Impacts to U.S. Ground-based Facilities

Dr. B. Ashley Zauderer-VanderLey
Senior Advisor for Facilities
Division of Astronomical Sciences
National Science Foundation

Talk Overview

I. National Science Foundation (NSF) Overview

II. Ground-based facilities in NSF's Astronomy portfolio

III. Impacts to Astronomical Ground-based facilities

IV. Existing regulatory protections and limitations

V. Workshops/Studies funded by NSF

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National Science Foundation (NSF)

With an annual budget of $8.5 billion (FY 2021), NSF is the funding source for approximately 25 percent of all federally supported basic research conducted by America's colleges and universities. In many fields, NSF is the major source of federal backing.

- NSF's goals -- discovery, learning, research infrastructure and stewardship – *Dark and quiet skies are critical for astronomical research.*
- NSF actively supports activities designed to *increase the participation of women and minorities and others underrepresented in science and technology.*

Bridging the digital divide

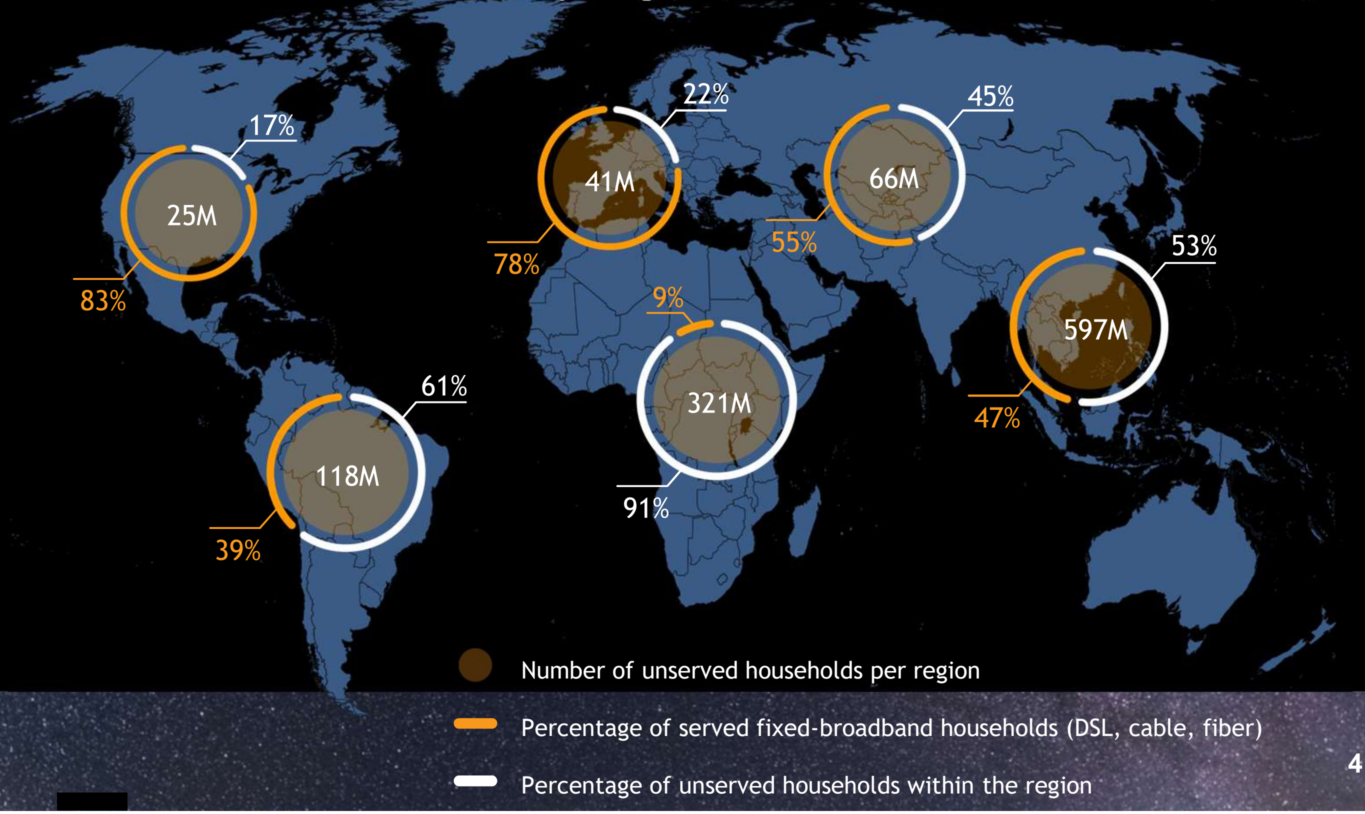
There are billions of people on Earth without reliable broadband. NGSOs will bridge the gap in places where service is unreliable or expensive, or where it doesn't exist at all.

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

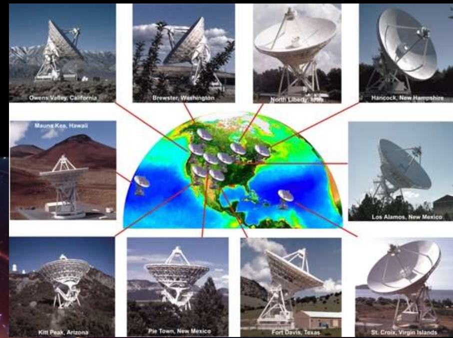


Division of Astronomical Sciences (AST)

- Within Directorate for Mathematical and Physical Sciences
- Support includes major facilities, mid-scale infrastructure, instrumentation development, individual investigator support
  - Key NSF Federally Funded Research and Development Facilities (FFRDCs):
    - National Radio Astronomy Observatory (NRAO)
    - National Optical-Infrared Research Laboratory (NOIRLab)
  - There are many other optical/infrared and radio telescopes critical to cutting-edge research that NSF supports that are not part of these two FFRDCs.

Major Radio Facilities

- National Radio Astronomy Observatory (NRAO)
  - Very Long Baseline Array (VLBA)
  - ALMA
  - VLA
  - Central Development Laboratory
- Green Bank Observatory



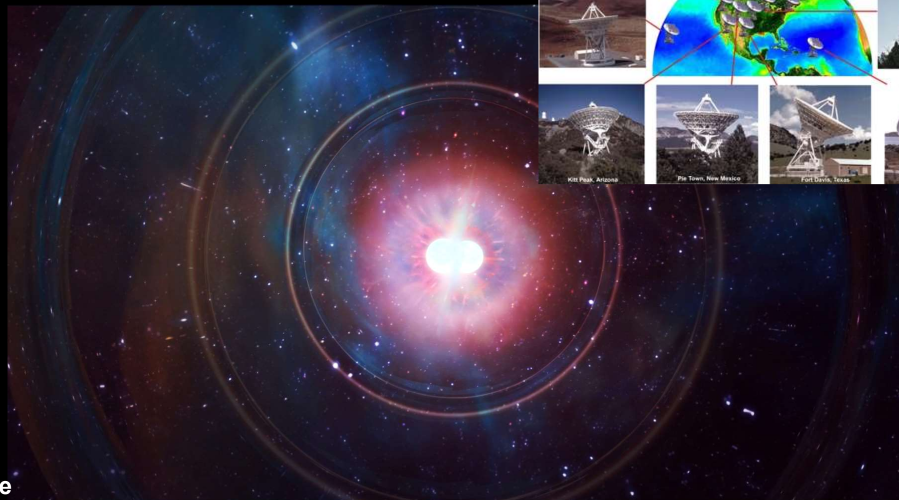


Image: Artist's impression of gravitational waves emitted during merging of neutron stars. **Astronomers used the VLBA, VLA and GBT to make radio observations of the gravitational wave event; may aid in measurement of the Universe's rate of expansion.** *Nature Astronomy, 3, 940-944 (2019).*

Credits: NRAO/AUI, SeaWiFS Project (NASA/GSFC and ORBIMAGE), NRAO/AUI/National Science Foundation

Major Radio Facilities

- National Radio Astronomy Observatory (NRAO)
  - VLBA
  - Atacama Large Millimeter/submillimeter Array (ALMA)
  - VLA
  - Central Development Laboratory
- Green Bank Observatory

Image: International team of astronomers discovers most distant quasar more than 13 billion light-years from Earth powered by a supermassive black hole more than 1.6 billion times more massive than the Sun. **Scientific result included observations from ALMA, the 6.5-meter Magellan Baade telescope, the Gemini North telescope and W.M. Keck Observatory in Hawaii, and the Gemini South telescope in Chile.** *ApJ Letters, Vol. 907, Number 1 (2021).*

Credits: ALMA (ESO/NAOJ/NRAO) (Creative Commons Attribution 4.0 International); NOIRLab/NSF/AURA/J. da Silva

Major Radio Facilities

- National Radio Astronomy Observatory (NRAO)
  - VLBA
  - ALMA
  - Karl G. Jansky Very Large Array (VLA)
  - Central Development Laboratory
- Green Bank Observatory

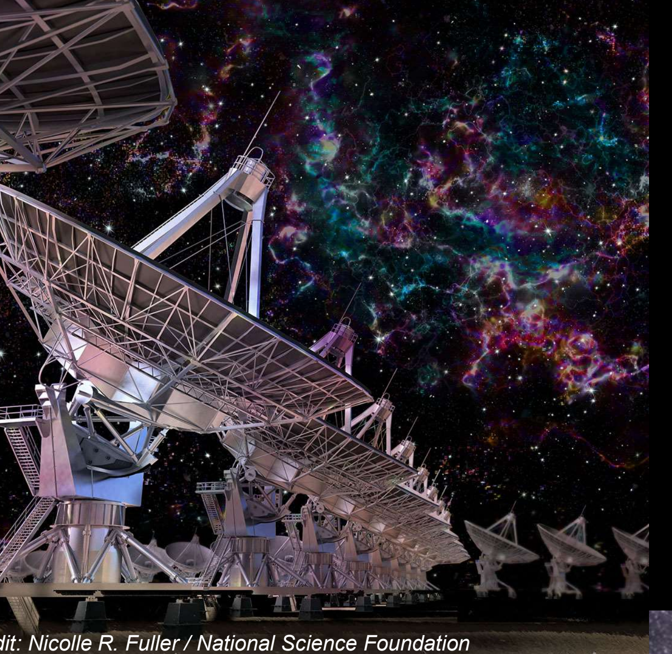


Image: Illustration of the Karl G. Jansky Very Large Array (VLA) in Socorro, New Mexico. **These 27 radio antennas are capable of observing between 1.0 and 50.0 GHz as well as at select lower frequencies in the 90 cm band.**

Credit: Nicolle R. Fuller / National Science Foundation

Major Radio Facilities

- National Radio Astronomy Observatory (NRAO)
  - VLBA
  - ALMA
  - VLA
  - Central Development Laboratory (CDL)
- Green Bank Observatory

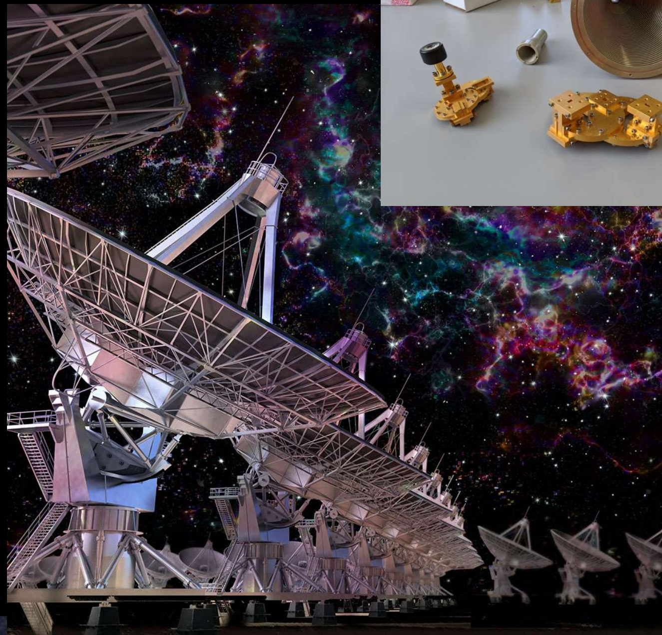


Image: Selected waveguides and feedhorns. CDL performs innovative research and development on necessary instrumentation and processing advances for radio astronomy including antennas, transistors, low-noise amplifiers, and cryogenic coolers.

Credits: Nicolle R. Fuller / National Science Foundation, NRAO/AUI/NSF

Major Radio Facilities

- National Radio Astronomy Observatory (NRAO)
  - VLBA
  - ALMA
  - VLA
  - Central Development Laboratory
- Green Bank Observatory

Image: Complex carbon-based molecules discovered with the Green Bank Telescope in the interstellar medium using observations in the range 8 to 33.5 GHz. While in the U.S. National Radio Quiet Zone, this zone affords no special protections from satellite downlinks. *Science, Vol. 371, No. 6535 (2021)*

Credit: National Science Foundation / Glen Langston

Major Optical Facilities and Instrumentation

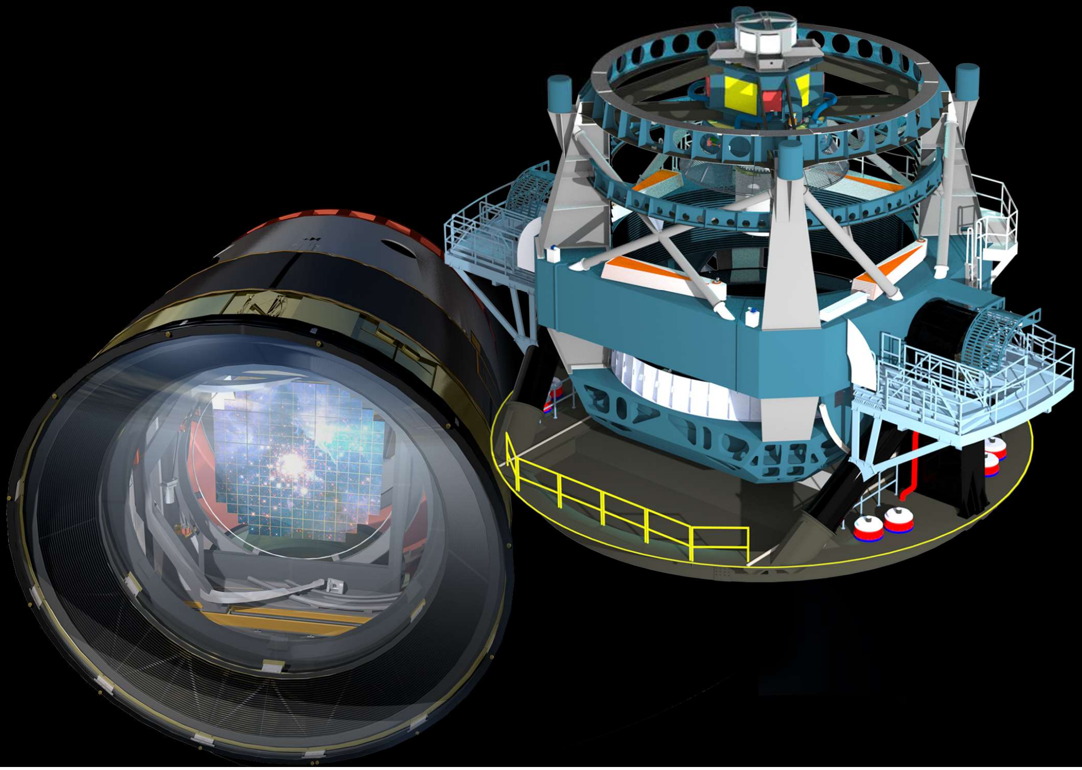
- NOIRLab
  - Midscale Observatories: Kitt Peak National Observatory & Cerro Tololo Inter-American Observatory
  - Gemini Telescopes
  - Community Science and Data Center (CSDC)
  - Vera C. Rubin Observatory

Image: Gemini Observatory's Gemini South Telescope in Chile. The Gemini Observatory consists of twin 8.1-meter diameter optical/infrared telescopes; the other is located on Mauna Kea, Hawai'i. These telescopes are capable of spectroscopy and imaging, with many available instruments.

VERA C. RUBIN OBSERVATORY

LSST

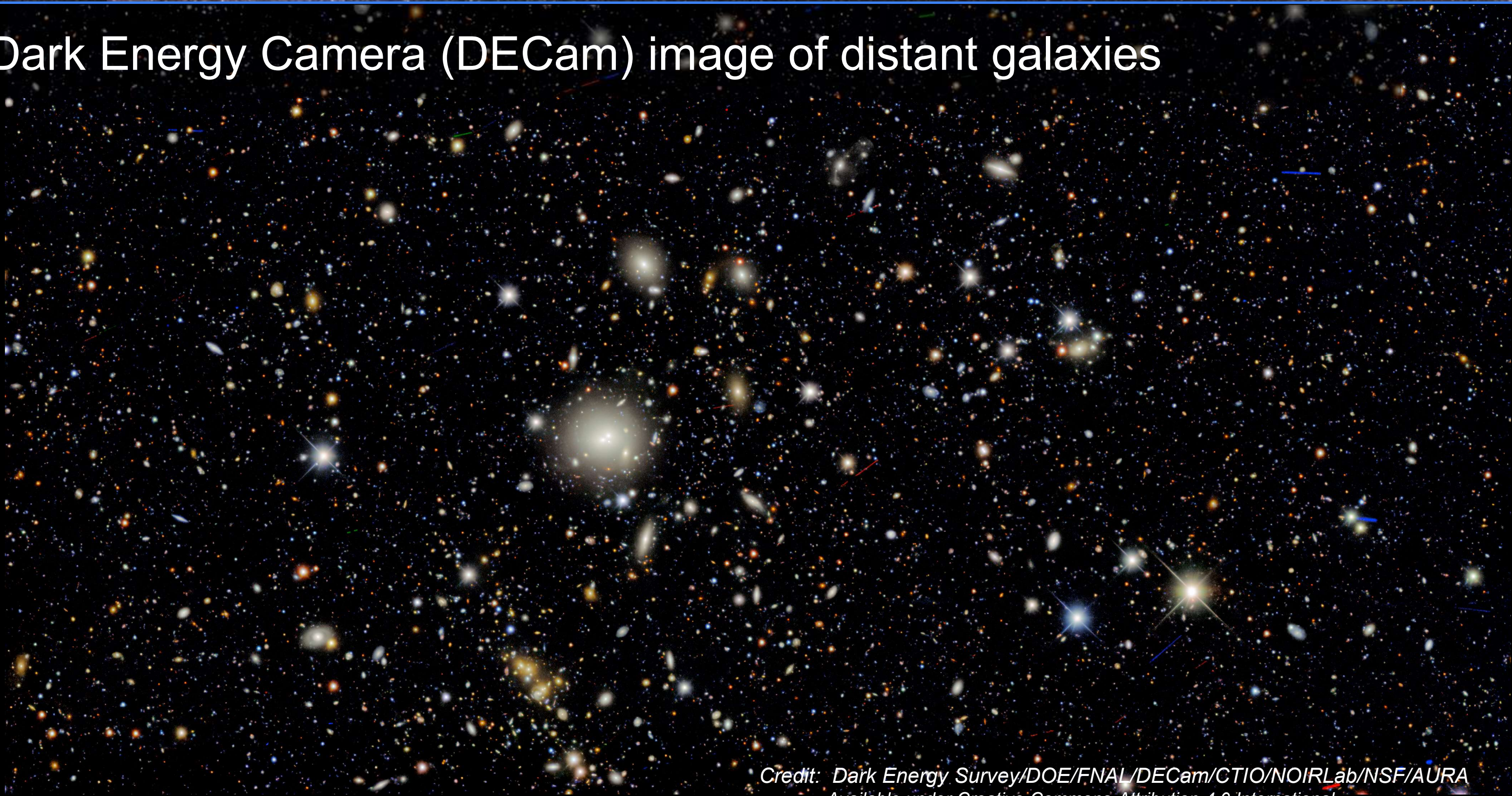
Legacy Survey of Space and Time



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**

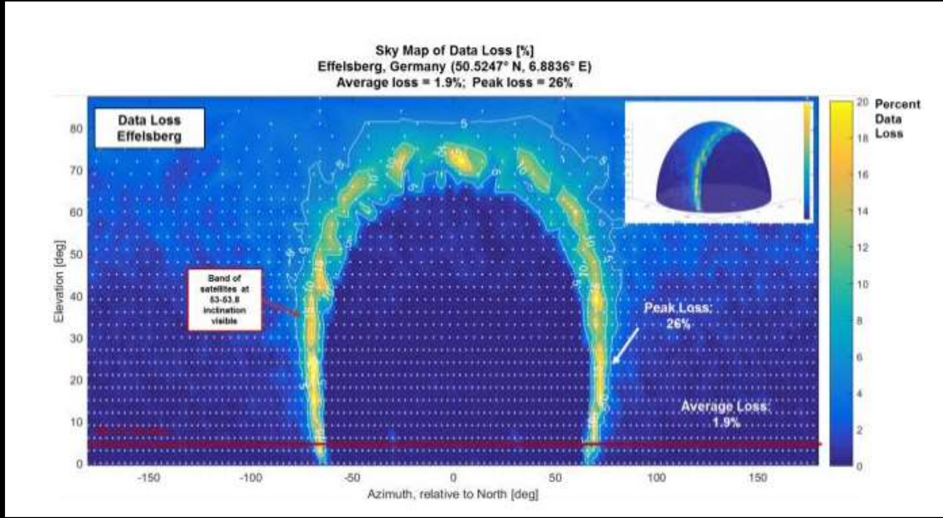
Dark Energy Camera (DECam) image of distant galaxies



Credit: Dark Energy Survey/DOE/FNAL/DECam/CTIO/NOIRLab/NSF/AURA

Impacts to Radio Facilities

- Up to 5% data loss permitted for protected radio astronomy passive band (10.68 – 10.7 GHz); larger impacts in some areas of the sky



Credit:ECC Report 271 (26 January 2018)

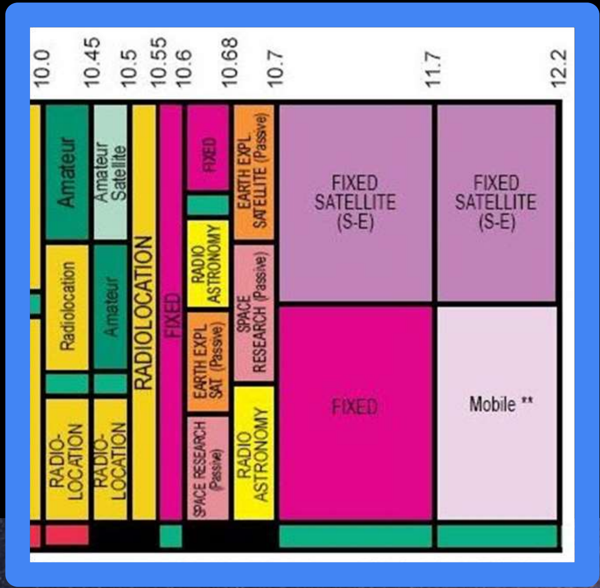
Radio Astronomy Protections

- U.S. domestic rules: US131 Coordination agreement for downlinks
- National Radio Quiet Zone: coordination of mobile/fixed

US131 In the band 10.7-11.7 GHz, non-geostationary satellite orbit licensees in the fixed-satellite service (space-to-Earth), prior to commencing operations, shall coordinate with the following radio astronomy observatories to achieve a mutually acceptable agreement regarding the protection of the radio telescope facilities operating in the band 10.6-10.7 GHz:

Observatory	North latitude	West longitude	Elevation (in meters)
Arecibo Observatory, PR................	18° 20' 37"	66° 45' 11"	497
Green Bank Telescope (GBT), WV.............	38° 25' 59"	79° 50' 23"	807
Very Large Array (VLA), Socorro, NM.........	34° 04' 44"	107° 37' 06"	2115
Very Long Baseline Array (VLBA) Stations:			
Brewster, WA..................................	48° 07' 52"	119° 41' 00"	250
Fort Davis, TX.................................	30° 38' 06"	103° 56' 41"	1606
Hancock, NH....................................	42° 56' 01"	71° 59' 12"	296
Kitt Peak, AZ....................................	31° 57' 23"	111° 36' 45"	1902
Los Alamos, NM..................................	35° 46' 30"	106° 14' 44"	1962
Mauna Kea, HI....................................	19° 48' 05"	155° 27' 20"	3763
North Liberty, IA................................	41° 46' 17"	91° 34' 27"	222
Owens Valley, CA................................	37° 13' 54"	118° 16' 37"	1196

United States (US) Footnotes 4-134 *May 2013 Edition (Rev. 9/2015)*



Impacts to Radio Facilities

- Radio astronomy facilities also observe in non-protected bands in remote locations; no location on Earth is remote enough to escape satellite transmissions -> problematic for all radio astronomy facilities and CMB telescopes in Chile and at the South Pole
- Out-of-band and spurious emissions into protected radio astronomy bands may be a problem in aggregate
- Sidelobes in aggregate may be problematic

Credit:ECC Report 271 (26 January 2018)

Pathways forward for Radio Astronomy Facilities

- Domestic coordination agreements
- International coordination to achieve 5% international aggregate impact recommendation when more than 2 satellite providers (e.g., each is allowed 2%, but 5% total)
- Smaller satellite footprints are desirable: avoid main beam illumination of key radio astronomy sites
- Minimize out-of-band, spurious emissions and sidelobes from satellites; avoid placement of user terminals and uplinks near Radio Astronomy facilities
- Astronomers continue to work on developing robust receivers and post-processing algorithms

Credit:ECC Report 271 (26 January 2018)

Impacts to Optical Facilities

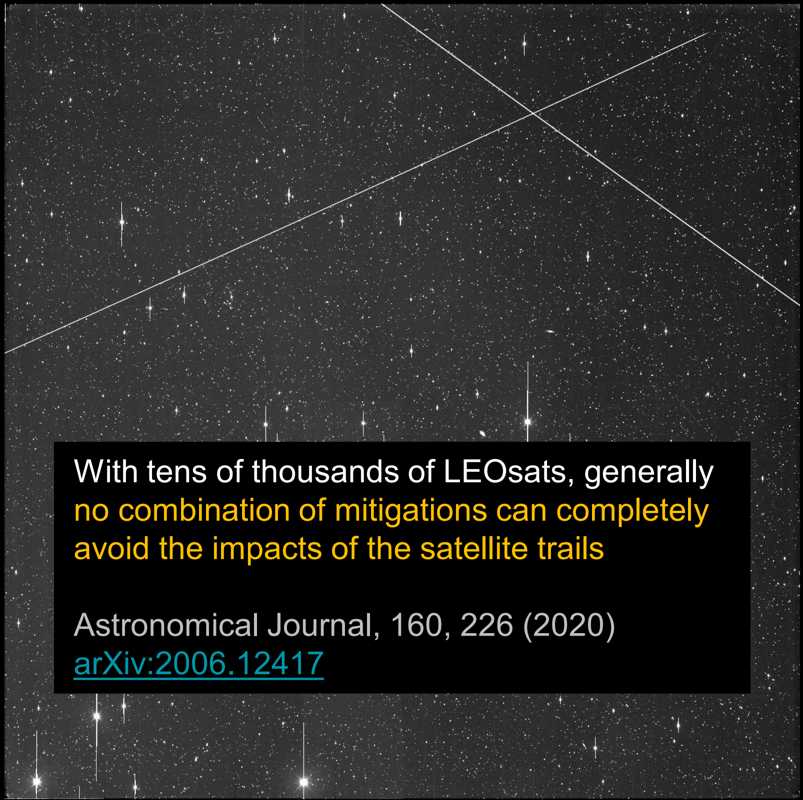
2020
~6,000 satellites

2030
10,000+ satellites

2040
40,000+ satellites

Optical image of NGC 5353/4 galaxy group (25 May 2019)

Image Credit: Victoria Girgis / Lowell Observatory - https://www.iau.org/public/images/detail/ann19035a/



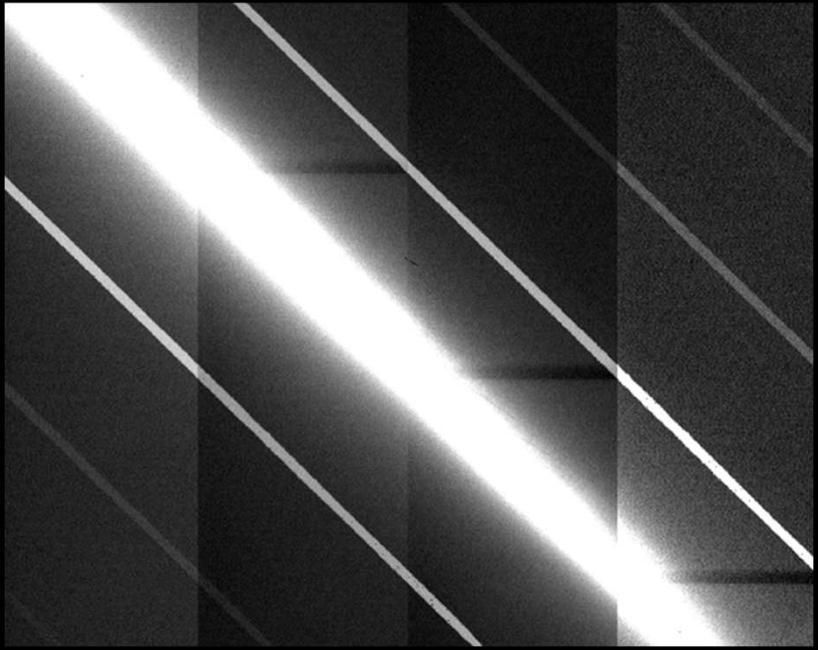
With tens of thousands of LEOsats, generally no combination of mitigations can completely avoid the impacts of the satellite trails

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

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

John Tonry
U Hawaii

How do bright satellites affect observations on telescopes?



Diversity of impact to optical spectroscopy and imaging

Examples from imaging:

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

NSF Funded Workshops and Studies

- **SATCON I and SATCON II -**
  - Hosted by NSF's NOIRLab and the American Astronomical Society; we appreciated international participation!
  - Four working groups: Observations, Algorithms, Community Engagement, Policy
    - SATCON I: Mitigation recommendations that include quantitative metrics: https://aas.org/satellite-constellations-1-workshop
    - SATCON II: Define and quantify resources, metrics, and collaborations needed to implement recommendations;
      - Engage astronomers and satellite operators collaboratively in exploring framework and developing policy points for operations in LEO;
      - Increase diversity of stakeholders and perspectives working to address the challenges and opportunities.
      - Report forthcoming; public press conference available - https://www.youtube.com/watch?v=7DF99GIIR04

NSF Funded Workshops and Studies

- **JASON report -** ***"The Impacts of Large Constellations of Satellites"***
  - Independent science advisory group
  - Charged by NSF to better understand
    - Types and numbers of spacecraft planned in next decade;
    - The current regulatory process;
    - To characterize types of interference and types/range of observations being made and foreseen in the future; and
    - Suggest additional data that should be gathered to understand the scope of the problem for the future.
  - Report also considered long-term sustainability and space debris
  - Full report available: https://www.nsf.gov/news/special_reports/jasonreportconstellations/

JASON report: Recommendations for Optical/Infrared

- Highest priority: If at all possible, avoid higher orbits above 600 km. Orbits at 1000 km and higher are visible for a much longer fraction of the night.
- Continuous, accurate position information can enable astronomical observations to plan and avoid directions where satellites are present
- NSF should support mitigation, including software for community and optical facilities
- Rubin Observatory should undertake a comparative study of other known sources of systematic error due to saturation and cross-talk and assess incremental impact of satellite trails relative to other sources of error.
- Rubin Observatory should use 2 x 15 second observations rather than a single 30 second for lessening satellite impact on data
- Absent significant regulation of large constellations, astronomical community needs to be prepared for a future with tens of thousands of LEO satellites bright enough to impact observations

https://www.nsf.gov/news/special_reports/jasonreportconstellations/

JASON report: Recommendations for Radio Astronomy

- Radio – document impact of large constellations
- Protect bands currently allocated primarily to radio astronomy; out-of-band leakage in only a fraction may have significant impacts
- Get quantitative measurements of RFI in both protected and unprotected bands; baseline measurements needed
- NSF should support efforts to mitigate on existing and future radio astronomy facilities. Mitigations likely to involve hardware and software.
- NSF should support efforts to increase regulatory protection of radio astronomy sites, vulnerable to emissions.

https://www.nsf.gov/news/special_reports/jasonreportconstellations/

JASON report Recommendations for CMB science

- Satellite vendors should power off transmission above 20 GHz when clear horizon of several prime CMB/radio observing sites, especially Atacama site of ALMA and Simons Observatory and the South Pole.

https://www.nsf.gov/news/special_reports/jasonreportconstellations/

JASON report Recommendations - General

- Regulatory licensing should include a 3-step process to try and avoid catastrophic debris generation
- Publish accurate locations of satellites (<50 m)
- Evaluate collision risks and don't neglect ascent and descent phases of satellite's lifetime

https://www.nsf.gov/news/special_reports/jasonreportconstellations/

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

NSF Actions

- Sponsorship of, and coordination with, work at FFRDCs (e.g., NRAO, NOIRLab)
- Working with satellite operators (e.g., coordination agreements with SpaceX, others)
- Coordination with government agencies (Department of Commerce and NTIA, FCC, NASA, OSTP)
- Work in international forums (ITU-R Working Party 7D, COPUOS)

NSF Actions

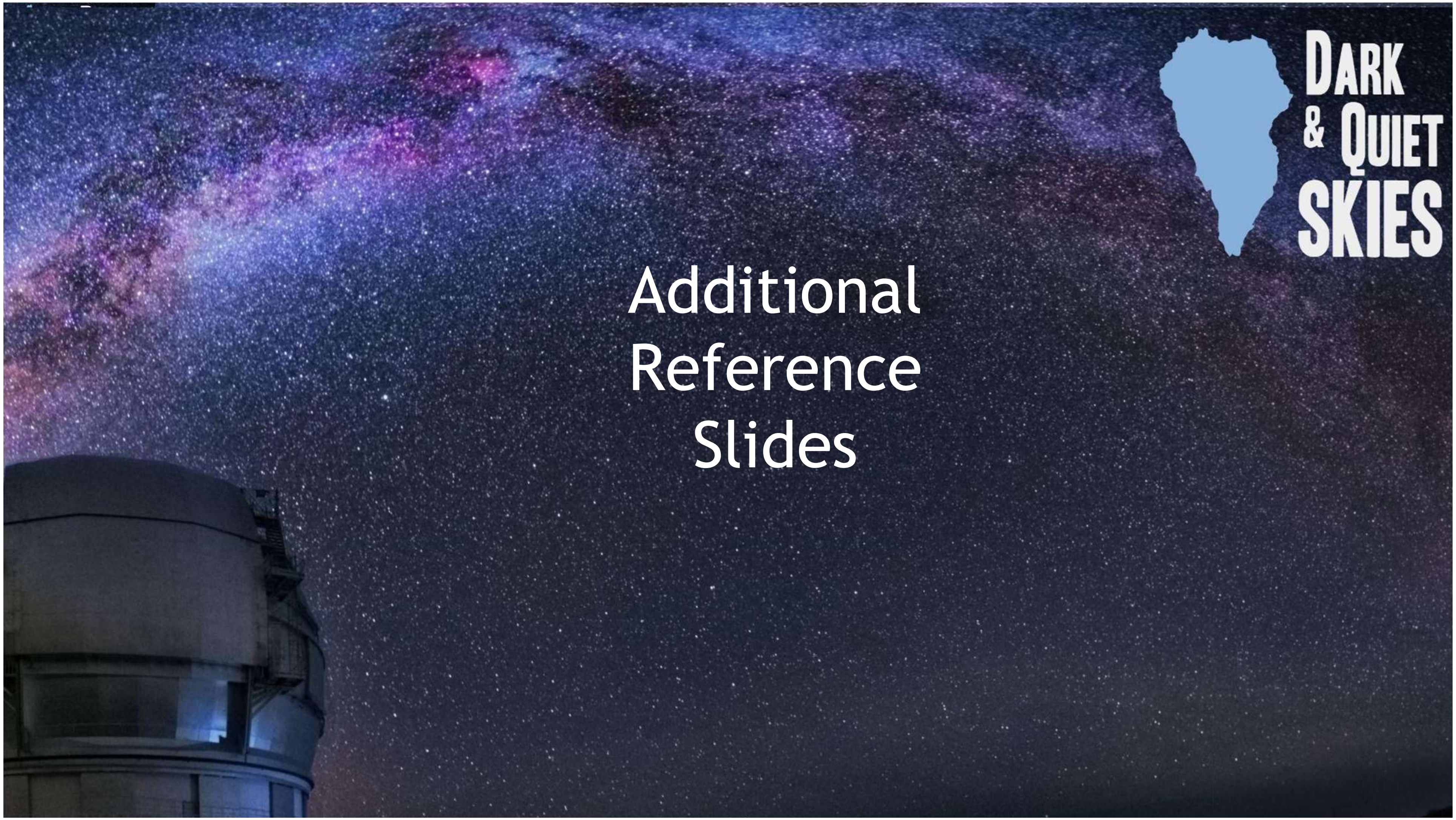
- Spectrum Innovation Initiative
  - Funding opportunity to address pressing challenges arising from growing demand for usage of the electromagnetic spectrum, including passive and active applications.
  - Includes four thrusts:
    - National Center for Spectrum Innovation: Awarded recently to SpectrumX (*spectrumx.org*)
    - National Radio Dynamic Zone: To pilot avenues of more effective dynamic spectrum sharing as we think about next generation quiet and coordination zones and pilot new technologies
    - Spectrum Integrative Activities: Solicitations like SWIFT (NSF 21-539)
    - Education and Workforce Development

https://nsf.gov/mps/oma/spectrum_innovation_initiative.jsp

Summary

- Tradeoffs between stakeholders (optical/infrared, radio) – one size does not fit all
- There is a total quantity of satellites for which mitigations become harder; e.g., currently there are fields of view without satellites in view
- Work to be done by both satellite operators and astronomy community
  - Radio: not all frequency downlinks currently require any coordination; avoidance of main-beam illumination to key sites vey helpful (smaller footprints better), but doesn't eliminate impact
  - Optical: achieving 7th magnitude brightness a key goal (closer orbital altitudes better); integrating satellite location into telescope schedulers will be useful
- Provision of broadband is an important goal; let's keep working together!


DARK
& QUIET
SKIES
Questions and
Comments:
esm@nsf.gov
NSF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Additional
Reference
Slides

Early solutions

- Some promising improvements from darkening or including visors to block sunlight; when satellite operators implement technical upgrades with more capable satellites, these should be considered.
- Work with industry to develop joint operations solutions to minimize science impact including <u>tools for efficient scheduling</u> and <u>predictive models</u>.
- Develop observing strategies and new data analysis methods to partially correct for statistical and systematic effects caused by satellite trails.
- Explore science impacts of residuals via end-end simulations.

However, *even if mitigations work*, evidence of satellite trails will clearly be in the data – complicating data analysis, requiring longer science missions, limiting discoveries

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