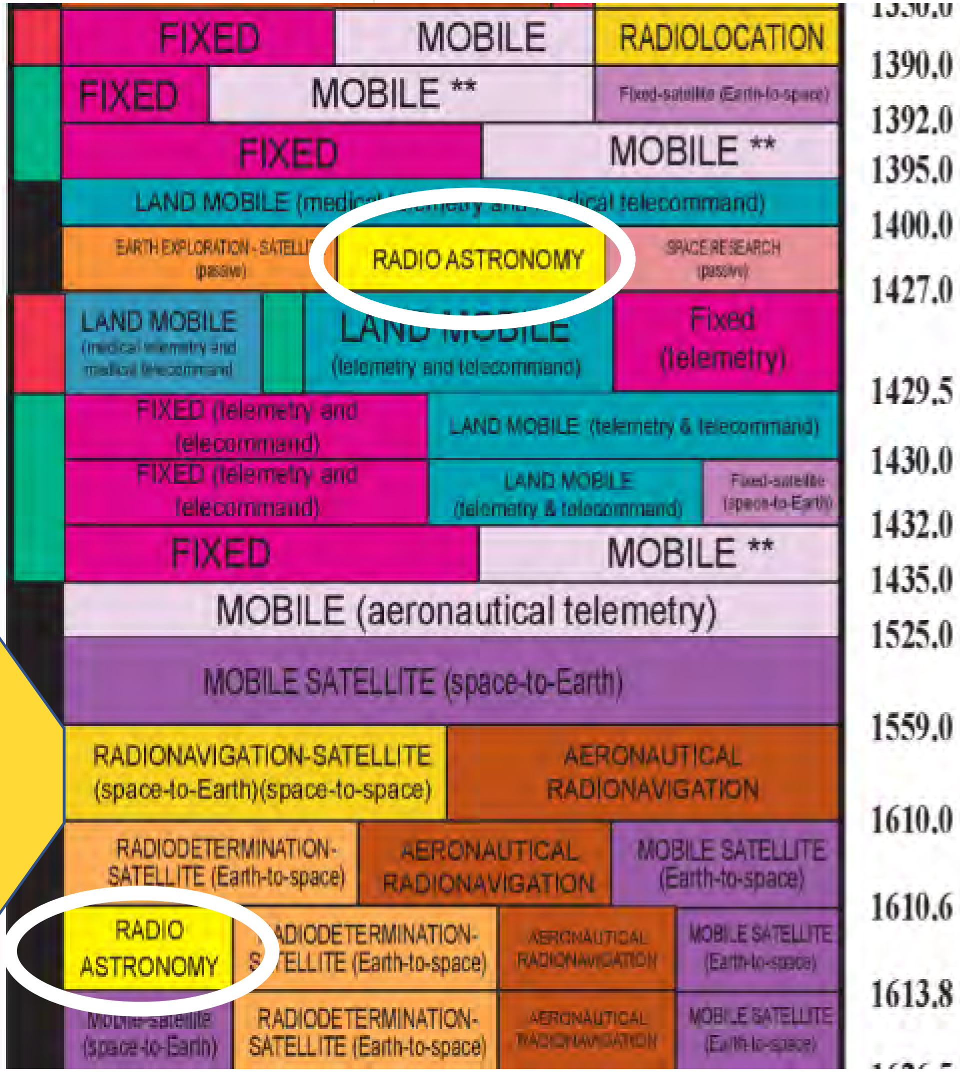


Figure Credit: https://techcrunch.com/2016/02/05/new-air-force-satellites-launched-to-improve-gps/

Frequency Allocations: 1390 – 1614 MHz

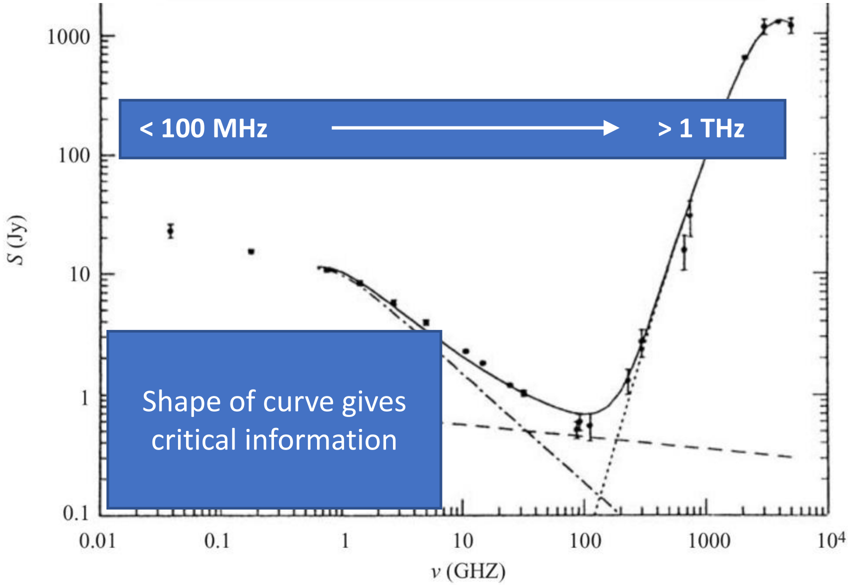
Radio Astronomy relies on unprotected frequencies

- To measure chemicals in space, astronomers use *spectral lines*
  - Many spectral lines are at unprotected frequencies
  - Protected lines can arrive at unprotected frequencies
    - Frequencies change because emitters move & universe expands

- Some observations require wide bandwidth, not just lines
  - Continuum emissions
  - Weak signals

  - **CMB science utilizing sensitive bolometers**
  - **Fast Radio Bursts (FRBs)**
  - **Epoch of Reionization (HI @ <200 MHz)**
  - **Protoplanetary disks**

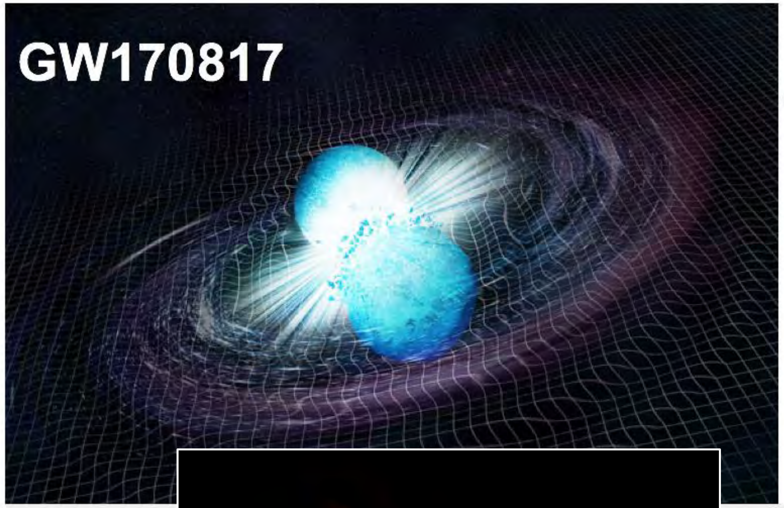
Study of M82, a star-forming galaxy with a black hole



ITU report on spectral lines: International Telecommunication Union *RA 314 Series: Preferred Frequency Bands for Radio Astronomical Measurements*, June 2003
Image: many contributors, see https://chandra.harvard.edu/photo/2006/m82/
Graph: J.J. Condon, *Radio Emission from Normal Galaxies*, Annu. Rev. Astron. Astrophys. 1992

Wide bandwidth measurements are critical for weak signals

- Example
  - First multi-messenger observation of merging neutron star, 2017
  - Radio counterpart to gravitational wave detection
  - This event could not have been detected by the VLA using only Radio Astronomy spectrum

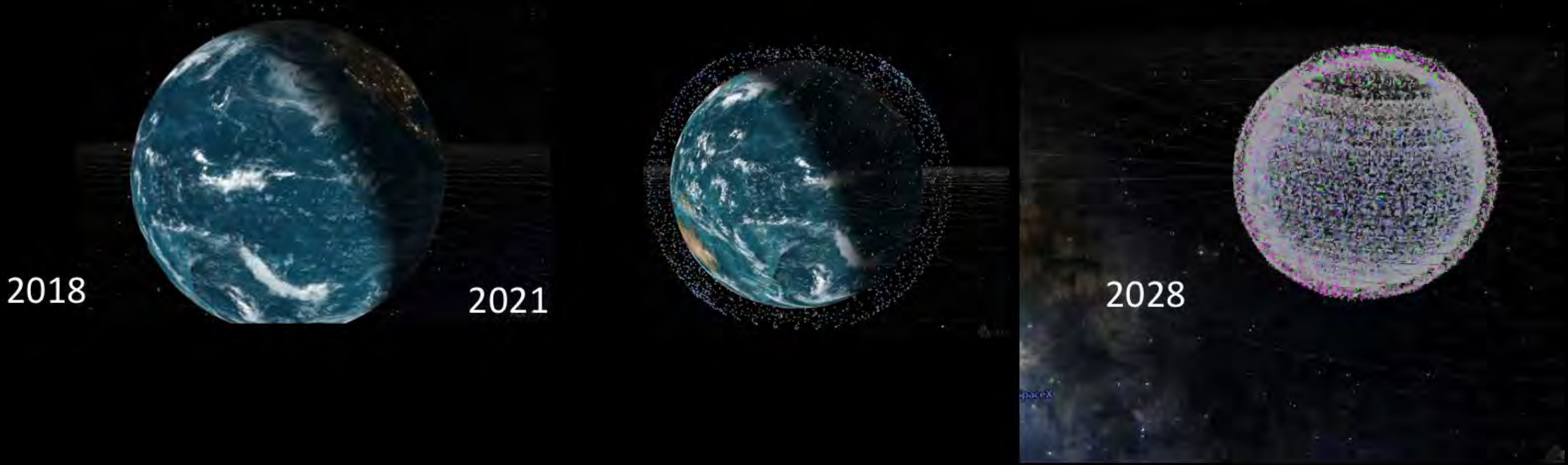


- Key measurement: 2 GHz wide @ 3 GHz center frequency
  - 1.4 GHz of usable bandwidth
  - Astronomy allocations cover only 50 MHz of that range
  - Detection time @ 1.4 GHz of data : ~6 hours
  - Detection time @ 50 MHz of data : ~100 hours

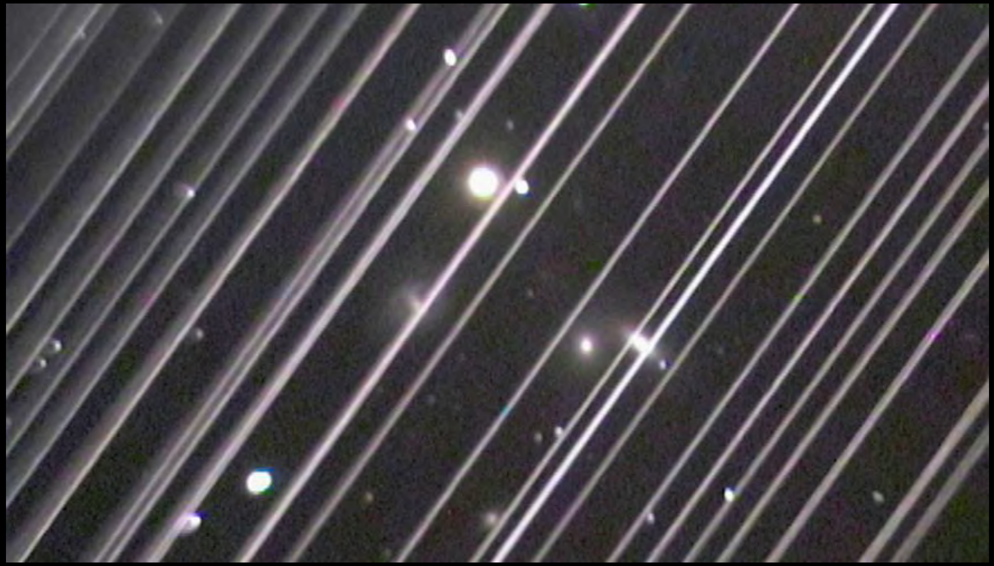
Image Credits: Hallinan et al., Science (16 Oct 2017); https://public.nrao.edu/news/radio-eyes-unlocking-secrets/
~100 hours figure calculated by NSF staff using data from the Science paper and VLA Exposure Calculator: https://obs.vla.nrao.edu/ect/

There is a proposed space population like we've never seen before!

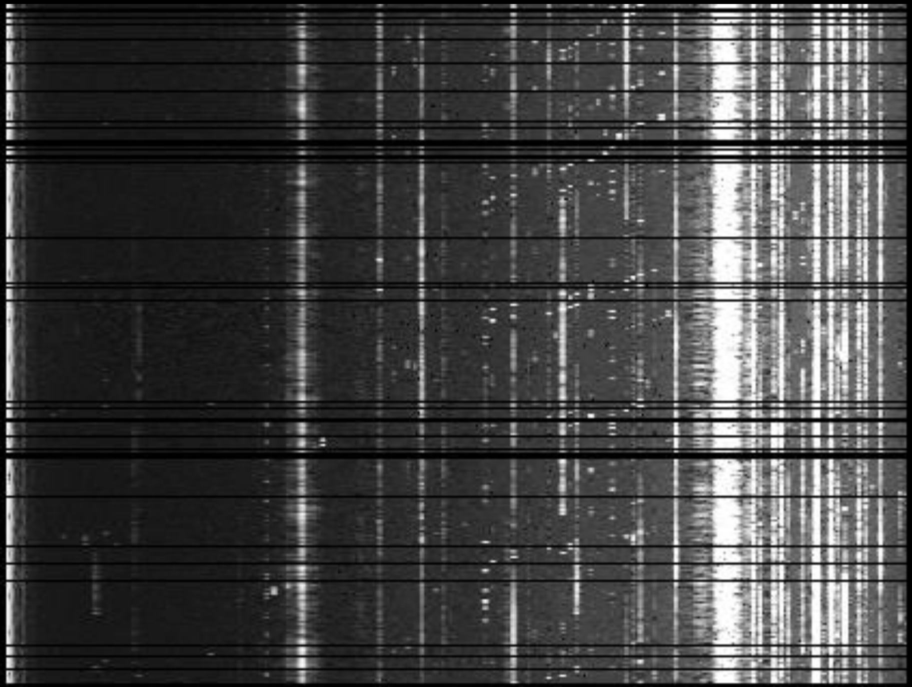
More than 50,000 new spacecraft proposed globally in next ten years



Images: Screen shots from animation based on applications filed with the ITU and the U.S. FCC. Credit SSC.



optical interference



radio interference

Siting telescopes in remote locations is no longer sufficient for protection.

Recent NSF activities related to new satellite constellations

Optical and Infrared

- 2 NSF-funded workshops
  - SATCON1 – July 2020
  - SATCON2 – July 2021
- NSF's Rubin Observatory working closely with satellite operators
- NSF/Satellite Industry Association joint technical presentation for the USA to UN Committee on the Peaceful Uses of Outer Space (COPUOS)

Radio Frequency

- Spectrum coordination agreements
  - SpaceX, 2019
    - Being updated (new & modified FCC license)
  - Other US-licensed operators to come
- R&D on satellite interference mitigation/coexistence
  - Spectrum Innovation Initiative
  - SWIFT program

- NSF-supported JASON study (July 2021)
  - Optical impacts on NSF/Rubin Observatory
  - Mitigation opportunities
  - Good practices for satellite vendors
- Analytic study of radio interference, including
  - Single-dish telescopes
  - Interferometers
  - Cosmic Microwave Background-Stage 4

SATCON1: https://aas.org/satellite-constellations-1-workshop-report SATCON2: https://aas.org/satellite-constellations-2-workshop
NSF/SIA briefing to UN COPUOS: https://www.unoosa.org/oosa/en/ourwork/copuos/technical-presentations.html
JASON study: https://www.nsf.gov/news/special_reports/jasonreportconstellations/

Technical Presentation at 64th Session of Committee on Peaceful Uses of Outer Space (COPUOS)

Selection of presentation in slides 14 - 26

https://www.unoosa.org/documents/pdf/copuos/2021/COPUOS-DQS-SATAST-USA-2021Aug30.pdf

COPUOS Presentation Overview

I. Benefits of Broadband Low Earth Orbit Satellites to Society
II. Challenges to Astronomy and Sustainability
III. Studies and Workshops
IV. Example U.S. Industry – Astronomer Collaboration
V. Lessons Learned and Future Work

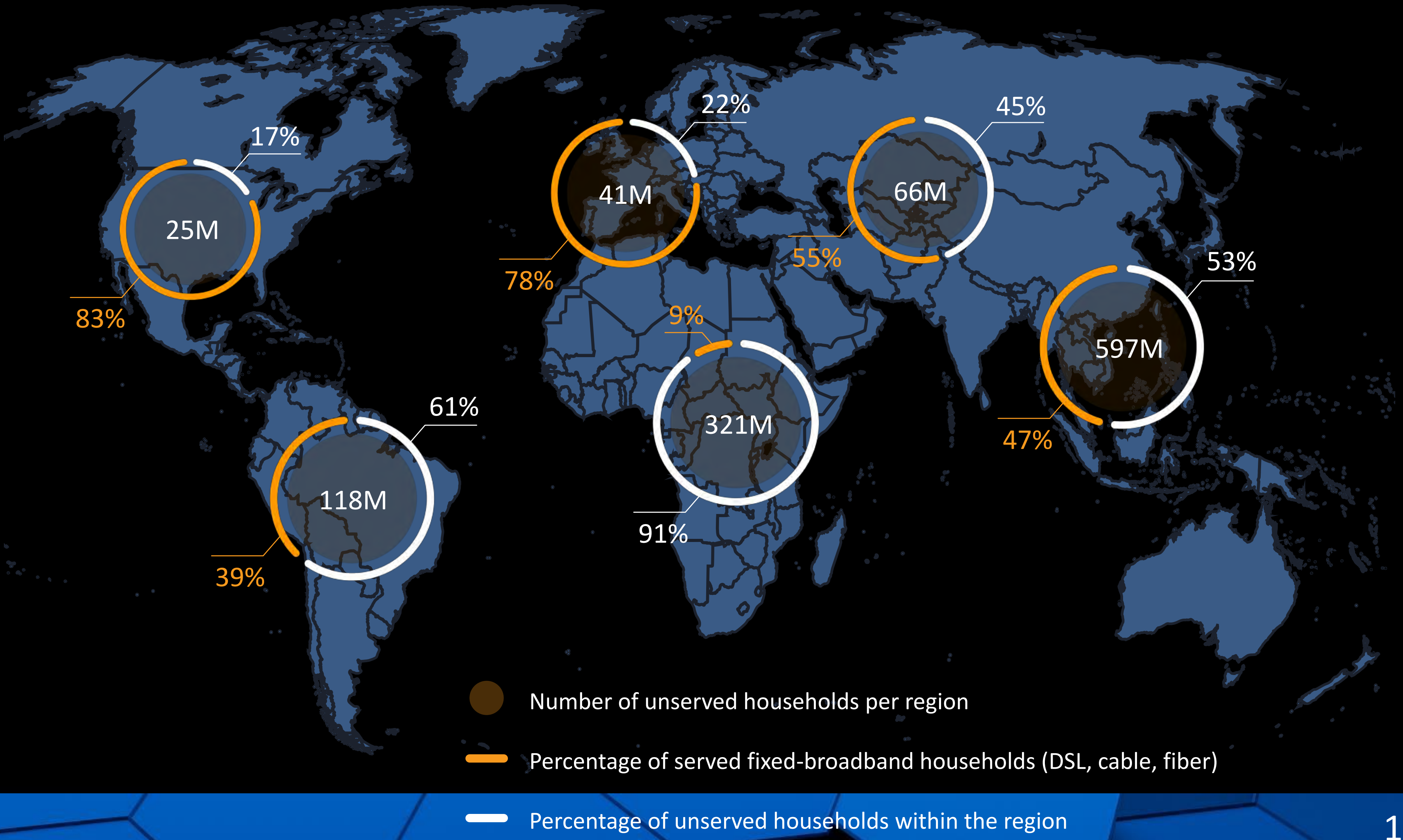
Bridging the digital divide

There are billions of people on Earth without reliable broadband. NGSOs will bridge the gap in places where service is unreliable or expensive, or where it doesn't exist at all.

1 billion
unserved households across the globe have no fixed broadband today (50% of the global total).

300 million
underserved households are on legacy technologies.

100 million
business, enterprise, and public sector endpoints lack reliable connectivity.



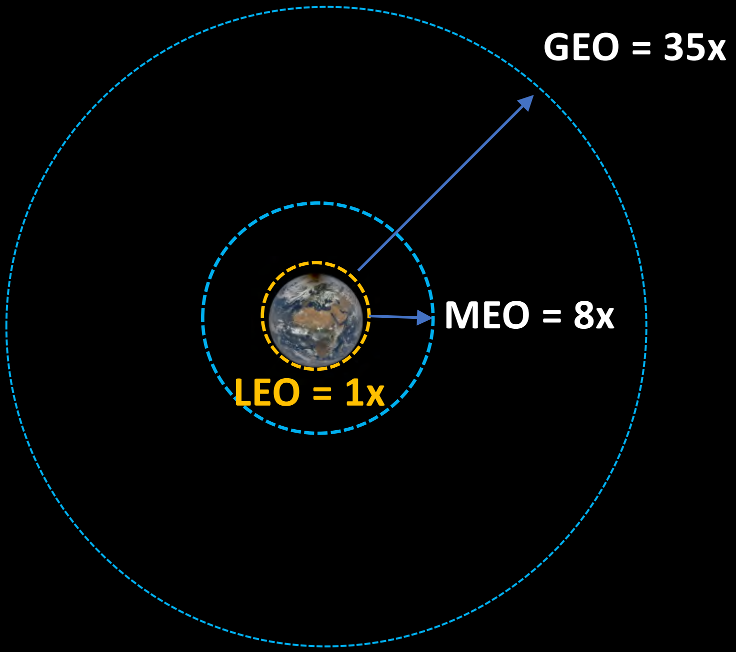
Source: S&P Market Intelligence

Advantages of Low Earth Orbit

1

Relative distance of satellites from Earth

1x = 1,000 km



GEO = Geostationary Orbit

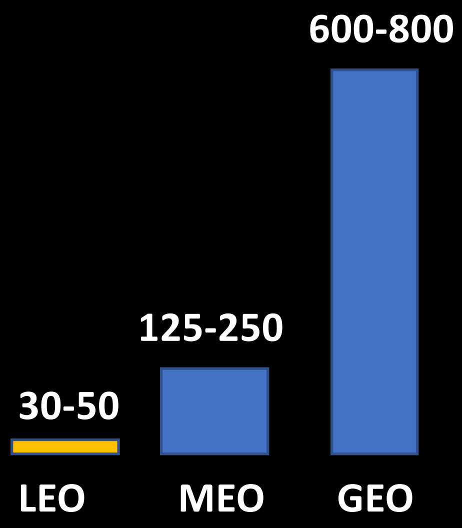
MEO = Medium Earth Orbit

LEO = Low Earth Orbit

2

Packet roundtrip time to Internet

Milliseconds



3

Customer Experiences

Faster Web Pages

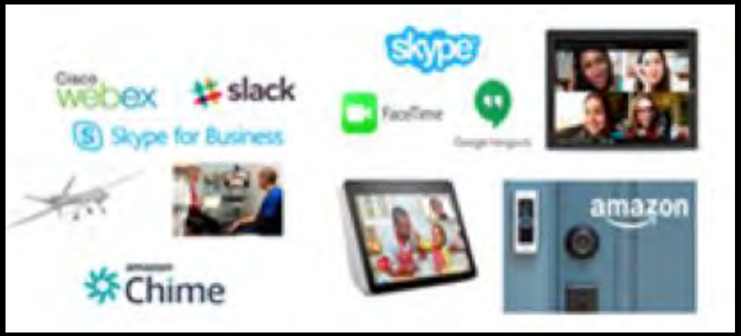
LEO loads Web Pages

-similar to fiber

-2x faster versus MEO

-6-8x faster versus GEO

Real-time over-the-top (OTT) media applications

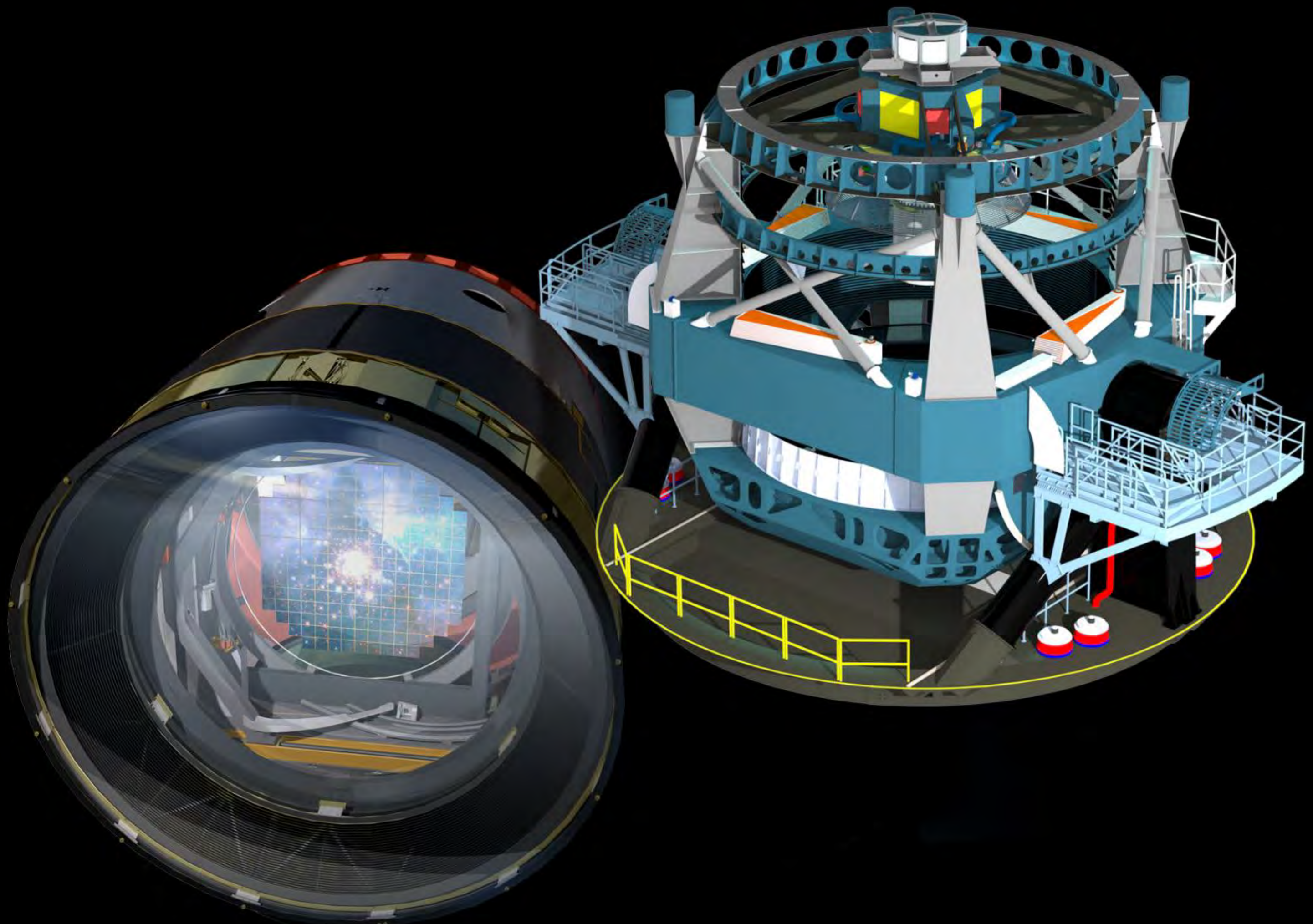


VERA C. RUBIN
OBSERVATORY

LSST
Legacy Survey of Space and Time

Rubin Observatory will execute the *Legacy Survey of Space and Time*, producing the deepest, widest, view of our dynamic Universe:

- 8.4-m mirror
- 3200 megapixel camera
- Each image the size of 40 full moons
- Scans the sky with 2000 images per night
- 10 year survey of the sky 2024-2034
- 37 billion stars and galaxies
- 10 million alerts, 20 Terabytes of data - every night!
- **Significantly impacted by bright satellite trails**



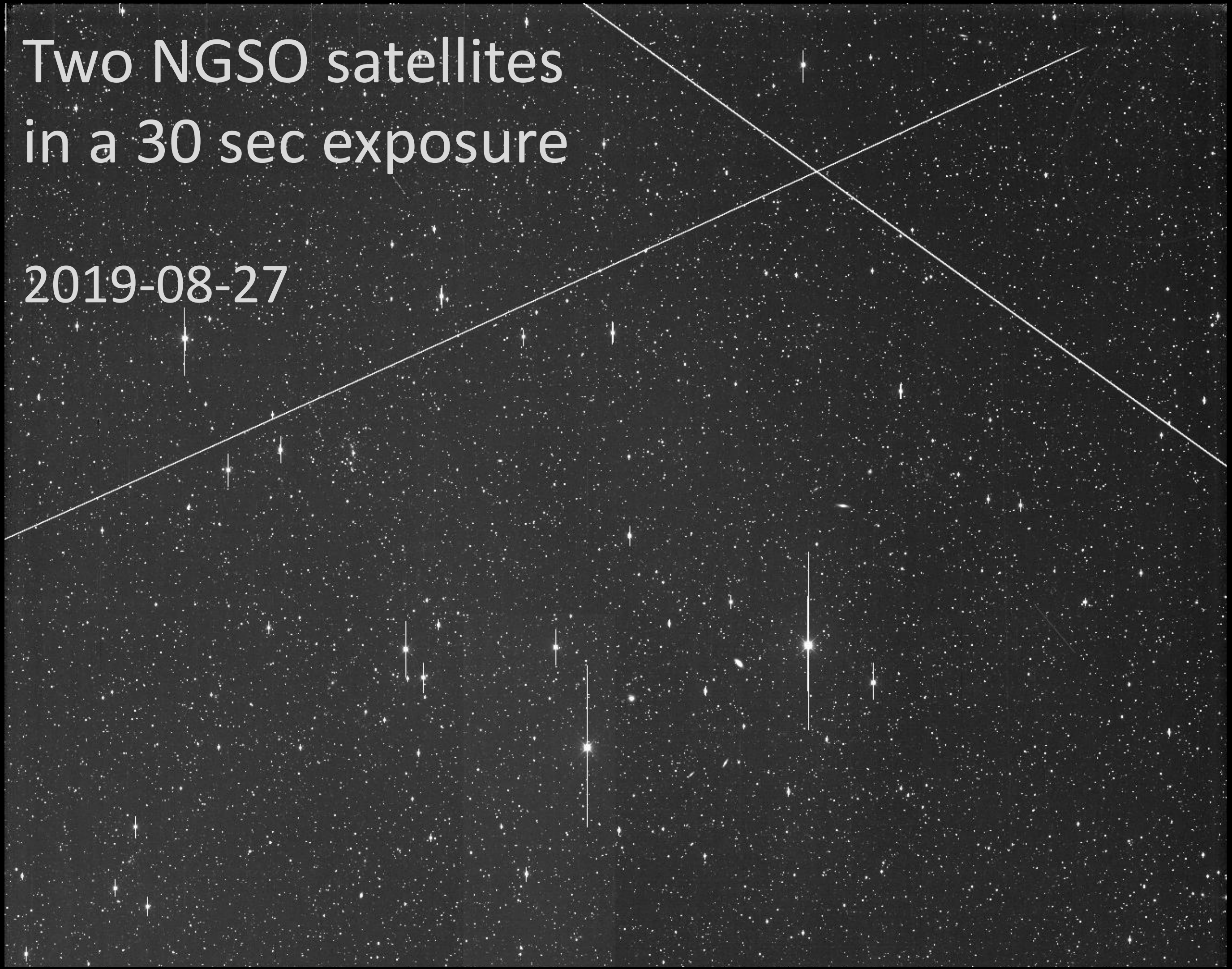


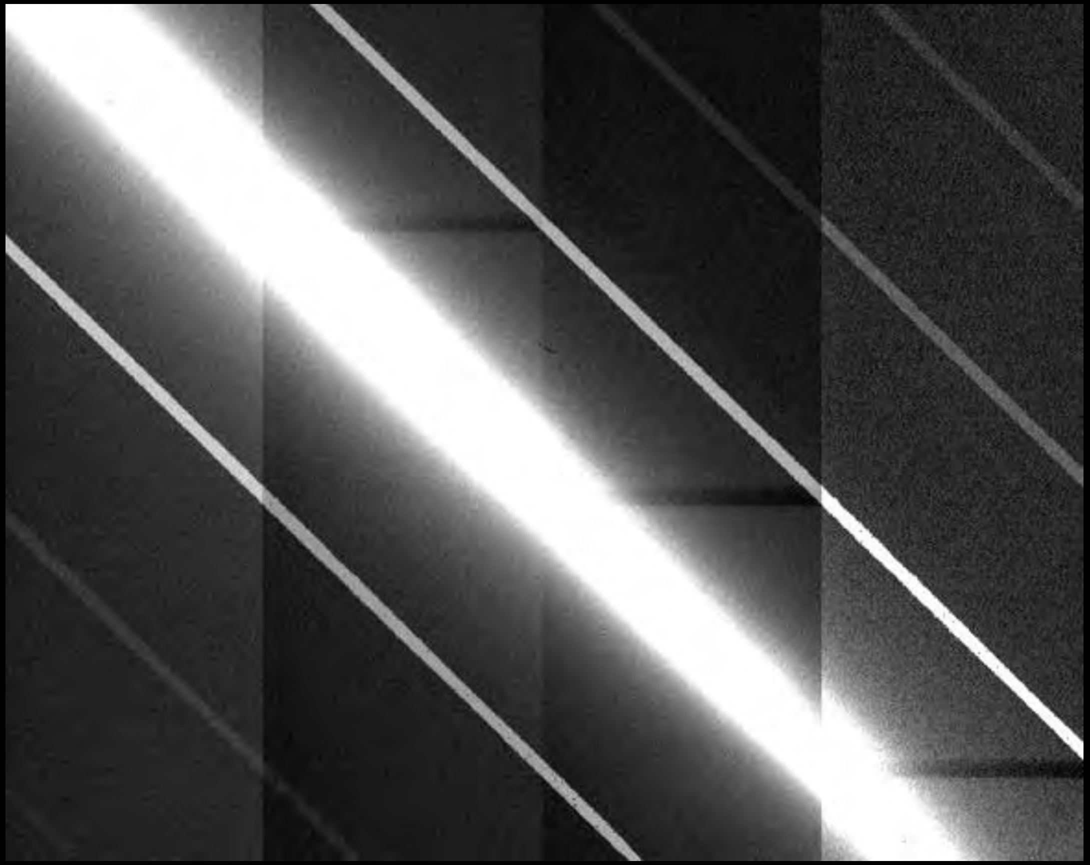
Image on left taken with very small telescope with wide field of view (above).

John Tonry
U Hawaii

With tens of thousands of LEOsats, generally no combination of mitigations can completely avoid the impacts of the satellite trails

Astronomical Journal, 160, 226 (2020) arXiv:2006.12417

How do bright satellites affect observations on telescopes?



- Diversity of impact to radio astronomy, optical spectroscopy and imaging

Examples from imaging:

  - Loss of information in pixels
  - Cross-talk in electronics
  - Ghost images
  - Possible residual images
  - Creates harmful artifacts

Many factors contribute to overall scientific impact

Satellite Operator:

- Orbital altitude / dwell time of satellite in field of view (FOV)
- Constellation total number
- Size of individual satellites
- Reflectivity properties of material
- Geometry of reflected light
- Orbit/De-orbit plans

Astronomers:

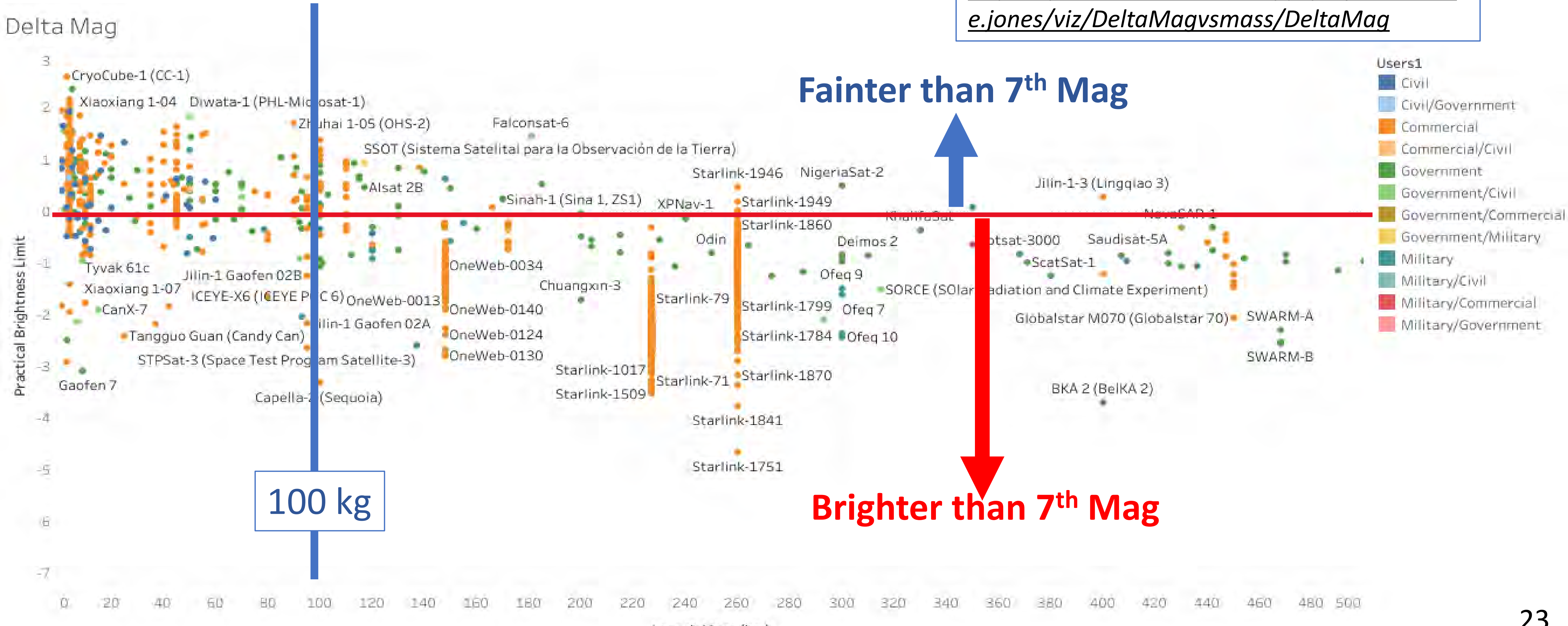
- Telescope
    - Camera detector properties
    - Scheduling
    - Field of View
    - Image sensitivity
- Post-processing algorithms
- Observational requirements

Cooperation, Coordination and Collaboration

- U.S. satellite industry has been closely cooperating with U.S. scientists, especially at the Vera Rubin Observatory, a limiting case, to
  - Understand the challenge to astronomy
    - Satellite brightness (launch, mission, de-orbit phases)
    - Numbers of satellites
    - Satellite orbital altitude (<700 km versus > 1100 km)
  - Quantify metrics for target goals
    - For example, Astronomers have recommended that operators design satellites to appear no brighter than approximately 7th magnitude.
  - Find solutions
- We also emphasize the importance of international cooperation and recognize the important role of the IAU and the satellite industry internationally; Coordination discussions are ongoing .

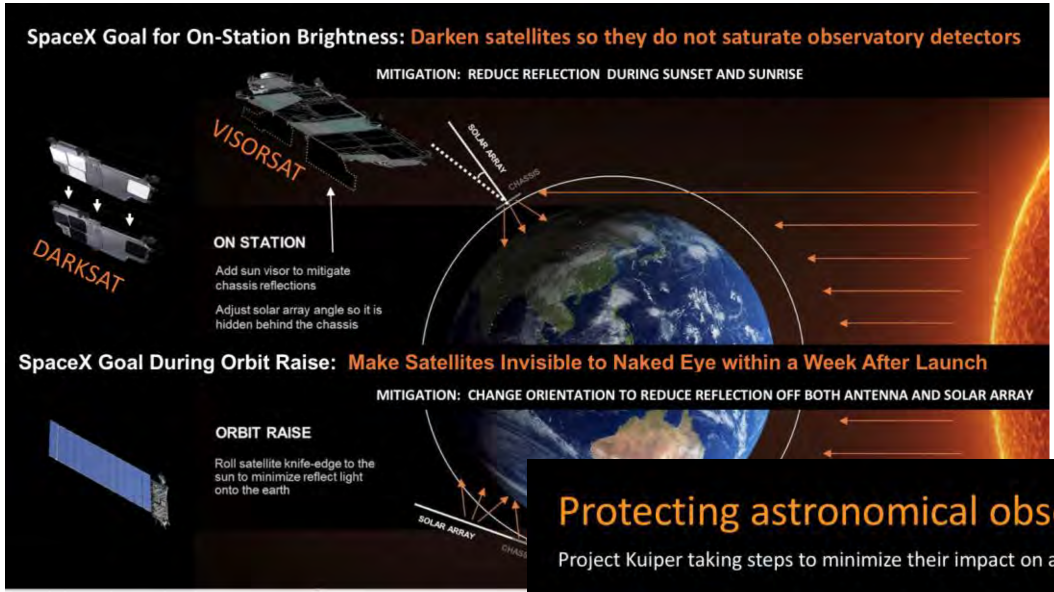
Satellites in the 100+ kg range typically exceed the 7th magnitude threshold for astronomers, but many smaller sats do as well

Interactive data: *https://public.tableau.com/app/profile/therese.jones/viz/DeltaMagvsmass/DeltaMag*

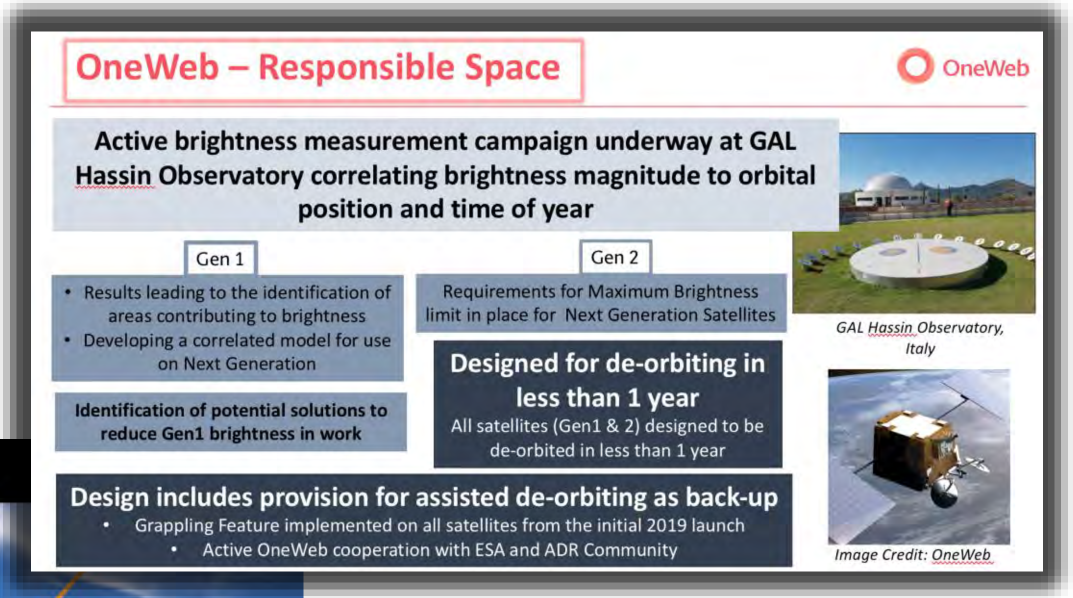


Data source: Union of Concerned Scientists Satellite Database and MMT-9 Database

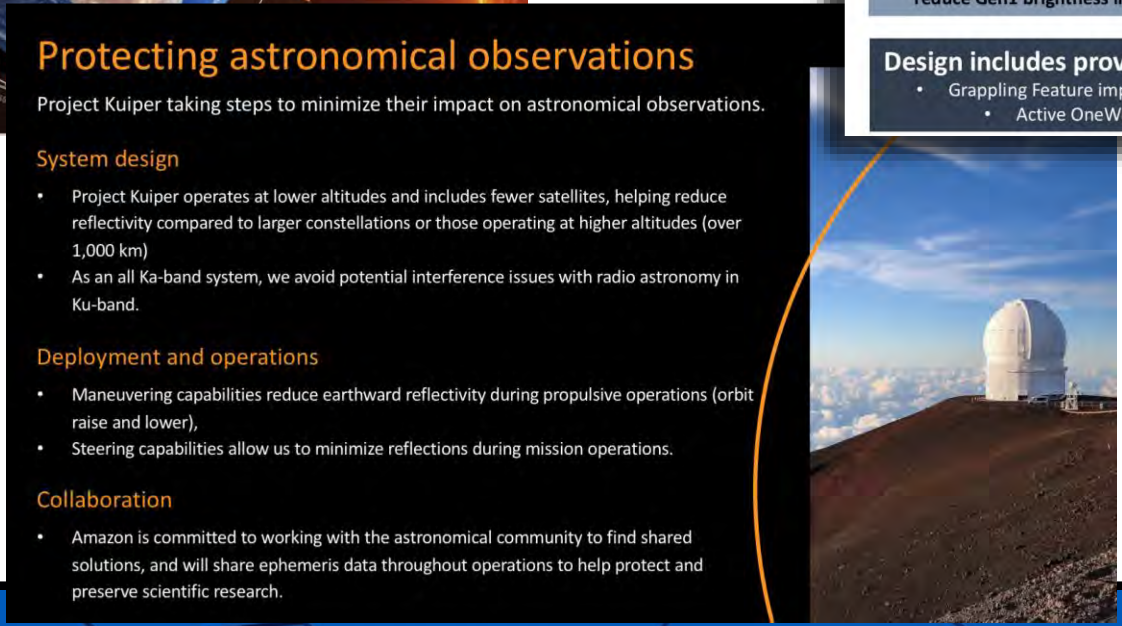
US Examples from Industry



SpaceX Starlink



OneWeb



Amazon Kuiper

Further Work: Satellites and Telescopes

- More precise tracking information for satellites is needed to assist in astronomical observation planning and development is needed in astronomical community to implement observation planning (although this alone does not mitigate, especially for wide field-of-view astronomy telescopes like the Rubin Observatory)
  - Open Architecture Data Repository (OADR) in U.S. Department of Commerce a first step
- Tools used to model satellite brightness pre-launch as well as best practices for stakeholders across the industry will be critical
  - Additional basic research on materials/design may provide further guidance
- Development of software application available to general astronomy community to identify, model, subtract, and mask satellite trails in images as well as detailed simulations of effects on data analysis systematics and data reduction signal-to-noise impacts
- Collaboration and coordination with diversity of stakeholders
  - Profile of space actors is rapidly changing– while communications satellites are the current focus of these mitigation issues, remote sensing satellites are rapidly increasing in number on orbit
  - Telescope technology is evolving and there are a diversity of observational parameters to consider

Summary

The United States supports efforts to study these challenges and encourages all administrations to carefully and thoughtfully consider the individual recommendations within the Dark and Quiet Skies report.

International cooperation is required to agree on priorities and accelerate practical, scalable solutions.

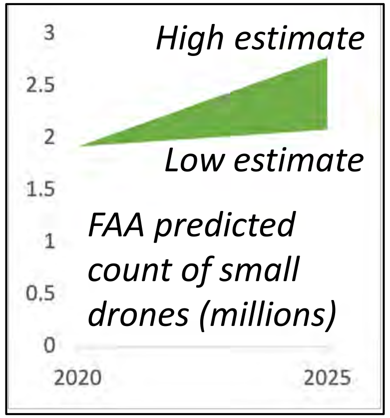
Astronomers and Satellite providers within the United States will continue to work together *and with the international community* towards a sustainable future – for the important provision of low-latency broadband service, for future discoveries enabled by astronomy, for long-term sustainability, and for society at large.

Anticipate rapid growth in formerly clear sites / bands

New satellite constellations

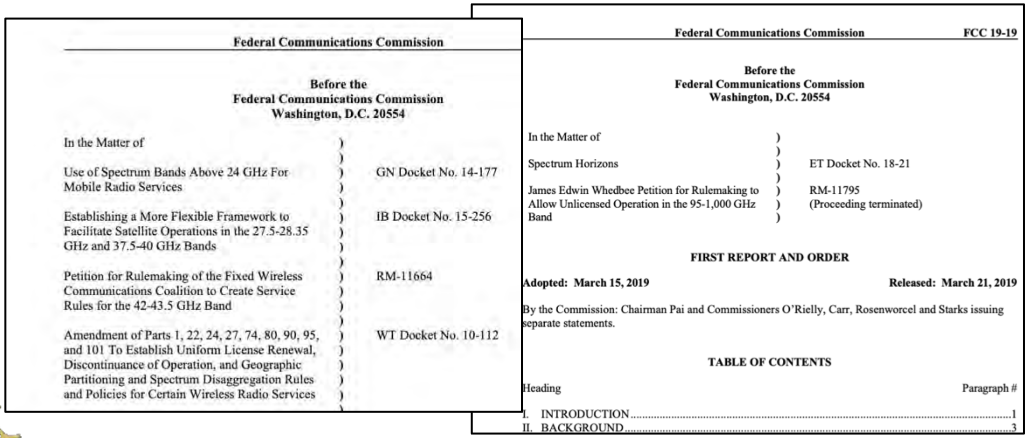
FCC recently-approved satellite constellations	Space to earth frequencies (GHz)			
	10.7 – 12.7	17.7 – 20.2	27.5 – 30	37.5 – 42.5
SpaceX Starlink	*	*		*
Telesat Lightspeed		*	*	
Kepler	*	*		
OneWeb	*	*		
Amazon Kuiper		*		

Increased airborne activity



New operations at higher frequencies

FCC Spectrum Frontiers > 24 GHz *FCC Spectrum Horizons > 95 GHz*



Federal Communications Commission

Before the
Federal Communications Commission
Washington, D.C. 20554

In the Matter of

Use of Spectrum Bands Above 24 GHz For Mobile Radio Services) GN Docket No. 14-177

Establishing a More Flexible Framework to Facilitate Satellite Operations in the 27.5-28.35 GHz and 37.5-40 GHz Bands) IB Docket No. 15-256

Petition for Rulemaking of the Fixed Wireless Communications Coalition to Create Service Rules for the 42-43.5 GHz Band) RM-11664

Amendment of Parts 1, 22, 24, 27, 74, 80, 90, 95, and 101 To Establish Uniform License Renewal, Discontinuance of Operation, and Geographic Partitioning and Spectrum Disaggregation Rules and Policies for Certain Wireless Radio Services) WT Docket No. 10-112

Federal Communications Commission FCC 19-19

Before the
Federal Communications Commission
Washington, D.C. 20554

In the Matter of

Spectrum Horizons) ET Docket No. 18-21

James Edwin Whedbee Petition for Rulemaking to Allow Unlicensed Operation in the 95-1,000 GHz Band) RM-11795 (Proceeding terminated)

FIRST REPORT AND ORDER

Adopted: March 15, 2019 Released: March 21, 2019

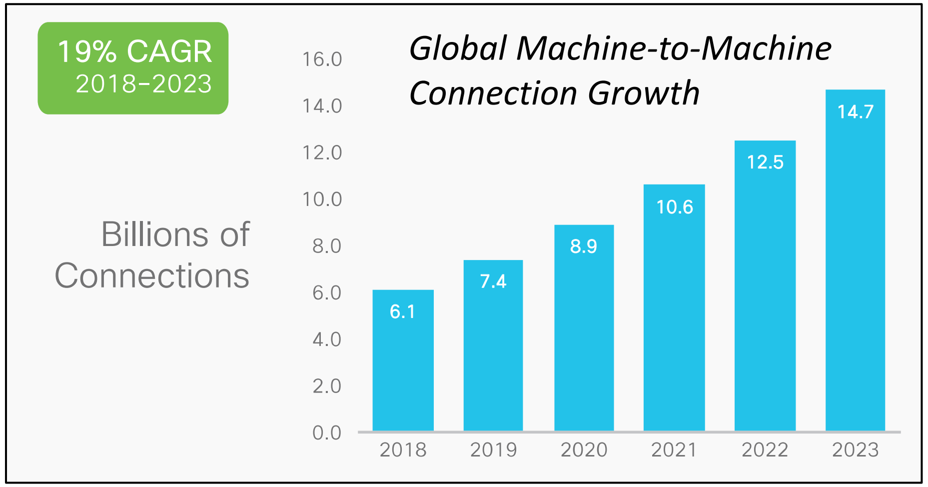
By the Commission: Chairman Pai and Commissioners O'Rielly, Carr, Rosenworcel and Starks issuing separate statements.

TABLE OF CONTENTS

Heading Paragraph #

I. INTRODUCTION 1
II. BACKGROUND 3

Increased congestion in general



Drone forecast data: https://www.faa.gov/data_research/aviation/aerospace_forecasts/media/Unmanned_Aircraft_Systems.pdf
Constellation list and frequencies: JASON study 2021 https://www.nsf.gov/news/special_reports/jasonreportconstellations/
FCC rulings: https://www.fcc.gov Machine to machine connections graph: Cisco Annual Internet Report, 2018–2023

NSF activities towards enhanced astronomy protections

- International
  - US Head of Delegation for ITU-R Working Party 7D, Radio Astronomy
    - Started process to recommend coordination for 5G at 42 GHz (working with FCC and NTIA)
    - Recently approved updates to ITU report on Radio Quiet Zones
    - New reports initiated by US this year include
      - Bolometers
      - Low-frequency arrays (<300 MHz)
      - Widely distributed millimeter-array systems (e.g., EHT)
      - Sharing and compatibility >71 GHz
      - Impact of Harmonic emissions
      - Technical and operational factors and mitigation techniques for prevention of interference to radio astronomy systems in the Shielded Zone of the Moon
  - Regular tag-ups with NASA and NOAA spectrum managers

NSF activities towards enhanced astronomy protections

- Domestic
  - Represents NSF on NTIA's Interdepartment Radio Advisory Committee (IRAC) on behalf of radio astronomy and other scientific spectrum uses
  - Working with astronomy community to develop actionable recommendations
  - Regular coordination with National Radio Quiet Zone, review of Special Temporary Authorizations (STAs)

Site Type	Anticipated locations covered by recommendations
Current protected zones	National Radio Quiet Zone, West Virginia Coordination Zone, Puerto Rico
Large telescopes/arrays outside protected zones	New Mexico
Key sites for Cosmic Microwave Background studies	Atacama, Chile South Pole, Antarctica
Dispersed small telescopes	All US&P

Potential recommendations *(least intrusive first)*
Data sharing
Notification prior to usage
Coordination
Restrictions on usage

NSF-supported research relies on access to the electromagnetic spectrum *and* catalyzes its efficient usage

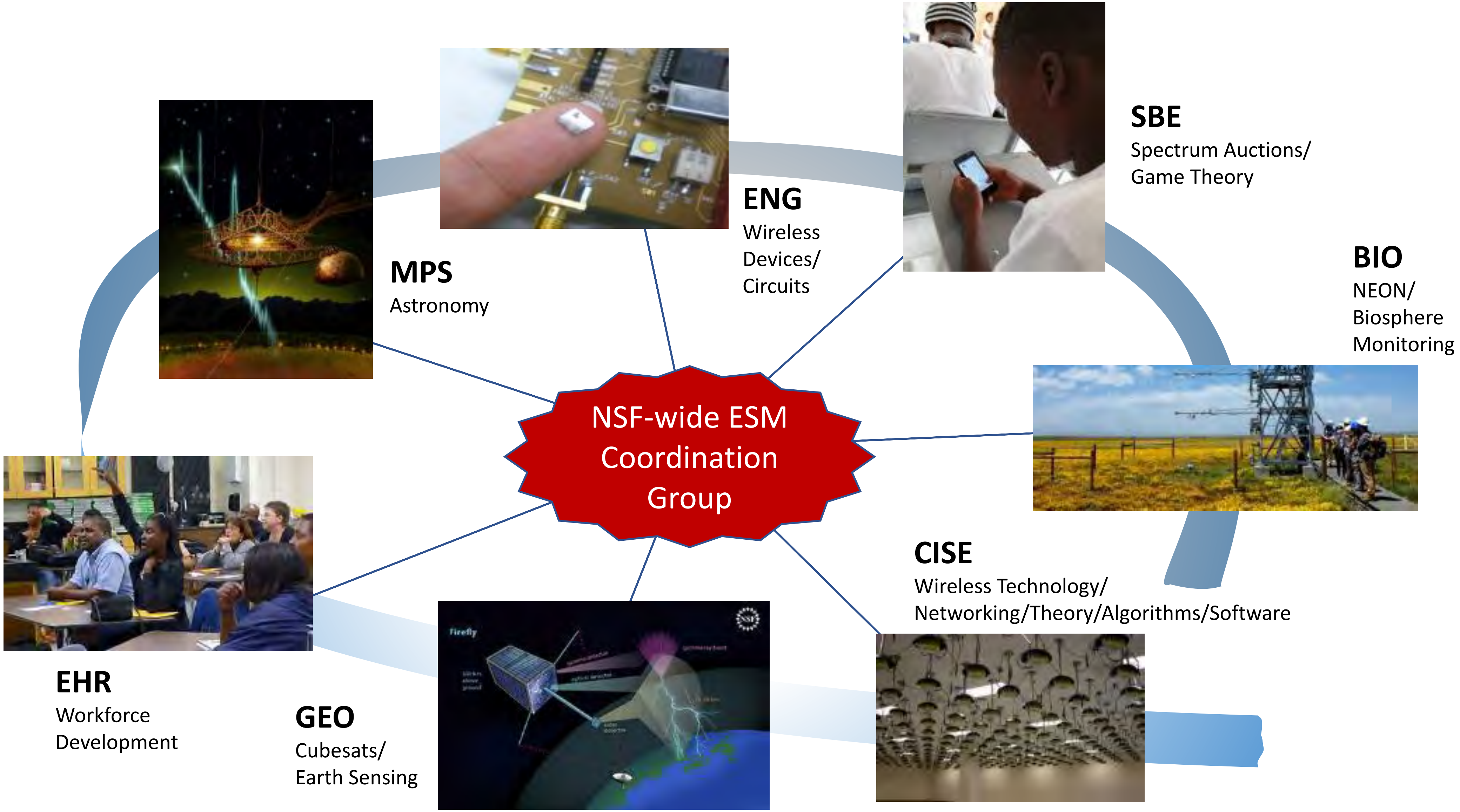
Passive – "listen only"

- GPS Radio Occultation
- Radio Astronomy
- Geodesy

Active – "transmit"

- Wi-Fi, Bluetooth, Television Whitespaces, Millimeter Wave/ TeraHertz Bands
- Research Drones, Cubesats
- Radar

Spectrum Connections Across NSF



Two Sides to the Spectrum Coin

Spectrum for basic research

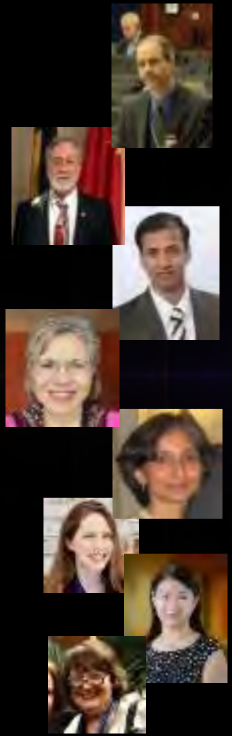
Radio quiet environment is critical for scientific observations, such as Cosmic Microwave Background experiments at the South Pole.

Spectrum for communications and operations

Access to the spectrum for communications is essential for many operations, both for logistical purposes and for relaying data.

NSF ESM Coordination Group

- *Formed March 2018*
- *Includes NSF input across all Directorates*

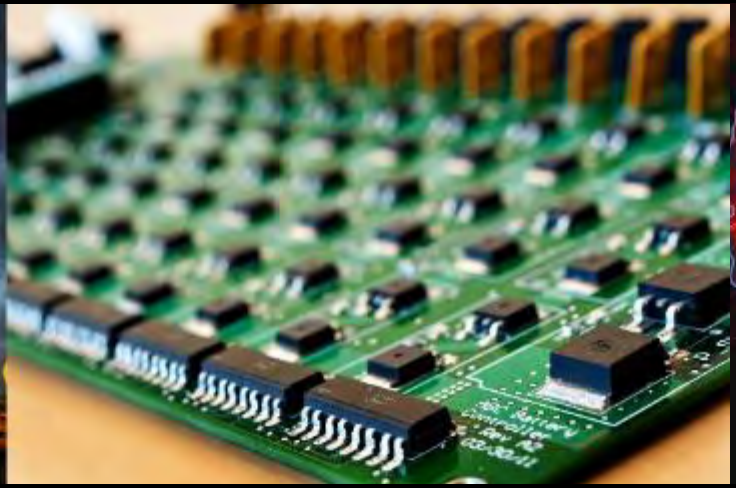


Jonathan Williams	*Chair, MPS/AST, ESM Unit*
Patrick Smith	*GEO/OPP*
Thyaga Nandagopal	*CISE/CCF*
Carmiña Londoño	*ENG/ECCS*
Mangala Sharma	*GEO/AGS*
Ashley VanderLey	*MPS/AST, ESM Unit*
Li Yang	*EHR*
Nancy Lutz	*SBE*

Jim Ulvestad — *Chief Officer for Research Facilities, Office of the Director*

NSF's Spectrum Innovation Initiative

Cross-Directorate, housed in MPS Office of Multidisciplinary Affairs (OMA)
(via a stewardship model similar to NSF Big Ideas)

I. National Radio Dynamic Zone

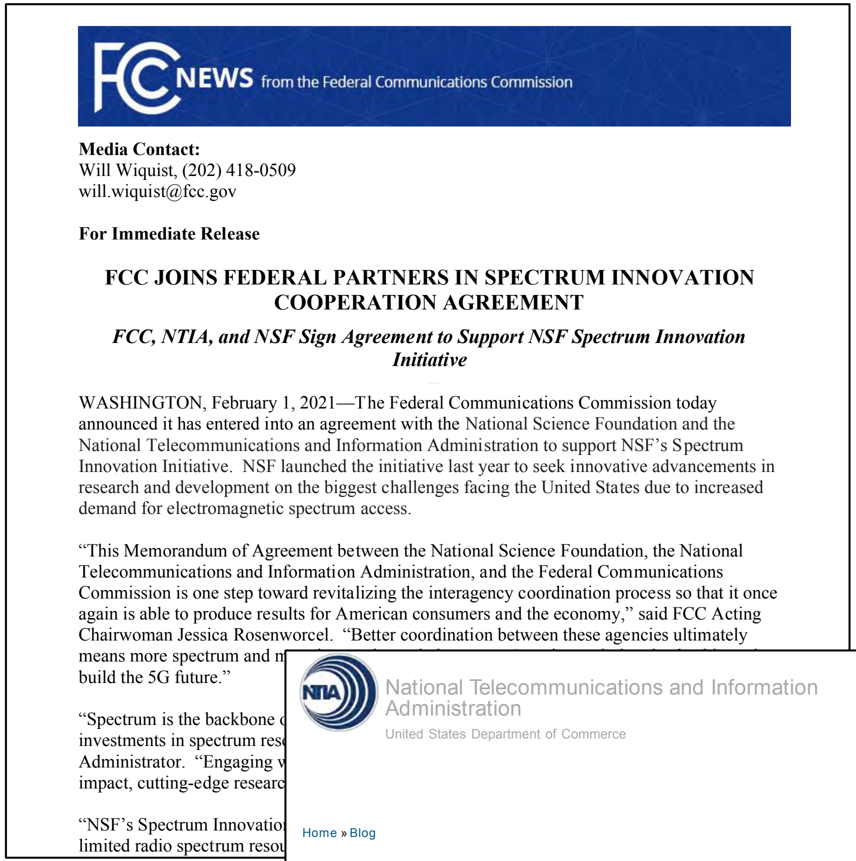
II. National Center for Wireless Spectrum Research

III. Spectrum Research Integrative Activities

IV. Education and Workforce Development

Partnership and Collaboration: NSF, FCC and NTIA

- Memorandum of Agreement announced Feb 2021
- FCC and NTIA staff will
    - provide subject matter expertise to NSF
    - help align NSF's investments with U.S. spectrum regulatory and policy objectives, principles, and strategies
- Key research areas include
    - spectrum flexibility and agility
    - near real-time spectrum awareness
    - improved spectrum efficiency and effectiveness through secure and autonomous spectrum decision-making
- Establish the first National Center for Wireless Spectrum Research


FCC NEWS from the Federal Communications Commission

Media Contact:
Will Wiquist, (202) 418-0509
will.wiquist@fcc.gov

For Immediate Release

FCC JOINS FEDERAL PARTNERS IN SPECTRUM INNOVATION COOPERATION AGREEMENT

FCC, NTIA, and NSF Sign Agreement to Support NSF Spectrum Innovation Initiative

WASHINGTON, February 1, 2021—The Federal Communications Commission today announced it has entered into an agreement with the National Science Foundation and the National Telecommunications and Information Administration to support NSF's Spectrum Innovation Initiative. NSF launched the initiative last year to seek innovative advancements in research and development on the biggest challenges facing the United States due to increased demand for electromagnetic spectrum access.

"This Memorandum of Agreement between the National Science Foundation, the National Telecommunications and Information Administration, and the Federal Communications Commission is one step toward revitalizing the interagency coordination process so that it once again is able to produce results for American consumers and the economy," said FCC Acting Chairwoman Jessica Rosenworcel. "Better coordination between these agencies ultimately means more spectrum and n
build the 5G future."

"Spectrum is the backbone
investments in spectrum res
Administrator. "Engaging
impact, cutting-edge researc

"NSF's Spectrum Innovatio
limited radio spectrum resou


National Telecommunications and Information Administration
United States Department of Commerce

Home » Blog

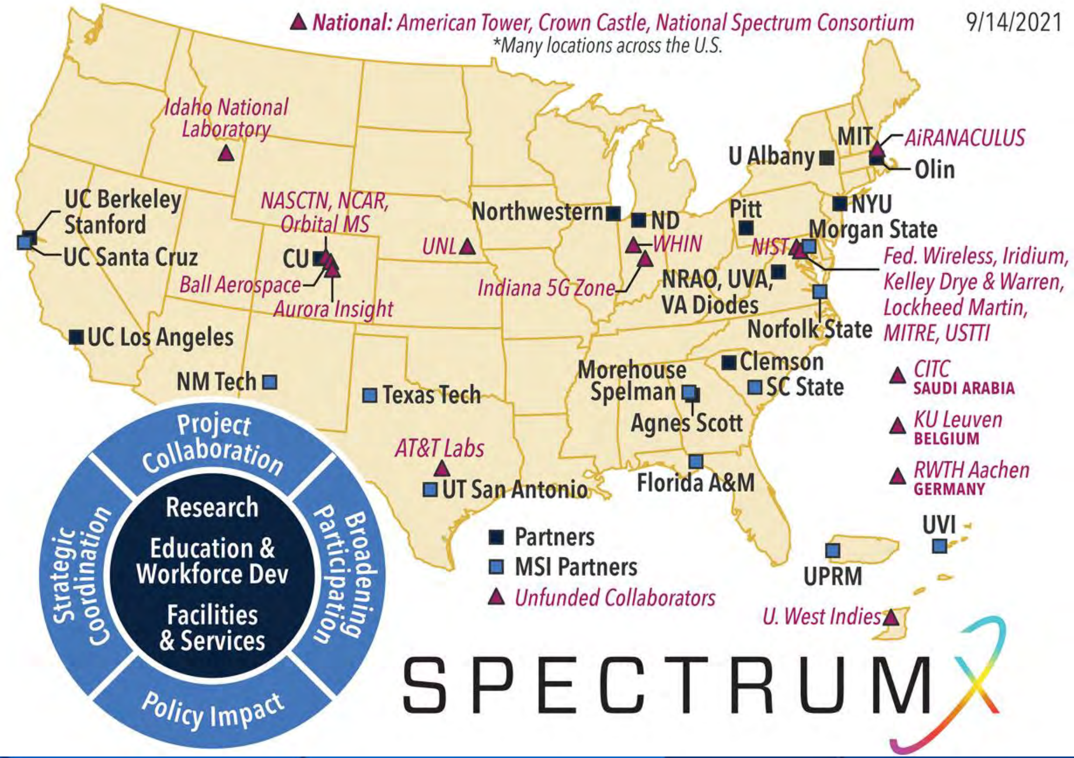
NTIA, FCC Experts Will Support the National Science Foundation's Spectrum Innovation Initiative

March 01, 2021 by NTIA

entered into an agreement

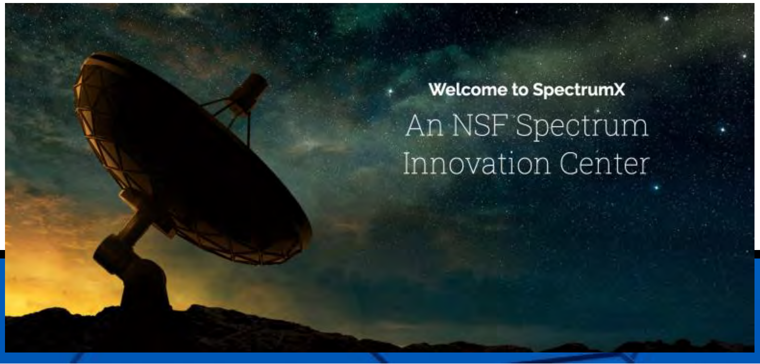
SpectrumX: An NSF Spectrum Innovation Center

- The first national center focused on the transformation of radio spectrum management
  - Research — new ways to share and manage spectrum – flexible, automated, cloud-based
  - Collaboration — a hub for researchers, industry, regulators, and others
  - Workforce — develop the diverse workforce needed for growth
- Maximize the benefits of the radio spectrum for society
- A partnership on multiple levels
  - Created by NSF under MOA with NTIA, FCC
  - Participants: 29 institutions (12 minority serving)
    - led by University of Notre Dame
    - grow into a hub for all stakeholders
  - Expertise: convergence across field boundaries
    - communications, passive science, sensing, radio technology, policy/economics, data science, control systems
- Federal investment $25m over 5 years



SpectrumX Workforce Development Activities

1. **Build a comprehensive spectrum education community, including multiple minority serving institutions**
2. **Develop curricula to engage students from middle school through graduate studies**
   a. High school lesson plans, published on the web, piloted in underserved communities
   b. Interdisciplinary undergraduate- and masters-level courses, shared on an e-learning platform
   c. Professional development program using hybrid workshops
3. **Research, training, and mentoring experiences**
   a. Summer-long research and training experiences
   b. Undergraduate research fellowships
   c. Week-long summer day camps for undergraduates, both in-person and remote
4. **Attract, train, and retain under-represented minorities (URMs), women, persons with disabilities and veterans**
5. **Improve the quality of spectrum education at feeder middle/high schools and partner institutions**
6. **Promote public awareness, understanding and appreciation of spectrum nationwide**



Web site: spectrumx.org

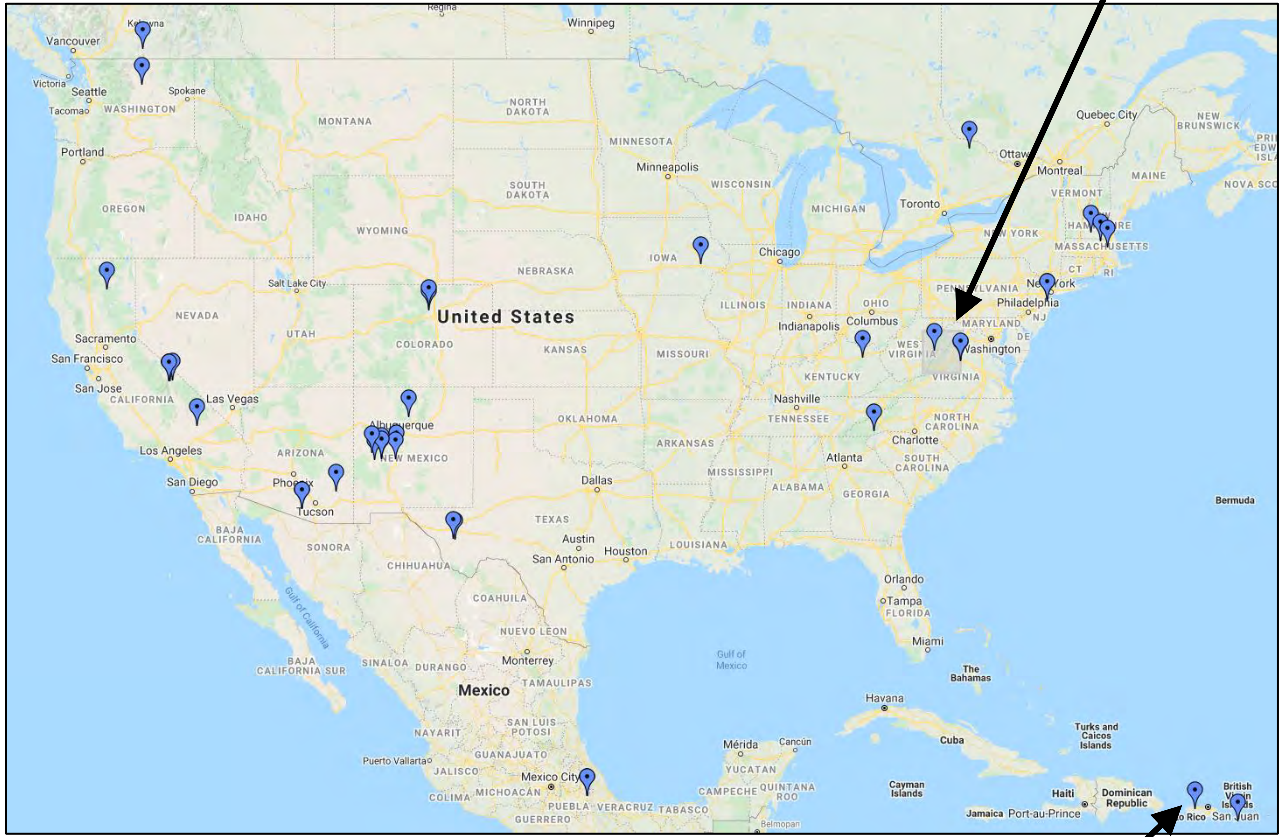
Many radio telescopes are at unprotected sites

- Large radio telescopes and arrays
  - at remote places with clean spectrum
  - critical for the progress of science

- Small radio telescopes
  - at hundreds of educational institutions
  - critical for training, public awareness, broadening participation

National Radio Quiet Zone

Sites of large telescopes and arrays



Puerto Rican Coordination Zone

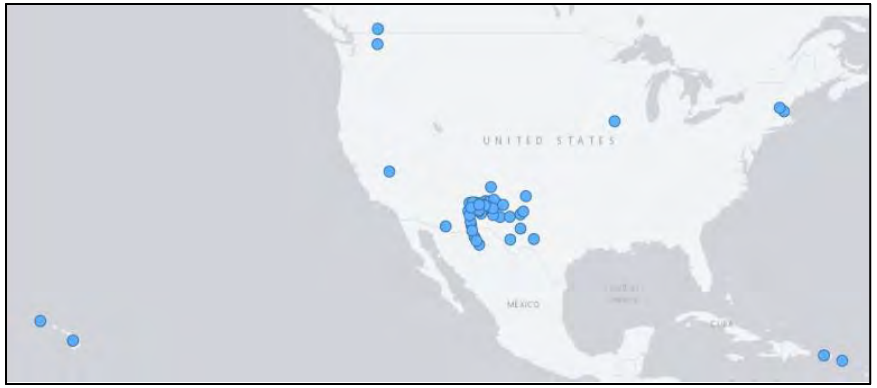
Radio Astronomy’s long-term future

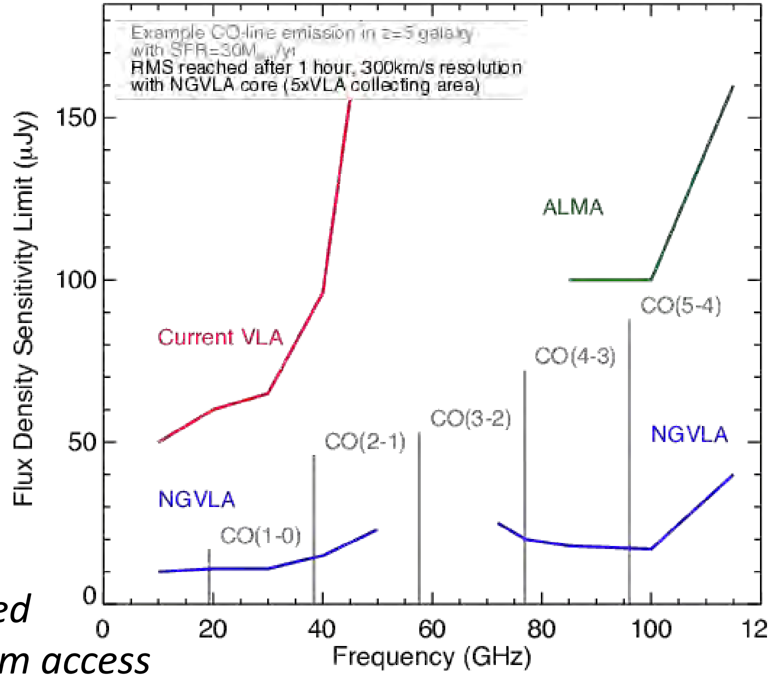
- New instruments to answer new questions
  - Broader bandwidth
  - Higher sensitivity
  - Wider spread on Earth
  - Fundamentally new receiver types
- Dispersed small telescopes in congested locations
  - Critical for inspiring STEM careers and broadening participation

<u>Example</u>

- Proposed Next Generation Very Large Array (ngVLA)
  - Study formation of planets, initial conditions for life, early galaxies
  - ~ 200 dishes, spread widely including in Mexico
  - Desired spectrum access 1.2 – 116 GHz continuous
    - excluding 50-75 GHz

NGVLA proposed sites





NGVLA proposed spectrum access

Graph credit: Decarli et al. 2018 (arxiv/1810.07546)
Map credit: Ellingson, , “Radio Astronomy Instrumentation,” NRDZ Partnership Workshop, March 16, 2021.

Radio Astronomy's long-term future: enhanced protections needed!

- Dynamic spectrum sharing is essential
- Example comments in support
  - President's Council of Advisors on Science and Technology – The ***norm for spectrum use should be sharing***, not exclusivity.

    Realizing the Full Potential of Government-Held Spectrum to Spur Economic Growth, 2012

  - NTIA – As the electromagnetic environment becomes increasingly congested and complicated, ***both scientific and commercial operators have to innovate and attempt to find new solutions to pilot dynamic sharing and other advanced sharing techniques***.

    Activities on Ensuring Spectrum Access for Science, June 2020

  - National Academy of Science Committee on Radio Frequencies – Dynamic Scheduling and Access Coordination… has the potential to revolutionize spectral access by taking advantage of the ***most important aspect of the spectrum as a resource—its nearly instantaneous renewability***.

    Handbook of Frequency Allocations and Spectrum Protection for Scientific Uses, 2015

PCAST report 2012: https://obamawhitehouse.archives.gov/blog/2012/07/20/making-most-wireless-spectrum
CORF Handbook 2015: https://www.nap.edu/read/21774/chapter/1

Summary

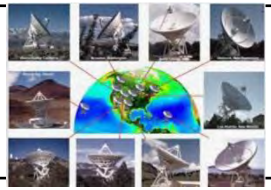
- **Enhanced regulatory protections are needed to preserve current research capabilities**
  - Radio Astronomy is vulnerable to interference despite existing protections; Optical/infrared has little regulatory oversight
- **NSF is investing in spectrum R&D for astronomical research and spectrum management more broadly, and workforce development/broadening participation**
  - Future Radio Astronomy research capability depends on dynamic spectrum sharing; Optical Astronomy depends on technical advances and industry/international coordination and collaboration with the growth of satellite megaconstellations

Credit: Sophia Dagnello, NRAO/AUI/NSF; NASA, STScI

Questions

Reference Material

Radio Astronomy Existing Protections

Site	Type of protection	Summary	Shortfall	Map
Green Bank Observatory **(in National Radio Quiet Zone)**	Geographic (47 CFR § 1.924) US113 US131 US161 US385 Allocations	Required coordination for all land and mobile transmitters	Limited protection from airborne transmitters including satellites	
Very Large Array	US113 US117 US131 US161 US385 Allocations	Controls observatory property only; limited protections at some frequencies	Limited geographic protections via footnote in certain bands	
Arecibo Observatory **(in Puerto Rico Coordination Zone)**	Geographic (47 CFR § 95.42) US113 US131 US385 Allocations	Fixed/base stations in frequencies below 15 GHz must coordinate, some coordination with air traffic	Limited protection from airborne transmitters including satellites	
Very Long Baseline Array (10 sites)	US131 US161 US385 Allocations	Controls observatory property only; limited protections at some frequencies	Limited geographic protections via footnote in certain bands.	

Required Coordination by Geographic Location

- National Radio Quiet Zone
- Puerto Rico Coordination Zone

Coordination by Frequency

- 10.6 – 10.7 GHz (US131)
- 2655 – 2690 MHz (urged to; US385)
- 81 – 86 GHz, 92 – 94 GHz, 94.1 – 95 GHz (US161)

Every “practicable” effort

- 4825 - 4835 MHz (US113)
- 14.47 – 14.5 GHz (US113)
- 1350 – 1400 MHz(US385)
- 4950 – 4990 MHz (US385)