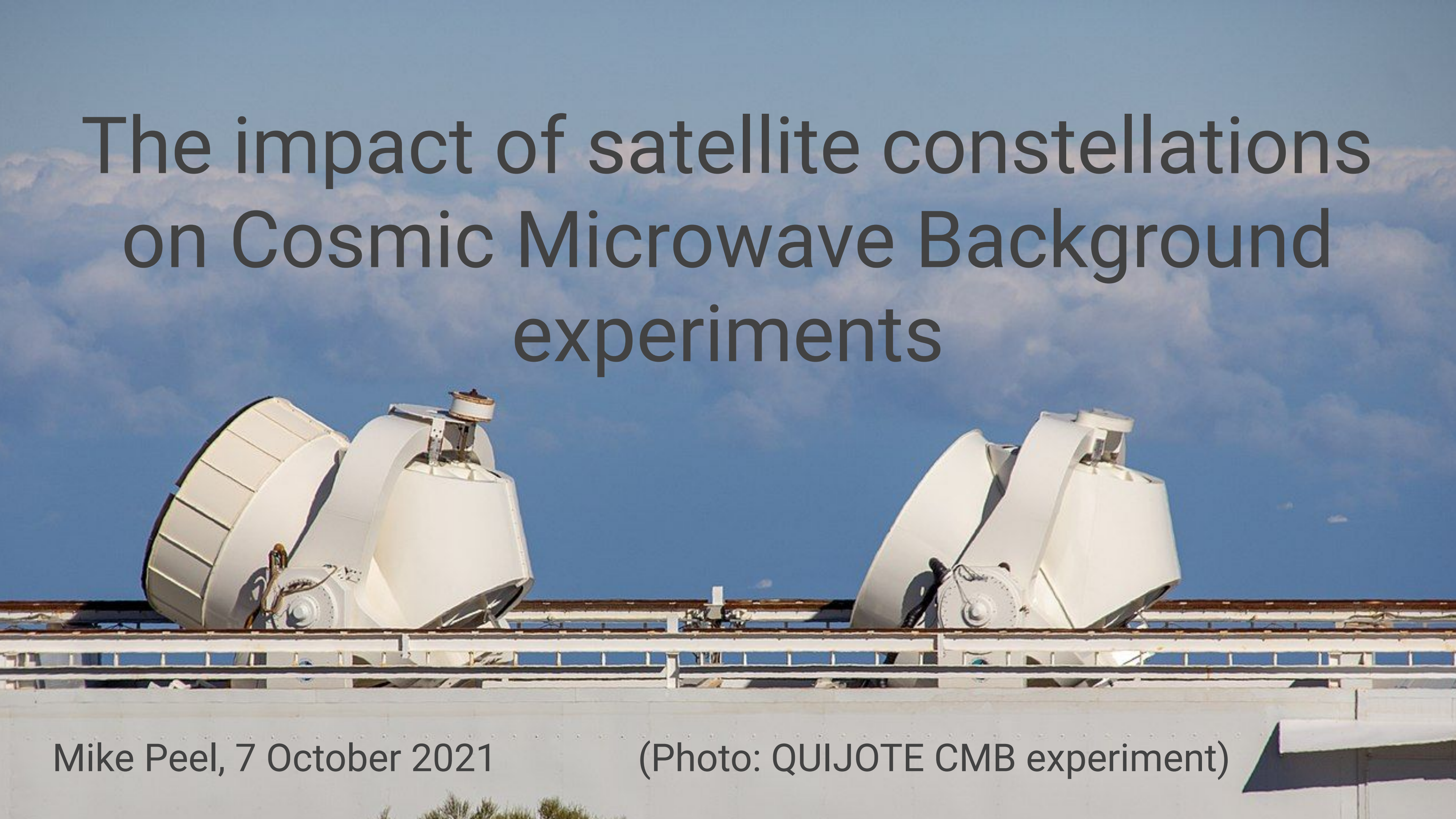
The impact of satellite constellations on Cosmic Microwave Background experiments



Mike Peel, 7 October 2021

(Photo: QUIJOTE CMB experiment)

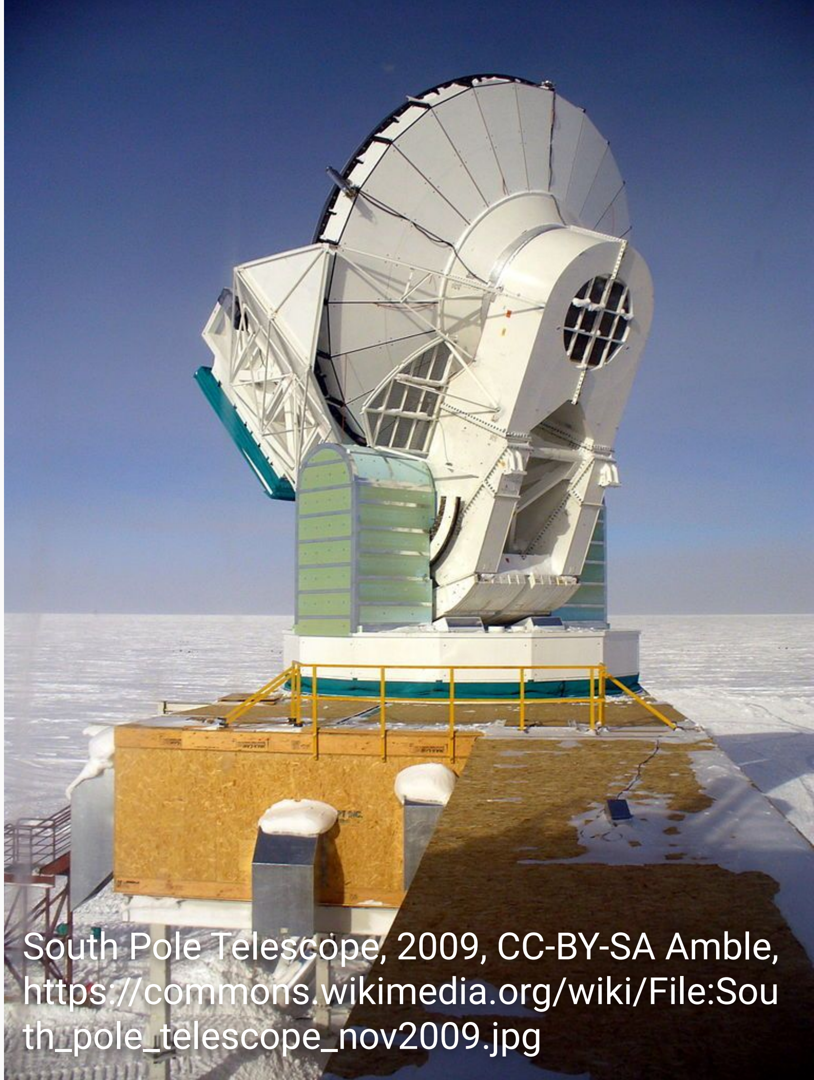
Observing the earliest light in the Universe

At frequencies 10–300 GHz

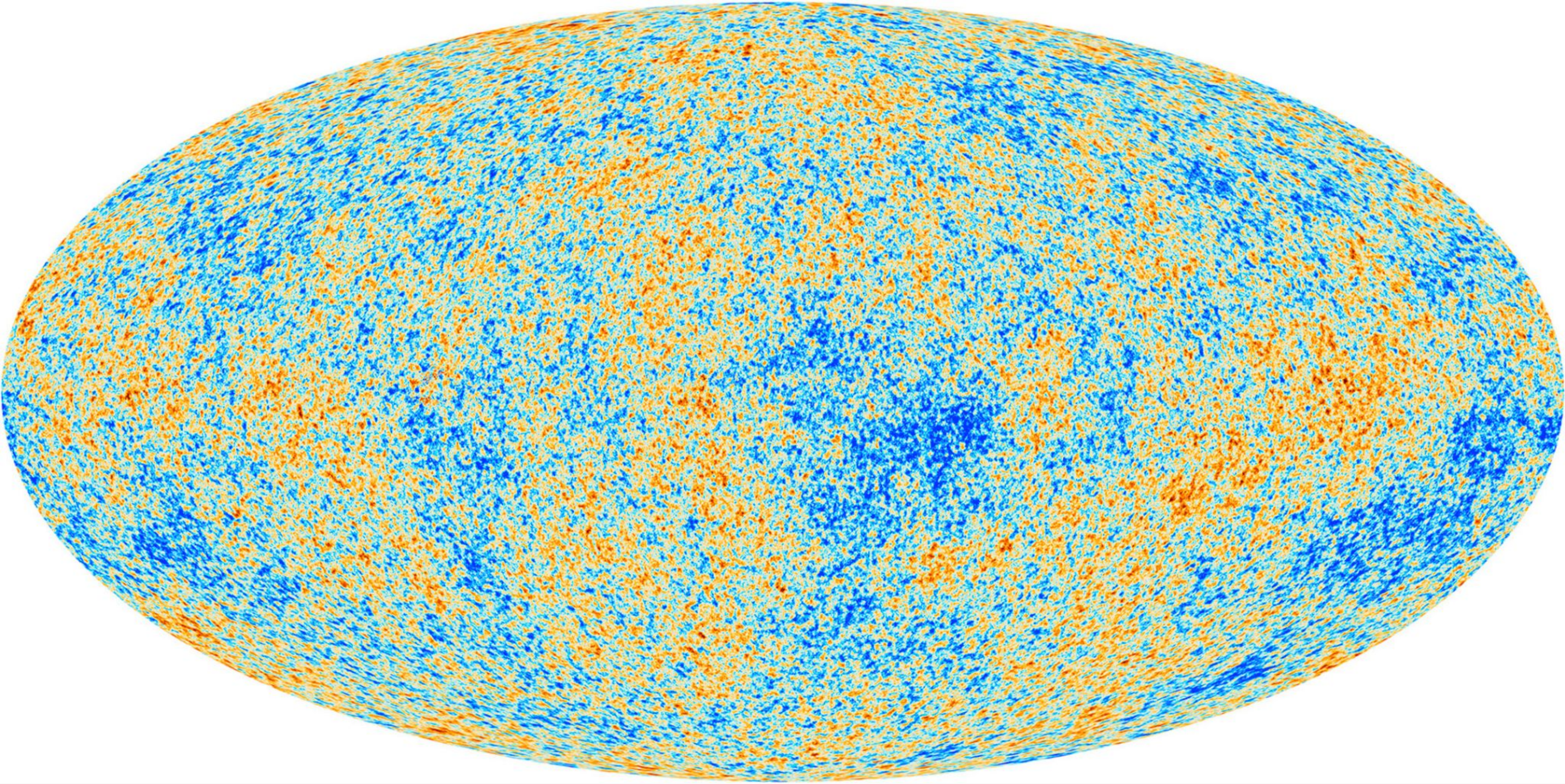
Large angular scales

High sensitivity experiments costing millions to billions

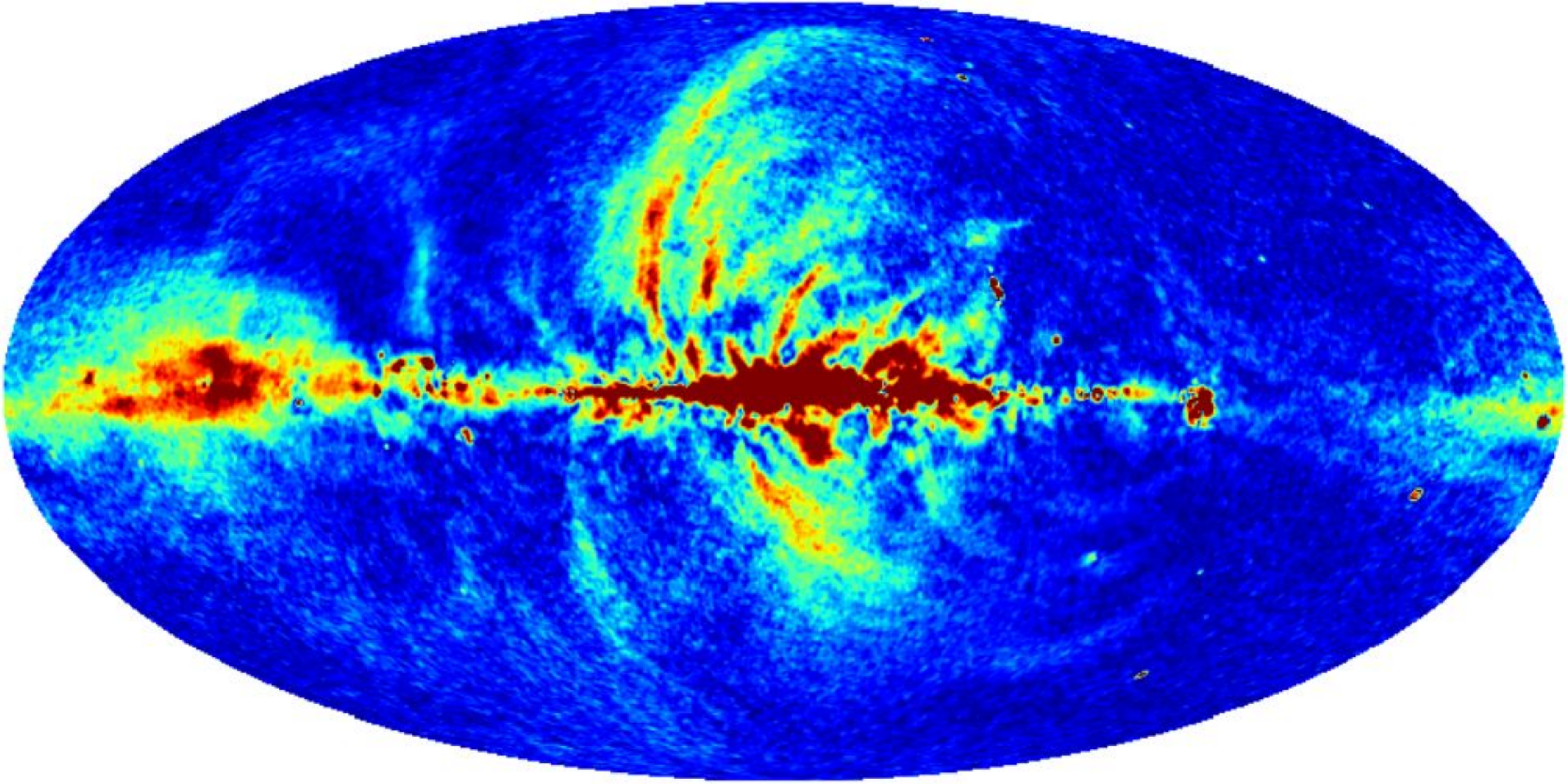
Experiments in remote locations around the world (South Pole, Chile, Tenerife, ...)



South Pole Telescope, 2009, CC-BY-SA Amble, https://commons.wikimedia.org/wiki/File:South_pole_telescope_nov2009.jpg



What we want to observe: the cosmic Microwave Background
(full sky, in intensity, from the Planck Satellite—polarisation fainter)

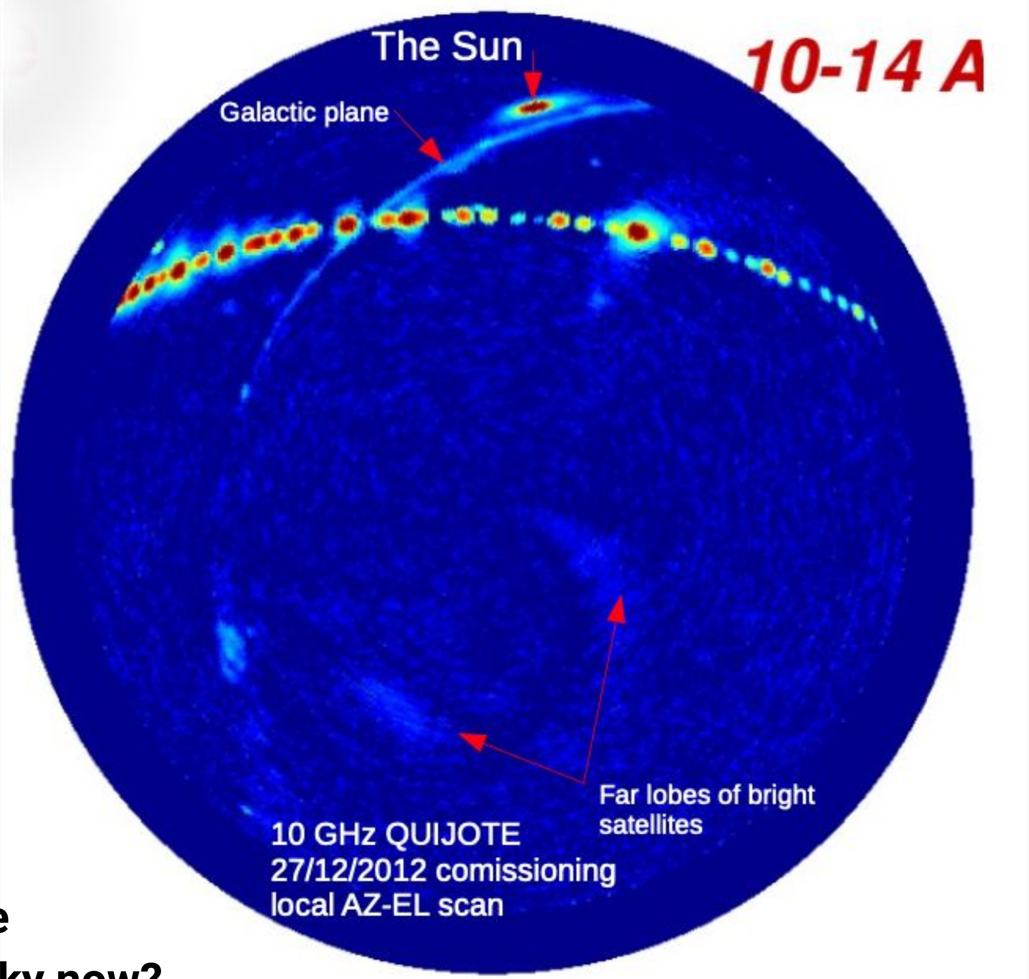


What we actually see: all sky at ~20 GHz combining Planck+WMAP satellites
Large scale polarised Synchrotron emission (similar at high freq from dust emission)

What we really see

- 10–20 GHz local sky from Tenerife
- The Sun, our Galaxy, ...
- Geostationary satellites!
    - **Brighter than the sun!**
- Satellite signals reflected from the edges of the dish
    - (Using special telescopes to minimise sidelobes!)
- This was 2012...
- Satellite numbers now doubled
- Restarting observations this year...

Will we see the equivalent of the geostationary band everywhere in the sky now?



Why is there a problem?

- We observe **broad frequency ranges** (reserved bands very narrow)
  - Sensitivity goes as sqrt(bandwidth x integration time)
  - Can only see some phenomenon at some freqs (spectral lines, spinning dust, ...)
- We survey **large sky areas** to observe earliest moments (largest scales) in the Universe
- We need **high sensitivity** to observe very faint signals
  - Using 10,000+ pixels (large focal planes—unprecedented at radio frequencies!)
  - Observe for multiple years
- Previously could **avoid interference** by going to remote parts of the planet
  - Local radio quiet zones: no transmitters/mobiles, sometimes cars/cameras banned!
  - >10 GHz frequencies mostly clear free of interference—until now!

What do signals look like? (small dish)

Presumed **Starlink** satellites

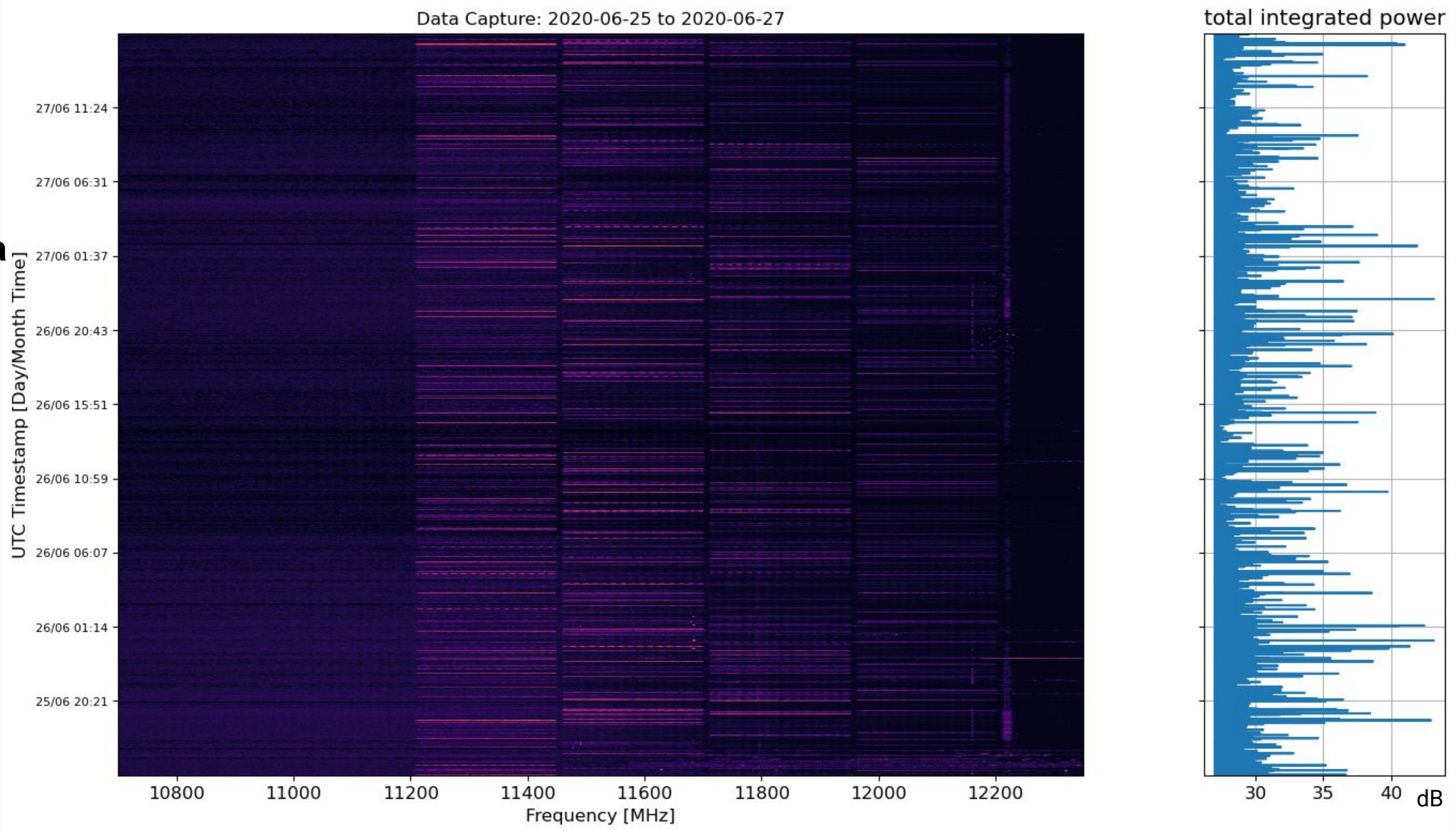
Single pointing direction

11.2-12.2GHz **data badly contaminated** (1GHz band!)

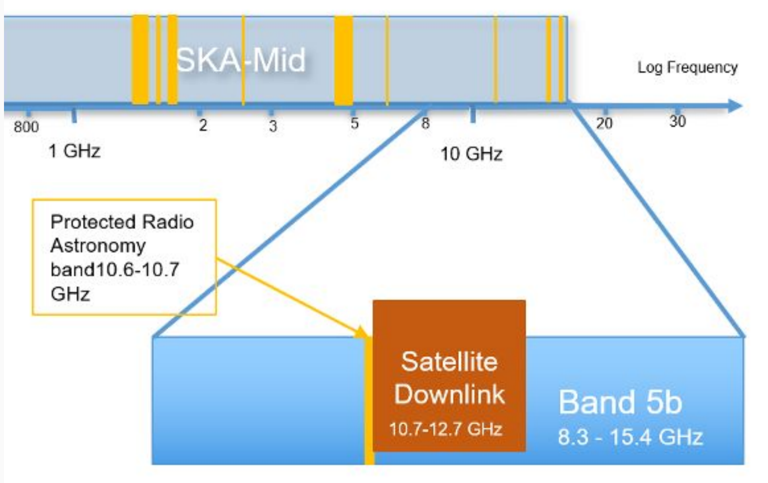
Variable (due to satellite movement)

This is over 1.5 days

Thanks to Federico Di Vruno (SKAO)



What will be impacted?

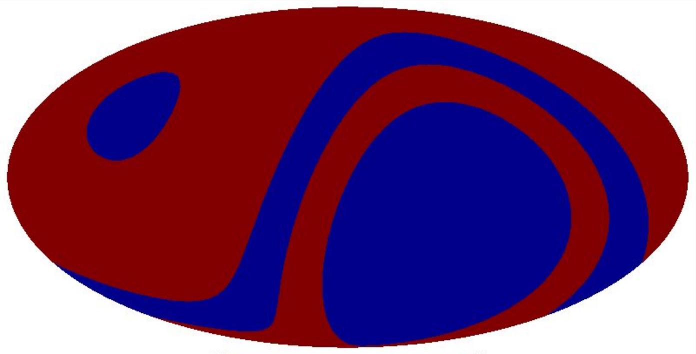


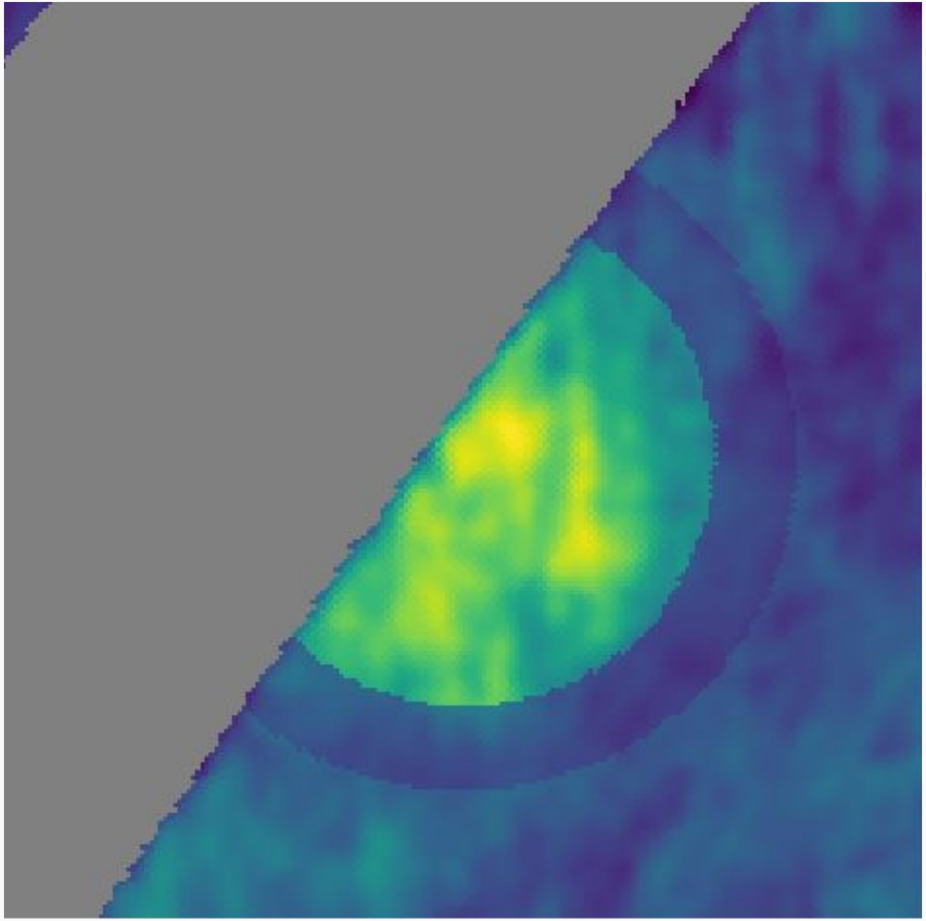
- Big radio projects running or being planned:
- **CMB:** CMB-S4 ($700m), GroundBIRD (>$3m), QUIJOTE (>€10m), ...—Single dishes with 0.1% sidelobes: still see satellites in sidelobes
- **Interferometers:** Square Kilometer Array ($1b?), ALMA ($1.4b), VLA (>$100m), eMerlin (>£50m), VLBI (>$50m), ...
  - See satellites at 500 km with 1000 km separated telescopes!
- **Single dishes:** Sardinia Radio Telescope (>€70m), Green Bank Telescope (>$95m), Effelsberg (>€50m)
- **Multi-frequency surveys** (separate different astronomical components via frequency)

(All cost estimates are approximate based on public info)

Real on-sky impact?

- Zeta Ophiuchus
- One of my favourite sources
- Really complex to understand
- Seems to have more high-freq signal than expected (but not spinning dust?)
- Multi-freq component separation would be nice
- But we only see half the source with QUIJOTE—thanks GEO sats!
- (Maybe could be filled in with a southern telescope—but $$$!)





How radio astro can manage the issue (1/2)

- Use **digital backends** to split broadband receivers into narrow frequency channels
  - Can be selective about received frequencies within bandwidth
  - Expensive! Particularly at high frequencies.
  - Can only be used for some receivers (not bolometers/KIDs/etc.)
  - Depending on satellite transmissions, may still lose a lot of bandwidth
- **Avoid** looking at satellites
  - Need to predict where satellites will be, and actively steer around them.
  - Difficult for survey telescopes scanning at fixed elevations
  - Sidelobes still an unavoidable issue

How radio astro can manage the issue (2/2)

- **Early observations**
  - Feedback to satellite operators to minimise bandpasses/sidelobes
  - Knowing **out-of-band transmissions** from satellites particularly important (e.g., see Iridium transmissions in protected radio astro band!)
  - **Share observations** within radio astro community
- **Observe for longer**
  - Estimates depend on bandwidth and time lost, but perhaps 50% longer.
  - Construction costs same—but more maintenance/running costs.
  - **Huge impact on costs** of observing and analysis/scientist time (varies between projects, can easily be >50% of telescope costs—or more!)

How operators can help radio astronomy

- **Narrower frequency bands** and strict control of out-of-band signals (& tested!)
  - Best thing that can be done—but remember out-of-band leakage!
- **Fewer satellites** (and less duplication of coverage)
  - Turn them off when passing over all radio telescopes (pro & amateur)
- **Steerable beams**? (Avoid telescopes, or just cause worse sidelobes?)
  - Need to confirm how this impacts telescopes in reality.
- **Fainter transmissions** (lower power—and **stable**!)
- More **publicly available information** (via SatHub?)
  - Bandpasses/transmission frequencies (from measurements)
  - Accurate position predictions

General issues

- Need **better**, and more **transparent**, **policy decisions**
  - Increased awareness of the impact on astronomy (both radio + other wavelengths) before approval!
  - Requiring more publicly available info (positions etc.)
- Need **more astronomy funding**
  - Solutions require more telescope hardware, and more development time
  - Or 50% more observing time (could reduce by doubling telescopes/people)
  - Could satellite operators contribute to this extra cost?
- Need **more coordination**
  - SatHub & IAU centre critical
  - Should do a survey of all potentially affected observatories?
- Need to **document more** (JASON report was good; SATCON2 report soon)

Summary

Radio astronomy strongly affected by satellites

Particularly by active transmissions

Digital back-ends can help, but expensive

Satellite swarms could close spectral windows for radio astronomy forever

Need to talk to each other to find solutions (technical + social + funding)

SatHub + IAU centre critical to have more transparent communication

(BTW, what is the military doing...?)

Acknowledgments

- With thanks to:
  - The SATCON2 Observation Working Group, including Meredith Rawls, Darcy Barron, Olga Zamora, ...
  - The QUIJOTE collaboration, including Bob Watson, Jose Alberto-Rubino, Ricardo Genova Santos, Federica Guidi, ...
  - The SKA Organisation, including Federico Di Vruno, ...
  - Others at IAC & elsewhere, including Amanda Aguiar, Simon Garrington, ...
- (This is a significant issue affecting global collaborations!)

Digital back-ends?

- Rather than detecting RF within a broad band, split into multiple frequencies
- Replaces the board-band detector (~€100) with a digital system
- Can do ~16,000 channels with one FPGA and a pair of ADCs now
- Really expensive! Circa ~€20k for 2.5GHz bandwidth (need 4+ per pixel!)
- ROACH (old), SKARAB (new), Xilinx (commercial) + others
- They are not compatible with some detector types:
  - OK for radiometers (coherent transmission of freqs+phase)
  - But bolometers/KIDs detect broadband signals defined by optical filters
- Recovered bandwidth depends on satellite transmissions (might be <50%?)