

Beam Mapping Radio Telescopes using GNSS-SDR for 21 cm Cosmology

Shronim Tiwari
PhD student, McGill University
Supervisor: Prof. Jonathan Sievers

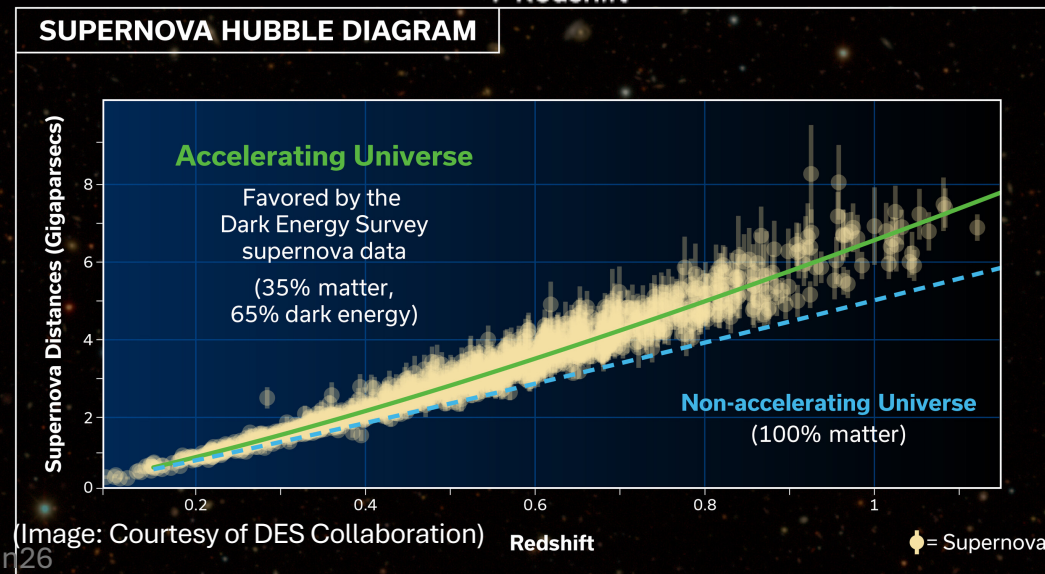
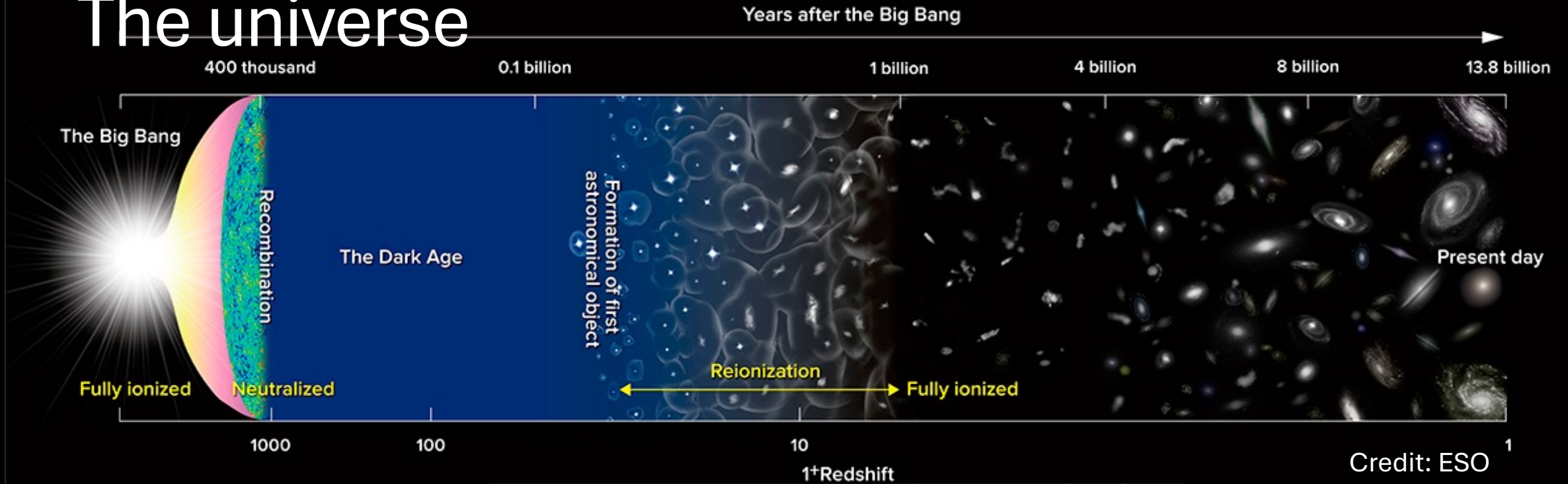
23rd September 2026
GRCon26, Raleigh, North Carolina



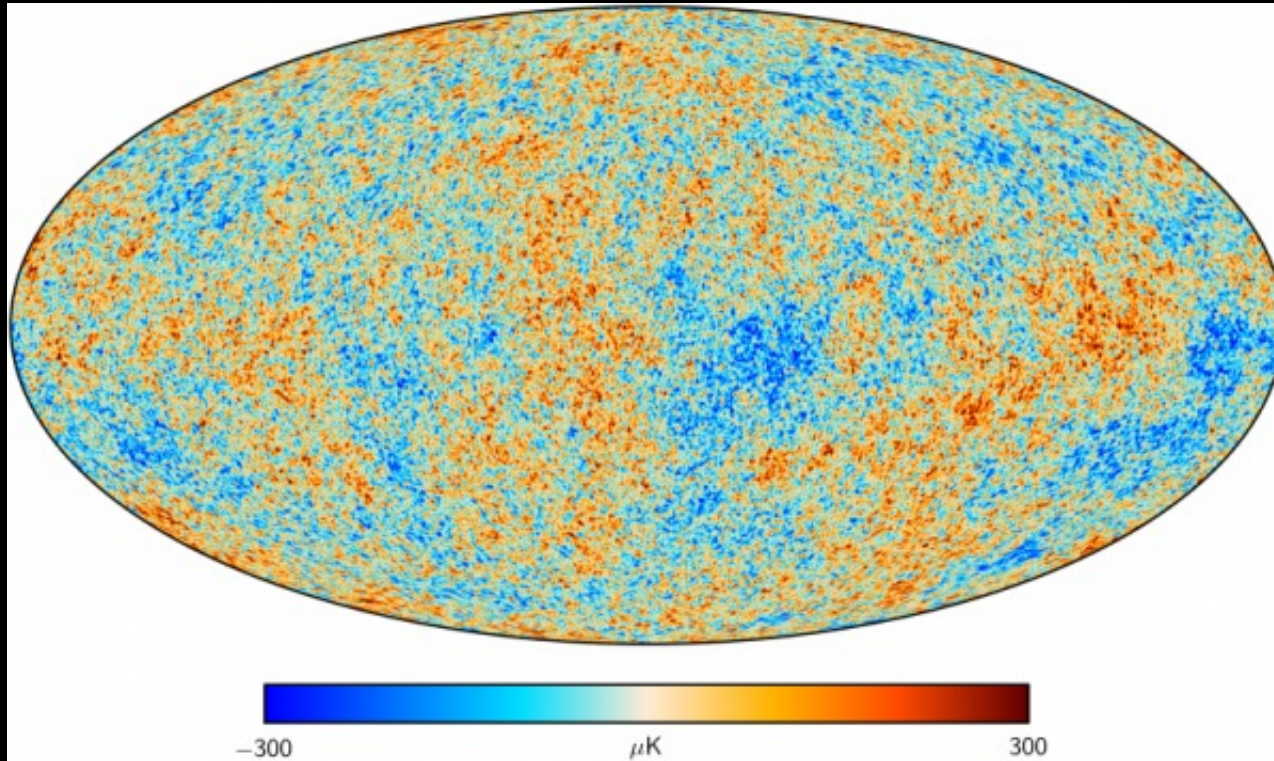
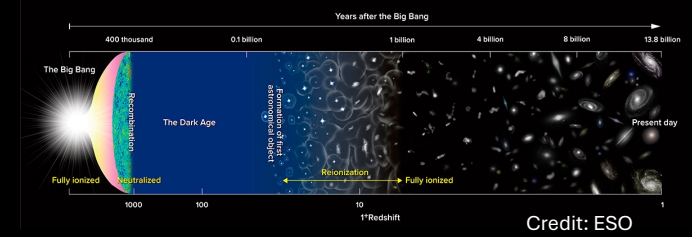
McGill



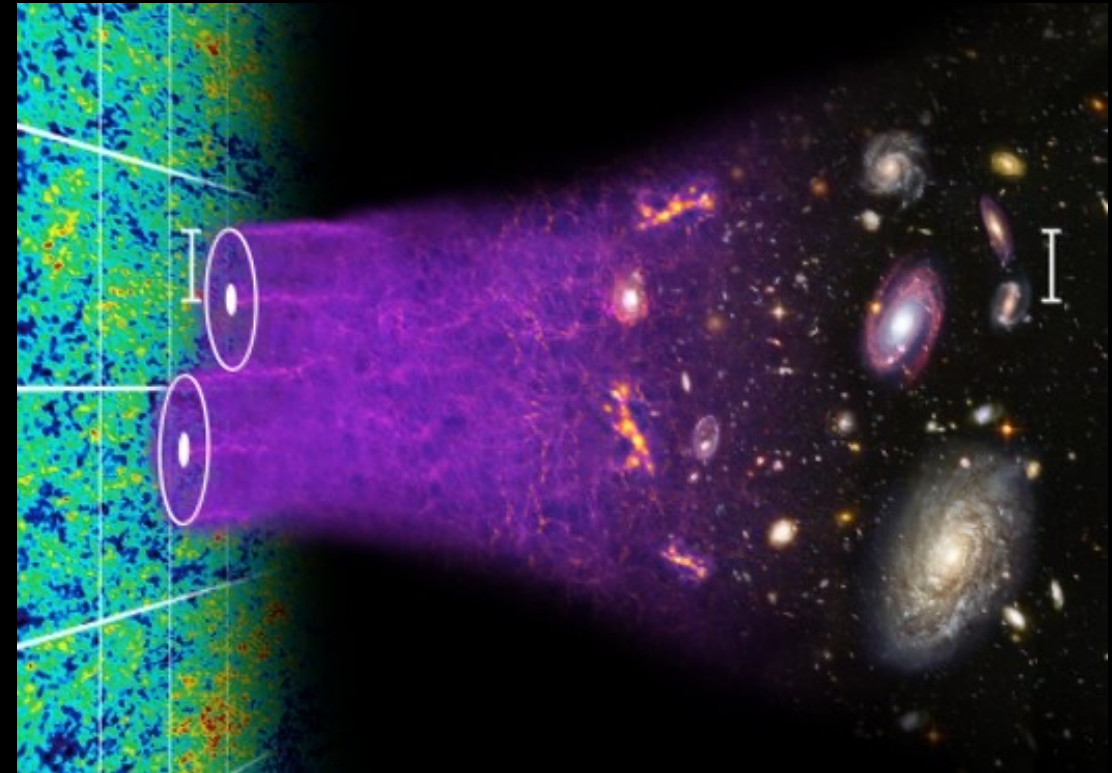
The universe



Expansion history of the universe



Credit: Planck Collaboration

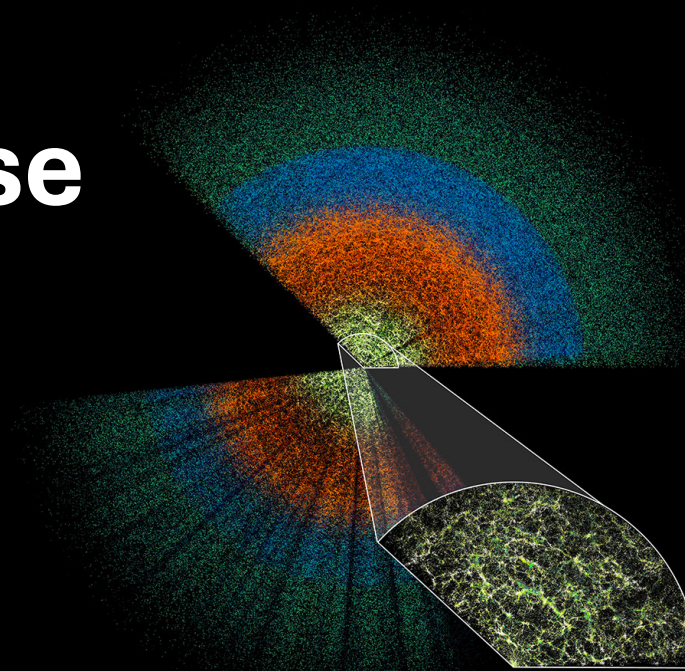


<https://www.sdss3.org/surveys/boss.php>

Mapping the universe

Large galaxy surveys:

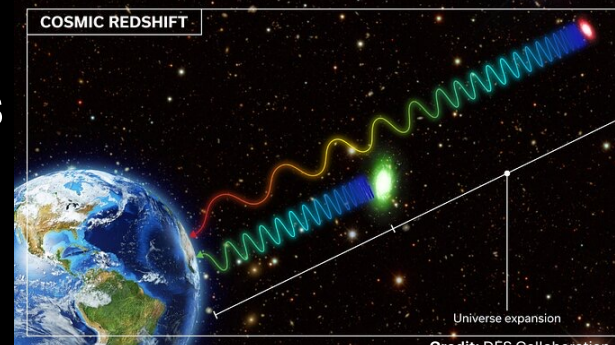
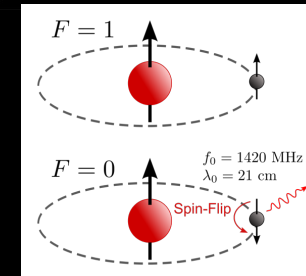
- Resolving individual galaxies



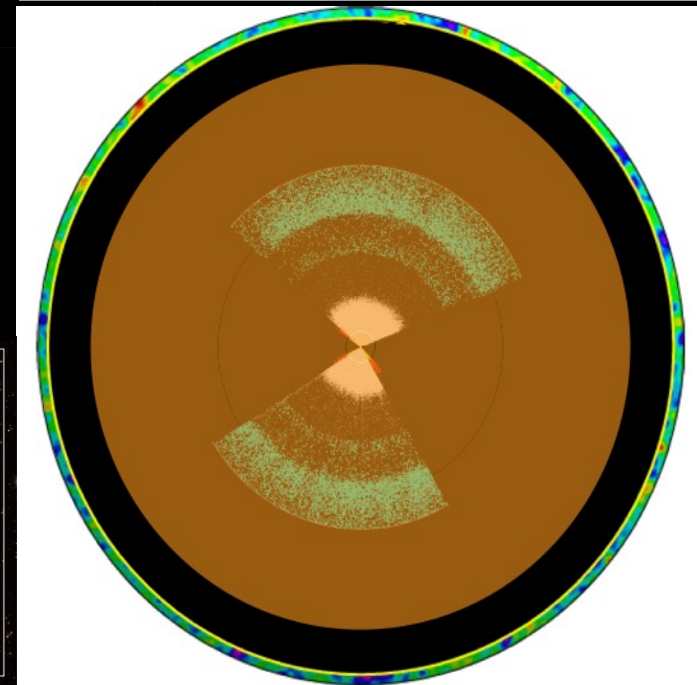
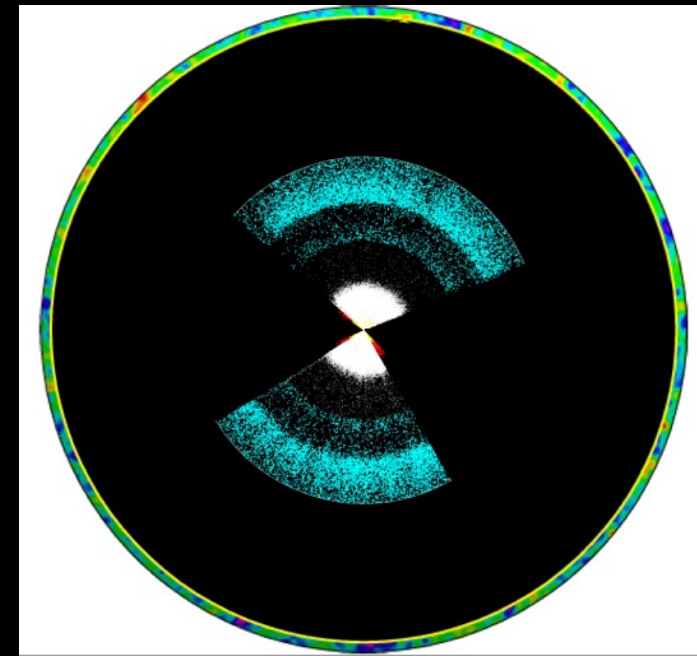
Credit: Claire Lamman/DESI collaboration

Another probe: Hydrogen

- Neutral Hydrogen glows in 21 cm (1420 MHz)
- Hydrogen is present everywhere in the universe (~75% of normal matter)
- Redshift turns frequency into distance (radio spectrum turns into 3d map)
- Don't need to resolve individual galaxies (intensity mapping)



Credit: DES Collaboration



Credit: Adrian Liu
shronim.tiwari@mcgill.ca



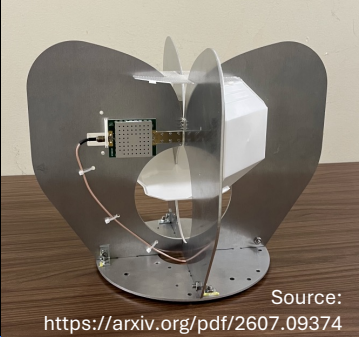
THE CANADIAN HYDROGEN OBSERVATORY AND RADIO-TRANSIENT DETECTOR

Dominion Radio Astrophysical Observatory (DRAO),
British Columbia, Canada



Slide credit: Bryan Schlenberg
Picture credit: HAA, National Research Council Canada

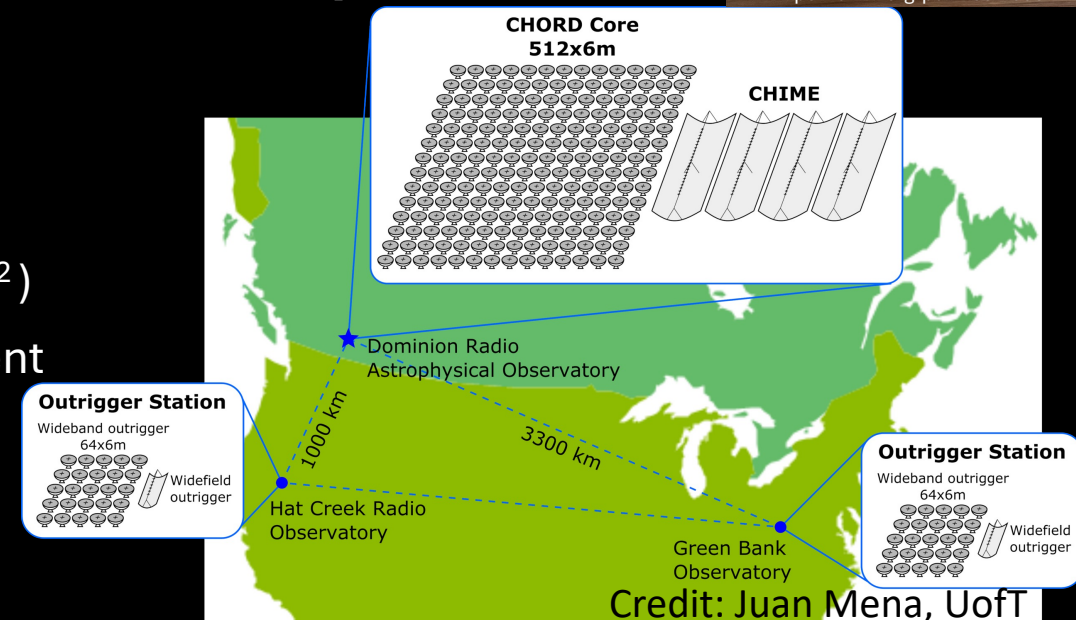
Canadian Hydrogen Observatory and Radio-transient Detector (CHORD)



Dish geometry	6 m (f/D 0.21)	
Antenna	Modified Vivaldi	
Array size	512 x 6 m dishes (collecting area 14,500 m ²)	
Observing mode	Drift scan with manual elevation adjustment	
Receiver noise	30K	
Frequency range	300 MHz	1500 MHz
Field of view	12 deg	2.5 deg
Formed beam size	17 X 23 arcmin	3.4 X 4.5 arcmin

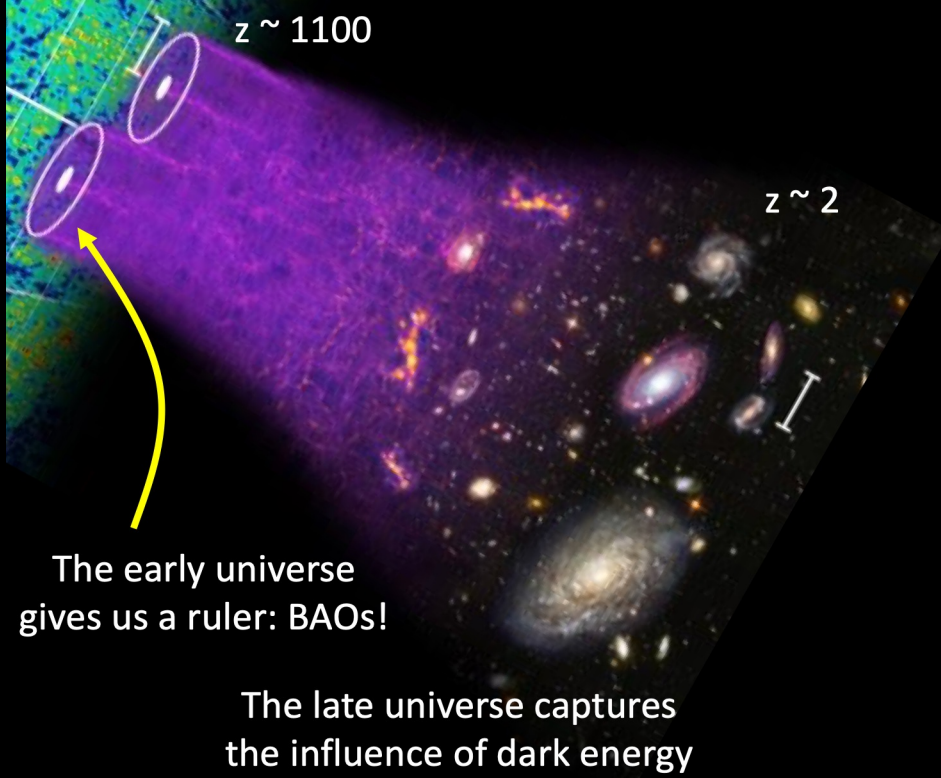
- 64-dish pathfinder array coming online in 2026.
- 512-dish full array commissioning in 2028.

More on: <https://arxiv.org/pdf/2607.09374>



Picture credit: HAA, National Research Council Canada

21-cm Cosmology



Slide credit: Ian Hendricksen

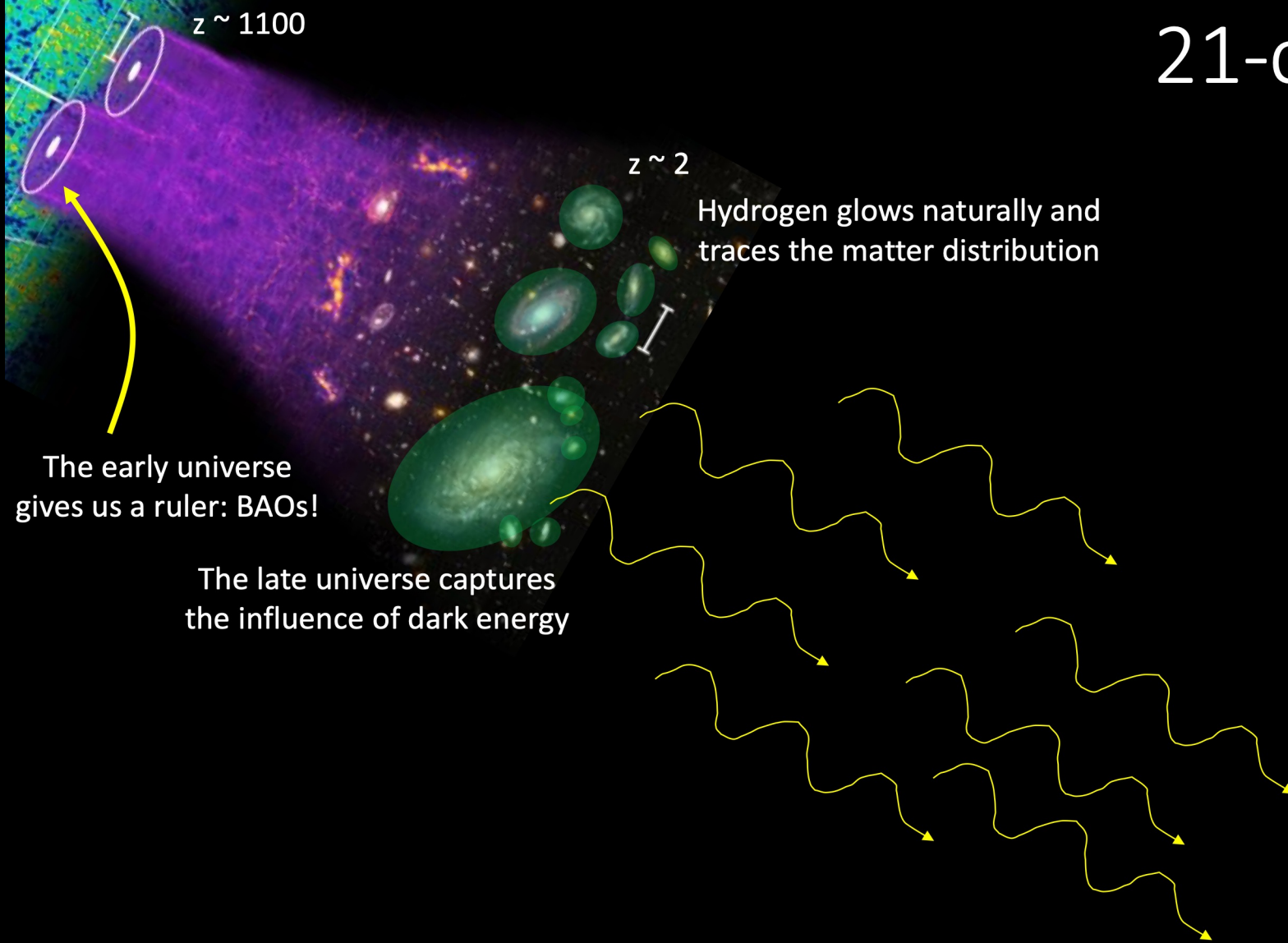
Milky Way at radio frequencies: <https://apod.nasa.gov/apod/ap990403.html>

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21-cm Cosmology



Slide credit: Ian Hendricksen

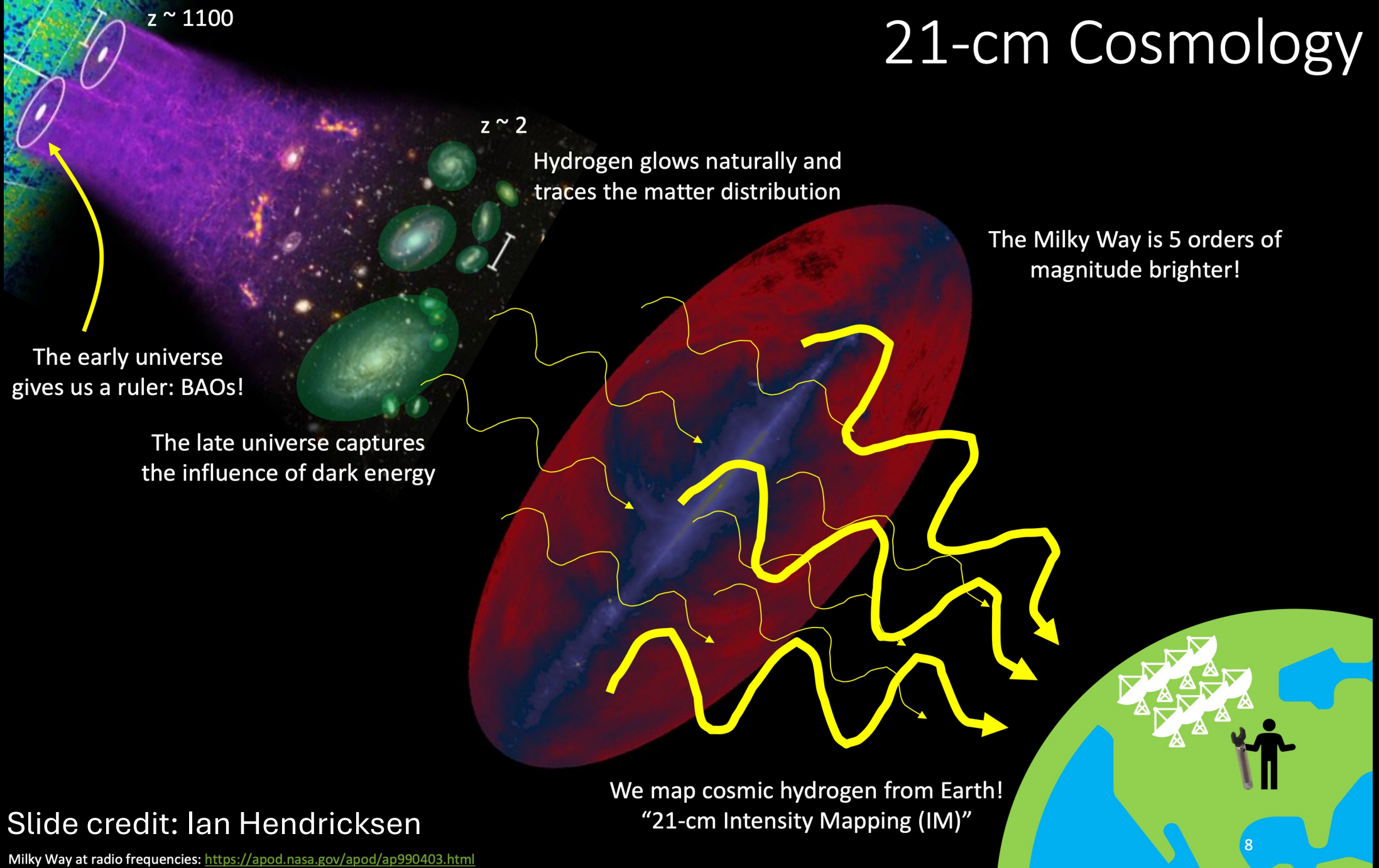
Milky Way at radio frequencies: <https://apod.nasa.gov/apod/ap990403.html>
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We map cosmic hydrogen from Earth!
"21-cm Intensity Mapping (IM)"



shronim.tiwari@mail.mcgill.ca

21-cm Cosmology



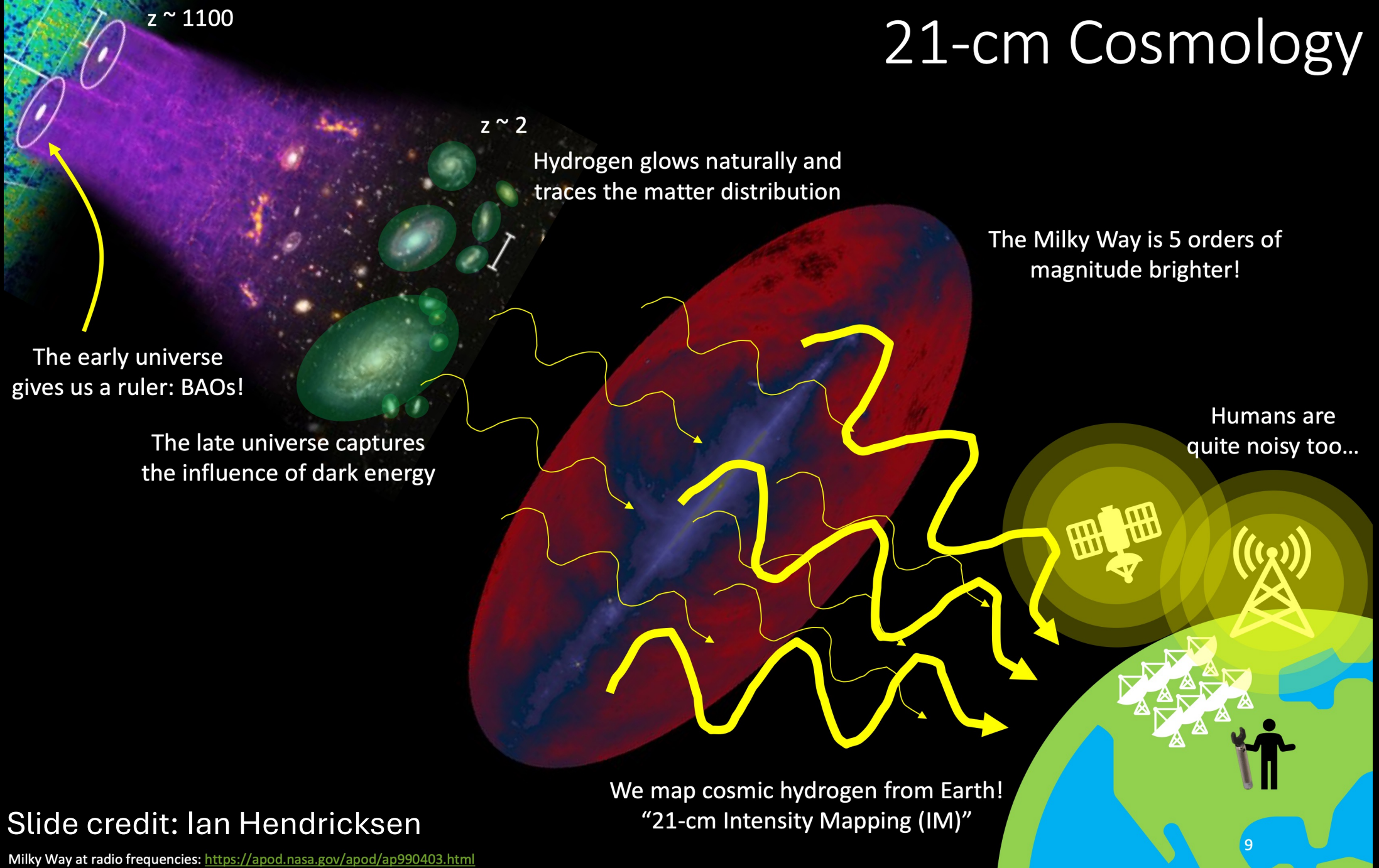
Slide credit: Ian Hendricksen

Milky Way at radio frequencies: <https://apod.nasa.gov/apod/ap990403.html>

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21-cm Cosmology



Slide credit: Ian Hendricksen

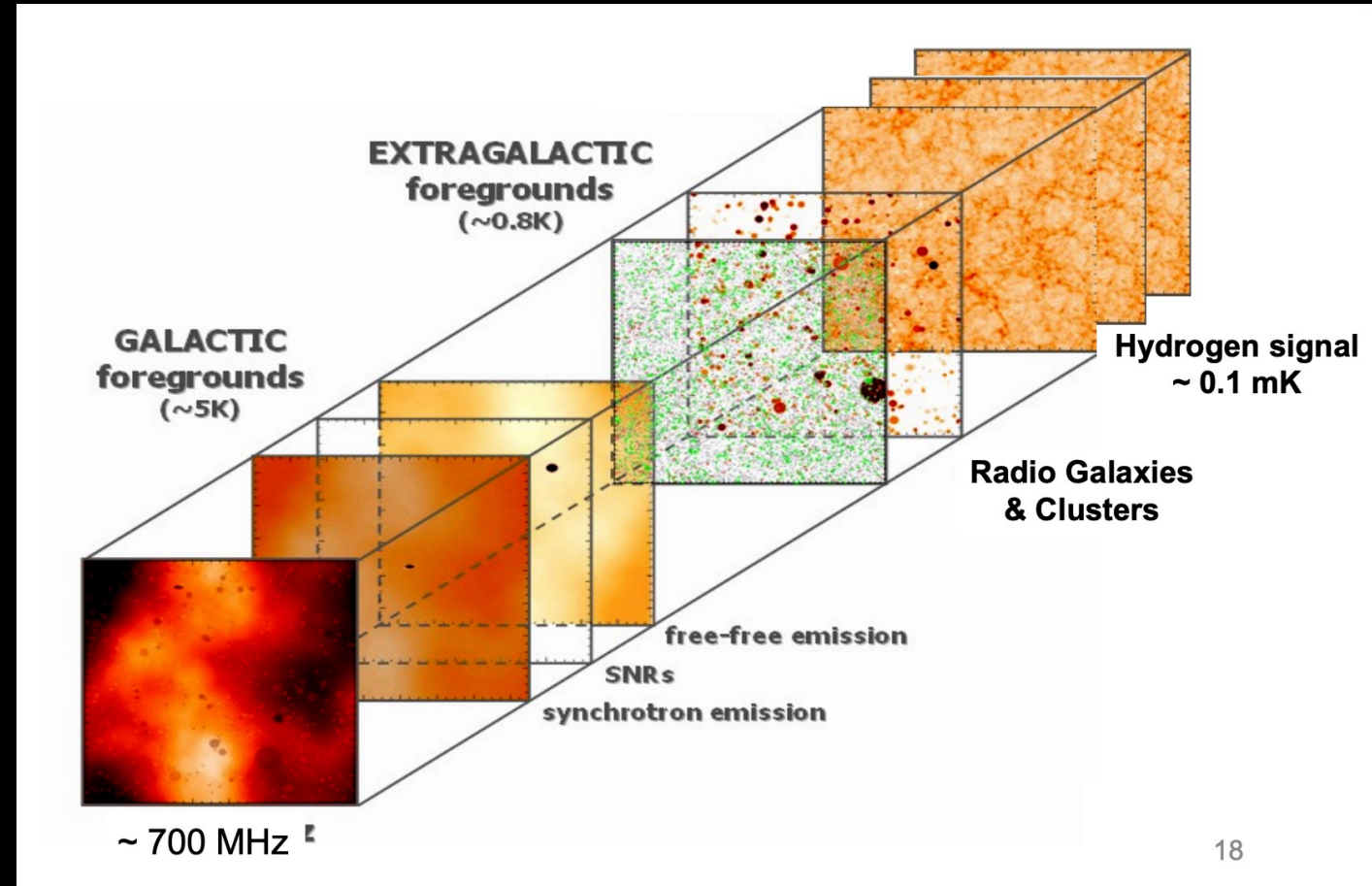
Milky Way at radio frequencies: <https://apod.nasa.gov/apod/ap990403.html>

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Challenges

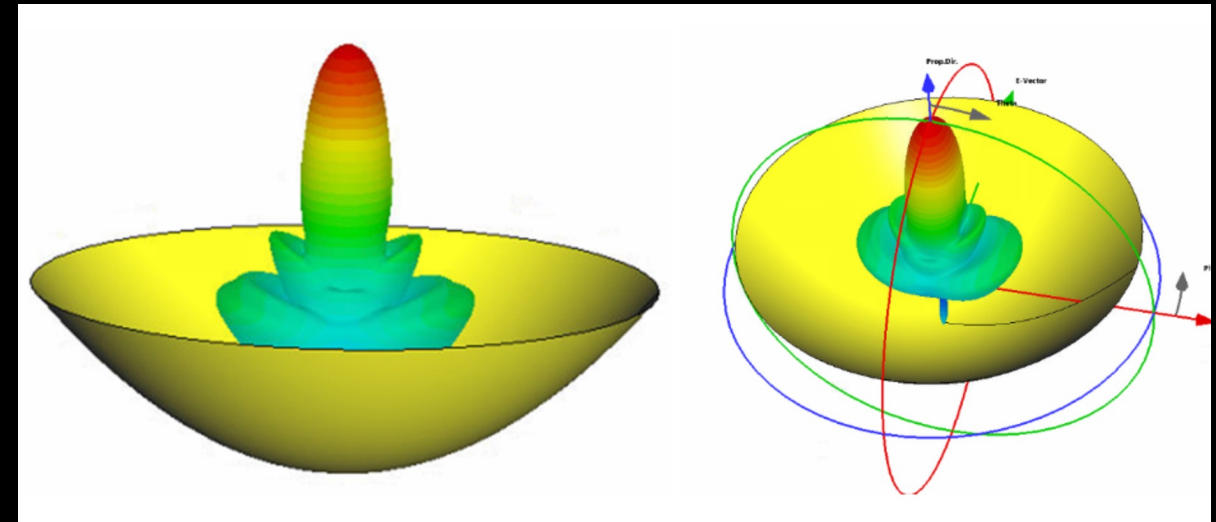
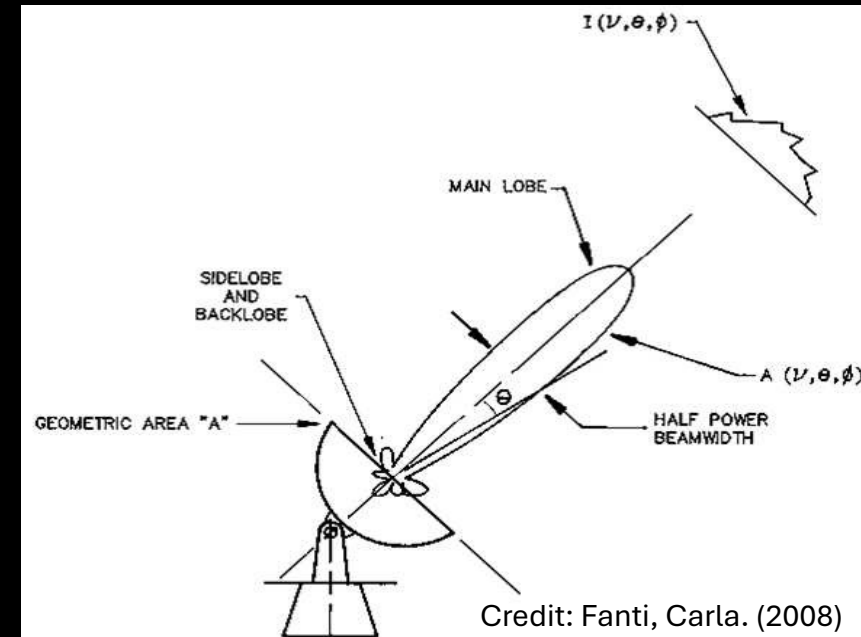
- 21 cm signal is very weak
 - Lots of dishes for sensitivity
- The foreground is very bright, many orders of magnitude brighter
 - But foreground are spectrally smooth
- Need to know the dish beam to $\sim 0.1\%$ accuracy to remove foreground successfully.



Beam

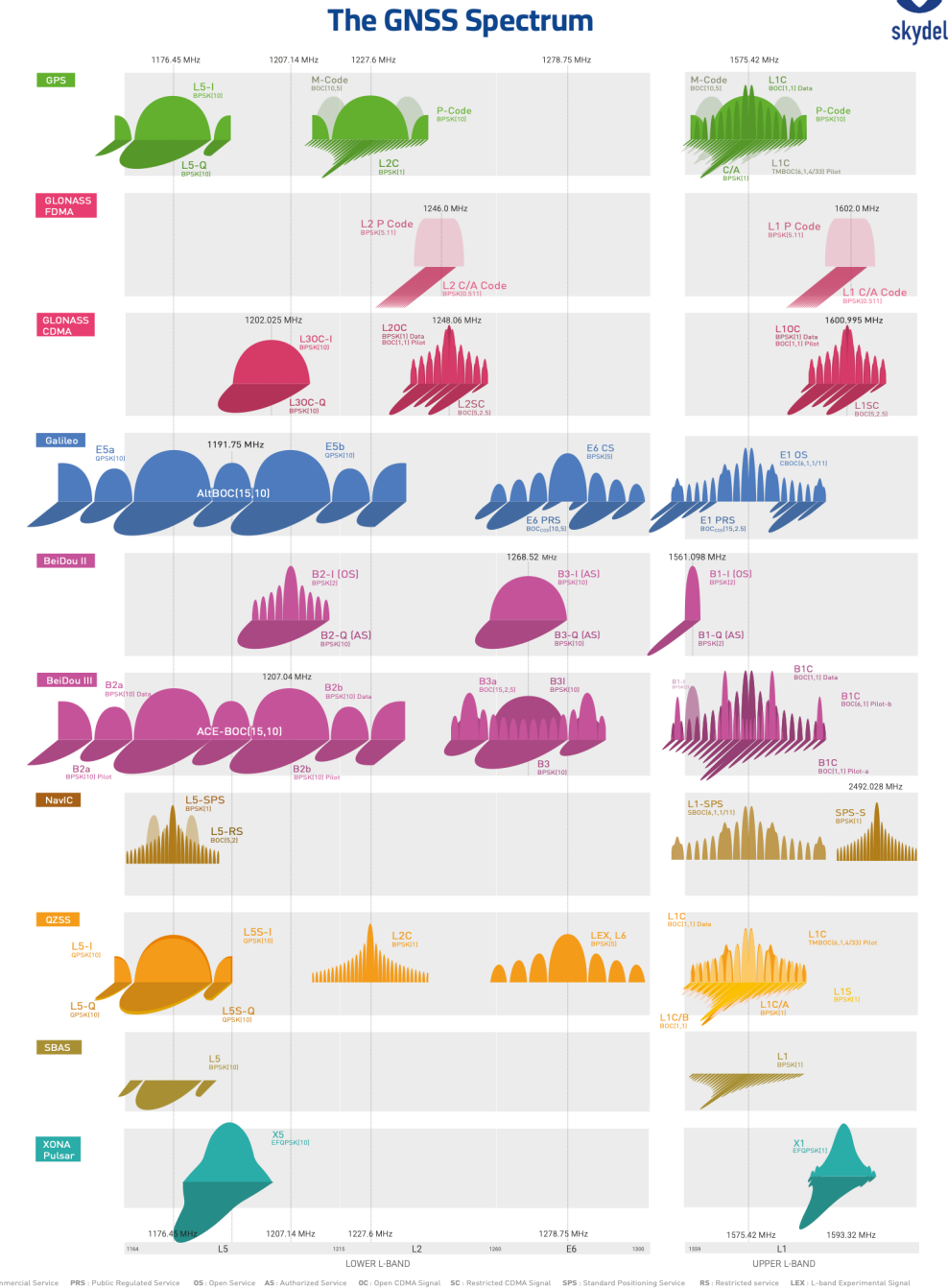
- Directional sensitivity of the dish
- Ways to characterize beam (among many):

- Simulation
- Astronomical transit
 - Drones
 - Satellites



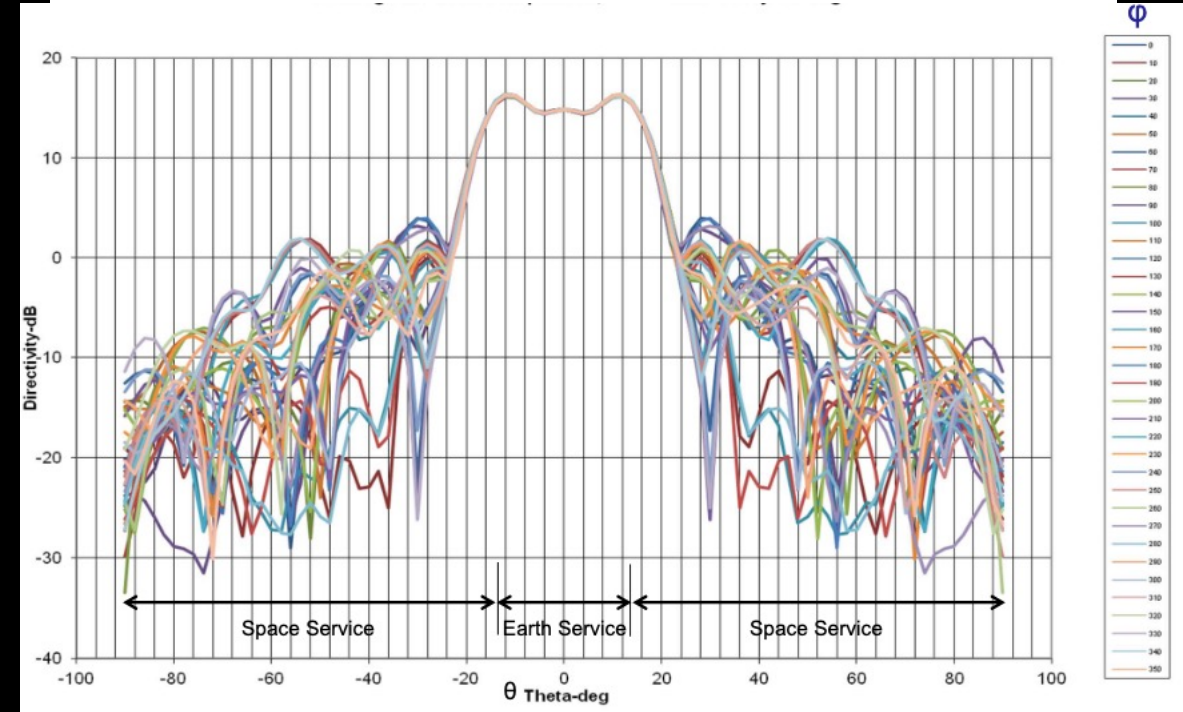
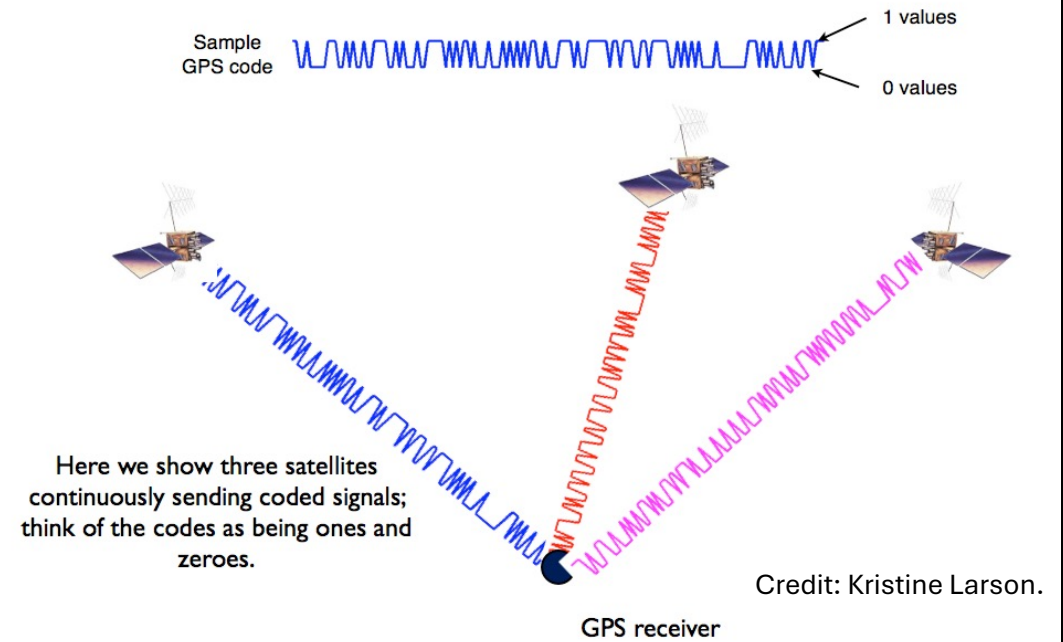
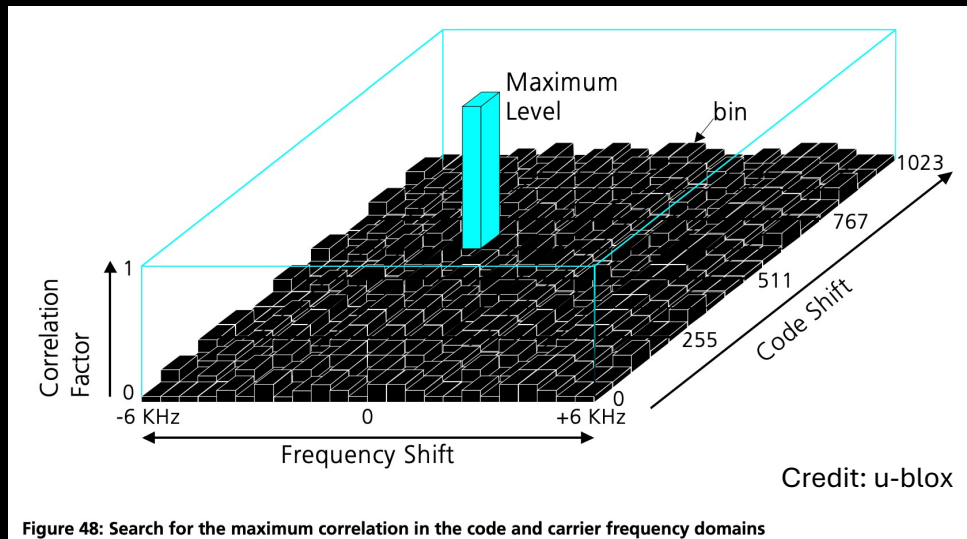
EM simulation of HIRAX dish (6m) at 400MHz using CST. Credit: Aditya Karigiri

Global Navigation Satellite System (GNSS)



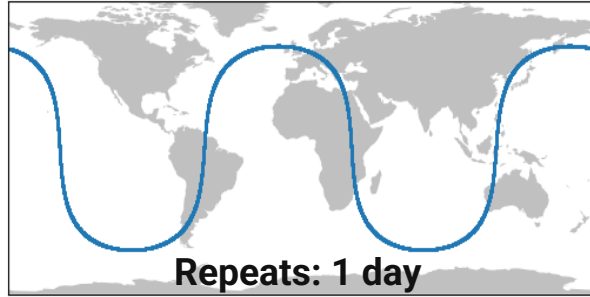
GNSS signal

- Around 40 GNSS satellites are visible at any time.
- Map all dishes simultaneously.
- Monitor beams 24/7.

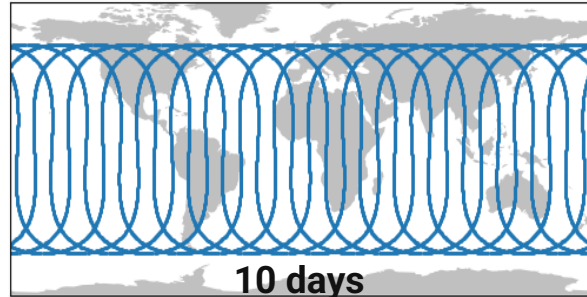


Satellite tracks

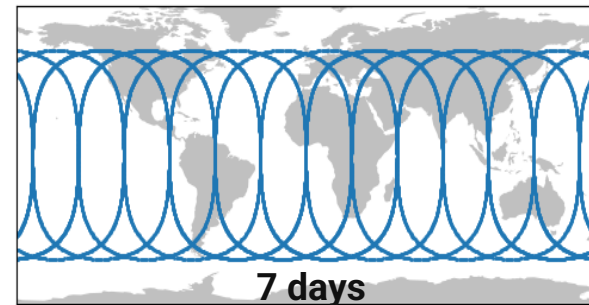
GPS Ground Track



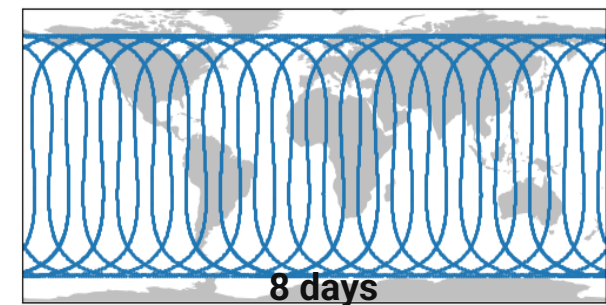
GALILEO Ground Track



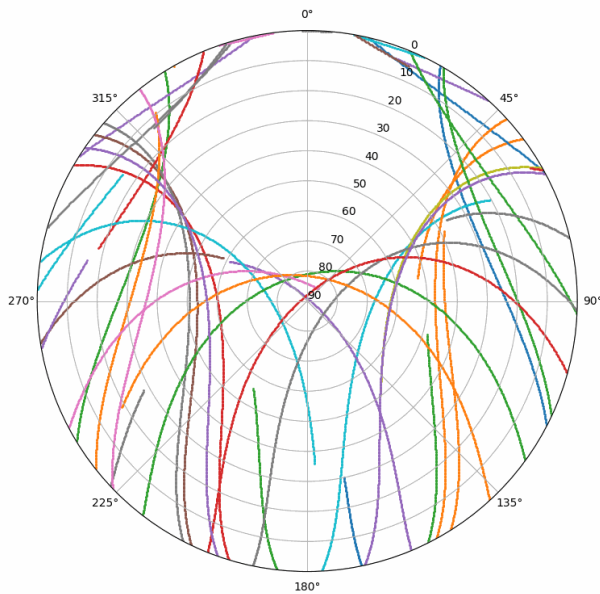
BEIDOU Ground Track



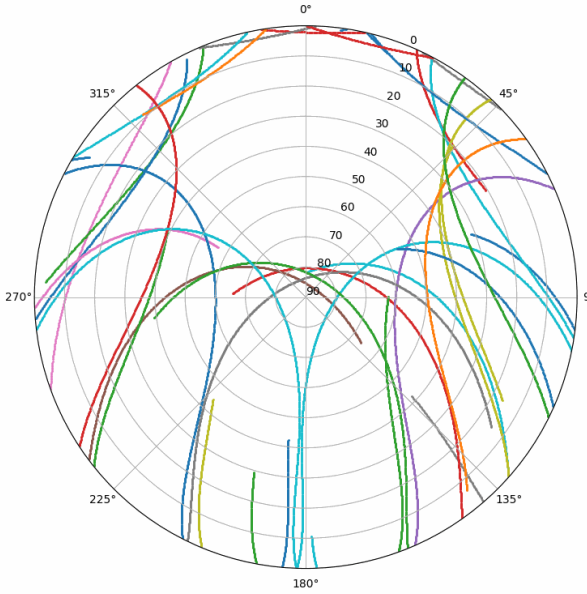
GLONASS Ground Track



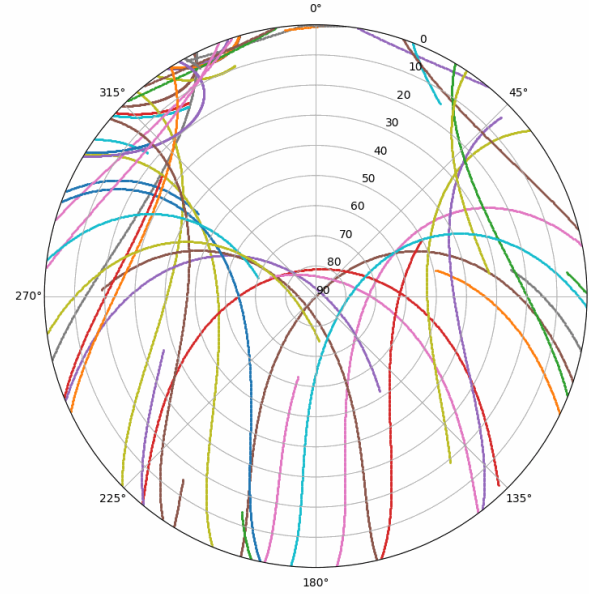
Coverage for GPS over 0.5 days



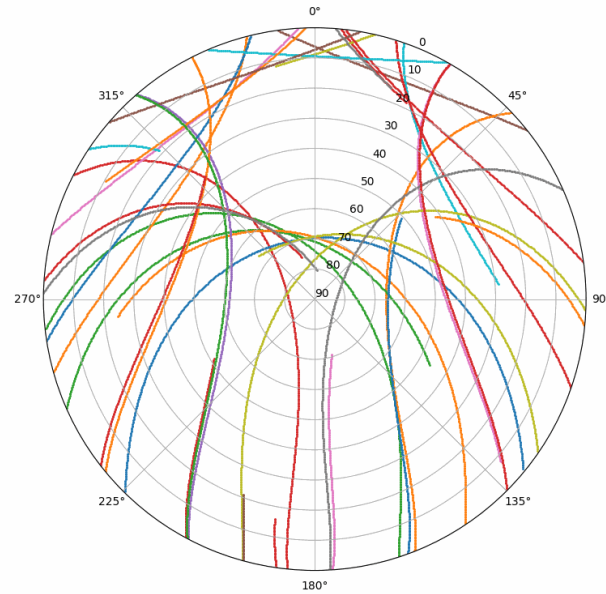
Coverage for GALILEO over 0.5 days



Coverage for BEIDOU over 0.5 days



Coverage for COSMOS over 0.5 days

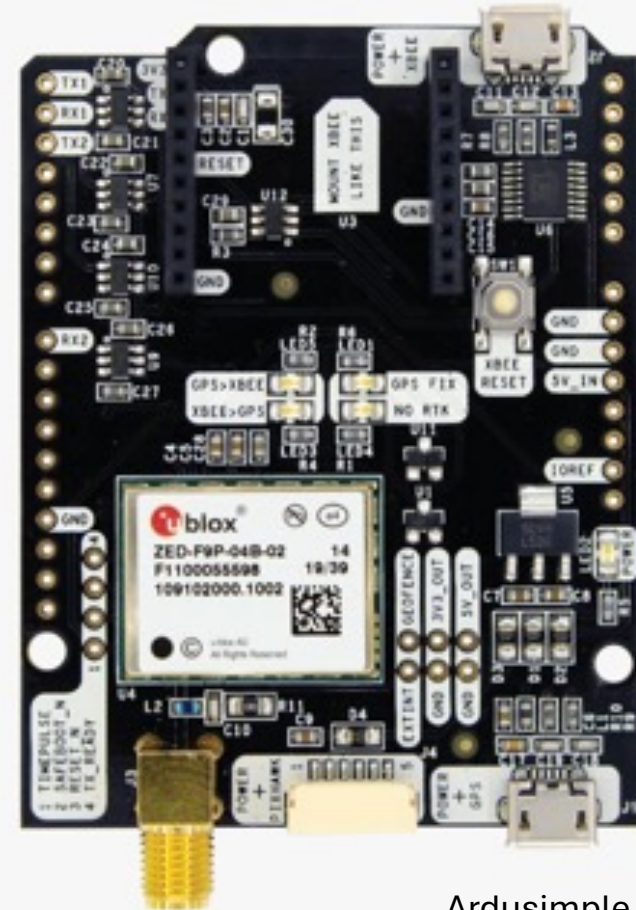
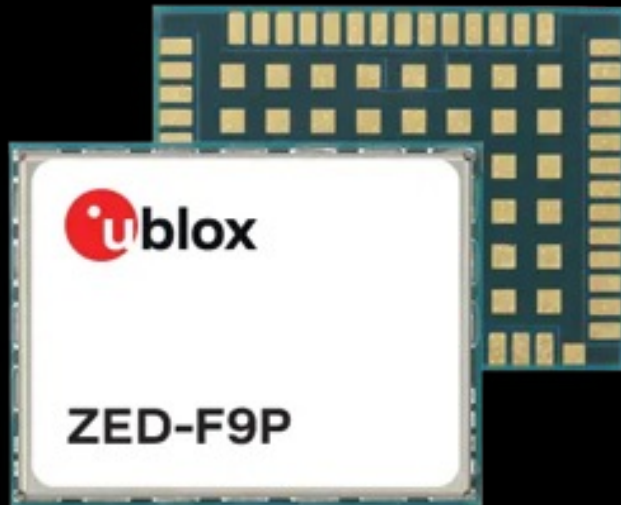


Visibility at location of Dominion Radio Astrophysical Observatory (near Penticton, BC)

Receiver: simpleRTK2B with ublox ZED-F9P

- Multi-band GNSS receiver
- Tracks L1 (~1550MHz) and L2 (~1200MHz)
- Cost: around USD 250

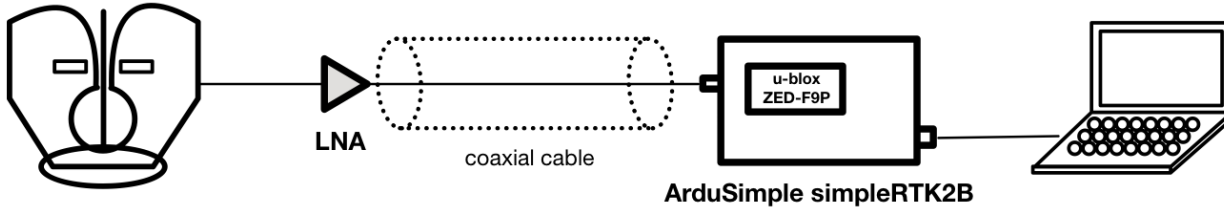
1583.46 MHz and 1224.01 MHz (span: 128 MHz)



ArduSimple simpleRTK2B
(ZED-F9P-02B-00)

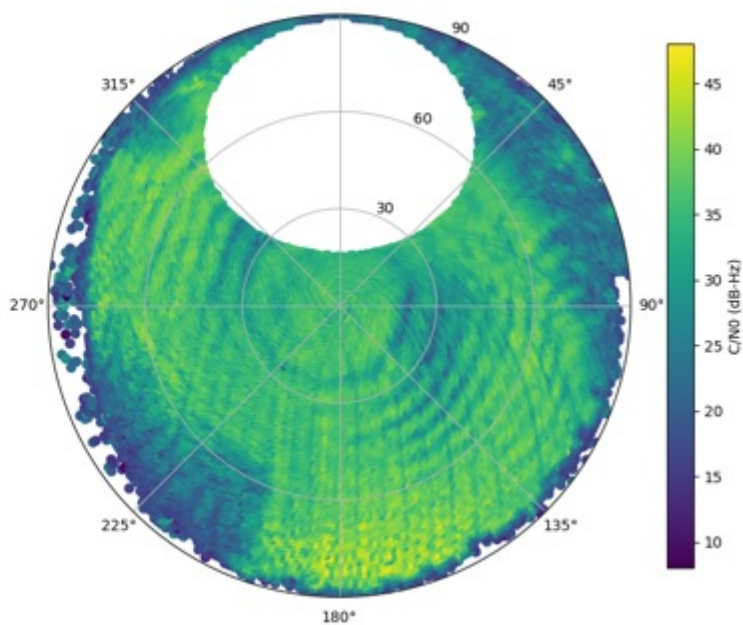
Work with CHORD feed

Roof of Rutherford Physics Building at McGill University

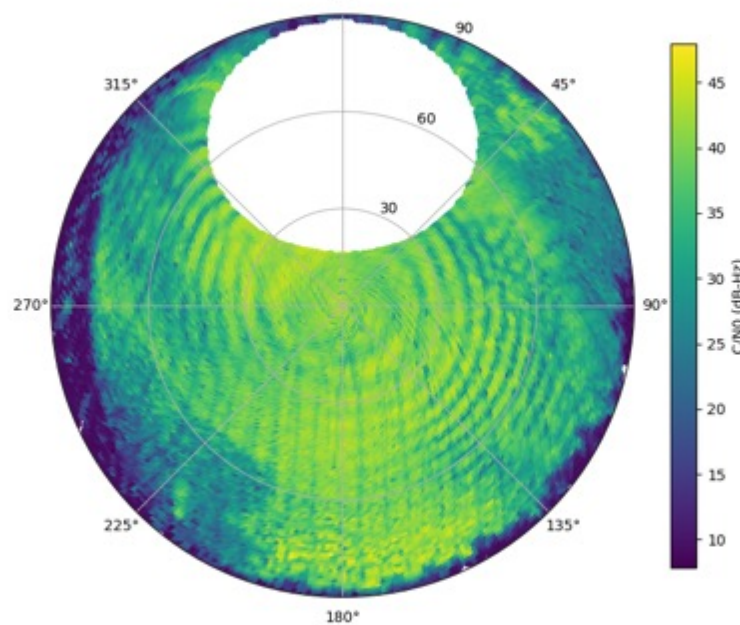


Beam Map with GNSS data averaged over 2-3 months

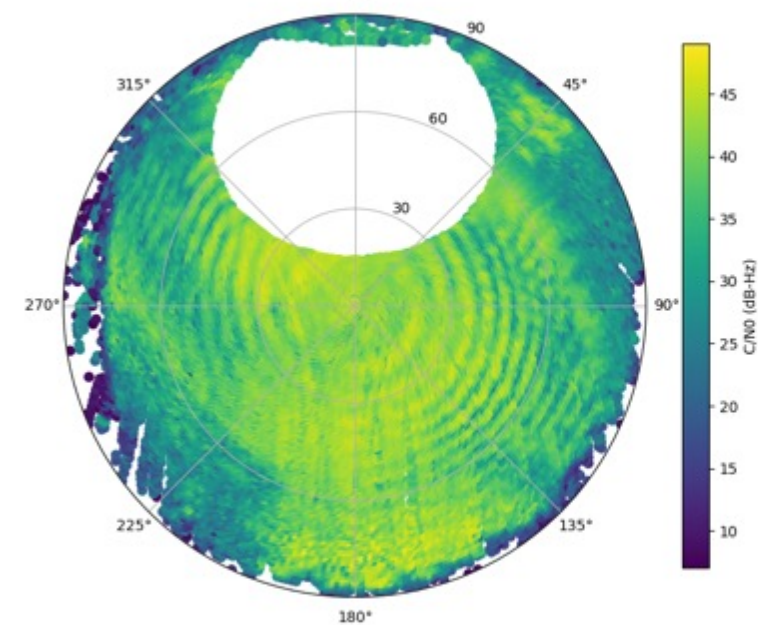
Measured Beam 1207.140 MHz GALILEO (antenna height: 132 cm)



Measured Beam 1575.420 MHz GALILEO (antenna height: 132 cm)



Measured Beam 1561.098 MHz BEIDOU (antenna height: 132 cm)



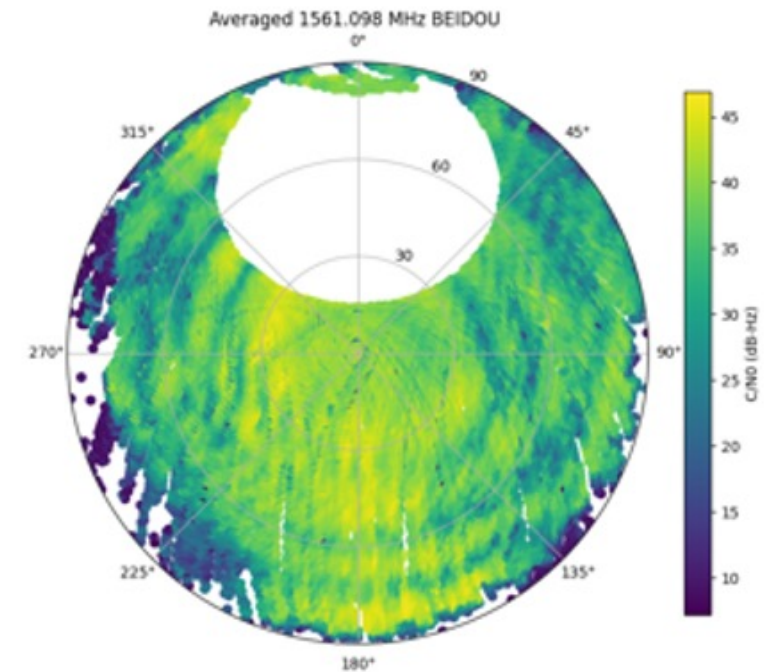
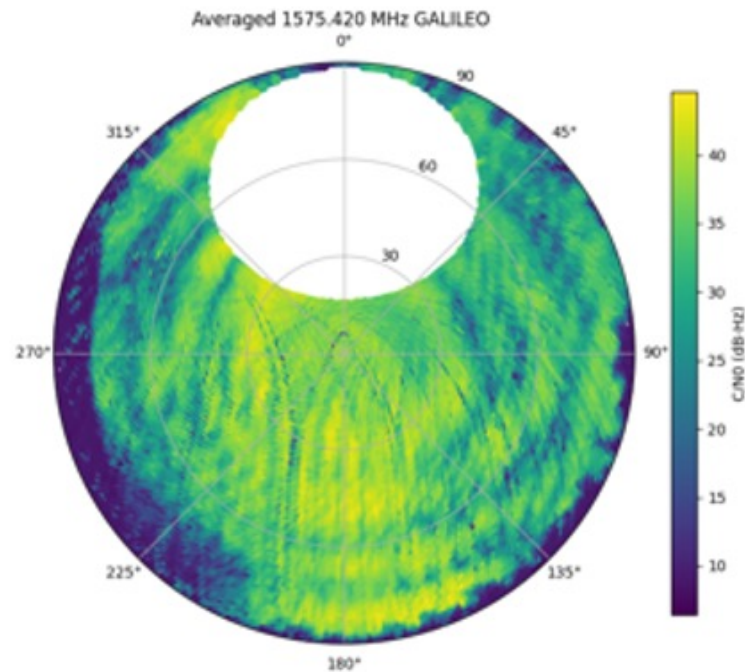
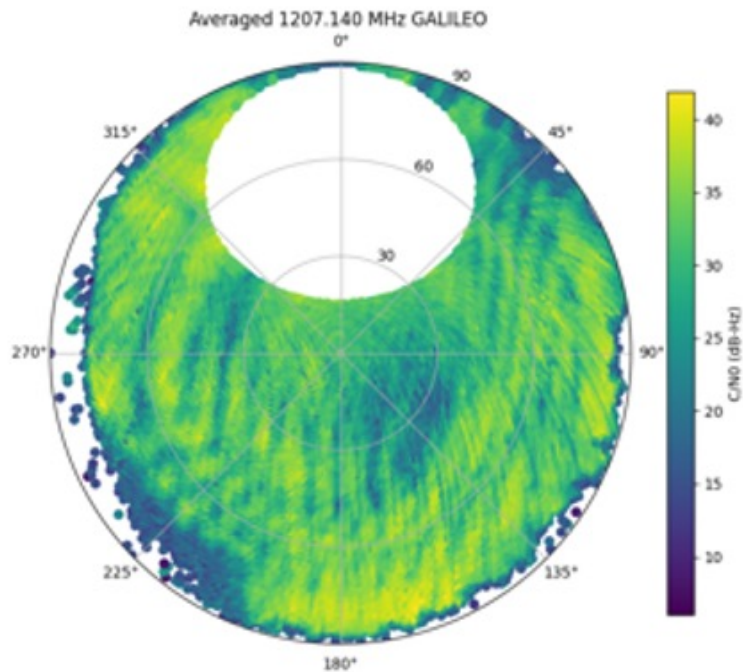
- High dynamic range

Work with CHORD feed

Roof of Rutherford Physics Building (closer to ground)

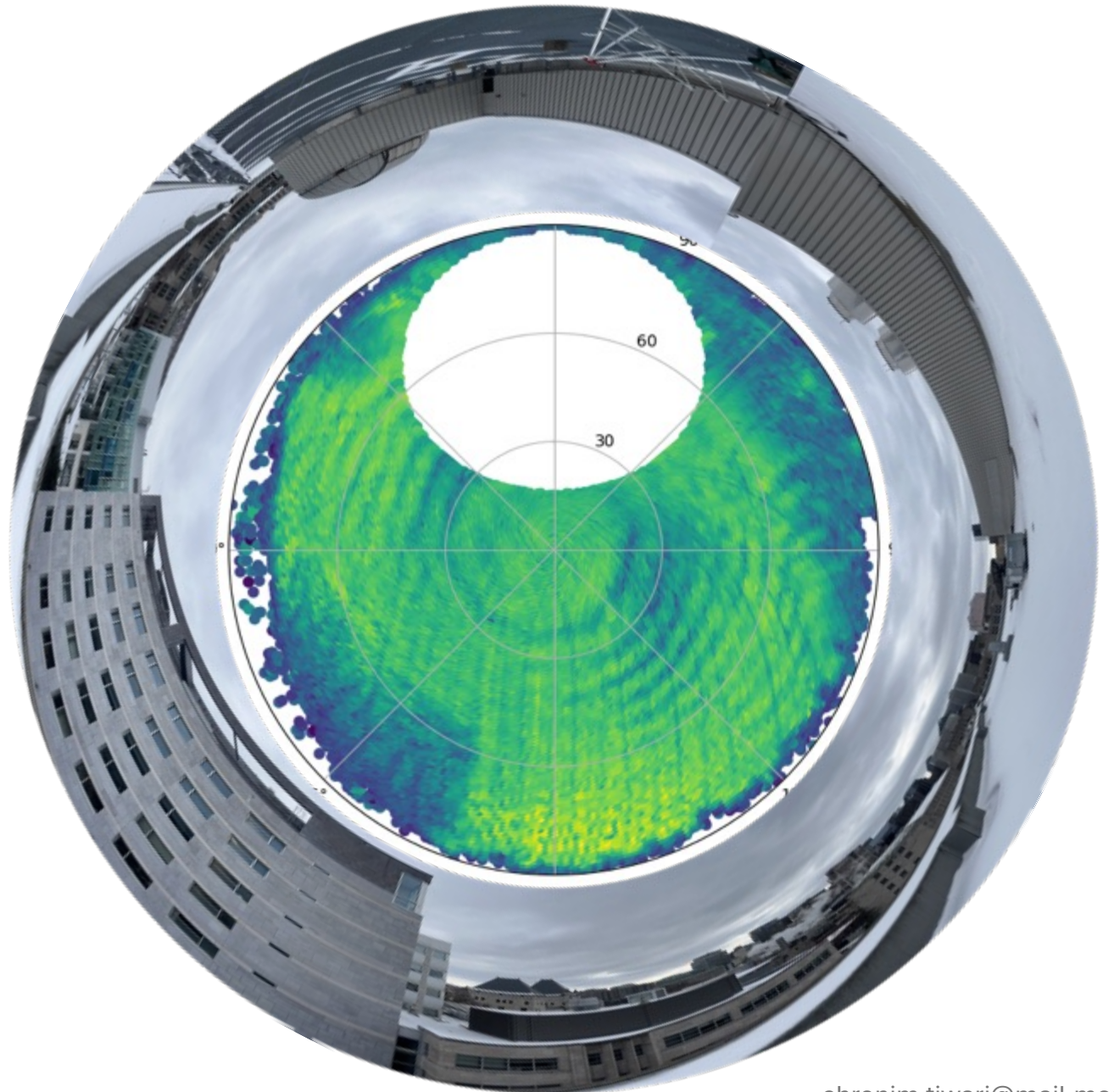
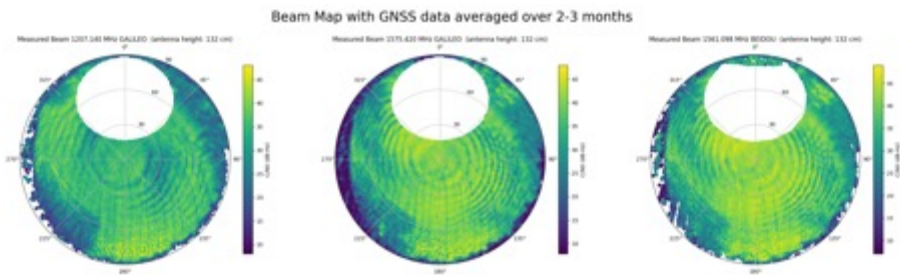


RoofPoINS 261 hours 25 Nov Mon 1309 - 6 Dec Fri 0941



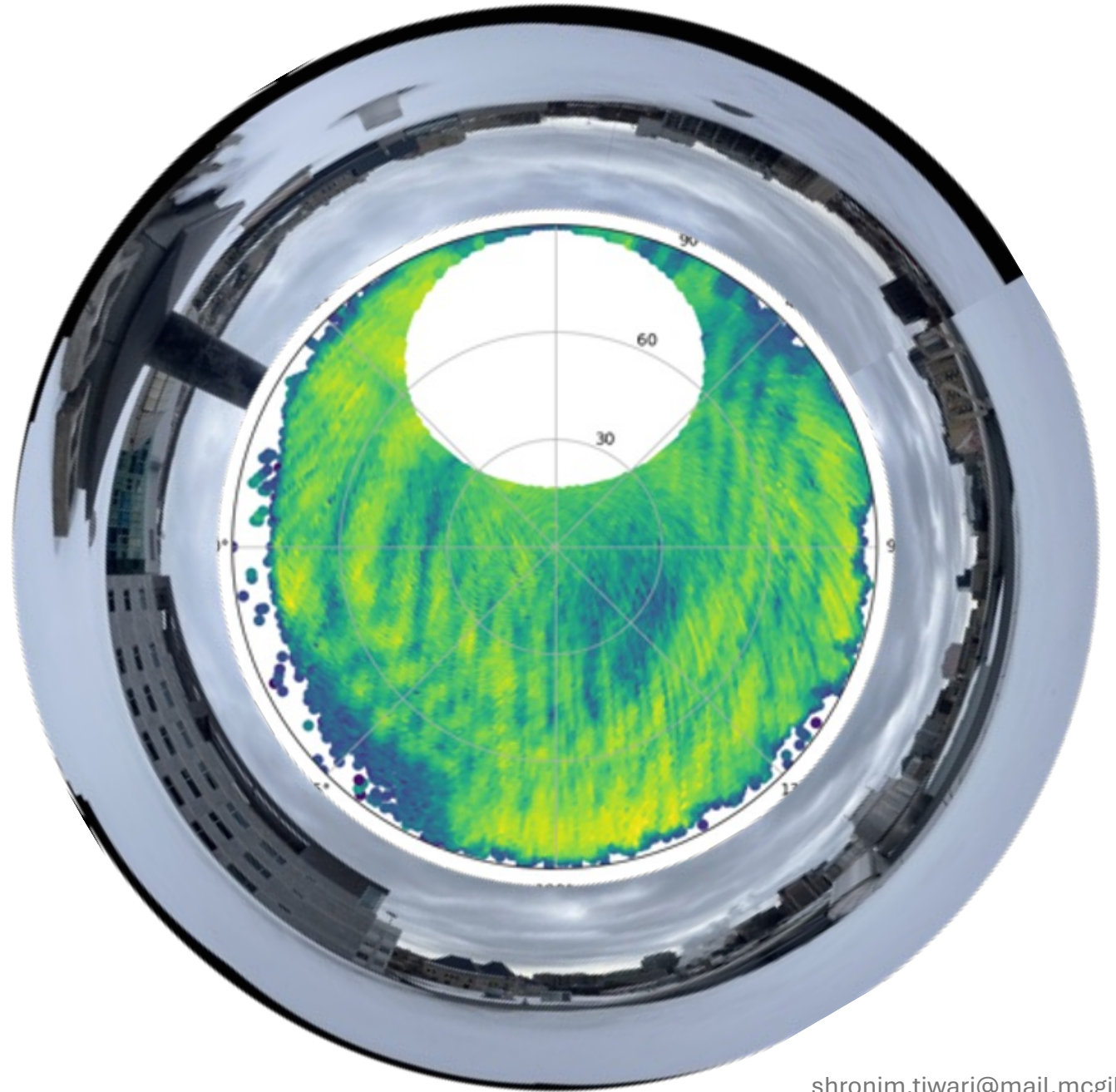
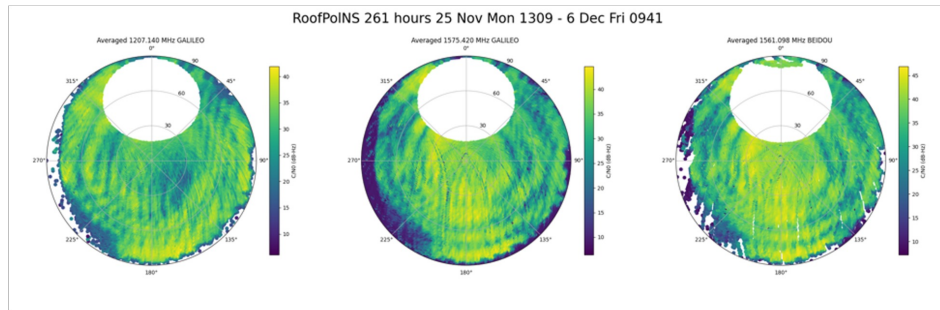
Work with feed

- Surrounding visible in the beam

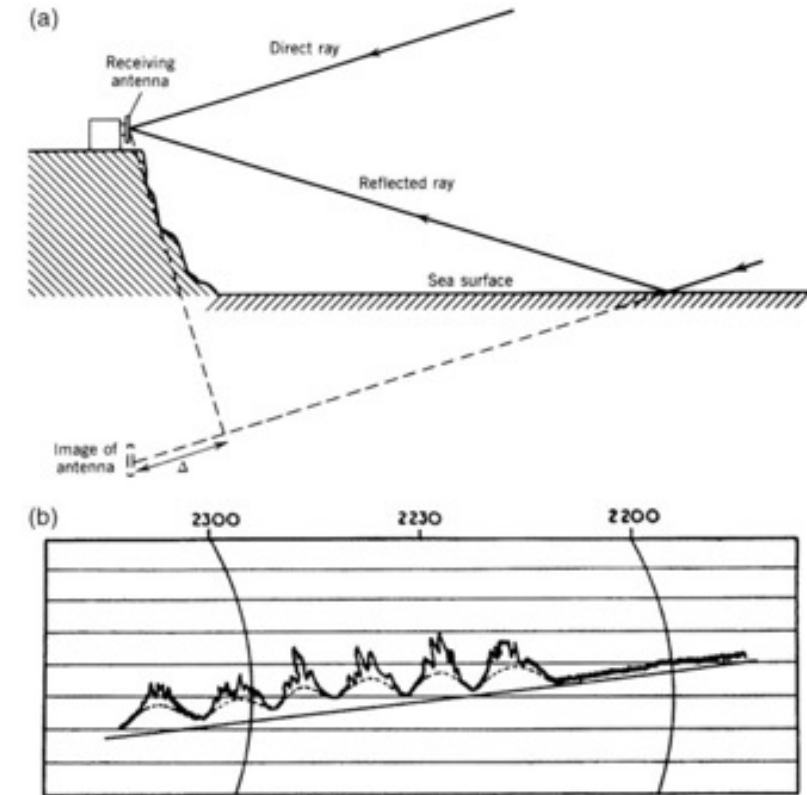
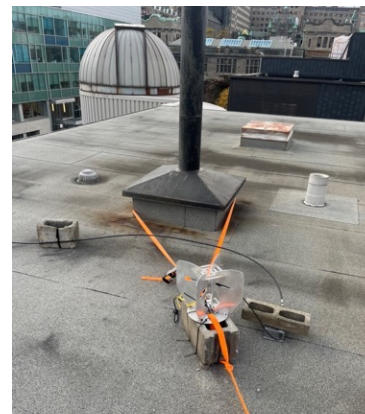
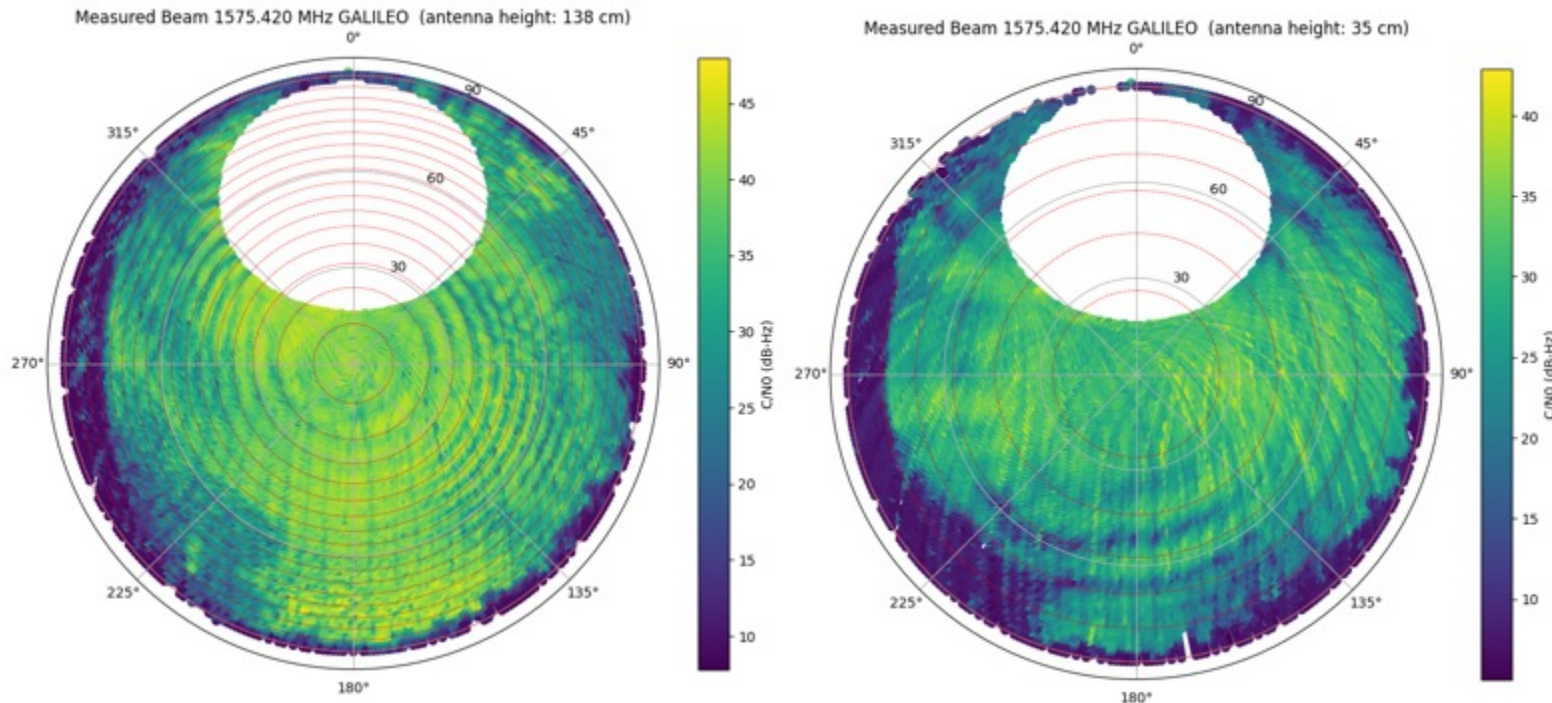


Work with feed

- Surrounding visible in the beam

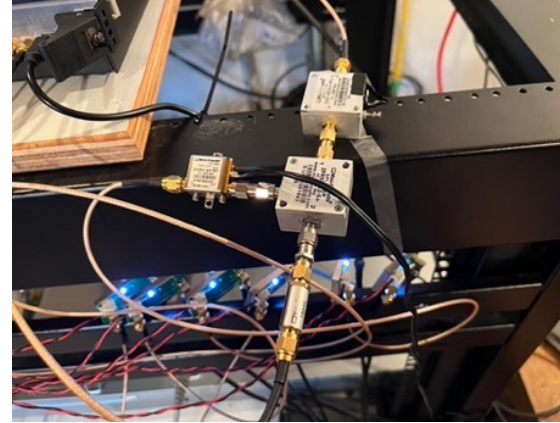
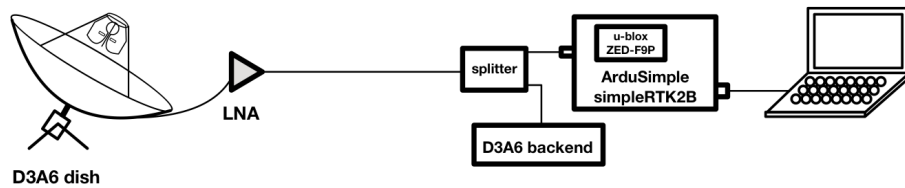


Characterizing ripples

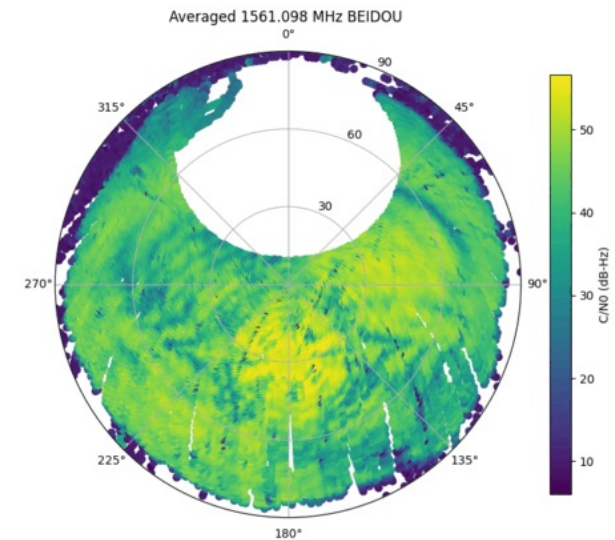
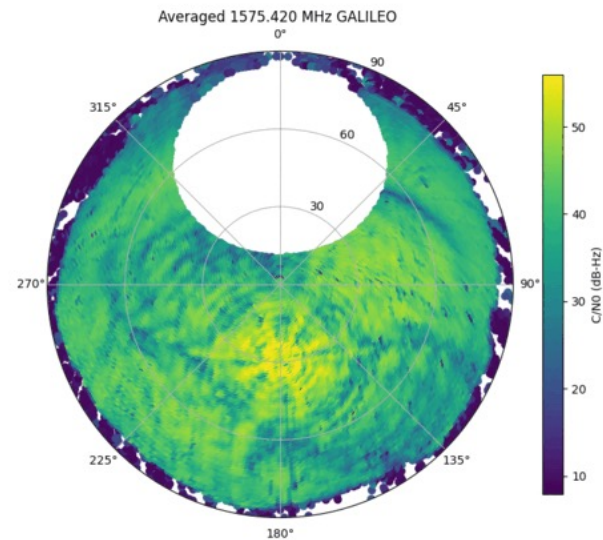
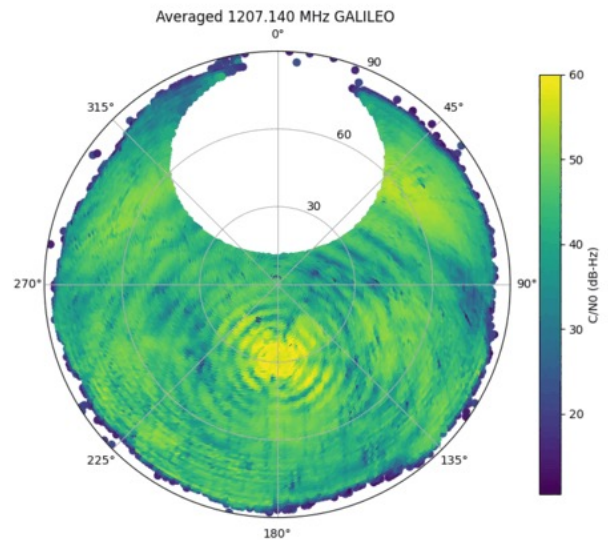


Source: Interferometry and Synthesis in Radio Astronomy, 3rd edition; TMS

Deep Dish Development Array 6-m (D3A6) dishes at DRAO

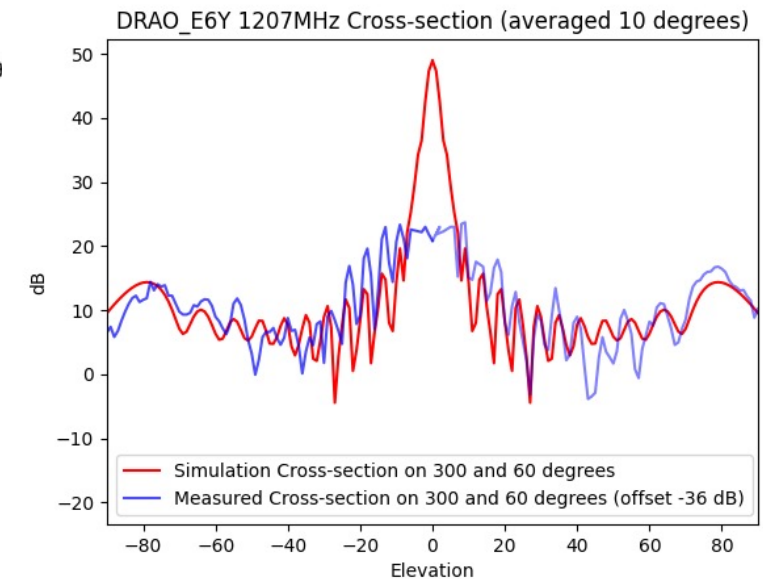
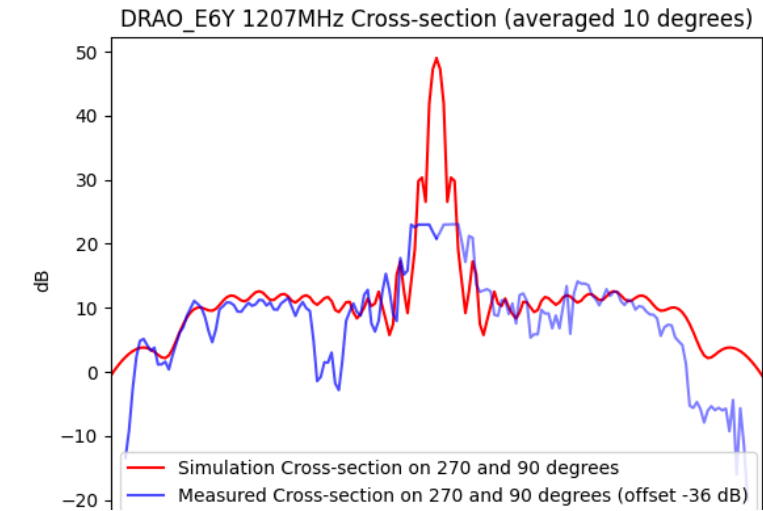
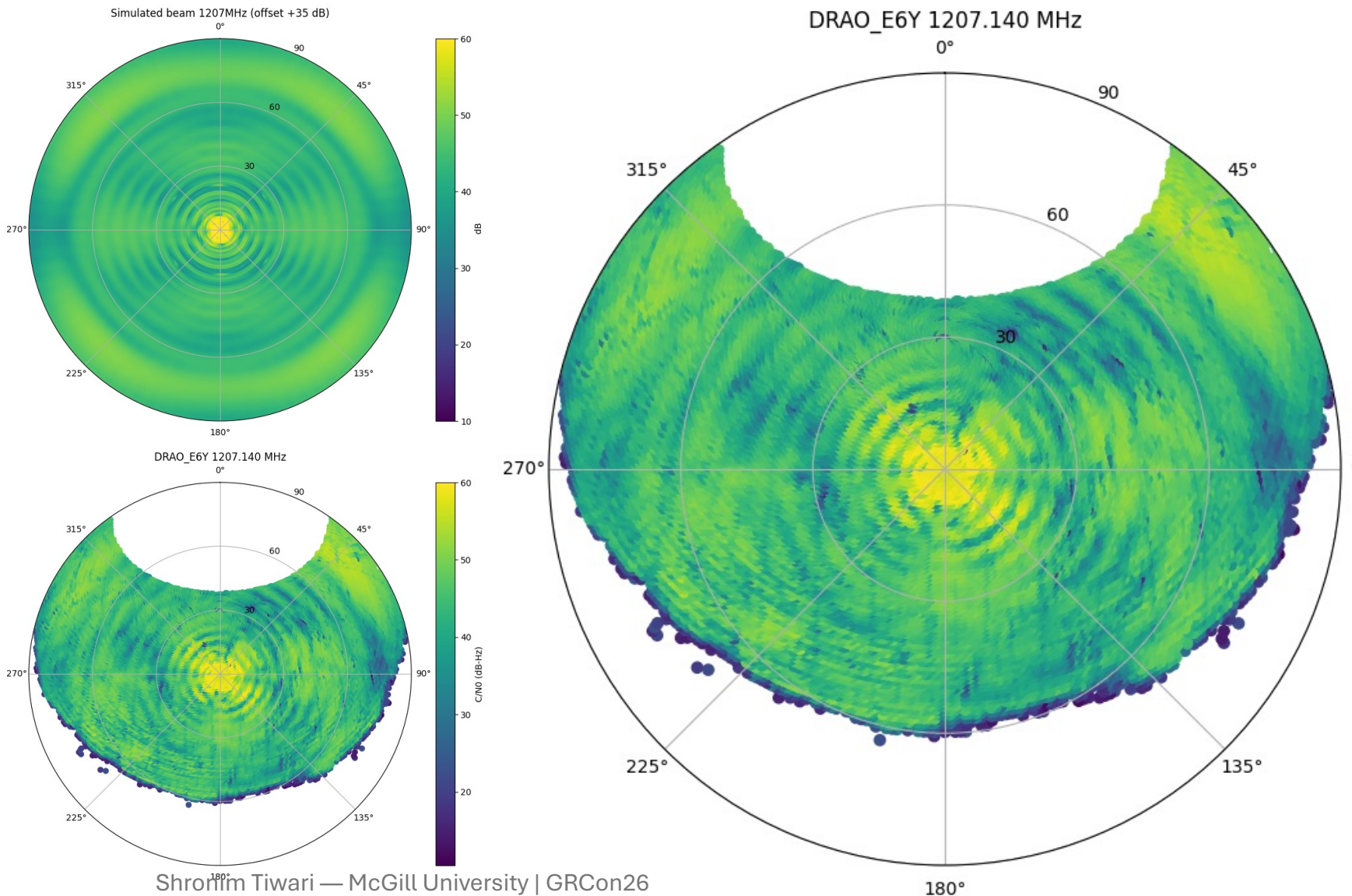


DRAO E6Y pointed -27.3 south 264 hours Wed 22 Jan 1628 - Sun 02 Feb 1612



Comparison with Simulation

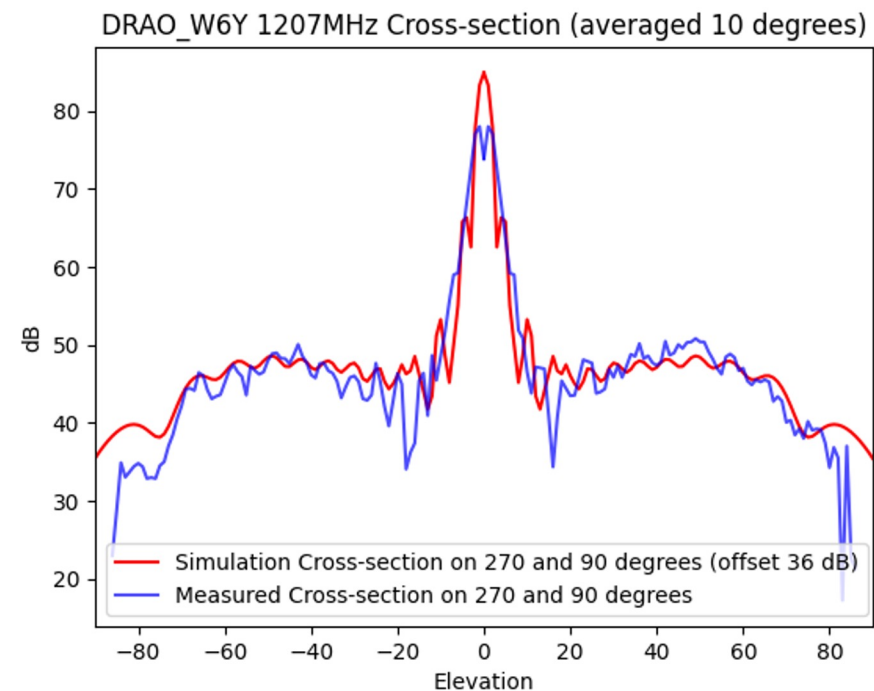
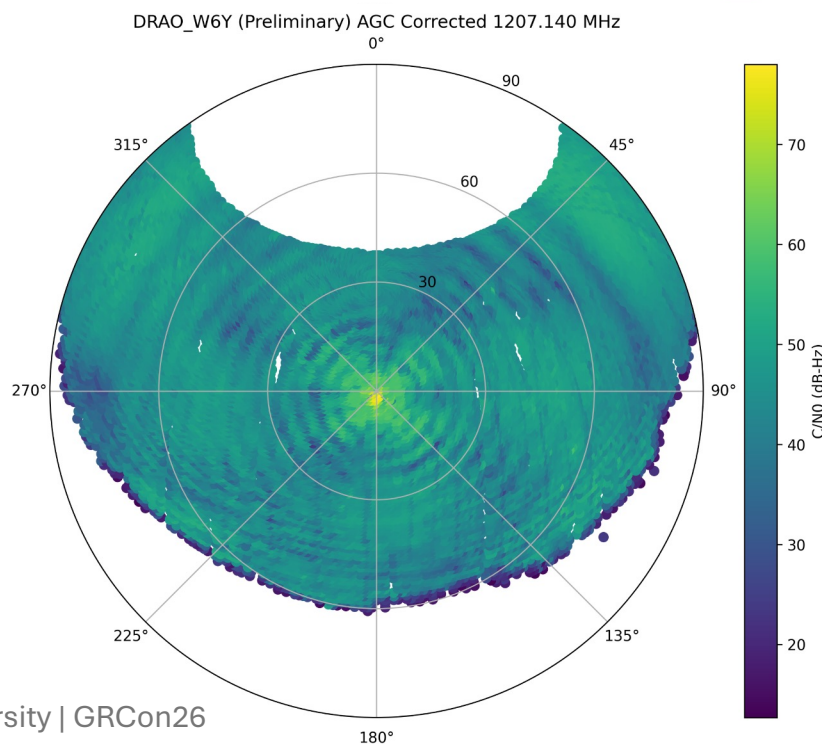
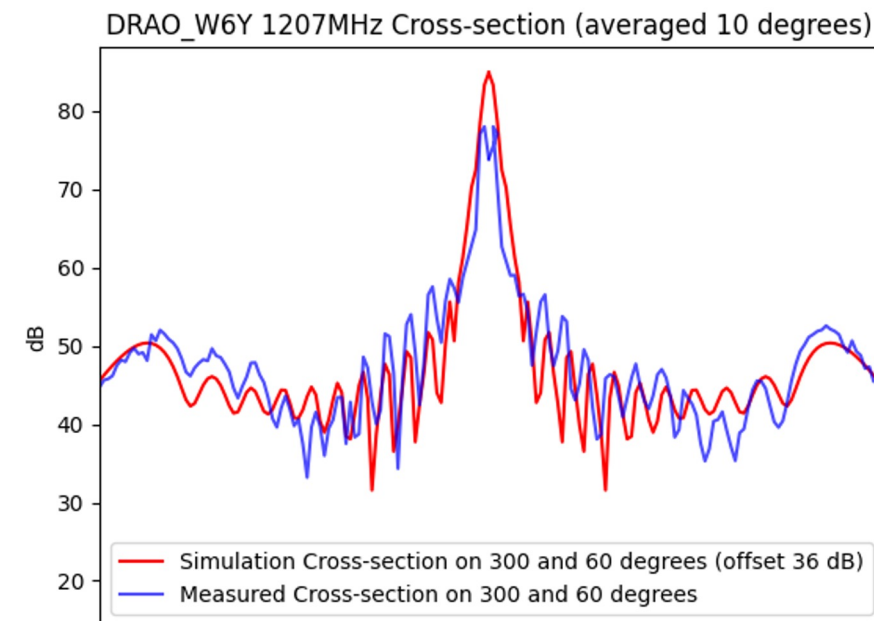
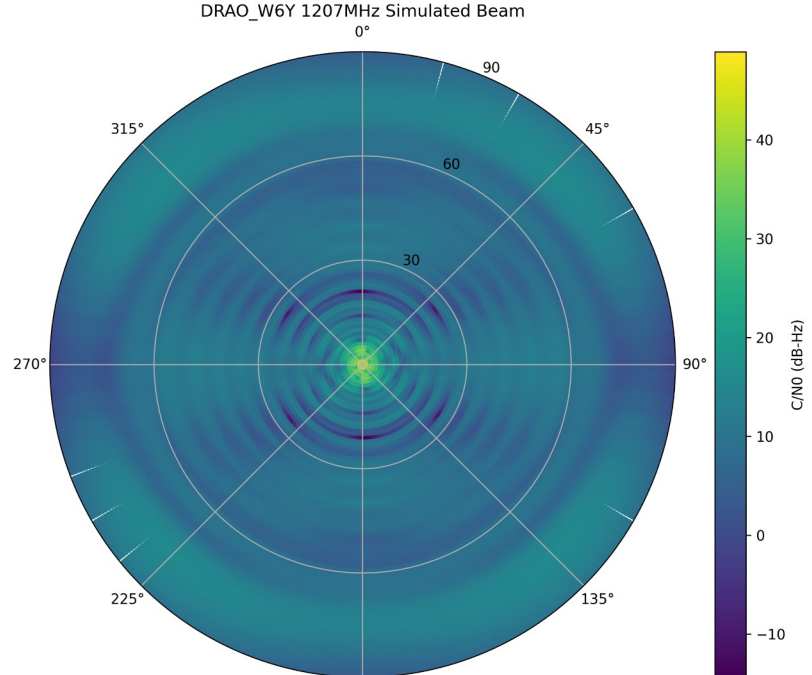
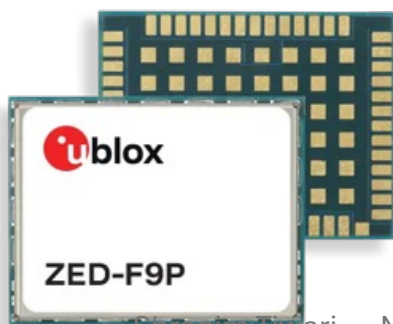
(Simulation credit: Vincent MacKay)



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PRELIMINARY RESULT FOR CORRECTING SATURATION

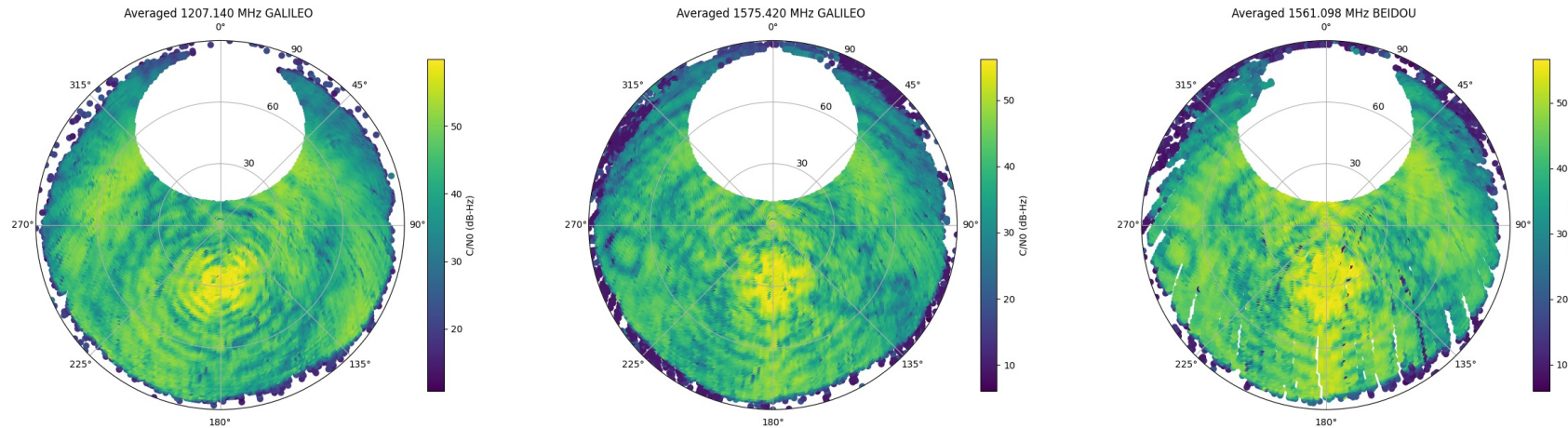
*has not been
corrected for satellite
beam



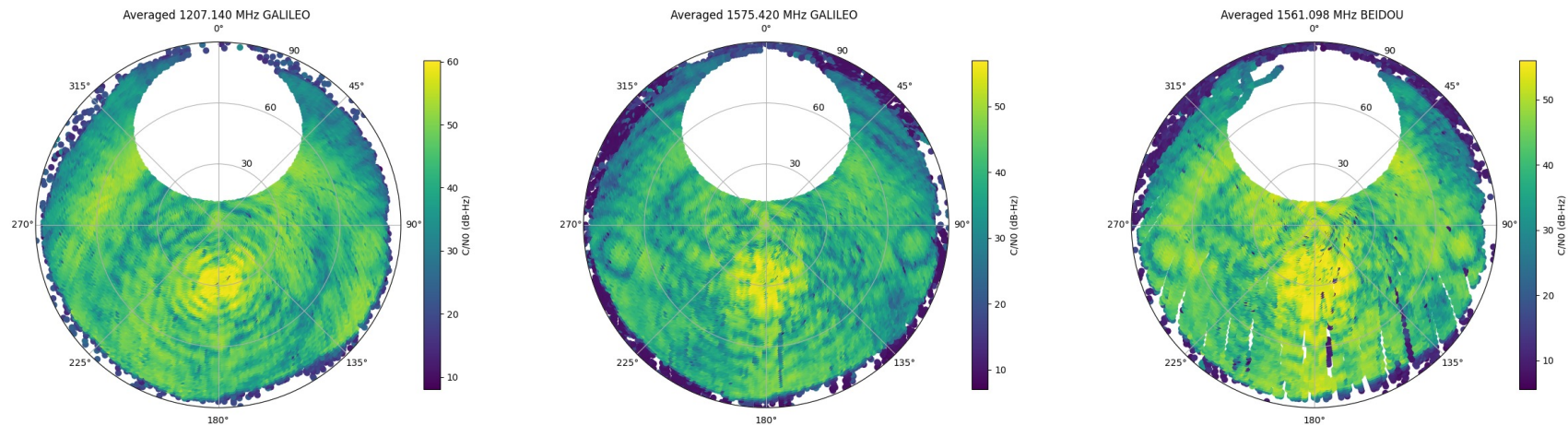
Beams for CHORD dishes



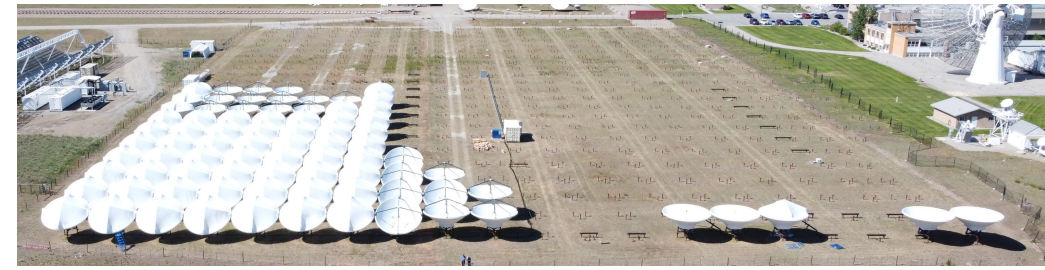
CHORD A7X 223 hours Sun 05 Apr 1505 - Tue 14 Apr 2224



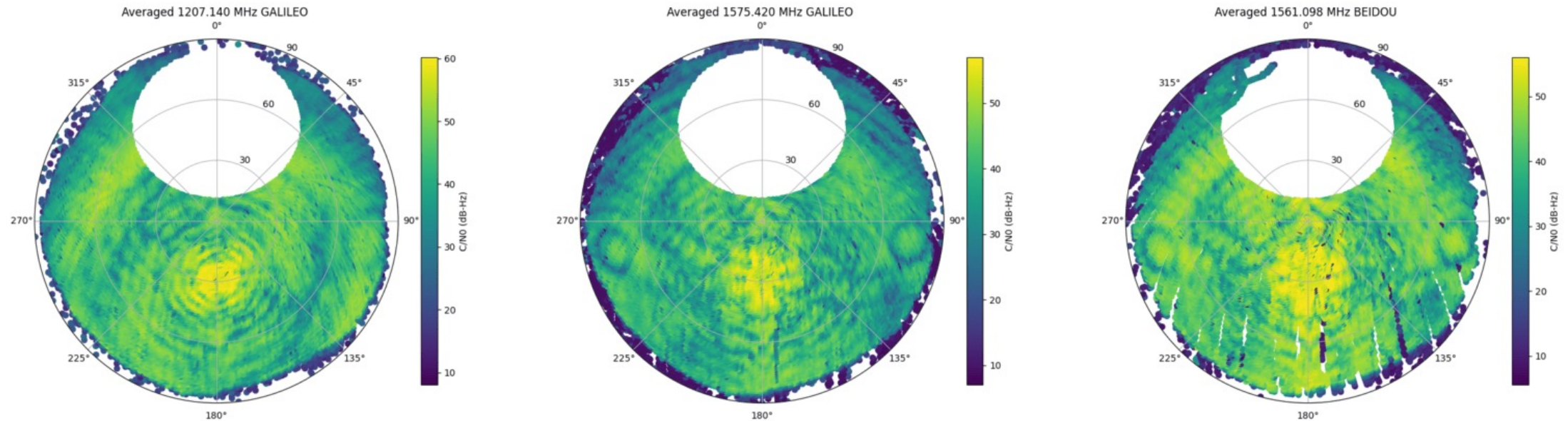
CHORD A6X 286 hours Wed 13 May 2026 0915 - Mon 25 May 0652



Beams for CHORD dishes



CHORD A6X 286 hours Wed 13 May 2026 0915 - Mon 25 May 0652

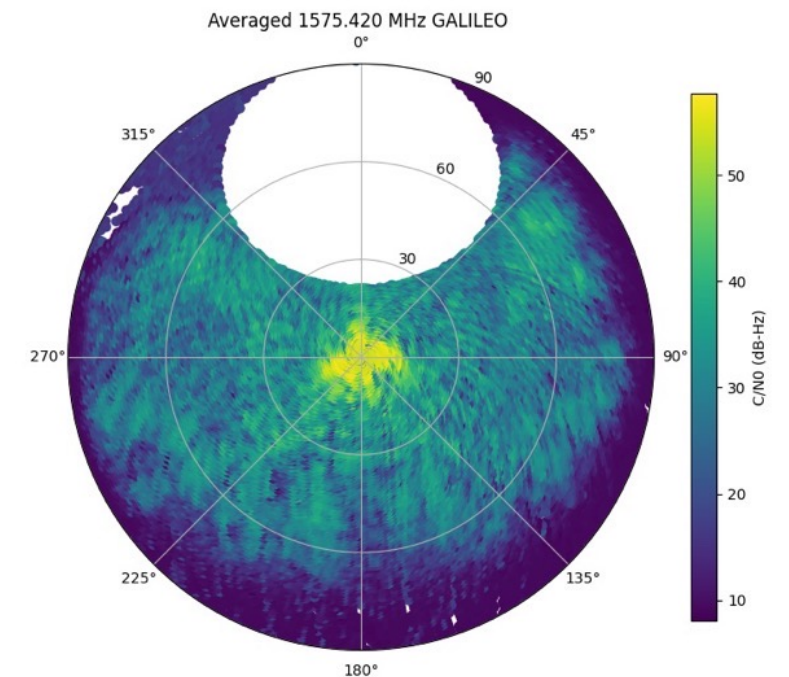
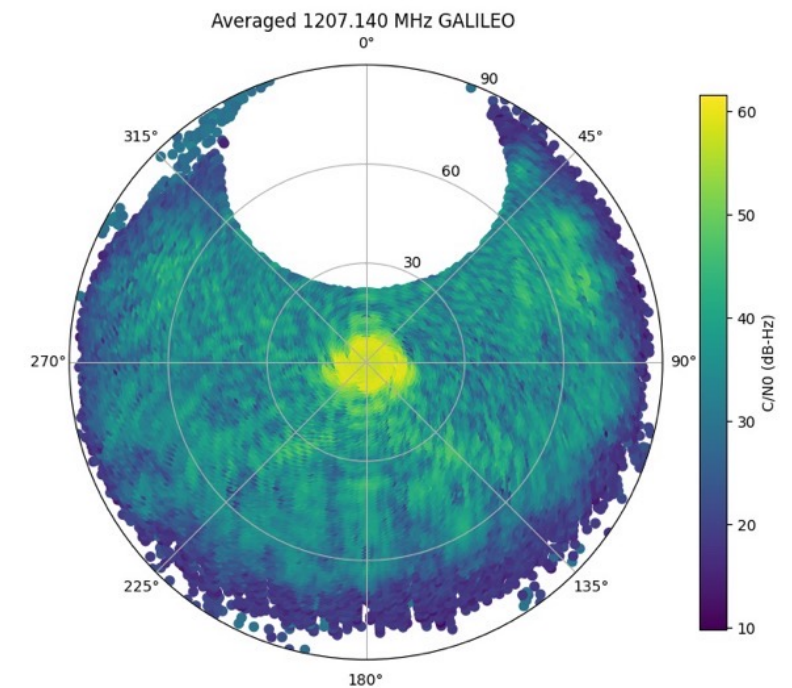


Baryon Mapping eXperiment (BMX)



Collaboration with
Dr. Anze Slozar and Astrophysics & Cosmology Group, Physics Department at
Brookhaven National Laboratory

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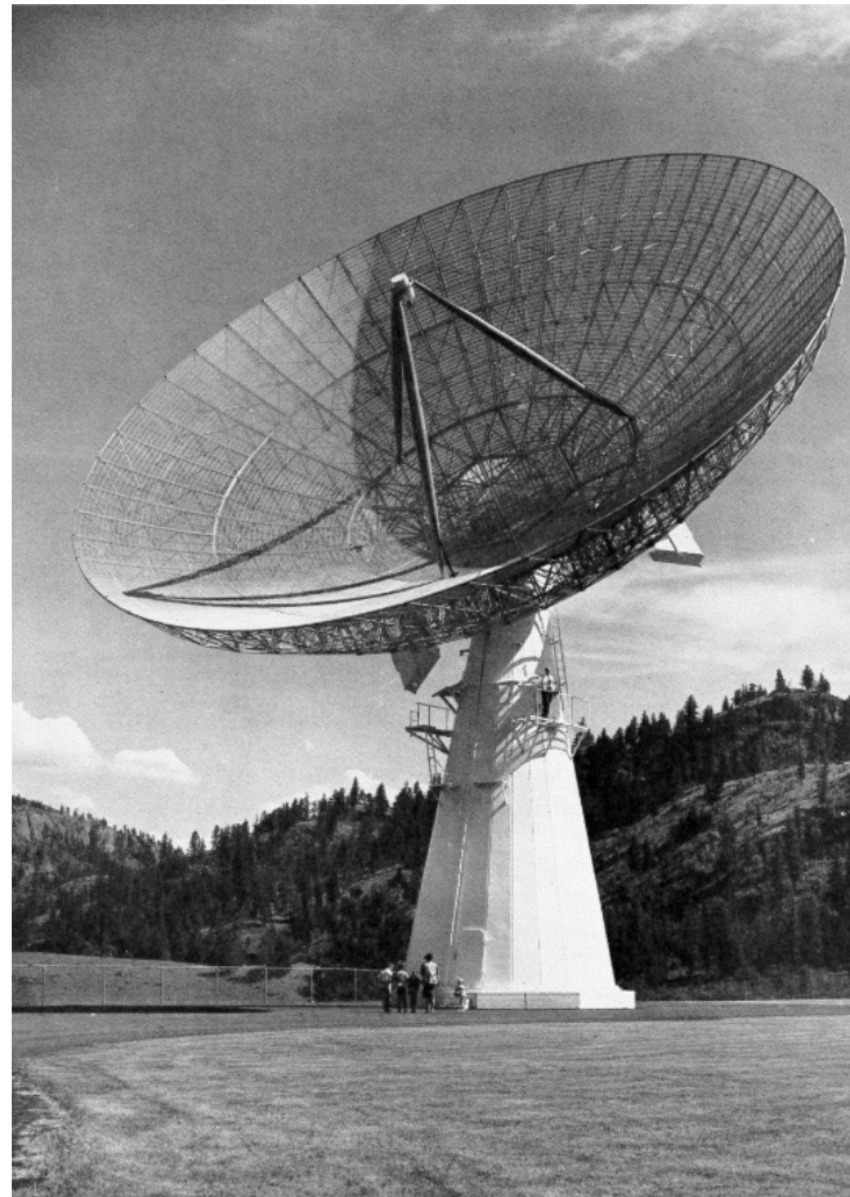


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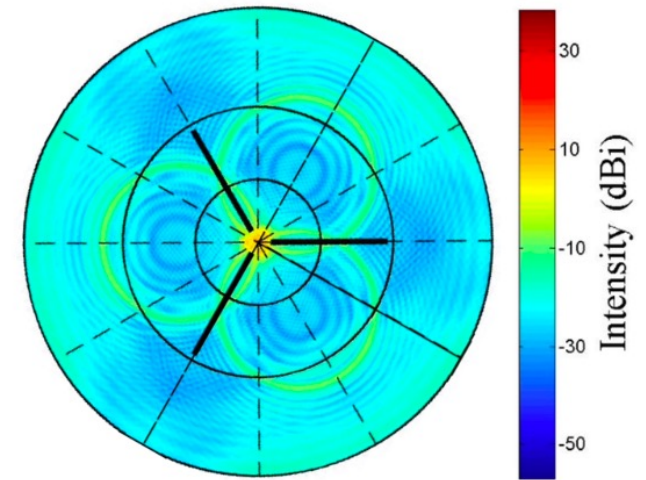
John A. Galt 26m dish at DRAO



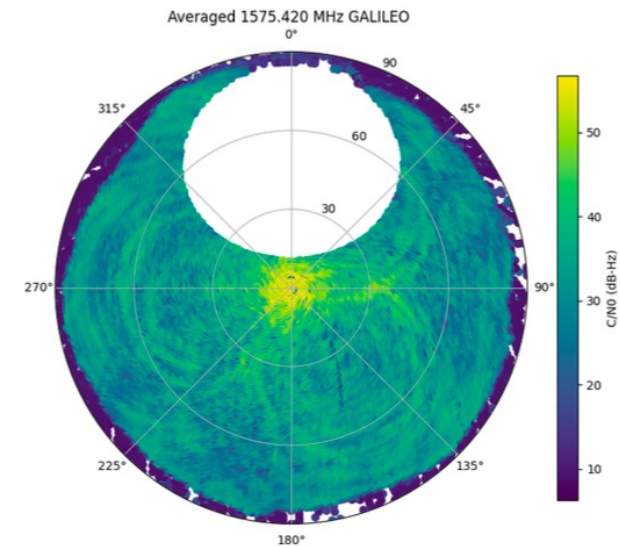
Collaboration with
Dr. Timothy Robishaw



(a) JAG 26-m telescope. Image credit: Locke et al.
(1965)



(b) Simulated Stokes I at 1400 MHz.
Credit: adapted from Du et al. (2016)



(c) Measured beam at 1575.42 MHz
with Galileo constellation signal.

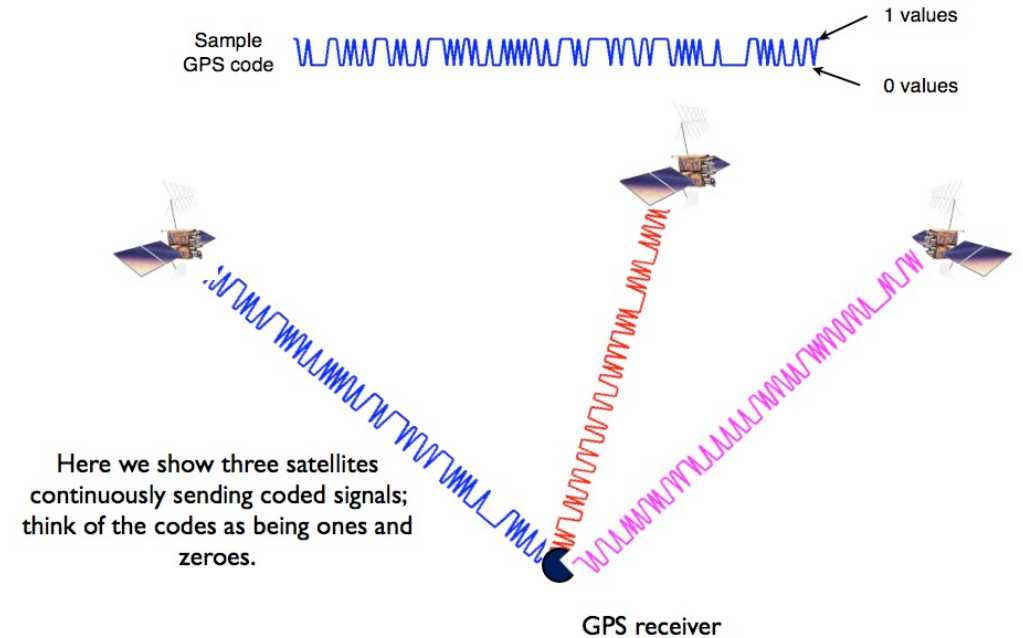
Moving away from commercial receiver

Commercial receivers:

- **Black box:** Proprietary information and limited configurability hinder some ability.
- Commercial receiver is not scalable to map 500+ dishes simultaneously.

Solution:

Signal processing with SDR



The receiver is going to try to decrypt each of the GPS signals separately.

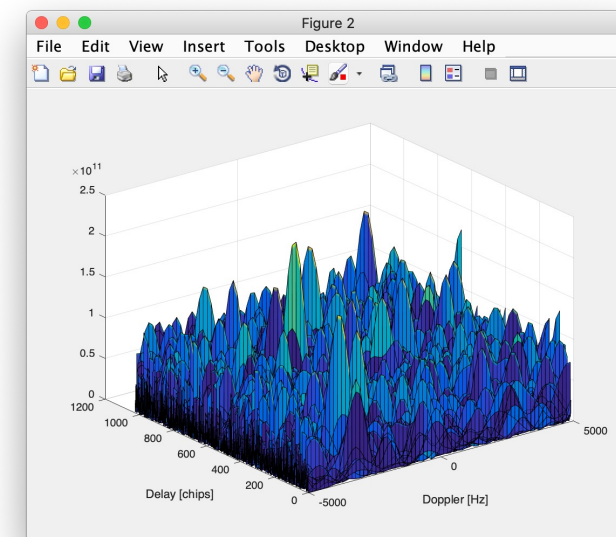
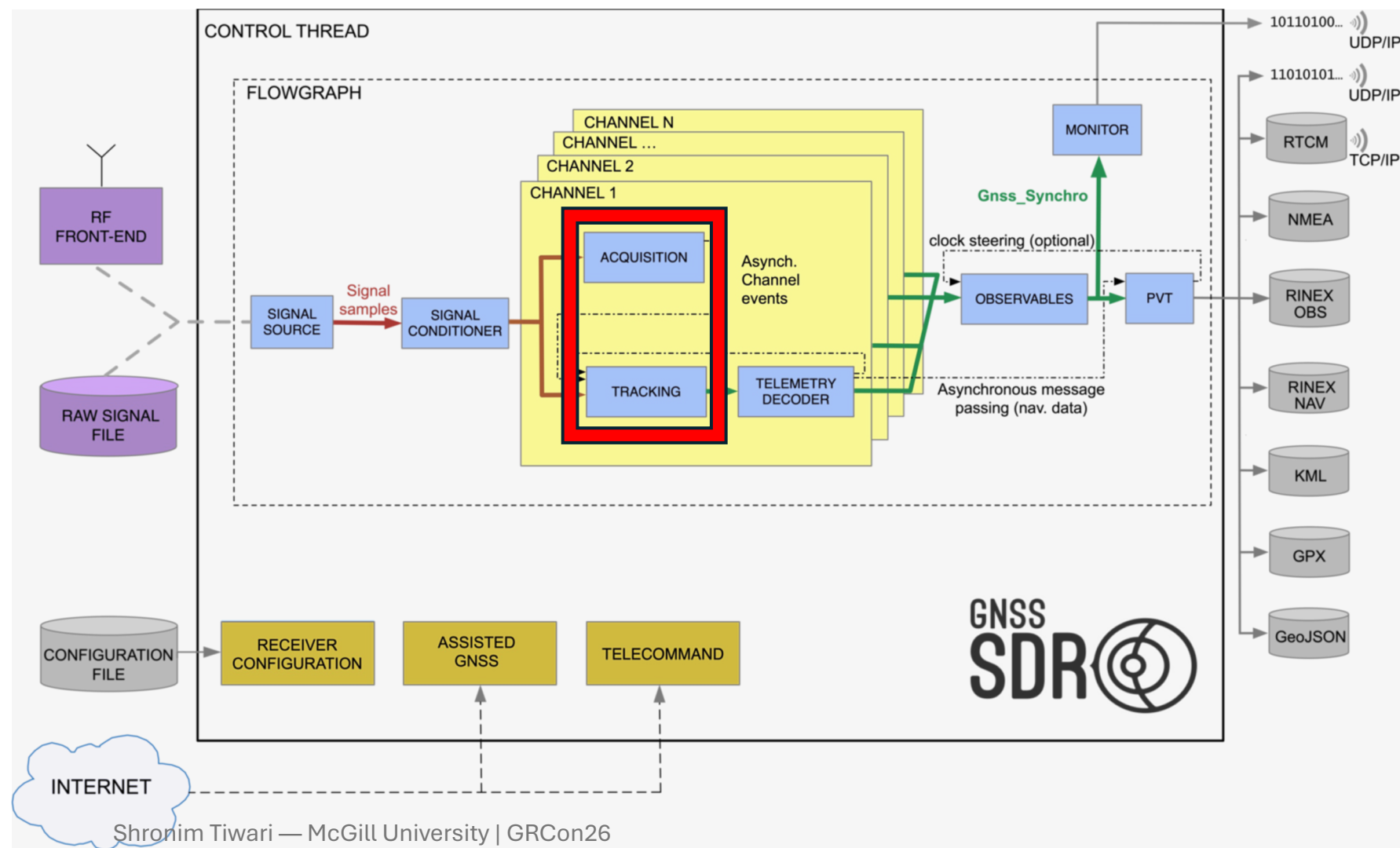
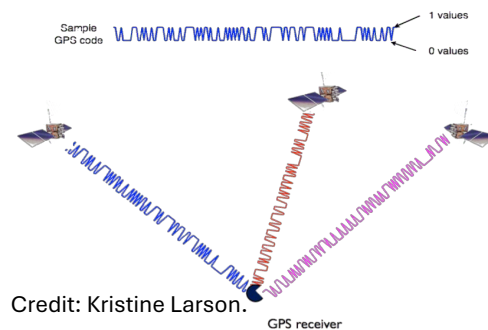
Credit: Kristine Larson.



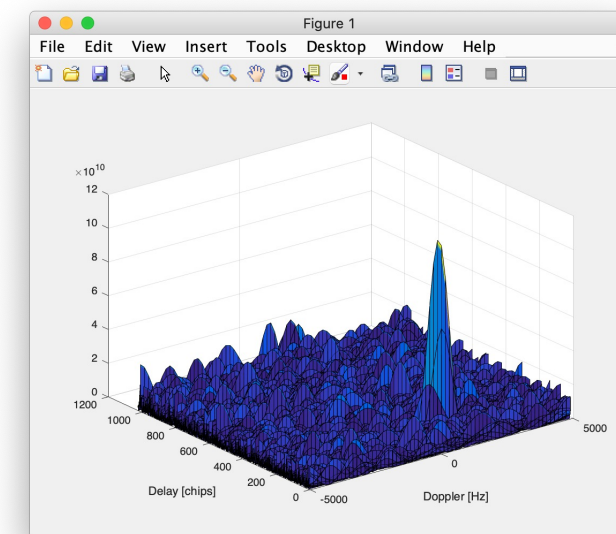
Built on top of GNU
Radio framework



GNSS-SDR

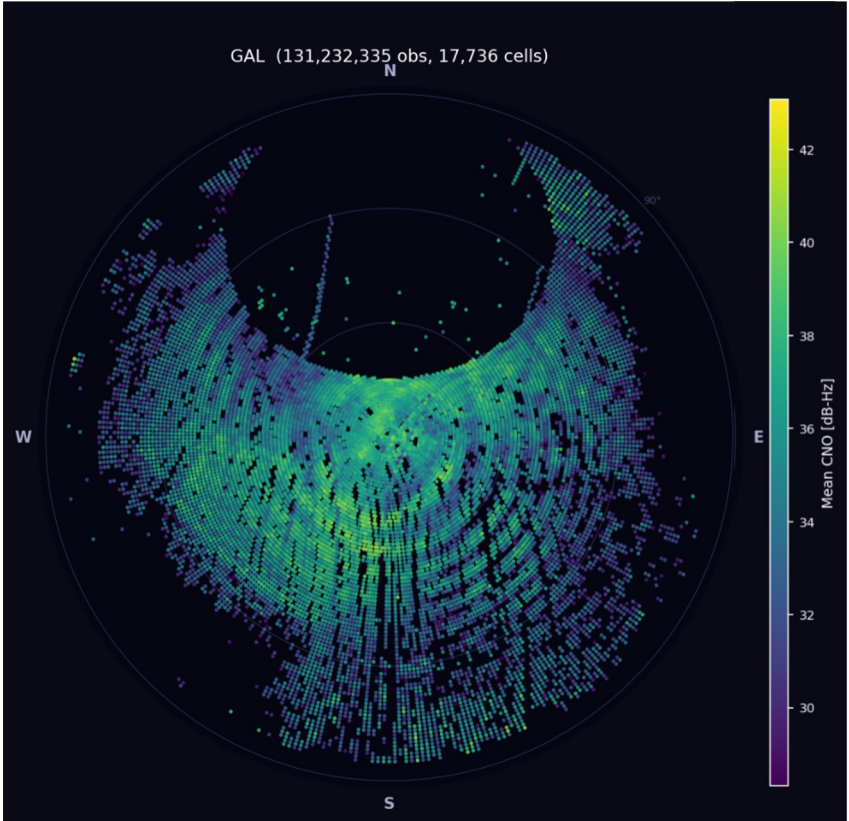
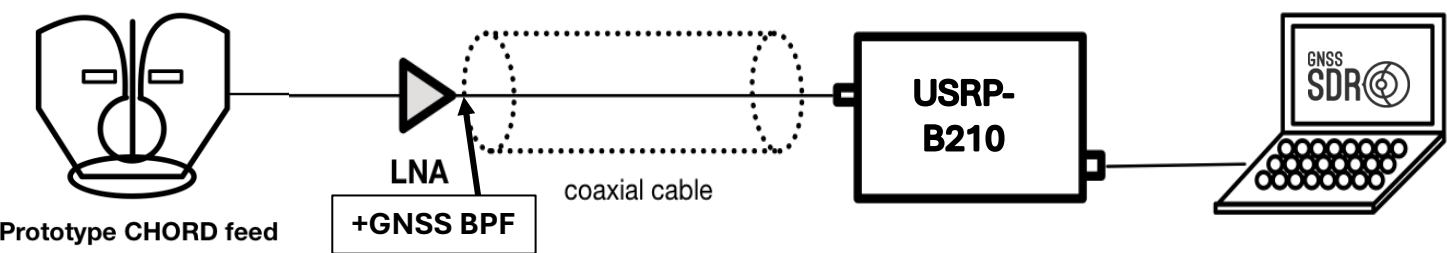


Negative acquisition.



Positive acquisition.

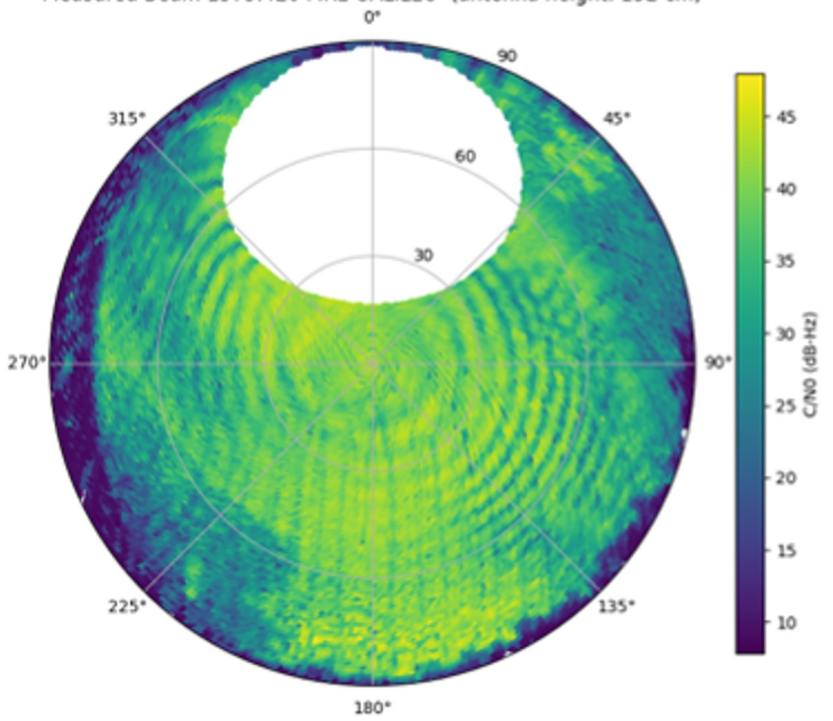
Beam for CHORD feed



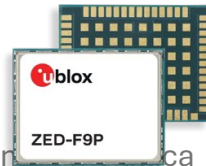
Using gnss-sdr and USRP B210

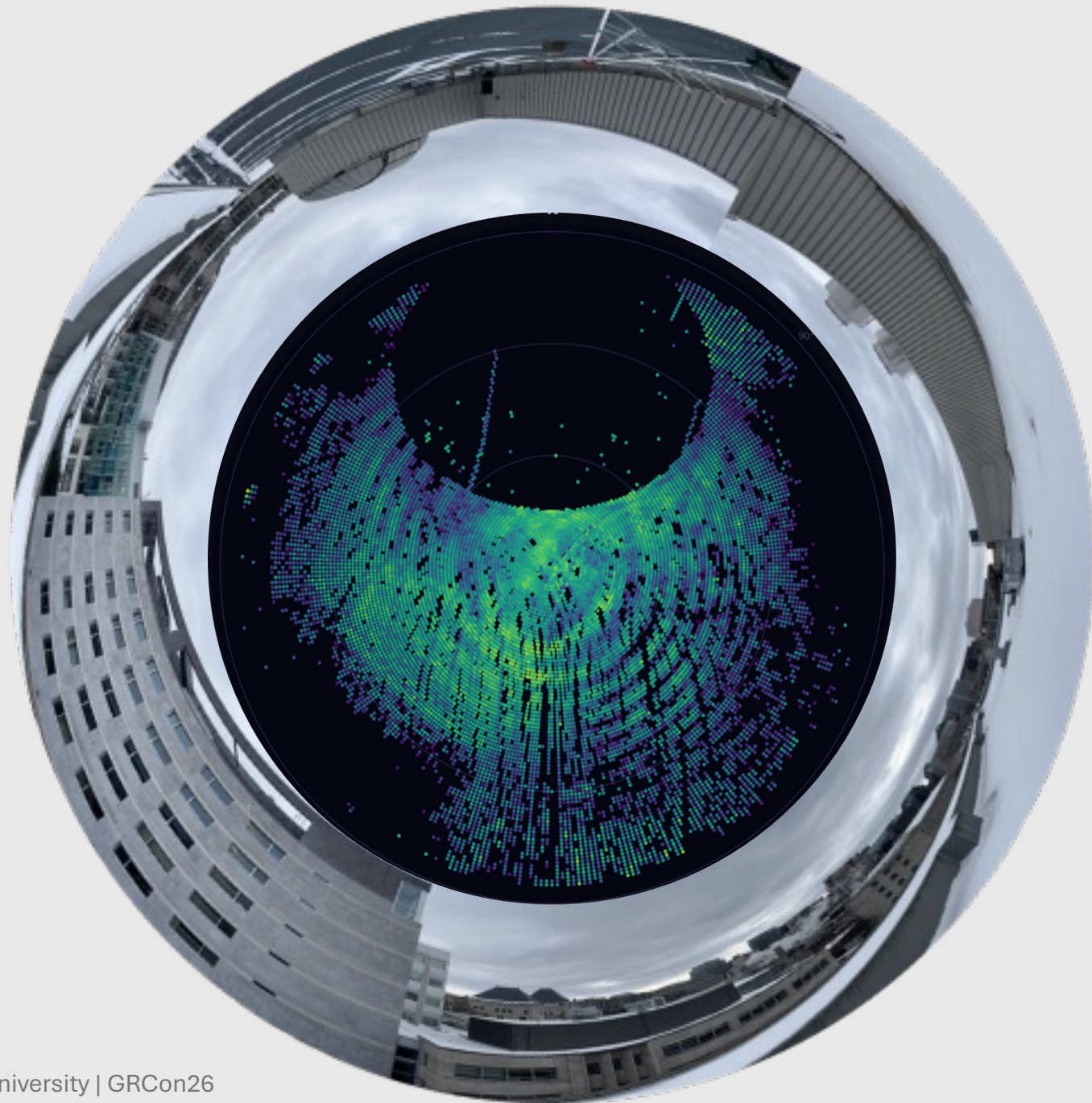


ublox-receiver
Measured Beam 1575.420 MHz GALILEO (antenna height: 132 cm)

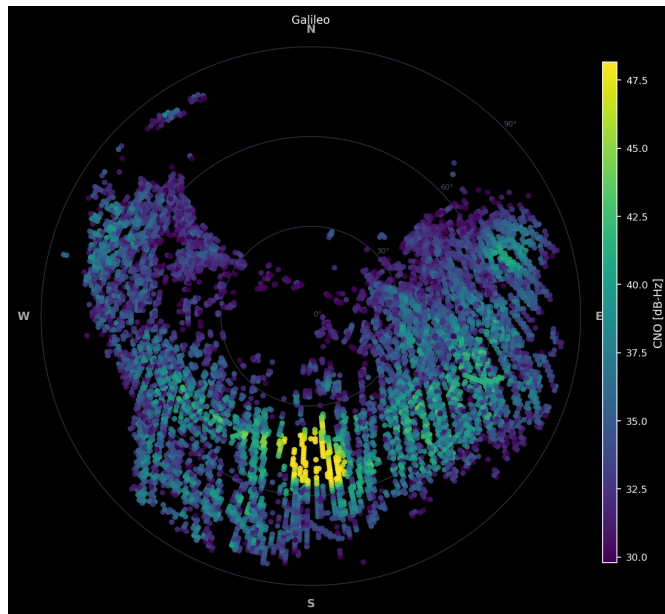
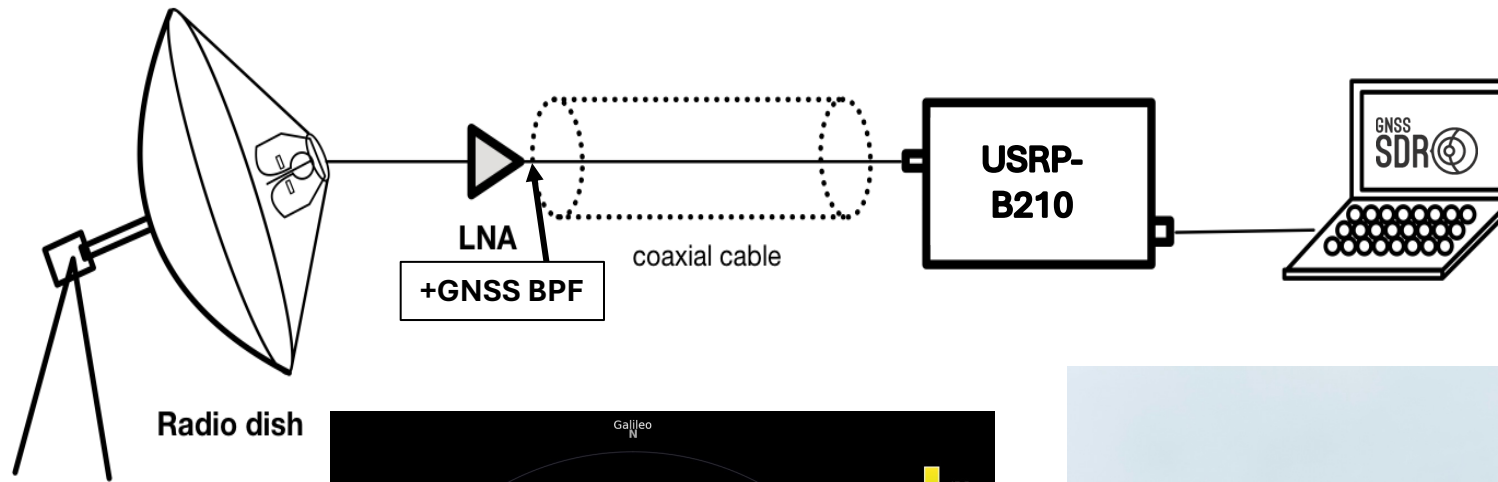


Using ublox receiver





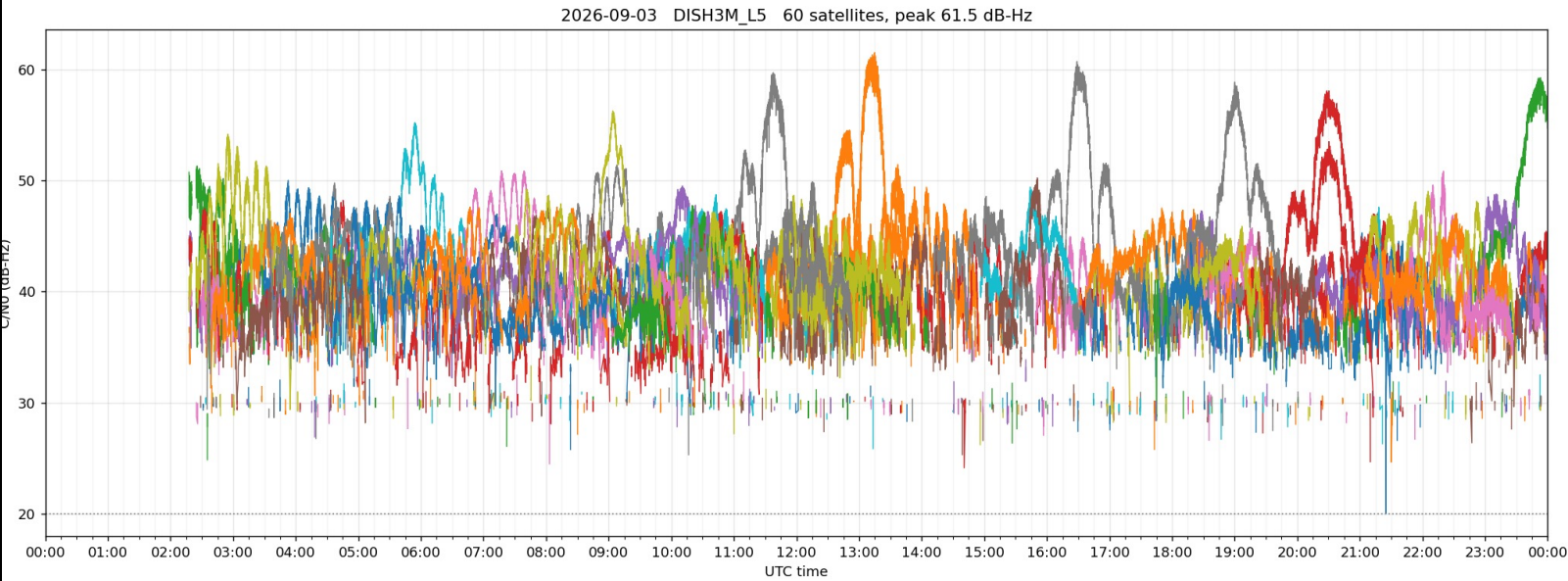
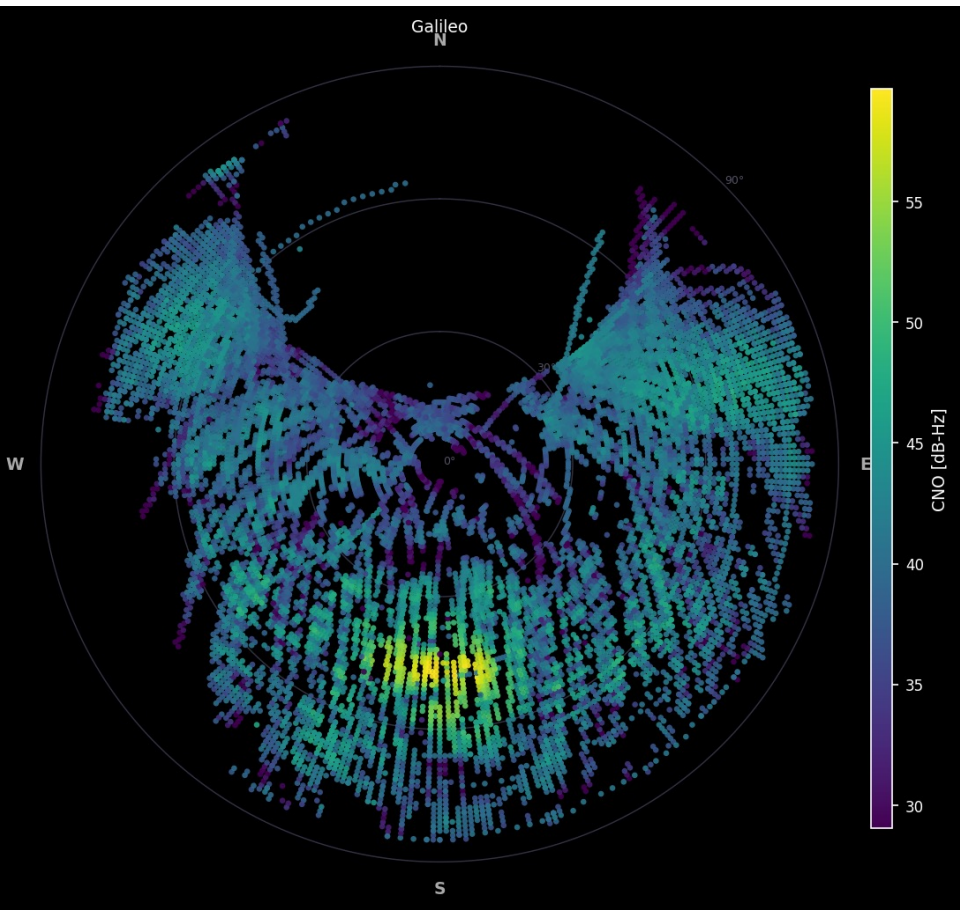
McGill Physics Building Roof 2m Dish



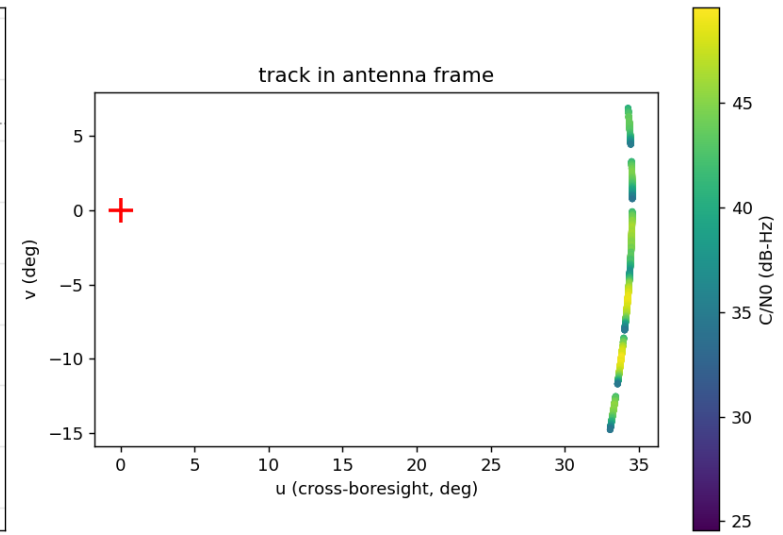
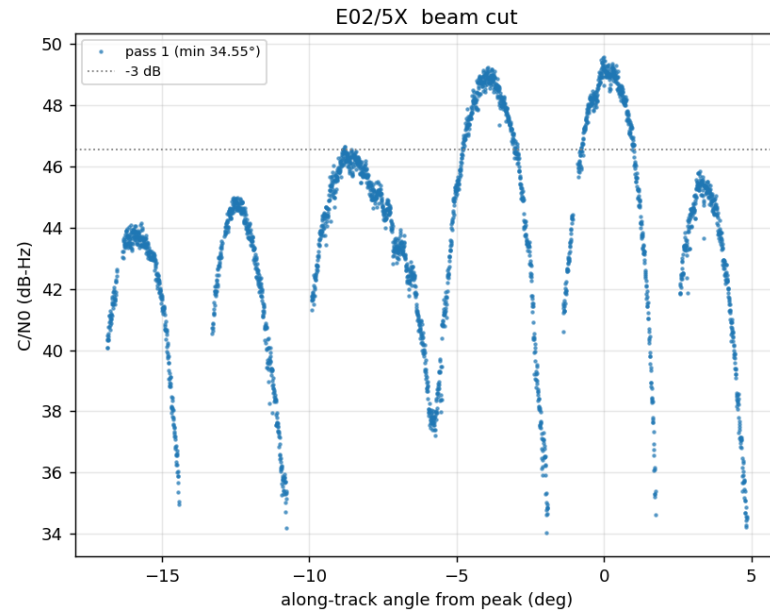
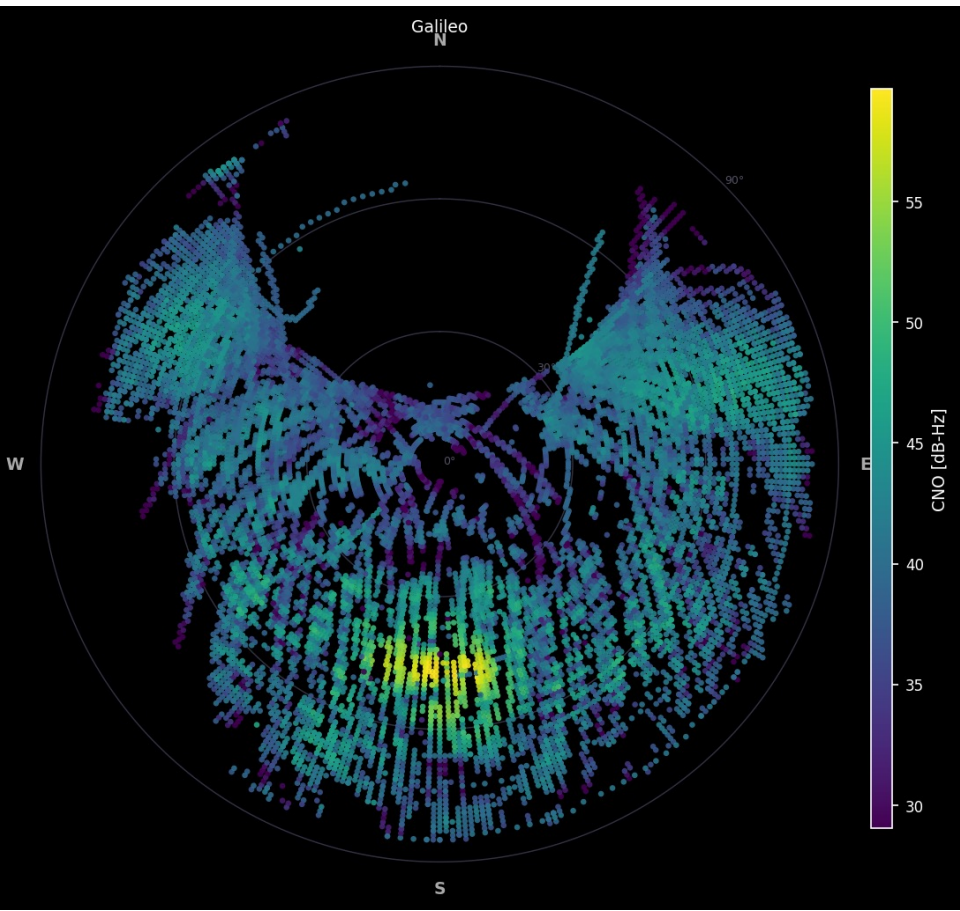
GNSS-SDR at L1 (1575 MHz)



At L5 and E5a ~1150 MHz

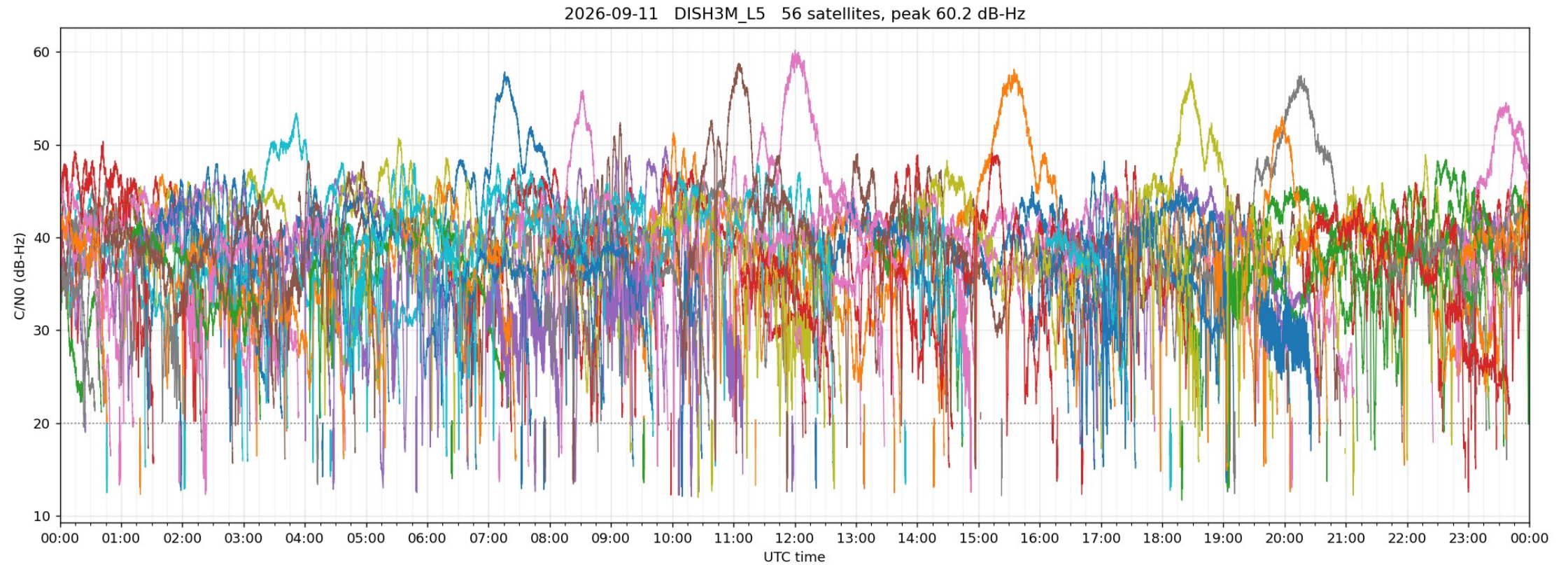


At L5 and E5a ~1150 MHz



Problem: Acquisition needs higher signal to noise, tracking is easier but once tracking lost, higher CN0 needed to get the lock again

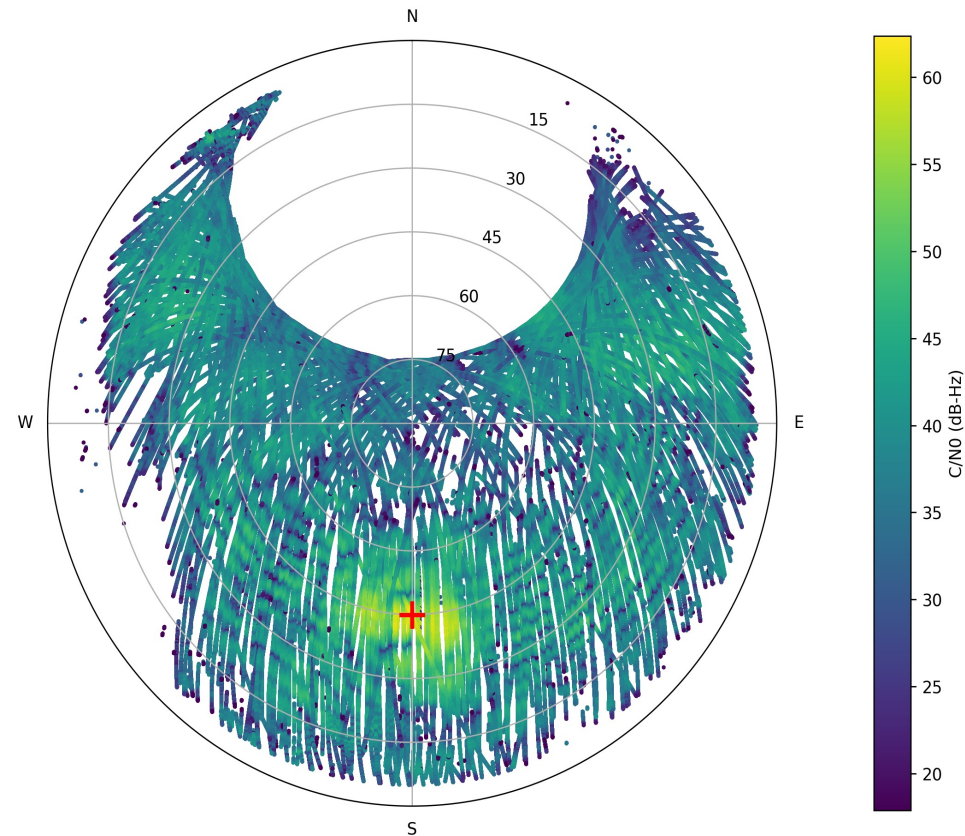
Optimized tracking



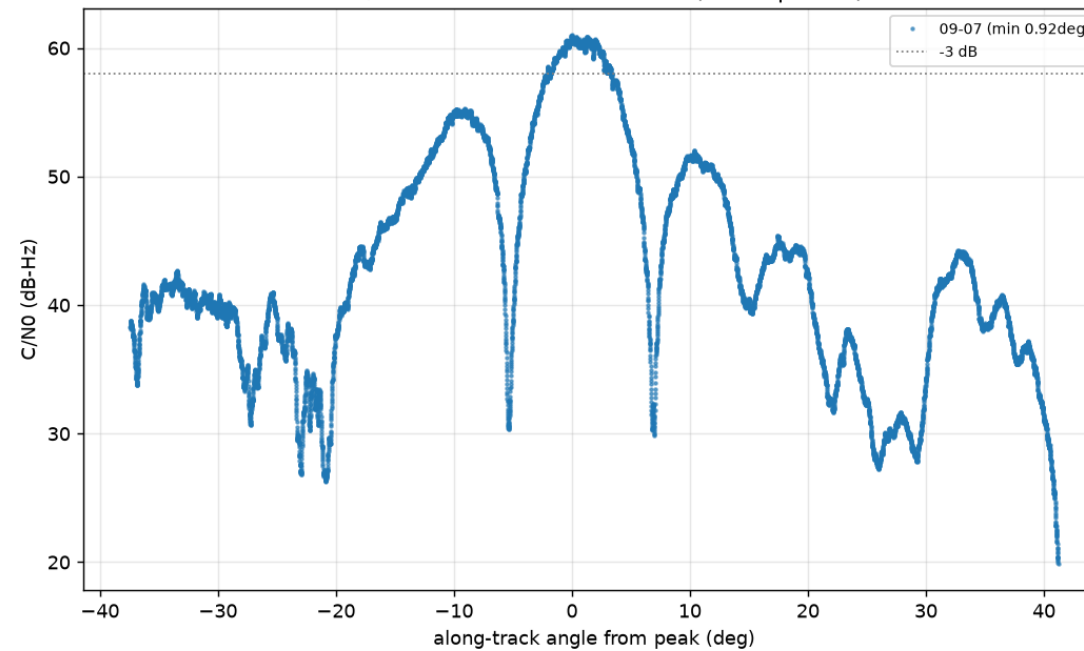
Optimized tracking block:

Current progress: making tracking better given higher dynamic range, but still once lock is lost, satellites needs to get back to around 40dB to lock again

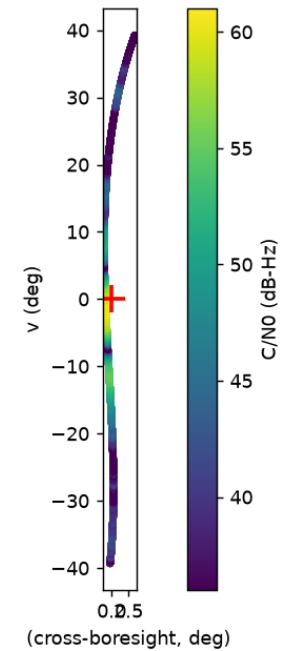
sky map C/N0 (peak 62.4, min 7.9 dB-Hz) [L5,5X]

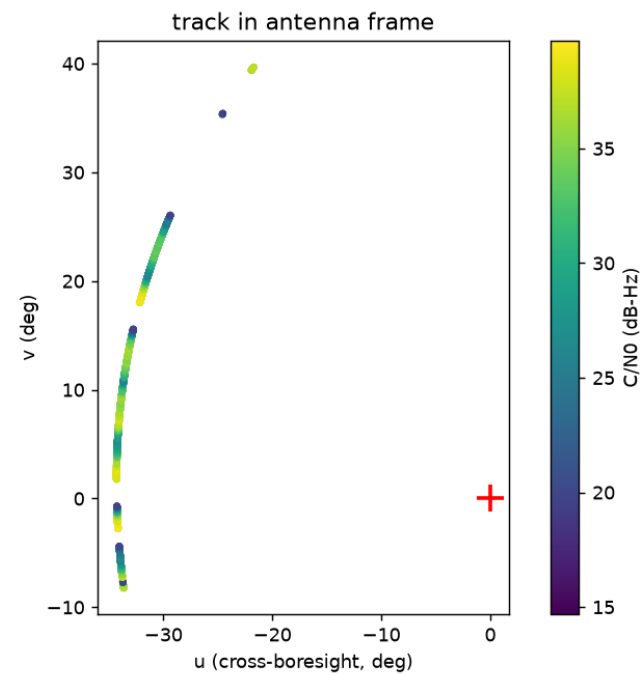
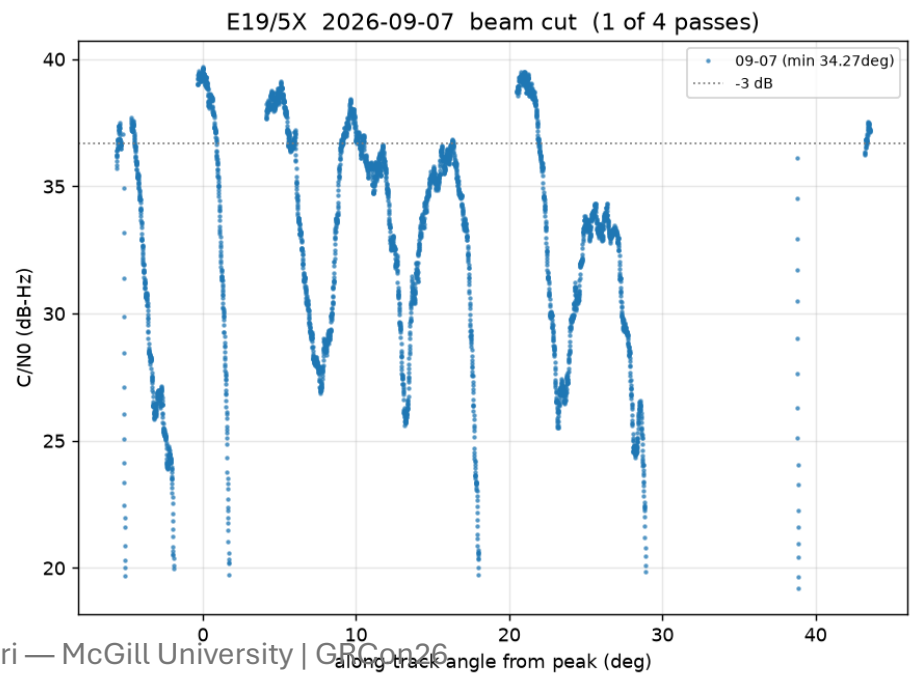
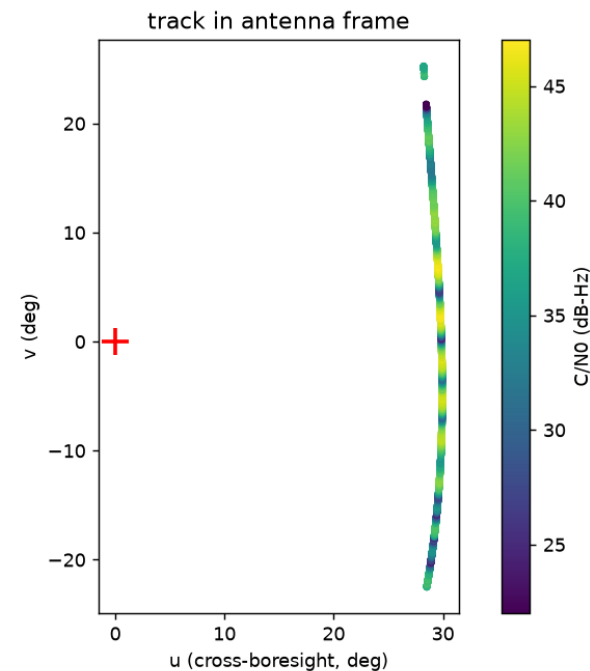
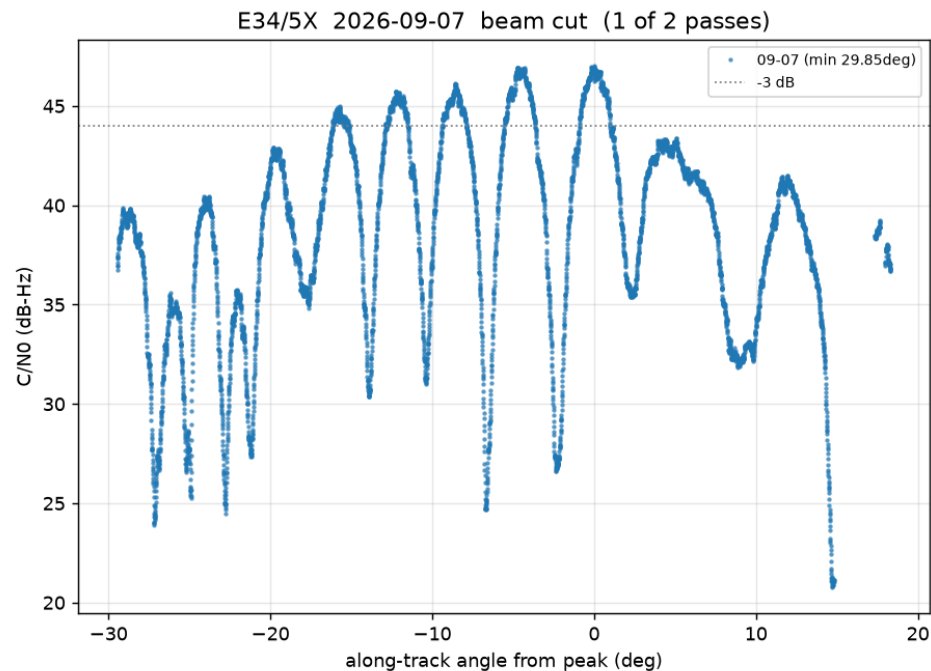


E15/5X 2026-09-07 beam cut (1 of 2 passes)

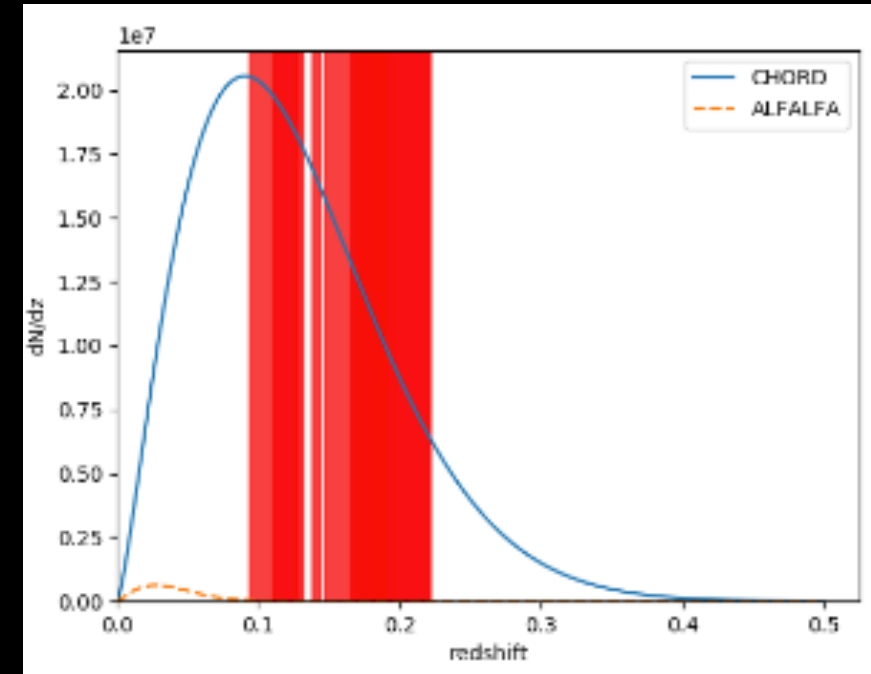
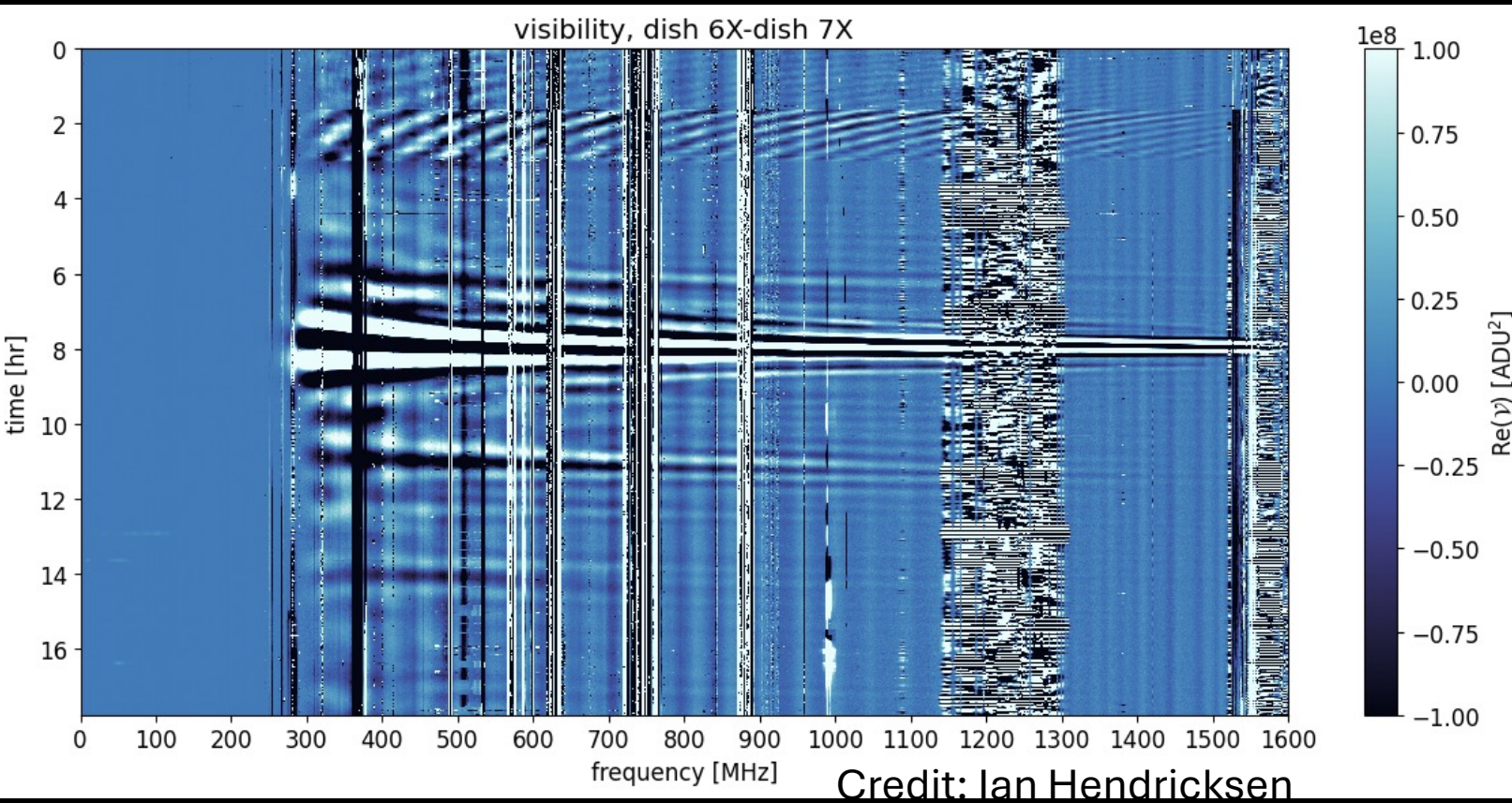


ck in antenna frame





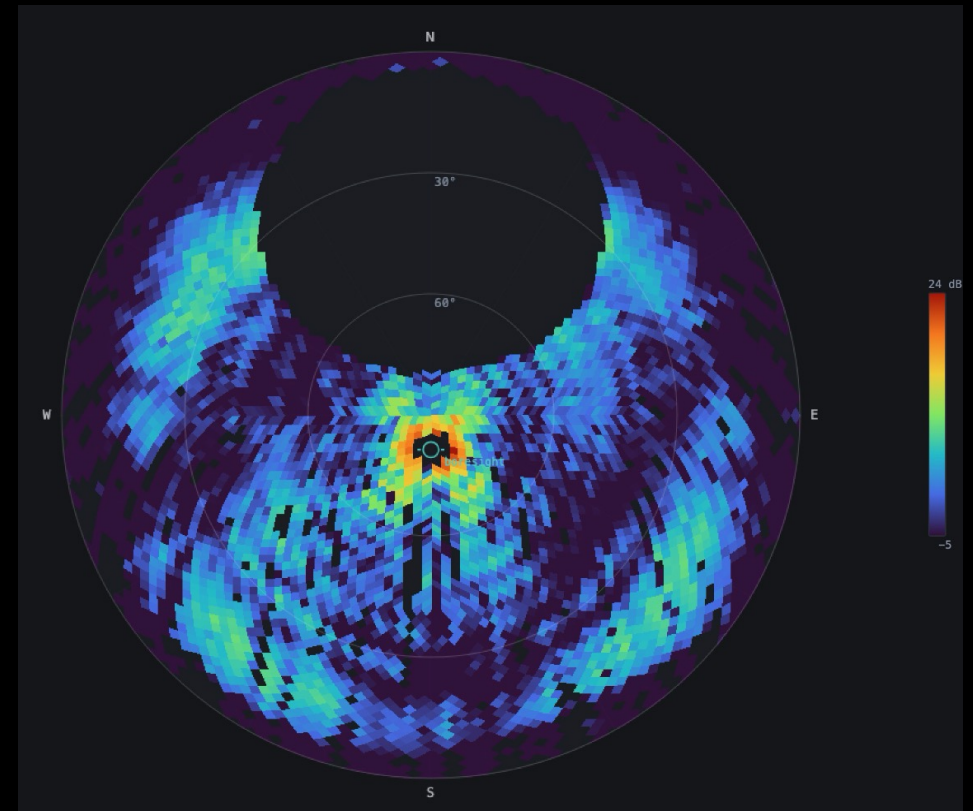
RFI due to GNSS



Vanderlinde et al 2019

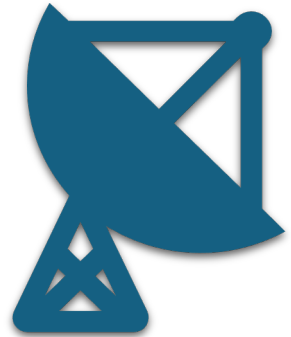
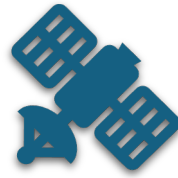
Outlook

- Optimize GNSS-SDR for beam mapping
 - Excellent to map few dishes
- CHORD:
 - 512 dishes (dual polarization): 1024 beams
 - Signal processing in correlator (X-engine)
 - Preliminary work being done
 - RFI removal
 - Calibration
 - Continuous mapping
 - Mapping ionosphere



Credit: Prof. Keith Vanderlinde, University of Toronto

Summary



High dynamic range beam map with GNSS signals

Simultaneously map all dishes

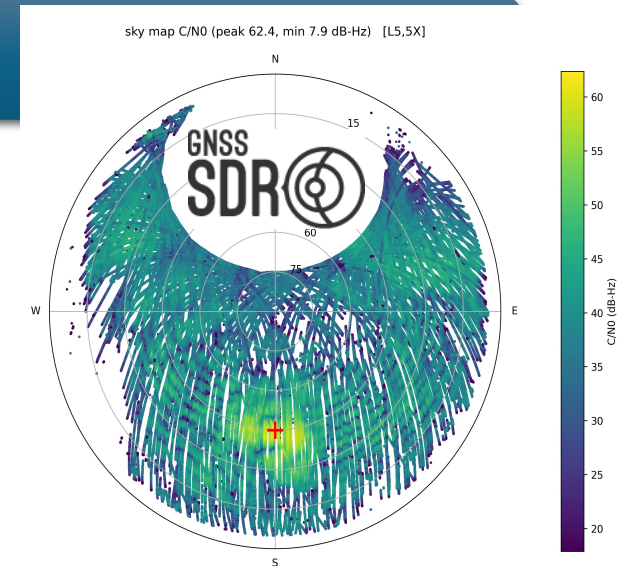
Continuous *in-situ* beam characterization

Removal of GNSS RFI (future-work)

Relative calibration of the array

THANK YOU!!

Email: shronim.tiwari@mail.mcgill.ca



McGill



Trotter
Space Institute
at McGill



Backup Slides

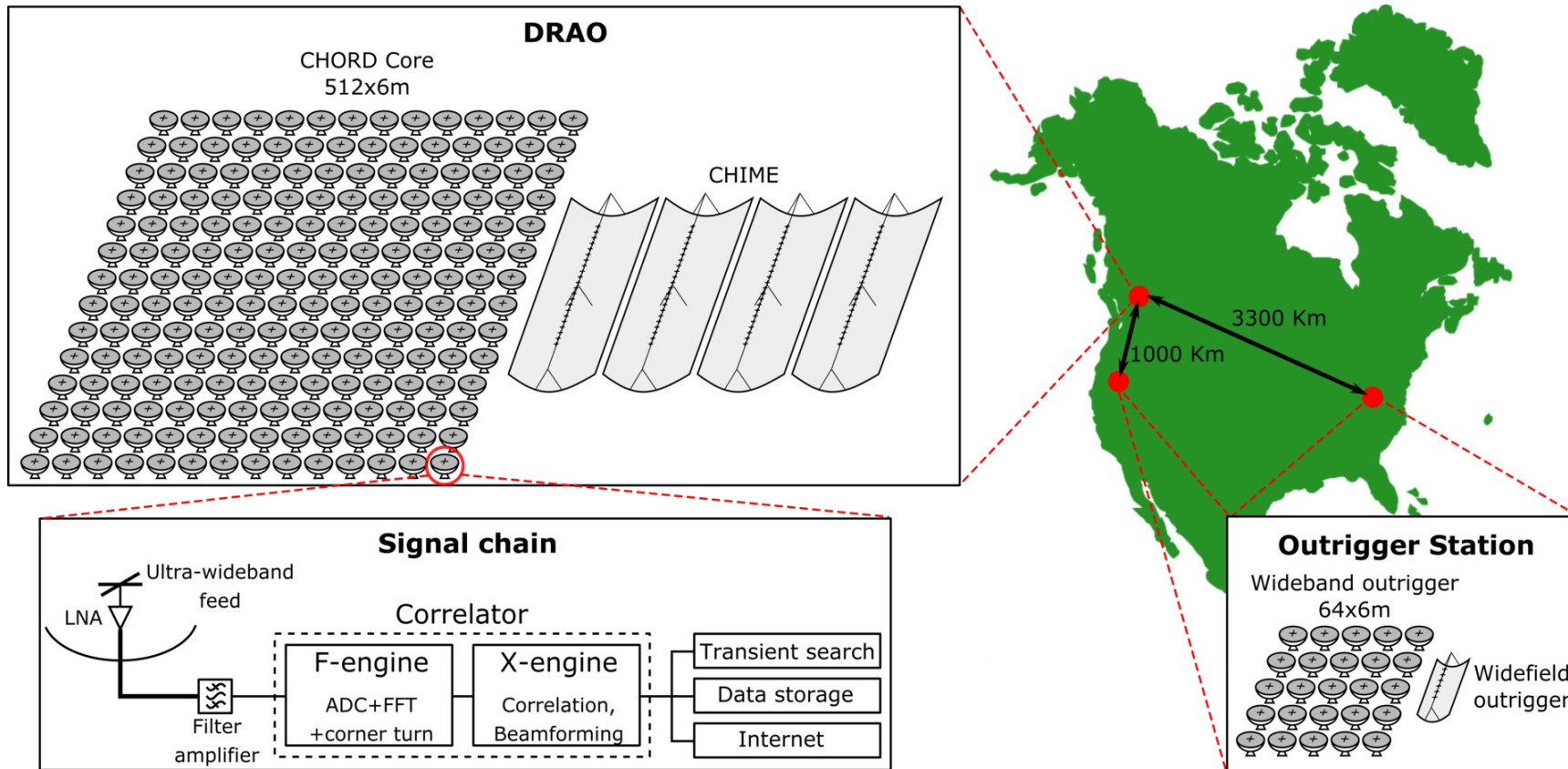
Latest overview of CHORD: <https://arxiv.org/pdf/2607.09374>

Overview of the Canadian Hydrogen Observatory and Radio Transient Detector (CHORD) Project

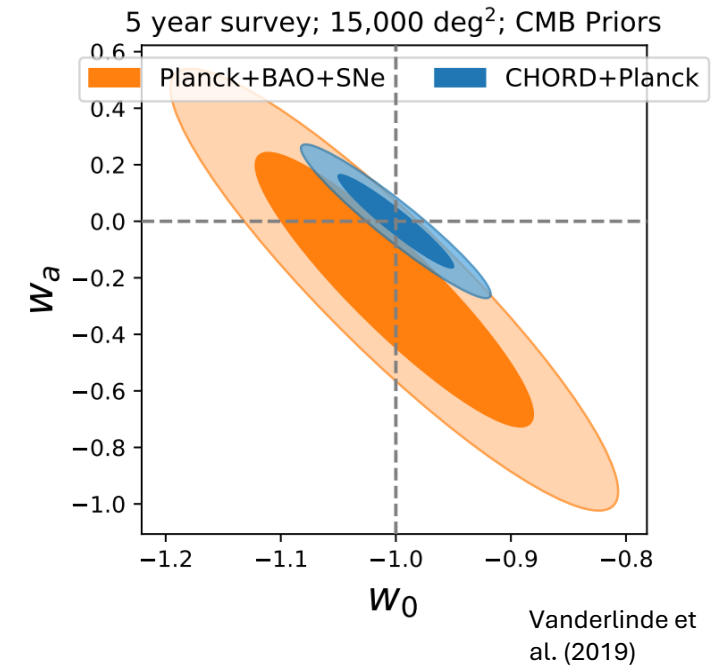
The CHORD Collaboration¹, Kevin Bandura^{a,b}, Leonid Belostotski^c, Lindsay Berkhout^{d,e}, Gianni Bernardi^{f,g,h}, Akanksha Bijⁱ, Duncan Cameron-Steinke^j, Arnab Chakraborty^{d,e}, Hsin Cynthia Chiang^{d,e}, Jean-Francois Cliche^{d,e}, Sophia Da Costa^{k,l}, Evan Davies-Veile^{d,e}, Matt Dobbs^{d,e}, Emmanuel Fonseca^{a,b}, Simon Foreman^m, Qwin Goodwinⁱ, Ian Hendricksen^{d,e}, Jason Hessels^{d,e,n,o}, Alex S Hill^{j,p}, Mohammad Islam^p, Michael Jafs^{d,e}, Aditya Krishna Karigiri Madhusudhan^{d,e}, Gordon Lacy^p, Dustin Lang^{q,r}, Calvin Leung^s, Jessie Lin^{k,t}, Adrian Liu^{d,e}, Vincent MacKay^u, Kiyoshi W. Masui^{u,v}, Juan Mena-Parra^{k,l}, James Mertens^{w,x}, Daniele Michilli^y, Kenzie Nimmo^z, Robert Pascua^{w,q}, Maura Pilia^{aa}, Andrea Possenti^{aa}, Aniket Prasad^y, Andre Renard^k, Sophia D'Agostino Rubens^{d,e}, Mawson Sammons^y, Erik Schnetter^{q,r}, Paul Scholz^{ab}, Seth Siegel^{ac,q,d,e}, Jonathan Sievers^d, Kendrick Smith^q, Kristine Spekkensⁱ, Shronim Tiwari^{d,e}, Martin Topinka^{ad}, Matteo Trudu^{d,e,aa}, Keith Vanderlinde^{k,l}, Dallas Wulf^{d,e}, and Yifan Zhao^k



CHORD and Dark Energy



Credit: Juan Mena, UofT



Observing Strategy

Drift scan

Azimuthal pointing: fixed to local meridian

Elevation pointing: manually adjusted
between Dec = 20° – 80°

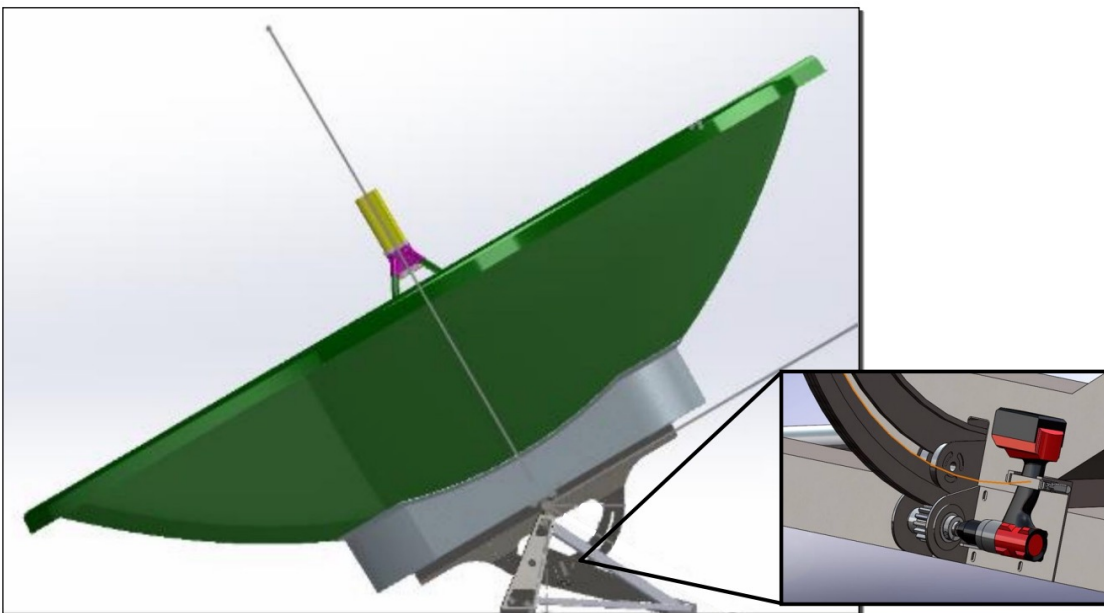
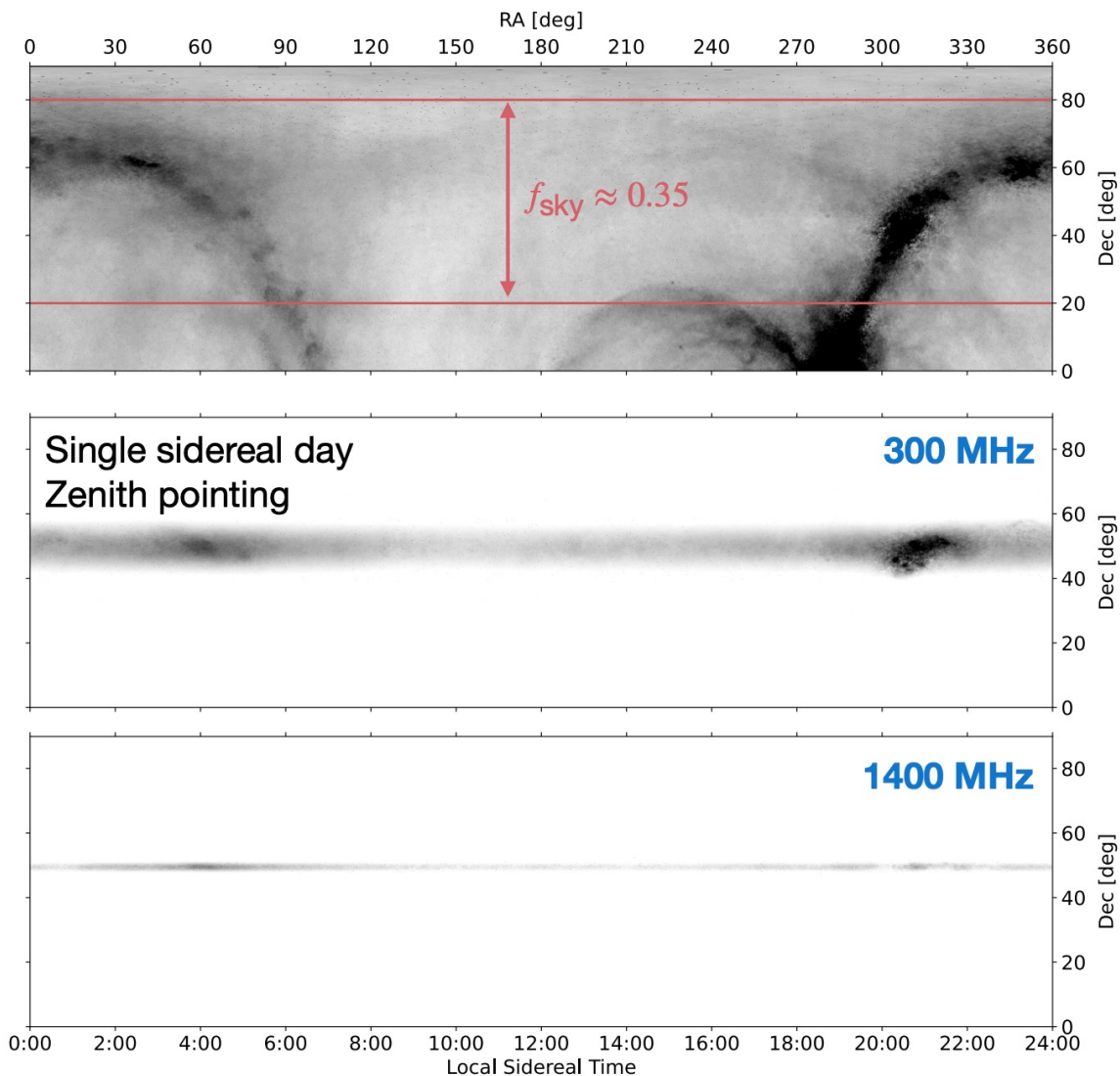
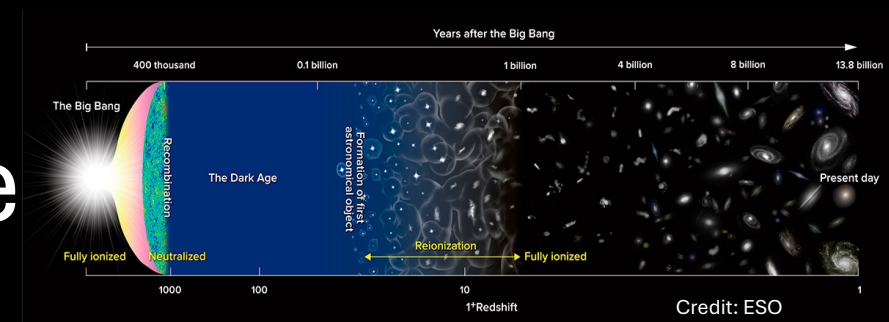


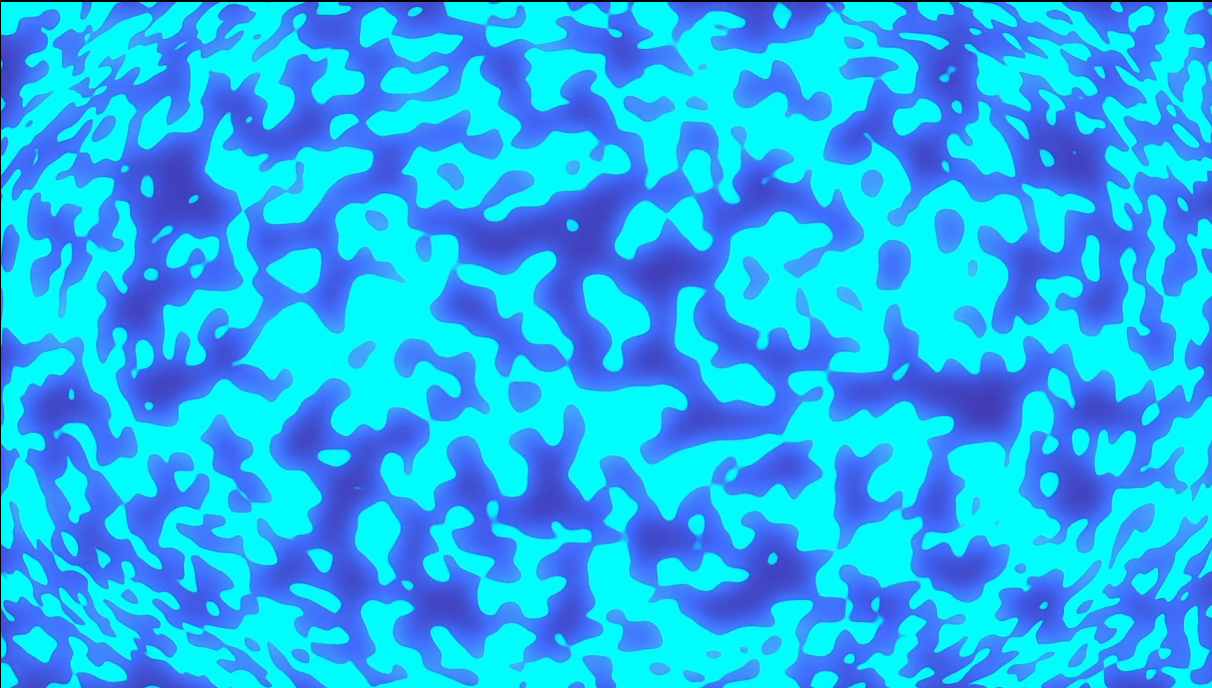
Image by Mohammad Islam (DRAO)



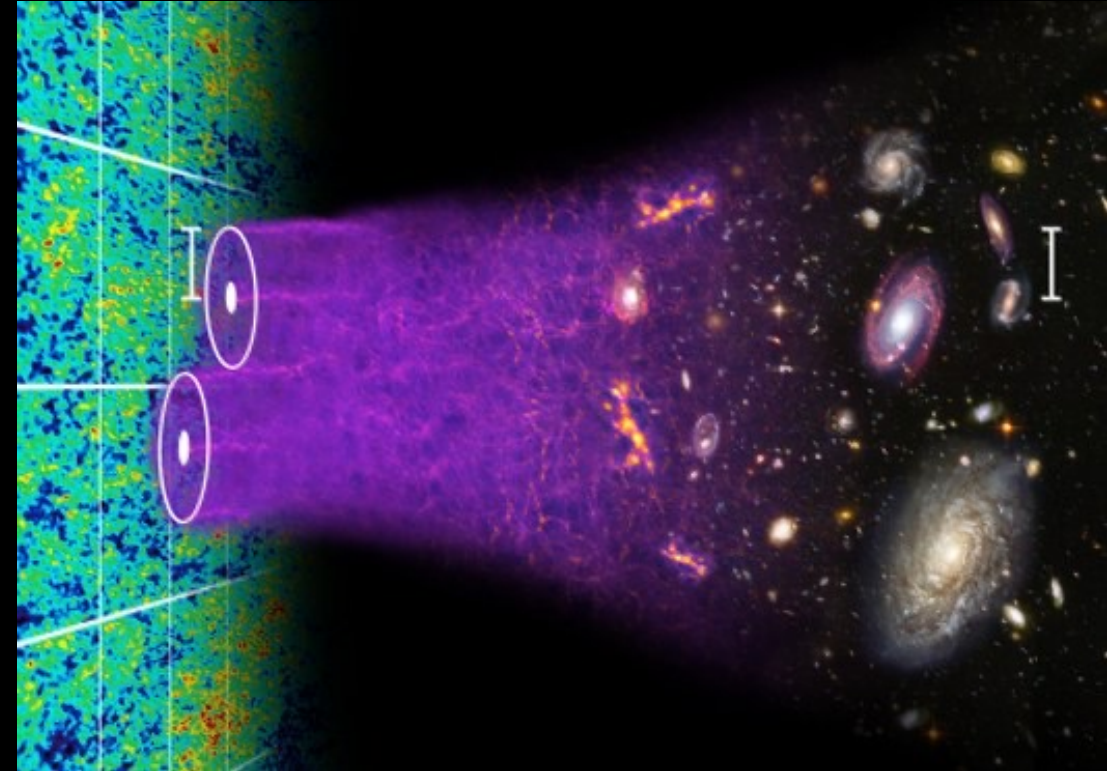
Expansion history of the universe



Baryon Acoustic Oscillations (BAOs)

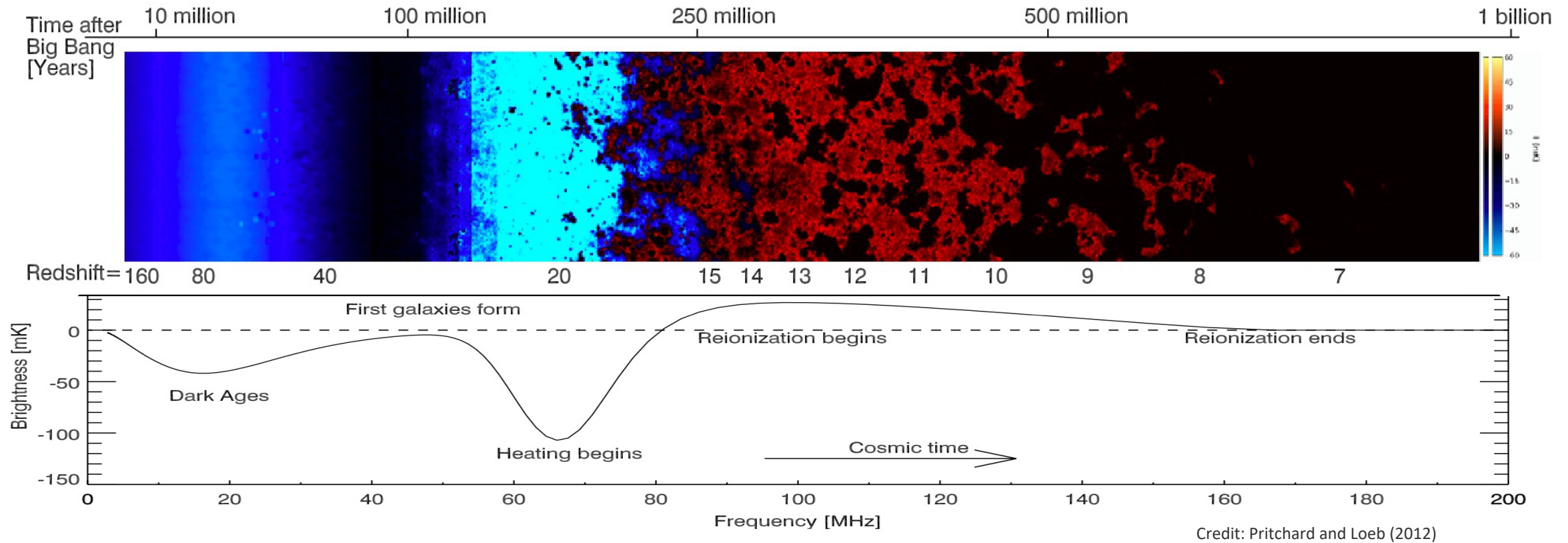


[NASA Goddard's Scientific Visualization Studio](#)

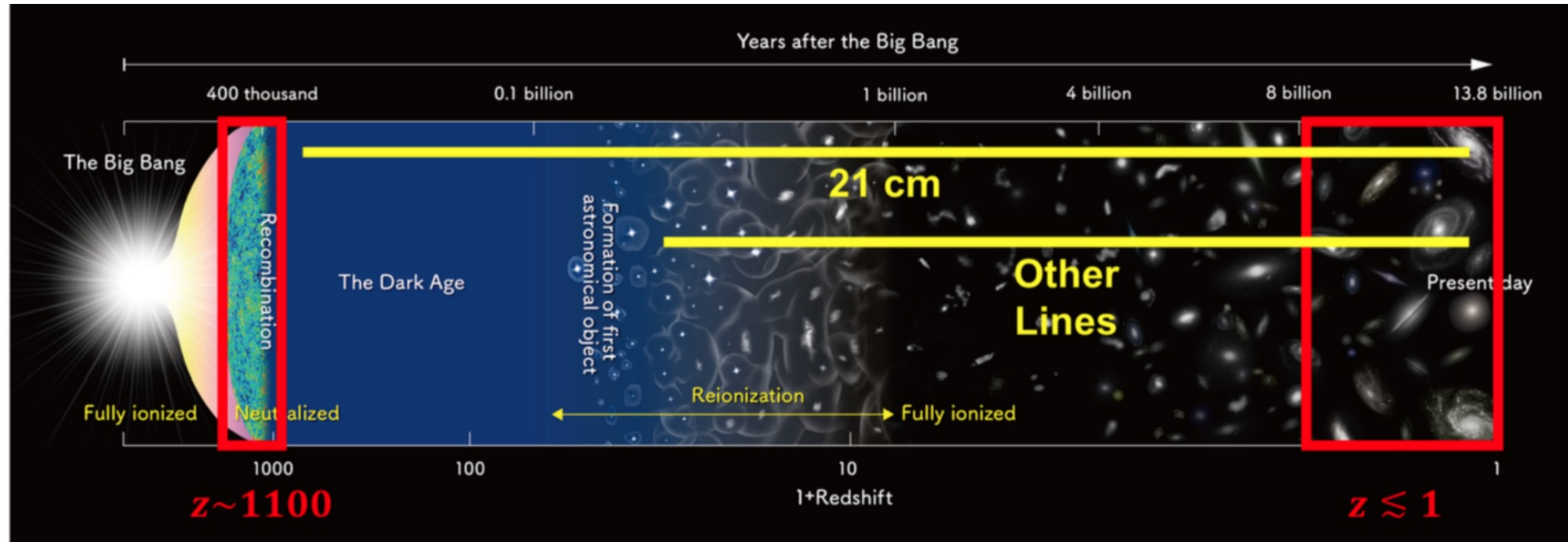


<https://www.sdss3.org/surveys/boss.php>

21 cm cosmology



Line Intensity Mapping



Source:

<https://arxiv.org/pdf/1709.09066>

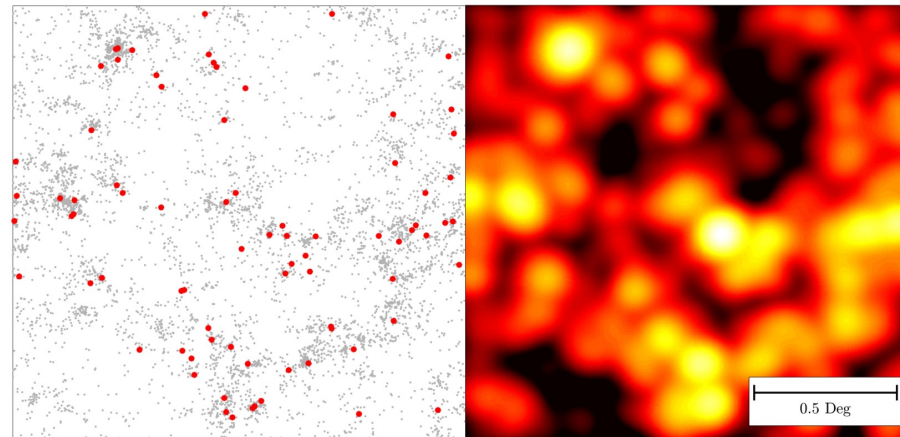


Figure 1. A simulated 2.5 deg² field with galaxy positions (Left) and the corresponding CO intensity map (Right). Luminosities were drawn from a Schechter function model (Breyse et al. 2016). Sources bright

CHIME detection

DRAFT VERSION MARCH 30, 2026

Typeset using L^AT_EX **twocolumn** style in AASTeX7.0.1

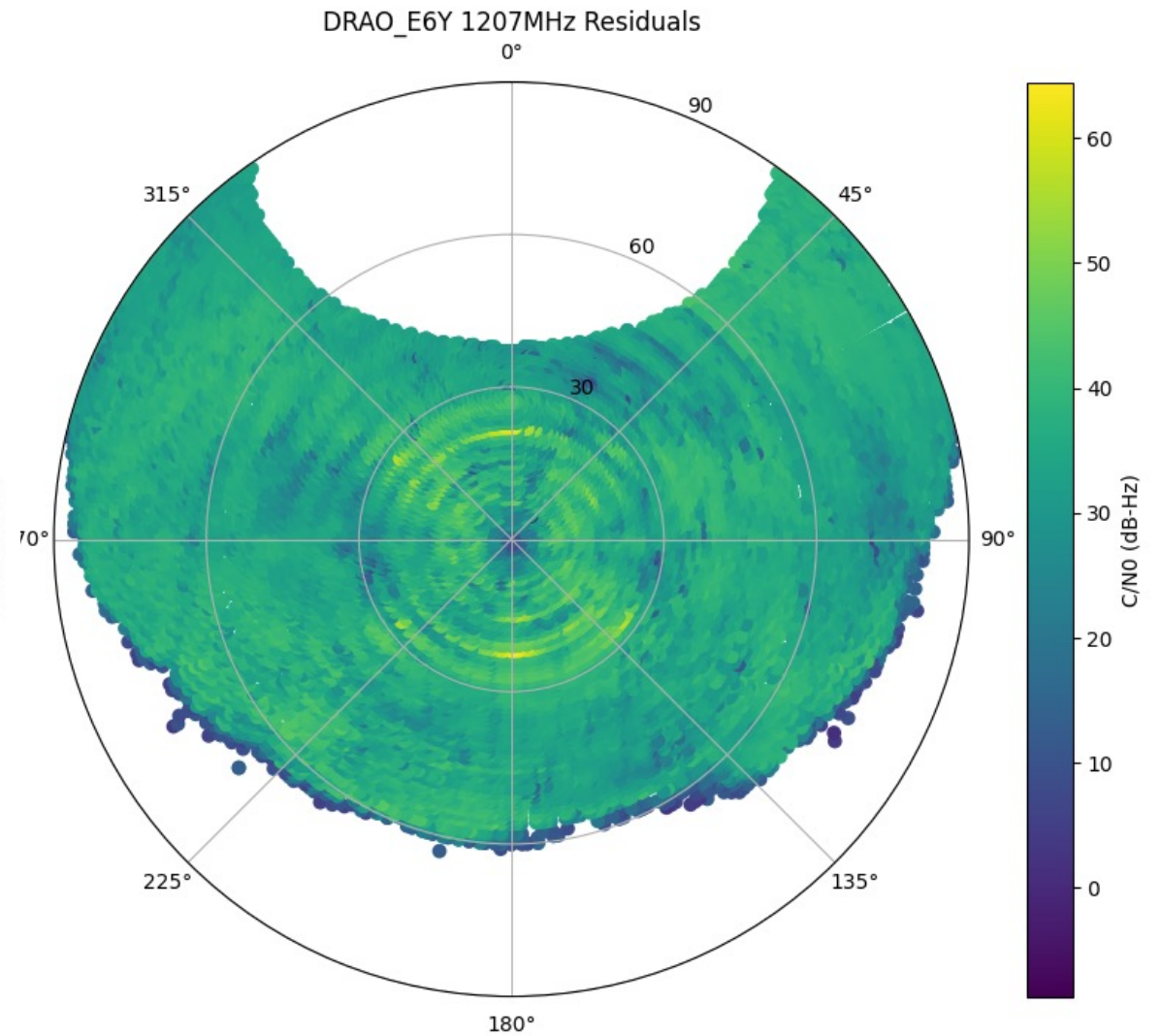
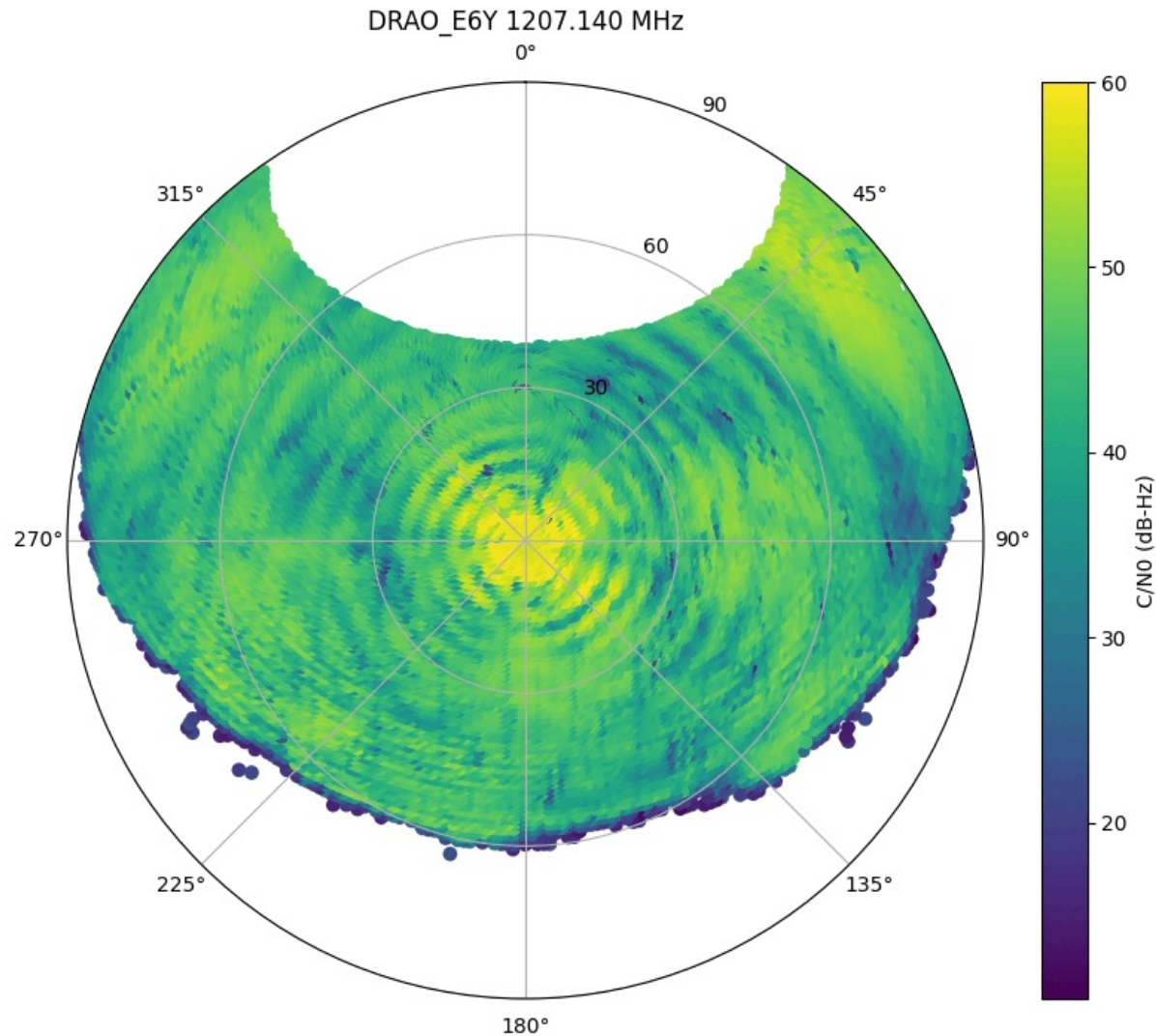
Detection of the Cosmological 21 cm Signal in Auto-correlation at $z \sim 1$ with the Canadian Hydrogen Intensity Mapping Experiment

THE CHIME COLLABORATION:

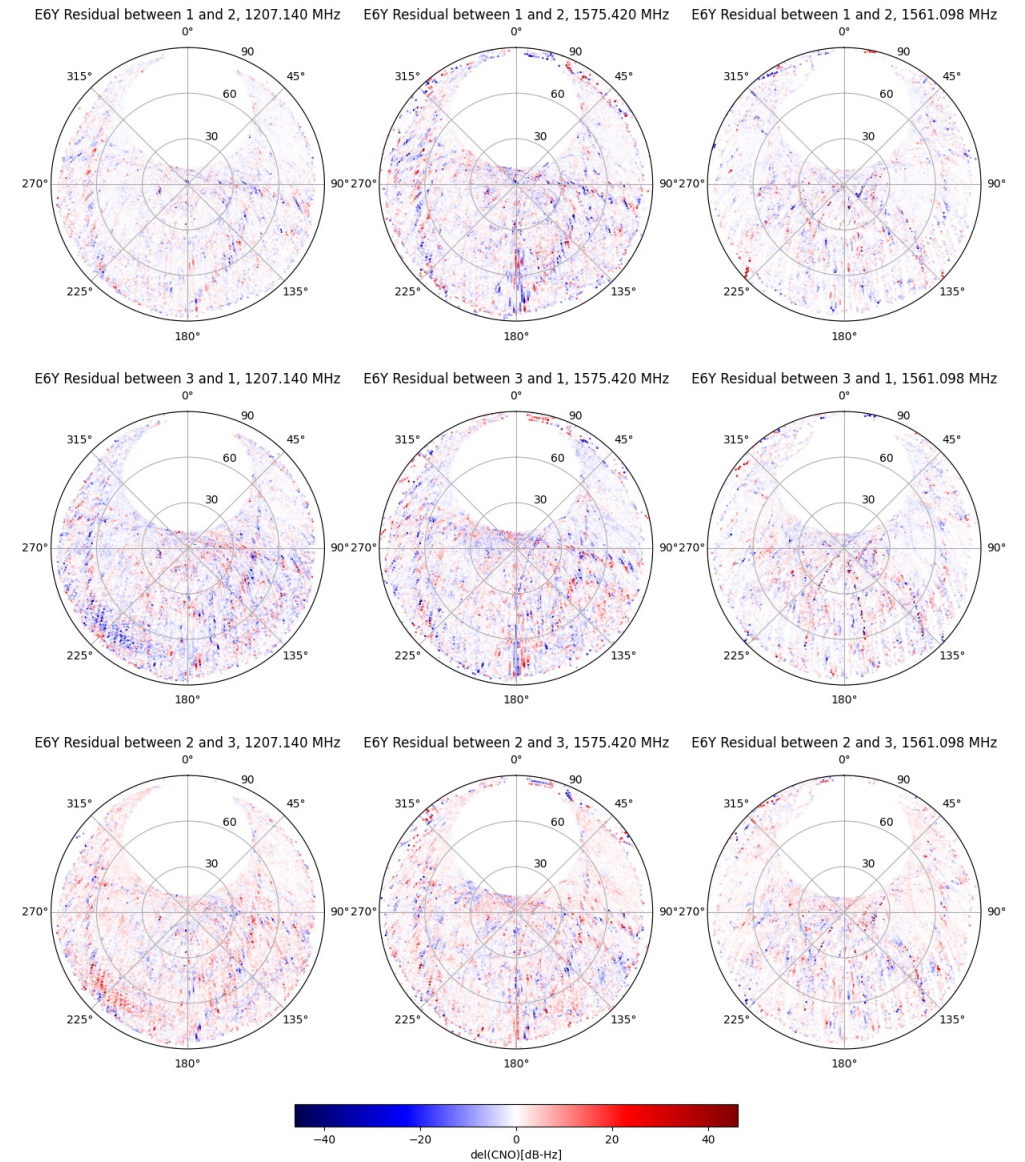
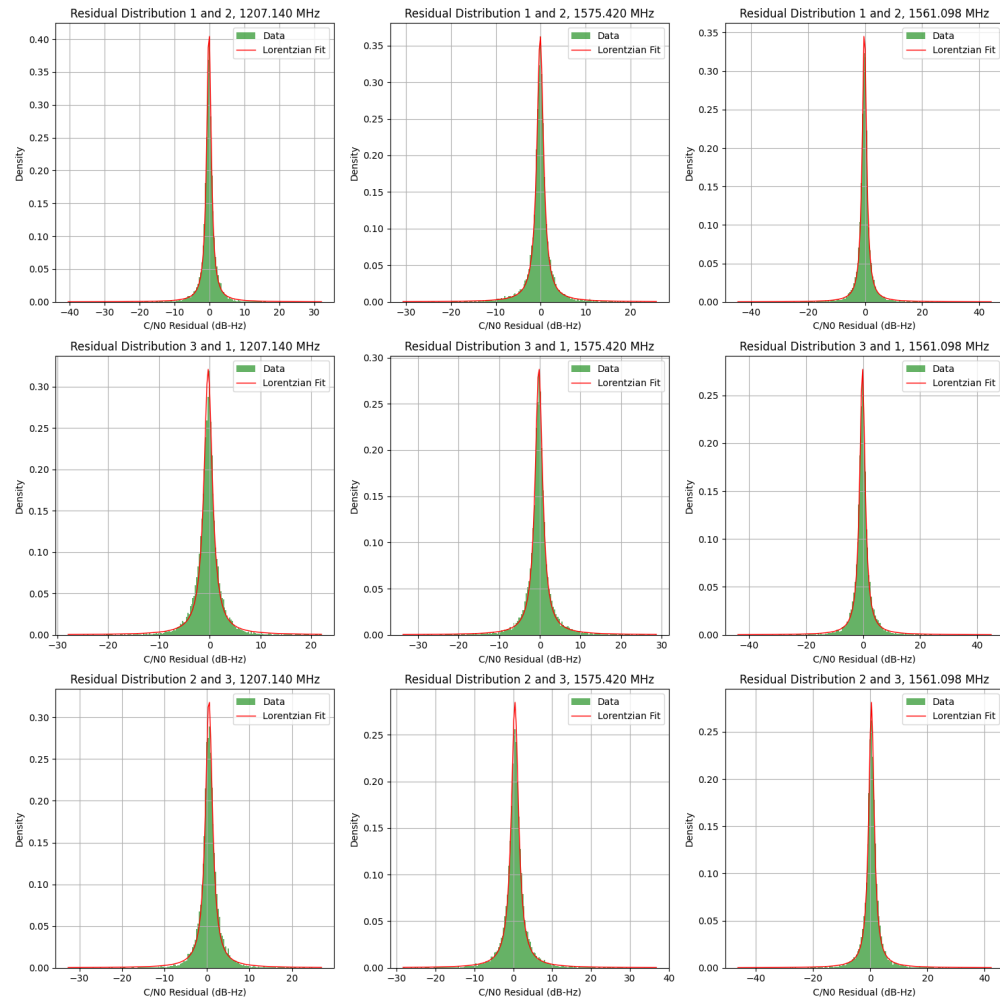
MANDANA AMIRI,¹ KEVIN BANDURA,^{2,3} ARNAB CHAKRABORTY,^{4,5} JEAN-FRANÇOIS CLICHE,^{4,5} MATT DOBBS,^{4,5}
SIMON FOREMAN,⁶ LIAM GRAY,¹ MARK HALPERN,¹ ALEX S HILL,^{7,8} GARY HINSHAW,¹ CAROLIN HÖFER,^{9,1} ALBIN JOSEPH,⁶
NOLAN KRUGER,⁶ T.L. LANDECKER,⁸ RIK VAN LIESHOUT,^{10,11} JOSHUA MACEachern,⁸ KIYOSHI W. MASUI,^{12,13}
JUAN MENA-PARRA,^{14,15} KYLE MILLER,⁴ NIKOLA MILUTINOVIC,¹ ARASH MIRHOSSEINI,¹ LAURA NEWBURGH,¹⁶
ANNA ORDOG,^{7,8,17} UE-LI PEN,^{14,18,10,19,20} TRISTAN PINSONNEAULT-MAROTTE,^{21,22} ALEX REDA,¹⁶ ANDRE RENARD,¹⁴
KANA SAKAGURI,¹⁶ J. RICHARD SHAW,¹ SHABBIR SHAIKH,⁶ SETH R. SIEGEL,^{20,4,5} SAURABH SINGH,²³ DAVID SPEAR,^{1,8}
YUKARI UCHIBORI,¹ KEITH VANDERLINDE,^{15,14} HAOCHEN WANG,^{13,12} DONALD V. WIEBE¹ AND DALLAS WULF^{4,5}

First detection of the cosmological 21 cm intensity mapping signal in auto-correlation at $z \sim 1$ / Using 94 nights of observation measured the 21 cm auto-power spectrum over a frequency range from 608.2 MHz to 707.8 MHz ($z = 1.34$ to 1.01) at $0.4 \text{ h Mpc}^{-1} \lesssim k \lesssim 1.5 \text{ h Mpc}^{-1}$, with a detection significance of 12.4σ .

Residual from simulation

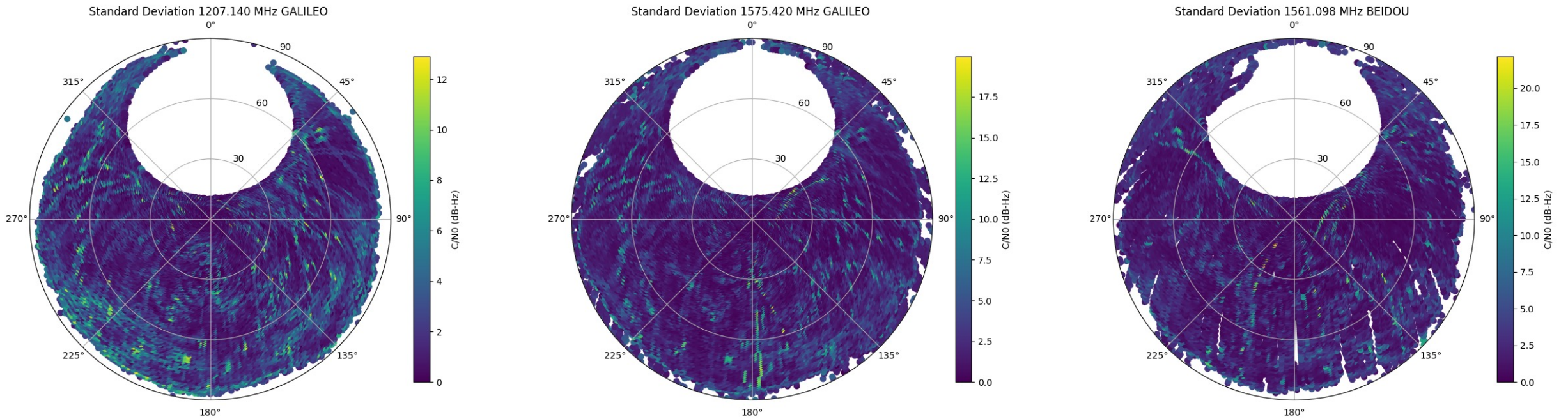


Residuals E6Y

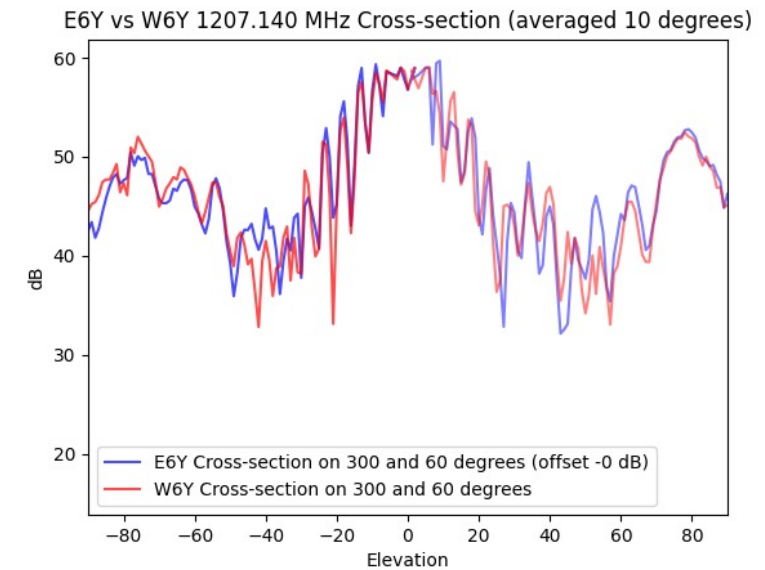
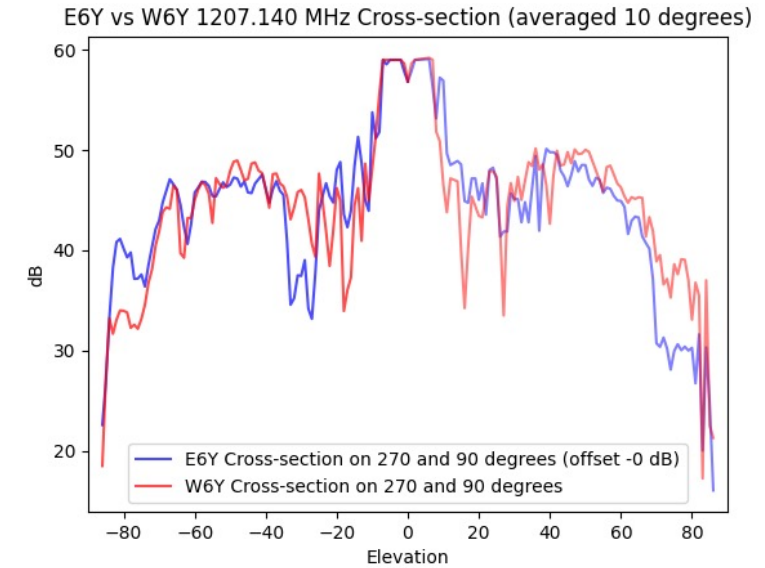
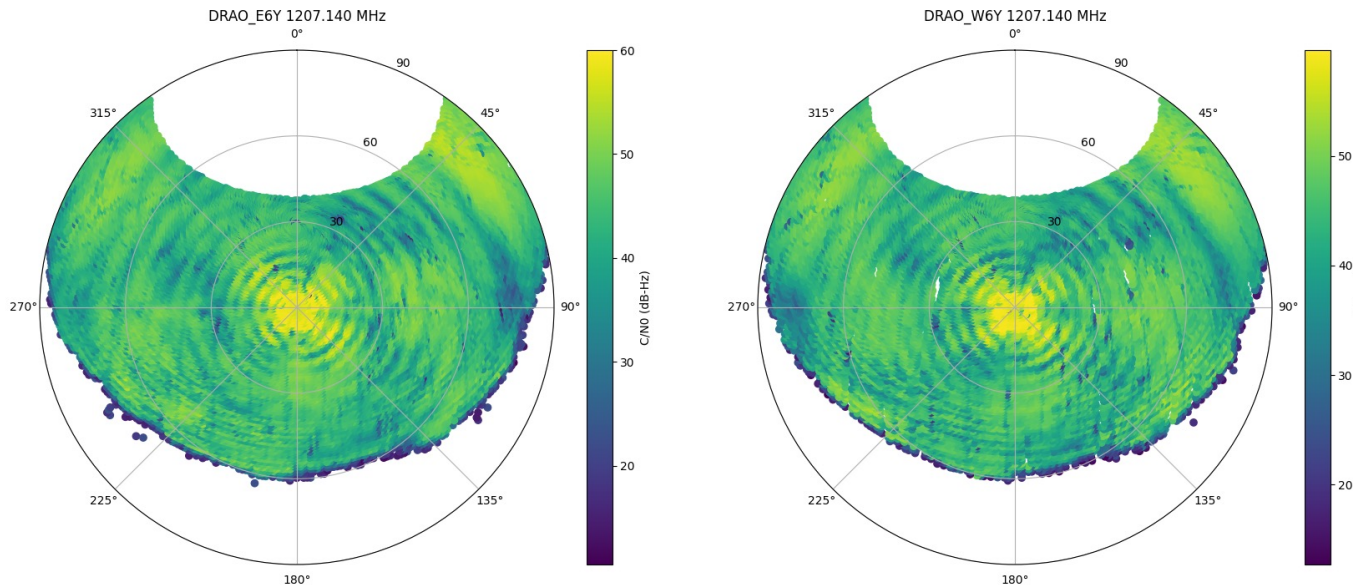


Standard Deviation Map

StDev DRAO E6Y pointed -27.3 south 264 hours Wed 22 Jan 1628 - Sun 02 Feb 1612

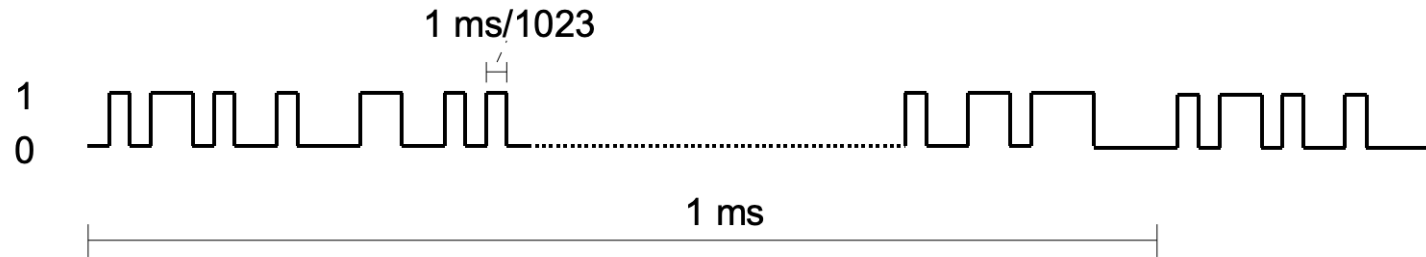


D3A6 West VS East



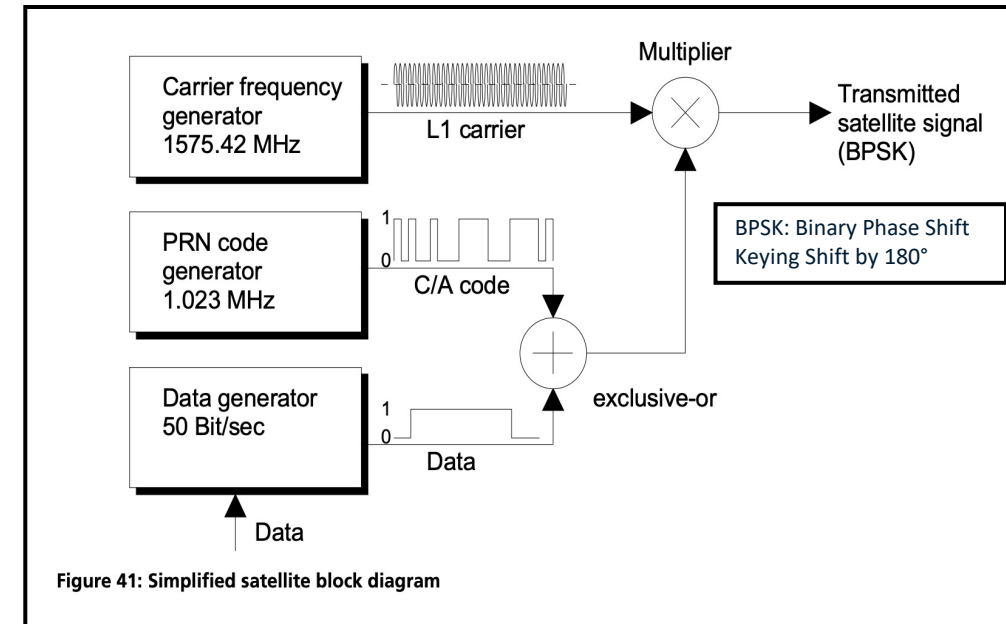
Pseudo Random Noise (PRN)

E.g. for GPS L1 C/A (1575MHz)



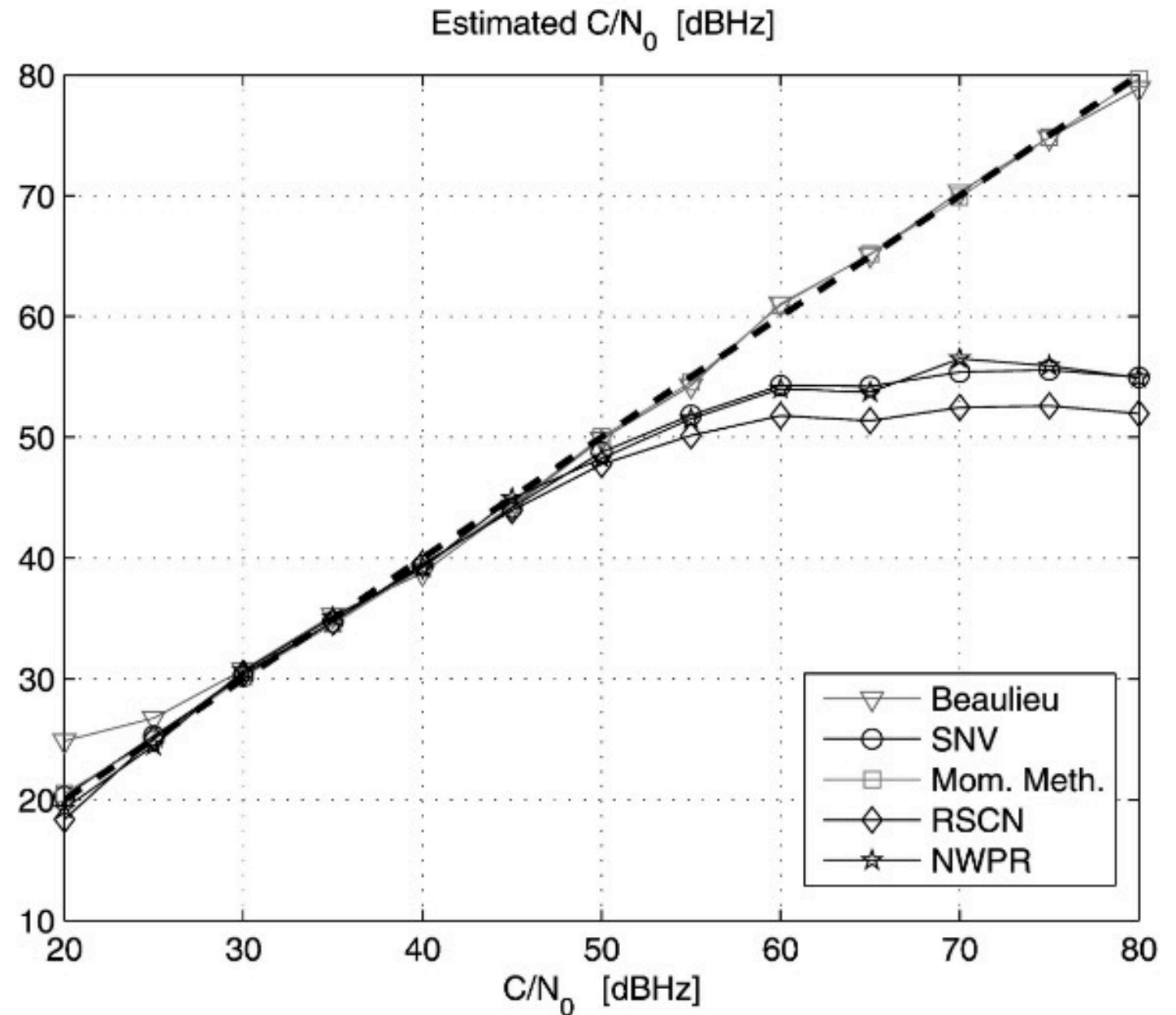
Each satellite signal is modulated with a unique PRN code (1023 zeros and ones, broadcast with a duration of 1ms and continually repeated).

- Locally generate a signal with a known PRN code and correlate it with the incoming signal to detect even faint satellite signals.



C/N0 Estimators

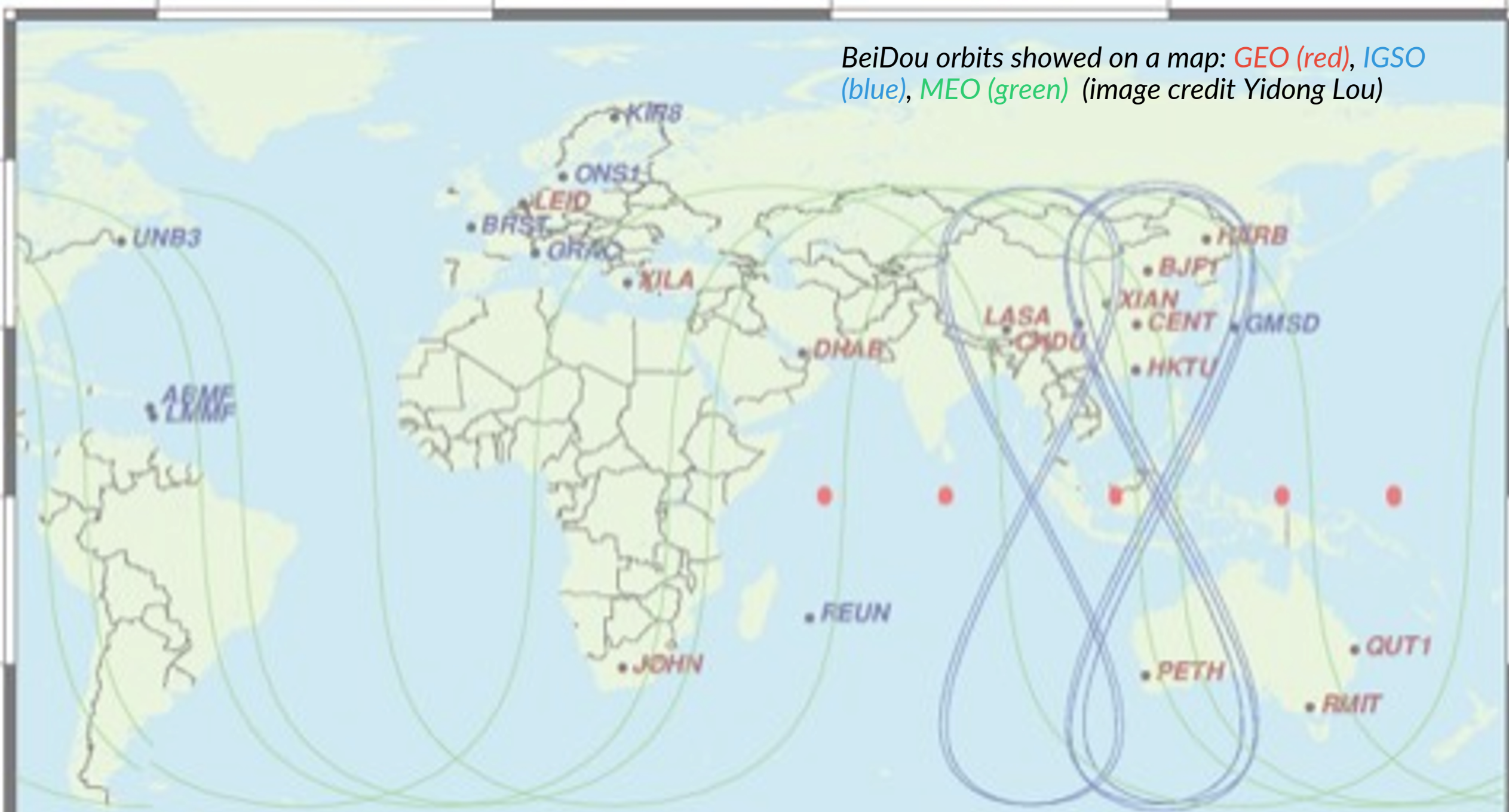
- Carrier-to-Noise ratio (C/N0) represents strength of the signal
- SNR over bandwidth of 1 Hz (thus unit [dBHz]).
- Mainly used to determine which satellites are used for location calculation.
- Many C/N0 estimators are discussed in the literature.
- Some are more reliable than others.
- Ublox: proprietary information



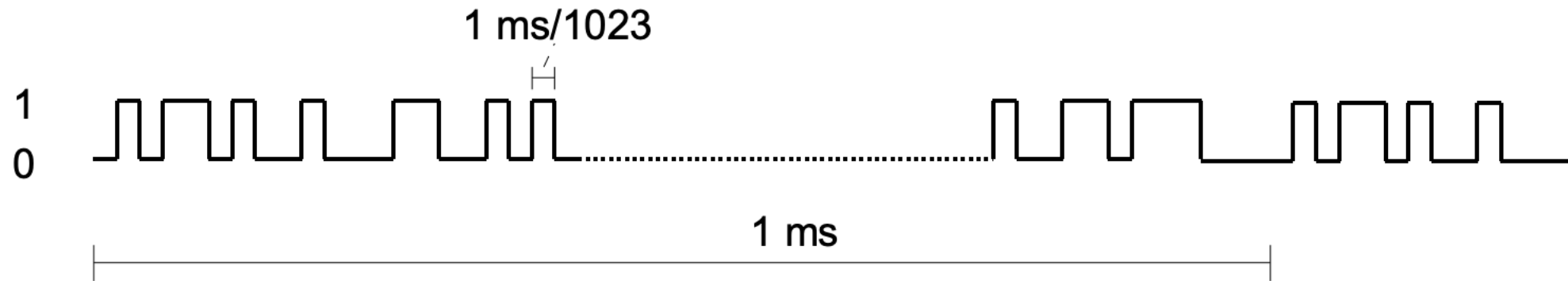
Source: Falletti et al., 2011

shronim.tiwari@mail.mcgill.ca

BeiDou orbits showed on a map: GEO (red), IGSO (blue), MEO (green) (image credit Yidong Lou)



Pseudo Random Noise (PRN)



Each satellite transmits a unique signature assigned. This signature consists of a Pseudo Random Noise (PRN) Code of 1023 zeros and ones, broadcast with a duration of 1ms and continually repeated .

- Identification: the unique signature pattern identifies the satellite from which the signal originated.
- Signal travel time measurement

Signal Structure

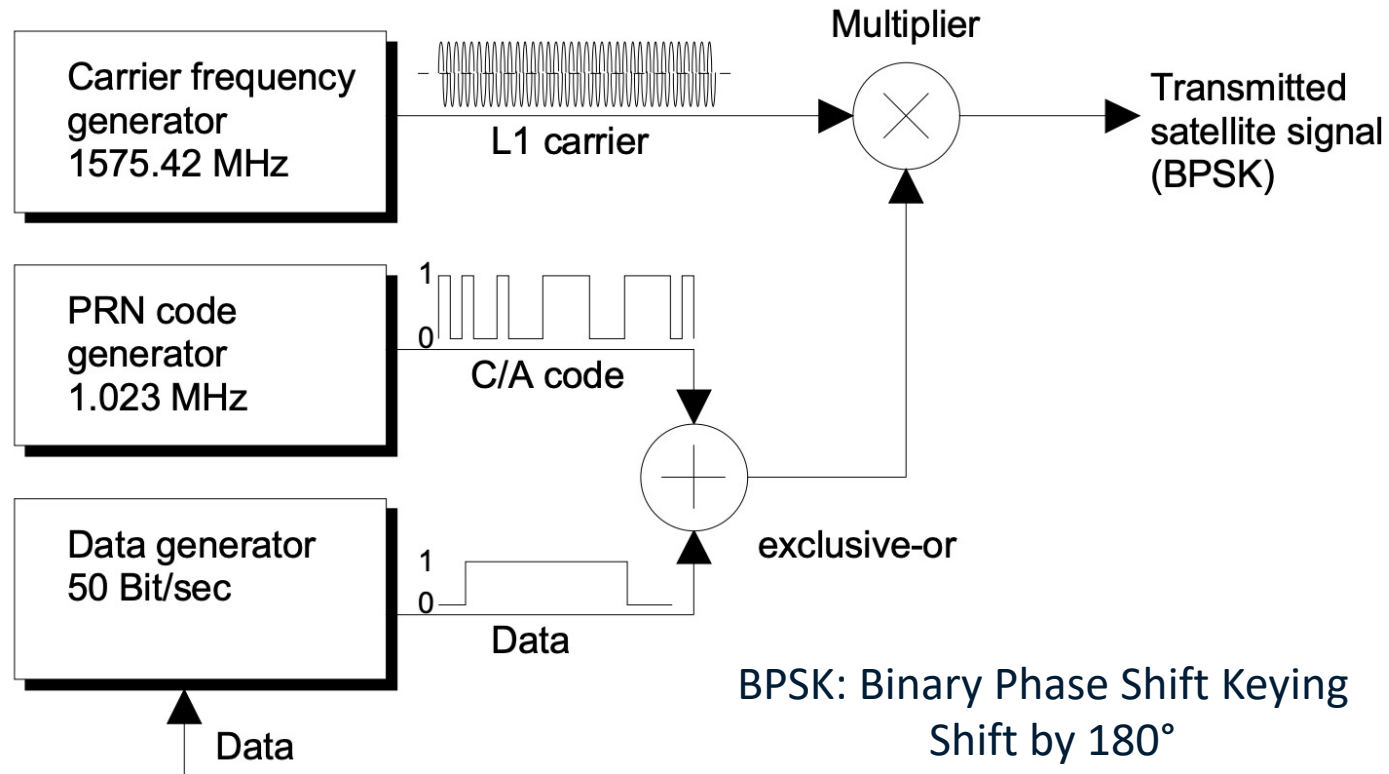
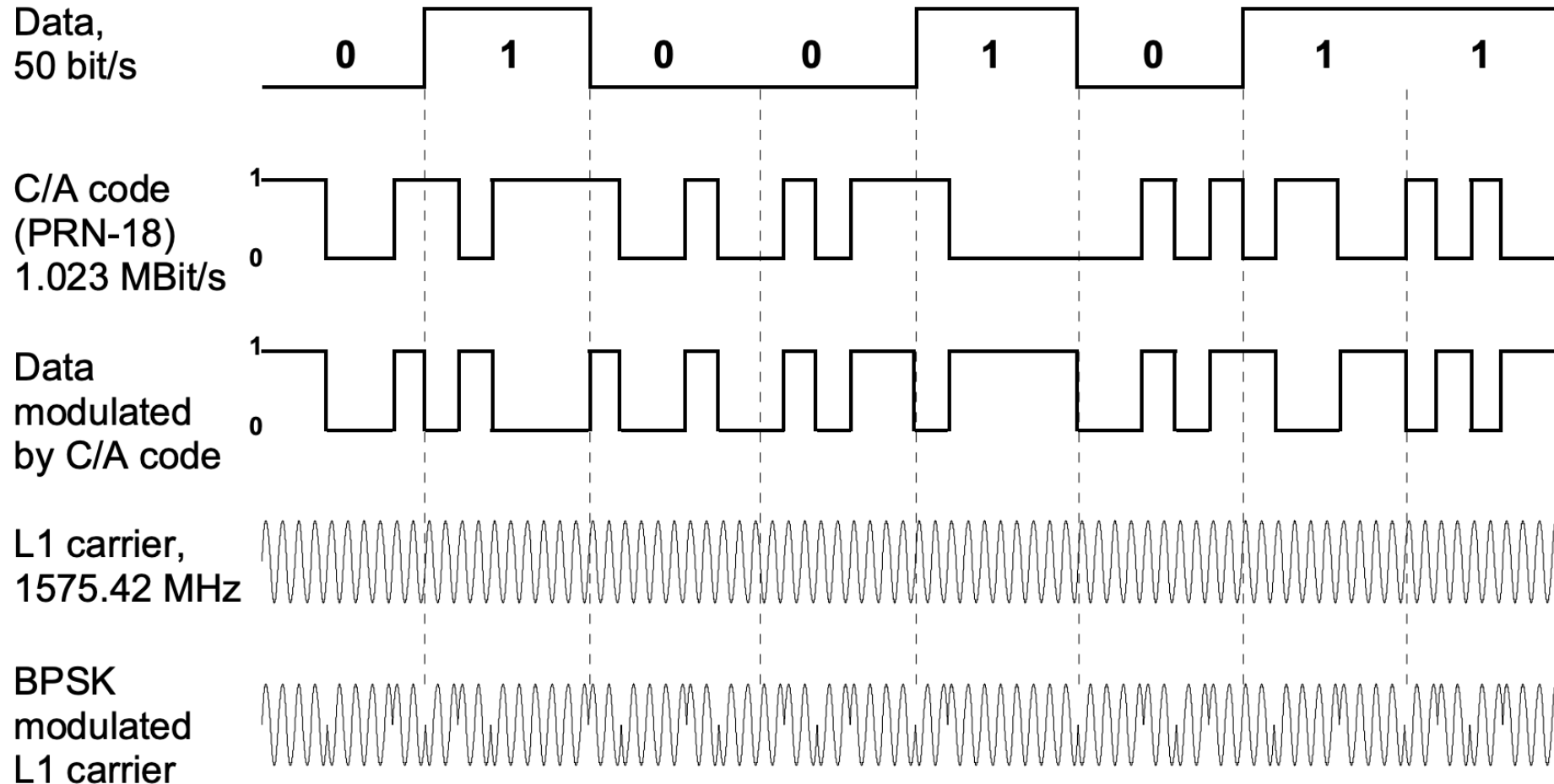


Figure 41: Simplified satellite block diagram

Signal Structure



Data structure of a GPS signal

Signal Structure

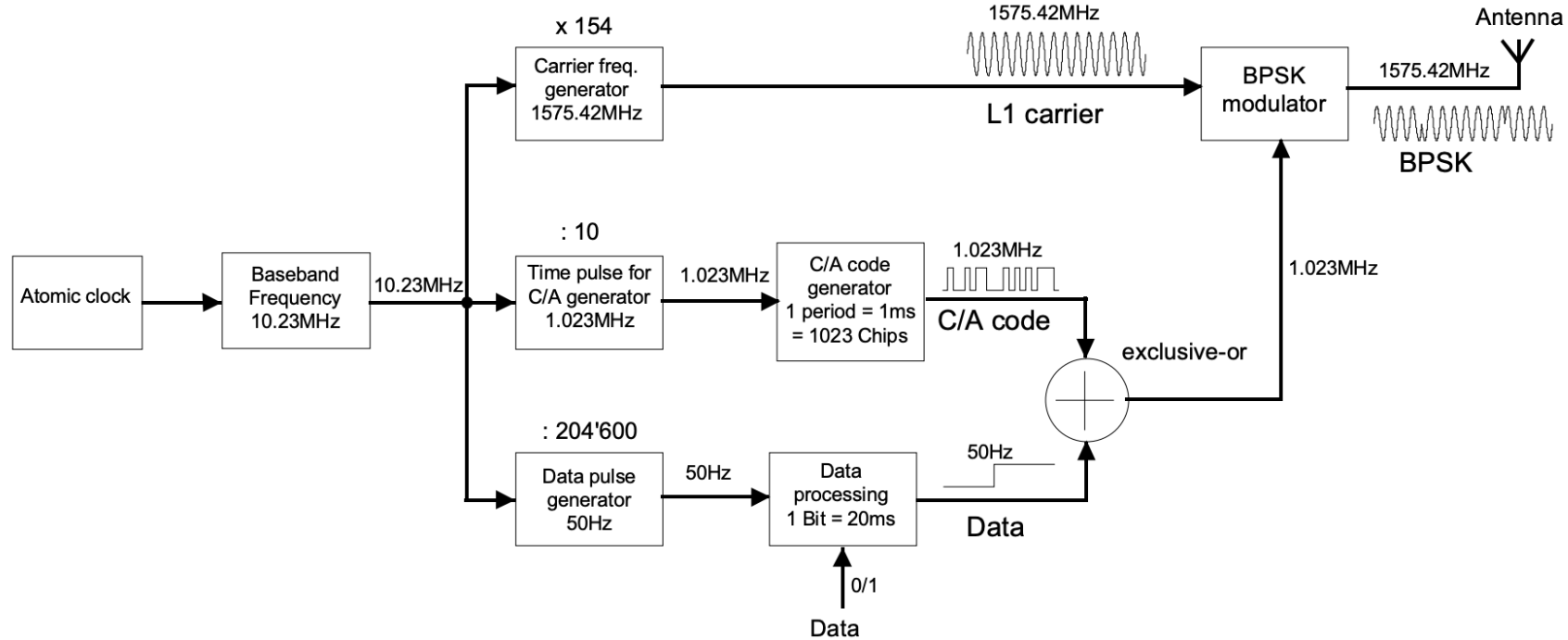
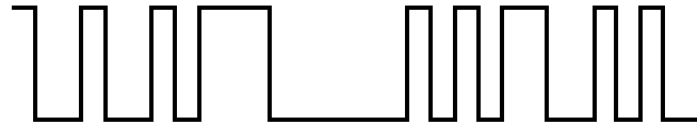


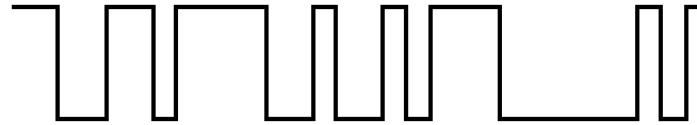
Figure 43: Detailed block diagram of a GPS satellite

Signal Structure

Incoming signal from PRN-18
bit 11 to 40, reference

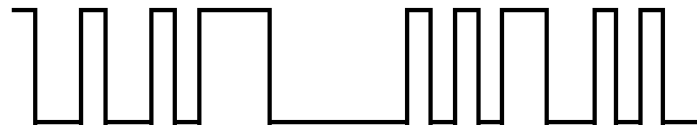


Reference signal from PRN-18
bit 1 to 30, leading



CF = 0.00

Reference signal from PRN-18
bit 11 to 40, in phase



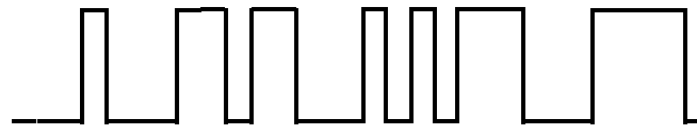
**Correlation
point:
CF = 1.00**

Reference signal from PRN-18
bit 21 to 50, trailing



CF = 0.07

Reference signal from PRN-5
Bit 11 to 40, in phase



CF = 0.33

Figure 47: Demonstration of the correction process across 30 bits

Signal Structure

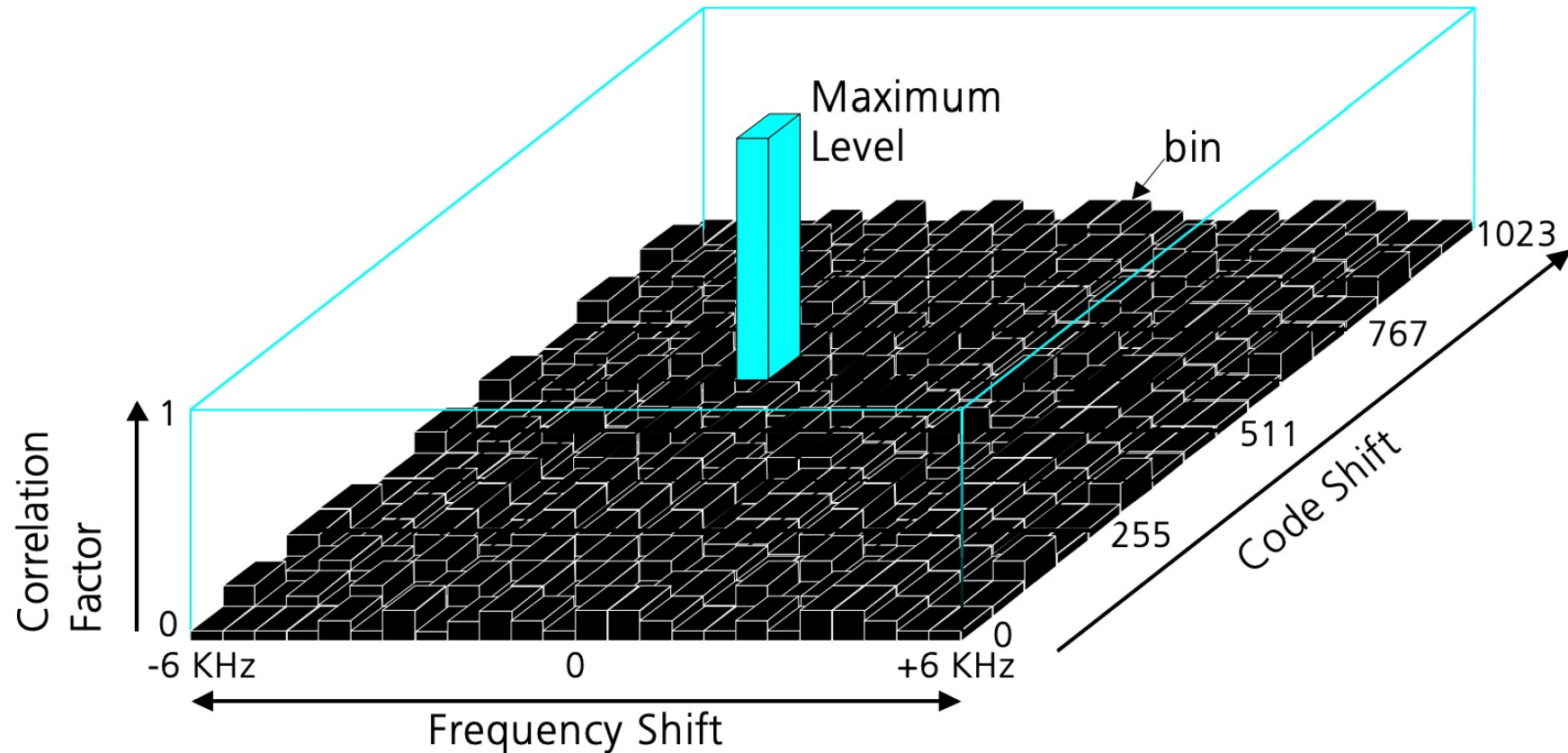


Figure 48: Search for the maximum correlation in the code and carrier frequency domains