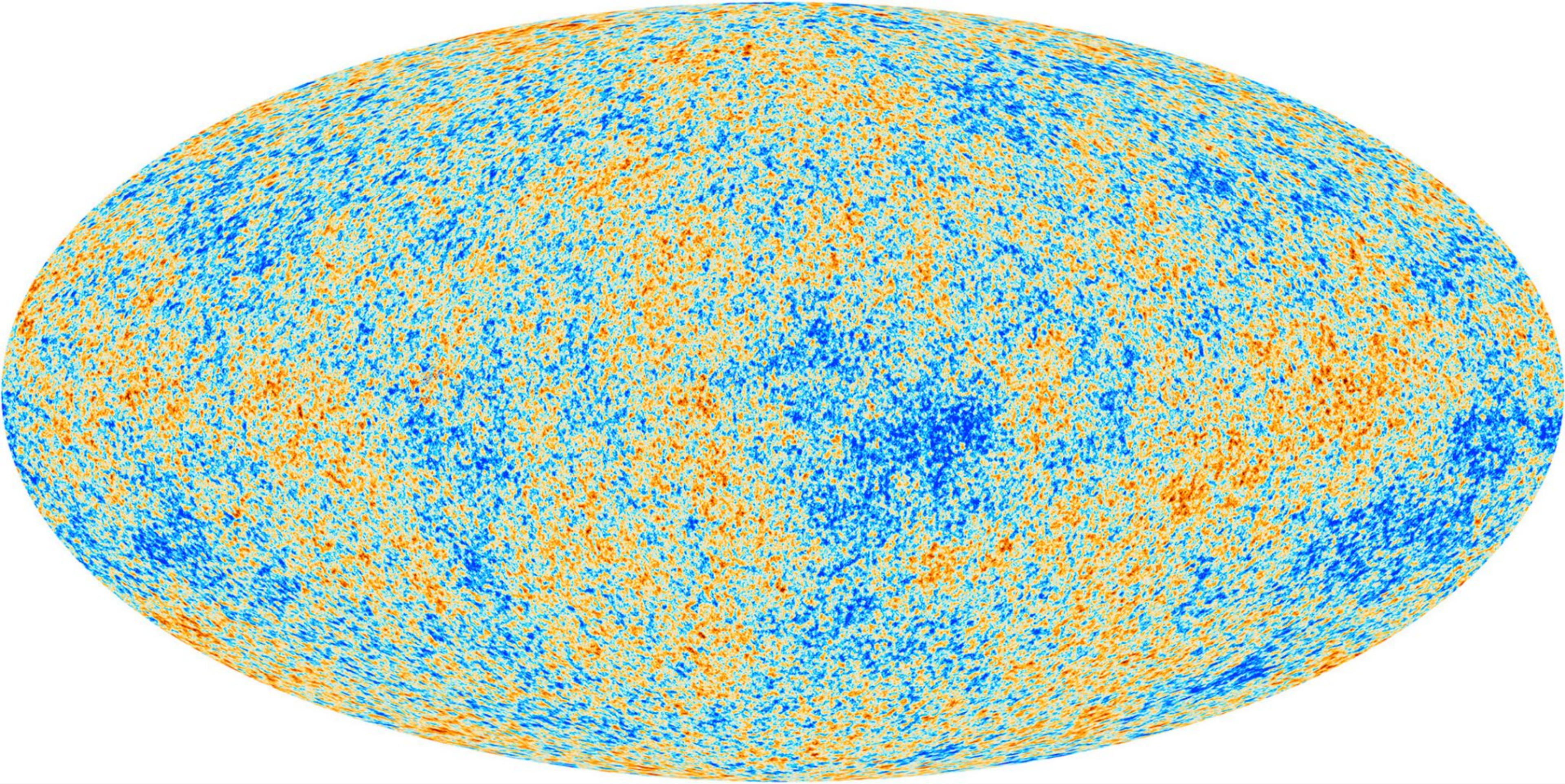
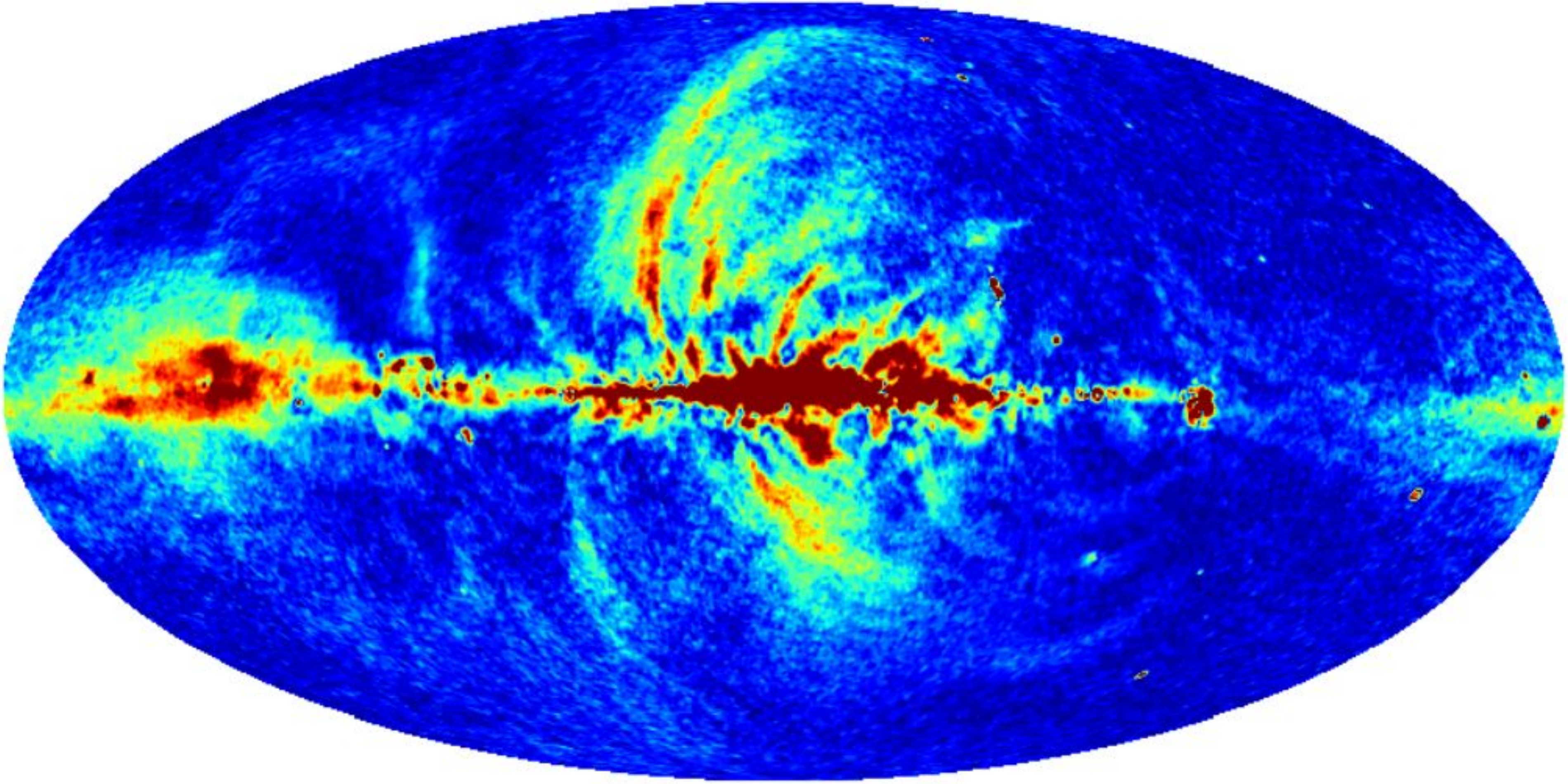
The impact of satellite constellations on radio astronomy

Mike Peel, 5 October 2022 (Photo: QUIJOTE CMB experiment)



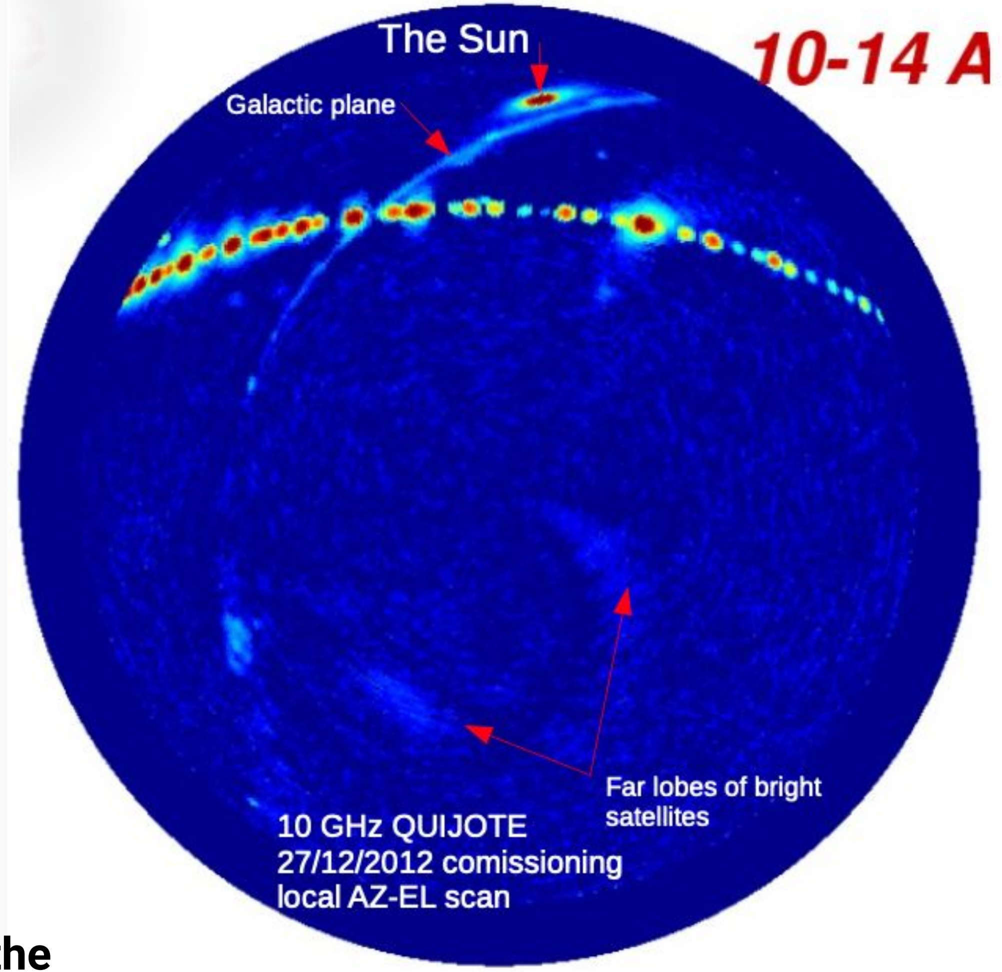
Example of what we want to observe: the cosmic Microwave Background
(full sky, in intensity, from the Planck Satellite—polarisation fainter)



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)

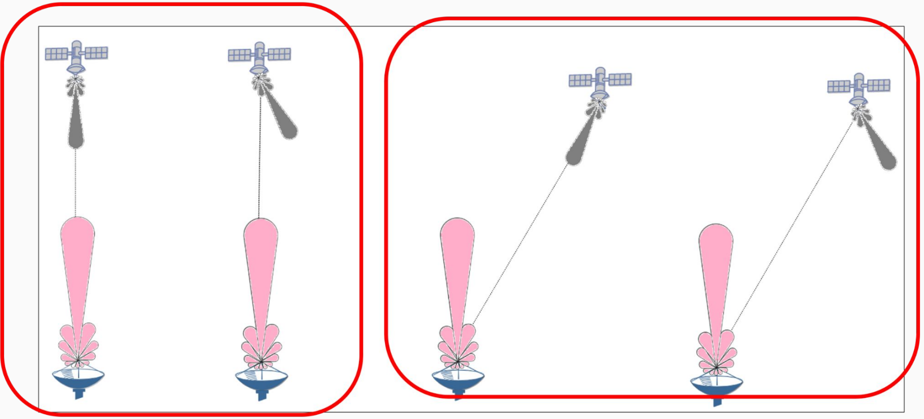
What we really see

- 10–14 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! Adding extra baffles reduced this.
- This was 2012...
- Satellite numbers now doubled
- Restarting observations this year...

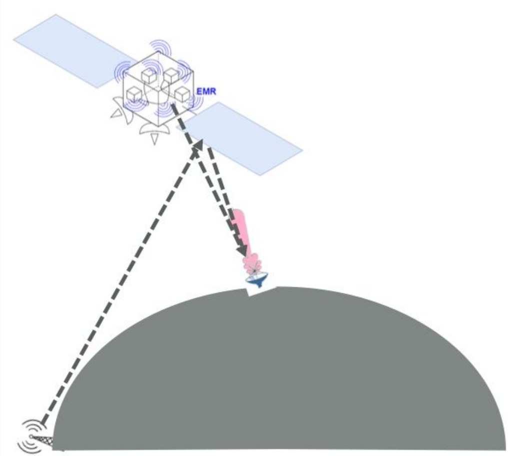


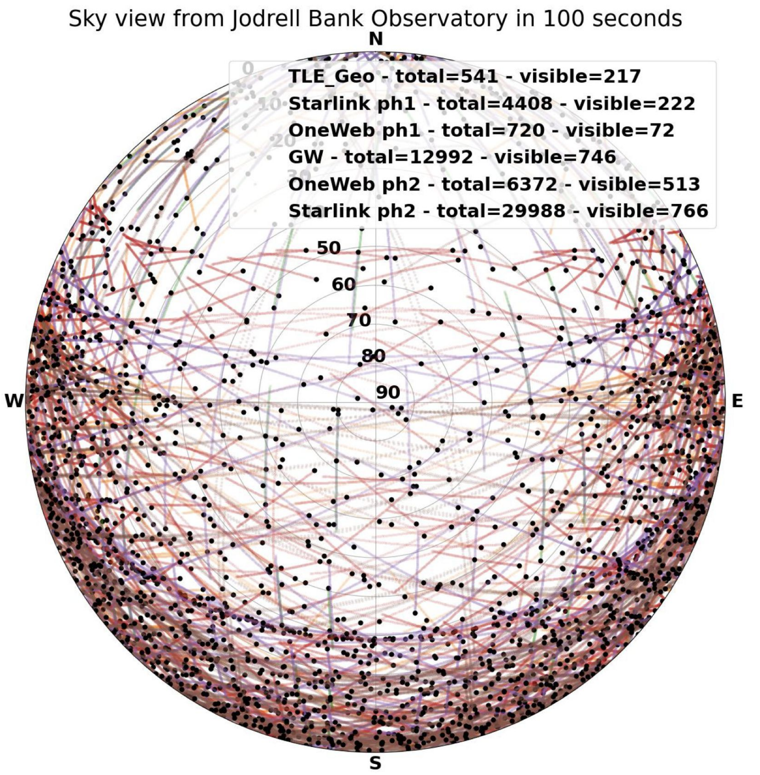
Will we see the equivalent of the geostationary band everywhere in the sky now?

What we might see?



High power Prx **Low power Prx**





Direct transmissions, in main beam or sidelobes

Unintentional emission from satellite or reflections

Satellites everywhere in the sky all of the time

Figures courtesy Federico Di Vruno

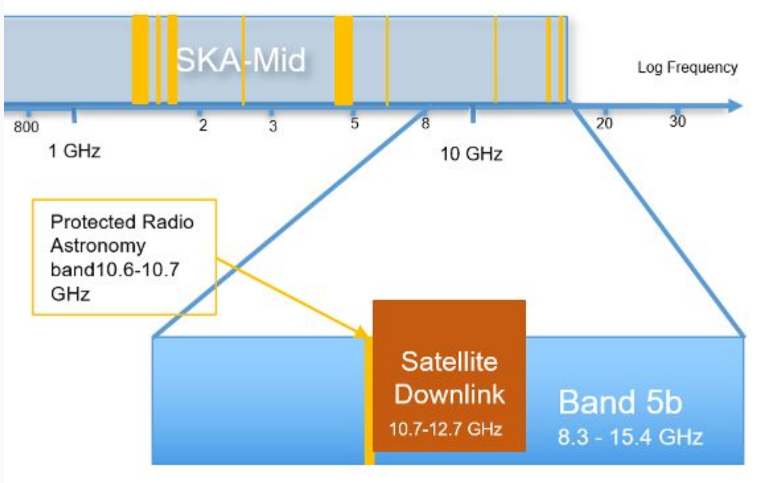
Why is there a problem (part 1)?

- Radio frequencies regulated by ITU-R
- Includes protected radio astronomy bands
    - Mostly for spectral lines, narrow bands
- Astronomy is 'passive' - normally no transmissions - to detect faint signals
- Most other uses are 'active' transmissions with high power
- Transmissions can also 'leak' into unintended bands
    - Has happened with constellations like Iridium
    - 10.6-10.7GHz band protected, 10.7+ used for Starlink etc...
- Local radio quiet zones: no transmitters/mobiles, sometimes cars/cameras banned!
    - Basically: have telescopes as far away from people, and in protected areas!

Why is there a problem (part 2)?

- 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
  - Even signals in sidelobes can cause significant problems
- Previously could **avoid interference** by going to remote parts of the planet
  - Radio quiet zones don't include satellites...
  - >10 GHz frequencies mostly clear free of interference—until now!

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! Super-bright signals (even out of band) can make receivers go non-linear, losing observation time (and maybe even damaging receivers)
- **Single dishes:** Sardinia (>€70m), Green Bank (>$95m), Effelsberg (>€50m)
- **Multi-frequency surveys** (separate different astronomical components via frequency)

(All cost estimates are approximate based on public info)

What do signals look like? (small dish)

Presumed **Starlink** satellites

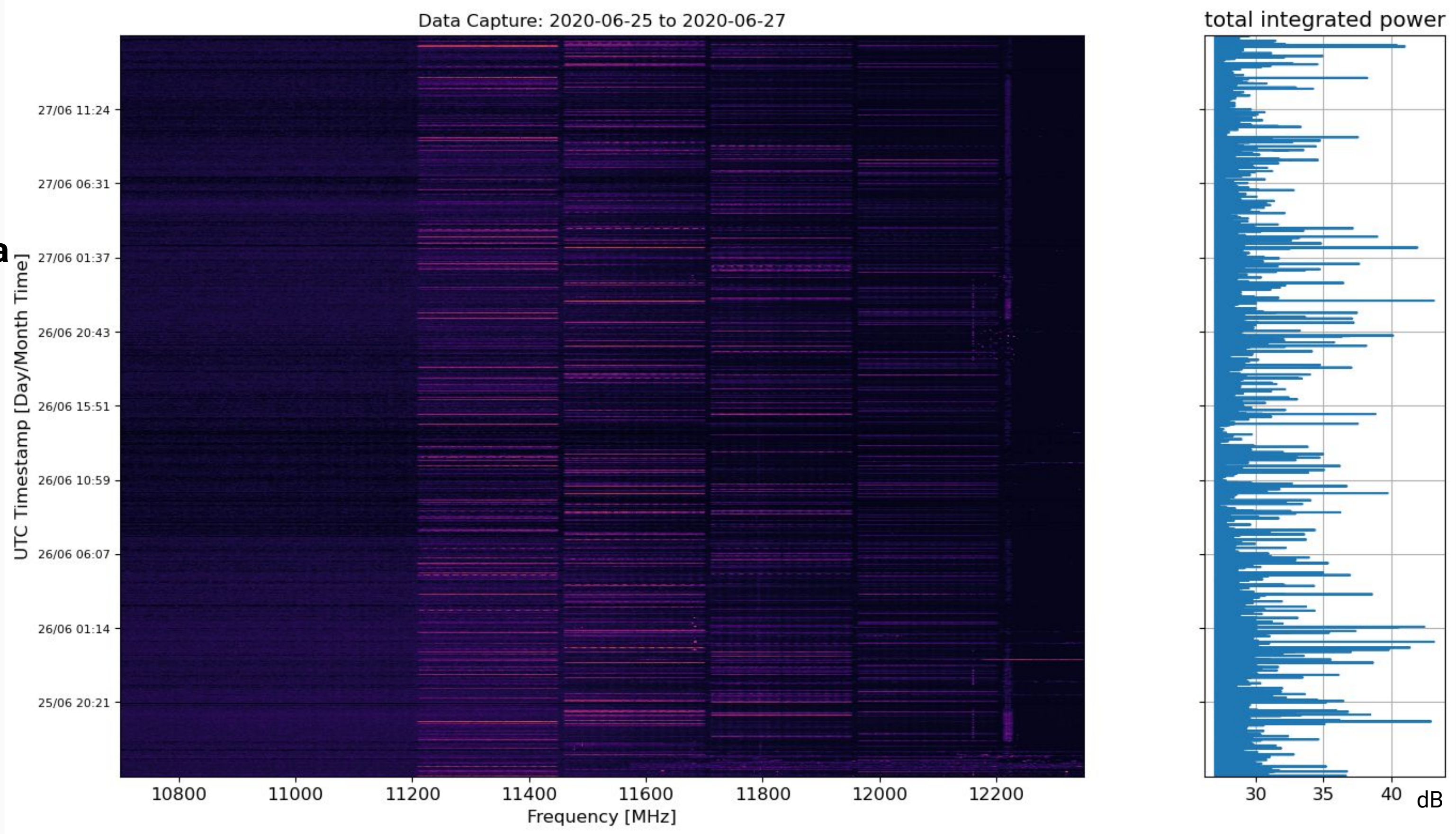
Single pointing direction

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

Variable (due to satellite movement)

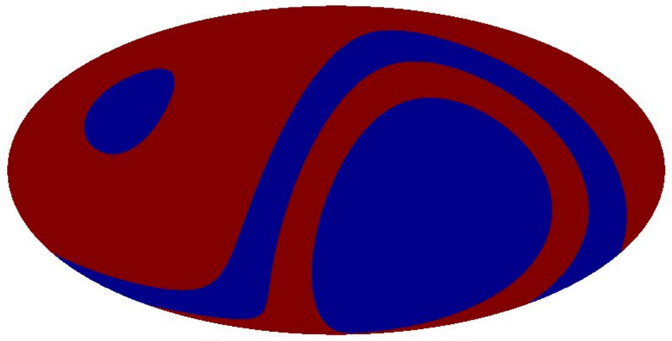
This is over 1.5 days

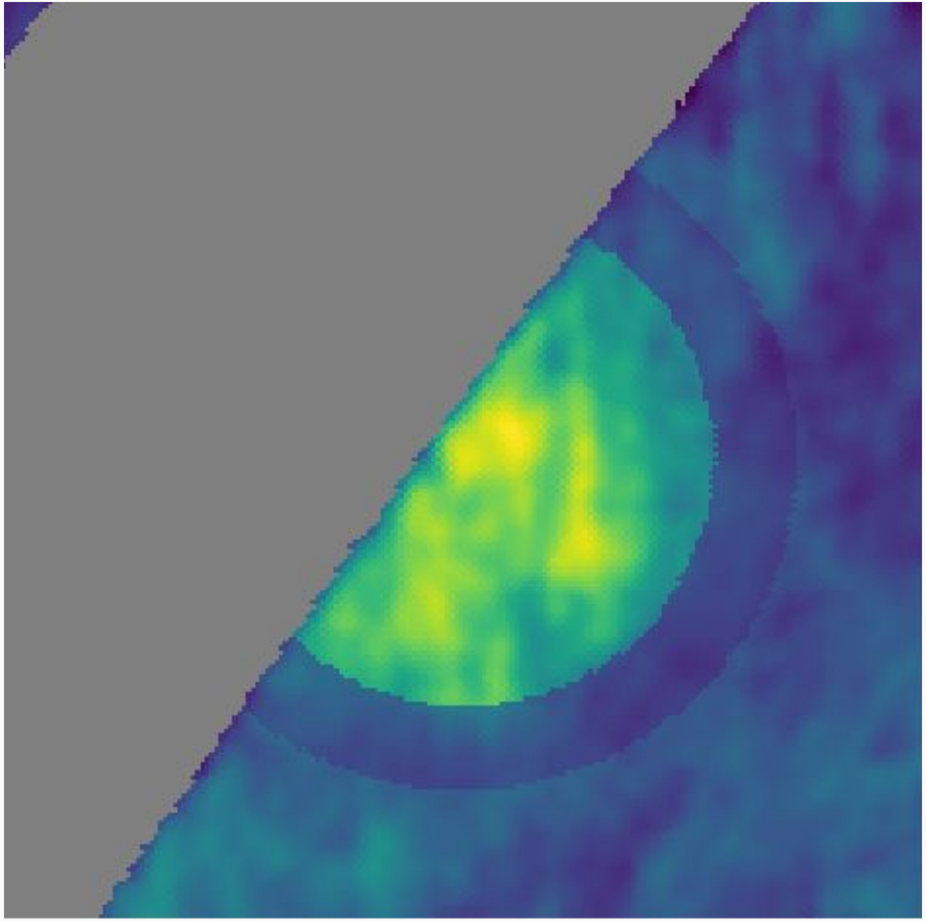
Thanks to Federico Di Vruno (SKAO)



Real on-sky impact?

- Zeta Ophiuchus
- Complex to understand (mix of free-free, sync, maybe AME, acts as Faraday screen, ...)
- 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! Have to mask ~10° around dec=0° (~100% data loss).
- (Maybe could be filled in with a southern telescope—but $$$!)





What astronomers can do (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

What astronomers can do (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!)

What we need others to do

- **Narrower frequency bands** and strict control of out-of-band signals (& tested!)
  - Best thing that can be done—but remember out-of-band leakage! (simulated impact from GPS on 21cm: Harper & Dickinson, arXiv:1803.06314)
- **Fewer satellites** (and less duplication of coverage)
  - Turn them off when passing over all radio telescopes (pro & amateur)
  - Current situation time-consuming + painful, ~100,000 satellites impossible!
- **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

New **IAU Centre for the Protection of the Dark and Quiet Sky from Satellite Constellation Interference.**

Led by **NOIRLab** (USA) and **SKAO** (UK), with 'Contributing Members' and 'Affiliated Members'
Now **open for membership!**.

Director: Piero Benvenuti. Co-directors by Connie Walker & Federico Di Vruno. Four hubs:

- **SatHub** (leads: Meredith Rawls, Mike Peel)
  - Collection & analysis of satellite observations
  - Software tools
  - Training + outreach
- **Policy** (leads: Andrew Williams, Richard Green)
  - Coordinate policy action & diplomacy
- **Community Engagement** (leads: John Barentine, Jessica Heim): beyond professional astronomers
- **Industry and Technology** (leads: Chris Hofer, Tim Stevenson): engaging industry

https://cps.iau.org/

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, particularly if we end up dealing with ~100,000 LEO satellites!

Need more data (MFI2 starting observations soon, initial observations with satellite dishes ongoing...)

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

IAU CPS critical to have more transparent communication and collaborate on the problems (Please join it!)